Independent Scientific Panel Inquiry into Hydraulic Fracture Stimulation in Western Australia

Final Report to the Western Australian Government
September 2018

Independent Scientific Panel Inquiry into Hydraulic Fracture Stimulation in Western Australia

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Letter of transmittal

The Hon. Stephen Dawson MLC

Minister for Environment

12th Floor, Dumas House

2 Havelock Street

WEST PERTH WA 6005

Dear Minister,

On 5 September, last year, the Western Australian Government announced the establishment of the Independent Scientific Inquiry into Hydraulic Fracture Stimulation in Western Australia (the Inquiry), and subsequently appointed a Panel of experts from a diverse range of expertise, under Section 25 of the *Environmental Protection Act 1986*, to deliver that Inquiry.

As the Panel Chair, I am pleased to present to you the Inquiry's Report on the potential risks arising from the implementation of hydraulic fracture stimulation on the onshore environment of Western Australia and recommendations that may be employed to mitigate these risks.

This Report follows a comprehensive review of scientific literature and evidence, multiple public meetings in the Kimberley, the Midwest and Perth, the consideration of more than 9,500 public submissions, and targeted stakeholder consultations with agencies, industry and non-governmental organisations. The Report also reflects and incorporates independent peer review by experts from across Australia.

As part of its Report, the Panel has made 91 Findings regarding the risks, public concern and regulation of onshore hydraulic fracture stimulation, and 44 Recommendations as to how those risks and concerns might be further reduced should the Government choose to lift the current moratorium on hydraulic fracture stimulation in Western Australia.

The Panel was not invited to make a recommendation regarding the moratorium, and we have not done so in this Report.

The Panel is deeply grateful to the many people who contributed to this Inquiry over the past 12 months. Their input greatly enriched the depth and thoroughness of our considerations. We are also grateful for the respect to our independence shown by the Government, and the Panel emphasises that the findings and recommendations contained in this Report are absolutely the independent view of the Panel, and based solely upon an unbiased assessment of the available evidence.

Sincerely,

Dr Tom Hatton PSM FTSE

Mr Philip Commander

Prof Fiona McKenzie

Dr Jackie Wright

Dr Ben Clennell

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Glossary/Shortened forms

Abandonment	A process which involves shutting down the well and rehabilitating the site. It includes decommissioning the well
ACOLA	Australian Council of Learned Academies
AEMO	Australian Energy Market Operator
Aeolian	Relating to or arising from the action of the wind, for example Aeolian dust
AH Act	*Aboriginal Heritage Act 1972* (WA)
AHD	Australian Height Datum
AHDDG	*Aboriginal Heritage Due Diligence Guidelines 2013* (WA)
AICS	Australian Inventory of Chemical Substances
ALARP	As Low As Reasonably Practicable
ALMAG2	Airborne Laser Methane Assessment Generation 2
ANCA	Australian Nature Conservation Agency
ANSI	American National Standards Institute
API	American Petroleum Institute
APPEA	Australian Petroleum Production and Exploration Association
APVMA	Australian Pesticides and Veterinary Medicines Authority
Aquiclude	A geological formation that is capable of absorbing and holding water, without transmitting it at a rate sufficient to be considered a source of water. Sometimes used synonymously with 'aquitard' because it retards transmission of water
Aquifer	An underground layer of water-bearing permeable rock
ATSE	Australian Academy of Technology and Engineering

AWE	Australian Worldwide Exploration Limited
Barrier failure	When a single, specific barrier fails to contain fluids (remaining barriers maintaining containment)
Basin	A sedimentary basin is an area of the Earth's crust subject to long term subsidence, commonly over hundreds of millions of years, allowing the accumulation of up to 15,000 metres of sedimentary rocks
BCA	*Biodiversity Conservation Act 2016* (WA)
Bioregion	A geographically defined place or area that constitutes a natural ecological community
Bottom-up	Local measurements to make inferences about large scale phenomena (Science definition)
Brackish water	Water that has a higher salinity content than fresh water, but not as much as seawater
BTEX	Benzene, Toluene, Ethylbenzene, Xylene
CALM Act	*Conservation and Land Management Act 1984* (WA)
Carboniferous	A geological period of 60 million years that spans from the end of the Devonian Period 358.9 million years ago, to the beginning of the Permian Period
Casing	A pipe placed in a well to prevent the wall of the hole from caving in and to prevent movement of fluids from one formation to another
CAS Number	A unique numerical identifier assigned by the Chemical Abstracts Service (CAS) to every chemical substance described in the open scientific literature
CASP	Critical Appraisals Skills Programme
Catchment	A catchment (also called a watershed) is an area of land where water from different sources is drained through a river network. Also called a basin
CBI	Confidential Business Information

CCWA	Conservation Council Western Australia
CEBMa	Centre for Evidence-based Management
Cementing	The application of a liquid slurry of cement and water to various points inside and outside the casing
CEO	Chief Executive Officer
CH_4	Methane
CNG	Compressed Natural Gas
CO_2	Carbon dioxide
COAG Energy Council	Council of Australian Governments Energy Council
Coal Seam Gas	Gas trapped in a shallow coal seam, usually 300 m to 1000m below the grounds surface
CoC	Chemicals of Concern
Containment	The prevention of the escape of fluids (i.e. liquids or gases) from a well to the surrounding environment.
Contingent resources	Quantities of petroleum that are estimated to be potentially recoverable but not currently considered to be commercially recoverable
Conventional gas	Natural gas that is extracted from the earth through traditional drilling methods, where gas is extracted by the natural pressure from wells and pumping operations
Cretaceous	A geologic period of 79 million years that spans from the end of the Jurassic Period 145 million years ago, to the beginning of the Paleogene Period
CSG	Coal Seam Gas
CSIRO	Commonwealth Scientific and Industrial Research Organisation

DAA	Department of Aboriginal Affairs (WA) This Department was amalgamated into the Department of Planning, Lands and Heritage on 1 July, 2017
DBCA	Department of Biodiversity, Conservation and Attractions (WA)
Decommission	The process of closure, relinquishment and abandonment of infrastructure.
Desertification	The transformation of land to desert, caused by changes in the climate or destructive land use
Devonian	A geological period of 60 million years that spans from the end of the Silurian Period 419.2 million years ago, to the beginning of the Carboniferous Period
Dieback	The gradual dying of a plant as a result of various diseases or climatic conditions
DMIRS	Department of Mines, Industry Regulation and Safety (WA)
DMP	Department of Mines and Petroleum (WA) This Department was amalgamated into the Department of Mines, Industry Regulation and Safety on 1 July, 2017
DNAPL	Dense Non-Aqueous Phase Liquids
DoEE	Department of Environment and Energy (Aus)
DoH	Department of Health (WA)
DoW	Department of Water (WA) This Department was amalgamated into the Department of Water and Environmental Regulation on 1 July, 2017
DPLH	Department of Planning, Lands and Heritage (WA)
Drainage Basin	A collection of catchments in Australia
DRASTIC	An index developed by the U.S. Environmental Protection Agency that provides a basis for assessing groundwater vulnerability to pollution based on hydrogeologic parameters

DWER	Department of Water and Environmental Regulation (WA)
EDO	Environmental Defender's Office (WA)
EIA	Environmental Impact Assessments
Emissions factor	A representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity
EMP	Environmental Management Plan
EP	Petroleum Exploration Permit
EPA	Environmental Protection Authority (WA)
EP Act	*Environmental Protection Act 1986* (WA)
EPA Red Book	The EPA Redbook Recommended Conservation Reserves 1976-1991 contains the boundaries of areas recommended for conservation by the Environmental Protection Authority of Western Australia, as set out in a series of maps and text in the publication Red Book Status Report (1993)
EPBC Act	*Environmental Protection and Biodiversity Conservation Act 1999* (Aus)
EWR	Ecological Water Requirement
Ferruginised	Cemented or suffused with iron
Fissile	Easily split, as in rock
Flowback water	Wastewater returned to the surface in the period immediately following hydraulic fracture stimulation
FMP	Field Management Plan
FOI	Freedom of Information
Fracking	Fracturing of rock with a liquid under high pressure to create cracks in the rocks to increase the rock's permeability. Also see Hydraulic Fracture Stimulation or Hydraulic Fracturing

FSANZ	Food Standards Australia and New Zealand
Fugitive emissions	The unintentional release of environmentally harmful substances into the air, water and land
GA	Geoscience Australia
GDA	Geometric Datum of Australia
GDE	Groundwater Dependent Ecosystems
Gel	A fluid with a higher than normal viscosity created by a material such as polymer.
GHG	Greenhouse Gas
GISERA	Gas Industry Social and Environmental Research Alliance
Government	Western Australian Government
Groundwater	Water beneath the surface at more than atmospheric pressure such that it will flow into a bore or well
GSWA	Geological Survey of Western Australia
GWP	Global Warming Potential
HDPE	High-density Polyethylene
HDV	Heavy Duty Vehicle
Health Act	Health Act 1911 (WA)
HF	Hydraulic Fracturing
HFF	Hydraulic Fracturing Fluid
HFS	Hydraulic Fracturing Stimulation
HHRA	Human Health Risk Assessment
Horizontal drilling	The drilling of multiple wells that radiate laterally at the target depth from a single well pad

HSIS	Hazardous Substances Information System
Hydraulic Conductivity	The ability of a material (soil, regolith, rock)to transmit water
Hydraulic Fracture Stimulation	Fracturing of rock with a liquid under high pressure to create cracks in the rocks to increase the rock's permeability. Also see Hydraulic Fracturing or Fracking
Hydraulic Fracturing	Fracturing of rock with a liquid under high pressure to create cracks in the rocks to increase the rock's permeability. Also see Hydraulic Fracture Stimulation or Fracking
Hydrocarbon	A class of organic chemical compound that is composed only of carbon and hydrogen elements
IBRA	Interim Biogeographic Regionalisation for Australia
IEA	International Energy Agency
IESC	Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development
IMAP-DOAS	Iterative Maximum A Posteriori Differential Optical Absorption spectroscopy
Imbibe	To absorb or assimilate moisture, gas, light or heat
Induced seismicity	Earthquakes or tremors caused by human activity.
Inquiry	Scientific Inquiry into Hydraulic Fracture Stimulation in Western Australia
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organisation
JPL	Jet Propulsion Laboratory
Jurassic	A geological period of 56 million years that spans from the end of the Triassic Period 201.5 million years ago, to the beginning of the Cretaceous Period

Karst	An area of land comprised of limestone or dolomite rock formations that have been partially dissolved to form sinkholes, fissures, caves and solution pipes
KPCA	Kimberley and Pilbara Cattlemen's Association
Laminated	A rock that is made up of many thin layers
Laterite	A soil layer that is rich in iron oxide and derived from a wide variety of rocks weathering under strong oxidising and leaching conditions
Leachate	A liquid that results from passing through a landfill and extracting dissolved and suspended matter from it
Lithification	The process that converts unconsolidated materials (loose sediments) into coherent solid rock, through compaction or cementation
Lithology	The branch of geology that studies the general physical characteristics of rocks
LNAPL	Light Non-Aqueous Phase Liquid
LNG	Liquefied Natural Gas
Lock the Gate	Lock the Gate Alliance
Mesozoic	A geological era of about 186 million years, beginning approximately 252 million years ago
Minister for Environment	Western Australian Minister for Environment
Minister for Mines and Petroleum	Western Australian Minister for Mines and Petroleum
Minister for Water	Western Australian Minister for Water
Miscibility	The ability of two fluids to mix in all proportions
MNES	Matters of National Environmental Significance
Moratorium	A legally authorised temporary prohibition of an activity

MoU	Memorandum of Understanding
MSDS	Material Safety Data Sheet
NASA	National Aeronautics and Space Administration
Nationals WA	The National Party of Western Australia
Native Title Act	*Native Title Act 1993* (Aus)
Natural gas	Flammable gas, mainly consisting methane and other hydrocarbons, naturally occurring underground.
Natural gas liquids	Liquid hydrocarbonss in the same family of molecules as natural gas and crude. Examples include ethane, propane, butane, isobutane and pentane
NEPC	National Environmental Protection Council
NEPM	National Environmental Protection Measure
NGER Act	*National Greenhouse and Energy Reporting Act 2007* (Aus)
NGGI	National Greenhouse Gas Inventory
NGL	Natural Gas Liquids
NHMRC	National Health and Medical Research Council
NICNAS	National Industrial Chemicals Notification and Assessment Scheme
NOAA	National Oceanic and Atmospheric Administration
NOEC	No Observed Effect Concentration
Non aqueous fracture fluids	Waterless fracture fluids, for example, based on carbon dioxide, nitrogen or a hydrocarbon liquid such as alcohol.
NORM	Naturally Occurring Radioactive Material
NOx	Oxides of Nitrogen
NSW	New South Wales

NT	Northern Territory
NWQMS	National Water Quality Management Strategy
OEPA	Office of the Environmental Protection Authority
Oil Shale	Fine-grained sedimentary rock from which oil can be extracted.
Ordovician	A geological period of 41.2 million years that spans from the end of the Cambrian Period 485.4 million years ago, to the beginning of the Silurian Period
Overpressure	Local air pressure (for example, in a gas reservoir) greater than surrounding atmospheric pressure
PAGER	*Petroleum and Geothermal Energy Resources Act 1967* (WA)
PAHs	Polycyclic Aromatic Hydrocarbons
Paleodrainage	A water channel that was cut by a river or stream, but is no longer used by that river or stream. This is almost always buried
Paleozoic	A geological era occurring between 541 million years and 252 million years ago
Panel	A group of independent scientific experts undertaking the Scientific Inquiry into Hydraulic Fracture Stimulation in Western Australia
Pastoral Lease	An arrangement used in Australia where Crown land is leased by government, generally for the purpose of grazing on rangelands
PDWSA	Public Drinking Water Source Area
PER	Public Environmental Review
Permeability	The ability of a material (soil, regolith, rock) to transmit fluids (gases and liquids)
Permian	A geologic period of 47 million years that spans from the end of the Carboniferous period 298.9million years ago, to the beginning of the Triassic period

Petroleum Acts	*Petroleum and Geothermal Energy Resources Act 1967, Petroleum (Submerged Lands) Act 1982 and Petroleum Pipelines Act 1969* (WA)
Petroleum Environment Regulations	*Petroleum and Geothermal Energy Resources (Environment) Regulations 2012, Petroleum (Submerged Lands) (Environment) Regulations 2012 and Petroleum Pipelines (Environment) Regulations 2012* (WA)
PGA	Pastoralists and Graziers Association of Western Australia
PGER Act	*Petroleum and Geothermal Energy Resources Act 1967* (WA)
PGER (Hydraulic Fracturing) Regulations	*Petroleum and Geothermal Energy Resources (Hydraulic Fracturing) Regulations 2017* (WA)
PGER (Management of Safety) Regulations	*Petroleum and Geothermal Energy Resources (Management of Safety) Regulations 2012* (WA)
PM	Particulate Matter
PP Act	*Petroleum Pipelines Act 1969* (WA)
Precambrian	Pertaining to the earliest era of earth history, ending 570 million years ago
Production water	Formation water extracted in association with oil and gas production
Proppants	Solid material such as sand or ceramic beads designed to keep the resulting factures open
Prospective resources	Quantities of petroleum which are estimated to be potentially recoverable from undiscovered accumulations
PSL Act	*Petroleum (Submerged Lands) Act 1982* (WA)
Quaternary Sandplains	Quaternary pertains to the present period of earth history (2.58 million to present)
REC	Reduced Emissions Completion

Recharge	A hydrologic process where water moves downward from surface water to groundwater and is the primary method through which water enters an aquifer
Reserves	Resources which are commercially recoverable and have been justified for development
Resource Management Regulations	Petroleum and Geothermal Energy Resources (Resource Management and Administration) Regulations 2015 and Petroleum (Submerged Lands) (Resource Management and Administration) Regulations 2015
RIWI Act	*Rights in Water and Irrigation Act 1914* (WA)
Runoff	Water from rainfall, that is not absorbed into the ground and flows over the surface of land, carrying with it any loose sediments or other substances
SA EPA	South Australian Environmental Protrection Authority
SCIAMACHY	Scanning Imaging Absorption spectrometer for Atmospheric CHartographY
SDS	Safety Data Sheets
Shale gas	Natural gas that exists within, and can be extracted from, shale rock formations
Shale oil	Oil that exists within, and can be extracted from, shale rock formations
SIA	Social Impact Assessment
SKM	Sinclair Knight Merz
Slickwater	Hydraulic fracturing fluid with reduced viscosity
SMP	Safety Management Plan
SPP	State Planning Policies
SRC	Seismology Research Centre

SRON	Space Research Organisation Netherlands
2015 Standing Committee Report	2015 Report of the Standing Committee on Environment and Public Affairs of the Western Australian Parliament
Standing Committee	The Standing Committee on Environment and Public Affairs of the Western Australian Parliament
Stratigraphy	The scientific discipline that is concerned with describing rock successions and interpretations, relative to a geological time scale.
Sub-basin	A structural subdivision of a sedimentary basin containing a part of the basin's sedimentary sequence
Subterranean	Occurring or existing beneath the Earth's surface
TAMEST	The Academy of Medicine Engineering and Science of Texas
TDS	Total Dissolved Solids
TEC	Threatened Ecological Community
TGA	Therapeutic Goods Administration
Tight gas	Natural gas that exists in reservoirs locked within highly impermeable, hard rock, causing the underground formation to be very 'tight'
Tight Oil	Oil that exists within low permeability rock
Tight Sands	Low permeability sandstone
Top-down	Large scale measurements to make inferences about local phenomena
TOR	Terms of Reference
Transect	A fixed path across the earth's surface, along which observations and measurements are observed
Triassic	A geologic period of 50.6 million years that spans from the end of the Permian Period 251.9 million years ago, to the beginning of the Jurassic Period

Triggered seismicity	Human activity influencing patterns of natural seismicity
UG	Unconventional Gas
UIL	UIL Energy Limited
UK	United Kingdom
Ultimate Recoverable Resource	Estimate of the total amount of oil or gas that will be recovered and produced
Unconventional gas	Natural gas extracted by drilling methods that are used due to an increasing scarcity in retrieving oil and gas using conventional methods. This method involves drilling down, drilling horizontally, and fracturing the land to extract gasses. Includes shale gas, shale oil, tight gas, tight oil and coal seam gas (shallow and deep)
Undiscovered accumulations	The estimated prospective resource beyond those determined to be in reserves and contingent resources
Undiscovered prospective petroleum liquid resources	Petroleum liquid potentially recoverable from undiscovered accumulation
URR	Ultimate Resource Recovery
U.S.	United States
U.S. EPA	United States Environmental Protection Agency
USA	United States of America
USDW	Underground Source of Drinking Water
VOC	Volatile Organic Compound
VWA	Vegetables WA
WA	Western Australia

WAFarmers	Western Australian Farmers Federation (Inc)
WAPC	Western Australian Planning Commission
WAPIMS	The Western Australian Petroleum Information Management System
Warramba	An Indigenous term to describe an annual flood which cleans out the river torrent
WCA	*Wildlife Conservation Act 1950* (WA)
Well barriers	A system of one to several well barrier elements that contain fluids within a well to prevent the uncontrolled flow of fluids within or out of the well
Well integrity	Maintaining the full control of fluids within a well at all times by employing and maintaining one or more well barriers to prevent unintended fluid movement between formations with different pressure regimes or loss of containment to the environment
Well integrity failure	When all barriers have failed and there is a pathway for fluid to flow in or out of the well
Well integrity incidents	A failure or barrier resulting in an unintentional flow, leak or release of fluids to the environment
WFM-DOAS	An algorithm for interpreting Differential Optical Absorption Spectroscopy
WHPZs	Well Head Protection Zones
Workovers	When wells have to be redeveloped or reconditioned.
WMP	Well Management Plan

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Units of measurement

Unit	Definition
$b	Billion dollars
˚C	Degrees Celsius
Bbbl	Billion barrels
Bcm	Billion cubic metres
CO_2e	Carbon dioxide equivalent emissions. A metric for the measurement of the global warming potential of a substance.
CO_2e/t	Carbon dioxide equivalent emissions per tonne of product
(dB(A))	Decibels. The (A) means weighted for the way the human ear hears
g	Grams
gCO2e/MJ	Carbon dioxide equivalent emissions per megajoule
GL	Gigalitre
GL/a	Gigalitre per annum
GM^3	Billion cubic metres
ha	Hectare (10,000 m^3)
kg	Kilograms
kg/d	Kilograms per day
kg/hr	Kilograms per hour
kL	Kilolitre
kL/a	Kilolitre per annum
km	Kilometre

Unit	Definition
km^2	Square kilometres
L	Litre
L/s	Litres per second
m	Metre
m/year	Metre per year
m^3	Metres cubed
mD	Milli Darcy. (measurement of fluid permeability)
mg/L	Milligrams per litre
M_L	Magnitude Local
MJ	Megajoule (1 joule x 10^6)
ML	Megalitre (1 litre x 10^6)
ML/day	Megalitre per day
ML/year	Megalitre per year
mm	Millimetre
mm/y	Millimetres per year
mmbbl	Million barrels
mmcfd	Million cubic feet per day
MPa	Megapascal (a measure of pressure = 1 million Pascal)
mS/cm	Millisiemens per centimetre (=1000µS/cm)
Mt CO_2e	Million tonnes of carbon dioxide equivalent
Mt/y CO_2e	Million tonnes per year of carbon dioxide equivalent
Mt/y	Million tonnes per year

Unit	Definition
M_w	Moment magnitude. The moment magnitude scale is based on the total moment release of the earthquake. Moment magnitude estimates are about the same as Richter magnitudes for small to large (ie <8) earthquakes.
MWh	Megawatt-hour
NaCl	Sodium Chloride
PJ	Petajoules (10^{15})
PJ/y	Petajoules/year
ppm	Parts per million
t	Tonne (1,000kg)
t/km/y	Tonnes per kilometre of fault per year
tcf	Trillion cubic feet
TDS	Total dissolved solids
TJ	Terajoule (1 joule x 10^{12})
TJ/d	Terajoule (1 joule x 10^{12}) per day
TOC	Total organic content
TSS	Total suspended solids
µS/cm	Microsiemens per centimetre
URR	Ultimate Recoverable Resource

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Foreword

Dr Tom Hatton
CHAIRMAN
Independent Scientific Panel Inquiry into Hydraulic Fracture Stimulation in Western Australia

When the Western Australian Government announced a scientific inquiry into the risks and regulation of hydraulic fracture stimulation in September last year, there was a widely-expressed view that such an inquiry was not needed as there had been numerous previous reviews and inquiries, both overseas and in most Australian jurisdictions, including the 2015 report by the Western Australian Legislative Council's Standing Committee on Environment and Public Affairs. Interestingly, this view was held by stakeholders expressing confidence in the technology's safety as well as those opposed to its use.

Contrary to this expectation, what has emerged through this Inquiry is a unique and distinctive Western Australian representation of risk and public concern, and how and where those risks and concerns might be further reduced with changes to regulation or practice, if the current moratorium is lifted.

One factor that distinguishes this Inquiry's Report from previous ones is the pace of new scientific understanding, as well as the pace of technological developments in hydraulic fracture stimulation, making older reviews and assessments somewhat dated. Much more importantly, the distinctive nature of our findings and recommendations reflect the unique geologies, environments, communities and existing regulatory arrangements of Western Australia. And while the 2015 Western Australia Standing Committee Report was in this same context, it could not and did not go into the same level of scientific review and analysis requested of this Panel.

In short, it is the Panel's view that this Report is a contemporary and original consideration of the safety and regulation of hydraulic fracture stimulation of immediate relevance and value to the Western Australian community.

Another reaction to the announcement of this Inquiry was in respect to its Terms of Reference and scope. Some stakeholders expressed concern that the scope was too broad and that a scientific inquiry should be narrowly limited to the technical risks and regulation of hydraulic fracture stimulation *per se* (in other words, limited to the risks of shattering rock

at depth with fluid under pressure). At the other extreme, some wanted the scope to extend to all the social and economic benefits and impacts of an onshore oil and gas industry, and much of the material submitted to the Inquiry extended to these dimensions. In this regard, the Panel was ultimately guided by the recognition that it was convened under the Western Australian *Environmental Protection Act 1986,* which in turn provides a relatively broad interpretation of what is 'environment', including some consideration of impacts on people and their beneficial use of the environment. Given the nature of concerns and information provided to the Panel by a wide range of stakeholders, it was our view that a broad interpretation of our scope would be of greater value, and be more respectful, to the community and to the Western Australian Government.

The Panel received and considered hundreds of original written submissions and thousands of *pro forma* submissions to the Inquiry. We thank those who put the time and effort into contributing to the Inquiry in this way. The Panel is also grateful for the many contributions made through the public meetings in the Kimberley, the Midwest and in Perth. Given the polarised views amongst those attending the public meetings, the Panel is particularly grateful for everyone's respectful, patient and considerate engagement. The ongoing dialogue with all stakeholders in this Inquiry has been genuine, reflecting the passion the Western Australian community feels for its land, people and broader environment. The information from stakeholders complemented the immense volume and diversity of scientific literature considered by the Panel. This Report makes liberal use of direct quotes from these contributions and that of submitters so these voices and thoughts may be heard along with our own.

This Report makes findings on the risks associated with the onshore use of hydraulic fracture stimulation as well as recommendations on how the risks and impacts might be further reduced through changes in regulation and practice. It is silent on whether the moratorium should be lifted. The lifting of the current moratorium is a matter for Government, and we hope this Report is useful and valuable in that consideration. In making our recommendations, the Panel notes that in many cases and in many ways, some operator and regulatory practice is already commensurate with our advice. In that regard, our recommendations are aimed at ensuring public confidence that these standards and practices are expected from all operators, and are enforceable and accountable.

The length of this Report in part reflects the Inquiry's scope, the inherent complexity of the issues, and the vast amount of pertinent information considered. It was the Panel's view that this complexity and consideration required documentation in support of whatever findings and recommendations we might make. Consequently, the Report is lengthy and contains much detail. As a guide for the reader, **Sections 1 to 4** provide the background to the Inquiry, our approach, a summary of issues raised by stakeholders, and a description of the current regulatory environment. **Sections 5 and 6** provide detailed background to the oil and gas resources that might be accessed by the technology, and the technology itself. **Sections**

7 to 12 cover the risk assessments and associated findings and recommendations in regards to land, water, greenhouse gas, public health and social surroundings. **Section 13** considers regulatory reform, and **Section 14** summarises all findings and recommendations. The Report's appendices include regulatory documentation associated with previous onshore operations incorporating hydraulic fracture stimulation.

The Panel and the Inquiry have greatly benefited from a dedicated support team, led by Helen Butterworth. To Helen, Sandra Dowding, Jason Medd, Allan Boyd, Vivienne Ryan, Jayne Rickard, Alanna Fandry, Ryan McDonald, Frances Hoskins, Adam Turnbull, Geordie Thompson, and Les Buchanan, we extend our deepest appreciation. We cannot overstate the challenge and complexity of executing such an Inquiry, and we are grateful for their commitment, knowledge, competency and integrity.

This was a scientific inquiry, and the Report greatly benefited from extensive review by qualified peers from across Australia. We thank them for their critique and their suggestions, all of which have improved the soundness and completeness of this Report.

Finally, I extend my personal gratitude and esteem to my fellow Panel Members Philip Commander, Dr Fiona McKenzie, Dr Jackie Wright and Dr Ben Clennell. Their technical acumen as well as their professional and personal integrity were of the highest standard, and their commitment to an immense and challenging task of public engagement, technical review, analysis, and synthesis across an incredibly complex scope of concern is both humbling and beyond any reasonable expectation.

The Western Australian community can be assured this Report is an independent and thorough assessment of the risks and regulatory framework surrounding the onshore use of hydraulic fracture stimulation in this State.

Dr Tom Hatton

Chair of the Independent Scientific Panel Inquiry into Hydraulic Fracture Stimulation in Western Australia

12 September 2018

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Summary

On 5 September 2017, the Western Australian Government announced an independent scientific inquiry into hydraulic fracture stimulation and appointed an independent Panel of experts, under provisions of the *Environmental Protection Act 1986*, to report on the potential impacts arising from the implementation of hydraulic fracture stimulation on the onshore environment of Western Australia, outside of the Perth metropolitan, Peel and South-West regions.

The Terms of Reference for the Inquiry were to:

- Identify environmental, health, agricultural, heritage and community impacts associated with the process of hydraulic fracture stimulation in Western Australia, noting that impacts may vary in accordance with the location of the activity;
- Use credible scientific and historical evidence to assess the level of risk associated with identified impacts;
- Describe regulatory mechanisms that may be employed to mitigate or minimise risks to an acceptable level, where appropriate;
- Recommend a scientific approach to regulating hydraulic fracture stimulation; and
- Hold community meetings in Perth, and the Midwest and Kimberley regions.

The Panel was not asked to advise on the lifting of the current moratorium on hydraulic fracture stimulation, and this Report is silent in that regard.

In addressing these Terms of Reference, the Panel considered evidence, opinion and concerns expressed through seven public meetings attended by 204 people, more than 9,500 written public submissions, invited submissions from more than two dozen organisations including State and Federal agencies, industry, environmental groups and Aboriginal bodies, as well as direct consultation with key stakeholders. The Panel also made extensive review of many hundreds of published scientific and technical papers and reports, as well as environmental plans and compliance reports.

The Panel's assessment and advice contained in this Report is largely organised through the following set of themes (across the range of potential risks): land (including biodiversity); water (including the use of chemicals); greenhouse gas; public health; and social surroundings.

Where appropriate, the Report separately considered the distinct environmental settings between the two principal regions prospective for the development of onshore oil and gas resources using hydraulic fracture stimulation, the (northern) Perth Basin and the Canning Basin. Finally, where possible, the Report differentiates between the risks and regulation

associated with the exploration phase of unconventional oil and gas development (involving the construction and stimulation of one to several wells) and the development and production phase of oil and gas fields with multiple well pads and wells, and extensive connecting infrastructure.

Fundamental to the consideration of risk and regulation, the Panel developed realistic and plausible development scenarios over the foreseeable future. The scenarios were based on industry submissions, demand forecasts by the Australian Energy Market Operator, the contracted supplies of conventional gas to the Western Australian domestic market, and the remote nature of the resource and existing infrastructure.

The Report contains 91 findings, resulting in 44 recommendations (see **Section 14**) regarding the risks, concerns and regulation of hydraulic fracture stimulation and its associated activities.

Overall, the findings support a broad conclusion that the international standards for the design, construction and operation of an individual petroleum well (incorporating hydraulic fracture stimulation) if properly executed and located, generally limit risks to the environment and people to a low level. However, the Report identified the opportunity to further reduce risks with a set of recommendations for additional prescriptive regulation. Many of these recommendations are technical or procedural in nature, related to environmental baselining and monitoring, chemical use, waste and emissions management, separation distances, decommissioning, and rehabilitation. The Report recommends that most of these could be given effect through an enforceable Code of Practice. The associated recommendations in this regard directly deliver to the Terms of Reference request for 'a scientific approach to regulating hydraulic fracture stimulation'.

Many of the findings reflect concerns over public confidence in the processes by which acreage for onshore oil and gas resources likely to require hydraulic fracture stimulation is considered for release and development. The main areas of concern included how the release of this acreage is:

- Consulted upon;
- Assessed for safety for people and the environment;
- Licensed;
- Audited for compliance; and
- Reported upon in such a way that minimises public liability over the lifetime of the development and beyond the decommissioning of infrastructure.

The recommendations that resulted in this regard are aimed at minimising the cumulative impacts, improving public confidence and limiting public liability.

Significant findings of this Inquiry with respect to the potential impacts of onshore oil and gas development, based on hydraulic fracture stimulation, include:

- The risk to water resources through below-ground pathways for contaminants is generally low, with the greater risk arising from surface spills of chemicals or wastewater. While this latter risk was also deemed to be low, the Inquiry concluded that given the value of potable water resources in the prospective regions, a degree of precaution was justified. The Report makes a number of recommendations regarding the assessment and use of chemicals, monitoring of groundwater and wastewater, ecotoxicity testing, and a minimum separation distance of 2,000 metres between stimulated oil and gas wells and bores used for public drinking water sources.
- A link between air pollution arising from onshore oil and gas production involving hydraulic fracture stimulation and the health of nearby people has not been clearly established with compelling and definitive science. While the Inquiry concluded the risk is low to medium, the link is sufficiently plausible and the potential consequences serious enough that a measure of precaution is warranted. The Report recommends baseline and ongoing monitoring for volatile organic compounds, dust and noise as well as site-specific health risk assessments reviewed by the Department of Health. Further, in the absence of a local health risk assessment indicating otherwise, the Report recommends a minimum separation distance of 2,000 metres between stimulated oil and gas wells and sensitive receptors such as residences, schools and settlements, consistent with current Environmental Protection Authority guidelines.
- The pressures and impacts that onshore oil and gas development involving hydraulic fracture stimulation place upon the broader environment depends very much on the scale of the development and where it takes place. These pressures (for example the clearing of native vegetation, traffic, noise, artificial lighting, fire risk, soil disturbance and increased seismicity) are similar to other types of development across Western Australia, such as for mining, infrastructure, energy or agriculture, and the State already has a framework for assessing the environmental impacts of significant developments and their acceptability or otherwise. However, the Inquiry noted the current environmental assessment process for onshore oil and gas development and production is limited to individual wells and does not extend to the consideration of potential oil and gas field development as a whole. This Report recommends that in addition to the assessment of individual exploratory wells, once an operator proposes to move from the exploratory phase to development, the proposed gas field be sufficiently defined and then referred for assessment under the *Environmental Protection Act 1986*, like any other significant development. Further, recognising that Western Australia is rich in places of high environmental and cultural significance or sensitivity, from the earliest consideration of the release of new

acreage for petroleum exploration, broad consultation with the community regarding the exclusion of such places should be a standard requirement.

- The Inquiry was asked to consider impacts on the community, and the Report contains a number of findings in that regard. These findings recognise the impact of uncertainties regarding the proposed scale and proximity of new onshore oil and gas fields involving hydraulic fracture stimulation to landholders and communities, the importance of informed consent for land access, and how the potential impacts on local environment influence perceptions of quality of life and ultimately, well-being. The Report contains a number of recommendations to minimise community impacts, including the baseline documentation and monitoring of those aspects of amenity and sense of place that a local community considers important and extending to a social impact analysis prior to development. Additional recommendations are aimed at ensuring consultation and consent from Traditional Owners in regard to recognising and protecting their heritage and traditional land is effective, appropriate and accountable.
- The Inquiry found that the impacts on global climate as a consequence of greenhouse gas (GHG) emissions from an onshore oil and gas industry based on hydraulic fracture stimulation is directly dependent on the scale of development. It is likely that such developments will emit more GHG per unit of production than conventional oil and gas development, to a limited degree. The Report presents the estimated volumes of GHG for development scenarios and considers these estimates in the context of global emissions and Australia's international mitigation commitments. The Report contains recommendations requiring baseline measurements of atmospheric levels of GHG prior to development, and a requirement for monitoring for leaks and any necessary remediation work over the full development lifecycle, including post-decommissioning. The Report recommends a requirement for 'reduced emissions (green) well completions' that capture the produced gas during well completions and well workovers following hydraulic fracture stimulation for all but exploratory stimulated wells. Finally, the Report recommends the appropriate offsetting of GHG emissions.

The Inquiry also examined the broader regulatory process for considering onshore hydraulic fracture stimulation and identified a number of opportunities to improve safety and public confidence in its use. Significant among these findings were:

- There is a place within an overall risk-based, outcome-focused regulatory framework for some prescriptive regulation. These prescriptions may extend to explicit requirements for consultation, exclusions, assessment, environmental standards, monitoring, disclosure and reporting. An enforceable Code of Practice, embodying necessary prescriptive requirements and standards across the entire development

lifecycle, is a useful mechanism to bring all such activities to an acceptable, high standard across the industry.

- As Low as Reasonably Practical (ALARP) is a useful working concept for the protection of the environment in the design and realisation of unconventional oil and gas development, but should be explicitly linked to environmental acceptability through and within regulation.
- Environmental and public health assessment, approval, conditioning and compliance would be strengthened if executed through the *Environmental Protection Act 1986*, and this would go some way toward alleviating public concern over consultation, environmental protection standards, cumulative impacts, rehabilitation standards and compliance. This assessment should extend not only to individual wells during the exploratory phase of a development, but to the environmental assessment of proposed onshore unconventional oil and gas fields. Further, Environmental Plans for onshore unconventional oil and gas developments broadly serve the equivalent function of environmental review documents provided to environmental agencies under other environmental regulatory regimes, and similar expectations on their availability for public review should apply.
- The default treatment of environmental monitoring data required by regulation or Ministerial Statement should be that it is not subject to commercial confidentiality and should be made public, including a requirement that all chemicals and additives in fracturing fluids be publicly declared and that availability be regularised through open publication by government.
- Site rehabilitation and the long-term environmental performance of wells is the clear responsibility of the operator. Appropriate financial assurance is required to ensure that any necessary remediation of impacts to the environment can be funded. Additionally, industry contributions to fund the remediation of legacy issues associated with the industry would further protect the State from future liability.
- The penalties available for environmental offences under the *Petroleum and Geothermal Energy Resources Act 1967* and subsidiary legislation are too low to provide an effective incentive for compliance.
- Clear and demonstrable separation of the function of ensuring environmental compliance from that of industry promotion and allocations of tenure would better conform to best practice in government and would greatly increase confidence in environmental protection and public safety. This is not adequately achieved through present arrangements.

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Background and purpose of the Inquiry

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1 Background and purpose of the Inquiry

1.1 Establishment of this Inquiry

On 5 September 2017, the Western Australian Government announced a ban on hydraulic fracture stimulation (fracking) on existing and future petroleum titles in the Perth metropolitan, Peel and South-West regions, and put in place a moratorium on hydraulic fracture stimulation for the rest of the State.

In conjunction with the ban and moratorium, the Government constituted an independent scientific panel (the Panel) under section 25 of the *Environmental Protection Act 1986* (EP Act) to inquire into the effects of the hydraulic fracture stimulation process on the Western Australian environment, using credible scientific and historical evidence to assess each level of risk associated with fracking and outline regulatory mechanisms to identify and minimise potential risks to the environment, health, agriculture, heritage and community in Western Australia.

1.2 Terms of reference

In constituting the Panel, the Western Australian Government provided the following terms of reference:

The scientific inquiry is to undertake an assessment and report on the potential impacts arising from the implementation of hydraulic fracture stimulation (fracking) on the onshore environment of Western Australia, outside of the Perth metropolitan, Peel and South-West regions.

The Inquiry will:

- *Identify environmental, health, agriculture, heritage and community impacts associated with the process of hydraulic fracture stimulation in Western Australia, noting that impacts may vary in accordance with the location of the activity;*
- *Use credible scientific and historical evidence to assess the level of risk associated with identified impacts;*
- *Describe regulatory mechanisms that may be employed to mitigate or minimise risks to an acceptable level, where appropriate;*
- *Recommend a scientific approach to regulating hydraulic fracture stimulation; and*
- *Hold community meetings in Perth, and the Midwest and Kimberley regions.*

1.3 Scope and the identification of potential impacts

The EP Act, under which this Inquiry is established, guides the scope and extent of the potential impacts examined through this Inquiry. The Act provides for the prevention, control and abatement of pollution and environmental harm; for the conservation, preservation, protection, enhancement and management of the environment; and for matters incidental to or connected with those purposes.

Therefore, this Inquiry considered the potential impacts on the environment, and any material harm that those impacts may in turn have on the social surroundings (including heritage, human health and safety) or the beneficial uses of that environment.

The onshore regions of Western Australia where there is potential interest in developing unconventional oil and gas resources already have a history of conventional oil and gas development. While the infrastructure, operations and associated impacts of developing unconventional oil and gas resources through hydraulic fracture stimulation have much in common with conventional resource development, including basic well construction, access, land clearing and transport of equipment and product, there are also important differences. This Inquiry considered the impacts of hydraulic fracture stimulation and the processes and activities that are by necessity associated with its application. Further, the Inquiry's assessment of risk and regulation extended over the full life-cycle of development, operations and closure, consistent with environmental assessment of resource developments in Western Australia (Environmental Protection Authority 2016) and elsewhere (Department of Energy and Climate Change 2014).

The scope of this Inquiry, and the EP Act, does not extend to considerations of harm to social or economic values that do not arise directly or indirectly from degradation, pollution or loss of physical or biological values.

Thus, the Inquiry does not broadly extend to the future of the oil and gas industry in Western Australia, to considerations of the comparative impacts of oil and gas versus other energy sources, or to the consequences of resource development more generally.

Neither does the Inquiry consider any social or economic benefits that hydraulic fracture stimulation might bring to the community.

The Panel recognised that there is inevitably a grey area in which the impacts on people and their communities through impacts on the environment merges into the broader social and economic context. In the course of the Inquiry, much of the public input extended to issues beyond a strict interpretation of the scope of the Inquiry. The Panel concluded that it was both proper and useful to represent that input in full, and where appropriate acknowledge those dimensions in the Report.

1.4 The role of the State and Federal Government in regulating hydraulic fracture stimulation

Hydraulic fracture stimulation in Western Australia is assessed and regulated by the State, under the Petroleum Acts, which include the *Petroleum and Geothermal Energy Resources Act 1967* (PGER Act), *the Petroleum (Submerged Lands) Act 1982* (PSL Act) and the *Petroleum Pipelines Act 1969* (PP Act). A detailed explanation of the regulatory framework is provided in **Section 4**.

The Federal Government assesses and regulates hydraulic fracture stimulation operations on a case by case basis, if it is likely that the operation will have an impact on Matters of National Environmental Significance (MNES). MNES are protected under the Australian *Environmental Protection and Biodiversity Conservation Act 1999* (EPBC Act) and include:

- Nationally threatened species and ecological communities;
- Migratory species;
- Wetlands of international importance;
- Commonwealth marine areas;
- World heritage properties;
- National heritage places;
- The Great Barrier Reef Marine Park;
- Nuclear actions (including uranium mining); and
- A water resource, in relation to coal seam gas (CSG) development and large coal mining development.

CSG developments are another form of unconventional gas development sometimes employing hydraulic fracture stimulation. At the time of this reporting, the 'water trigger' that requires all coal seam gas developments to be assessed by the Federal Government through their Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) does not extend to a requirement to assess other petroleum resource developments (such as shale or tight oil and gas) potentially using hydraulic fracture stimulation.

1.5 Relationship to the Western Australian Parliamentary Inquiry 2015

In August 2013, the Standing Committee on Environment and Public Affairs of the Western Australian Parliament (the Standing Committee) resolved to investigate hydraulic fracture stimulation and its implications for the State, with an emphasis on environmental considerations. The purpose of their inquiry was to provide a comprehensive body of factual information and findings to assist the Parliament of Western Australia, future decision makers and the public in their contemplation of this industry. This resolution was followed by two years of evidence gathering, research and community engagement through public hearings and submissions, and examination of sites with operational and decommissioned wells that had been fractured, culminating in a Final Report published in 2015.

Through that process, the Standing Committee discovered that the broad issues of concern are 'universal', and therefore much can be learnt from other jurisdictions through their experience with the practice. The Committee noted the competing views about the level and likelihood of risks related to hydraulic fracture stimulation: proponents of the technology argue many risks are exaggerated, while opponents of the technology argue for precaution and the avoidance of any risk by prohibiting the practice entirely.

At the highest level, that inquiry concluded that the truth about the risks generally lies between these two points of view, that debate on hydraulic fracture stimulation has become over-simplified and clouded by irrelevant issues, and that policy-making must acknowledge the inherent risks in energy production and make those risks clear and understood. The Standing Committee also concluded that the debate surrounding such policy-making should be informed by further scientific study of some aspects of the technology and its potential impacts.

The Standing Committee's report comprised of 51 Findings and 12 Recommendations and these are provided in **Appendix 1**. The full report can be viewed here: http://www.dmp.wa.gov.au/Documents/Petroleum/Report42-HydraulicFracturing_UnconventionalGas.pdf

Among the Standing Committee's recommendations was that any future consideration of hydraulic fracture stimulation for unconventional gas should be based on established facts, with an acknowledgement that the science and innovations in the technology are constantly evolving. Throughout their report, the Standing Committee identified the value in further scientific consideration of the risks and their potential avoidance or mitigation through regulation or practice.

This Inquiry was established to meet this call for further scientific scrutiny, based on the most contemporary evidence available and considered within the current regulatory environment, with independent, expert analysis.

This Inquiry is neither designed nor resourced to repeat the extensive community engagement and public hearing process undertaken by the Standing Committee. Their work in that regard was comprehensive and remains a contemporary sounding of concerns, perspectives and opportunities for improvement in the protection of the environment and people. Nevertheless, public submissions have been sought and public meetings held in the course of this Inquiry.

The purpose of this Inquiry is to undertake a contemporary and comprehensive scientific examination of the evidence informing the risks of harm arising from hydraulic fracture stimulation, in the context of current regulations and practice, and to advise on how any risks might be avoided or mitigated by changes in regulation or practice, should Western Australia allow this technology to be used in the future.

In doing so, it is an opportunity for an informed and independent reflection on the findings and recommendations of the 2015 Report of the Standing Committee on Environment and Public Affairs of the Western Australian Parliament (2015 Western Australia Standing Committee Report).

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2

Approach of the Inquiry

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2 Approach of the Inquiry

2.1 The Panel

An independent panel of experts (the Panel) was appointed by the Western Australian Government to provide advice under the Terms of Reference. The Panel consists of Dr Tom Hatton (Inquiry Chair), Philip Commander, Dr Ben Clennell, Professor Fiona Haslam McKenzie and Dr Jackie Wright. The membership of the Panel reflects a range of scientific expertise including hydrology, hydrogeology, geology, petrology, ecology, natural resource management, toxicology, sociology and risk assessment. Information about the Panel members is available in **Appendix 2**.

The Panel convened on seven occasions over the preparation of this Report. The following stakeholders were invited to present their information and views at a number of those meetings:

- Lock the Gate Alliance (attended 14 February 2018);
- Pastoralists and Graziers Association of Western Australia (PGA) (attended 14 February 2018);
- Australian Petroleum Production and Exploration Association (APPEA), accompanied by Condor Energy (attended 14 February 2018);
- Environs Kimberley (attended 27 February 2018);
- Australian Worldwide Exploration (AWE) (attended 13 April 2018);
- Finder Shale Pty Ltd (attended 13 April 2018);
- Conservation Council of Western Australia (CCWA) (attended 13 April 2018);
- Buru Energy (attended 11 May 2018);
- MC Resources (attended 11 May 2018); and
- Department of Health (DoH) (attended 11 May 2018).

The Panel Chair also met with technical experts and other individuals over the course of the Inquiry, including:

- Professor Richard Davies, Professor of Energy, Durham University (28 September 2017); and
- Dr Damian Barrett, Research Director, Commonwealth Scientific and Industrial Research Organisation (CSIRO) Onshore Gas Program (5 June 2018).

2.2 Evidence

The Inquiry's imperative was to evaluate the risks potentially posed by hydraulic fracture stimulation for onshore unconventional oil and gas in Western Australia, as well as how those potential risks might be further mitigated or avoided through changes in regulation and practice, if possible. Accordingly, the evidence gathered and considered was of three basic natures:

- Evidence on the breadth of potential impacts of concern to the environment and the Western Australian community;
- Technical evidence informing the likelihood and consequences of those impacts in the Western Australian environment; and
- Information on how practices and regulation in Western Australia currently, or potentially, reduces the likelihood or consequence of those impacts (that is, risk).

The Inquiry benefited from an immense and growing body of technical literature and analysis on the risks and regulation of hydraulic fracture stimulation. G.E. King (King 2012) estimated that the literature up to that time extended to over 550 technical papers on shale fracturing and 3,000 technical papers on all aspects of horizontal wells. The vast bulk of this literature comes from outside Western Australia and has been considered by multiple technical reviews and through multiple inquiries. The Report of the Standing Committee on Environment and Public Affairs of the Western Australian Parliament 2015 Standing Committee Report acknowledged the benefit of using such information to learn from other jurisdictions and stakeholders with experience in developing unconventional gas resources. While this information was of broad relevance to this Inquiry, great care was taken in every case to test its applicability to the Western Australian context of industry, geography and environment. A priority was to identify and access the most recent technical information and findings, particularly any emerging since the conclusion of the Standing Committee Report.

2.3 Previous inquiries and reviews

The widespread interest in the opportunities presented by unconventional oil and gas resources over the past two decades has been accompanied by widespread concerns over the safety of hydraulic fracture stimulation. Consequently, a significant number of jurisdictions have undertaken technical inquiries into the matter and concerns have also prompted many other significant technical reviews.

Major Australian reviews include three parliamentary inquiries:

- Implications for Western Australia of Hydraulic Fracturing for Unconventional Gas (Western Australia Legislative Council Standing Committee on Environment and Public Affairs 2015);

- Inquiry into Onshore Unconventional Gas in Victoria: Final Report (Parliament of Victoria Legislative Council Environment and Planning Committee 2015); and
- Inquiry into Unconventional Gas (Fracking) in the South East of South Australia (Parliament of South Australia Natural Resources Committee 2016).

Additional government reviews in Australia include:

- Engineering Energy: Unconventional Gas Production. A study of shale gas in Australia (Cook et al. 2013) and the related recommendations made by the Office of the Chief Scientist (Office of the Chief Scientist 2013);
- Report of the Independent Inquiry into Hydraulic Fracturing in the Northern Territory (Hawke 2014);
- Review of Hydraulic Fracturing in Tasmania (Department of Primary Industries Parks Water and Environment 2015);
- Hydraulic fracturing for Shale and Tight Gas in Western Australian Drinking Water Supply Areas – Human Health Risk Assessment. (Department of Health 2015); and
- Scientific Inquiry into Hydraulic Fracturing in the Northern Territory Final Report (Northern Territory Government 2018).

Additional government-led reviews of coal seam gas (CSG) were undertaken in Queensland and New South Wales (New South Wales Parliament Legislative Council 2012; NSW Government Chief Scientist & Engineer 2014; Queensland Department of Health 2013). However, these reviews are largely set in a context of a fundamentally different technique for obtaining unconventional gas than has been or is likely to be employed in Western Australia because, to date, there has been no hydraulic fracture stimulation of CSG in Western Australia and CSG has not been identified as prospective in Western Australia. Consequently, these reviews were of less direct value to this Inquiry. Of more direct value is the recent publication of risk assessments of the chemicals used in association with the development of CSG (Department of the Environment and Energy 2017a), many of which are in common with chemicals used for hydraulic fracture stimulation in Western Australia. The risks via direct exposure to these chemicals are of relevance to this Inquiry.

Reviews of relevance to this Inquiry were also commissioned by overseas governments, including:

Canada

- Environmental Impacts of Shale Gas Extraction in Canada (Council of Canadian Academies 2014);
- New Brunswick Commission on Hydraulic Fracturing Final Report (New Brunswick Commission on Hydraulic Fracturing 2016); and
- Newfoundland and Labrador Hydraulic Fracturing Review Panel Final Report (Newfoundland and Labrador Hydraulic Fracturing Review Panel 2016).

South Africa

- South Africa's Technical Readiness to Support the Shale Gas Industry (Academy of Science of South Africa 2016); and
- Shale Gas Development in the Central Karoo: A Scientific Assessment of the Opportunities and Risks (Scholes et al. 2016).

United Kingdom (UK)

- Shale gas extraction in the UK: a review of hydraulic fracturing (The Royal Society and The Royal Academy of Engineering 2012);
- Review of the Potential Public Health Impacts of Exposures to Chemical and Radioactive Pollutants as a Result of the Shale Gas Extraction Process (Kibble et al. 2014);
- Environmental risks of fracking, (UK House of Commons Environmental Audit Committee 2015); and
- Task Force on Shale Gas: Final Conclusions and Recommendations, (UK Task Force on Shale Gas 2015).

United States (U.S.)

- A Public Health Review of High Volume Hydraulic Fracturing for Shale Gas Development (New York State Department of Health 2014);
- Final Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program: Findings Statement (New York State Department of Environmental Conservation 2015);

- Assessment of Risks from Unconventional Gas Well Development in the Marcellus Shale of Western Maryland (Final Draft) (Maryland Department of the Environment and Maryland Department of Natural Resources 2015);
- Well Stimulation in California (California Council on Science and Technology 2015a);
- Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States, (U.S. Environmental Protection Agency 2016); and
- Environmental and Community Impacts of Shale Development in Texas (The Academy of Medicine Engineering and Science of Texas 2017).

The terms of reference and scope of the above reviews or inquiries vary but in common they consider the potential impacts and risks associated with developing shale or tight oil and gas with hydraulic fracture stimulation, and all contain findings for making the practice safer or more acceptable to the community. Notwithstanding the variation in existing regulations, natural environments, the nature of the gas resources and the communities potentially affected, where they consider similar risks and challenges, there is some consistency in findings among these reports that are of relevance to this Inquiry:

- The potential impacts of greatest concern are generally on water resources and human health;
- To a considerable extent, the concerns over impacts to water resources and human health depend on the chemicals used and the chemicals recovered from well development;
- There is a need for good scientific information to reduce uncertainty surrounding risks;
- There is a need for baseline environmental data before development, and for close environmental monitoring and reporting over the operating life of the fractured wells;
- Monitoring data needs to be accessible and transparent to all stakeholders;
- The risks associated with hydraulic fracture stimulation for unconventional gas strongly depend on the local geography, particularly with respect to geology and water resources;
- The risks associated with hydraulic fracture stimulation for unconventional gas strongly depend on the scale of development (for example, the number of wells);
- The quality of well design, construction and operation, as it manifests in the risk of containment failure, is a crucial variable in mitigating many potential environmental impacts; and

- The local regulatory environment governing hydraulic fracture stimulation is crucial to protecting the environment and communities.

2.4 Commissioned work

To facilitate and help ensure access to the most contemporary and relevant technical literature, the Australian Academy of Technology and Engineering (ATSE) was commissioned to provide an initial bibliography of the key relevant literature, capturing higher-level reviews and extending to research publications that summarise technologies and best practice, and assessments of potential impacts. The bibliography provided by ATSE is in **Appendix 3**.

2.5 Call for public submissions

Following the establishment of the Inquiry and the Panel, a public website was created to keep the public informed about the Inquiry and its processes (https://frackinginquiry.wa.gov.au/), including basic information on hydraulic fracture stimulation (https://frackinginquiry.wa.gov.au/about-hydraulic-fracture-stimulation). In early October 2017, members of the public were invited to register their interest (1173 registrations); subsequent announcements were both published on the website and notified individually to registrants. In November and December of 2017, the Panel published on this website a set of papers to inform stakeholders about the Inquiry and to serve as background for those interested in making a submission:

- A Background and Issues Paper, which detailed the Terms of Reference and Inquiry scope as well as an overview of hydraulic fracture stimulation and its potential impacts;
- An Introduction to Hydraulic Fracture Stimulation, which provided a more detailed description of the history and technology of the practice in Western Australia;
- A paper on Resource Description and Hydrogeology, which provided an overview of the shale resources and associated hydrogeology for regions of Western Australia where hydraulic fracture stimulation might be considered; and
- A paper describing The Regulatory Environment, which provided an overview of current hydraulic fracture stimulation regulation in Western Australia.

The Panel invited written submissions to inform its assessment of risk and regulation (https://frackinginquiry.wa.gov.au/have-your-say). In doing so, the Panel asked stakeholders and the public to assist the Inquiry to ensure the Panel had:

- A full and appropriate understanding of the environmental values potentially at risk from unconventional oil and gas developments involving hydraulic fracture stimulation;

- Any data or other evidence that might inform a scientific risk analysis of those impacts, with an emphasis on local geographies and geologies, and local evidence from Western Australia; and
- Any reflections or experience on what a regulatory framework should ideally look like if the Government lifted the current moratorium.

In addition to the public call, submissions were directly invited from organisations that in the Panel's view, were likely to have significant information of interest to the Inquiry:

- CCWA;
- APPEA;
- The CSIRO;
- The Kimberley Land Council;
- The Lock the Gate Alliance;
- ATSE;
- The Department of the Environment and Energy (DoEE);
- The Western Australian Department of Health (DoH WA);
- The Environmental Defender's Office (EDO WA);
- Geoscience Australia (GA);
- The International Association of Hydrogeologists (Western Australian Chapter);
- The National Environmental Law Association;
- PGA;
- The Society of Petroleum Engineers;
- The Western Australian Farmers Federation;
- The Bundiyarra Aboriginal Community;
- The Aboriginal Lands Trust;
- The Bush Heritage Australia;
- The Marra Worra;
- The Kimberley Aboriginal Law and Culture Centre;
- The Winun Ngara Aboriginal Corporation;
- Nyamba Buru Yawuru;
- The Goldfields Land and Sea Council;

- The South West Aboriginal Land and Sea Council;
- The Western Desert Lands Aboriginal Corporation;
- The Yamatji Marlpa Aboriginal Council; and
- The Central Desert Native Title Services.

At the request of stakeholders, the submission period was extended from 27 November 2017 to 19 March 2018. A total of 9,910 written submissions were received. Of the submissions received, there were five separate pro forma submissions, of which three advised against and two advocated for hydraulic fracture stimulation. The pro forma submissions received generally offered repetitive information, however, all comments were captured and considered. All submissions were made publicly available on the Inquiry's website (https://frackinginquiry.wa.gov.au/submission-library). A list of submitters appears in **Appendix 4**.

2.6 Public meetings

In establishing the Panel, the Government committed and resourced the Inquiry to hold three public meetings (one each in the Kimberley, the Midwest and Perth). In response to requests from stakeholders for more locations and meetings, the Panel held three meetings in the Kimberley, two meetings in the Midwest and two sessions in Perth, as follows:

- Broome (27 February 2018), 27 attended;
- Perth (28 February 2018), 67 attended;
- Dongara (1 March 2018), 28 attended;
- Dandaragan (2 March 2018), 42 attended;
- Fitzroy Crossing (12 April 2018), two attended; and
- Noonkanbah Community (12 April 2018), 38 attended.

The Fitzroy Crossing meeting was originally scheduled to take place on 26 February 2018, however due to cyclone events flooding and the inability of registrants being able to travel to Fitzroy Crossing, the public meeting was rescheduled to 12 April 2018. The Panel also visited Noonkanbah, as requested by the community.

In order to reach as many people as possible, the Panel advertised details of the registration process by the following means:

- Inquiry website https://frackinginquiry.wa.gov.au/public-meetings;
- Sending emails to those people that had registered for inquiry updates;
- Posting on Twitter; and
- Newspaper advertisements in the following newspapers (**Appendix 5**):

- Broome Advertiser (18 and 25 January 2018);
- Countryman (18 and 25 January 2018);
- Geraldton Guardian (16 January 2018);
- Geraldton Midwest Times (17 January 2018);
- Kimberley Echo (18 and 25 January and 29 March 2018);
- Sunday Times – Perth (21 January 2018);
- The West Australian (18 January 2018);
- Dongara-Denison Rag (18 and 25 January 2018); and
- Northern Valley News (2 February 2018).

The registration process was open for a period of two weeks, from Monday 22 January to Sunday 4 February 2018, and again for the Fitzroy Crossing meeting from Friday 23 March to Wednesday 4 April 2018.

In calling for expressions of interest and registrations for these meetings, the Panel encouraged attendance by people living or working locally in that area, echoing the 2015 Standing Committee's finding that the views of those communities directly affected by hydraulic fracture stimulation operations should hold significant weight in any decision-making related to the development of unconventional gas resources.

The Panel itself was the audience at these meetings and participants were reminded that the meetings were not venues for public debate or for resolving conflicting information or views. The meetings were designed and facilitated to provide a safe and considerate environment, and maximum opportunity for all participants to share their information with the Panel.

2.7 Visits to well sites

The majority of the Panel had some previous experience with oil and gas operations. During the course of the Inquiry, members of the Panel undertook visits to the following sites where historic and recent gas wells had been or were being developed, including wells that had been hydraulically stimulated:

- AWE Waitsia 01, near Dongara (1 March 2018);
- AWE Waitsia 04, near Dongara (1 March 2018);
- Mitsubishi/Buru Valhalla North 1 (12 April 2018); and
- Mitsubishi/Buru Asgard 1 (12 April 2018).

The figures below show the wells visited or flown over to gain a thorough understanding of the impacts of scale.

Figure 2.1: The Panel members at the Waitsia 04 well site

Figure 2.2: The Panel members at the Waitsia 01 well site

Figure 2.3: Asgard-1 well site

Figure 2.4: Valhalla North 1 well site

2.8 External peer review

In order to validate the research and the findings of the Panel, the final report has been peer reviewed by technical experts in each of the following fields:

- Greenhouse gas emissions;
- Water resources;
- Toxicology and public health;
- Seismicity and geophysics;
- Conservation and biodiversity; and
- Social surroundings.

3

Summary of issues raised during submissions and at public meetings

3.1 Submissions 71

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3 Summary of issues raised during submissions and at public meetings

3.1 Submissions

Through submissions and public meetings, the Panel heard and received large amounts of information and many views regarding hydraulic fracture stimulation, its associated activities and its regulation. A summary of what was received and heard is presented below.

The full submissions, including what was heard from each of the public meetings, is available in the submissions library on the Inquiry's website.(https://frackinginquiry.wa.gov.au/submission-library).

It should be noted that during the public meetings and review of submissions, the Panel received many divergent points of view, often with conflicting information and often outside the Inquiry's scope and Terms of Reference. To keep faith with everyone who made contributions to this Inquiry, the summary presented below does not attempt to resolve or weight differences in opinion or information, nor does it exclude contributions that extend beyond the specified reach of the Inquiry.

3.1.1 Land

A number of submissions considered that there is a risk that hydraulic fracture stimulation and its associated activities will have an adverse impact on the land, soil, terrestrial ecosystems and biodiversity, specifically:

- Fragmentation and loss of the landscape and habitat, including water course edge impacts;
- Spread of Phytophthora dieback, weeds, feral animals and increased fire risk;
- Impacts to fauna habitats directly associated with stormwater runoff and change of surface water flows;
- Impacts to stock, flora and fauna due to exposure to chemical and wastewater, including spills during transportation;
- Damage to public and private roads;
- Impacts to agricultural soil and crop productivity (including product safety and marketing certification) from soil or water contamination;
- Loss of agricultural productivity due to land degradation or restricted or disrupted access; and
- Induced seismic events.

3.1.2 Water

The most consistently raised concern in all public meetings and submissions was the impact of hydraulic fracture stimulation and its associated activities on water. This included the risk of contamination to groundwater and surface water as a result of:

- Surface spills and leaks of flowback water or produced fluids;
- Surface spills of chemicals due to inadequate management or accidents including transportation;
- Groundwater contamination by hydraulic fracturing fluids left behind in the formation or due to loss of well containment;
- Unsafe disposal of hydraulic fracturing fluids and inadequately treated wastewaters;
- Release of radon gas or other radioactive materials to the surface environment;
- Activation of sealed/dormant fractures and faults or interception of older abandoned or unplugged wells, creating pathways for upward migration of gas, hydrocarbons and other contaminants, or lower quality water into aquifers;
- The uncertainty of the long term stability of casing and cement; and
- Sediment discharge as a result of the construction of well pads, pipelines and other associated infrastructure.

Some submissions considered that hydraulic fracture stimulation and its associated activities could cause changes to water supply and distribution due to:

- Over extraction of water resources inducing water shortages or conflicts with other water users, particularly in water-scarce areas, resulting in competition for water with urban water supplies and agricultural use;
- The impact on environmental flows, with additional reference to a drying climate;
- The risk of damage to the confining layers causing water loss and subsidence; and
- Natural surface water (sheet flow) impairment from linear infrastructure.

3.1.3 Greenhouse gas (GHG)

Some submissions noted that hydraulic fracture stimulation and its associated activities would have an adverse impact on air quality and climate change, specifically:

- Increased GHG emissions and their implications to our climate, including fugitive emissions and emissions resulting from fractures developing pathways to the groundwater and atmosphere;
- Loss of carbon sequestering woodland and bushland as a result of land clearing activities; and

- Outdated and inadequate measurement or estimation of GHG emissions.

3.1.4 Public health

Many people commented that hydraulic fracture stimulation and its associated activities could have an adverse impact on human and animal health, specifically from:

- Exposure to potentially dangerous chemicals via soil and water contamination, especially water used for drinking, washing, stock watering and food production. While most chemicals used in hydraulic fracture stimulation have been assessed by the chemical safety regulator, the toxicity of many contaminants are not satisfactorily understood;
- Exposure to noxious gases and particles, including methane, ozone, hydrocarbons and Volatile Organic Compounds (VOC), and radon released from venting, flaring, use of drilling engines and compressors, and waste water evaporation;
- The risk of severe stress and mental health challenges for land owners, traditional owners and people living in adjacent communities, due to fears for their future health and their livelihoods; and
- The risks to public safety from transport accidents, induced earthquakes, fires and explosions.

3.1.5 Social surroundings

Submissions commented that hydraulic fracture stimulation and its associated activities could have an adverse impact on social surroundings, specifically:

- The risk of a reduced quality of life due to the potential degradation of the landscape, including loss of amenity for recreation, tourism and traditional rural lifestyles;
- Increases in noise, dust, traffic and road depreciation;
- The lack of a minimum set back distance between hydraulic fracture stimulation operations and homes, schools and parks;
- Concerns that sites could not, or would not be fully restored following abandonment, particularly in areas with high agricultural, natural and cultural value;
- Loss of land market value;
- The risk to Aboriginal heritage, knowledge and culture through damage to places of significance, or the loss of bush tucker or medicine;
- Concerns over proper consultation (informed and prior consent) with Traditional Owners and the wider community, and the lack of landowner rights to refuse access;
- Concerns regarding the honesty of petroleum companies, the restrictions of non-disclosure agreements, no provision for legal assistance to landholders who may

have to negotiate a compensation agreement, no independent referee between landholders and companies, unclear ongoing liabilities, economic loss to farmers through time spent negotiating with companies, and limited compensation payable to landholders; and

- Impacts of green activist groups increasing stress and anxiety within communities by manipulating the public.

3.1.6 Regulation

Many submissions commented on the current or potential regulatory regime for hydraulic fracture stimulation and its associated activities, specifically:

- Even the strictest regulations are not capable of preventing harm and the world's best practice well construction is not enough to protect the environment;
- Current regulations are not robust and legislation is not protecting water, public health or the environment;
- Current regulations are appropriate for managing hydraulic fracture stimulation and the industry is over regulated;
- The current regulator is not appropriate because there is a direct conflict of interest having the Department of Mines, Industry Regulation and Safety (DMIRS) responsible for monitoring and regulating the industry, and also promoting the industry, and therefore the regulator should be an independent body;
- The industry may fail to report spills and other incidents, and government departments are not responsive to reports of contamination;
- The fines available to the regulator for non-compliance are too small;
- Mistrust arises as only a summary of the Environmental Plan and the list of chemicals used has to be made publicly available, and because Environmental Plans under the current legislative framework are not enforceable;
- Monitoring should be carried out by an independent expert, and baseline and ongoing monitoring data and compliance reporting should be publicly available to clarify that hydraulic fracture stimulation is not having an impact on the environment;
- There are insufficient resources to monitor unconventional gas projects due to staffing shortfalls;
- There is a lack of water quality protection in Public Drinking Water Supply Areas (PDWSAs);
- Bonds are insufficient to pay for future remediation and so liability falls on the State;

- The precautionary approach should be adopted for all hydraulic fracture stimulation and associated activities where there is scientific uncertainty on impacts to environment and human health;
- The principle of intergenerational equity should be adopted, ensuring that the health, diversity and productivity of the environment is maintained or enhanced for the benefit of future generations; and
- Having the ban in place in the Perth metropolitan, Peel and South-West regions is confusing, when areas of the Kimberley are just as significant.

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4

The current regulatory framework

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4 The current regulatory framework

4.1 Petroleum and Geothermal Energy Resources (Hydraulic Fracturing) Regulations 2017

On 5 September 2017, the State Government announced a ban on hydraulic fracture stimulation in the Perth metropolitan, Peel and South-West regions, and a moratorium for the rest of the State. A map showing the areas where hydraulic fracture stimulation is banned is shown here http://www.dmp.wa.gov.au/Documents/Petroleum/PET-FrackingExclusionsArea_Map.pdf

On 8 December 2017, the State Government gazetted the *Petroleum and Geothermal Energy Resources (Hydraulic Fracturing) Regulations 2017*. These Regulations provide for a ban in the Perth metropolitan, Peel and South-West regions, and a moratorium for the rest of the State until 30 June 2020.

4.2 A whole of Government approach

The process for obtaining a licence to conduct petroleum activities is complex and involves many steps. A range of State Government agencies, principally the Department of Mines, Industry Regulation and Safety (DMIRS), regulate a variety of elements with respect to all oil and gas developments under State jurisdiction, under legislative powers relevant to each agency.

These agencies' roles include conducting detailed environmental impact assessments where activities may result in significant environmental impacts, providing licences to extract water, protecting drinking water, protecting Aboriginal heritage and governing land access.

A whole of government approach is a key element in the development of the State's mineral and petroleum resources. Public sector agencies are meant to work collaboratively across portfolios to achieve an integrated response to the development of these resources. This responsibility applies at every stage of resource development, from assessment and approval of development proposals, regulation of resource projects and monitoring for compliance, to decommissioning and rehabilitation.

With specific reference to shale and tight gas resources, the Western Australian Government published a 'Guide to the Regulatory Framework for Shale and Tight Gas in Western Australia - A Whole of Government Approach' in 2015. This guide includes a description of each stage of the process to explore for and produce shale and tight gas, as well as explaining how the agencies work together, using a number of Memoranda of Understanding (MoU) to regulate shale and tight gas in Western Australia (Department of Mines and Petroleum 2015a).

4.3 Statutory framework

The extraction and development of petroleum resources is regulated under legislation administered by DMIRS and other agencies.

The regulatory framework rests on five key principles:

- Transparent, effective and risk-based regulation;
- A whole of government approach;
- Consistent State and Federal Government objectives;
- Effective engagement with stakeholders, particularly local communities; and
- Compliance and enforcement.

4.3.1 Department of Mines, Industry Regulation and Safety (DMIRS)

DMIRS is the lead agency responsible for the regulation of onshore and some offshore petroleum activities in Western Australia. With respect to shale and tight oil and gas, the key statutes administered by DMIRS *are:*

- *Petroleum and Geothermal Energy Resources Act 1967 (PGER Act);*
- *Petroleum (Submerged Lands) Act 1982 (PSL Act); and*
- *Petroleum Pipelines Act 1969 (PP Act).*

These Acts (together, the Petroleum Acts) and the Regulations made under them create a framework under which the Minister for Mines and Petroleum grants a range of titles in relation to petroleum, such as:

- Exploration permits, special prospecting authorities and retention leases, which authorise exploration for petroleum;
- Access authorities, which authorise exploration operations or operations related to the recovery of petroleum;
- Production licences, which authorise the recovery of petroleum;
- Drilling reservations, which authorise drilling for petroleum; and
- Pipeline licences, which authorise the construction and operation of pipelines and the conveyance of petroleum.

Petroleum exploration or recovery activities are prohibited unless an appropriate title is first obtained. DMIRS maintains a publicly available register of these titles on its website (http://www.dmp.wa.gov.au/Petroleum-Geothermal-Register-1505.aspx). In assessing an application for an exploration permit or drilling reservation, the Minister or his delegate will consider technical matters and publicly available criteria relating to the applicant, geological

evaluation of the resource and exploration rationale, and the proposed management of environmental impacts, native title, heritage and land access.

After the grant of a petroleum title, an operator may also need further approvals from DMIRS and other government agencies (discussed below) before commencing its activities.

4.3.1.1 Land access

The PGER Act places certain restrictions on access to private land by petroleum titleholders. Certain types of private land covered in a title may only be accessed with the prior written consent of the owner or trustee of the land where the private land is less than 0.2 hectares in extent, cemeteries or burial places, reservoirs or places less than 150 metres from the aforementioned or any 'substantial improvements'.

Compensation must be paid to the owner or occupier, or a neighbouring owner or occupier, where their property is damaged or they are deprived of possession of their land. The amount of compensation may be agreed, in which case it is usually a confidential matter between the landowner or occupier and the details will not be provided to DMIRS.

The titleholder must not commence any operations on private land unless the required amount of compensation has been paid or an agreement has been reached with the owner or occupier.

Additional processes and rights to compensation may apply if the area is subject to a native title claim under the Australian *Native Title Act 1993*.

4.3.1.2 Petroleum environmental regulations

The Regulations made under the Petroleum Acts deal with environment, safety and well integrity issues. Environmental Plans covering these matters must be submitted for assessment and approved by the Minister for Mines and Petroleum prior to any petroleum activity being undertaken.

The objects of the *Petroleum and Geothermal Energy Resources (Environment) Regulations 2012, the Petroleum (Submerged Lands) (Environment) Regulations 2012* and the *Petroleum Pipelines (Environment) Regulations 2012* (together, the Petroleum Environment Regulations) are to ensure that any petroleum, geothermal or pipeline activity in the State is:

(a) Carried out in a manner consistent with the principles of ecologically sustainable development; and

(b) Carried out in accordance with an Environment Plan that:

i. Demonstrates that the environmental impacts and environmental risks of the activity will be reduced to as low as is reasonably practicable;

ii. Has appropriate environmental performance objectives and environmental performance standards; and

iii. Has appropriate measurement criteria for determining whether those objectives and standards have been met.

Environmental Plans

An Environment Plan must include the following information:

(a) A comprehensive description of the proposed activity, including location, details of construction and layout, description of operational details and information relevant to environment impacts;

(b) Details and evaluation of environmental impacts and risks of the activity;

(c) Environmental performance objectives, environmental performance standards, and measurement criteria for these objectives and standards;

(d) Description of legislative requirements, international conventions or agreements or codes of practice that apply to the activity and are relevant to its environmental management;

(e) An implementation strategy, which must:

- Include measures to ensure the objectives and standards set by the Environment Plan will be met;
- Identify specific systems, practices and procedures to ensure that the environmental impacts and risks are continuously reduced to as low as is reasonably practicable, and the objectives and standards will be met;
- Establish a clear chain of command, and ensure employees and contractors comply with the Environment Plan;
- Provide for monitoring and management of non-compliance, particularly in relation to specified emissions and discharges;
- Where the activity involves injection or re-injection of water recovered from a reservoir into wells, specify the maximum permissible concentration of petroleum in the water;
- Include details of any chemicals or other substances that may be in, or added to, any treatment fluids to be used for the purposes of drilling or hydraulic fracture stimulation or otherwise introduced into a well, reservoir or subsurface;
- Include an oil spill contingency plan; and
- Provide for appropriate consultation with relevant authorities and other relevant interested persons or organisations;

(f) Arrangements for monitoring and recording information to enable the Minister to determine whether the Environment Plan has been complied with;

(g) A statement of the operator's corporate environmental policy;

(h) A report on all consultations between the operator and relevant authorities, and other relevant interested persons and organisations in the course of developing the Environment Plan; and

(i) A list of all incidents that are classified as reportable incidents in relation to the activity.

Before approving an Environment Plan, the Minister or his delegate must be reasonably satisfied that the Environment Plan:

(a) Is appropriate for the nature and scale of the activity;

(b) Demonstrates that the environmental impacts and environmental risks of the activity will continuously be reduced to as low as is reasonably practicable;

(c) Demonstrates that the environmental impacts and environmental risks of the activity will be of an acceptable level;

(d) Provides for appropriate environmental performance objectives, environmental performance standards and measurement criteria;

(e) Includes an appropriate implementation strategy and monitoring, recording and reporting arrangements;

(f) Demonstrates that there has been an appropriate level of consultation with relevant authorities and interested persons and organisations; and

(g) Complies with Division 3 of the Petroleum and *Geothermal Energy Resources (Environment) Regulations 2012*, which sets out the information required to be included in an Environment Plan.

When the Environment Plan is approved by the Minister for Mines and Petroleum, the operator is required to comply with its provisions. The consequences of breaching the Environment Plan can include directions from the Minister, withdrawal of approval for the Environmental Plan, prosecution or cancellation of the petroleum title.

A revised Environmental Plan must be submitted and approved prior to commencing an activity where a significant new, or increased environmental impact or environmental risk is identified. DMIRS has developed a guideline for the development of petroleum and geothermal Environmental Plans in Western Australia (Department of Mines and Petroleum 2016a).

The requirements under the *Petroleum and Geothermal Energy Resources Environment Regulations* and an approved Environment Plan are in addition to any applicable

requirements under the EP Act or the Australian *Environmental Protection and Biodiversity Conservation Act 1999* (EPBC Act), discussed further below.

Field Management Plans

The *Petroleum and Geothermal Energy Resources (Resource Management and Administration) Regulations 2015* and the *Petroleum (Submerged Lands) (Resource Management and Administration) Regulations 2015* (together, the Resource Management Regulations) (subject to regulation 58(1) and 59(1) of the Resource Management Regulations) require a licensee to have a Field Management Plan approved by the Minister before recovering petroleum in its licence area.

Once approved, a Field Management Plan provides a description of the life cycle of the petroleum project covered by the production licence and how the project will be managed by the operator. It covers all stages of the production phase from pre-commissioning, commissioning, start-up and recovery operations, to decommissioning. It also covers all the anticipated facilities located on the surface (such as production and storage facilities).

Information contained in the Field Management Plan typically includes:

- The number and type of wells to be drilled and their locations;
- A description of the subsurface geology, including rock properties and fluid pressures;
- Estimated production over time, including the maximum rate of recovery from the petroleum field;
- Details of how produced fluids and wastes will be monitored and managed; and
- Decommissioning and rehabilitation processes, including surface facilities, following completion of resource extraction.

The Field Management Plan must be revised and approved as a result of any major changes to the project. Non-compliance with an approved Field Management Plan can result in directions, prosecution or cancellation of the petroleum title. Field Management Plans are not referred to the Environmental Protection Authority (EPA).

Well Management Plans

The Resource Management Regulations also require an operator to have a Well Management Plan approved by the Minister before undertaking a well activity in a title area.

The objective of a Well Management Plan is to ensure that the well activity is managed in accordance with sound engineering principles, codes, standards and specifications, and consistently good oil-field practice.

A Well Management Plan must contain:

(a) Details of the proposed wells and each well activity, including location and proposed timetable for each activity;

(b) An explanation of philosophy of, and criteria for, the design, construction, operational activity and management of the well; and the possible production or injection activities of the well, showing that each well activity will be carried out in accordance with sound engineering principles, codes, standards and specifications and, if the activity relates to the exploration for or recovery of petroleum, good oil-field practice;

(c) Performance objectives and measurement criteria;

(d) An explanation of how the title holder will identify, monitor, mitigate and otherwise deal with a well integrity hazard and a significant increase in an existing risk for the well, including the possibility of continuing a well activity for the purpose of dealing with the well integrity hazard or the risk;

(e) Details of chemicals and other substances that may be in, or added to, treatment materials to be used for the purposes of drilling or hydraulic fracture stimulation undertaken in the course of each well activity, introduced into a well or underground formation, or otherwise used in the course of each well activity;

(f) The proposed total volume and composition of fluids and other materials to be used in the course of each well activity, returned fluids, and produced formation materials, including the proposed management of the fluid and materials;

(g) Details of how and when the title holder will notify or report to the Minister on well activities, well integrity hazards, significant increases in risks and other relevant matters, and the record-keeping process for this information;

(h) A list of the principal Australian and international standards that apply in relation to each well activity and plant used in connection with each well activity; and

(i) In relation to drilling activity, technical information such as proposed depth, path, and description of the equipment to be used, among other things.

The titleholder must apply for a revision of an approved Well Management Plan if any of the following occur:

(a) A change in the understanding of the geology or underground formation that may have a significant impact on the integrity of a well or a well activity to which the approved well management plan relates;

(b) The occurrence or potential occurrence of a significant new detrimental risk to or effect on the integrity of a well or a well activity to which the approved well management plan relates; or

(c) A significant increase in a detrimental risk to or effect on the integrity of a well or a well activity to which the approved well management plan relates.

Once approved, a Well Management Plan must be adhered to and failure to comply with a requirement in the plan can result in directions, withdrawal of approval for the Well Management Plan, prosecution or cancellation of the petroleum title.

The Resource Management Regulations also create a general offence for a titleholder who fails to control an identified well integrity hazard or an existing risk to the well that has significantly increased.

An example of a Well Management Plan is available in **Appendix 6**.

Safety Management Systems

The *Petroleum and Geothermal Energy Resources (Management of Safety) Regulations 2010* require a Safety Management System to be in place and complied with in relation to any onshore petroleum operation.

The Safety Management System must contain:

(a) A description of the operation;

(b) Acknowledgment of the duties that various persons have in relation to the operation;

(c) A detailed explanation of how the operator proposes to:

i. Meet its obligations; and

ii. Ascertain whether other persons meet their obligations, to the extent that it is practicable for the operator to do so, including details of the systems and procedures to be used for those purposes.

(d) A detailed explanation of how compliance with the Safety Management System would be measured, evaluated and maintained;

(e) A detailed explanation of how the Safety Management System would be reviewed;

(f) A risk assessment for the operation that identifies potential hazards, assessment of the risk of each hazard, and measures to reduce risk to a level that is as low as is reasonably practicable;

(g) A system for ongoing and systematic management of hazards and safety; and

(h) Means for implementation, and the ongoing and systematic improvement of the Safety Management System.

Non-compliance with a Safety Management System can result in directions, improvement notices, prohibition notices, a direction to cease activity instructions, fines and cancellation of the petroleum title.

An example of a Safety Management System is available in **Appendix 7**.

4.3.2 Environmental Protection Authority (EPA)

The EP Act establishes the broad framework by which the environmental impacts from potential developments are assessed and authorised. Responsibility for the execution of much of this Act is given to the EPA, an independent statutory authority established under the provisions of the EP Act.

The object of the EP Act is to protect the environment of the State, having regard to the following principles:

1. *The precautionary principle*

Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation.

In the application of the precautionary principle, decisions should be guided by:

(a) Careful evaluation to avoid, where practicable, serious or irreversible damage to the environment; and

(b) An assessment of the risk weighted consequences of various options.

2. *The principle of intergenerational equity*

The present generation should ensure that the health, diversity and productivity of the environment is maintained or enhanced for the benefit of future generations.

3. *The principle of the conservation of biological diversity and ecological integrity*

Conservation of biological diversity and ecological integrity should be a fundamental consideration.

4. *Principles relating to improved valuation, pricing and incentive mechanisms*

1. Environmental factors should be included in the valuation of assets and services.
2. The polluter pays principle – those who generate pollution and waste should bear the cost of containment, avoidance or abatement.

3. The users of goods and services should pay prices based on the full life cycle costs of providing goods and services, including the use of natural resources and assets, and the ultimate disposal of any wastes.
4. Environmental goals, having been established should be pursued in the most cost effective way, by establishing incentive structures, including market mechanisms, which enable those best placed to maximise benefits and/or minimise costs to develop their own solutions and responses to environmental problems.

5. *The principle of waste minimisation*

All reasonable and practicable measures should be taken to minimise the generation of waste and its discharge into the environment.

One of the EPA's primary roles is to conduct environmental impact assessments, which involves assessing proposals that are likely, if implemented, to have a significant effect on the environment.

The EPA makes recommendations to the Minister for Environment, who consults and reaches an agreement with other relevant decision-making authorities on whether the proposal should be implemented, and if so, whether any conditions should be imposed on its implementation.

The role and processes of the EPA aim to protect the Western Australian environment, incorporating the following key elements:

- Independence - the EPA is an independent board comprising five members appointed by the Governor on the recommendation of the Minister for Environment. The EPA is independent in that it is not subject to direction by the Minister.;
- Transparency - all recommendations made by the EPA to the Minister for Environment are made public in the EPA's Report and Recommendations; and
- Public involvement - providing opportunities for public participation is an integral part of environmental impact assessment in Western Australia. The EPA publishes all documents open for public comment on its consultation hub. (https://consultation.epa.wa.gov.au/)

A decision-making authority must refer a significant proposal to the EPA for assessment and a proponent or any other person may refer a significant proposal.

The EPA's Statement of Principles, Factors and Objectives (Environmental Protection Authority 2018) describes matters that the EPA considers in determining whether a proposal is likely to have a potentially significant impact. These include:

- Values, sensitivity and quality of the environment that is likely to be impacted;

- Extent (intensity, duration, magnitude and geographic footprint) of the likely impacts;
- Consequence of the likely impacts (or change);
- Resilience of the environment to cope with the impacts or change;
- Cumulative impact with other projects;
- Connections and interactions between parts of the environment to inform a holistic view of impacts to the whole environment;
- Level of confidence in the prediction of impacts and the success of proposed mitigation; and
- Public interest about the likely effect of the proposal, if implemented, on the environment, and public information that informs the EPA's assessment.

In determining whether the impact of a proposal will be significant, the EPA also considers each of the environmental factors identified in its Statement of Principles, Factors and Objectives, and whether the proposal is likely to meet the objective set by the EPA for that factor. For example, the EPA's objective for the factor 'Inland Waters' is to maintain the hydrological regimes and quality of groundwater and surface water so that environmental values are protected.

When a proposal is referred to the EPA, the EPA decides if the proposal should be assessed and, if so, the level of assessment.

If a proposal is not assessed, the EPA may give advice or make recommendations on the environmental aspects of the proposal to the proponent or any other relevant person or authority but that advice is not binding.

Once the EPA decides to assess a proposal, no other decision-makers can issue approvals in relation to the proposal until the EPA has completed its assessment and an implementation agreement or decision has been made.

The EPA has a wide discretion under s.40 of the EP Act to determine information required for its assessment and the level of public review to be provided. The most common levels of assessment are:

- Referral information;
- Environmental review – no public review; and
- Public environmental review (PER).

In deciding the level of assessment and whether public review is required, the EPA considers:

- The level of information provided in the referral and other documents;

- The number and complexity of preliminary key environmental factors relevant to the proposal;
- Whether it is a common type of proposal where there is an established condition-setting framework; and
- The level of public interest about the proposal.

The EPA completes its assessment by providing a report to the Minister for Environment, which sets out what the EPA considers to be the key environmental factors in relation to the proposal, and its recommendations as to whether the proposal may be implemented and on what conditions.

Any person, including members of the public and the proponent, can appeal against the content of the EPA's report and the recommendations contained in it.

After the EPA has reported, and after any appeals have been determined, the Minister for Environment consults and reaches agreement with relevant decision-making authorities on whether the proposal may be implemented. If an agreement is reached that the proposal may be implemented, a Ministerial Statement is issued, setting out the conditions to which the proponent must adhere.

An example of an EPA assessment for a 3D Seismic survey is available in **Appendix 8**.

4.3.2.1 Western Australian Environmental Offsets Policy

During the assessment of a project, the EPA may give consideration to the Western Australian Environmental Offsets Policy. Environmental offsets are actions that provide environmental benefits that counterbalance the significant residual environmental impacts or risks of a project or activity. Unlike mitigation actions, which occur on-site as part of the project and reduce the direct impact of that project, offsets are undertaken outside of the project area and counterbalance significant residual impacts.

Environmental offsets are most often applied to proposals subject to environmental impact assessment and as a condition of permits for clearing of native vegetation under the EP Act but may be considered in relation to other legislation, including planning developments under the *Planning and Development Act 2005* and mining proposals under the *Mining Act 1978.*

The Federal Government applies environment offsets under the EPBC Act to protect matters of national environmental significance where these are affected by a development or activity.

An example of an offset is available in **Appendix 9**.

4.3.3 Department of Water and Environmental Regulation (DWER)

4.3.3.1 Water regulation

In Western Australia, access to water is regulated by the Department of Water and Environmental Regulation (DWER) under the *Rights in Water and Irrigation Act 1914* (RIWI Act).

DWER also provides advice on petroleum proposals where they may pose a significant risk to water resources, and on petroleum exploration and development proposals located in proclaimed Public Drinking Water Source Areas (PDWSA).

Most water for petroleum activities is sourced from underground aquifers relatively close to the surface. Non-potable water can be used for hydraulic fracture stimulation, including water with salinity equivalent to seawater, which may be available in deeper aquifers.

To construct a water bore, a construction licence is required. To take water from a proclaimed groundwater or surface water area, a licence to take water must be issued by DWER. This licence allows a licence holder to take water from a watercourse, wetland or underground source in accordance with a set of terms and conditions issued by DWER. As most of the State is proclaimed for either ground and/or surface water, a project involving hydraulic fracture stimulation in such an area requires a licence to extract a specified volume of water.

New licences will only be issued where the water allocation limit has not been reached, thereby protecting existing users and the environment. This process addresses the issue of cumulative impacts of water use in a particular area. In fully allocated areas, water could possibly be obtained by the discovery of new groundwater resources, and also trucking or trading with existing water licence holders, as specified in DWER's Trading Policy.

DWER also identifies, proclaims and manages PDWSAs to protect the quality of water sourced by drinking service providers. Drinking Water Source Protection Plans have been developed by DWER to identify the potential risks to water quality and public health in a PDWSA and how these are managed.

Permits to interfere with the bed and banks of a watercourse or wetland are required for any activity or work that may disturb, destroy or interfere with the bed and banks or flow of a watercourse within a proclaimed surface water resource. DWER may refuse to issue a permit if the activity cannot be made acceptable to DWER. Where issued, permits may bind operators to certain conditions and restrictions.

4.3.3.2 Environmental regulation

DWER also regulates contaminated sites, clearing of native vegetation, controlled waste, and the licensing of prescribed premises under Part V of the EP Act, the *Contaminated Sites Act 2003* and *Soil and Land Conservation Act 1945.*

Some shale and tight oil and gas activities may require a works approval and/or licence under Part V of the EP Act. Premises on which more than 5,000 tonnes per year of crude oil, natural gas or condensate is extracted and treated or separated to produce stabilised crude oil, purified natural gas or liquefied hydrocarbon gases are 'prescribed premises' under the Environmental Protection Regulations 1987.

The EP Act requires a person or occupier to hold a works approval in order to carry out any works that cause a premise to become a prescribed premise. A licence is needed to authorise any emissions from a prescribed premise. Emissions include noise, odour, electromagnetic radiation and discharge of waste. Waste includes liquid, solid, gaseous and radioactive matter that is discharged to the environment.

DWER also administers provisions for the clearing of native vegetation. Some exemptions from the requirement to obtain a clearing permit are available in relation to petroleum activities. Where a permit is required, the Chief Executive Officer (CEO) of DWER, under the EP Act, has delegated the power to determine applications for clearing permits relating to petroleum activities regulated under the Petroleum Acts to DMIRS.

DWER also regulates the transportation of controlled waste on roads in Western Australia through the *Environmental Protection (Controlled Waste) Regulations 2004.* The Regulations provide for the licensing of carriers, drivers, and vehicles involved in transporting controlled waste in order to ensure that controlled waste is safety transported to an approved licensed waste facility for disposal.

4.3.4 Department of Biodiversity, Conservation and Attractions (DBCA)

The Department of Biodiversity, Conservation and Attractions (DBCA) manages many areas of land under the *Conservation and Land Management Act 1984* (CALM Act), some of which are national parks, nature reserves and other natural areas to conserve and protect Western Australia's native flora and fauna. The department also regulates the taking of native species, provides advice to regulatory agencies in relation to these natural areas and administers regulations potentially relevant to shale and tight oil and gas projects under the following legislation:

- *Conservation and Land Management Act 1984;*
- *Wildlife Conservation Act 1950;*
- *Biodiversity Conservation Act 2016; and*
- *Sandalwood Act 1929.*

Operators of shale or tight oil and gas projects are subject to regulations under these Acts through licences and permits issued in relation to protected plants and animals, and activities undertaken on lands and waters managed under the CALM Act.

Written consent of the Minister for Environment is required to 'take' (disturb in any way through direct or indirect means) flora that is protected or declared as rare flora. DBCA and the Minister for Environment will seek to minimise the impact on protected or declared rare flora to provide for its conservation. The habitat of declared rare flora is expected to be avoided.

Fauna gazetted by the Minister for Environment as threatened fauna are specially protected. Licence applications to take (disturb or interact in any way) are assessed by DCBA with the objective of ensuring the conservation of the species. The habitat of threatened fauna is expected to be avoided.

Ecological communities defined and declared by the Federal Minister for Environment under the EPBC Act as Threatened Ecological Communities (TEC) are regarded as being of specific conservation value. The conservation of threatened ecological communities is included in environmental impact assessment under Part IV and V of the EP Act.

When the *Biodiversity Conservation Act 2016* and Regulations become fully operational, both the *Wildlife Conservation Act 1950* and the *Sandalwood Act 1929* will be repealed, and new laws will be introduced for the listing of native species, ecological communities and threatening processes, and the regulation of other activities impacting biodiversity and conservation that require lawful authority.

4.3.5 Agricultural Protection Board of Western Australia

The Agricultural Protection Board of Western Australia manage weeds under the *Agriculture and Related Resources Protection Act 1976*. Other Western Australian legislation relevant to onshore oil and gas operations include:

- *The Plant Disease Act 1924;*
- *Plant Disease Regulations 1989;*
- *Biosecurity and Agricultural Management Act 2007; and*
- *Biosecurity and Agricultural Management Regulations 2013.*

4.3.6 Department of Planning, Lands and Heritage (DPLH)

4.3.6.1 Aboriginal heritage

The Department of Planning, Lands and Heritage (DPLH) administers the *Aboriginal Heritage Act 1972* (AH Act).

Section 17 of the AH Act makes it an offence to excavate, destroy, damage, conceal or in any way alter any Aboriginal site unless with the authorisation of the Registrar or consent of the Minister for Aboriginal Affairs.

The State Government's Aboriginal Heritage Due Diligence Guidelines (Department of Aboriginal Affairs & Department of the Premier and Cabinet 2013), provide guidance on the obligations of the AH Act and how risks in relation to Aboriginal heritage may be managed. This may involve detailed consultations with Traditional Owners or native title parties in affected areas and, where appropriate, the completion of site identification or avoidance surveys and heritage surveys.

If an impact to an Aboriginal heritage site is likely, consent of the activity must be obtained from the Minister for Aboriginal Affairs under section 18 or from the Registrar of Aboriginal Sites under section 16 of the AH Act. Failure to comply with any conditions imposed on the Minister's consent is an offence.

The Australian *Aboriginal and Torres Strait Islander Heritage Protection Act 1984* also applies. Under this Act, declarations can be sought from the Federal Minister for Environment to preserve and protect from injury or desecration, objects of particular cultural significance to Aboriginal and Torres Strait Islander people.

4.3.6.2 Planning and local government

The Western Australian Planning Commission (WAPC) is the statutory authority with statewide responsibility for urban, rural and regional land-use planning and land development matters. WAPC responds to the strategic direction of the State Government and is responsible for the strategic planning of the State.

WAPC operates with the support of the DPLH, which provides professional and technical expertise, administrative services, and resources to advise WAPC and implement its decisions. In this partnership, WAPC has responsibility for decision-making and a significant level of funding, while DPLH provides the administrative and technical advice.

Local governments are involved in planning for local communities by ensuring appropriate planning controls exist for land use and development. They do this by, among other things, preparing and administering local planning schemes and strategies.

Local planning schemes contain planning controls such as designation of appropriate land uses, residential densities and development standards. Local governments must base their planning decisions on the provisions and controls in their local planning scheme.

All local government planning schemes and policies are required to give due regard to State Government planning objectives and requirements. Proponents should consult local governments to determine if exploration and/or operation requires development approval under their relevant local planning scheme.

State Planning Policies (SPPs), which are specifically provided for in the *Planning and Development Act 2005*, are required to be prepared and kept under review by WAPC.

SPPs can be subject or location specific, and are generally used for the following purposes:

- To assist WAPC in its decision-making with respect to the subdivision of land and development approval under region schemes; and
- To provide guidance to local government on the matters they need to take into account in preparing local planning schemes.

Local government is required to have due regard to SPPs in preparing or amending a local planning scheme and the Minister for Planning may order a local government to amend its scheme to be consistent with a SPP.

In some instances, planning legislation can be overridden. An example of this is a State Agreement Act. A State Agreement Act is a contract between the Government of Western Australia and a proponent of a major resource project that is ratified by an Act of State Parliament. They specify the rights, obligations, terms and conditions for development of the project and establish a framework for ongoing relations and cooperation between the State and the project proponent. For more than 50 years, State Agreements have been used by successive Western Australian governments to foster major developments, including mineral, petroleum, wood processing and related downstream processing projects, together with associated infrastructure investments. Such projects require long-term certainty and extensive or complex land tenure, and are often located in relatively remote areas of the State requiring significant infrastructure development.

4.3.7 Department of Health (DoH)

The Department of Health (DoH) provides advice on petroleum exploration and development proposals where there is a potential health risk to the public or there is significant public interest related to health concerns.

The regulation of Naturally Occurring Radioactive Materials (NORM) associated with the petroleum industry is managed through the *Radiation Safety Act 1975.*

The *Health (Miscellaneous Provisions) Act 1911* provides protection for public drinking water supplies. It also provides protection from pollution for any water supply or catchment area, including any river, stream, watercourse, creek, swamp, water hole, well, tank, lake, or reservoir containing water intended or available for human consumption. The local government or the Chief Health Officer can direct the closure of a water supply that is

considered to be polluted. As with any industry, shale and tight oil and gas operators must comply with all relevant legislation.

4.3.8 Referral to the Australian Department of Environment and Energy (DoEE)

Federal legislation also potentially regulates the development of shale and tight oil and gas projects. The EPBC Act applies where a proposed exploration or development action is likely to have a significant impact on a Matter of National Environmental Significance (MNES).

The Australian Government, through the Australian Department of Environment and Energy (DoEE), is required to assess any action that is likely to have a significant impact on MNES. MNES are defined under the EPBC Act and include:

- World Heritage properties;
- National Heritage places;
- Wetlands of international importance (Ramsar wetlands);
- Listed threatened species or ecological communities;
- Migratory species protected under international agreements;
- The environment where nuclear actions are involved (including uranium mines); and
- A water resource, in relation to Coal Seam Gas (CSG) development or large coal mine development.

Western Australia has more than ten wetlands protected under the Ramsar Convention, which aims to halt the worldwide loss of wetlands and to ensure wise use and management conserves those wetlands that remain. If an onshore petroleum activity is likely to have a significant impact on one of these wetlands, the operator must refer the action to DoEE and obtain approval prior to commencing any activities, in addition to any approvals from State agencies.

Similarly, if an operator proposes onshore petroleum activities in a National Heritage place that is likely to have a significant impact on those values, such as the Dampier Archipelago/Burrup Peninsula or the West Kimberley National Heritage Area, the action must be referred to DoEE and appropriate Federal approvals need to be obtained before activities can start.

Table 4.1: Overview of Western Australian legislation relevant to the shale and tight oil and gas industry

Source: Department of Mines, Industry Regulation and Safety (DMIRS), and updated by the Inquiry Panel

Agency	Role	Legislation
WESTERN AUSTRALIA		
Department of Mines, Industry Regulation and Safety (DMIRS)	DMIRS is the State's lead agency in regulating minerals and energy resources in Western Australia and ensuring that safety, health and environmental standards are of the highest standard and are consistent with relevant State and Federal legislation, regulation and policies. The Department has a role in the provision of geoscientific information on minerals and energy resources, administering the collection of royalties and management of an equitable and secure titles system for the mining, petroleum and geothermal industries. The Department is committed to educating the community about resource development and regulation in Western Australia and ensuring the responsible development of the resources industry to maximise the economic and social return to all Western Australians. Safety Regulation: regulation of all safety obligations associated with the petroleum operation including the health and safety of workers. Regulated through the operator's submission of a Safety Management System and Safety Case. Environment Regulation: regulation of all potential environmental impacts as a result of the petroleum activity, that is, impacts on land, air, water, the subsurface, flora and fauna. Regulated through the operator's submission of an Environmental Plan for each activity at each stage, bringing together and identifying all environmental impacts, risk mitigation measures and implementation strategies. Native Vegetation Clearing: certain powers under Part V Division 2 of the EP Act for regulation of the clearing of native vegetation for petroleum activities as provided for by delegation. Resource Management and Administration: regulation of the technical aspects/operation of petroleum activities, ensuring they comply with international standards and best practice. Regulated through applications for exploration surveys and wells and various management plans governing these activities.	*Petroleum and Geothermal Energy Resources Act 1967* *Petroleum Pipelines Act 1969* *Environmental Protection Act 1986* (EP Act) (Delegated Authority for native vegetation clearing) *Petroleum (Submerged Lands) Act 1982* *Dangerous Goods Safety Act 2004* *Occupational Safety and Health Act 1984*

Agency	Role	Legislation
Department of Water and Environmental Regulation (DWER)	DWER has the primary responsibility for conserving, protecting, managing and assessing water resources and planning for the use of water resources under the *Water Agencies (Powers) Act 1984*, as well as the regulation of water resources, pollution, unreasonable emissions, environmental harm and clearing of native vegetation, assessment and classification of contaminated sites based on risks to the community and the environment, and management of waste to promote the efficient use of resources and prevent environmental harm, specifically: The *Rights in Water Irrigation Act 1914* provides for a licensing system to take water and construct water wells in proclaimed areas from artesian and non-artesian sources; and a permit system for activities that may damage, obstruct or interfere with water flow or the beds and banks or watercourses and wetlands in proclaimed rivers, surface water management areas and irrigation districts. The Country Areas Water Supply Act 1947 and Metropolitan Water Supply, Sewerage and Drainage Act 1909 and associated by-laws protect public drinking water sources. The *Country Areas Water Supply Act 1947* and the *Country Areas Water Supply (Clearing Licence) Regulations 1981* provide for a licensing system for the clearing of vegetation in the Denmark River, Harris River Dam, Mundaring Weir, Wellington Dam and Warren River catchment areas and the Kent River Water Reserve. This licensing system applies when there is an exemption under the *Environmental Protection (Clearing of Native Vegetation) Regulations 2004.* The *Waterways Conservation Act 1976* provides for a licensing system for dredging, reclamation, dewatering, drainage, excavation and construction activities in the Albany waterways, Avon River, Wilson Inlet, Peel–Harvey estuaries and Leschenault Inlet management areas. The regulation of activities with potential impacts on the environment through works approvals and licences for premises prescribed under Schedule 1 of *the Environmental Protection Regulations 1987* to prevent unacceptable risks to the environment and public health. The development and implementation of policies and strategies that promote environmental outcomes. Reducing the environmental impact of waste.	*Environmental Protection Act 1986* *Contaminated Sites Act 2003* *Waste Avoidance and Resource Recovery Act 2007* *Rights in Water and Irrigation Act 1914* *Metropolitan Water Supply, Sewerage and Drainage Act 1909* *Country Areas Water Supply Act 1947* *Water Agencies (Powers) Act 1984* *Waterways Conservation Act 1976*

Agency	Role	Legislation
Department of Biodiversity, Conservation and Attractions (DBCA)	DCBA has primary responsibility for managing the State's national parks, marine parks, State forests and other reserves that cover a total area of more than 27 million hectares; for conserving and protecting native animals and plants; and for managing many aspects of the access to and use of the State's wildlife and natural areas. DCBA also provides support to the Marine Parks Reserves Authority and the Conservation Commission (which, under proposed amendments to the *Conservation and Land Management Act 1984*, will be amalgamated to form the Conservation and Parks Commission).	*Conservation and Land Management Act 1984* *Wildlife Conservation Act 1950* *Biodiversity Conservation Act 2016* *Sandalwood* Act 1929
Environmental Protection Authority (EPA)	EPA is an independent authority established by the EP Act, under which the EPA is to: 'use its best endeavours – a) to protect the environment; and b) to prevent, control and abate pollution and environmental harm.' EPA's functions include: Conducting environmental impact assessments; Preparing statutory policies for environmental protection; Preparing and publishing guidelines for managing environmental impacts; and Providing strategic advice to the Minister for Environment.	*Environmental Protection Act 1986*
Department of Health (DoH)	DoH provides a number of functions to support the delivery of health services across the State, including the area of public health. This activity encompasses the regulation of the quality of drinking water in Western Australia, in addition to providing advice about potential environmental hazards impacting health.	*Health (Miscellaneous provisions) Act 1911*
Radiological Council	The Radiological Council is an independent statutory authority appointed under the Radiation Safety Act 1975 in Western Australia to assist the Minister for Health to protect public health and to maintain safe practices in the use of radiation. The Act regulates the keeping and use of radioactive substances, irradiating apparatus and certain electronic products. Registration and licensing are the principal means by which the use of radiation is regulated. The officers of the Radiological Council also provide radiation health advice.	*Radiation Safety Act 1975*

Agency	Role	Legislation
Department of Planning, Lands and Heritage (DPLH)	DPLH is Western Australia's lead land use planning agency and provides professional and technical expertise and assists in the development and implementation of land use plans and policies across the State. The *Planning and Development Act 2005* provides statutory powers to the Western Australian Planning Commission and the Minister for Planning, as well as establishes the statutory force of local planning schemes administered by Local Governments. DPLH is responsible for developing strategic policy to guide and inform service delivery to Aboriginal people; coordinating service delivery to Aboriginal Western Australians through chairing and supporting the Aboriginal Affairs Coordinating Committee; preserving and protecting Aboriginal heritage by supporting the work of the Aboriginal Cultural and Material Committee; and support the Aboriginal Lands Trust in the management of lands held by the Trust in accordance with wishes of people of Aboriginal descent.	*Planning and Development Act 2005* *Aboriginal Heritage Act 1972* *Aboriginal Affairs Planning Authority Act 1972*
AUSTRALIAN GOVERNMENT		
Department of the Environment and Energy (DoEE)	Conducts an environmental impact assessment of actions likely to have an impact on matters of national environmental significance as defined in the EPBC Act.	*Environment Protection and Biodiversity Conservation Act 1999*

Compliance

All approvals issued by each agency are subject to that agency's compliance function, for example, all conditions and licences issued under Part IV and V of the EP Act are subject to audit by the DWER. The information below relates to the compliance of plans approved by DMIRS.

Auditing

An Environmental Plan for a petroleum activity must outline the arrangements that are in place for the environmental auditing of the activity, along with the frequency or schedule of audits, in order to review the effectiveness of the implementation strategy.

Audits are expected to be undertaken by the proponent, at least annually. However, where an activity is undertaken in multiple stages (for example, drilling a well and production testing), has a higher level of risk, or is in the vicinity of a sensitive receptor, audits should be undertaken on a more regular basis.

Environmental audits are meant to:

- Ensure all significant environmental aspects of an activity are covered in the Environmental Plan;
- Ensure that mitigation measures implemented onsite are appropriate and reduce environmental impacts and risks to As Low As Reasonably Practicable (ALARP);
- Ensure that management strategies are effective in achieving objectives and standards, and that these are implemented, reviewed, and amended where necessary;
- Identify non-compliance and opportunities for continuous improvement; and
- Ensure that all environmental completion criteria have been met prior to completing, suspending or decommissioning an operation.

DMIRS will undertake site audits and inspections during the activity to determine the level of compliance in relation to the Environmental Plan, Well Management Plan and Safety Management System.

DMIRS also conducts inspections in relation to complaints. Enforcement action is undertaken when there is non-compliance.

Reporting

Once petroleum activities commence, regular reports such as daily drilling reports, well completion reports and annual reports must be submitted to DMIRS.

Under an approved Environmental Plan, the operator must submit an annual report outlining its progress against its environmental objectives, standards and implementation strategy detailed in that Plan. Reports must contain:

- A detailed summary of the activities undertaken during the reporting period;
- Details of any clearing and/or rehabilitation undertaken during the reporting period;
- A statement of compliance for each objective and standard in the Environmental Plan, including justification based on the measurement criteria;
- A summary of audits undertaken, including the findings and corrective actions;
- A summary of any incidents that occurred (recordable and reportable) and lessons learned;
- A summary of all emissions and discharges, and any trends or anomalies;
- Details of methodology and results of any biological or environmental monitoring undertaken, and a discussion of any trends or anomalies identified;
- Details of any new or increased environmental impacts or risks identified during the reporting period;
- Details of all training and exercises undertaken; and
- Details of all stakeholder engagement and consultation undertaken through the period.

The operator must monitor and report every three months on all emissions and discharges to any land, air, marine, seabed, sub-seabed, groundwater, sub-surface or inland water environment that occur in the course of the activity.

Incident Reporting

The operator must also notify DMIRS of any incidents that may have potential to cause adverse environmental impacts.

There are two types of incident reporting, as shown in **Table 4.2**.

Table 4.2: Incident reporting requirements for activities relevant to the oil and gas industry
Source: DMIRS

Incident Type	Description	Timing
Reportable	The operator must notify DMIRS of any unplanned event identified as having a moderate or more serious than moderate consequence level. For example, uncontrolled release or loss of containment, fire, quarantine incident, disturbance to an environmental sensitivity.	Notification as soon as practicable, but within two hours, followed by a detailed written report within three days.
Recordable	Any non-reportable incident arising from the activity that breaches an objective or standard identified in the Environmental Plan. For example, all spills (<80L to water or <500L to other areas), inadequate waste management, unplanned gaseous release (<500m^3), exceeding limits or concentrations of specified discharges, death or injury to fauna, unplanned flora disturbance.	Monthly in writing on or prior to the 15th day after the end of the month to which it relates.

Written reports must contain detailed information about the incident, corrective actions taken and the outcomes of any investigations undertaken. Further information may be required by DMIRS, depending upon the level of environmental impact caused.

All reportable and recordable incidents that have occurred in Western Australia since 2012 are shown in **Appendix 10**.

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5

The unconventional oil and gas resources of Australia with special emphasis on Western Australia

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5 The unconventional oil and gas resources of Australia with special emphasis on Western Australia

5.1 Unconventional onshore oil and gas resources of Australia

Australia is considered to have substantial resources of onshore unconventional oil and gas, which includes shale oil and gas, tight oil and gas, and coal seam gas (CSG). To date, the bulk of gas produced by unconventional methods in Australia is CSG, mainly from the Bowen and Surat basins in Queensland, with some production from the Sydney Basin in New South Wales. Shale oil and gas resources, developed with hydraulic fracture stimulation, have recently been accessed in the Cooper Basin in South Australia. While it is likely that Australia possesses significant unconventional oil and gas resources, these are poorly quantified because exploration in Australia has only recently commenced, and estimates have a high degree of uncertainty (Geoscience Australia & Bureau of Resources and Energy Economics 2014).

Geoscience Australia (GA) has assessed Australia's potential for unconventional gas, as shown in **Table 5.1** and **Figure 5.1** (Geoscience Australia 2018a).

Early exploration for shale gas resources has defined 12,252 Petajoules (PJ) or 11 trillion cubic feet (tcf) of contingent resources (quantities of petroleum that are estimated to be recoverable but are not currently considered to be commercially recoverable), and 9,577,353 PJ or 8,707 tcf of prospective resource (quantities of petroleum estimated to be potentially recoverable from undiscovered accumulations). Exploration for tight gas has defined 1,709 PJ or 2 tcf of contingent resources, and 2,650,622 PJ or 2,410 tcf) of prospective resource. Australia's total identified conventional and unconventional gas resources are approximately 279,685 PJ or 257 tcf. These resources are equal to approximately 106 years of gas at current production rates (Geoscience Australia 2018a). For context, in 2014 the world gas production was 136,264 PJ or 122 tcf. (Geoscience Australia 2018a).

Australia's total annual energy consumption from all sources in 2015-2016 was 6,066 PJ of which 1,120 PJ (18.5 percent) was used in Western Australia. Total gas consumption was 1,505 PJ, which was 24.8 per cent of all sources (Department of the Environment and Energy 2017b).

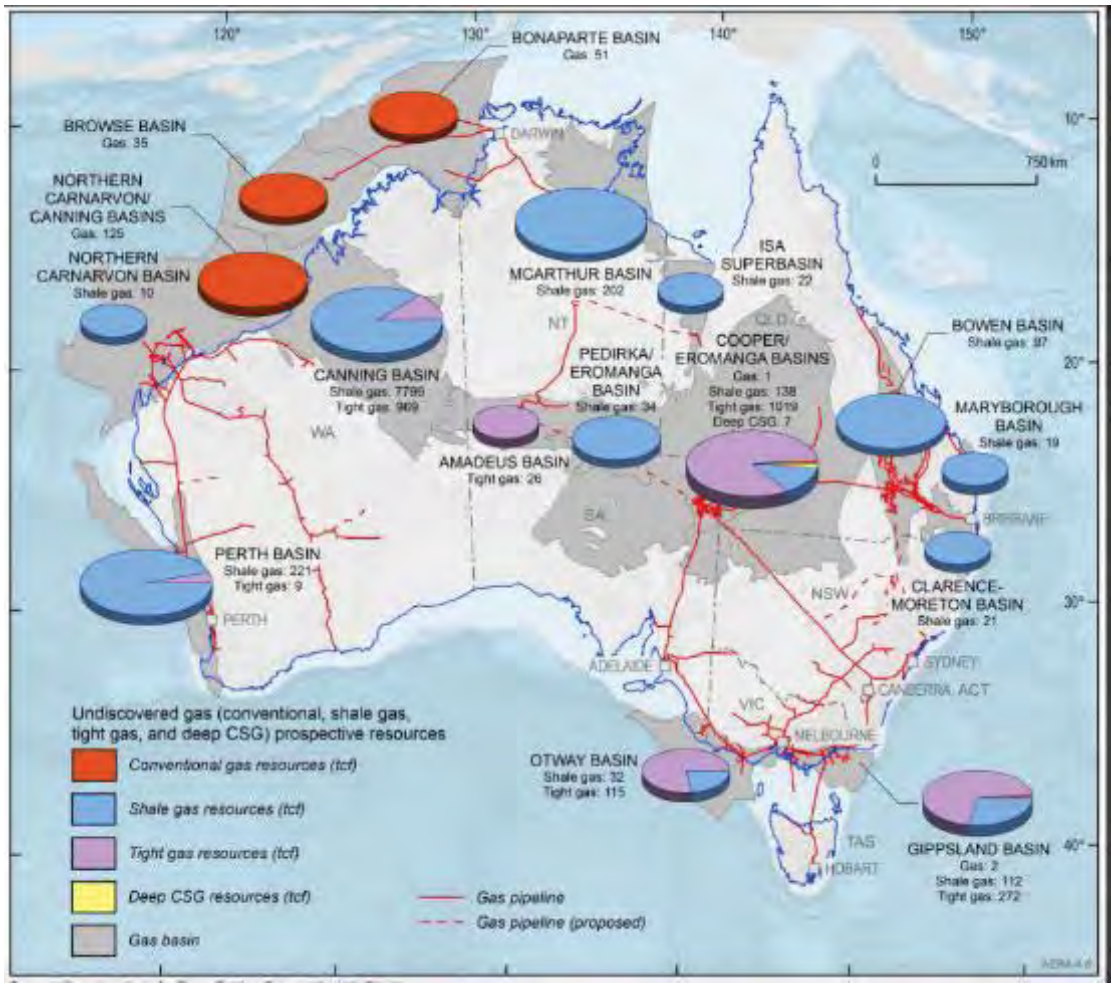
Table 5.1: Summary of Australia's prospective gas resources

Source: GA (Geoscience Australia 2018a)

Resource category	Conventional gas		Coal seam gas		Tight gas		Shale gas		Total Gas	
	PJ	tcf	PJ	tcf	PJ	tcf	PJ	tcf	PJ	tcf
Reserves (resources which are commercially recoverable and have been justified for development)	77,253	70	45,895	43	39	0	0	0	123,241	114
Contingent resources (quantities of petroleum that are estimated to be recoverable, but are not currently considered to be commercially recoverable)	108,982	99	33,555	32	1,709	2	12,252	11	156,498	143
All identified resources	186,235	169	79,450	75	1,748	2	12,252	11	279,685	257
Prospective resources (quantities of petroleum which are estimated to be potentially recoverable from undiscovered accumulations)	235,913	215	6,890	7	2,650,622	2,410	9,577,353	8,707	12,470,778	11,337

Figure 5.1: Australia's undiscovered gas (conventional, shale gas, tight gas and deep CSG) prospective resources

Source: GA (Geoscience Australia 2018a) Accurate at August 2017



Australia also has a large potential for unconventional petroleum liquid resource hosted in oil shales, and shale and tight gas deposits. Prospective resources are estimated at 9,025,546 PJ (which is 1,534,939 million barrels (mmbbl)) of shale oil, oil shale and tight oil resources in various onshore basins in Australia (Geoscience Australia 2018b).

GA has assessed Australia's potential for undiscovered prospective petroleum, as shown in **Table 5.2** and **Figure 5.2** (Geoscience Australia 2018b). For context, in 2014 the world oil production was around 32,400 mmbbl.

Total oil consumption was 2,243 PJ, which was 37% of all energy sources (Department of the Environment and Energy 2017b).

Table 5.2: Australian undiscovered conventional and unconventional oil resources at P50 confidence

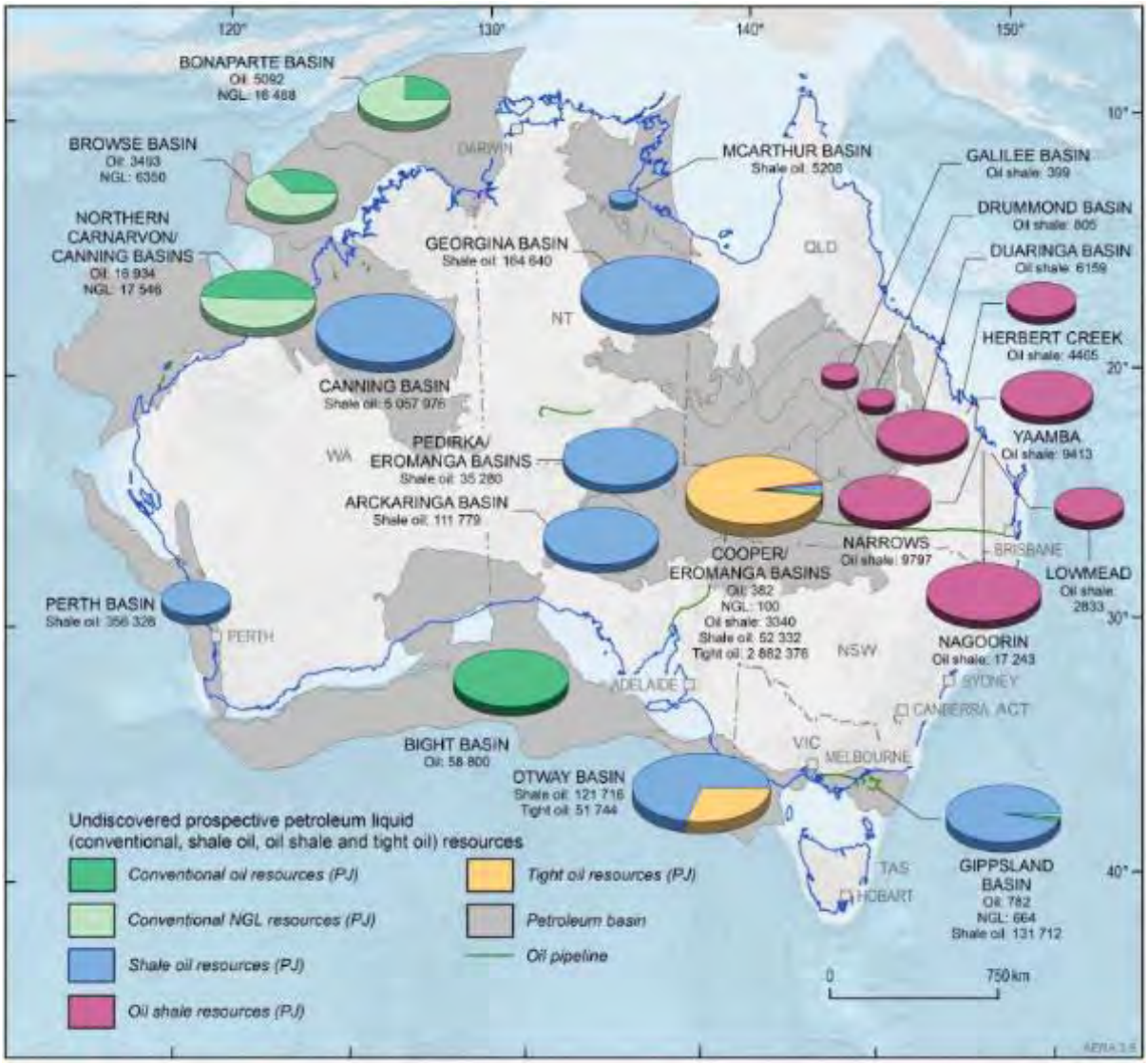
Source: GA (Geoscience Australia 2018b)

Basin	Product	Oil	NGL	Oil	NGL	Total	Total
		mmbbl*		PJ		PJ	mmbbl*
Bonaparte	Conventional	866	2,804	5,092	16,488	21,580	3,670
Browse	Conventional	594	1,080	3,493	6,350	9,843	1,674
Cooper-Eromanga	Conventional	65	17	382	100	482	82
Gippsland	Conventional	133	113	782	664	1,447	246
Great Australian Bight	Conventional	10,000	0	58,800	0	58,800	10,000
Northern Carnarvon-Canning	Conventional	2,880	2,984	16,934	17,546	34,480	5,864
Total conventional	**Conventional**	**14,538**	**6,998**	**85,483**	**41,148**	**126,632**	**21,536**
Arckaringa	Shale oil	19010		111,779		111,779	19,010
Canning	Shale oil	860,200		5,057,976		5,057,976	860,200
Georgina	Shale oil	28,000		164,640		164,640	28,000
McArthur	Shale oil	868		5,208		5,208	868
Perdirka/Eromanga	Shale oil	6,000		35,280		35,280	6,000
Cooper	Shale Oil	8,900		52,332		52,332	8,900
Perth	Shale oil	60,600		356,328		356,328	60,600
Gippsland	Shale Oil	22,400		131,712		131,712	22,400
Otway	Shale Oil	20,700		121,716		121,716	20,700
Total shale oil	**Shale Oil**	**1,026,678**		**6,036,971**		**6,036,971**	**1,026,678**

Basin	Product	Oil	NGL	Oil	NGL	Total	Total
		mmbbl*		PJ		PJ	mmbbl*
Condor - McFarlane	Oil shale	0		0		0	0
Drummond	Oil shale	137		805		805	137
Duaringa	Oil shale	1,047		6,159		6,159	1,047
Cooper-Eromanga	Oil shale	568		3,340		3,340	568
Galilee	Oil shale	68		399		399	68
Herbert Creek - Boundary Flat	Oil shale	759		4,465		4,465	759
Lowmead	Oil shale	482		2,833		2,833	482
Nagoorin	Oil shale	2,933		17,243		17,243	2,933
Narrows - Stuart oil shale	Oil shale	1,666		9,797		9,797	1,666
Yaamba	Oil shale	1,601		9,413		9,413	1,601
Total oil shale	**Oil shale**	**9,261**		**54,455**		**54,455**	**9,261**
Cooper	Tight oil	490,200		2,882,376		2,882,376	490,200
Otway	Tight oil	8,800		51,744		51,744	8,800
Total tight oil	**Tight oil**	**499,000**		**2,934,120**		**2,934,120**	**499,000**
Grand total		**1,549,477**	**6,998**	**9,111,030**	**41,148**	**9,152,178**	**1,556,475**

*1mmbbl = 1 million barrels

Figure 5.2: Australia's undiscovered prospective petroleum liquid resources (PJ)
Source: GA (Geoscience Australia 2018b) Accurate at August 2017



5.2 Unconventional onshore oil and gas resources of Western Australia

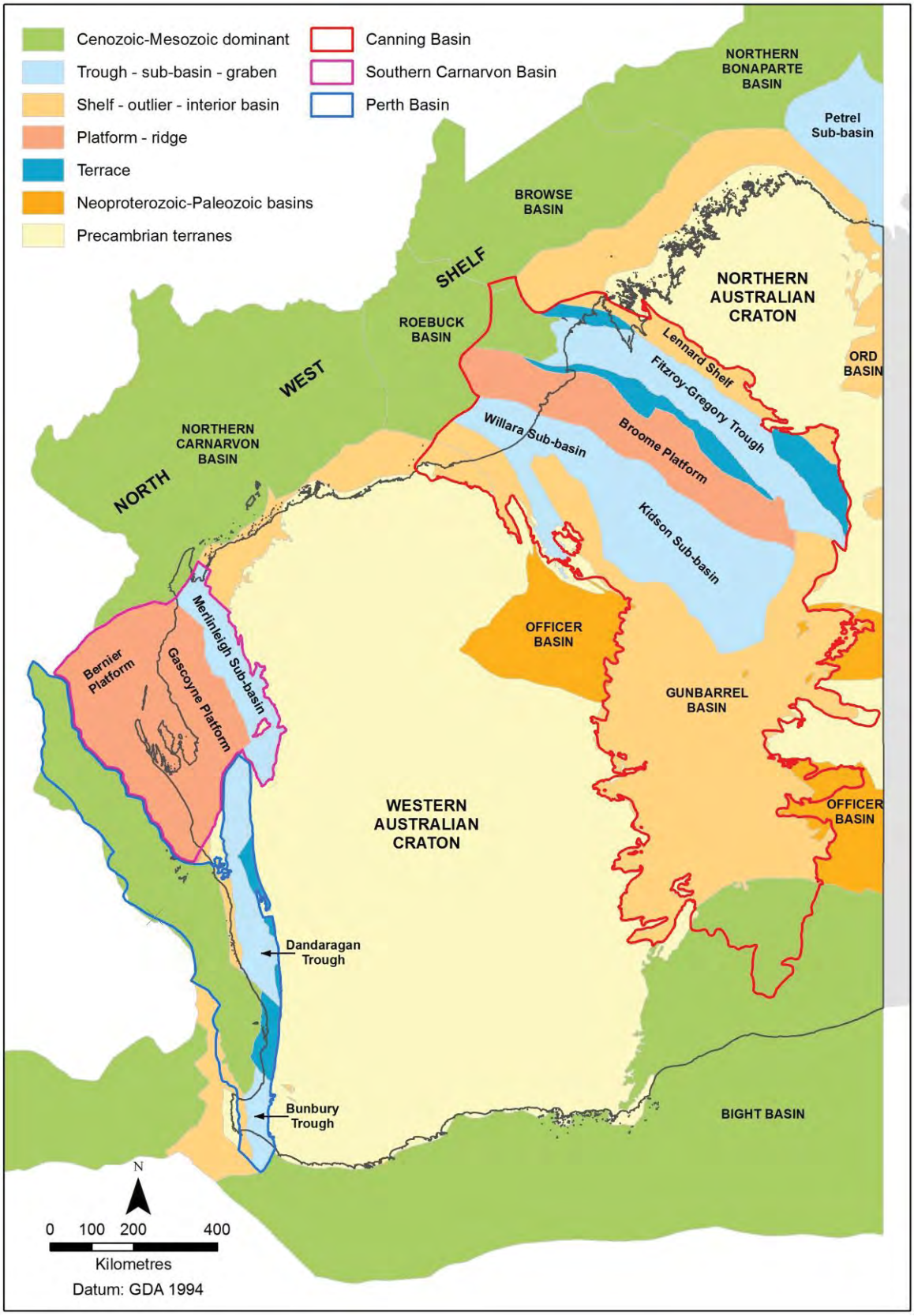
Using the data provided by GA, Western Australia holds 92 percent of Australia's prospective shale gas resources (8,020 tcf), 40 percent of Australia's prospective tight gas resources (978 tcf) and 90 percent of prospective shale oil resources (920,800 mmbbl). It should be noted that these figures are based on a rate of 50 percent probability of gas being in place and the liklihood that 5% of the gas could be recoverable (Geoscience Australia 2018a). To date, CSG has not been demonstrated to be prospective in Western Australia.

Sedimentary basins in Western Australia have also been identified as potentially prospective for shale oil and gas and tight gas by DMIRS and the United States Energy Information Agency (U.S. Energy Information Administration 2015).

DMIRS estimated that Western Australia holds significant shale gas resources of approximately 1,300 tcf (Department of Mines and Petroleum 2015a). Of this resource, DMIRS estimated that around 100–190 tcf could be produced, depending on how much of the resource can be recovered given current knowledge of the geology of the area and future technological advances. These estimates are unconstrained by market demand or economics. To put this figure into perspective, one tcf is enough energy to supply a city of one million people with electricity for 20 years. Western Australia currently produces around one tcf of gas per year, mostly from offshore conventional gasfields.

Of the prospective oil and gas in Western Australia approximately 12 percent is tight oil and gas and 88 percent is shale oil and gas. The primary areas that have been identified for unconventional oil and gas are the Canning Basin and the Perth Basin. Within these basins there are deep sub-basins and troughs, which comprise rock layers or geological formations of varying ages, from 70 million years old to more than 500 million years old. Some of these formations contain shale oil and gas or tight gas resources, along with other conventional oil and gas resources. There is also the potential for onshore shale oil and gas sources in the Southern Carnarvon Basin, however minimal exploration has been carried out compared to the Canning and Perth Basins. **Figure 5.3** shows the locations of the sedimentary basins, sub-basins and troughs in Western Australia. For more detail on shale oil and gas and tight gas resources in the Canning, Perth and Southern Carnarvon Basin, see **Section 5.7**.

Figure 5.3: A map of Western Australia's sedimentary basins
Source: Mory and Haines (Mory & Haines 2013), updated by DWER



5.3 Shale gas and tight gas compared with Coal Seam Gas (CSG)

While the CSG industry is established in Queensland and New South Wales, there is no CSG industry in Western Australia because, as previously noted, potential prospectivity for CSG has not been demonstrated.

CSG typically lies at depths of 300 to 1,000 metres (m). In Western Australia, shale and tight gas resources generally lie at depths between 2,000 and 4,000 m. These depths generally lie significantly below groundwater resources and under multiple thick layers of low permeability rock that act as barriers, or seals, between the gas formation and any water resources and the land surface.

With CSG, gas is extracted by drilling wells into the coal seam. The goal is to decrease the water pressure by pumping groundwater from the well, a process known as dewatering. The decrease in pressure allows gas to be released from the coal and flow up the well to the surface.

CSG extraction relies upon dewatering and only sometimes requires water for hydraulic fracture stimulation of the coal seam. The production of shale and tight gas does not require the removal of groundwater to release gas, but will almost always require hydraulic fracture stimulation. **Table 5.3** below shows the difference between CSG and shale and tight gas.

Table 5.3: Typical differences between coal seam gas and shale and tight gas

The data given in the table below will vary from case to case

Sources: CSIRO, Northern Territory Government, updated by the Inquiry

	Coal seam gas	Shale and tight gas
Source	Shallow coal seams	Deeper shales and tight rocks
Depth	300m – 1,000m	2,000m – 4,000m
Drilling direction	Mainly vertical	Horizontal and vertical
Proximity to aquifers	Shallow and therefore closer to potable water resources	Deeper and therefore further away from potable water sources
Surface footprint	Single exploration well per drill pad (a drill pad is the area disturbed by the installation of the drilling and extraction equipment) meaning a larger number of wellheads in a given area.	Multiple wells can be drilled from each well pad meaning a lower number of completed wellheads in a given area than for coal seam gas.
Hydraulic fracture stimulation	Hydraulic fracture stimulation in some coal seams with low permeability	Always requires hydraulic fracture stimulation
Hydraulic fracture stimulation extent (length x height)	200 – 300m x 5 – 30m	200 – 6,000m x 30 – 300m
Hydraulic fracture stimulation pressure	35MPa or 5,000psi	35 – 70MPa or 5,000 –10,000psi
Water use	Requires the dewatering of coal seams, and the disposal of large amounts of saline water	No dewatering, but water is used for drilling and hydraulic fracture stimulation
Hydraulic fracture stimulation fluid per volume per well	Approximately 1ML (0.1 – 3ML)	Approximately 20ML (5 – 40ML)
Number of wells required	Larger number of wells	Fewer wells required than for coal seam gas
Productivity (over lifetime of well)	Lower gas recovery (0.5 – 2PJ per well)	Higher gas recovery (2 - >10PJ per well)

5.4 Petroleum geology formation

Oil and gas exists within sedimentary basins. These basins developed over hundreds of millions of years and gradually fill with sediment and organic matter that is buried, compacted under pressure, and heated to form rock. Within these rock formations, oil and gas develops from the decomposition and heating of organic matter. Formations that generate oil and gas are called 'source rocks', and most of oil and gas generated in these rocks remains trapped within the source rock itself. Over long periods of time oil and gas, which is more buoyant than other fluids, may migrate upwards towards the surface of the Earth. However, a small proportion of this migrating oil and gas may reach an impermeable rock formation and become naturally sealed or trapped, and thus prevented from rising to the surface. Petroleum operators typically extract natural gas by locating and drilling into underground traps where large amounts of oil or gas have accumulated.

5.5 Shale

Shale is a fine-grained sedimentary rock that forms from the compaction of silt and clay-size mineral particles that we commonly call mud. This composition places shale in a category of sedimentary rocks known as mudstones. Shale is distinguished from other mudstones because it is laminated and fissile. Laminated means that the rock is made up of many thin layers. Fissile means that the rock readily splits into thin pieces along the laminations.

Black organic shales are the source rock for many of the world's most important oil and gas deposits. These shales obtain their black colour from tiny particles of organic matter that were deposited with the mud when the shale formed (**Figure 5.4**). As the mud was buried and heated within the earth, some of the organic material was transformed into oil and natural gas.

Figure 5.4: An organic rich shale source rock
Source: DMIRS

The pore spaces in shale are so tiny that the gas has difficulty moving through the shale. Most gas generated in black shales will never migrate and will not flow freely into a petroleum well because of this low porosity and low permeability. To produce gas directly from these shales, operators usually perform hydraulic fracture stimulation. This involves increasing the permeability of the shale by pumping water down the well under pressure high enough to fracture the shale. These fractures liberate some of the gas from the pore spaces and allow that gas to flow into and up the well.

5.6 Tight gas reserves

'Tight gas' is the term commonly used to refer to low permeability reservoirs that produce mainly dry natural gas. Many of the low permeability reservoirs that have been developed in the past are sandstone, but significant quantities of gas are also produced from low permeability carbonates, shales and coal seams. (**Figure 5.5**).

Figure 5.5: A core sample of a tight gas sandstone
Source: DMIRS

In the 1970s, the United States Government defined a tight gas reservoir as one in which gas permeability is less than 0.1 milli Darcy (mD). Similarly, in Western Australia, the *Petroleum and Geothermal Energy Resources Act 1967* defines a tight petroleum reservoir as having permeability less than 0.1 mD.

Tight gas formations are generally more permeable than shale gas formations but hydraulic fracture stimulation is often also required to produce tight gas.

5.7 Sedimentary basins with unconventional oil and gas potential in Western Australia

5.7.1 Canning Basin

The onshore Canning Basin covers an area of about 530,000 square kilometres (km^2) in central-northern Western Australia, and extends offshore for a total basin area of more than 640,000 km^2, of which 110 000 km^2 is in State waters.

Petroleum exploration activity began in the Canning Basin in the early 1920s. Since then, 287 onshore and 14 offshore wells have been drilled in the region, accompanied by the acquisition of 175,591 kilometres (km) of 2D seismic data, of which about half was for defining onshore resources.

DMIRS estimated in 2016 that the onshore Canning Basin contains 1,000 tcf of shale gas, of which about 73–147 tcf may be recoverable. Tight gas resources also exist in the Basin, notably in the Laurel Formation.

Figure 5.6 shows the potentially prospective areas for shale oil, shale gas and tight gas from the Laurel and Goldwyer formations in the Canning Basin.

Sedimentary systems of four geological periods (Ordovician, Devonian, Lower Caboniferous and Permian) containing layers of source rock (petroleum-bearing rock) have been identified in the onshore Canning Basin.

Proven Ordovician source rock intervals exist within the Goldwyer and Bongabinni Formations. Source rock intervals in the Devonian include the fossiliferous Gogo Formation; the first commercial discovery in the Canning Basin was the Blina oilfield sourced from this formation. The Lower Carboniferous section includes effective source rocks in the Laurel and Anderson Formations, which likely sourced the Lloyd 1, West Kora 1 and Point Torment 1 hydrocarbon accumulations. Permian sequences include globally distributed source rocks in the upper Grant Group shales and in the Noonkanbah Formation.

The Goldwyer Formation lies at an average depth of 1,330 m and has an average thickness of 350 m. It is thickest in the northern half of the Canning Basin, but may also be prospective for oil and gas in the central Great Sandy Desert and in the southeast of the Basin. This area remains highly underexplored.

The Carboniferous Laurel and Devonian Gogo Formations could possess additional shale gas potential in the deeper parts of the Canning Basin.

5.7.1.1 Likely areas of shale gas development in the Canning Basin.

Figure 5.7 shows the current extent of granted petroleum titles in the Canning Basin as well as the areas of potentially prospective areas for shale oil, shale gas and tight gas. **Figure 5.8** shows the interest holders for each of the granted petroleum exploration permits in the Canning Basin.

Figure 5.6: Petroleum wells (2000 to 2017) in the Canning Basin showing the extent of the potentially prospective areas for shale oil, shale gas and tight gas from the Laurel and Goldwyer Formations

Source: DWER

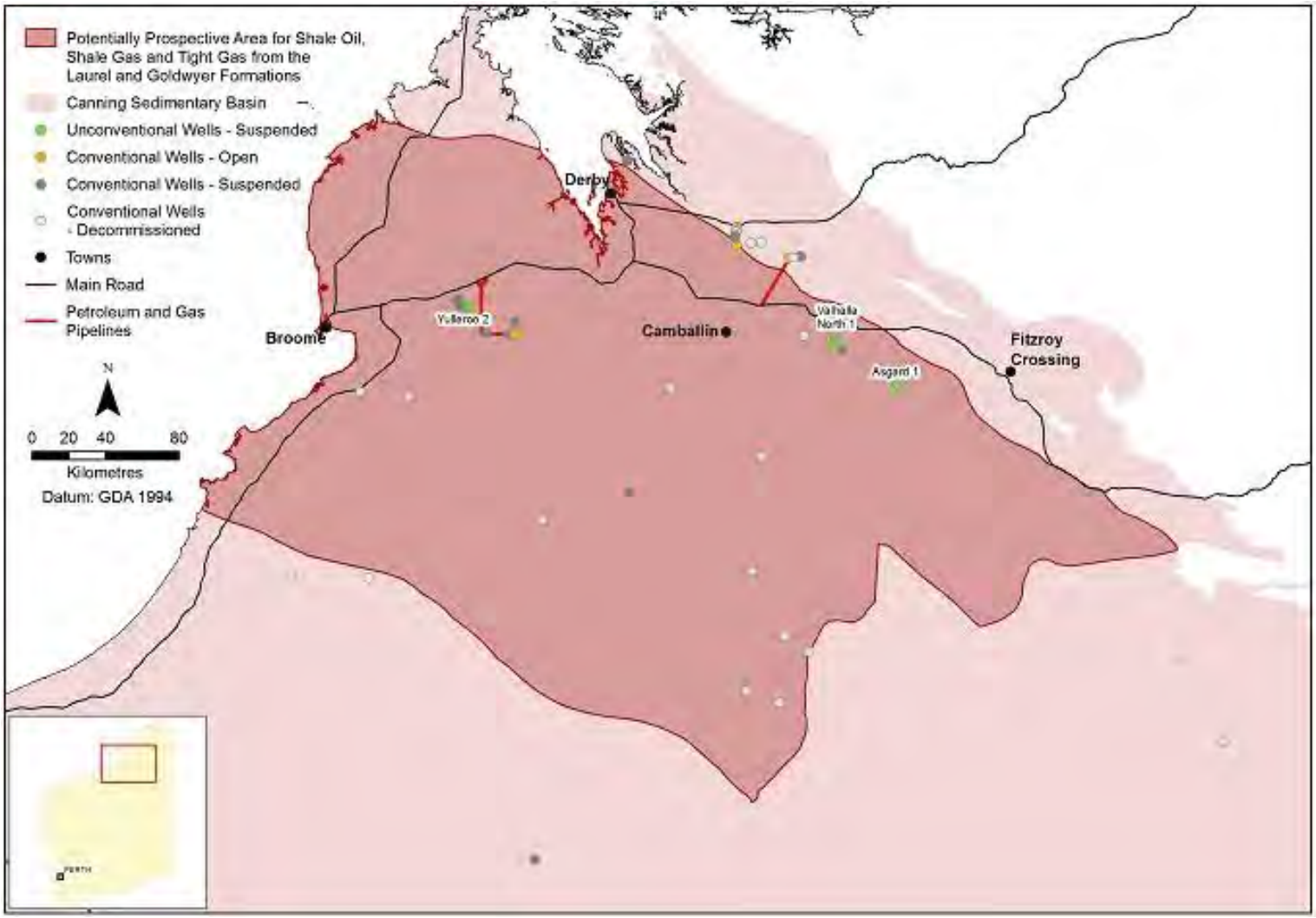


Figure 5.7: Granted petroleum titles in prospective areas for shale oil, shale gas and tight gas in the Canning Basin
Source: DWER, Accurate as of June 2018

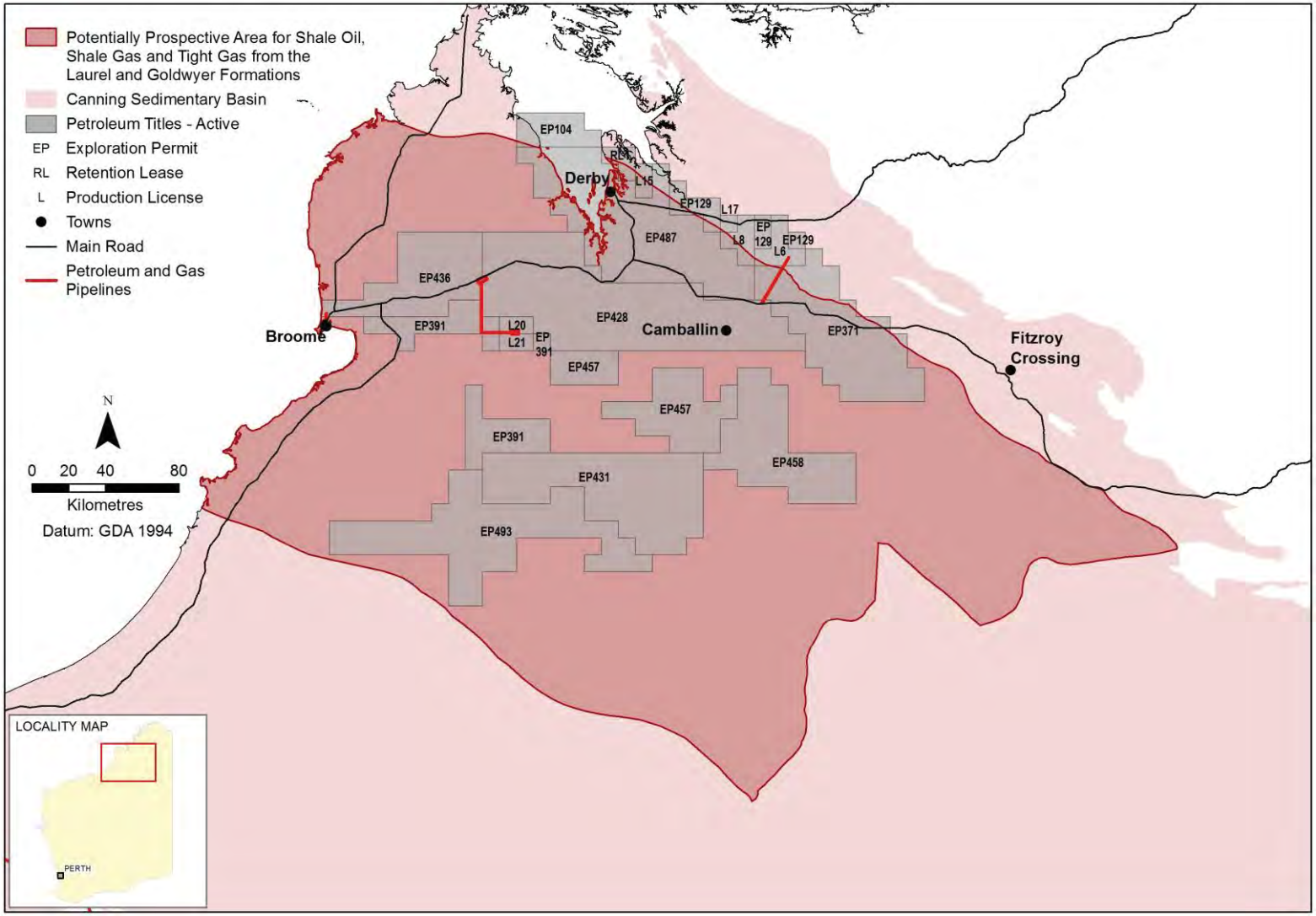
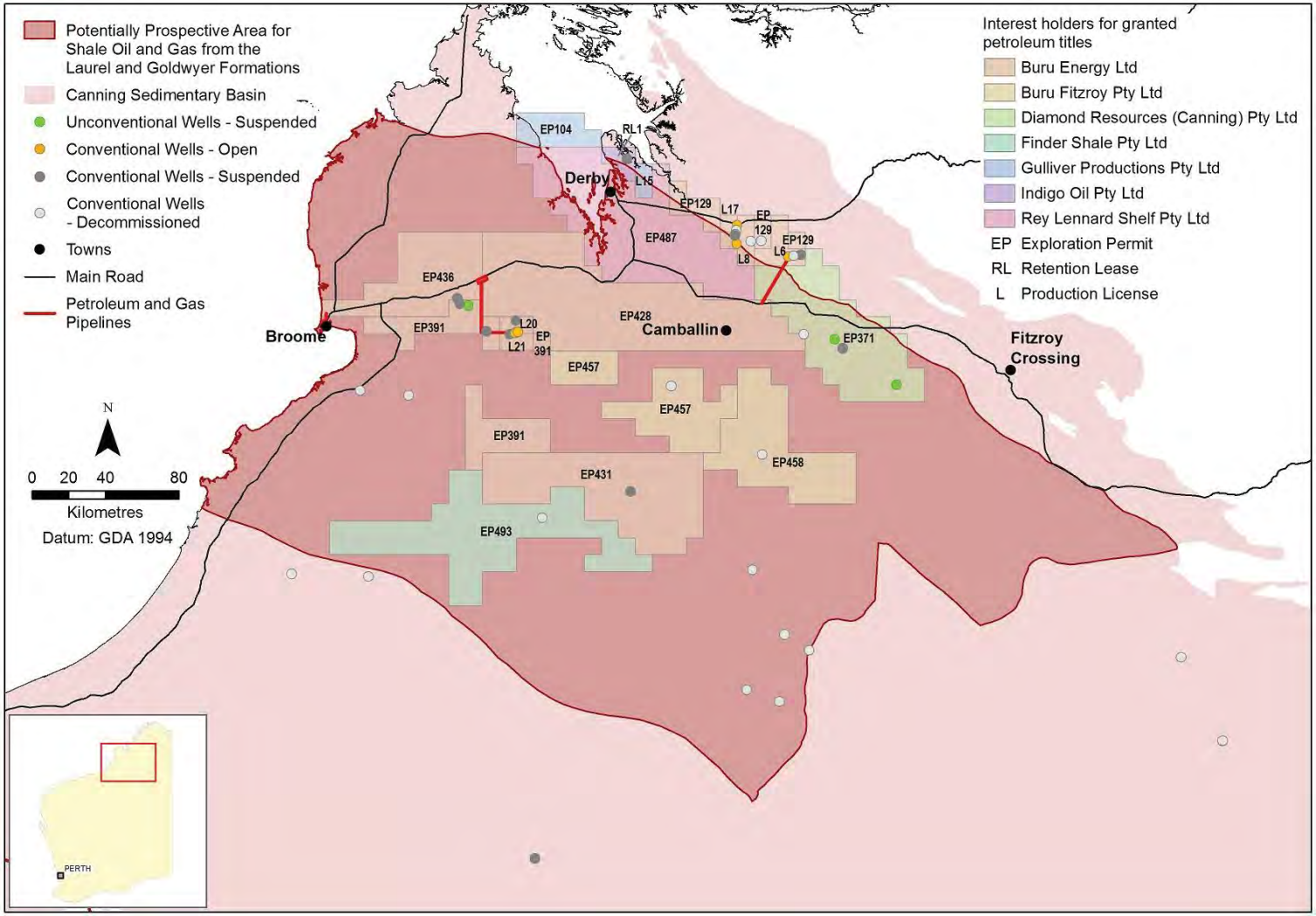


Figure 5.8: Interest holders for granted petroleum titles in prospective areas for shale oil, shale gas and tight gas in the Canning Basin (Wells 2000 to 2017)

Source: DWER, Accurate as of June 2018



5.7.2 Perth Basin

The Perth Basin extends south from the Southern Carnarvon Basin and covers an area of about 100,000 km^2, from the Yilgarn Craton in the east to the edge of the continental shelf in the west.

In 2016, DMIRS estimated 220 tcf of shale gas, of which about 17– 34 tcf may be recoverable, and 12 tcf of tight gas resources exist in the Perth Basin.

The Basin is close to petroleum industry infrastructure, including two major gas pipelines and trucking facilities to an oil refinery 30 km south of Perth. The Parmelia Gas Pipeline provides ready access to markets and allows economic exploitation of small discoveries. **Figure 5.9** shows the potentially prospective areas for shale oil and gas from the Kockatea and Carynginia Formations in the Perth Basin.

The main source for gas is the Permian Irwin River Coal Measures, with reservoirs in the Upper Permian and Jurassic. The main source for oil is the base of the marine Lower Triassic Kockatea Shale, with reservoirs in Lower Triassic and Permian sandstones.

5.7.2.1 Northern Perth Basin

The Northern Perth Basin is being explored for tight gas. The Basin has several known tight gasfields, including Warro, Gingin, Corybas, Senecio and West Erregulla. The formations with the highest tight gas potential include the Cattamarra Coal Measures, Cadda Formation, Irwin River Coal Measures, Dongara Sandstone and Willespie Formation, however, little evaluation of these formations has been conducted to date.

DMIRS has conducted an evaluation of the Northern Perth Basin shale gas resources and has identified the Kockatea Shale, the Irwin River Coal Measures and the Carynginia Formation as the most prospective formations.

5.7.2.2 Southern Perth Basin

No commercial fields have been discovered to date in the onshore Southern Perth Basin, even though hydrocarbon shows were encountered in several wells. The Permian to Cretaceous stratigraphic and structural evolution of the Southern Perth Basin is similar to that of the Northern Perth Basin but marine intervals are not present in the south, where continental depositional environments dominated until the late Neocomian stage. Consequently, thick regional shales are absent and the area may have poor sealing potential.

In the Southern Perth Basin, the Whicher Range gasfield has been known as a potentially productive source of gas since 1968, when the first Whicher Range exploratory gas well was drilled. During testing, gas flowed from the Permian Sue Coal Measures in wells in the Whicher Range field.

Although hydraulic fracture stimulation has occurred on five separate occasions in the Southern Perth Basin at Whicher Range since 1980, in all instances it has proven unsuccessful in increasing gas flow to surface. The 2012 Western Australian Energy Research Alliance study Whicher Range Tight Gas Sands (West Australian Energy Research Alliance, Geological Survey of Western Australia & Department of Mines and Petroleum 2012) found that the introduction of water based fluids to the Whicher Range gas formation hindered the flow of gas to surface and was not recommended.

5.7.2.3 Likely areas of shale gas development in the Perth Basin

Figure 5.10 shows the current extent of granted petroleum titles in the Perth Basin as well as areas of potentially prospective for shale oil and shale gas.

The potentially prospective area is based on the depth and thermal maturity of source rocks in the Kockatea Shale and Carynginia Formation and includes the Dandaragan Trough north of Eneabba, and the Dongara Terrace, Donkey Creek Terrace, Allanooka Terrace, Allanooka High, Cadda Terrace and Beagle Ridge structural subdivisions. The potentially prospective area has been revised from previously published distributions (Department of Mines and Petroleum 2015a), which considered the Badgingarra – Dandaragan – Moora area of the Dandaragan Trough to be prospective for shale gas. The potentially prospective area for shale gas and oil includes the existing gas and oil fields between Woodada and the Dongara area. The potential has yet to be proven, and testing at the Drover 1 site by AWE has found the Kockatea shale to be unsuitable for shale gas production in that location.

Figure 5.11 shows the interest holders for each of the granted petroleum exploration permits in the Perth Basin.

Figure 5.9: Petroleum wells (2000 to 2017) in the Perth Basin showing the extent of the potentially prospective areas for shale oil and shale gas from the Kockatea and Carynginia Formations.

Source: DWER

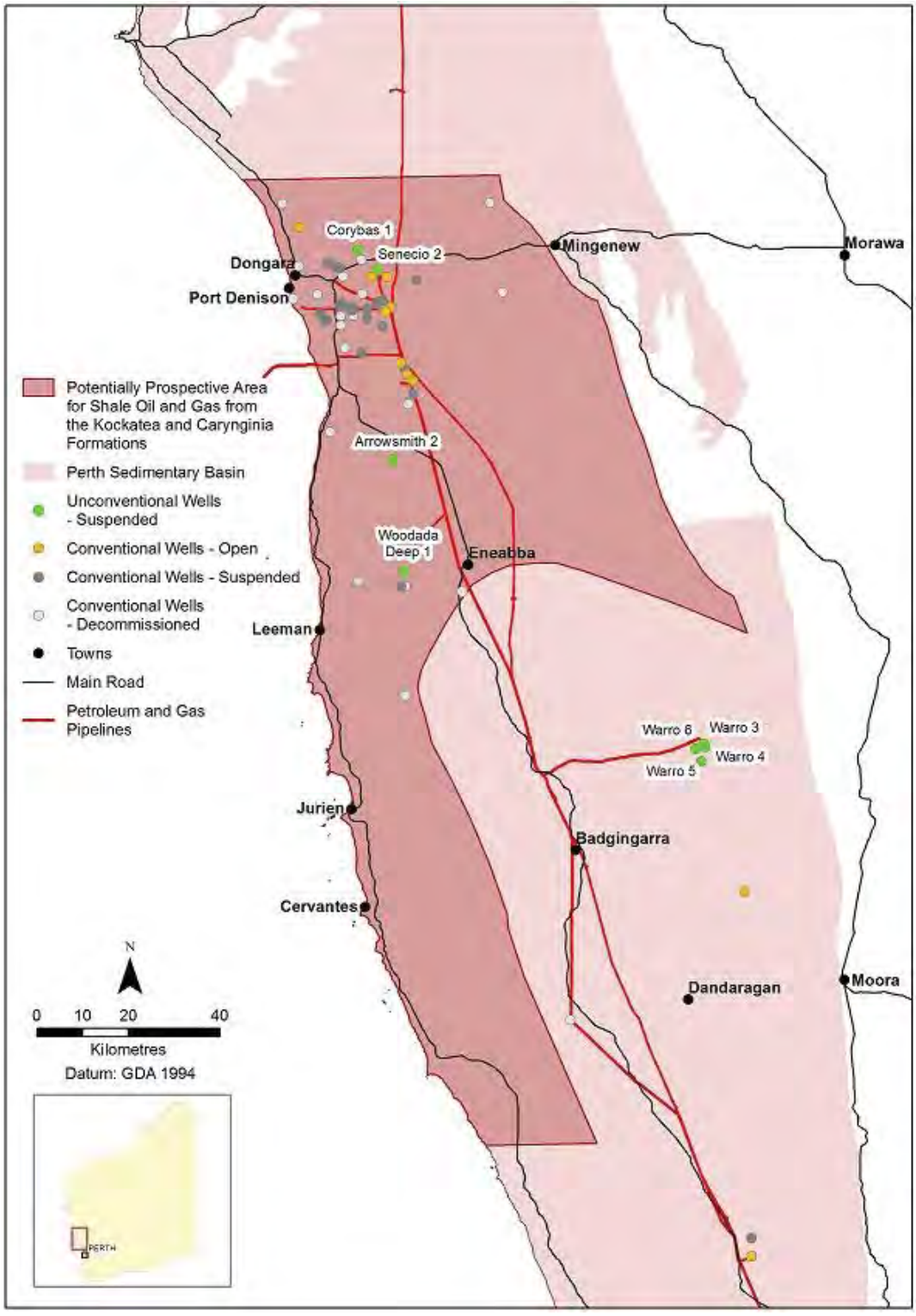


Figure 5.10: Granted petroleum titles in prospective areas for shale oil and shale gas in the Perth Basin

Source: DWER, Accurate as of June 2018

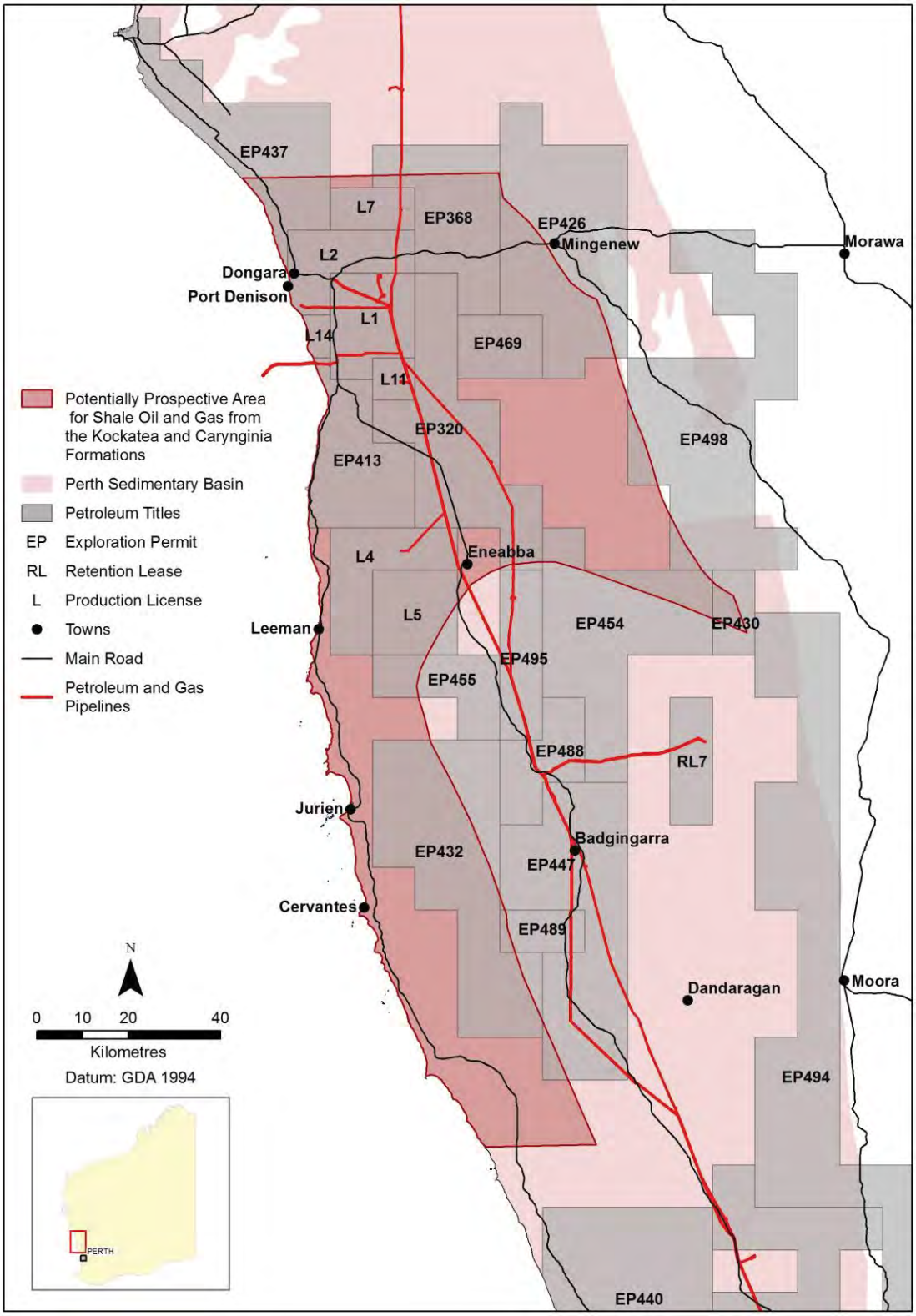
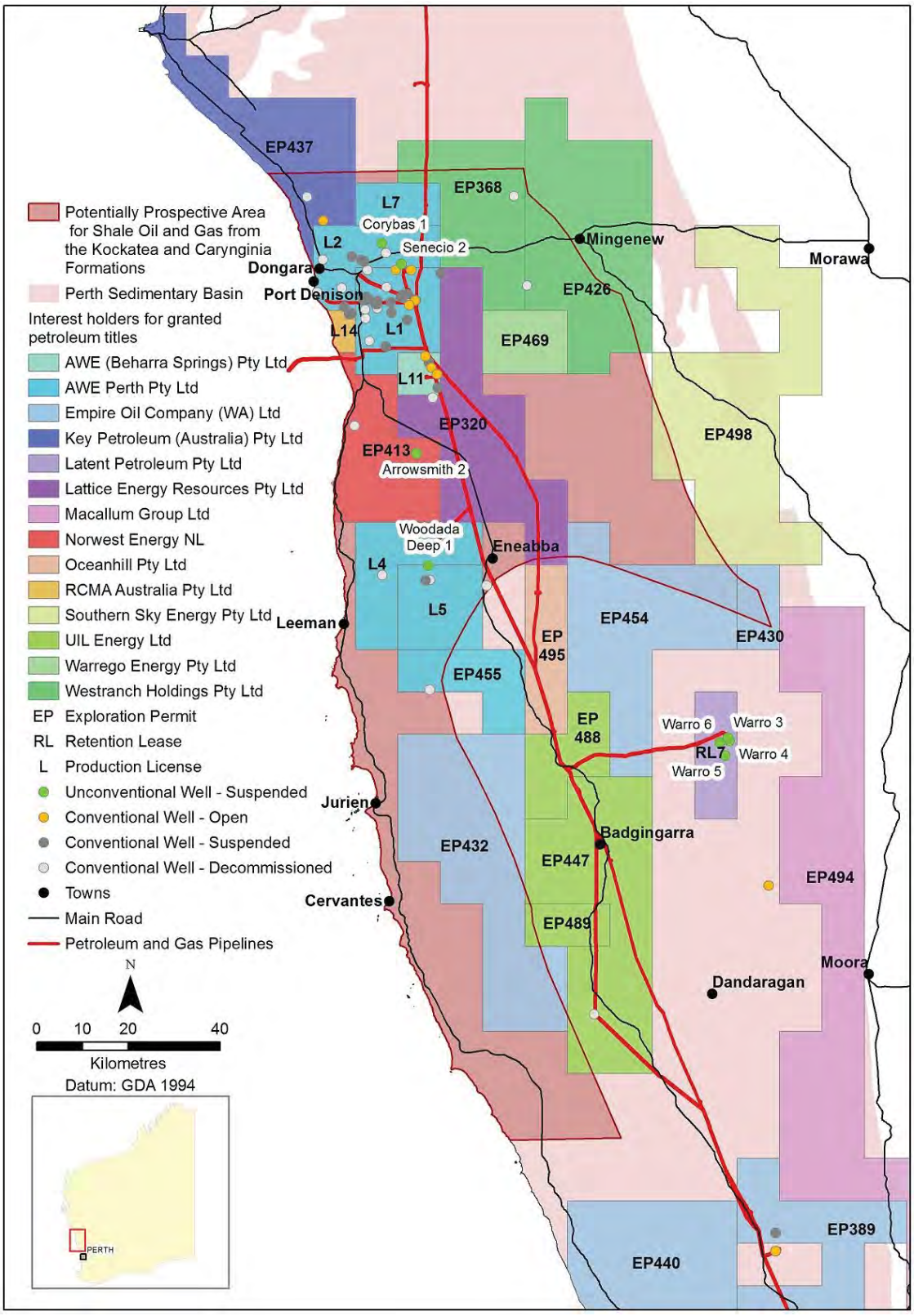


Figure 5.11: Interest holders for granted petroleum titles in prospective areas for shale oil and shale gas in the Perth Basin. (Wells 2000 to 2017)

Source: DWER, Accurate as of June 2018



5.7.3 Southern Carnarvon Basin

The onshore, Southern Carnarvon Basin has seen minimal exploration compared to the adjoining Perth Basin and offshore Northern Carnarvon Basin. The Southern Carnarvon Basin extends west from the Precambrian Shield to the offshore Perth and Northern Carnarvon Basins, and covers approximately 200,000 km^2.

The northerly portion of the Southern Carnarvon Basin is composed of two principal structural elements: the Gascoyne Platform to the west, and the Merlinleigh and Byro Sub-basins to the east. The Paleozoic section is up to 7 km thick and is covered by Triassic rocks in the north. Northerly and northwesterly-trending faults are also present.

Petroleum exploration commenced in the Southern Carnarvon Basin in the 1930s. West Australia Petroleum Pty Ltd was the first company with serious exploration programs in the 1950s and 1960s, following its oil discovery at Rough Range. After early exploration proved non-commercial, the main exploration activity moved north to the offshore Northern Carnarvon Basin. DMIRS assessed the shale gas potential for three formations in the Merlinleigh Sub-basin in 2016, to contain 95 tcf of shale gas, of which about four to nine tcf may be recoverable.

To date, 105 onshore and five offshore wells have been drilled in the Southern Carnarvon Basin. No onshore fields or accumulations have yet been discovered, therefore the Southern Carnarvon Basin will not be a focus of this Inquiry.

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6

Overview of hydraulic fracture stimulation for oil and gas resource development

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6 Overview of hydraulic fracture stimulation for oil and gas resource development

6.1 Introduction

This section provides a broad overview of the processes involved in developing oil and gas wells incorporating hydraulic fracture stimulation, with a focus on those aspects that create potential risks or risk pathways for the environment or for people. Where appropriate, those processes are identified and described in the context of current best practice and regulation, and any emerging consensus among the many inquiries and reviews of the risks and regulation of oil and gas development using hydraulic fracture stimulation that preceded this Inquiry is noted. Detailed risk assessment in the specific context of Western Australia follows in subsequent sections of this Report.

It is worth noting here that the Inquiry has made its best endeavours to consider all the impacts that are reasonably associated with developing oil and gas resources with hydraulic fracture stimulation, but this does not extend to the broader issues of the value of onshore oil and gas development, either conventional or unconventional, nor to more general social impacts beyond those resulting directly from impacts to or through the environment.

6.2 Hydraulic fracture stimulation to develop oil and gas

Hydraulic fracture stimulation involves pumping fluids and proppants under high pressure into rock to create fractures.

The practice of hydraulic fracture stimulation to access unconventional oil and gas reserves incorporates or builds upon technologies and processes invented for exploiting conventional oil and gas resources, but has significantly advanced over recent years for specific application to shale and tight gas (Golden & Wiseman 2015). The general staging of exploration and development of conventional and unconventional gas fields are similar but the former can take advantage of natural accumulations of oil and gas in more porous material in structural or stratigraphic traps of limited area (often flowing to the surface under its own pressure) and thus can be exploited with fewer wells (Department of Mines and Petroleum 2015a). Unconventional gas resources generally extend over a larger area (more diffuse). As a result, more drilling is required to effectively access gas over a larger area and hydraulic fracture stimulation is necessary to increase the flow of gas to the well. Modern approaches to drilling for unconventional gas often involve the drilling of multiple wells that radiate laterally at the target depth from a single well pad ('horizontal drilling'), followed by hydraulic fracture stimulation of sections of the lateral component (Cook et al. 2013). Key to the safety and effectiveness of unconventional oil and gas development is the

design and life cycle of the wells themselves, and the chemicals and infrastructure used to hydraulically stimulate the fractures.

6.3 History - worldwide

Pumping fluids and proppants under pressure down a well was first trialled in Kansas in 1947. In this experiment, 3,800 litres of gelled petroleum and sand were injected into a gas producing limestone formation at a depth of 730 metres, followed by an injection of a gel breaker. While this experiment failed to produce a significant increase in gas production, it did mark the beginning of hydraulic fracture stimulation.

In 1949 Halliburton became the first company to extract natural gas in commercial quantities through hydraulic fracture stimulation. The technology available at the time only enabled the stimulation of weakly consolidated geological formations. Thereafter, the process was commercially successful in stimulating gas wells and began to grow rapidly from 1950. Horizontal drilling allowed the wells to access more of the hydrocarbon bearing formation. The first horizontal well was drilled in the 1930s and became common by the late 1970s. In the mid-1970s, a partnership of private operators and United States government agencies fostered technologies that eventually became crucial to the production of natural gas from shale rock, including horizontal wells and multi-stage fracturing.

Modern day hydraulic fracture stimulation did not begin until the 1990s, when George P. Mitchell (of Mitchell Energy and Development Corporation) combined horizontal drilling with hydraulic fracture stimulation. This enabled the commercially viable production of gas from the Barnett Shale in North-Central Texas.

The Society of Petroleum Engineers estimates that 2.5 million hydraulic fracture operations have been undertaken worldwide, with over one million in the United States, while hundreds of thousands of horizontal wells have been completed over the past 60 years (King 2012; U.S. Energy Information Administration 2016).

Recent technology trends in hydraulic fracture stimulation include: multi-stage fracture programs; systems that recover, treat and re-use returned fracture fluids; the use of saline and brackish water in fracturing fluid; and the use of lower toxicity chemicals. In the last decade, driven by resource recovery and public concerns, there has been a focus on developing ways to increase the effectiveness of hydraulic fracture stimulation treatments. This includes exploring alternatives to, or strategies to minimise, the use of water and chemicals such as substituting pressurised gas for fracturing liquids. To date, hydraulic fracture stimulation using water-based fluids has been the predominant method used in Australia with limited experimental application of high-pressure nitrogen and propellants.

6.4 History - Western Australia

In Western Australia, more than 600 wells have undergone hydraulic fracture stimulation in conventional reservoirs since 1958. The first hydraulic fracture stimulation in Western Australia was conducted in that year on the Goldwyer 1 well, 100 km southeast of Broome in the Canning Basin. Fracture stimulation or re-fracturing has been conducted on 563 wells on Barrow Island off the coast of Western Australia since 1965. These activities involved small scale fracturing and were conducted at relatively low hydraulic fracture stimulation pressures (~1,300 pounds per square inch (psi), or 8,963 kilopascal (kPa)) for the purpose of improving oil recovery from the oil producing sands on Barrow Island.

More recently, 12 hydraulic fracture stimulations were performed in Western Australia between 2004 and 2015, all conducted in vertical wells and using more contemporary hydraulic fracture stimulation methods. To date, no horizontal, multi-stage hydraulic fracture stimulations have been carried out in Western Australia. **Table 6.1** below is a complete list of stimulated wells in Western Australia.

Table 6.1: Stimulated petroleum wells in Western Australia

Source: Department of Mines, Industry Regulation and Safety (DMIRS)

Well Name	Well Completion Date	Onshore /Offshore	Basin	Approximate Location	Range of Stimulation Depth (metres)
Barrow Island (500+ wells)	1964 onwards	Onshore	Carnarvon	Barrow Island	Various
Arrowsmith 2	18/06/2011	Onshore	Perth	30 km north of Eneabba	2639 - 3293.3
Asgard 1	29/09/2012	Onshore	Canning	50km wsw of Fitzroy Crossing	2567.9-3403.4
Blina 3	04/10/1982	Onshore	Canning	100 km south east of Derby	1459.5 - 1478.5
Bootine 1	22/11/1981	Onshore	Perth	West of Gingin	3752.5 - 4085
Corybas 1	07/03/2005	Onshore	Perth	Dongara area	2514 - 2536
Dongara 03	18/09/1966	Onshore	Perth	Dongara area	1602 - 1696
Dongara 09	08/05/1969	Onshore	Perth	Dongara area	1685 - 1726

Well Name	Well Completion Date	Onshore /Offshore	Basin	Approximate Location	Range of Stimulation Depth (metres)
Dongara 15	04/11/1969	Onshore	Perth	Dongara area	1652 - 1717
Dongara 21	05/03/1980	Onshore	Perth	Dongara area	1589.5 -1601.2
Dongara 24	28/03/1981	Onshore	Perth	Dongara area	
East Lake Logue 1	28/01/1983	Onshore	Perth	Dongara area	2324 - 2335
Ejarno 1	25/06/1981	Onshore	Perth	Dongara area	2727 - 2734
Gingin 1	15/07/1965	Onshore	Perth	West of Gingin	3949 - 3956
Goldwyer 1	22/11/1958	Onshore	Canning	100 km south east of Broome	1161 - 1196
Great Sandy 1	13/11/1981	Onshore	Canning	150 km south east of Broome	1478 - 1494.7
Grevillea 1	21/09/1982	Onshore	Canning	100 km south west of Fitzroy Crossing	1635 - 1639
Hedonia 1	27/09/1984	Onshore	Canning	100 km south east of Broome	1512 - 1535
Indoon 1	14/12/1982	Onshore	Perth	Dongara area	2191 - 2208
Meda 1	21/11/1958	Onshore	Canning	100 km south east of Derby	1600 - 2041
Mondarra 2	18/02/1969	Onshore	Perth	Dongara area	2736 - 2740
Nita Downs 1	30/09/1983	Onshore	Canning	150 km south east of Broome	1510 - 1540
Pictor 2	05/12/1990	Onshore	Canning	100 km south of Derby	929 - 956
Setaria 1	31/05/1989	Onshore	Canning	200 km south of Fitzroy Crossing	436 - 447

Well Name	Well Completion Date	Onshore /Offshore	Basin	Approximate Location	Range of Stimulation Depth (metres)
Senecio 2	21/15/2005	Onshore	Perth	16 km east of Dongara	2785 - 2860.5
South Pepper 04	17/05/1984	Offshore	Carnarvon	30 km south of Barrow Island	1230 - 1236
Turtle 1	09/03/1984	Offshore	Bonaparte	150 km north east of Wyndham	1615 - 1624
Turtle 2	02/07/1989	Offshore	Bonaparte	150 km north east of Wyndham	2420 - 2446
Valhalla North 1	22/02/2012	Onshore	Canning	90km wnw of Fitzroy Crossing	2827.9-3270.9
Walyering 2	25/12/1971	Onshore	Perth	Badgingarra Area	3702 - 3722
Warradong 1	14/04/1981	Onshore	Perth	Dongara area	3178 - 3188
Warro 1	20/09/1977	Onshore	Perth	55km north of Dandaragan	3971 - 4093
Warro 2	05/04/1978	Onshore	Perth	55km north of Dandaragan	3991 - 4073
Warro 3	20/03/2009	Onshore	Perth	55km north of Dandaragan	3744 - 4254.1
Warro 4	11/05/2011	Onshore	Perth	55km north of Dandaragan	3878 - 4079
Warro 5 (ST)	05/09/2015	Onshore	Perth	55km north of Dandaragan	4331-4394
Warro 6	03/11/2015	Onshore	Perth	55km north of Dandaragan	4306-4459
Whicher Range 1	22/09/1968	Onshore	Perth	20 km south of Busselton	4050 - 4285

Well Name	Well Completion Date	Onshore /Offshore	Basin	Approximate Location	Range of Stimulation Depth (metres)
Whicher Range 2	27/07/1980	Onshore	Perth	20 km south of Busselton	3951 - 4026
Whicher Range 3	08/05/1982	Onshore	Perth	20 km south of Busselton	4020 - 4357
Whicher Range 4	03/11/1997	Onshore	Perth	20 km south of Busselton	4045 - 4380
Whicher Range 5	21/01/2004	Onshore	Perth	20 km south of Busselton	4001 - 4262
Woodada Deep 1	18/04/2010	Onshore	Perth	20 km north east of Leeman	2283 - 2424.4
Woodada 02	03/08/1980	Onshore	Perth	20 km north east of Leeman	2309 - 2460
Woodada 03	11/01/1981	Onshore	Perth	20 km north east of Leeman	2413-2478.5
Woodada 04	05/04/1981	Onshore	Perth	20 km north east of Leeman	2138 - 2271
Woodada 05	18/03/1982	Onshore	Perth	20 km north east of Leeman	4372 - 4378, 2402 - 2407
Woodada 06	08/05/1982	Onshore	Perth	20 km north east of Leeman	2140 - 2238
Woodada 08	18/09/1983	Onshore	Perth	20 km north east of Leeman	2146 - 2231
Woodada 16	01/10/1999	Onshore	Perth	20 km north east of Leeman	2248 - 2286
Yowalga 3	17/01/1981	Onshore	Officer	550 km east of Wiluna	2057 - 2062

Well Name	Well Completion Date	Onshore /Offshore	Basin	Approximate Location	Range of Stimulation Depth (metres)
Yulleroo 1	05/12/1967	Onshore	Canning	100 km east of Broome	3394 - 3407
Yulleroo 2	10/05/2008	Onshore	Canning	100 km east of Broome	2853 - 3119

6.5 Developing shale or tight gas resources in Western Australia

It is widely accepted that hydraulic fracture stimulation is necessary to effectively access unconventional gas resources in Western Australia.

While there is some limited experience with modern hydraulic fracture stimulation in some vertical wells in recent years, there is currently no wholly unconventional gas field under development in Western Australia and certainly not one using contemporary techniques involving multiple wells on a single pad and horizontal drilling, as is underway in the Cooper Basin in South Australia, for example. Thus, anticipating and describing the stages of development of a gas field employing hydraulic fracture stimulation in the prospective Canning or Perth Basins, evaluating the concomitant risks, and evaluating current and potential regulation and best practice must be based on:

- Local experience with the development of conventional onshore oil and gas fields and hydraulic fracture stimulation in a limited set of vertically drilled wells;
- Projections of the potential rate and scale of development; and
- Experience with modern shale gas development outside of Western Australia.

The development of an oil or gas field, conventionally or unconventionally, is characterised by four general phases:

1. Exploration

Exploration is the initial phase of the development life cycle in which data is gathered, a resource target is identified and a first exploration well is drilled. Exploration usually includes non-invasive, remote surveying such as seismic or gravity/magnetic surveys. Hydraulic fracture stimulation may be necessary on the exploration well to determine if further appraisal of an unconventional target is warranted.

2. Appraisal/Development (Proof of concept/assessment)

Appraisal/development follows the exploration phase, if an exploration well has successfully discovered oil or gas. Appraisal/development includes drilling additional wells (~2-4) to determine the size of the gas field and which methods could develop it most efficiently.

3. Production

The production phase of operations is when oil or gas is produced (recovered from the field). This phase usually involves drilling additional production wells and (potentially) pipelines (new or by tying into existing lines) to transport the petroleum.

Hydraulic fracture stimulation may be necessary during any of the above phases of petroleum operations but is generally only required to produce unconventional resources.

4. Decommissioning

In this final phase of operations, in which the field is abandoned, the hydrocarbon reservoir is sealed off, all wells are permanently cemented and plugged off, facilities removed and the area is rehabilitated.

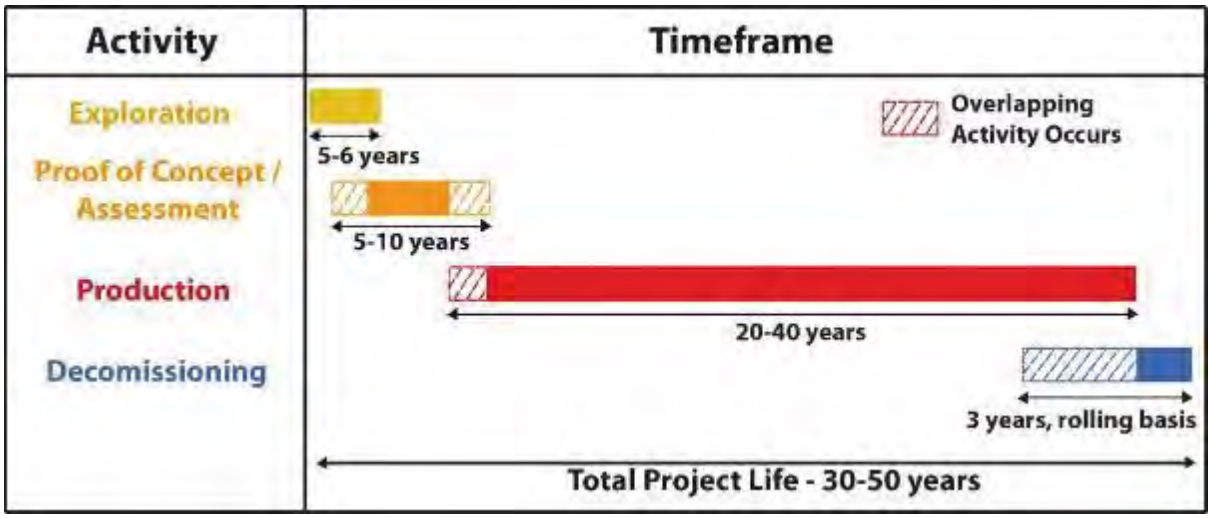
6.5.1 Timeframes

Before any petroleum activity can occur, proponents must obtain a petroleum exploration permit. In Western Australia, exploration permits are granted for an initial six-year period. Exploration permits can be renewed for two further periods of five years each (for a total term of 16 years), with a 50 percent relinquishment of the area at the end of each term.

Realised timeframes for development of unconventional gas projects in Western Australia are difficult to define because there have been no unconventional gas projects developed to date. A generic timeframe for the overall life of an unconventional gas field appears in **Figure 6.1**, assuming a best-case scenario where success in each activity phase is achieved (for example, the first exploration well discovers oil or gas).

Figure 6.1: Possible timeframe for an unconventional gas development in Western Australia

Source: DMIRS



More specifically, potential development timeframes are further informed by the Western Australian context and local experience, such as:

- The time required to drill and hydraulically fracture a single well can range from 13-60 days;
- While one rig could hypothetically drill up to 15 wells per year, this has not been demonstrated in Western Australia, owing to various constraints including the logistics involved in site access during the wet season in the Canning Basin and harvesting/planting seasons in the Perth Basin;
- At present, there are few suitable drilling rigs in the State, and they must be moved long distances between sites; and
- Given the above, in Western Australia, a likely scenario is that one drilling rig might drill up to four wells per year.

6.6 The design of unconventional oil and gas fields

A well is usually drilled in the centre of a clearing, known as the well pad. The few limited sites with individual wells that have been hydraulically fractured in recent years in Western Australia have a typical well pad footprint of 1.5 to two hectares of land (Department of Mines and Petroleum 2015a). A drilling rig is erected on the well pad to carry out the drilling of the wells. The number of wells required to develop an unconventional gas field will depend on the quality and size of the resource being targeted. Most wells will be concentrated in areas where there is greater potential for petroleum recovery and will not cover the entire area containing the resource.

Horizontal well completion involves the drilling of a vertical well to a target depth and horizontally deviating the well to enable much greater exposure of a target rock formation to the well bore. Horizontal well completions can be over four kilometres deep and up to several kilometres horizontally, although one to three kilometres horizontal length is more typical.

Compared with conventional well designs, horizontal drilling technology significantly reduces the number of well pads, production wells, access roads, pipeline routes and production facilities for gas field development. Contemporary development scenarios involve multi-well pads: multiple wells in close proximity at the surface sharing a single pad but deviated out in different directions to access more of the target reservoir. The deviation through the target reservoir can be drilled at any angle from vertical to horizontal. Current shale gas field completions in the United States typically construct around eight horizontal wells per well site, with proposals of up to 32 horizontal wells per well site to be completed in the future. The final density (number) of well sites in a contemporary unconventional oil

and gas field depends largely on geologic factors, but in general well pad densities may range from one well pad every four square kilometres to a pad every 25 square kilometres.

Other equipment such as data monitoring vans, vehicles, sand and chemical storage units, pumping trucks and ponds will also be found on site for one to two weeks during hydraulic fracture stimulation operations. An example of this can be seen in **Figure 6.2**.

Figure 6.2: Hydraulic fracture stimulation equipment at the Arrowsmith 2 well site in the Northern Perth Basin
Source: DMIRS

At well completion, what remains visible on the well pad from this time is a series of sealed valves approximately two metres high, as shown in **Figure 6.3**. Equipment may return to the site to complete further hydraulic fracture stimulation or other workover activities for short periods of time. If the site has reached the production stage, it will also require a gas pipeline that will feed into a gas processing facility. Pipelines are normally buried or contained within a secure fenced area. At the end of the production period, the well will be decommissioned.

Conventional reservoirs have connected pore spaces that will allow gas to flow from a large area into the wellbore, but shale and tight gas reservoirs only allow gas to be recovered from the fractured zone. To maintain constant production, an unconventional oil or gas field requires ongoing drilling and completion of new wells, due to the initial rapid decline of gas flow from individual wells. Once a shale or tight gas well is producing, it can flow gas for several decades. For the duration of the project, operators are required to maintain the well and report on production and other activities to government agencies.

At the end of a well's production life, all surface equipment and infrastructure is removed, the well is plugged, sealed and decommissioned and the site is rehabilitated, as shown in **Figure 6.4**.

For a typical multi-well site (**Figure 6.5**), the total footprint for each well site including access roads, utility lines, pipelines, processing areas and water management areas can be approximated as:

- ~5 hectares during the exploration phase
- ~10 hectares during the construction phase
- ~4 hectares during the production phase

In their submission to this Inquiry, the Australian Petroleum Production and Exploration Association (APPEA) reported an industry estimate of the likely total footprint at about 14 hectares (0.14 km^2) per well pad developed. In the submission from Buru Energy, they estimated that a 130 TJ/d gas field at Yulleroo developed with eight pads (each supporting at least 10 horizontally-drilled wells per site), a central processing facility and a water handling facility would require a total of 100 hectares of clearing. In addition to the footprints of the developed oil and gas field, there may be additional footprints from exploration surveys and, if required, pipelines (with easements ten to twenty metres wide) to connect the field to market.

Figure 6.3: A completed multi-well pad site in Pennsylvania, United States
Source: DMIRS

Figure 6.4: A decommissioned single well at Dandaragan in the Northern Perth Basin
Source: DMIRS

In the Canning Basin, developing a well pad is highly likely to require clearing of native vegetation; this may or may not be the case in the Perth Basin depending on land use history. Similarly, access to new sites in the Canning Basin is likely to require significant additional clearing for access, while this need is likely to be less in the Perth Basin given the existing transport network and potential proximity to existing pipeline infrastructure. At this low-level scale of development, the impact on social surroundings (aesthetics, noise, amenity) and on the community through impacts on air quality is highly dependent on the proximity of individual wells to people and to sites of natural and cultural significance. It is worth noting that the assessment of these kinds of potential impacts is an established and regular process under the *Environmental Protection Act 1986* (EP Act).

Figure 6.5: Conceptual diagram of a two hectare well pad and central collection and processing facility

Source: Submission from Finder Shale Pty Ltd

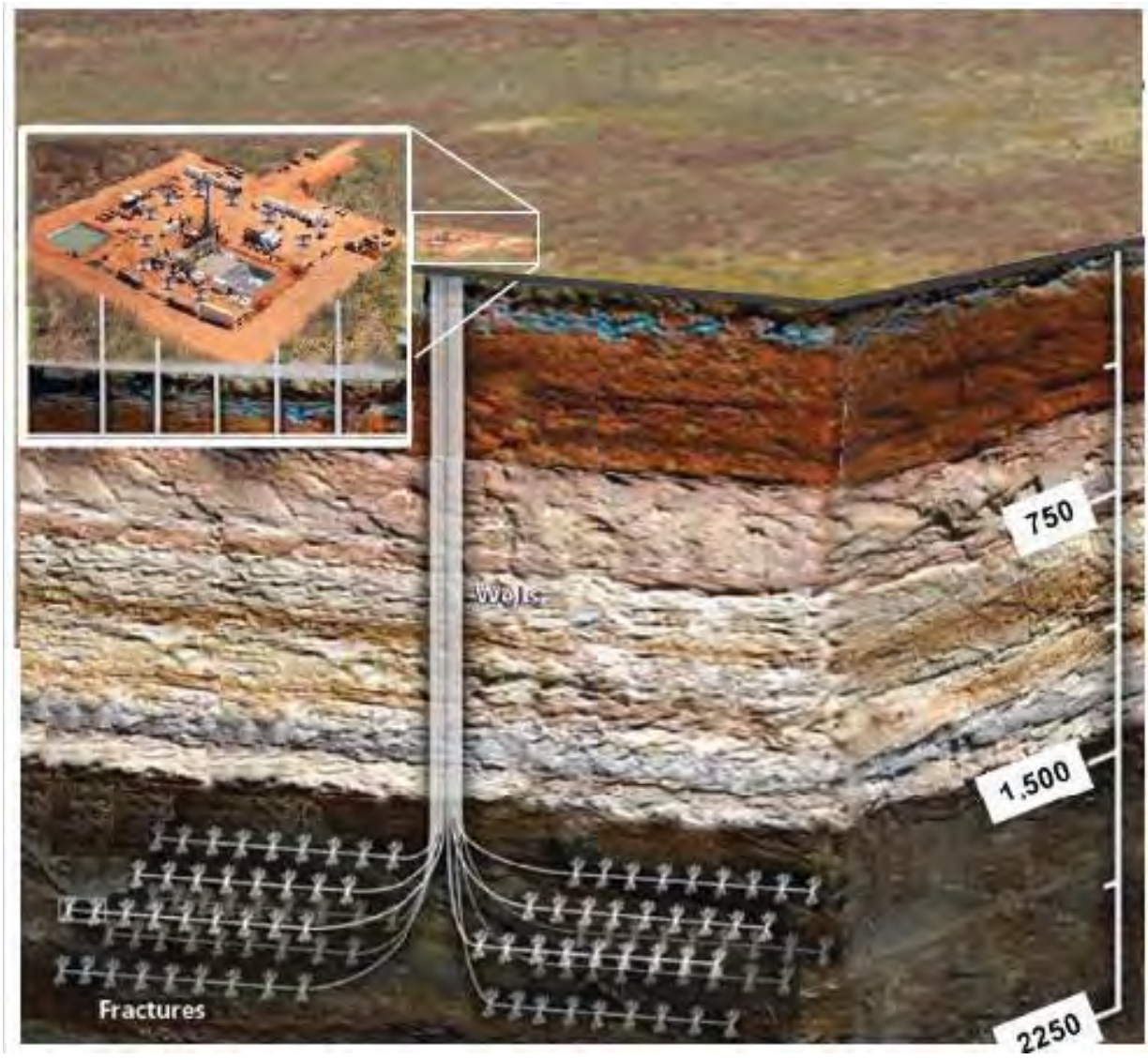


Figure 6.6: Conceptual hydrogeological profile of the Canning Basin, showing Finders Shale's interpretation of the various rock layers that form barriers to fracture propagation beyond the target formation

Source: Submission from Finder Shale Pty Ltd

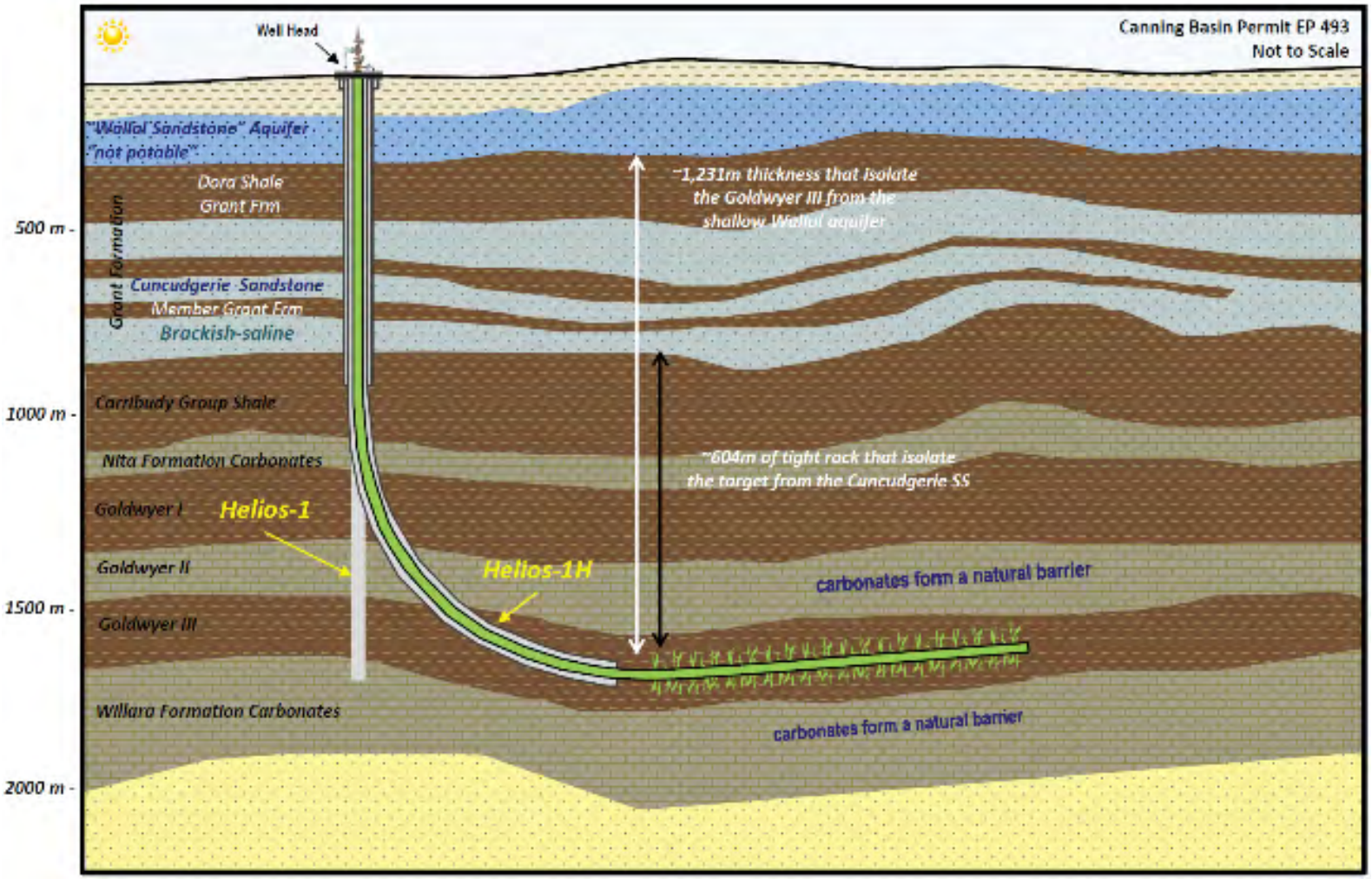


Figure 6.7: Conceptual layout of a shale oil and gas development in an area approximately 44 x 21 kilometres, with 42 well pads in Great Sandy Desert (about one pad per 23 km^2)

Each pad would have eight horizontal wells, 3.3 km laterals, four in each of north and south directions, 750 m apart. This was the most extensive gas field proposed among industry submissions to this Inquiry.

Source: Submission from Finder Shale Pty Ltd

6.7 What constrains hydraulic fracture growth and what barriers contain upwards propagation of hydraulic fractures?

A hydraulic fracture will continue to grow only when supplied with sufficient hydraulic energy, which becomes less available as the fracture tips extend further away from the wellbore and fluid drains off into the formation, so that the width and especially height are limited (Daneshy 2009; Detournay 2016; Lecampion, Bunger & Zhang 2017; Liu & P. Valko 2015). Fracture growth is limited by:

- Formation stress. The minimum horizontal stress limits the opening of a fracture in the vertical plane, and the variation of stress through a vertical layered sequence controls the limits of fracture propagation (Jeffrey & Bunger 2009; Xing et al. 2016). The major control on the horizontal stresses comes from the tectonic environment; the stresses are higher in compressional settings than in extensional settings. The vertical stress is determined by the cumulative weight of overlying rocks, and so relates to the thickness and density of the rock layers overlying the formation to be fractured. The balance between the stresses also relates to the elastic properties of the individual rock layers. Stiffer rocks will concentrate higher horizontal stresses where there are strong compressional forces. Counter-intuitively, when the highest

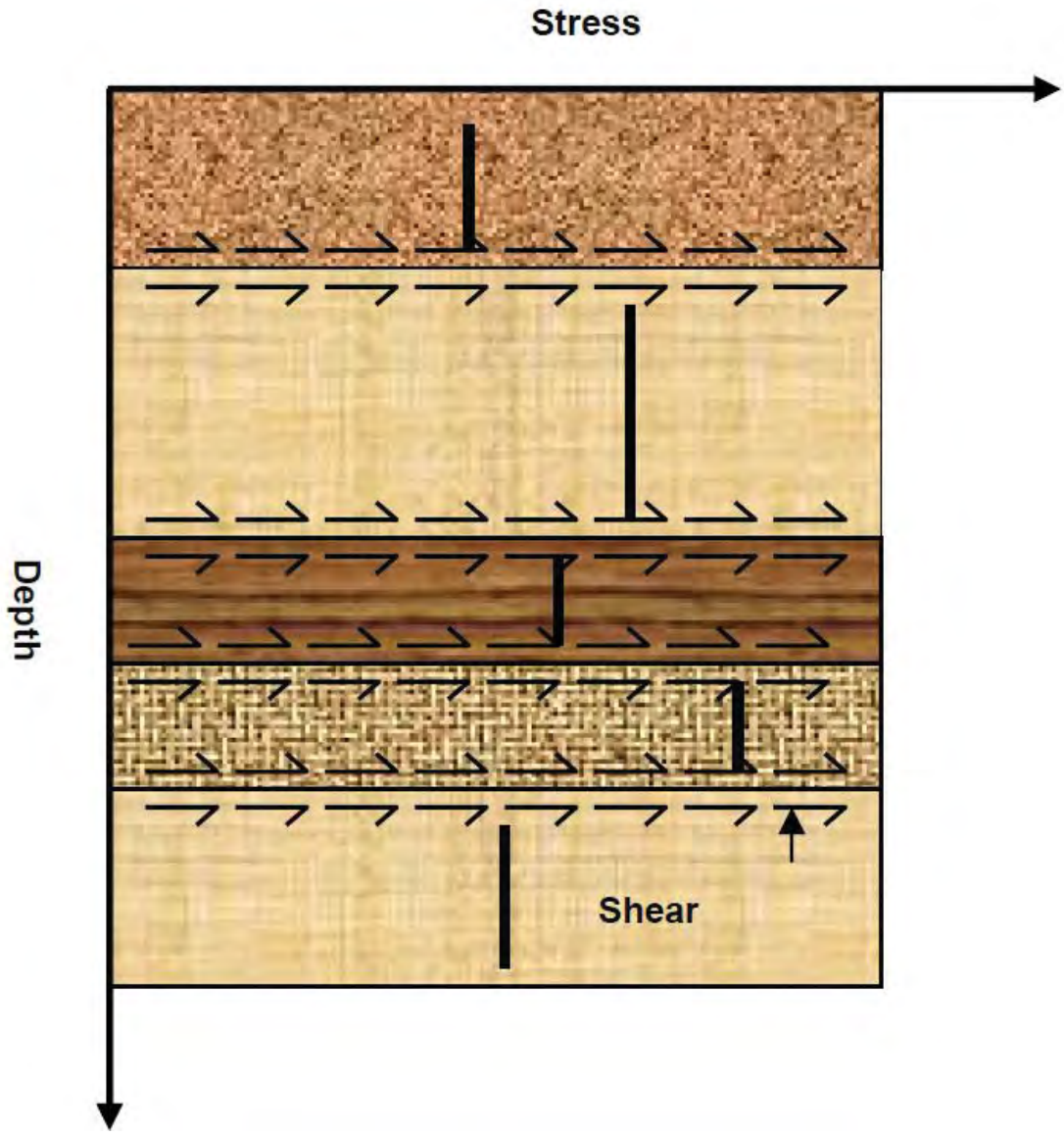
stress is the vertical stress, the higher horizontal stresses may be found in layers of less stiff rock reacting to the overburden load;

- Permeable rock layers. A hydraulic fracture will lose energy when it encounters a permeable rock layer such as a porous sandstone or limestone, as the driving fluid will leak off (for example, Li et al. 2018). In an impermeable formation, the fracture height growth drops off as an inverse square law and as the formation permeability increases the height rapidly reaches a plateau;
- Rock strength. The cohesive strength of a rock resists the initiation and growth of a hydraulic fracture according to the principles of linear elastic fracture mechanics; it is the fracture toughness that controls the energy needed for propagation (Detournay 2016). Tougher rocks, while requiring more energy to break, may not always arrest fracture growth, whereas weak layers can act as barriers owing to higher or anisotropic stresses (Barree et al. 2010; Xing et al. 2016);
- Pre-existing fractures, including bedding planes, which are horizontal planes of weakness but not completely cohesionless, modify the propagation of hydraulic fractures. Favourable oriented fractures can promote upwards fracture propagation, while fractures in an unfavourable orientation relieve stresses and allow the fluid to leak off. Several studies (Huang et al. 2018; Li et al. 2016; Yue, Olson & Schultz 2016), provide detailed simulations. The particular case where hydraulic fracture encounters a pre-existing geological fault is discussed in the context of anomalous events below;
- Injection rate: higher rates of injection lead to greater growth into zones of fracture arrest than lower rates, for the same fluid pressure (Detournay 2016; Jeffrey & Zhang 2010; Wasantha & Konietzky 2017); and
- Engineering interventions such as placement of a fracture barrier, for example, using gel ahead of proppant to increase energy loss at the fracture tip (Li et al. 2018).

Figure 6.8: Realistic state of stress in adjacent rock layers

Upward growth of fractures is typically arrested by high stress zones and dissipation of energy into interlayer slip, as well as leak off of fluid into natural fractures and/or more permeable horizons

Source: Daneshy (Daneshy 2009)



Generally, hydraulic fracture growth and limits to fracture extent are complex topics that depend on the geology and stress state. The science has advanced in parallel with the development of shale gas over the past two decades. It is fair to say that the current state of understanding of hydraulic fracture stimulation processes is mature, in that we have a reasonably complete view of the physical processes involved (see review by Detournay 2016) and computational speed and software availability no longer limit our ability to simulate and visualise many of these processes. However, collecting the required data on

stresses and geomechanical properties in any region of the subsurface is challenging and requires significant resources and modelling of fracture propagation is complex and requires considerable expertise. Therefore, practical solutions usually involve many simplifications (Lecampion, Bunger & Zhang 2017) while more complete models are usually only available in the format of research tools such as those available at the Lawrence Berkeley National Laboratory.

Equally significant is the lack of good data to populate the models. In Western Australia, there is relatively little information collected about either stress state or rock mechanical properties of target formations and overburden rocks. Few laboratories and companies are sufficiently specialised to be able to conduct in-house all the stages required to build, populate and interpret models that are genuinely predictive.

To predict maximum fracture growth with a reasonable margin of safety requires advanced 3D geomechanical modelling incorporating the correct physics of the process. Moreover, these models must be adequately parameterised with stress state, a geomechanical model with the correct properties of each rock layer and suitable representation of pre-existing fractures. Discussion of model adequacy is a common topic in industry and research forums (McPhee, Daniels & McCurdy 2014; Schultz 2016). Adequate models are based on fundamental physical principles, validated in controlled laboratory experiments and verified in-situ conditions, for example, information from minebacks or drilled fractures as shown in **Figure 6.9**. The outputs of geomechanical earth models need to include the range of uncertainty, and the models should be regularly updated based on results of drilling fracturing and monitoring. The geomechanical earth model should be fit for purpose, adequately parameterised with data from the local rock formations and the simulations should be conducted and verified by suitably qualified person. Meeting these standards is an essential part of mitigating risk.

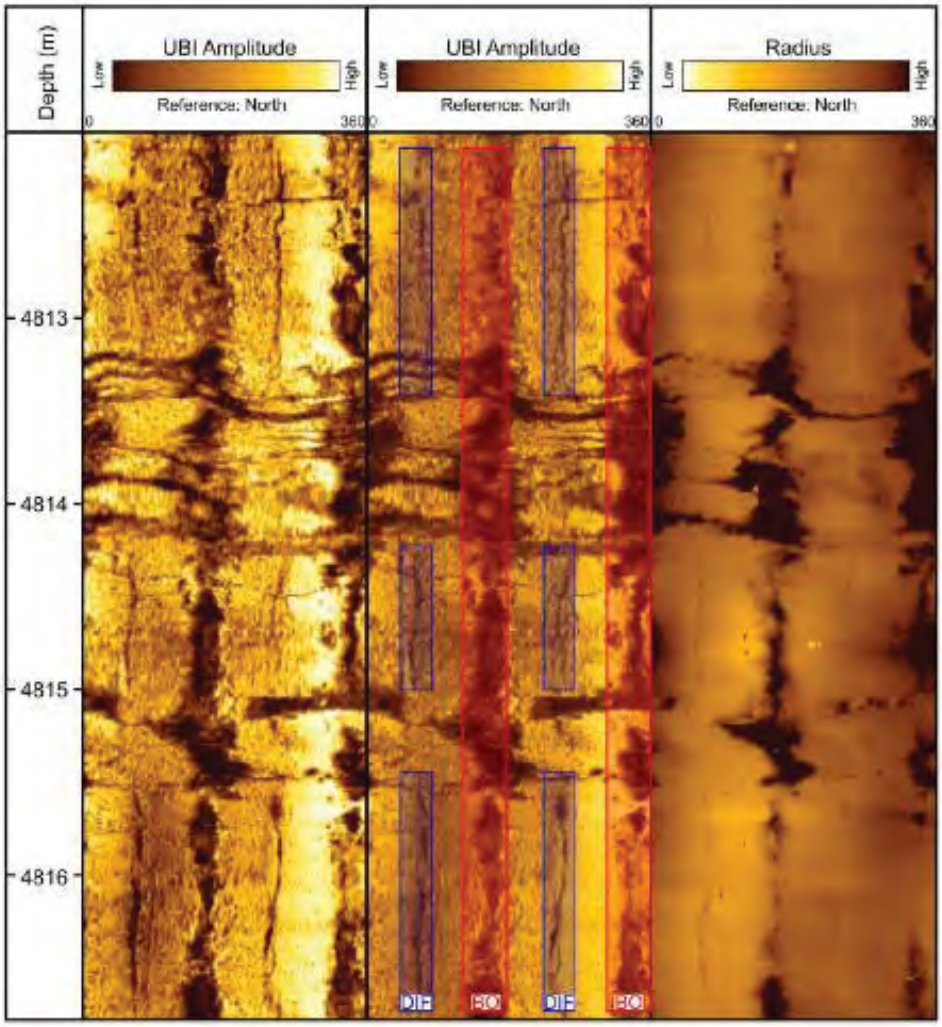
Recent developments have also included technologies for engineering interventions to limit fracture growth in formations without natural lithological or stress barriers. These may offer increased security in the face of uncertain geological conditions.

Best practice is likely to continue to advance, therefore, a good regulatory environment should encourage data collection, dating sharing and the development and uptake of new technologies to further reduce risks.

Figure 6.9: Example of borehole breakouts (BO) and Drilling Induced Fractures (DIF) in ultrasonic borehole images (UBI) showing the directions of maximum and minimum principal stresses relative to North

This information can and should be used to test and condition the modelling and subsequent design of the hydraulic fracture stimulation

Source: Rajabi et.al. (Rajabi et al. 2017) Australia stress map



6.8 What are likely and potential oil and gas field development scenarios for Western Australia

6.8.1 Background

To anticipate and assess the relevant impacts of employing hydraulic fracture stimulation to developing Western Australia's shale or tight oil and gas resources, some envisioning of the nature and scale of potential developments for both the Canning Basin and Perth Basin is necessary. While much of the potential impacts and risk will depend on the nature of specific wells and their fracturing, cumulative impacts to water resources, biodiversity,

amenity, air quality and aesthetics are highly dependent on the scale, intensity and location of wellfields, and the infrastructure that supports them, such as roads or pipelines.

Envisioning the potential level of development requiring (and attracting) hydraulic fracture stimulation in the Canning Basin or the Perth Basin is problematical. A much-cited estimate of the theoretical scale of development of Australian shale gas resources, based on overseas experience with well spacing and distribution of productive zones, was published by Frogtech (Frogtech 2013), indicating a potential drilling of 41,722 wells in the Canning Basin and 14,584 wells in the Perth Basin. However, the report cautions that in reality the actual level of development will be constrained by markets, remoteness and costs. It also notes that the estimates were not based on single well pads supporting multiple (horizontal) wells, all of which would combine to decrease the number of oil and gas well sites that are ultimately developed. Given the Western Australian context and experience with developing onshore oil and gas resources, such extreme estimates of development scale are highly implausible. In their submission to this Inquiry, Frogtech wrote the following:

"In 2013, Frogtech Geoscience was commissioned by the Australian Council of learned Academies (ACOLA) to report on the geological risks of shale gas production in Australia. In connection with our report to ACOLA, and for the benefit of the Panel, we note the persistent misquoting of the ACOLA report, by activist organisations. In the main we have observed third-party commentary on hydraulic fracturing in Western Australia citing the ACOLA report, and stating a figure of 41,722 shale gas wells could be developed in the Canning Basin. We reject such third-party assertions as manifestly perverse and damaging to proper debate. For clarity and avoidance of doubt, the reported figure of 41,722 wells in the ACOLA report represents an 800-meter grid space covering the entire Canning Basin only. It does not prescribe the number of wells for economic recovery, a number materially less than 41,722. For clarity and avoidance of doubt, there is no scientific basis to suggest petroleum resources are equally distributed across the Canning Basin to enable the economic recovery of petroleum resources via conventional or unconventional methods on an 800-meter grid spacing" - submission from Frogtech

However, the Frogtech (Frogtech 2013) estimates, when scaled with their assumption of 15 megalitres (ML) of water used per well, does provide one estimate of an extreme upper limit of water use for developing oil and gas for each basin. In the case of the Canning Basin, assuming a 25-year development, requiring the drilling of over 1,600 wells per year and also assuming that all the water used was from the fresh groundwater resource, this translated to 25 gigalitres (Gl) of water per year. This represents an estimated three percent of the sustainable groundwater yield in the Basin over that period (on top of the current use of some two percent). In the case of the Perth Basin, Frogtech's estimates required the development of some 580 wells per year using 0.5 percent of the sustainable groundwater

resource over that period, on top of an existing use of 42 percent of the sustainable yield, again, based on the assumption that no other water source was used.

The size of the existing and projected domestic gas market in Western Australia is also informative in projecting plausible scales of onshore gas development (with or without hydraulic fracture stimulation). In the latest available Western Australian Gas Statement of Opportunities (Australian Energy Market Operator 2017), as of December 2017, the Australian Energy Market Operator (AEMO) noted the following:

- The Western Australian domestic gas market continues to evolve, with new production facilities and gas suppliers, and greater pipeline and gas storage capacity.
- In the near term, to 2020, the domestic gas market is well-supplied. Western Australia has a Domestic Gas Policy that requires liquefied natural gas (LNG) export projects to make gas available to the Western Australian domestic gas market on a long-term basis by setting aside reserves equivalent to 15 percent of their LNG production. The forecast demand for domestic gas in Western Australia will probably remain below 1,100 TJ/day to at least 2027;
- Two new domestic gas producers commencing operations (Gorgon and Xyris) add 31 percent to production capacity, bringing the total state domestic gas supply to 1,659 TJ/day;
- Potential gas supply is expected to exceed forecast demand over the entire outlook period, assuming that new reserves are developed. Some uncertainty exists in the medium term, when reserves for domestic-only gas producers are expected to fall and forecast domestic gas prices remain low. If domestic gas prices remain low, new gas reserves may not be developed and supply may not meet demand in the medium to long term. This may be exacerbated given that exploration has fallen further since 2016. Exploration levels must be considered well in advance of potential supply shortfalls because it can take up to five years to develop a conventional petroleum field; and
- Western Australian domestic gas demand growth remains low. Continued gas demand growth in Western Australia is dependent on new resources and industrial gas-consuming projects. Under a separate modelling scenario that assumed committed and likely large-scale renewable generation projects proceed, total forecast gas demand is lower across the outlook period compared to the base scenario forecast.

Table 6.2: Nameplate domestic gas production capacities for current suppliers in Western Australia

Total contracted demand from Western Australian domestic consumers for 2018 is about 1,100 TJ/day. Two new domestic gas production facilities are expected to commence operations: Wheatstone (200 TJ/day in 2018) and Gorgon Phase 2 (118 TJ in 2020)

Source: Australian Energy Market Operator (Australian Energy Market Operator 2017)

Project	Nameplate Domestic Gas Production Capacity Tj/day
Perth Basin Onshore:	
Beharra Springs	20
Dongara	7
Red Gully	10
Xyris	10
Northwest Shelf Offshore:	
Devil Creek	220
Gorgon (Phase 1)	182
Karratha Gas Plant	630
Macedon	220
Varanus Island	360
Total	**1659**

In a report prepared for the Australian Council of Learned Academies (ACOLA), SKM (Sinclair Knight Merz 2013) found the feasible project sizes for unconventional gas, and foreseeable production for the domestic market when near existing infrastructure, to have a maximum of 135 – 270 TJ/d; for gas fields more than 500 km from infrastructure, they estimated a minimum economic scale of 135 TJ/d. The report further noted that the scale of opportunity is limited by market opportunities to replace lapsing supply contracts and new growth markets.

To develop an unconventional oil and gas field, for the purposes of this Inquiry we assume that in the future companies will propose contemporary technologies and approaches including the development of multiple wells using horizontal drilling, as is done for shale gas resources elsewhere, minimising the total above-ground footprint. Submissions to this Inquiry from companies anticipating tight or shale development indicate designs involving varying intensity of wells and well pads:

- Buru Energy anticipates a development approach using 10 horizontal wells of one to four kilometres (nominally two kilometres) in length from each well pad, ultimately

developing eight such pads supporting 80 wells over the 20-year life of project, delivering a nominal 130 TJ/d of gas;

- MC Resources Australia anticipates a development approach using at least 10 horizontal wells from each well pad, ultimately developing about 20 such pads supporting about 170 wells over the 20-year life of project, delivering a nominal 200 TJ/d of gas; and
- Finder Shale anticipates a development approach using at least eight horizontal wells of one kilometre in length from each well pad, ultimately developing about 45 such pads on a nominal grid spacing of 3.3 x 7 kilometres (one well pad per 23 square kilometres), supporting 360 wells over the 20-year life of project, delivering as much as 600 TJ/d of gas (and significant quantities of high quality light crude oil).

The ultimate impacts related to siting and scale of gas development on the environment, including social surroundings, depends on the cumulative scale of clearing of native vegetation, the cumulative impacts of associated infrastructure, the cumulative demands on water resources, and the proximity of the well field to people and places of cultural and natural significance. Again, we note that the environmental impact assessment and development approvals in Western Australia must take into account historical and reasonably foreseeable cumulative impacts on the environment.

It is important to note that the realised productivity and ultimate recovery of gas from individual gas wells will have a significant impact on the number of wells required to develop a gas field. Studies available from North America indicate significant variances between flow rates and recoveries among wells within gas fields, and variances between gas fields in differing basins. For example, in the Eagle Ford Basin in the United States, the United States Geological Survey (U.S. Geological Survey 2012) estimated a mean ultimate recoverable resource (URR) per shale gas well of 1.1 billion cubic feet (Bcf). A study by the Energy Information Administration (U.S. Energy Information Administration 2011) provided a mean URR of 5.0 Bcf. Subsequent analysis of URR for wells in this basin (Guo et al. 2016) resulted in a figure of 1.4 – 2.0 Bcf. The key point here is that until a gas field is explored and appraised, and some experience is gathered with respect to production rates, it is difficult to forecast the likely scale of development justified in developing a field.

6.8.2 Canning Basin hypothetical development scenarios

A hypothetical development in the Canning Basin would probably look very different to one in the Perth Basin, as most discovered shale and tight gas accumulations lie much further from towns and existing infrastructure, there are no gas or oil pipelines in Western Australia east of the Pilbara mining region. One development that could possibly occur in the Canning Basin in the next 20 to 30 years would be from a large accumulation of tight gas in the Laurel Formation.

Companies currently operating in the Canning Basin have each put forward their design oil and gas fields as part of submissions to this Inquiry. These designs are based on multiple well sites using horizontal drilling and hydraulic fracture stimulation and are described in some detail. They are summarised here.

MC Resources Australia's submission indicates a gas field at their Valhalla Gas Province envisioned in three stages (appraisal, pilot and full field development) of some 200 TJ/d capacity. The appraisal stage would involve (a further) one to four wells (potentially drilled from existing pads) lasting one to three years, producing 0.1-0.4 PJ, with a total footprint of up to 25 hectares. The pilot stage of development would last for ten to twenty years, with a production target of 10 TJ/d based on a single well pad supporting four to eight wells and a drilling phase surface footprint of about 10 hectares. This gas would meet 100 percent of the energy demands for electricity generation for Broome, Halls Creek, Derby and Fitzroy Crossing for 20 years, and would be transported by truck or small-scale pipeline, replacing gas currently trucked from Karratha as LNG. The Full Development Stage would require new pipeline infrastructure from Valhalla to the Pilbara (some 500 km), thereby connecting the field to markets there and through to the South-West of the State, supplying 200 TJ/d for 20 years (about 20 percent of the State's domestic gas demand), for a total of 1,460 PJ. This gas field would require 16 pads (well sites) supporting 160 (horizontal) wells, with a stated field footprint of about 150 hectares.

Buru Energy's submission included designs for an oil and gas field at Yulleroo, east of Broome, delivering 714 PJ of natural gas (as well as condensate and liquefied petroleum gas), proceeding in two stages. The first stage (local gas) would be a small-scale development on existing well pads to supply gas to the local market for power generation and mineral processing. This would require the drilling of up to eight wells from one or two existing well pads and the establishment of a scalable central processing facility, which would remove higher-value products and then process the gas as either liquefied (LNG) or compressed natural gas (CNG) for transport to local customers. Buru estimated the local market supplied by LNG trucked from Karratha as 6 TJ/d, with the potential to replace the current use of diesel for a total market of some 20 TJ/d. The total footprint, including a nine hectare processing facility, would likely be less than 15 to 20 hectares, including clearing to date. The second stage (domestic gas) would involve the construction of a pipeline to the

Pilbara and potentially through to the South-West and the nominal production of 130 TJ/d of gas over 17 years (with a tailing off of production to twenty years). This would require up to eight well pads each supporting 10 horizontal wells, with two to ten wells drilled and hydraulically fractured each year. Gas would be processed at an expanded facility and also involve a central water handling facility, for a total gas field footprint of about 100 hectares.

Finder Shale's submission anticipates an oil and gas field in the Great Sandy Desert east of Bidyadanga, based on an estimated unrisked resource of 26,000 PJ of gas and 35 billion barrels of oil. At an early stage of appraisal, the production scenario is less defined but there is a stated aspiration in the submission to this Inquiry of providing 'a quarter of Australia's oil and half Western Australia's domestic gas needs for decades to come'. This would translate to approximately 600 TJ/d of gas. Following results from an exploratory well (Theia-1), the next stage would be to construct a horizontal well on the existing well pad using hydraulic fracture stimulation to test production flow rates and commerciality. If progressed beyond this stage, Finder Shale anticipates using multi-pad and horizontal drilling technology resulting in eight wells on a single two hectare well site. In conceptual drawings provided as part of their submission, the well site layout might involve three lines spaced seven kilometres apart, each with a well site every 3.3 kilometres (a total of 45 well sites supporting 360 wells developed over 20 years). Finder anticipates the clearing of two hectares per well site (total 90 hectares) but this does not include clearing for the required road network. Using general figures from above, a conservative estimate of land clearing might come to some 600 hectares. The submission did not indicate how the product would get to market.

From the above submissions, the Inquiry considered the risks, where those risks are scale dependent, of development scenarios delivering between 100-200 TJ/d in the Perth and Canning Basins, and a higher scenario of 1,100 TJ/d (approximately the Western Australian domestic gas demand) if most of these envisioned gas fields were simultaneously realised. All the submissions identified the Western Australian domestic gas market as their target and this higher value is near the demand limit. It is noted that there has been, to date, no commercial arrangement substituting onshore unconventional gas for commitments requiring conventional gas exporters to reserve gas for the domestic market.

Separate consideration is given to a tight oil scenario in which, at least initially, none of the co-produced gas goes to market.

6.8.3 Perth Basin hypothetical development scenario

A timeline to full production from a gas field in the Northern Perth Basin would be much quicker than elsewhere in the State, as much of the required infrastructure already exists (for example, roads and gas pipeline infrastructure).

A reasonable scenario for a commercial development and production of a shale or tight gas resource in the Perth Basin might consist of producing ~100 (TJ/d) of gas for 20 years for the domestic gas market, noting that the domestic consumption of gas in Western Australia is expected to rise to 1,190 – 1,270 TJ/d by 2020 (DOMGAS Alliance 2013). This is the equivalent of ~730 PJ of gas over that 20-year period. We note in the submission to the Inquiry by Beach Energy, that with respect to their joint venture with AWE Limited, the recently discovered Waitsia field contains pressurised reserves that do not require fracture stimulation and will be developed prior to addressing the tight gas potential in and around those fields. The conventional Waitsia gas field, with a reserve of 820 PJ gross, will supply 9.6 TJ/d from two wells in its first stage of development; the second stage is expected to produce 100 TJ/d for at least 10 years from an additional two wells, supported by the Xyris production facility and transported through an existing pipeline (Parmelia).

Production from unconventional resources requiring hydraulic fracture stimulation to yield sufficient gas would require more well development to produce 100 TJ/d, which would vary with the URR of the wells.

Low case Ultimate Recoverable Resource (URR)

A low URR scenario with a mean URR for a gas well of 1.1 Bcf (1.13 PJ) translates to approximately 646 wells required to provide gas to a facility producing 100 TJ/d over 20 years. If the development was completed with eight wells per pad, about 80 well pad sites would be required over a 20-year period. It should be noted that nearly all these multi-well sites would need to be completed over the 20-year life of the project at a rate of approximately one multi-well site every 90 days.

In consideration of the large number of well completions, it is likely that this scenario would be sub-economic under prevailing completion costs and gas market price conditions.

High case Ultimate Recoverable Resource (URR)

A high URR scenario with a mean URR of a gas well of 5.0 Bcf (5.16 PJ) translates to approximately 141 wells required to provide gas to a facility producing 100 TJ/d over 20 years. If the development was completed with eight wells per well pad, 18 well pad sites would be required over a 20-year period. It should be noted that that nearly all these multi-well sites would need to be completed over the 20-year life of the project at a rate of about one multi well site each year.

6.9 Well design, construction, testing, operation and decommissioning

The performance of any oil or gas well in containing the fluids and gases it was intended to contain (that is, not leaking into the environment), in preventing unintended formation fluids from entering the well, and preventing natural fluids or contaminants leaking from one rock layer into another (including water aquifers) is termed 'well integrity' and is an essential determinant of safety and environmental protection.

There are international standards that address each phase of the life of any oil or gas well, aimed at conferring well integrity before, during and after production (International Standards Organisation 2017). These phases are described in the following subsections.

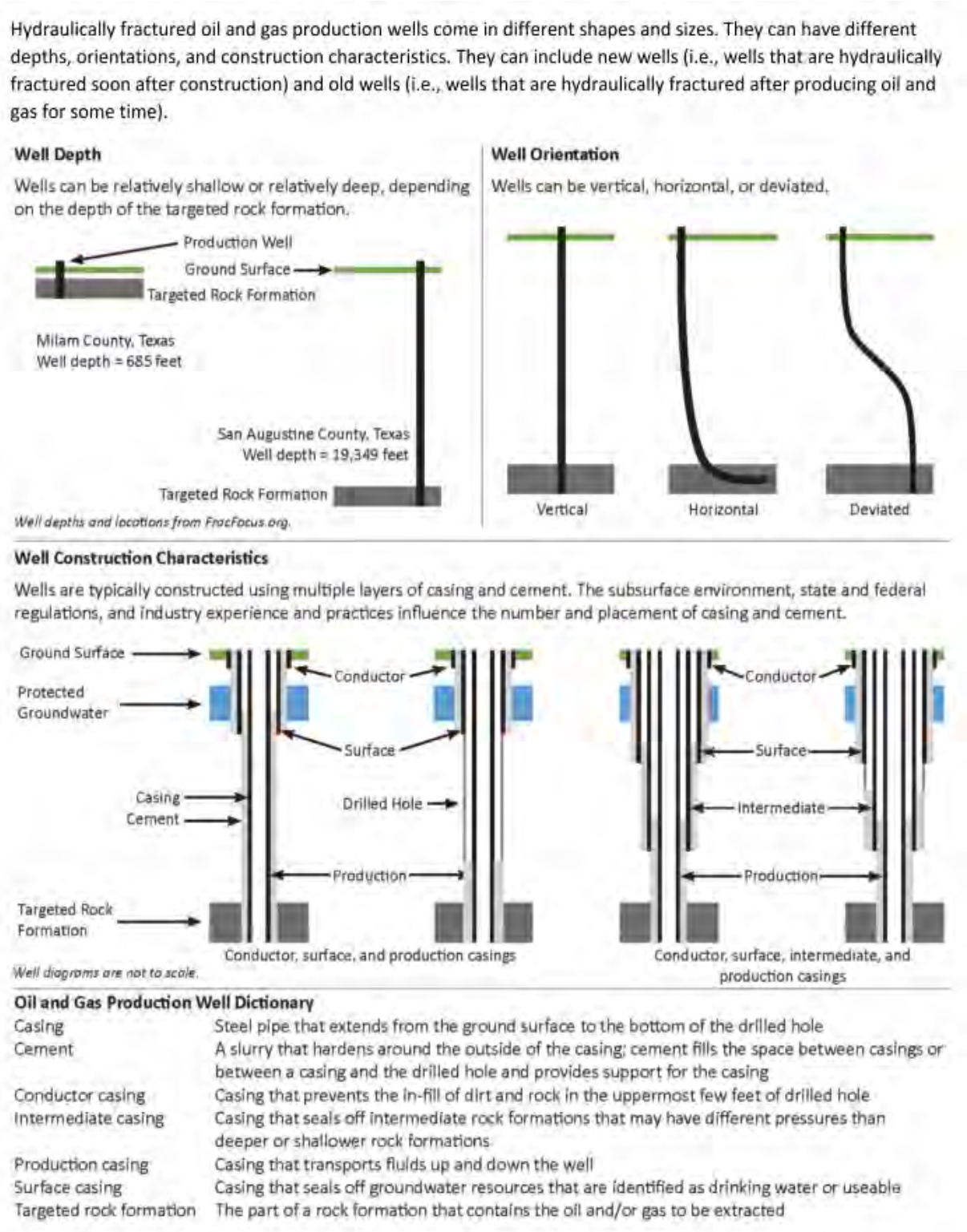
6.9.1 The basis of design

This initial phase is where the probable safety and environmental exposures to surface and subsurface hazards are identified, so that control methods through design and operation can be developed to maintain well integrity for the whole life cycle.

In this phase, the necessary controls to avoid, mitigate or minimise the potential hazards are incorporated into the well design. These controls must anticipate any changes that might occur over the life of the well to ensure that the required barriers in the well's design minimise risk exposure to people and the environment. Critical to well integrity is the specification of appropriate materials and components for casing and cementing the well, during the hydraulic fracture stimulation process and over the well's lifetime. The design for the sizes and lengths of casing, and the depths at which different casings are used depend upon the geology and the required isolation of rock layers and aquifers, the geochemical environment through which the well passes, the importance or sensitivity of the groundwater that the well penetrates, and the purpose of the well with its associated operational stresses and requirements (Huddlestone-Holmes et al. 2017; Taoutaou et al. 2010).

Best practice guidelines for the entire well life cycle continue to be further developed by industry; the Standards and Guidelines for Drilling, Well Constructions and Well Operations (International Association of Oil and Gas Producers 2015) lists dozens of guidelines covering drilling, operations, equipment, materials, and abandonment. While these design criteria imply potentially unique, bespoke solutions for each well to ensure integrity, some jurisdictions specify minimum requirements. For example, in the United Kingdom a third, outer casing and cement ('triple casing') is required for any length of a well passing through a surface groundwater aquifer, with casings cemented from the surface to well beyond the bottom of the aquifer (Fretwell et al. 2012; Oil and Gas UK 2016; The Royal Society and The Royal Academy of Engineering 2012; United Kingdom Onshore Oil and Gas 2016). While such triple casing is considered best practice, it is not explicitly and universally required by regulation for oil and gas wells in Western Australia.

Figure 6.10: Idealised schematics and nomenclature for oil and gas production wells
Source: U.S. EPA (U.S. Environmental Protection Agency 2016)



6.9.2 Construction

The 'Construction Phase' defines the elements to be constructed (including rework/repair) and verification tasks to be performed to achieve the intended design, and addresses any variations from the design that require a revalidation against the identified hazards and risks.

Relevant and detailed descriptions of well construction for shale gas are found in (Cook et al. 2013; Department of Mines and Petroleum 2015a; Hossain & Al-Majed 2015; Huddlestone-Holmes et al. 2017; King 2012; Oil and Gas UK 2016).

Following the development of access to the site and any necessary vegetation clearing and site preparation (which may involve levelling, erosion control structures, excavation of fenced pits with impervious liners to hold drilling fluids and drill cuttings, and developing a local source of water), the well is drilled and completed according to its specified design. Drilling involves the use of fluids (muds) that cool, lubricate, seal, lift cuttings to the surface and assist with controlling the pressures in the well as it is being drilled. Drilling fluids are continuously recirculated through the system during drilling operations and are disposed of to an onsite sump or removed from site. The drilling mud is distinct from any fluids that are subsequently associated with hydraulic fracture stimulation, and its composition may vary according to the depth and temperature of drilling and the rock formation encountered. Drilling operations in onshore Western Australia predominantly use water or occasionally synthetic based drilling fluids with approved chemical additives.

Drilling normally progresses in designed stages, with each consecutive section having a smaller diameter. When a design depth is reached, a casing string (a long section of pipe) is lowered into place and cemented such that the annulus (circular area) between the outside of the casing and the surrounding rock (or between subsequent casings) is filled and sealed. This process is repeated for subsequent casings as the drilling progresses, with the diameter of the casing decreasing in an arrangement like a telescope (see **Figure 6.11**).

The casing and cement layer at the level designed to access the gas are eventually perforated with small holes (a few centimetres in diameter) to access the gas-bearing rock. Thus, gas can flow to the surface through the innermost casing (called production tubing) with the outer casings designed to provide containment barriers. The well integrity ultimately achieved depends on the appropriate specification and application of the steel (International Standards Organisation 2014) and cement (International Standards Organisation 2017) to meet the design requirements, the quality and preparation of the bore (the drilled hole through the rock) and the positioning of casings within the bore relative to the stresses, fluid pressures and rock types being drilled through (Huddlestone-Holmes et al. 2017). Poor well construction can mean these multiple barriers fail to contain fluids and thus provide a pathway for pollution (King 2012).

In addition to the greenhouse gas (GHG) emissions associated with pre-production and construction, GHG is potentially emitted during the construction phase, particularly after completion of the stimulations as part of the flowback process. In some cases, this methane is flared or simply vented to the atmosphere. Flaring converts most of this methane to carbon dioxide (CO_2), which has a significantly lower GHG impact than methane itself (Cook et al. 2013) but may produce by-products such as 'black carbon' (Bodin 2012), Volatile Organic Compounds (VOCs), and nitrous oxide – all potentially harmful to human health. The GHG impact of the construction phase can be further reduced by capturing the gas for sale or for reinjection into the well (green completion). In 2016, the U.S. EPA introduced regulations requiring green completions for hydraulically stimulated wells (see **Section 10** (Greenhouse gas) of this Report for more details on reduced emissions).

Crucial to assuring the quality of well construction and subsequent integrity is the requirement for performance (pressure) testing at each stage of well development against the designed performance criteria (that is, for each cemented string) (King 2012; King & King 2013). There are global standards and methods for this testing (International Standards Organisation 2017). It is usual for one to five percent of initial completions of a well stage to require additional work to repair the well before it will pass the tests to drill further or to finish the drilling stage successfully (King 2012).

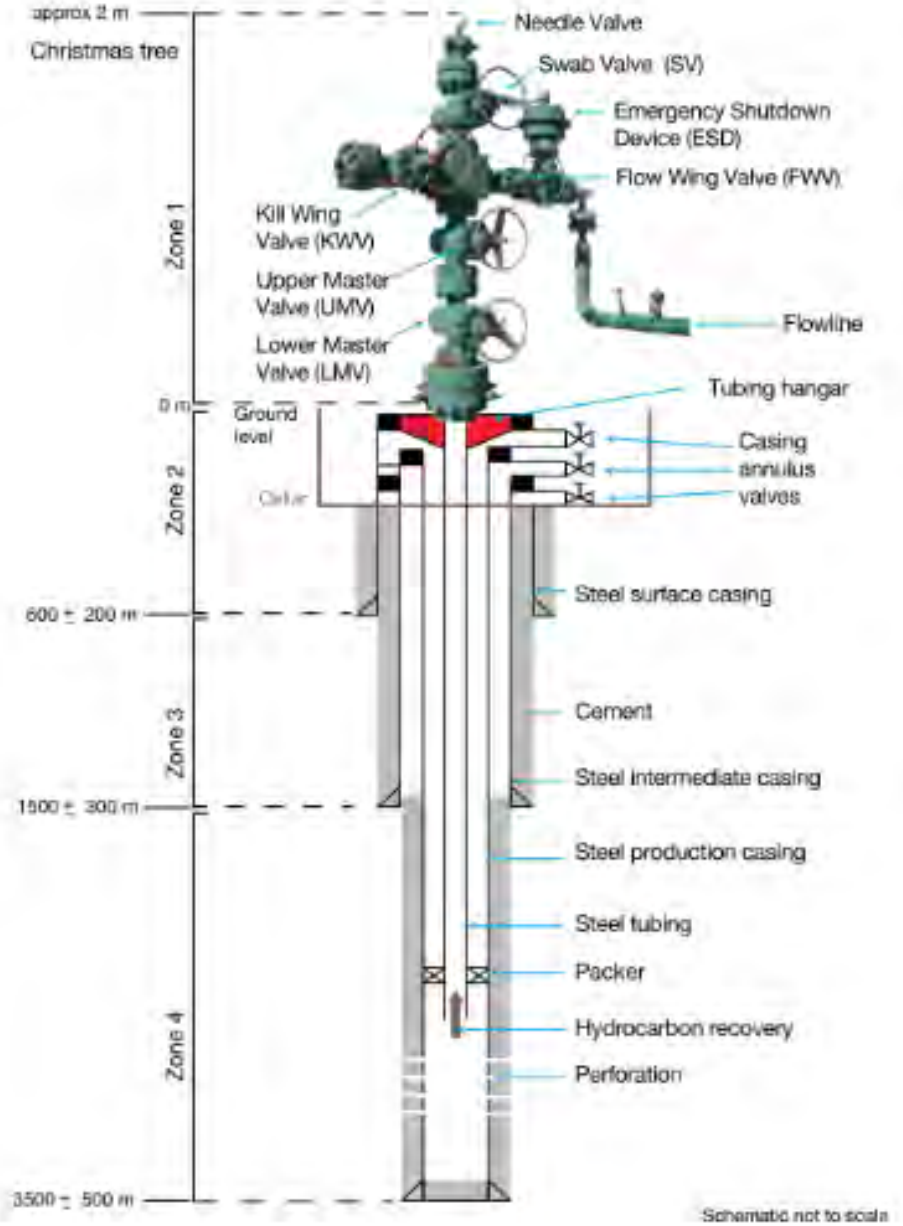
The successful cementation of all the casing layers in place is verified by pressure testing the well and by the use of downhole tools such as the cement bond log that use acoustic, density sensing or electromagnetic methods to sense any voids or poor contact between the cement, the casing strings and the rock formation (Kyi & Goh 2015). As the proper placement and curing of the cement all around the well annulus is critical, tools that can image the entire circumference of the well (for example, with ultrasonics) provide a much better verification that zonal isolation in meeting specifications.

A conventional gas well is 'completed' once all the components determining the well's integrity have been verified and the necessary instrumentation of hardware to control gas production is in place. The latter includes an assembly of wellhead valves and fittings at the surface that control flow (the 'Christmas tree'). In the case of wells developed for shale or tight gas, additional work and testing is required for hydraulic fracture stimulation (see below).

Figure 6.11: Photograph of a 'Christmas Tree'

This is part of an oil and gas production well above ground, sitting on an illustration showing the well barriers (casing and cement) below ground in cross section (not to scale)

Source: DMIRS



Poor well construction techniques are considered the most significant cause of well integrity failure by a number of the reviewed reports (Commonwealth of Australia 2014; New York State Department of Environmental Conservation 2015; Newfoundland and Labrador Hydraulic Fracturing Review Panel 2016). Major inquiries and reviews concluded the

following practices are expected to reduce the risk of well integrity failures due to poor well design and construction:

- Applying standards and leading practices to the design and construction of wells (Commonwealth of Australia 2014; Cook et al. 2013; Hawke 2014; New Brunswick Commission on Hydraulic Fracturing 2016; Newfoundland and Labrador Hydraulic Fracturing Review Panel 2016; The Academy of Medicine Engineering and Science of Texas 2017; U.S. Environmental Protection Agency 2016; UK Task Force on Shale Gas 2015; Western Australia Legislative Council Standing Committee on Environment and Public Affairs 2015).
- The requirement for a minimum standard of casing strings/barriers (New Brunswick Commission on Hydraulic Fracturing 2016; U.S. Environmental Protection Agency 2016; Western Australia Legislative Council Standing Committee on Environment and Public Affairs 2015).
- Using high quality cement and materials (Academy of Science of South Africa 2016; UK Task Force on Shale Gas 2015).
- Standardised verification of well integrity and quality of the cement seal after well completion using pressure tests and downhole cement bond logs, using advanced imaging tools and independent sign-off.
- Ensuring ongoing and independent well integrity and condition monitoring (Newfoundland and Labrador Hydraulic Fracturing Review Panel 2016; Parliament of Victoria Legislative Council Environment and Planning Committee 2015; UK Task Force on Shale Gas 2015).
- Implementing effective regulations, including reporting and compliance mechanisms, for example, (Academy of Science of South Africa 2016; Commonwealth of Australia 2014; Hawke 2014; Newfoundland and Labrador Hydraulic Fracturing Review Panel 2016; The Royal Society and The Royal Academy of Engineering 2012).

The regulatory requirements governing the construction and operation of oil and gas wells in Western Australia are described in detail in **Section 4** of this Report. These extend to: the approval of well design; baseline monitoring; monitoring (logging) and verification of cementing activities; real-time monitoring and daily reporting of pressures and drilling fluids during operations; and, where applicable, micro-seismic monitoring of hydraulically stimulated wells.

As an example of the extent of standards that apply to ensure well integrity, the following list was submitted by Finder Shale Pty Ltd as part of their submission to this Inquiry:

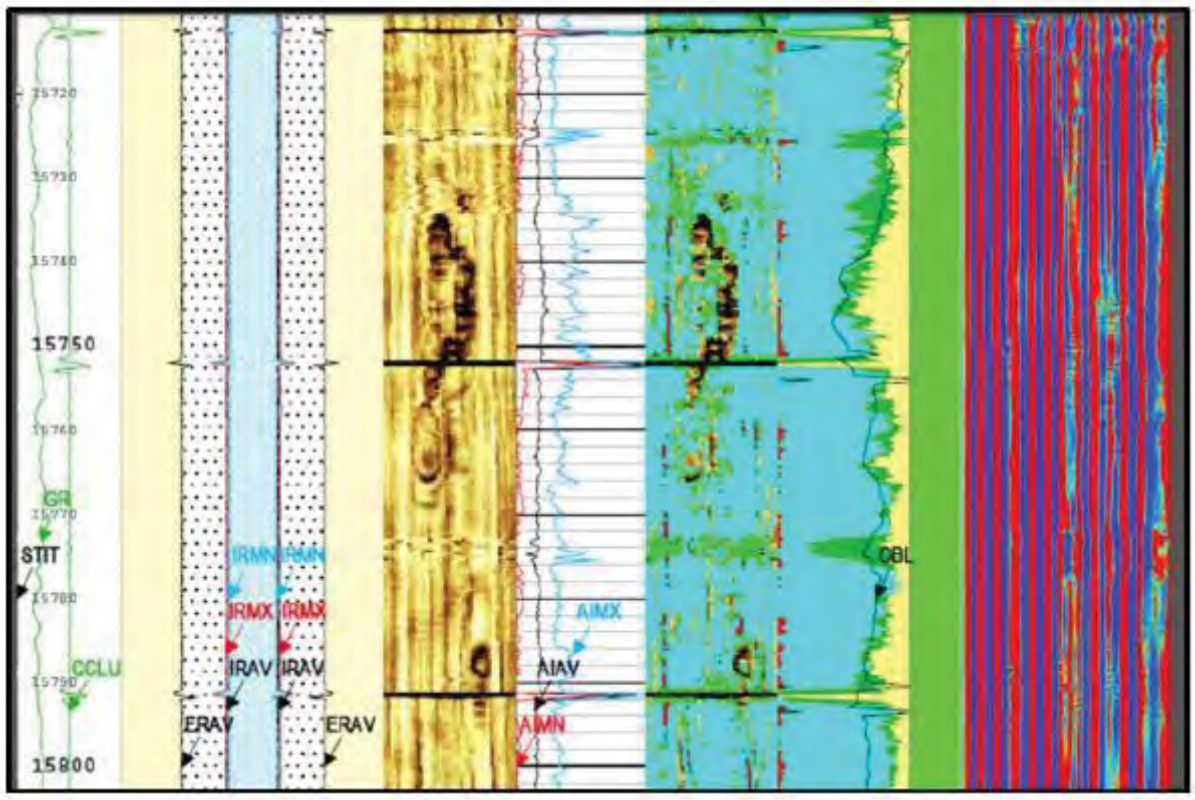
To ensure well integrity, the following standards and guidelines apply to the well design:

- API 5B Specification for Threading, Gauging, and Thread Inspection of Casing, Tubing, and Line Pipe Threads
- API 5CT/ISO 11960 Specification for Casing and Tubing
- API 10A/ISO 10426-1, Specification for Cements and Materials for Well Cementing
- API 10B-2/ISO 10426-2, Recommended Practice for Testing Well Cements
- API 10D-2/ISO 10427-2, Recommended Practice for Centralizer Placement and Stop Collar Testing
- API 10TR1, Technical Report Cement Sheath Evaluation
- API 10TR4, Technical Report on Considerations Regarding Selection of Centralizers for Primary Cementing Operations
- API 65-2, Recommended Practice Isolating Potential Flow Zones During Well Construction
- API Guidance Document – HF1 Hydraulic Fracturing Operations – Well construction and Integrity
- API Guidance Document – HF2 Water Management Associated with HFS
- API Guidance Document – HF3 Practices for Mitigation Surface Impacts Associated with HFS
- API Recommended Practice 65-2, Isolating Potential Flow Zones During Well Construction
- APPEA Code of Practice for Hydraulic Fracturing (2011) Guideline 5

Figure 6.12: Example of wireline log data used to assess wellbore integrity

Here acoustic imaging and the Cement Bond Log indicate voids and possible gas channelling in the cement behind casing.

Source: Kyi and Goh (Kyi & Goh 2015)



6.9.3 Hydraulic fracture stimulation phase

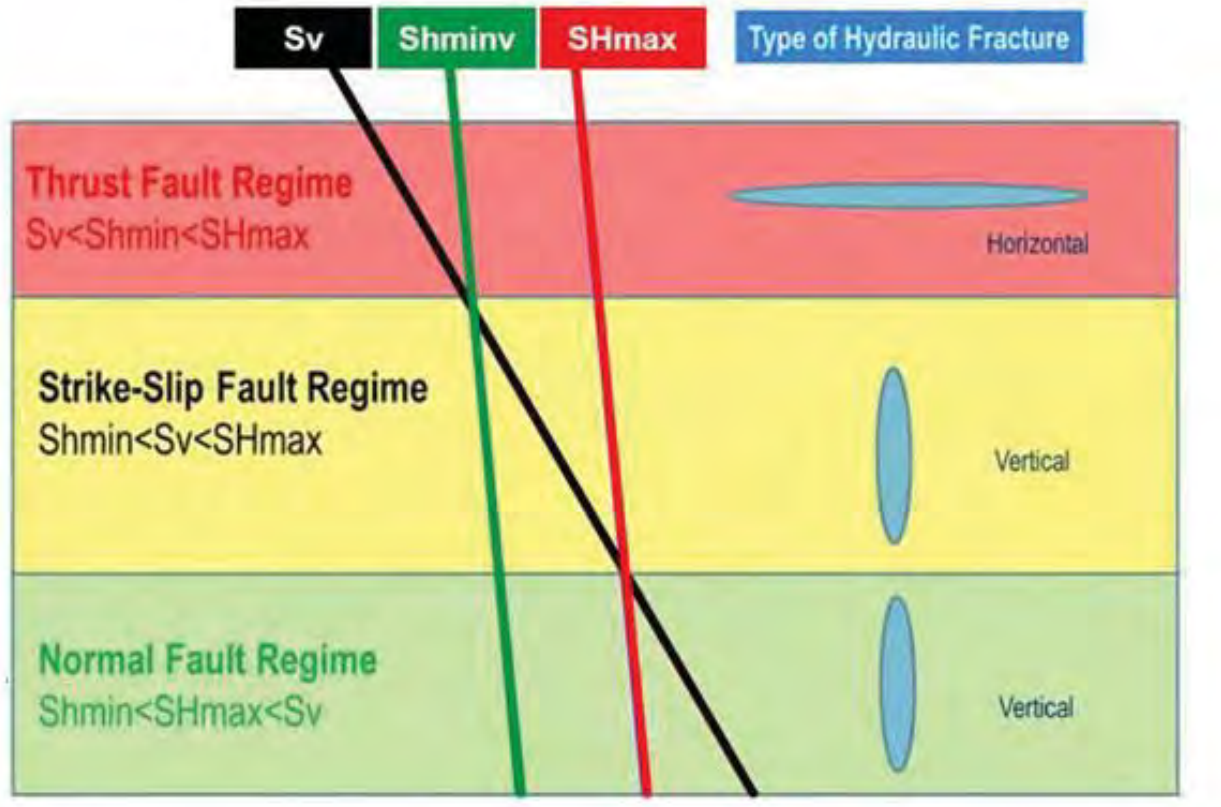
Logically and in practice, hydraulic fracture stimulation is part of both the design and construction phases in developing a shale or tight oil and gas well. It is treated separately here because it is the central process defining concerns and risks in this Inquiry.

Hydraulic fracture stimulation is designed to increase the flow of oil and gas from the target formation (rock layer) to the well. It involves pumping fluids and proppants (solid material such as sand or ceramic beads designed to keep the resulting factures open) under high pressure into low permeability rock to create fractures. This normally takes place in a set of intervals along the production zone of the well; where shale gas has been developed with lateral wells (commonly one to several kilometres long), it is now common for 40-100 fracture stages to be placed along a lateral (Huddlestone-Holmes et al. 2017). These stages are usually designed by either computer or local experience so that fluid volume, rate and pressures achieve design goals of fracture height and complexity, and for each stage the requisite pumping may last from 20 minutes to four hours (King 2012). During each stage, the target zone is isolated and pressurised until the surrounding rock fractures, with subsequent fracture propagation controlled by the flow of the fracturing fluid. Some of this fluid is adsorbed ('imbibed') by the rock (Birdsell et al. 2015) and a portion flows back to the well (flowback water).

To date, the only onshore oil and gas wells in Western Australia that have been hydraulically stimulated have been vertical, and the number of fracturing stages has ranged between two and 10 (Department of Mines and Petroleum 2015a).

The design objective is to create fractures in the target zone of oil and gas-bearing rock that maximise the flow of gas to the well. The direction of the fractures from the well depends on the natural stresses in the rock. At the depths typically accessed for shale and tight oil and gas, this normally results in vertical fractures in 'relaxed' sedimentary basins, though in tectonically complex geological settings such as mountain belts (Rajabi et al. 2017; Wikel 2011), and in the shallower overburden rocks the stress state is often different from that lower in the well, as depicted in **Figure 6.13**, for the particular case of one region of the Canning Basin.

Figure 6.13: Stress state in the region of the Theia-1 well, as depicted by geomechanical earth modelling results reported in the submission from Finder Shale Pty Ltd
Source: Finder Shale Pty Ltd Submission



The relative magnitudes of the vertical effective stress Sv-black line, the maximum horizontal stress SH- red line, and the minimum horizontal stress, Sh-green line, change with depth. In this scenario, vertical fractures will propagate in the lower part of the well, where a normal faulting regime prevails (green zone), and they will still be vertical if they penetrate into the zone above where strike slip faulting regime prevails (yellow zone). Fracture growth will likely be arrested by high horizontal stresses in the upper part (red zone) where a thrust fault regime prevails, or if fractures are created in this zone they will have a horizontal orientation since they will open normal to the minimum principal stress, which here is vertical.

The lengths of the fractures, particularly the longest, set limits to the potential pathways and risks of contamination beyond the gas-bearing rock layer. Knowing the likely maximum lengths of stimulated hydraulic fractures in sedimentary rocks is crucial to decisions on the safe vertical separation between the depth of stimulation and rock strata not intended for penetration. Following examination of fracture data from five different shale gas formations subjected to hydraulic fracture stimulation, and natural fracture data from three separate sedimentary formations from around the world, Davies et al. (Davies et al. 2012), reported

that the longest stimulated fracture from several thousand fracturing operations was around 600 metres. Based on this empirical data, they concluded that the probability of a stimulated fracture extending vertically more than 350 metres is about one percent and that very few naturally-occurring fractures or stimulated hydraulic fractures propagate past 500 metres because layered sedimentary rocks of contrasting stiffness provide natural barriers to growth.

Similarly, Flewelling et al. (Flewelling, Tymchak & Warpinski 2013) reported on the basis of modelling constrained by data from 12,000 hydraulic fracture stimulations that the maximum observed vertical fracture length was about 600 metres. They also reported that it was not physically plausible for induced fractures to create a hydraulic connection between the deep back shales and other tight formations and overlying potable aquifers, since all of the fracturing (in those studies) took place at depths much greater than this limit. They concluded that direct hydraulic communication between tight formations and shallow groundwater via induced fractures and faults is not a realistic expectation based on limitations to fracture height growth and potential fault slip.

Warner et al. (Warner et al. 2012) cautioned that geochemical evidence can be found for groundwater originating in the Marcellus Formation shale of Pennsylvania to have migrated into shallow aquifers naturally, despite the relatively longer distances involved. These pathways are natural, and unrelated to drilling or fracturing activities that are widespread in the region. The potential risk is that these pathways are subsequently reactivated when oil or gas activities occur in the region, leading to release of otherwise contained saline fluids or gas. Engelder (Engelder 2012), in a discussion of Warner et al.'s paper, pointed out that the Marcellus Formation section that is exploited for gas production is very depleted in water, and tends to naturally imbibe any fluids, rather than releasing them. Moreover, while gas is more mobile in these situations, there has been no recorded leakage of gas into aquifers in this setting. The general tendency for strong capillary retention of the hydraulic fluid that does not flow back from shales is also documented in the case of the Canadian Horn River shale by Edwards et al. (Edwards et al. 2017). Warner (Warner et al. 2012) defended the findings of their original paper that the shales can indeed transmit groundwater over long vertical distances, even if the timescales are often very long (thousands or millions of years). If we apply the precautionary principle, we should still take into account evidence of natural flow pathways when planning shale gas developments: generalizations such as 'gas shales are dry and imbibe fluids' oversimplify the complexity of natural hydrogeological systems.

Multiple reviews and inquiries recommended undertaking integrity testing of wells before, during, and after hydraulic fracture stimulation, (for example, (Hawke 2014; New Brunswick Commission on Hydraulic Fracturing 2016; Parliament of Victoria Legislative Council Environment and Planning Committee 2015; U.S. Environmental Protection Agency 2016)).

To further minimise the risks from unintended hydraulic fracture stimulation outcomes, anomalies such as fault and pre-existing fracture intersections should be avoided:

- The probability of an adverse event from intersecting a fault or from hitting an existing well should be low;
- The consequences of leakage resulting from a hydraulic fracture encountering a fault below the seismic resolution should be low;
- There should be a suitable distance to known or suspected hydrogeologically significant faults; and
- If the geophysical imaging and subsurface knowledge based on well density are insufficient to be able to reduce the probability of an anomalous event to a low level then either that region should be avoided, or additional data should be collected.

In certain areas, the residual risk of adverse events may be unacceptable owing to hydrologically significant faults, marginal capacity for vertical fracture containment, too much complexity or poor geophysical imaging such that geomechanical prediction is impossible.

A 'frac hit', according to King et al. (King, Rainbolt & Swanson 2017a) is a 'fracture initiated well to well communication event that occurs when frac energy from a simulated well extends into the drainage area or directly contacts an adjacent or offset well'. While affecting only a small proportion of wells, 'frac hits' are seen as an increasing problem in several areas of most intense unconventional oil and gas production (Jacobs 2017a, 2017b). The consequences of a 'frac hit' are usually restricted to economic impacts on well productivity. However, potentially uncontrolled pressures and flows could occur in the hit well, resulting in material damage or fluid leakage, and therefore steps must be taken to avoid these occurrences, or at least limit inter-well connections to the intended zone of fracture stimulation within the productive zone of the target formation (King, Rainbolt & Swanson 2017b; Rainbolt & Esco 2018).

While the various circumstances leading to undesired frac hits - such as close well spacing, multiple companies operating simultaneously in small adjacent exploration blocks, or old wells that may be poorly located or undocumented - are unlikely to arise in Western Australia, the issue should still be a managed risk. The causes and consequences of frac hits are now fairly well known from experiences in areas such as the Barnett and Wolfcamp Shale in the United States, so industry best practices should be formalised in Western Australia and adequately regulated so as to limit the adverse consequences of unplanned inter-well connections.

A hydraulic fracture may intersect a fault (see **Section 6.12** and **Section 6.12.1**), and again the consequences will depend on a number of factors. In the worst case, the fault could be 'hydrogeologically significant' and provide a flow pathway towards the surface or to a

potable water aquifer. Such faults would be large and detectable by adequate geophysical imaging. Small faults may be imaged by seismic data but not be seen as significant, or else may be below seismic imaging resolution. Typically, if a well or fracture hits such a fault then the consequences will not extend far, but even so, the risk of an adverse event is increased, and therefore steps should be taken to mitigate any consequences (stop drilling or pumping, if necessary reset casing, deviate the well, or abandon the well). If large quantities of fluid enter the region of a fault that is critically stressed, then movement along that fault may be induced (see **Section 6.12.3**).

The hydraulic fracturing fluid itself is a focus of concern as a potential risk to the environment and especially to people (Department of Health 2015; Krupnick, Gordon & Olmstead 2013; Liroff 2011). The fracturing fluid is predominantly water (98 to 99 percent of total volume) and proppant (one to two percent) plus an amount of other chemicals (0.1-0.5 percent), the latter added to improve fluid flow, improve stimulation performance, prevent corrosion and stop the growth of bacteria (Cook et al. 2013). Other sources identify the range of proppant to be between five and 25 percent of the total fluid volume (Department of Health 2015; Department of Mines and Petroleum 2015a, 2015b). The proppants are inert particles for keeping the fractures open, most commonly silica sand or engineered ceramic beads.

The amount of water used in a hydraulic fracture treatment depends on the type of fracture, with three to four times more water being used for slickwater fractures than gel placement, according to (Pearson et al. 2013).

The specific chemical compounds used in a particular fracturing operation will vary with company preferences, source water quality and site-specific characteristics of the target formation. In more permeable rock formations, hydraulic fracture stimulation is used to improve the flow to the well in a region extending a few tens of metres, and a more viscous drilling fluid based on natural or artificial polymer gels may be used. Thicker fracturing fluid can carry more proppant load. In shale formations, by far the most common fracturing fluid used at the present time is slickwater, which contains a much smaller amount of viscosifier added to reduce the frictional losses of flow in the tubing of the well itself. The proppant loading for slickwater is a smaller percentage of the total fluid, and a high rate of flow is used to carry the proppant grains into and along the created fracture network. The Inquiry notes the development of novel fracturing fluids that may or may not pose lower risks to the environment or people, including non-aqueous fluids (Gupta 2009; Middleton et al. 2015).

Table 6.3: Hydraulic fracture fluid types

Type	Volume of Water required	Use
Slickwater Proppant entrained by high velocity of fluid	Volume: ~40,000 litres per metre of completion. ~98% water, main additive is friction reducer	Used for large multi-stage fracturing in shales.
Gel Carries proppant owing to high viscosity	Volume: ~12,000 litres per metre of completion, >90% water. Main additive is viscosity enhancer	Used for shorter fractures in strong rocks/high stress, for example, in tight sands.
Non-aqueous or foam Ineffective for carrying large proppant volumes	No water, for example, CO2 or nitrogen	Special use where formation is sensitive to water. Not widely used, requires source of non-aqueous fluid

A list of the chemicals used in hydraulic fracture stimulation in recent times in Western Australia is in **Appendix 11**; the assessment of the potential risks they pose to the environment including people is in **Section 8** (Land), **Section 9** (Water), **Section 11** (Public Health) and **Section 12** (Social surroundings).

Emerging best practice is that all chemicals used in hydraulic fracturing fluid should be publicly disclosed and many jurisdictions stipulate this via regulations. Many types of chemicals are no longer permitted for this use. Major reviews and inquiries to date have drawn some broad common conclusions about this issue and it was a feature for any future regulation in submissions to this Inquiry:

- Requiring public disclosure of the composition of hydraulic fracturing fluids, for example (Hawke 2014; Kibble et al. 2014; Parliament of Victoria Legislative Council Environment and Planning Committee 2015; UK House of Commons Environmental Audit Committee 2015; Western Australia Legislative Council Standing Committee on Environment and Public Affairs 2015) or disclosure to regulators with access arrangements for health professionals, for example (Maryland Department of the Environment and Maryland Department of Natural Resources 2014, 2015; Newfoundland and Labrador Hydraulic Fracturing Review Panel 2016); and
- Minimising chemical use and using chemicals with no or low risk of health impacts, for example (American Chemical Society 2016; Hawke 2014; New Brunswick

Commission on Hydraulic Fracturing 2016); and banning high risk chemicals, such as Benzene, Toluene, Ethylbenzene and Xylene (BTEX), for example (California Council on Science and Technology 2015a; Hawke 2014; Western Australia Legislative Council Standing Committee on Environment and Public Affairs 2015).

For shale gas developments, the likelihood is that in the foreseeable future the majority of fracturing operations will use slickwater formulations that contain friction reducers as the main constituents, together with small quantities of biocides and corrosion inhibitors. Therefore, only a small subset of permitted chemicals is likely to be used in future hydraulic fracture stimulation operations.

6.9.4 Operational phase

The operational phase defines the requirements or recommendations and methods for managing well integrity during operation. A shale or tight gas well may be expected to produce gas for many years (Huddlestone-Holmes et al. 2017) and over that time it is standard practice to monitor the well's ongoing integrity and performance, with concomitant maintenance.

6.9.5 Intervention

The intervention phase (including work-over) defines the minimum requirements or recommendations for assessing well barriers prior to, and after, any well intervention that involves breaking the established well barrier containment system. Where monitoring indicates any lack of pressure containment or decline in flow, wells may be subject to further fracture stimulation or repair.

6.9.6 Decommissioning

The abandonment phase defines the requirements or recommendations for permanently abandoning a well. At the end of a well's productive life it is decommissioned, plugged, marked and then abandoned. The goal is to plug the well to ensure well integrity in perpetuity (International Association of Oil and Gas Producers 2015; International Standards Organisation 2017; Kiran et al. 2017). This includes forever preventing the release of formation fluids (for example, hydrocarbons and associated water) into the environment (particularly into fresh aquifers and surface waters), preventing the flow of fluids between different rock layers, and isolating any potentially hazardous material in the well.

Following Wu et al. (Wu et al. 2016), the potential leakage pathways for abandoned wells include:

- Interfaces between cement and casing, and between cement and formation due to well stress and pressure cycles during well-life operation;
- Within the cement sheath due to poor quality, fractured or degraded cement sheath;

- Across the casing due to corroded casing or fluid flow through casing connections; and
- Mixing of water from alluvial, confined and production zone aquifers in wellbores re-purposed for water extraction.

Wu et al. (Wu et al. 2016) note that occurrence of the above failure mechanisms for a particular well does not necessarily lead to lost integrity of the well, that is, a hydrological or environmental breach. This would depend on the extent of the failure mechanisms along the well and specific geological conditions.

There is, worldwide, an historic legacy of abandoned wells not properly decommissioned and plugged, with resultant pollutions of groundwater. Most of these wells predate the use of hydraulic fracture stimulation and were a feature of poor regulation and practice. Failure rates of well barriers constructed in a specific time period are reflective of the construction standards of that era and in that jurisdiction; they are not identical to failure rates of wells designed and completed later (King & King 2013). Western Australian petroleum legislation has defined procedures and responsibilities for the plugging and abandonment (decommissioning) of petroleum wells to isolate the subsurface formation for long term environmental protection. The intent of all decommissioning operations is to achieve the following:

- Isolate and protect all fresh water zones from ingress and egress from surface and subsurface;
- Isolate all hydrocarbon bearing zones;
- Prevent in perpetuity leaks from or into the well; and
- Remove surface structures so that the landform can be rehabilitated back to its former use (Department of Mines, Industry Regulation and Safety 2017a).

The performance of an abandoned well to continue to contain potential leakage of fluids or mixing of formation fluids between rock layers depends on the very same criteria for operational well integrity: effective containment by the casings and cement layers of the well (including the cement plug), and between the well and surrounding rock.

Because of the very long-term requirements for the cement plug to remain effective, studies of the projected effectiveness of cements in that regard have focused on relatively harsh (acidic) geochemical environments such as those with high CO_2 or hydrogen sulphide (Cao, Karpyn & Li 2013; Carroll et al. 2016; Jacquemet et al. 2012; Satoh et al. 2013). These laboratory and numerical geochemical modelling studies show limited alteration of the cement. No studies were available on the long-term durability of the cements used to plug wells in shale in Australia, noting that Huddlestone-Holmes et al. (Huddlestone-Holmes et al. 2017) concluded that the geochemical conditions of the aforementioned studies are much

more corrosive than found in a shale gas basin, with methane under pressure less corrosive than carbon dioxide (Popoola et al. 2013).

6.10 Well integrity

No single aspect of hydraulic fracture stimulation for developing unconventional oil and gas resources is more central to technical and community concerns that the integrity of the wells. It is the possibility of well integrity failures and associated pollution of the environment that underpins the preponderance of real and perceived risk to the environment and people.

In considering the issue of well integrity and its implications, the Inquiry greatly benefited from a CSIRO report (Huddlestone-Holmes et al. 2017), originally commissioned by the recent Scientific Inquiry into Hydraulic Fracturing in the Northern Territory. This Inquiry confirmed that the technical review of well integrity in that report remained current for consideration by the Panel. The Panel complemented that information with independent evaluation of extensive literature on conventional and unconventional oil and gas well integrity through published reviews by (Davies et al. 2014; International Standards Organisation 2017; Jackson 2014; Jackson et al. 2013; King & King 2013; Kiran et al. 2017; Wu et al. 2016).

6.10.1 Well integrity - definitions

It became apparent through the review of previous inquiries as well as through the submissions and consultation for this Inquiry, that in discussions of well integrity, confusion arises in the language used to describe the environmental and technical performance of oil and gas wells. Others have previously identified this challenge in communication and understanding, for example (Jackson 2014; King 2012; King & King 2013; Western Australia Legislative Council Standing Committee on Environment and Public Affairs 2015).

This Report is strict and mindful in the use of the following definitions in particular:

- Well integrity – maintaining the full control of fluids within a well at all times by employing and maintaining one or more well barriers to prevent unintended fluid movement between formations with different pressure regimes or loss of containment to the environment (International Organization for Standardization 2017).
- Well barriers – a system of one to several well barrier elements that contain fluids within a well to prevent the uncontrolled flow of fluids within or out of the well (International Organization for Standardization 2017).
- Barrier failure – when a single, specific barrier fails to contain fluids (remaining barriers maintaining containment).

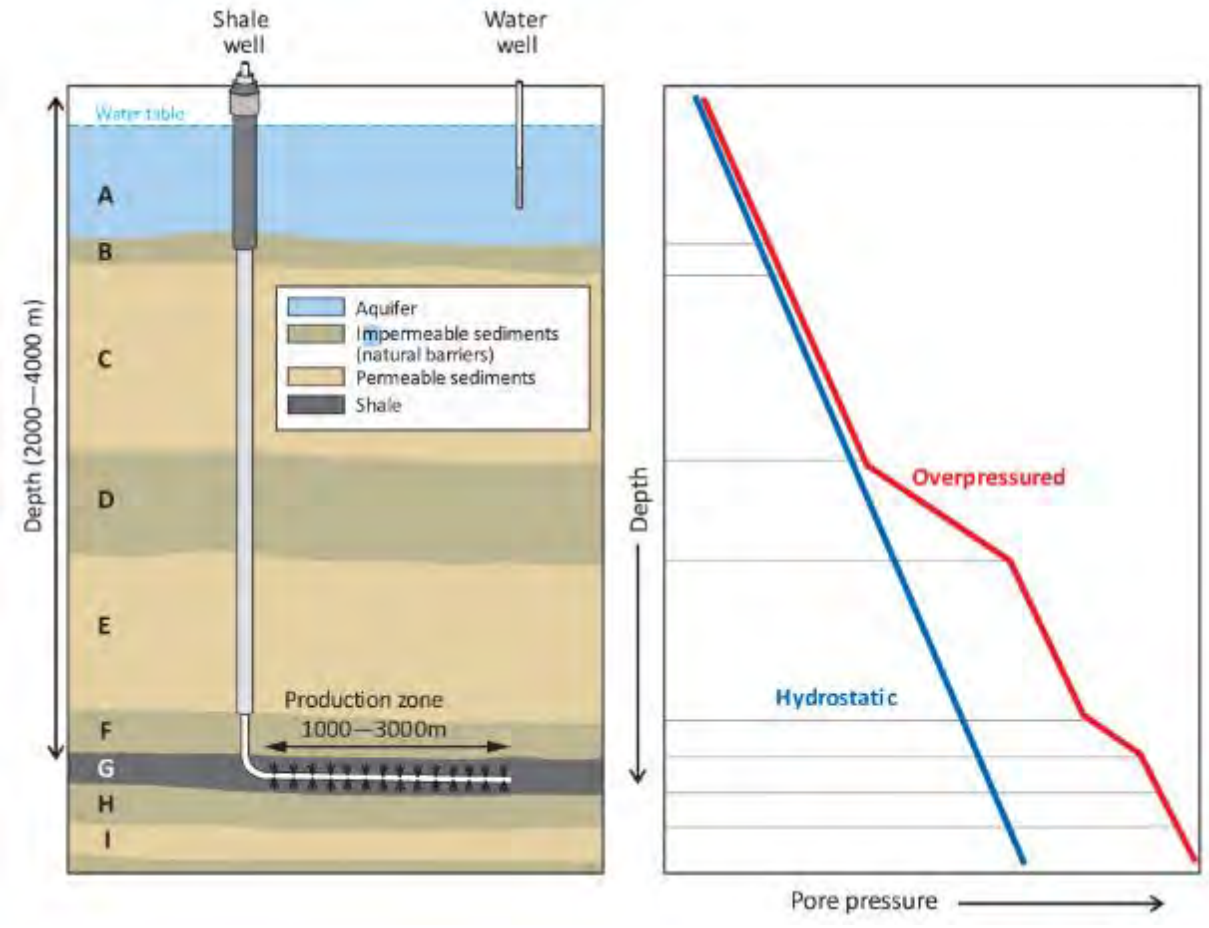
- Well integrity failure – when all barriers have failed and there is a pathway for fluid to flow in or out of the well.

In the context of this Report (and in a strict technical context), the term 'fluids' extends to both the liquids and gases under consideration.

Thus, the Report uses the term 'well integrity failure' only when a barrier (or set of barriers) fails to prevent a leakage pathway to the external environment. Not all issues of well integrity incidents result in such a failure. This is similar to the protocol used by the Standing Committee (Western Australia Legislative Council Standing Committee on Environment and Public Affairs 2015).

Consideration of well integrity and associated risk of leakage is underpinned by an understanding of the processes that drive fluids into or out of the well itself or through the surrounding rock. To facilitate this understanding, we reproduce below an explanatory figure and description from Huddlestone-Holmes et al. (Huddlestone-Holmes et al. 2017).

Figure 6.14: Layers A-F are overburden rocks of different types that could be permeable (and potentially filled with fresh or saline water) or impermeable (providing a barrier to fluid movement)
Source: Huddlestone-Holmes et al. (Huddlestone-Holmes et al. 2017). Not drawn to scale



In this example, layer D is a rock layer impermeable to fluid movement. The accompanying graph shows that pore pressures in all of the rock layers generally increase with depth. Where this pore pressure at a given depth is greater than the hydrostatic pressure (the weight of fluids above), then this creates the potential to force fluids upwards unless there is an impermeable layer to contain it. This is termed 'overpressure'. It creates the potential to force fluids up through fractures in the layers above, or wells with failed integrity.

High fluid overpressures in a rock layer penetrated by a well is a significant contributor to well integrity. While the shale formation itself contains gas at higher than hydrostatic pressure in order to produce to the well, overpressured formations are not common in the rock formations overlying unconventional oil and gas resources, as they are typically associated with rapidly subsiding offshore basins or basins loaded by nearby mountain ranges. Even in the absence of overpressure in the formation, natural gas (predominantly methane) is both more buoyant and less viscous than water, and is thus more likely to move vertically through any available pathways, natural or otherwise, towards the surface. The pathway potentially presented by a well with failed integrity will depend on the size and continuity of the breach. If a pathway from the target (stimulated) formation extends to the surface (for instance, resulting from poorly-constructed or damaged cement sheath between the outer casing and the surrounding rock), then formation fluids (particularly gas due to its buoyancy and low viscosity) may escape into the wider environment. In summary, well integrity is crucial to ensure a pathway is not created through which fluids, including gas, can travel upwards into protected formations (for example, water supply aquifers) or to the surface and atmosphere.

The design, construction, operation and abandonment of wells, their role in maintaining well integrity, and the various leakage pathways that can develop, have already been described previously. In this regard, there is little to necessarily differentiate risk between wells drilled for conventional oil and gas resources and those drilled for unconventional oil and gas. What does need consideration is the potential for the hydraulic fracture stimulation to induce a loss in well integrity if the containment barriers cannot withstand the stresses. Well performance is monitored during fracturing, and so there is some experience in the literature with this risk. A well integrity failure resulting from fracture stimulations was reported for the Franchuk 44-20 SWH well in North Dakota (U.S. Environmental Protection Agency 2015a). A submission by the Australian Department of Primary Industry and Resources to the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory, referred to a well shallow casing failure (barrier failure) during a hydraulic fracture stimulation in 2012, but because the well (the Baldwin 2HST-a) had multiple casings, the shallow aquifer was apparently protected. The well was subsequently abandoned.

6.10.2 Historical well integrity performance

The question then becomes, 'what have been the historic and recent well integrity failure rates relevant to this Inquiry?'

Previous inquiries and reports on unconventional gas and hydraulic fracture stimulation have investigated well integrity track records and reported failure rates. In work commissioned for the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory, CSIRO gathered statistics from available publications and open source records in Australia and around the world (Huddlestone-Holmes et al. 2017; Wu et al. 2016). In general, these records compile incidents reported for all oil and gas wells in a geographical area without regard for whether they were for conventional or unconventional resources, or whether hydraulic fracture stimulation was undertaken. Several of the information sources cite incidents of groundwater contamination, including surface spills and transportation operations, as well as well failures within the overall numbers. Therefore, extracting the historical rates of barrier and well integrity failures is difficult. Moreover, the reports often compile data over long periods of time (one or more decades) such that events arising from older and discontinued practices influence the statistics. Even given these uncertainties, it is clear that well barrier failures do occur but that the number of documented cases of loss of well integrity resulting in leakage to the surface is limited.

The U.S. EPA reviewed data from approximately 1,200 sources and citations on the environmental performance of hydraulically stimulated (fractured) wells, and concluded that there were no demonstrated cases of drinking water contamination resulting from fracturing at depth, but there was evidence of contamination of aquifers as a result of well integrity failure. While unconventional oil and gas wells subjected to hydraulic fracture stimulation are subjected to higher stresses during the well stimulation operations, this may reflect that the design criteria for well integrity are correspondingly higher. A review of well integrity written from the point of view of the oil and gas industry interprets essentially the same data sources cited above from Pennsylvania, Texas, Ohio and Colorado to conclude that older generation oil and gas wells have leak rates from 0.02 percent (2 in 10,000), whereas newer generation horizontal wells have leaks rates in the range 0.004-0.006 percent (4 to 6 in 100,000), as explained by King and Durham (Schug & Hildenbrand 2017).

King and King (King & King 2013) examined reviews and reports covering some 600,000 conventional and unconventional gas wells worldwide and concluded that individual well barrier failures (where containment was maintained) range up to a few percent of wells, while well integrity failure (leaks to the environment) are very rare. For example, wells constructed in Ohio and Texas between 1983 and 2008 had a barrier failure rate of 0.035 to 0.1 percent (3.5 in 10,000 to 1 in 1,000), but with leakage to the environment (loss of containment) in around 10 percent (1 in 10,000) of those cases.

Davies et al. (Davies et al. 2014) conducted a metastudy of well barrier and well integrity failure rates compiled from international data. The dataset included wells drilled for conventional and unconventional oil and gas, and for CO_2 storage, both onshore and offshore. The study found an enormous range of failure or potential failure rates (1.9 to 75 percent) owing mostly to the extended age range of the study, which encompassed legacy wells drilled decades before current international best practices were established.

The pertinent data is therefore from more recently drilled wells for unconventional oil and gas exploitation, at depths and in geological conditions comparable to those likely to be encountered in Western Australia. For unconventional onshore wells drilled in the Marcellus Shale in the United States, between 2008 and 2013, the well barrier leakage rate (data from (Vidic et al. 2013)) was reported as around 3.4 percent. Ingraffea et al. (Ingraffea et al. 2014) reviewed compliance reports for casing and cement impairment for conventional and unconventional wells in Pennsylvania, and found a higher rate of such incidents (up to 9.1 percent) in shale gas wells but also large differences in incident rates across different regions, but could not differentiate results with respect to higher inspection rates from real changes in construction competency. Considine et al. (Considine et al. 2013) found notifiable events related to actual or potential leakage in 2.6 percent of wells in Pennsylvania, whereas other authors studying essentially the same original data sources identified rates of 'well barrier issues' from 3.4 percent to 7.6 percent. The documented well integrity failure rates from these studies, that is, statistics related to notifiable and reported well blow-outs or release to the surface or to groundwater, ranged from zero (four cases) up to 1.27 percent.

In Australia, Cooke (Cooke 2012) found no evidence for hydraulic fracture stimulation fluid movement into surface aquifers following more than 1,300 fracture stimulations in the Cooper Basin in South Australia. Patel, Webster and Jonasson (Patel, Webster & Jonasson 2015) reviewed 1,035 of the approximately 1,060 oil and gas wells in Western Australia that had not yet been decommissioned (both onshore and in State waters), and found 122 of them (about 12 percent) to have had some form of failure. The majority (8.3 percent) were tubing failures that did not imply a loss of containment to the environment, but 22 wells (two percent) had casing failures, with the primary cause being corrosion. A further 14 wells (one percent) had failure of the above-ground assembly of valves and fittings (the 'Christmas tree'). The authors reported that none of the 122 failures resulted in any leakage to the environment, including any methane emissions, but it was not stated how this was determined or if it was only inferred. The authors concluded that failure rates were like those experienced overseas: they increased with age, noting the oldest wells in the study were 60 years old. They also concluded that plugged and abandoned wells, upon decommissioning, must be expected to maintain containment indefinitely (thousands of years) and there is no data available in Western Australia on the long-term performance of

decommissioned wells. Western Australia has no research or monitoring program aimed at ensuring the long-term containment of decommissioned oil and gas wells.

The available publications illustrate that barrier and well failures do occur, but instances of loss of well integrity (that is, failure of multiple barriers) resulting in leakage or in blow-outs are very rare, with many basins having no incidents reported to authorities. The geological conditions of stress and formation pressure, and the presence of corrosive formation fluids play a role in well integrity risk and need to be mitigated. The most important factor in overall well integrity risk appears to be the engineering design, specifically, sufficient number and quality of barriers. Documented cases of groundwater contamination resulting from well integrity failure are few, and linking potential contamination to potential harm is contentious when many of the reported cases involve the leakage of methane (as opposed to hydraulic fracturing fluids), which is not toxic under normal circumstances but has consequences for climate (see **Section 10** (Greenhouse gas)).

6.11 Water use and quality

As previously stated in this Report, perhaps no concern is more widely held with respect to developing unconventional oil and gas resources with hydraulic fracture stimulation than that regarding the supply and protection of water resources. In the first instance, these concerns revolve around ensuring that the flow and availability of water for uses like agriculture and public water supplies, and to aquatic ecosystems are not adversely affected.

Constructing wells, and then hydraulically stimulating fractures, uses water. For the Canning Basin and the Perth Basin, the questions are how much water future wells are likely to use, for how long, where that water comes from and will that amount to a significant draw upon the resource. A detailed consideration of these questions is in **Section 9** (Water) of this Report. Here we will generalise, as best is possible, about the volumes of water likely to be required in the Western Australian context.

Again, we note that the present approach to oil and gas wells subject to hydraulic fracture stimulation - single vertical wells requiring less than 10 fracturing stages - may not be the future approach, which is likely to be more like multiple horizontal wells with laterals as long as one to three kilometres, each receiving as many as 40 stimulations along their length. This implies a potential large variation in project total water demand for a region. ACOLA (Cook et al. 2013) approximated typical water use at one to two megalitres (ML) for well construction and about the same for each hydraulic fracture stimulation. On that basis, the current approach to stimulated wells might use five to 20 ML of water to establish. In addition to the water used to establish the wells, a multi-well site with six wells each requiring 20 fracture stimulations would use the following amount of water:

- 6 wells x 20 stimulations @ 1ML each = 120 ML; or
- 6 wells x 20 stimulations @ 2ML each = 240 ML.

Whether these volumes of water could be significant even over the short term of their use depends on the source, its environmental sustainable allocation limits and the degree to which it is already allocated.

To date, water for onshore gas development in Western Australia has come from local aquifers under licence from the Department of Water and Environmental Regulation (DWER), noting that there is no need for such water to be fresh (potable) and that often there are local saline or brackish sources in both the Canning Basin and the Perth Basin with little or no potential for other beneficial uses and no significance to aquatic ecosystems. Further consideration of the likely volumes of water needed, their potential sources and availabilities are in **Section 9** (Water) of this Report.

6.11.1 Wastewater production and potential composition

Constructing and stimulating a well produces wastewater. The need for, and disposal of, the wastewater associated with drilling mud was previously covered above. And like any conventional gas well, development will bring up formation water over the whole lifetime of operation (production water); this water is collected and treated at the surface. Of particular concern to this Inquiry is the volume and quality of the wastewater returned to the surface in the period immediately following hydraulic fracture stimulation (flowback water) and its subsequent containment and treatment.

At the completion of the final stage of fracturing, the rate of flowback water produced by the well can be as much as 1,000 litres per minute for a few hours, dropping off to a fraction of that amount over the next few days, with continual decrease over subsequent weeks and typically little flowback after about four to six weeks (King 2012). Of the fluid injected, typically 10 to 30 percent of the initial volume (but with reports as low as four percent and as high as 50 percent) flows back to the well and ultimately to the surface for treatment and disposal (King 2012; Kondash, Albright & Vengosh 2017; U.S. Environmental Protection Agency 2016). Most shales are 'under-saturated' with respect to water and will trap (imbibe) fluid (Birdsell, Rajaram & Lackey 2015), perhaps indefinitely unless displaced by gas pressure (King 2012). The ultimate degree that fluids could migrate away from the fracturing zone (if at all) has been a contentious issue for the Marcellus Shale (Engelder 2012; Warner et al. 2012). The scientific consensus at best suggests it is 'possible'.

Flowback water is usually temporarily stored either in tanks or lined ponds for potential re-use but ultimately conveyed to an evaporation pond and/or wastewater treatment plant ahead of final disposal.

6.11.2 Composition of flowback and produced water

Initially, much of this flowback wastewater is the fluid used for stimulation but it subsequently transitions to background formation water, which in the case of shales is often saline. The composition of the fluids potentially used in Western Australia for hydraulic fracture stimulation is described in **Appendix 11**. Because most the gas-bearing shales in Western Australia are generally of marine origin, their formation waters are generally very saline (> 50,000 parts per million of dissolved solids). As the flowback water transitions to produced wastewater, the composition changes to that of the formation including geogenic chemicals (those that occur in the shale itself). In addition to marine salts, these geogenic chemicals can include metals and metalloids, hydrocarbons, and other organic compounds, and Naturally Occurring Radioactive Material (NORM). A far greater variety of chemicals appear in production water compared to the hydraulic fracture stimulation fluid (U.S. Environmental Protection Agency 2015b). Geogenic chemicals potentially present include VOCs such as toluene, benzene, ethylbenzene, xylene, phthalates and polycyclic aromatics (Butkovskyi et al. 2017; Kahrilas et al. 2016).

The laboratory results of the fluid from the Asgard 1 and Valhalla North 1 flowback ponds pre and post flowback are available in **Appendix 12**.

The radiological results of flowback fluid from the Asgard 1 and Valhalla North 1 wells and flowback ponds are available in **Appendix 13**.

6.11.3 Management of wastewater

Wastewater must be stored for at least a time in either sealed tanks or in ponds. The latter are normally open ponds lined with impermeable membranes, and often the primary treatment is simply evaporation and then the subsequent solid waste (and ultimately, the liner) is disposed of in a suitable licensed waste facility (Department of Mines and Petroleum 2016b). Wastewater treatment may involve additional technologies and processes (Akob et al. 2016; Fakhru'l-Razi et al. 2009).

Figure 6.15: Photograph of a frack pond at the Warro 6 site, Western Australia
Source: DMIRS

An alternative to evaporation and disposal of wastewater is to treat and reuse wastewater, generally for subsequent batches of fracturing fluid (reinjection). This practice has the dual benefit of reducing the amount of water ultimately to be disposed of by other means and reducing the demand for additional water from the environment. The opportunity for reuse may be constrained by the quality of the wastewater with respect to the required performance of the fracturing fluid (Lira-Barragán et al. 2016).

Given the high salinities of shale gas wastewater expected in Western Australia, regardless of the chemical composition, it is unlikely that there will be many re-use opportunities beyond use for subsequent fracture stimulations.

Discharge of oil and gas well wastewater into the surface environment, treated or untreated, is not permitted in Western Australia.

6.11.4 Monitoring and management of chemicals and wastewater on a well site

The recovery, storage, treatment and transport of wastewater from shale gas well development and production poses a significant potential pathway for environmental pollution with both hydraulic fluid and formation water. In their review of impacts on

drinking water sources, the U.S. EPA (U.S. Environmental Protection Agency 2016) found evidence of contamination by spills of fracturing fluids or flowback water, either through spills directly into surface water systems or through seepage into and through the soil. Most such spills are associated with failures in storage tanks or pits, or in the transport of wastewaters, particularly in the first few years of production (Patterson et al. 2017).

The list of reportable spills from 1 July 2012 to present for Western Australian operations involving hydraulic fracture stimulation is available in **Appendix 10**. Reportable spills are defined in section 3.8.3.1 of the Guideline for the Development of Petroleum and Geothermal Environment Plans in Western Australia, and are subject to the *Petroleum and Geothermal Energy Resources (Environment) Regulations 2012.*

6.12 Seismicity, fault movements and land subsidence

Increased seismicity (earthquakes) over background levels has been associated with unconventional oil and gas development overseas. The topic of seismicity related to hydraulic fracture stimulation has been reviewed recently by Geoscience Australia (Drummond 2016).

Earthquakes happen when geological faults move rapidly, releasing elastic strain energy stored in the surrounding rocks. The necessary conditions for an earthquake to occur are:

- Presence of a fault, faults or zones of weakness in brittle rocks in the subsurface at sufficient depth to be under appreciable stress;
- Stress conditions in the Earth that are close to the critical stress level needed to move the fault;
- An event (natural or man-made) that changes the pressures and stresses in such a way that the remaining resistance to slip is overcome and the fault moves; and
- Release of energy that is rapid and not immediately dissipated, such that a sudden increment of rapid slip occurs on that fault plane that results in the radiation of vibrations (earthquake waves) away from the zone where slip occurred.

Earthquakes cannot occur in rocks that are too shallow or not under significant unbalanced stresses. They are rare in the absence of pre-existing faults or zones of weakness in which a new fault can nucleate and grow, as the shear stresses required to break intact rock are relatively higher.

An earthquake is usually taken to mean a movement of the Earth that is large enough to be felt, that is, with significant ground acceleration or intensity of shaking. Elastic strain energy is also released in smaller movements termed microseismicity that may involve slip on pre-existing faults, or the generation of new faults and fractures. The intensity of shaking felt at a particular place on the ground is measured using a Modified Mercalli (MM) scale. It depends on the distance to, and depth of, the fault that moved, and also the nature of the

subsoil. The intrinsic size of earthquakes is measured on a moment magnitude scale (Mw), similar to the Richter scale (being logarithmic, or increasing on powers of 10) but modified to more accurately define the energy release associated with the movement of mass and drop in stresses accompanying the event. Having a logarithmic scale means that very small seismic events detected only by instruments can have negative magnitudes.

Felt seismicity originates from earthquakes with moment magnitudes of around two or greater, whereas micro-seismicity extends down to levels of minus one to minus three. As each unit of magnitude increase implies a ~32 times increase in released energy (two steps on the moment scale corresponds to exactly 1,000 times increase in energy released), the difference in potential effects is very important to understand (**Table 6.4**).

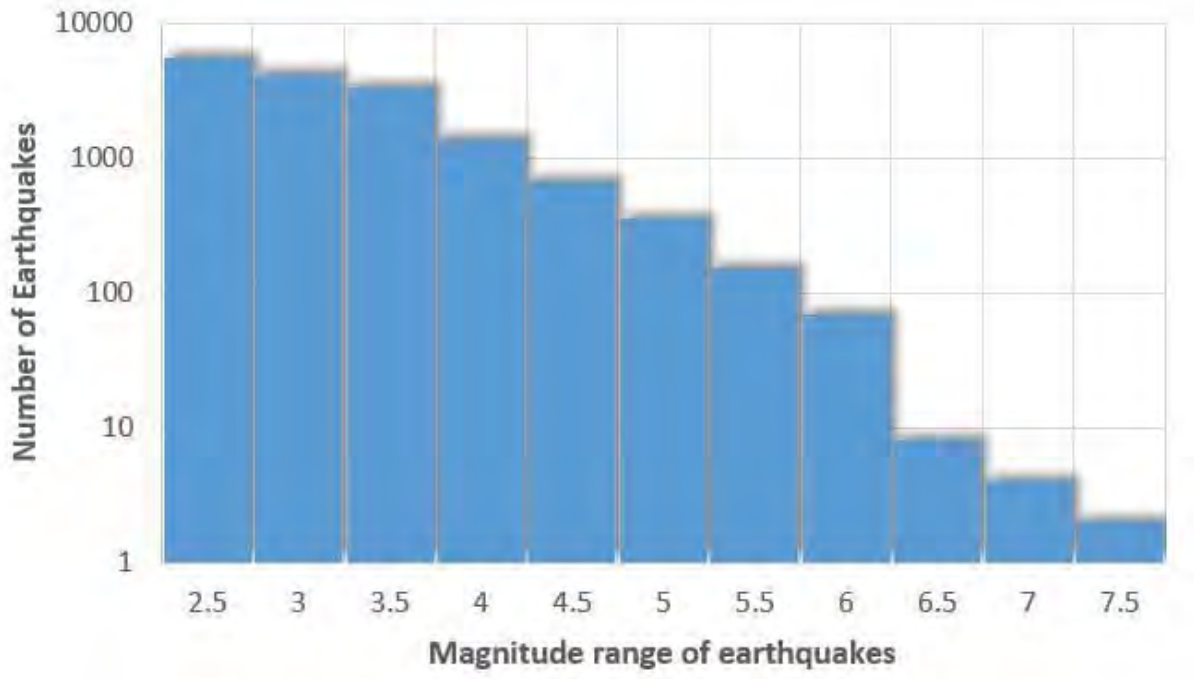
Table 6.4: Characterisation of earthquakes and their frequency of occurrence worldwide

Moment magnitude Mw	Category of earthquake	Length of fault rupture	Frequency of occurrence	Consequence	Modified Mercalli scale
-4 to 0	Microseismic	<m	Millions daily	Detected with local receivers only	-
0-2	Instrumental	Few to 10 m	Hundreds of thousands daily	Detected with global seismometer arrays	I-II
2-3	Very minor	10s-100s m	Thousands daily	Damage unlikely	II-IV
3-4	Minor	Up to a few km	Hundreds daily	Minor structural damage	IV-V
4-5	Light	Up to 10s km	Tens daily	Damage possible	VI-VII
5-6	Moderate	Low 10s km	Daily to weekly	Often damaging	VII-VIII
6-7	Strong	High 10s km	A few per week	Moderate to major destruction	VIII-IX
7-8	Major	Up to 100s km	Months to years	Major destruction likely, possible tsunamis	X+
8-9+	Great	Up to 1000s km	Years to Decades	Major to catastrophic destruction, tsunamis common	XI-XII

Drummond (Drummond 2016) provides a more detailed explanation of earthquake origins and the scales used for measuring intensity at the surface, and intrinsic magnitude in Australia. See also http://www.ga.gov.au/scientific-topics/hazards/earthquake.

The distribution of earthquakes shows that there are many more small tremors than large, destructive quakes and the distribution decreases approximately in a logarithmic manner. Though in Australia the number of large events greater than Magnitude 6.0 is smaller than this trend overall.

Figure 6.16: Frequency of earthquakes of varying magnitude in Australia since 1960
Source: Geoscience Australia (http://earthquakes.ga.gov.au/



6.12.1 Stresses in the earth

The forces in the Earth that ultimately give rise to earthquakes arise mainly at the plate boundaries. Ridges, where new oceanic crust is created give rise to large horizontal compressional forces, where plates sink in subduction zones the horizontal stresses can be much lower. Mountain ranges give rise to compressional stresses as gravitational forces tend to spread outwards and they may also mark zones of plate collision.

Within a sedimentary basin, the stresses may vary owing to contributions from plate boundary forces, mountain ranges gravitational subsidence, and at a more local scale from the influence of nearby faults.

Figure 6.17: Forces controlling the present-day tectonic stress field at the 'primary' plate-scale (large blue arrows) and 'secondary' broad regional scales (small blue arrows).
Source: Tingay et al. modified from Zoback (Tingay et al. 2006; Zoback 1992)

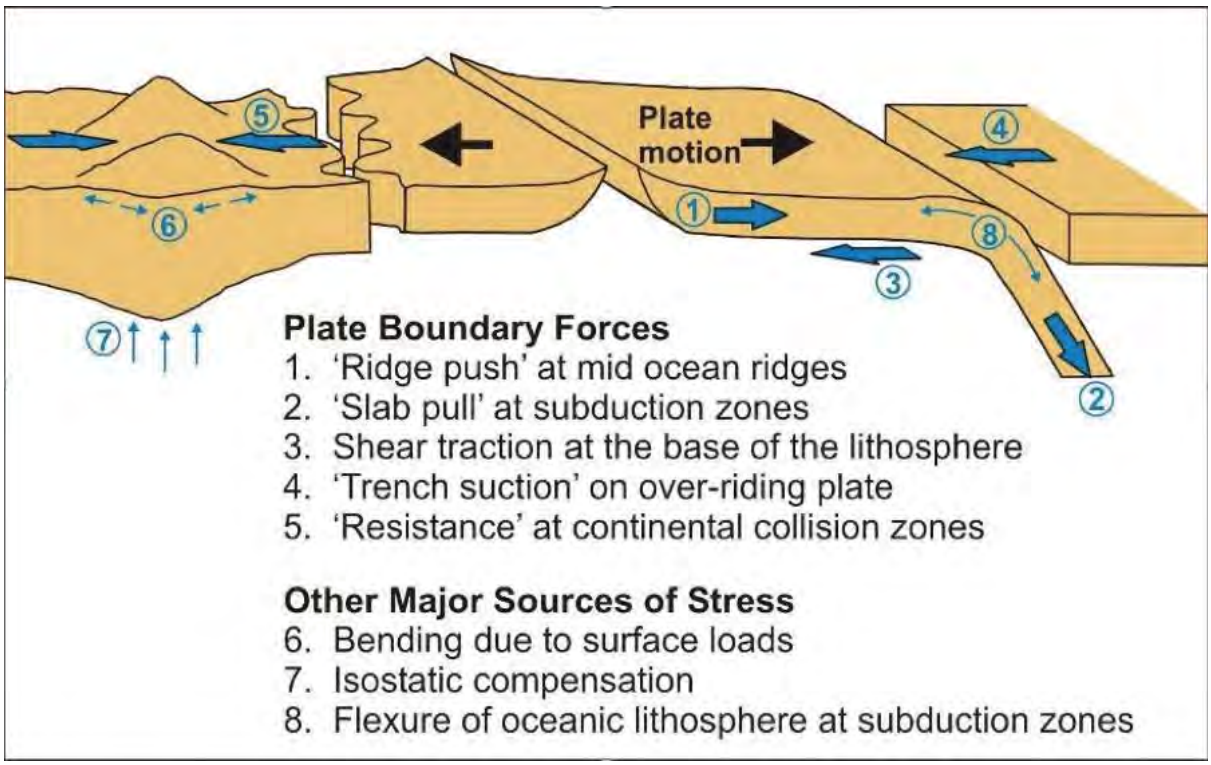
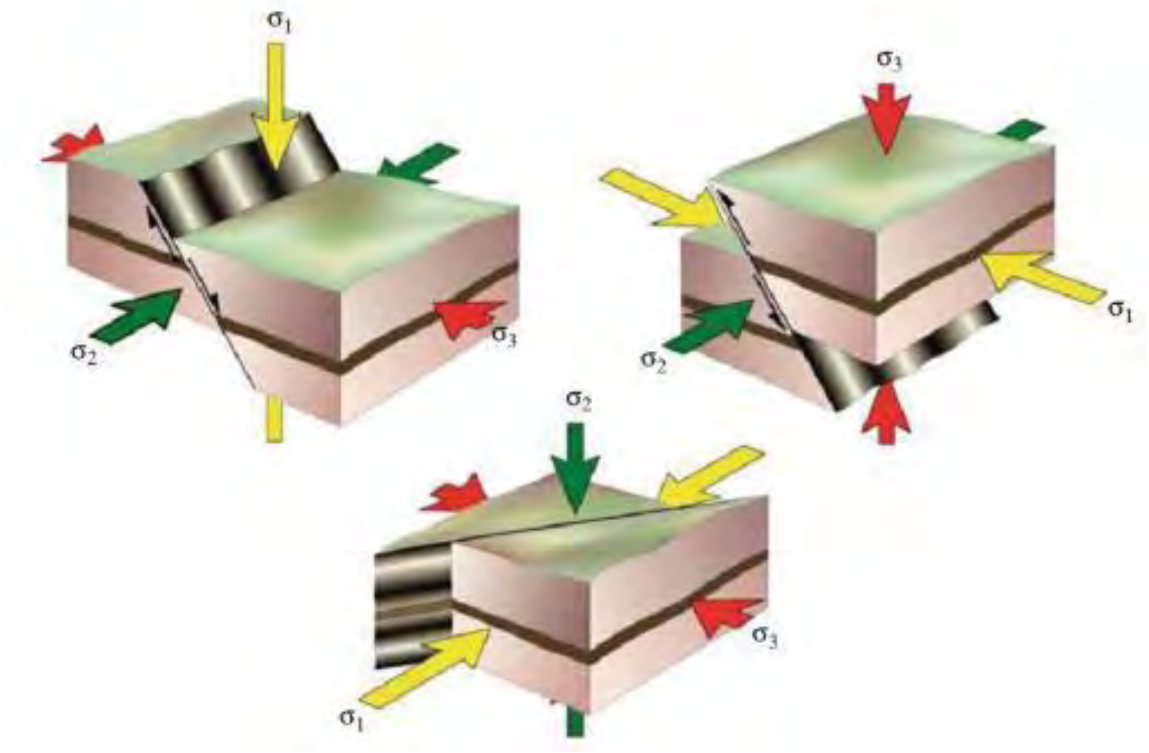


Figure 6.18: The Anderson (1905) relationship between stresses in the Earth and faulting patterns

Source: Drummond (Drummond 2016)

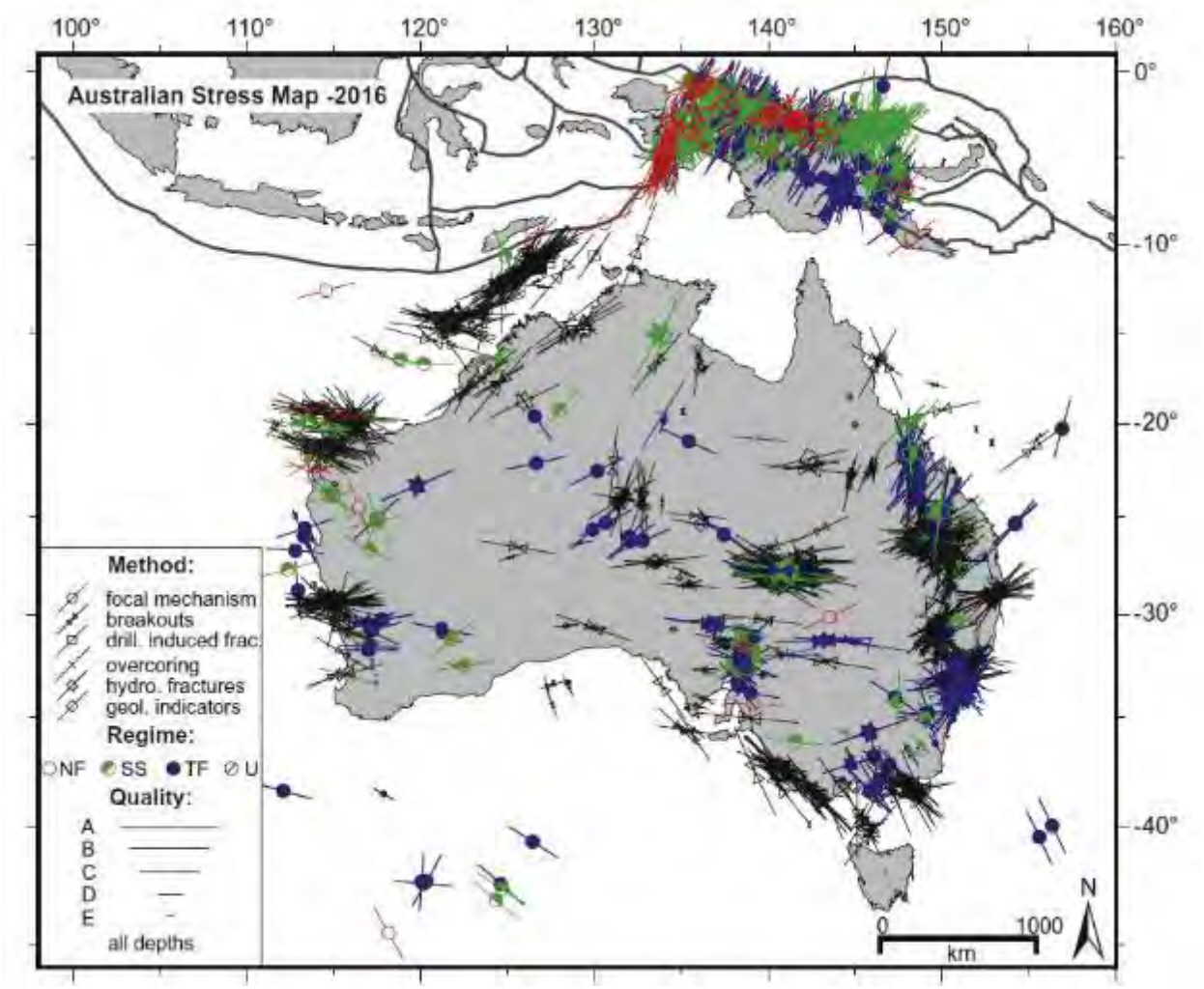
(a) Normal fault stress regime where the maximum principal stress (σ1 yellow) is vertical while the minimum (σ3 red) and intermediate (σ2 green) principal stresses are horizontal: faults move in extension. (b) Reverse or thrust fault stress regime where the maximum principal stress is horizontal and the minimum stress is vertical: faults move in contraction. (c) Strike-slip fault stress regime occurs where the intermediate principle stress is vertical, and the maximum and minimum stresses are horizontal. Favorably oriented vertical fault planes will slip with transcurrent shear motion. Further information on subsurface stresses can be found in (Drummond 2016).



In Australia the pattern of stresses is variable across the continent owing to complex interaction of forces generated by mid ocean ridges, subduction, and four major zones of continental collision (India, New Zealand, Timor and New Guinea. These forces have caused geologically recent compressional deformation, such as folding and thrust faulting (Hillis R.R., Reynolds S.D. Sandiford, M. Quigley 2008). However, data compiled by the World Stress Map project (Rajabi et al. 2017) shows that the present day stress state in sedimentary basins can vary across Australia and within individual basins, with thrust faulting, normal faulting and strike-slip faulting currently occurring across the continent. Data from the world stress map in Australia come mainly from oil and gas exploration wells, therefore the data is relatively well populated for the Perth Basin and the North West Shelf

oil and gas province but data on the stress state is sparse in the Canning Basin. The data on stress directions come from earthquake sources, breakouts in wellbores and fractures in wellbores.

Figure 6.19: Stress field in Australia from the world stress map project 2016 update
Source: Rajabi et al. (Rajabi et al. 2017)



6.12.2 Earthquakes in Western Australia

Felt earthquakes are relatively rare in Australia, with concentrations in a few localities in and around the major Precambrian basement areas, including the Pilbara and Yilgarn Cratons (the most intense and largest events are concentrated from Northam to the northern edge of the Wheatbelt), and in some offshore basins (**Figure 6.20**). Including the far more numerous small earthquakes (**Figure 6.21**) shows that natural background seismicity is widespread in Western Australia, most onshore basins, including the Perth Basin, are actually areas with relatively few earthquakes.

Figure: 6.20: Seismicity in Western Australia from Geoscience Australia database collected from 1955-2018, Earthquakes of felt magnitude, Mw>3.6 shown
Source: Geoscience Australia

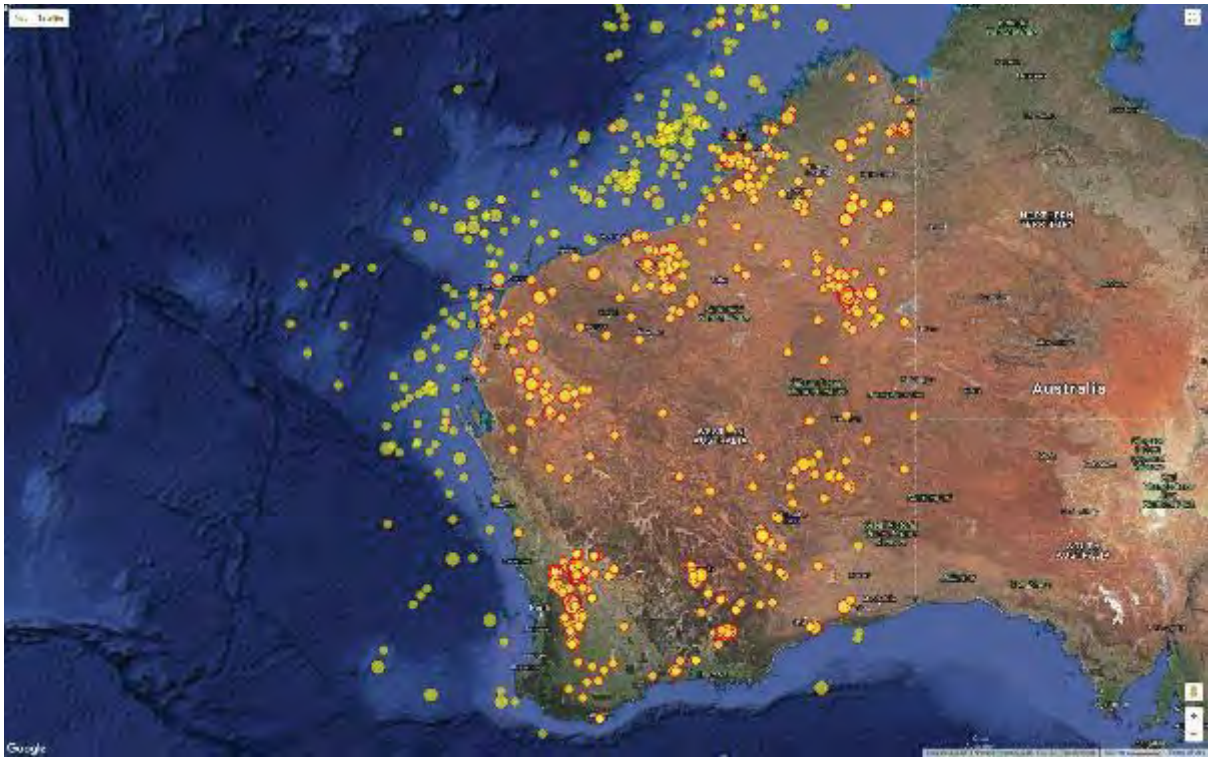
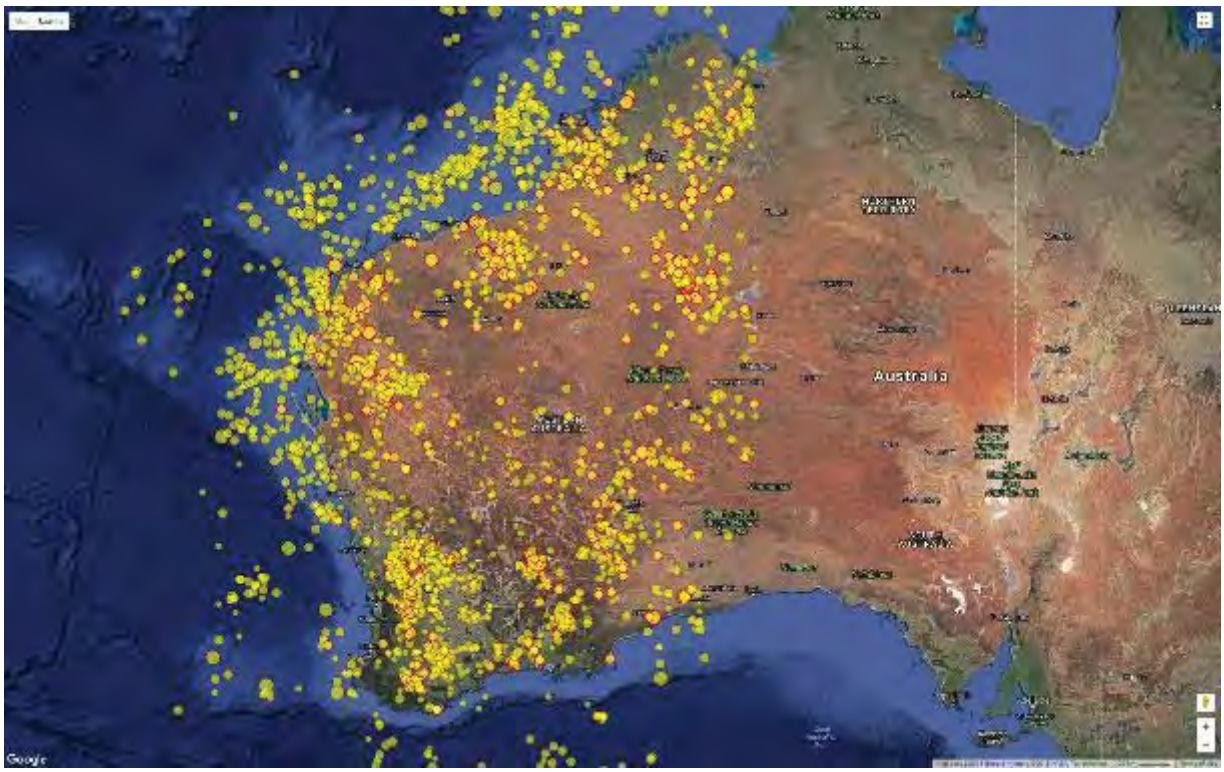


Figure 6.21: 5000 largest earthquakes in Geoscience Australia's database including smaller events Mw> 2.4

Source: Geoscience Australia



6.12.3 Induced seismicity

Human activities are not capable of creating entirely new large faults in an intact rock mass, but they can influence patterns of natural seismicity in several ways:

- Changes in surface loading, and/or the penetration of water into the subsurface from the creation and filling of large water storage or hydroelectric dams. Examples include the Hoover Dam in the United States in 1936, and the Koyna Dam in India in 1967, which induced a magnitude 6.5 earthquake that killed 180 people. The timeframe for seismicity to occur after the filling of a dam may be months to years. The seismicity associated with large surface water reservoirs can be significant, leading to destruction of property and loss of life. The process is well understood as there is a long historical record of seismicity induced by creation of large surface water reservoirs around the world, but the timing and patterns of seismicity are often very unpredictable.
- A large increase in fluid pressure in the subsurface from injection of significant volumes of fluids (generally water but can be gas storage). The fluid pressure reduces the effective stress acting to resist fault slip, such that the forces needed for the fault to move eventually decrease below the strength of the fault and it moves.

This may lead to an increase in seismicity and has been documented in several states in the United States where very large volumes of wastewater from oil and gas production have been deposed of in subsurface wells. An early example occurred in the Rocky Mountain Arsenal disposal well, Colorado, as reported by Evans (Evans 1966). The patterns of seismicity and the maximum size of earthquakes induced in this way vary from place to place. The risk factor is increased when water is injected deeply into the subsurface where there are fault zones that are under high stresses and already close to slipping. However, it is now known that induced seismicity from water injection is not restricted to 'basement' rocks. The induced seismicity that is well documented from North America can generally be shown to be associated with large cumulative volumes of injection and to require some months or years of injection to manifest. Induced seismicity tends to persist for months or years after the injection of fluids ceases.

- A large decrease in fluid pressure from the withdrawal of large quantities of water or hydrocarbons from a subsurface reservoir. Owing to the complex interplay of forces in the subsurface and the fact that a reservoir is both porous and elastic, the reduction in fluid pressure can change the stress balance such that a fault already near to failure can reactivate. This may occur gradually (aseismic slip), or rapidly enough to produce microseismicity or, very rarely, a felt earthquake. Typically, this scenario leading to felt seismicity is associated with very large and long term withdrawal of large fluid volumes from a reasonably deep but still compressible rock reservoir. González et al. (González et al. 2012) examined how the 5.1 magnitude 2011 Lorca earthquake in Spain, which led to nine deaths, was probably caused by extensive withdrawal of groundwater for agricultural use. The Groningen conventional gas field in the Netherlands is an example of an area where decades of gas production has led to tens of centimetres of cumulative ground subsidence, the reactivation of faults and sporadic felt seismicity in the vicinity ((Van Wees et al. 2017) and references therein).

There is now evidence of a cumulative effect at the scale of a sub-basin where the stress conditions have been changed by large volume injection of fluids over many years, so as to induce reactivation of some basement faults in basins without pre-existing overpressure, and where there has been little previous history either of seismicity, for example, midwestern USA (Ellsworth 2013; Keranen et al. 2014). It is important to point out that the very large volumes involved in such cases are related to wastewater reinjection wells and are one or two orders of magnitude larger than typical for even large-scale hydraulic fracture stimulation operations. Rubinstein et al. (Rubinstein et al. 2014) analysed a significant increase in seismicity in Harper and Sumner Counties in Kansas over the period 2013-2016, and found that deep injection of waste fluids was likely responsible, with no correlation to any hydraulic fracture stimulation in this area.

Hydraulic fracture stimulation creates new fractures, which if they slip sideways are new, small faults. Hydraulic fracture stimulation also opens and connects together pre-existing fractures and small faults to form the network of flow pathways that enables unconventional oil and gas, otherwise trapped in very impermeable rocks, to flow to a well. Micro-seismic monitoring is used as a tool by geophysicists to detect and map the pattern of deformation around the wellbore as fracture stages are stimulated in the subsurface. It requires sensitive instrumentation to be placed on the surface and/or a nearby monitoring well. Typically, the energy released in such microseismic events is orders of magnitude smaller than could be felt at the surface. The energy released by a detectable microseismic event has been likened to a pencil breaking. Analysis of the pattern of microseismic events shows that much of the deformation in the zone of hydraulic fracture stimulation involves slip on existing small fractures and other planes of weakness, and the average magnitude of the individual events is around Mw = -2.5 (Warpinski, Du & Zimmer 2012).

For many years, it was considered that hydraulic fracture stimulation for the extraction of hydrocarbons was not likely to lead to seismic events large enough to be felt. Indeed, this appears to be the case in many basins where the stress conditions in the target shale formations (for example, the Barnett Shale and the Eagle Ford Shale in Texas, United States) are relatively relaxed, such that the pre-existing population of faults is not vulnerable to reactivation when relatively small amounts of fluid are injected during hydraulic fracture stimulation operations. Conditions in the Appalachian region of North East United States, where the Utica and Marcellus Shale is encountered, have been considered to have a somewhat higher risk owing to greater complexity of structures (Arthur, Bohm & Layne 2008). Indeed, a series of induced earthquakes, including a felt magnitude 4.0 event, was recorded in the heart of the producing region of the Utica Shale in Youngstown, Ohio in 2011 (Skoumal, Brudzinski & Currie 2015).

Public attention was drawn to the topic of induced seismicity outside of North America following an earthquake of magnitude =2.3Mw close to the site of a hydraulic fracture stimulation operation near the city of Blackpool in Lancashire, in the United Kingdom (UK) in 2011 (Clarke et al. 2014). This gave rise to a series of investigations by government agencies and eventually to changes in regulations by the United Kingdom Oil and Gas Authority.

As unconventional gas activity has expanded within established producing basins and spread to areas where the geological stresses are naturally greater (such as Western Cordillera in North America), there have been more reports of seismicity induced by hydraulic fracture stimulation operations. This was first reported from the Montney Shale (BC Oil and Gas Commision 2012). Over subsequent years, this extended into many areas of western Canada (Bao & Eaton 2016) including the Horn River region (Atkinson et al. 2016) and the Duverney Shale (Schultz et al. 2016). Thus, it is possible that we may see a greater risk of felt seismicity where stresses are higher (for example, in basins close to large mountain ranges or active rift zones) and where there is a pre-existing population of faults close to failure. There is

evidence from the Duverney Shale in Alberta that the extent and size of seismic events increases in line with the amount of fluid pumped during a series of hydraulic fracture stimulations in a field (Schultz et al. 2018). This study noted that there can be a delay of months or years from the commencement of hydraulic fracture stimulation operations to the point where enough fluid has built up to have a noticeable effect on seismicity in a particular field. Follow-up investigations by Eaton and Shultz (Eaton & Schultz 2018) showed that the induced seismicity was concentrated where a high level of overpressure already existed within the shale formation, that is, the extra fluids injected during hydraulic fracture stimulation tipped some faults within these zones over the edge into a condition of failure. Atkinson et al. (Atkinson et al. 2016; Eaton & Schultz 2018) concluded that the increased pore pressure, rather than the tectonics of the basins per se, can be viewed as the main risk factor for induced seismicity. It is noteworthy that the rock formations in regions being targeted for hydraulic fracture stimulation in Western Australia are believed to have little or no overpressure.

Regardless of its origin, in general, induced seismicity occurs at an instrumental level, and does not produce felt earthquakes (Rubinstein & Mahani 2015). It should be noted that there are approximately 35,000 active wastewater disposal wells, 80,000 active enhanced oil-recovery wells, and tens of thousands of wells that are hydraulically fractured every year in the United States. Only a few dozen of these wells are known to have induced felt earthquakes. A combination of many factors is necessary for injection to induce felt earthquakes. These include:

- Faults that are large enough to produce felt earthquakes;
- Stresses that are large enough to produce earthquakes; and
- The presence of fluid path-ways from the injection point to faults, and fluid pressure changes large enough to induce earthquakes.

Sherburn (Sherburn 2012) concluded that there was no evidence that hydraulic fracture stimulation or long-term wastewater injection in the Taranaki Region of New Zealand between 2000 and 2011 triggered or had any observable effect on natural earthquake activity, nor posed any risk through increased earthquakes, even though Taranaki is an area of considerable seismic activity. No felt seismicity has been recorded in association with hydraulic fracture stimulation operations in Western Australia including in the Perth Basin and Barrow Island. In Australia, the only event of significant size (magnitude 3.0) associated with hydraulic fracture stimulation operations was in a very deep and high temperature geothermal well in the Cooper Basin, where fluid was deliberately injected into a critically stressed, pre-existing fault (Hogarth & Holl 2017).

Davies et al. (Davies et al. 2013) reviewed 198 potentially induced earthquakes greater than magnitude 1.0 since 1929 and concluded that there were three examples that were probably induced by hydraulic fracture stimulation (the Etsho and Kiwigana field in Horn

River, the Eola Field in Oklahoma, and in the example from Lancashire, United Kingdom, in 2011 mentioned previously), concluding that after hundreds of thousands of fracturing operations, only three examples of felt seismicity have been documented. Combining this data from before 2013 with the small number of reported events since, it appears that the likelihood of inducing felt seismicity by hydraulic fracture stimulation is extremely small but cannot be ruled out. Thus, it is necessary to account for induced seismicity in risk assessments.

Computer models that couple fluid injection with subsurface stresses in different structural configurations enable a risk analysis to be carried out to quantify the likelihood and possible size of earthquakes induced by hydraulic fracture stimulation operations. Numerical modelling of fluid injection into the vicinity of a fault (Rutqvist et al. 2013b) and directly into a fault (Rutqvist et al. 2015) at around 2,500 m depth found little likelihood of significant induced seismicity. While parts of the fault plane can be induced to slip, the seismic events produced in the numerical models were generally small or very small (Mw<1), with a larger event being produced only when the friction on the fault is modelled to weaken to a level below the prevailing stress state. In this worst-case scenario, events up to around Mw = 2.3 were found to be possible, in line with the sizes of the very few larger events recorded in worldwide hydraulic fracture stimulation operations. While (Rutqvist et al. 2015) caution that deeper shale units may be associated with larger stress drops when a fault plane reactivates, the possible event size would likely be barely perceptible at the surface.

6.12.4 Triggered seismicity

Triggered seismicity is a term used to describe an earthquake that occurs at a particular time owing to a distant external event disturbing an already unstable fault, leading it to reactivate. This is distinct from induced seismicity, where local changes in stress and fluid pressure directly lead to an earthquake happening. With regard to hydraulic fracture stimulation, this induced seismicity is usually within a few kilometres of an injection well. On rare occasions, seismicity can be induced up to tens of kilometres away from the area of fluid source when the cumulative volumes and consequent changes in the state of stress around a field of injection wells are very large and propagate along faults and fracture corridors over a period of years (Peterie et al. 2018).

Triggering, on the other hand, can be thought of as a process that tips a fault that is going to fail anyway, over the edge. Large earthquakes at plate boundaries are known to trigger smaller earthquakes hundreds or even thousands of kilometres away (*remote triggering*). Tidal forces can also trigger seismic activity when the stresses in the Earth are slightly larger than their usual values.

It is possible that the build-up of pressure and stresses caused by human activity could place a nearby fault close to its failure condition, and then an external event such as a large natural earthquake could tip that fault into an unstable state where it does fail and produce

a new rupture. While it could be argued that the earthquake was triggered, the conditions preparing it for failure are man-made, so it still would be seen as an induced event. This is the case even if it was one of a series of earthquakes associated with a human activity that appeared to elevate the level of seismic activity over that previously recorded in the area. Van Der Elst et al. (van der Elst et al. 2013) report an increase in the incidence of remote triggering within areas of suspected anthropogenic earthquakes in the American Midwest.

6.12.5 Seismic monitoring

The ability to detect new seismic events induced by human activities depends on there being sufficient baseline measurements of the background level of earthquake activity in the region of interest. The recording needs to be able to locate and quantify the size of earthquakes down to low intensities so that precursory small earthquakes can be detected ahead of any event of sufficient size to cause damage to infrastructure or risk to life. In Australia, the seismic recording network is rather sparse owing to the low population density and generally quiescent nature of the tectonic situation of our continent. The permanent seismic stations can be supplemented by transportable recording arrays (for example, http://www.fdsn.org/networks/detail/OA/), but at present these are not regularly deployed in a closely spaced configuration so as to enable good baselines to be obtained.

6.12.6 Faults as potential leakage pathways for fluids in the subsurface

It has long been recognised that faults and zones of intense fracturing may act as conduits for the flow of fluids over geological time, and be involved in the mineralisation process and the migration of oil and gas to and out of trapping structures. While coarse grained rocks such as sandstones provide permeable layers that may store water (aquifers) or conventional oil and gas accumulations, fine grained rocks such as shales and low porosity limestones tend to act as seals to vertical flow. Communication between oil and gas bearing layers, including unconventional oil and gas reservoirs, and overlying aquifers may therefore be facilitated by faults that cut across the normally sealing rocks. Note, however, that faults may also often impede the movement of fluids across them. The hydrogeology of faults, which involves an interplay of geological and hydrodynamic processes, has been reviewed recently by Bense et al. (Bense et al. 2013).

It is widely understood that faults that are highly stressed or active (that is, actually slipping) tend to have much higher permeability than ancient faults (Anderson & Menking 1994), which tend to heal and become cemented and less permeable over time. Therefore, the reactivation of faults is perceived as a geological risk for fluid leakage (Langhi et al. 2012; O'Brien et al. 1999) and may also be an engineering risk (Zoback 2007) if human activities change the stress state such that faults can leak owing to reactivation (Soltanzadeh & Hawkes 2009), which may cause seismicity or relatively slow slip (undetectable from the surface).

Geomechanical modelling is often used to assess the risks of fault reactivation and fluid leakage for geological storage of carbon dioxide (Whittaker et al. 2011), and also for understanding the potential risks of fluid escapes in conventional and unconventional oil and gas activities, including, specifically hydraulic fracture stimulation (Rutqvist et al. 2013a).

Where information is insufficient to build an accurate geomechanical model (and commonly rock mechanical test data and in situ stress measurements are lacking across many parts of Western Australia's sedimentary basins) more general risk factors may be examined, such as the proximity to known faults, indications from neotectonic features such as exposed fault traces, the density of faults and fractures, and especially the orientation of faults with respect to the stress field. Morris et al. (Morris, Ferrill & Henderson 1996) identified the ratio of shear to effective normal stress on a fault owing to its orientation in the prevailing stress field: this ranges from zero to one, and gives a rating for the tendency of the fault to slip.

For faults likely to slip, (Ferrill et al. 1999; Ferrill & Morris 2003) further identified a rating factor for the fault to become permeable during slip owing to an increase in volume or dilation: this factor is obtained from the relative magnitudes of all three stresses on the fault plane and also scales from zero to one (Whittaker et al. 2011). More dilation on a fault plane is also found when sealing shales cut by the fault have been deeply buried and become cemented (Corcoran & G. Dore 2002; Nygård et al. 2006), whereas shales that have never been densely lithified may undergo shearing in a fault plane and suffer neither dilation nor any increase in permeability. In geologically older onshore basins, where the rocks were deposited, deeply buried and uplifted, most of the subsurface rocks can be expected to exhibit relatively brittle behaviour, and so fault reactivation presents a risk that flow conduits with significant permeability will develop, enabling fault flow pathways (up or along) to breach through previously sealing layers (Moeck, Kwiatek & Zimmermann 2009).

Given the typical friction angle in a brittle shale, a slip tendency factor of approximately 0.6 would be sufficient to reactivate a fault plane that had no cohesion (Zoback & Townend 2001) and such levels of stress concentration are indeed associated with the minimum level of stress experienced by faults known to have leaked fluids over geological time (Bretan et al. 2011). Where higher levels of stress are supported, this provides evidence that the faults are healed and more cohesive (Tenthorey & F. Cox 2006). The value of stress changed needed to move a fault from its current state, into one of failure, also gives a good indication of reactivation risk. These values can be computed relatively easily, for example, using the 'FAST' method (Mildren et al. 2005) and provide a useful guide as to a fault being at high, moderate or low risk of reactivation during oil and gas operations. At depths of two to three kilometres, typical for overburden shales, a fault that requires a stress perturbation of 10 MPa or more to reactivate would be considered relatively stable. If less than five MPa

of increased shear stress on the fault were sufficient to cause reactivation, that would be considered higher risk (Mildren et al. 2005).

It is also important to consider the hydrogeology of the rock formations when assessing fault reactivation potential. In general, if the rocks are impermeable, then less fluid is needed for fault reactivation to occur, whereas permeable layers or existing fracture corridors will drain fluids away making fault reactivation less likely, unless very large volumes are injected. As noted above for induced seismicity, the cumulative amount of fluids injected over time must be taken into account.

A complete geomechanical risk assessment would thus take into account the distribution of fault and fracture sizes and orientations in the subsurface, best determined from 3D seismic mapping, such as recent examples from the Cooper Basin (Kulikowski & Amrouch 2018). The risk that geological containment in sealing rocks would be compromised can then be assessed based on how close this system of faults and fractures is to renewed movement and leakage during engineering operations such as drilling and hydraulic fracture stimulation. The risk assessment should commence with an analysis of the formation pressures (Van Ruth et al. 2003) and 3D stress state (Nelson et al. 2007; Reynolds et al. 2006), and proceed to analysing:

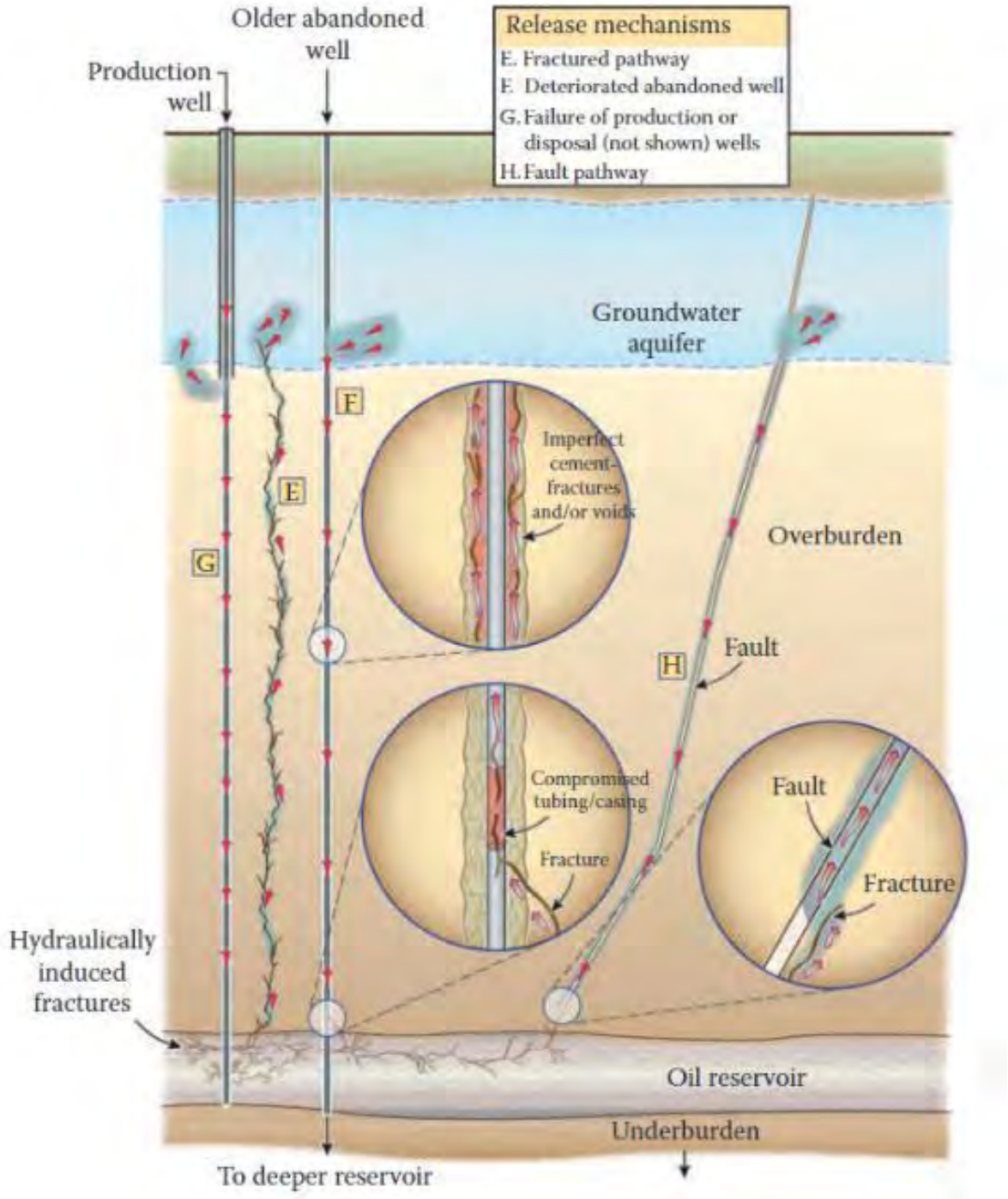
- Turn slip tendency for planes of weakness;
- Fracture stability with respect to renewed movement with and without cohesion on the slip plane; and
- Dilation tendency for fault planes to become permeable during reactivation (Kulikowski, Amrouch & Cooke 2016).

6.12.7 Hydrogeological impacts of fault and fracture interactions with stimulated and pre-existing wells

Aside from direct reactivation of faults and fractures from the injection of high pressure fluids, the consequences of geomechanical interactions in the region of the well that is being fractured, or impacts on pre-existing wells are another aspect of geomechanical risk assessment. **Figure 6.22** summarises the potential pathways for the leakage of fracture fluids and/or hydrocarbons in the subsurface. The risks of the different pathways being created all need to be assessed with regard to the prevailing stresses, the existing population of natural faults and fractures, and the potential for induced fault movements and newly interconnected fractures to compromise geological seals (overburden shales) and/or the engineered barriers in and around new and legacy wells.

Figure 6.22: Potential pathways of fluid leakage associated with out of formation fracture growth, frac hits to a well and fracture/fault intersections, and fault reactivation by influx of pressurised fluids

Source: California Council on Science and Technology (California Council on Science and Technology 2015b)



Given these associations, geomechanical data collection, understanding of the stress field from well measurements, mapping of faults and fracture zones geomechanically with analytical methods (such as slip tendency analysis), and numerical models are a pre-requisite in order to plan and conduct with a reasonable factor of safety, the various stages of engineering operations from exploration drilling, through well stimulation to production.

Predictive subsurface modelling using a range of scenarios can help to identify the risk factors for vulnerability of subsurface aquifers in relation to the pressure and stress changes induced by hydraulic fracture stimulation. Wilson et al. (Wilson et al. 2017) demonstrated the use of scenario modelling for the case of the Bowland Shale in Lancashire in the United Kingdom. They found that the risk increased with extent of hydraulic fracture growth, and high formation pressures. Less intuitively, when low permeability sealing formations were not combined with any permeable layers that would leak off fluids, there was a higher risk of loss of containment because fracture or fault growth was not arrested by leak off of the fluid. Scenarios that lead to leakage from the zone of fracture stimulation into the aquifer within 10,000 years all required modifications of the model away from the most likely hydrogeological configuration towards a 'worst case' situation.

An alternative to building geomechanical models with specified geometries for the faults and fractures and then varying the properties of the geological layers and structures in the model, is a probabilistic risk assessment. Westwood, Toon and Cassidy (Westwood, Toon & Cassidy 2017) used a Monte Carlo approach, where multiple different fracture networks were generated in the sealing shale unit that protected an overlying aquifer from fracturing operations below. The probability of leakage occurrence was then related to fracture density and the volume of fluid pumped in 50 different simulations. This enabled a safe offset distance from the well to the nearest hydrogeologically significant fault to be estimated probabilistically; in this case it was around 500 metres.

6.12.8 Ground subsidence associated with unconventional gas extraction

While a small amount of ground subsidence may occur whenever large volumes of fluid are extracted from compressible porous rocks in the subsurface, there is little likelihood that the extraction of unconventional gas contained in deep and stiff shale formations would lead to any significant problems of land subsidence. In this case, natural variations in ground level from earth tides and seasonal changes in aquifers would likely be of the same magnitude as those caused by oil and gas activities.

The potential risks to land stability associated with hydraulic fracture stimulation activity therefore relate to cumulative effects on the state of stress in the subsurface in areas with extensive and large-scale injection of water.

7

Risk assessment: Methods

7.1 Risk Assessment Framework 195

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7 Risk assessment methods

7.1 Risk assessment framework

The Inquiry tailored a standard risk assessment framework to enable a wide range of issues and concerns related to hydraulic fracture stimulation to be assessed in a systematic and consistent manner, based on the available information/evidence.

Risk assessment is a term used to describe the overall process where the following was considered:

- Identify the values at risk and the objectives for their protection;
- Identify the hazards and impacts, their likelihoods and the factors that influence them in relation to specific activities, operations or aspects of an oil and gas development based on hydraulic fracture stimulation;
- Utilise the available information/evidence to evaluate how likely it is that the hazard/impact may occur, as well as what the consequences are should the hazard/impact occur;
- Evaluate the risk; and
- How those activities or operations might be managed to further avoid hazards/impacts or identify measures that may be implemented to reduce risks to a low level.

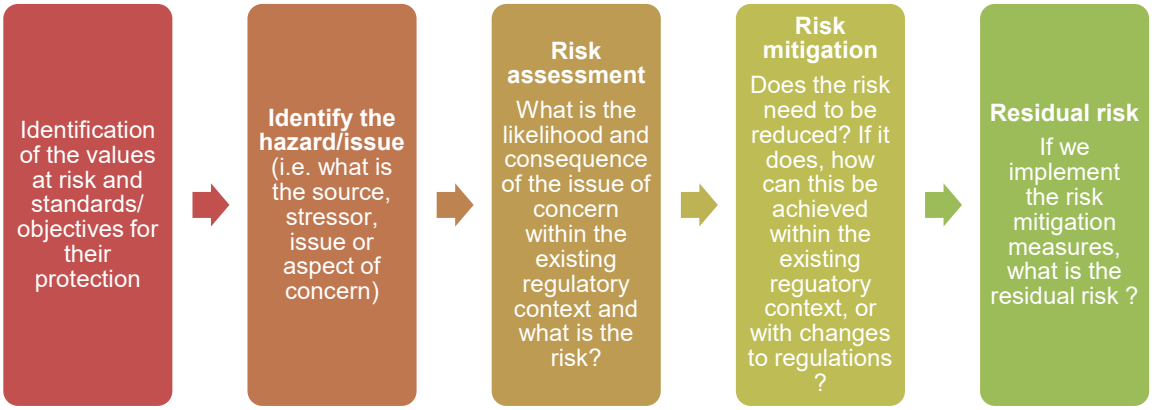
The Inquiry's risk assessment addressed risks to human health and the broader environment, including social surroundings.

When evaluating risks, it is important to recognise that a risk can only occur where there is a pathway of exposure or mechanism for the hazard to occur at a point or situation where people or the environment may be impacted. Where there is no pathway or mechanism for the hazard to occur and/or there is no potential for humans or the environment to be exposed, there is no risk.

Risks are inherent in a wide range of activities undertaken or experienced throughout a day and it is recognised that people have different levels of tolerance for different types of risk. Across the submissions to this Inquiry, and through comments made at the public meetings, there clearly is a wide range of personal views on what risk is, how it is characterised and what is acceptable. There are those in the community who feel no risk is acceptable at all. Others consider risk in comparison with the risks inherent in other activities. Hence, it is important that the risk assessment approach adopted by the Panel is clearly defined.

The Panel has adopted a staged and systematic approach to the identification, assessment and potential management of risks associated with hydraulic fracture stimulation. The staged approach is outlined below:

Figure 7.1: Risk assessment stages



An assessment of risk was undertaken on the fullest and best information/evidence available to the Panel. The assessment was undertaken in relation to the key areas of land, water, greenhouse gas, public health and social surroundings. Within each of these areas, the Panel identified the values at risk and an associated objective to be met.

The assessment of risk can be undertaken using 'qualitative', 'quantitative' or 'semi-quantitative' methods, as described in the Australian / New Zealand International Standard 31000:2009 Risk Management – Principles and guidelines (AS/NZS ISO 31000:2009). The type of risk assessment adopted by the Panel was qualitative. This method utilises evidence (information and/or data) to describe the magnitude of potential consequences and the likelihood that those consequences will occur.

A consequence is the outcome of an event occurring or the hazard posed by the event should it occur. The scale used to assess consequence range from insignificant to catastrophic.

The likelihood relates to the chance or probability of the event occurring. The scale used to assess likelihood range from rare to almost certain. Where no evidence or data is available to enable an assessment of the likelihood, the risk cannot be classified.

The scales of consequence and likelihood have been adapted to relate to the different aspects of hydraulic fracture stimulation considered by the Panel. The scales adopted by the Panel to assess likelihood and consequences are presented in **Tables 7.1** and **Table 7.2**.

Following AS/NZS ISO 31000:2009 guidance, a risk matrix has been used to determine the magnitude of the risk, based on the likelihood and consequence identified. The risk matrix used to determine if a risk may be considered low, medium, high or extreme, is presented in **Table 7.3**. **Table 7.4** presents the actions relevant for each level of risk.

Risks ranked as medium or higher have been considered by the Panel to require additional risk mitigation or management, to reduce the risk to a low level.

The Panel has applied the risk assessment approach in the context of the potential scale of the hazards. In particular, the assessment has considered the locality of the hazards, the nature and extent of their potential impacts (that is, localised or widespread), and the likelihood of their occurrence. An example of a localised impact is a chemical spill that impacts on soil close to the well. A more widespread impact is where a chemical spill may affect a regional aquifer that is used for irrigation. There may be some hazards where both localised and widespread impacts may be of concern. An example could be a chemical spill that is large and impacts the local soil and there is sufficient runoff to also impact a regional waterway.

Table 7.1: Likelihood table

DESCRIPTOR	EXPECTED FREQUENCY	DEFINITION
Rare	Rarely encountered (less than once in 50 years)	Highly unlikely but it may occur in exceptional circumstances; not forecast to be encountered under foreseeable future circumstances in view of current knowledge and existing controls.
Unlikely	Occasional (at least once in 10 years)	Not expected but it may occur at some time; could potentially occur under future foreseeable circumstances if management or regulatory controls fall below best practice standards.
Possible	Periodic (at least once in three years)	The event should occur at some time as there is a history of casual occurrence of similar issues with past projects/activities.
Likely	Likely to occur (at least once per year)	The event is expected to occur as there is a history of frequent occurrence with past projects/activities.
Almost Certain	Frequent/definite (more than once per year)	The event will occur in most circumstances as there is a history of continuous occurrence with past projects/activities.

Table 7.2: Consequence table

ASPECT	Severity Levels				
	Insignificant	Minor	Moderate	Major	Catastrophic
Environment	Low impact (does not exceed an environmental quality standard or objective) to isolated area	Impact that may exceed an environmental quality standard or objective at the point of release, but does not extend beyond point of release and would not be expected to have significant environmental effects (i.e. contained)	Impacts that may exceed an environmental standard or guideline or objective in the vicinity of a site that results in potential effects on the environment; however, the impacts can be rectified in less than a year	An ongoing or extensive impact that results in persistent exceedance of environmental standards/ guidelines/objectives; degradation of a habitat/environment requiring between one and five years to rehabilitate	Uncontained incident resulting in significant harm to the environment, including death of one or more species, that may take more than five years to rehabilitate; permanent loss of habitat
Human Health	Impacts are low and do not exceed a standard or guideline based on protection of human health	Impact that may exceed a standard or guideline at the point of release but does not extend beyond point of release and would not be expected to have health effects (i.e. contained)	Impacts that may exceed a standard or guideline that has the potential for health effects on people in the vicinity of a site and includes effects from noise, odour or traffic. The duration of impacts is less than one year	An ongoing or extensive impact that results in persistent exceedance of human health standards or guidelines that has the potential to result in harm to members of the public; or injury that requires medical intervention	Uncontained incident or ongoing discharge resulting in harm to members of the public over a wide area (e.g. due to contamination of drinking water supplies); accidents resulting in death or serious injury to workers or the public

ASPECT	Severity Levels				
	Insignificant	Minor	Moderate	Major	Catastrophic
Injury/ Worker Safety	First aid or equivalent only, no lost time injury or restricted duties	Medically treated injury to one person, maximum five days lost time injury	Medically treated Injury to one or more persons, maximum 10 days lost time injury	Single death, or permanent loss of function (sensory motor neuron, physiological or intellectual)	Multiple losses of life or permanent disability, extensive injuries to several people.
Public amenity and aesthetic enjoyment	Reasonable use, enjoyment and amenity of the residents in the area. Insignificant community concern. The community can easily and readily adapt to changes	Some minor impacts on the use, enjoyment and amenity of residents in area. Minor level of community concern. Individuals perceive the change will cause limited adverse indirect impacts to their wellbeing, changes take time to adapt to	Moderate impacts on the use, enjoyment and amenity of residents in area. Moderate level of community concern. Some members of community perceive the change will affect their ability to maintain their livelihood or quality of life/wellbeing to an unacceptable extent	Major impacts on the use, enjoyment and amenity of residents in area. Significant level of community concern. Many members of community perceive the change will affect their ability to maintain their livelihood or quality of life/wellbeing to an unacceptable extent	Significant impacts on the use, enjoyment and amenity of residents in area, and significant numbers of complaints. Community outrage. Many members of community perceive the change will affect their ability to maintain their livelihood or quality of life/wellbeing such that they may have to leave the area/community
Heritage	Minor/localised change of heritage materials or settings	Change or damage to many of the key heritage materials or settings such that the heritage resource is slightly altered	Change or damage to many of the key heritage materials or settings such that the heritage resource is considered modified	Change or damage to most of the heritage materials or settings such that the heritage resource is permanently changed	Widespread change or damage to heritage materials or settings such that the heritage resource is permanently changed

Table 7.3: Risk matrix

		Consequence or hazard classification					
		Insignificant	Minor	Moderate	Major	Catastrophic	No data
Likelihood	Rare	Low	Low	Low	Low	Medium	Not classifiable
	Unlikely	Low	Low	Medium	Medium	High	
	Possible	Low	Medium	Medium	High	High	
	Likely	Low	Medium	High	Extreme	Extreme	
	Almost certain	Medium	High	High	Extreme	Extreme	
	No data	Not classifiable					

Table 7.4: Risk levels and actions

LEVEL OF RISK	URGENCY FOR IMPLEMENTATION OF MANAGEMENT
Low	Risk is acceptable. Managed by routine procedures with no additional risk management measures.
Medium	Risk considered unacceptable and risk mitigation measures should be considered. The level of risk management is expected to be lower than required for risks identified as high or extreme.
High	Risk considered unacceptable and risk reduction measures are required to be considered.
Extreme	Risk considered unacceptable and risk reduction measures must be implemented to reduce risk.

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8

Risk assessment: Land

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8 Risk assessment: Land

8.1 Introduction

An expanded Western Australian onshore oil and gas industry, based on hydraulic fracture stimulation, represents a new pressure on the landscapes of prospective areas as well as on plants and animals native to those places. This pressure is not generally distinctive in nature but is in addition to existing and historic development on the landscape, which has included grazing, agricultural clearing, mining and regional infrastructure. While Western Australia's planning and environmental approvals processes works to avoid or minimise these pressures and impacts, and considers cumulative impacts, the Inquiry has considered the specific land and biodiversity values of the State's prospective onshore regions at risk, the nature of those risks and how they could arise from unconventional oil and gas development. The Inquiry has also considered how those risks might be further mitigated beyond the existing regulatory arrangements.

In making this assessment, attention has been given to the following:

- Regional terrestrial biodiversity;
- Places of high and recognised environmental and conservation values;
- Soil health and the beneficial use of land; and
- Seismicity.

Potential pressures identified include clearing for roads and other infrastructure, associated ecosystem fragmentation, visual impacts, spread of pests and weeds, chemical contamination, soil degradation, changed fire regimes, direct injury to wildlife and increased seismic activity. The potential impacts on surface and groundwater regimes have been considered separately in **Section 9** (Water) of this Report. The implications of an onshore unconventional oil and gas industry on climate, and indirectly on land, are considered in **Section 10** (Greenhouse gas) of this Report.

8.2 Setting objectives for assessing risk to land

The environmental objectives for landscape and biodiversity, against which risk was assessed, were derived from the environmental factor objectives and guidelines of the Environmental Protection Authority (EPA) (Environmental Protection Authority 2018). These are as follows:

- Flora and fauna are protected so that regional biological and ecological integrity are maintained;

- The integrity of places of distinctive ecological and conservation value is preserved;
- Soil and land health is maintained so that environmental values including beneficial use are protected; and
- Induced seismic activity causes no harm.

8.3 Environmental values of prospective regions

The regions prospective for oil and gas development in Western Australia have differing and distinct land, biodiversity and nature conservation values. Most of the differences are due to inherent biogeography, while some reflect a different land use history and level of development. In turn, these distinctions very much colour the risks (and their mitigations) associated with developing unconventional oil and gas resources.

8.3.1 Canning Basin

The area of the Canning Basin prospective for unconventional oil and gas development lies across the boundary between the south-western Kimberley and Pilbara regions. While the southernmost end of the Canning Basin extends into the Interim Biogeographic Regionalisation for Australia (IBRA) Eremaean botanical province, the region prospective for unconventional oil and gas development corresponds closely to the IBRA Dampierland biogeographic region in (Thackway R & Cresswell I D 1995). **Figure 8.1** shows Western Australian IBRA sub-regions.

Figure 8.1: Map showing the IBRA regions of Western Australia

Source: Department of Water and Environmental Regulation (DWER)

8.3.1.1 The Dampierland interim biogeographic regionalisation for Australia sub-region

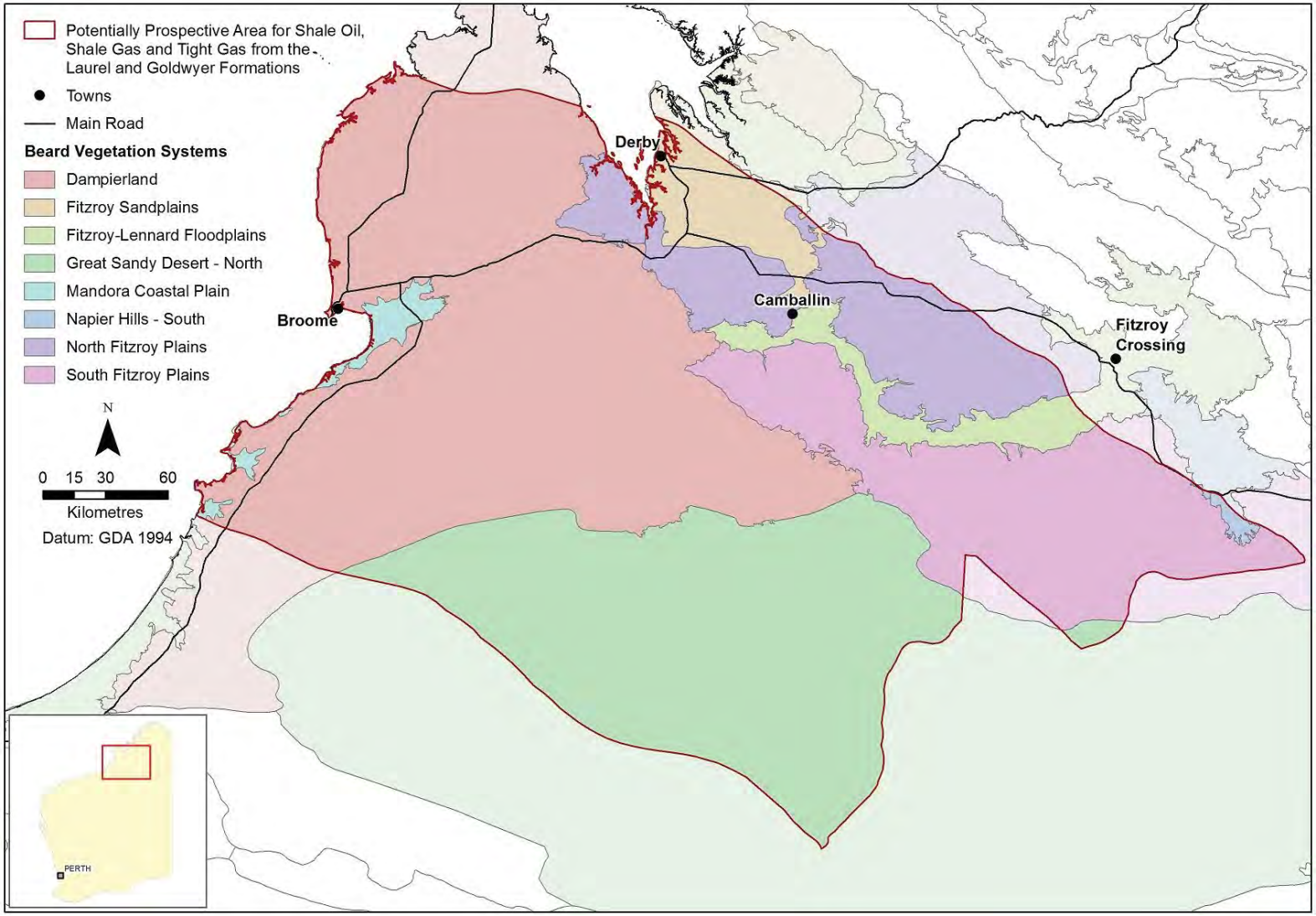
The Dampierland sub-region has a dry hot tropical and semi-arid climate, with much of it receiving 300 millimetres (mm) to 800 mm annual rainfall, mostly in summer. The soils are largely Quaternary sandplains over sandstone, mudstones or siltstone and typically do not hold much surface water. Broadly, the vegetation is characteristically 'pindan'. There is some woodland on the Dampier Peninsula, but the majority of the area is pindan with low trees elsewhere, dominated by acacias (*Acacia humida, Acacia sericea, Acacia eripoda*) with some areas of bunch-grass savanna and shrub-steppe. This region is part of Western Australia's Northern Province vegetation (Beard, Chapman & Gioia 2000), although at the driest end of that region.

Figure 8.2: Low sand dune within the pindan showing evidence of cattle grazing
Source: DWER

The region's vegetation is largely uncleared, although much of it is subject to pastoral use. The 2002 assessment of the bioregion (McKenzie, May & McKenna 2002) found that vegetation cover had declined throughout the region, due to an inappropriate fire regime in combination with grazing. According to the 2008 assessment of the Dampierland bioregion by the Western Australian Rangeland Monitoring System (Bastin 2008), about 73 percent of the region is grazed. This same report notes that fires were extensive throughout the bioregion between 1997 and 2001, and again in 2004. In each of those years, 31 to 48 percent of the area was burnt and this frequency of fires was higher relative to other IBRA regions.

Figure 8.3: Vegetation map in potentially prospective areas of the Canning Basin

Source: DWER



The prospective part of the Canning Basin under consideration by this Inquiry has limited vesting in the conservation estate which is mostly concentrated at or near the coast. The extreme north-eastern strip of the region (mostly north of the Great Northern Highway and the Fitzroy Valley, downstream of Fitzroy Crossing) is part of the West Kimberley National Heritage Area. The Australian Heritage Council's assessment of this listing (Australian Heritage Council 2010) identifies inspirational landscapes, special geological features and biological richness, mostly outside of the prospective areas considered in this Inquiry apart from those at or near the coast on the Dampier Peninsula itself or at Roebuck Bay.

According to the best information currently available, those portions of the Canning Basin that extend into the Heritage Area, including places such as Windjana Gorge National Park, Devonian Reef Conservation Park, Brooking Gorge Conservation Park and Geikie Gorge Conservation Park, are not prospective for oil and gas development, even with hydraulic fracture stimulation. The listed national heritage values are protected under national environment law to ensure the places' outstanding heritage values are appropriately considered when making decisions about development.

The following fauna species, identified at risk under the Australian *Environmental Protection and Biodiversity Conservation Act 1999* (EPBC Act), are present in the prospective area:

- Two bird species listed as endangered, the Night Parrot and the Gouldian finch;
- One mammal listed as endangered, the Northern Quoll;
- Six species of sea turtle listed, three as endangered (Loggerhead, Olive Ridley and Leatherback) and three as vulnerable (Green, Hawksbill, Flatback);
- Three mammals listed as vulnerable, the Ghost Bat, the Bilby, the Black-footed Rock-wallaby; and
- Three birds listed as vulnerable, the Greater Sand Plover, the Red Goshawk and the Princess Parrot.

As of 2013, there are a number of Threatened Ecological Communities (TEC) listed under State legislation in the bioregion:

- Bunda Bunda organic mound spring assemblages (Vulnerable);
- Big Springs organic mound spring assemblages (Vulnerable);
- Mandora Mounds organic springs and mound springs (Endangered);
- Monsoon vine thickets on the Dampier Peninsula (Endangered); and
- Dragon Tree Soak organic mound spring assemblages (Endangered) located just to the south of the Dampierland bioregion.

Flora species listed as threatened under Western Australian legislation include:

- *Seringia exastia* (Fringed Fire Bush)
- *Pandanus spiralis var. flammeus* (Edgar Ranges Pandanus)

There are an additional 31 flora species in the region listed as Priority 1 by the State Government.

Weeds known to occur in the region include *Calotropis procera*, *Parkinsonia aculeate*, *Jatropha gossypifolia*, *Xanthium occidentale*, *Lantana camara*, *Cuscuta campestris*, *Hyptis suaveolens*, *Prosopis spp*., *Themeda quadrivalvis*, *Ziziyphus mauritiana*, *Asystasia gangetica subsp*. *Micrantha* and *Cryptostegia grandiflora*.

Invasive animals known to occur in the bioregion include feral pig, fox, rabbit, wild dog, feral cat, camel, donkey and horse.

8.3.1.2 The conservation estate of the Canning Basin

Within the oil and gas region of the Canning Basin considered prospective for unconventional oil and gas are places vested in the Western Australian Conservation Estate. At or near the coast is the Yawuru Nagulagun/Roebuck Bay Marine Park (jointly managed by the Yawuru Traditional Owners and the State Government and recognising the fringing Yawuru Conservation Estate Reserves, Yawuru Birragun Conservation Park, Yawuru Minyirr Buru Conservation Reserve, and Yawuru Northern Intertidal Area), and to the north of Roebuck Bay is Coulomb Point Nature Reserve on the Dampier Peninsula. In the extreme southeast of the region is the Kurriji pa Yajula (Dragon Tree Soak) Nature Reserve.

Located outside and south of the prospective area is the Jinmarnkur Conservation Park, Jinmarnkur Kulja Nature Reserve, the Kujungurru Warrarn Nature Reserve, the Walyarta Conservation Park (including the Mandora Marsh) and the northern end of the Eighty-Mile Beach Marine Park (a Ramsar wetland).

Roebuck Bay is an area of immense Yawuru cultural significance, and also holds international significance for its environmental values as a Ramsar wetland. Exploration permit EP 473 covers this area, conferring the right to carry out petroleum exploration in a marine park, as discussed later in this Section. The Buru Energy-Mitsubishi Corporation joint venture voluntarily relinquished these exploration rights in 2011, in consultation with the Yawuru, placing a condition on the permit that prevents exploration in Roebuck Bay and surrounding wetlands. The Yawuru Nagulagun/Roebuck Bay Marine Park was gazetted in October 2016.

Figure 8.4: The conservation estate in proximity to the potentially prospective areas of the Canning Basin

Source: DWER

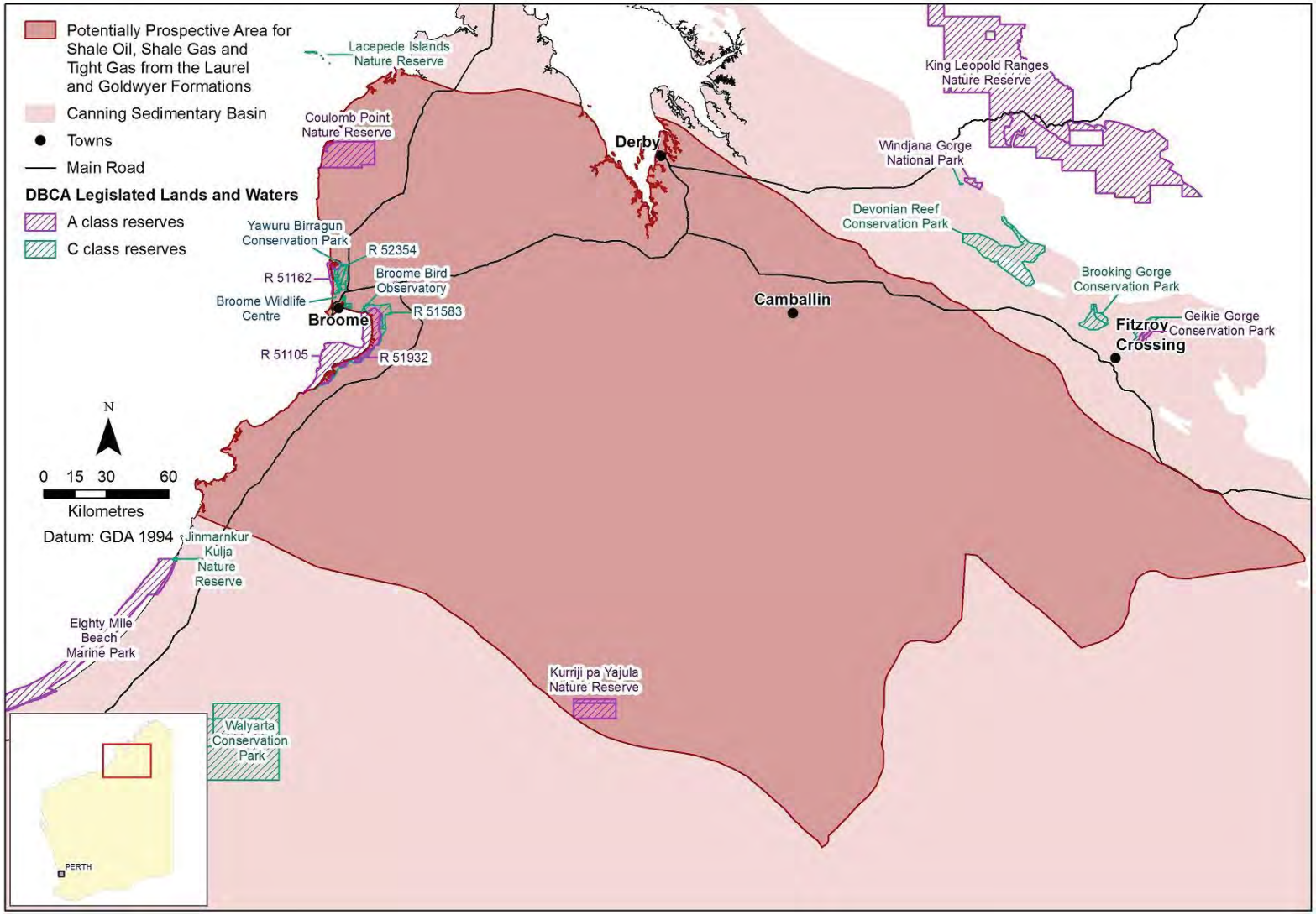
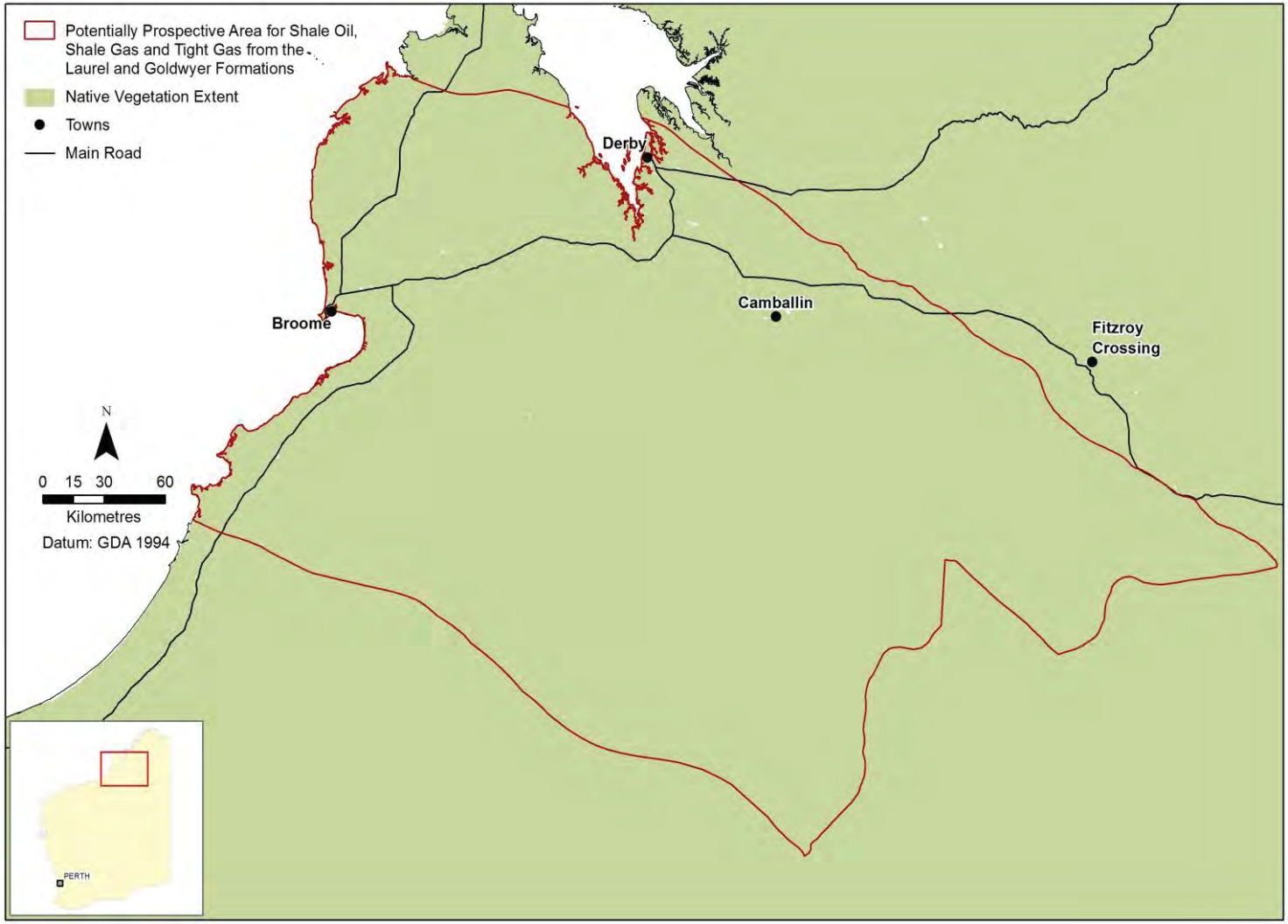


Figure 8.5: Remnant vegetation in potentially prospective areas for oil and gas in the Canning Basin

At this scale of resolution the Canning Basin is effectively uncleared

Source: DWER



8.3.1.3 Structures, stresses and seismicity of the Canning Basin

The Canning Basin (Geological Survey of Western Australia 2017) is a complex extensional basin comprising several sub-basins, separated by platforms with substantially thinner sedimentary succession. On the gravity map of the basin, shown in **Figure 8.6**, the main areas of thicker sediments appear as depressions (Fitzroy Trough and Kidson Sub-basin), while the basement highs appear as ridges and promontories (Broome Platform, Crossland Platforms, Lenard Shelf, Anketell Shelf). The sediments range in age from Paleozoic, including the main shale sequences prospective for unconventional oil and gas, through Mesozoic overburden sediments, to recent river sediments and aeolian dunes.

Figure 8.7 to **Figure 8.13** provide maps and interpretations of the Basins geology, geological stress, seismic monitoring and recorded earthquakes.

Figure 8.6: Main structural elements of the Canning Basin
Source: Geological Survey of Western Australia (GSWA) (Geological Survey of Western Australia 2017)

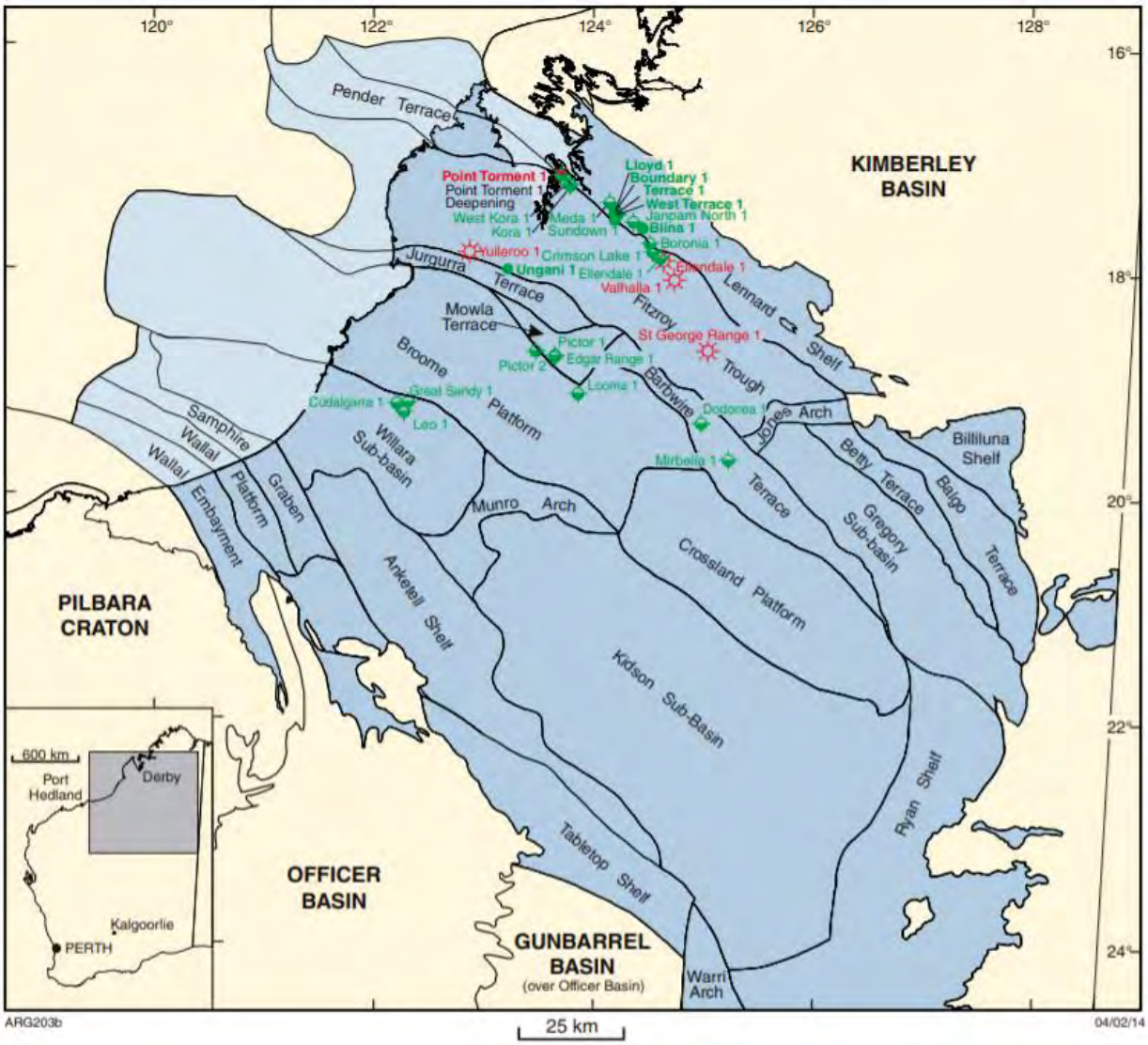
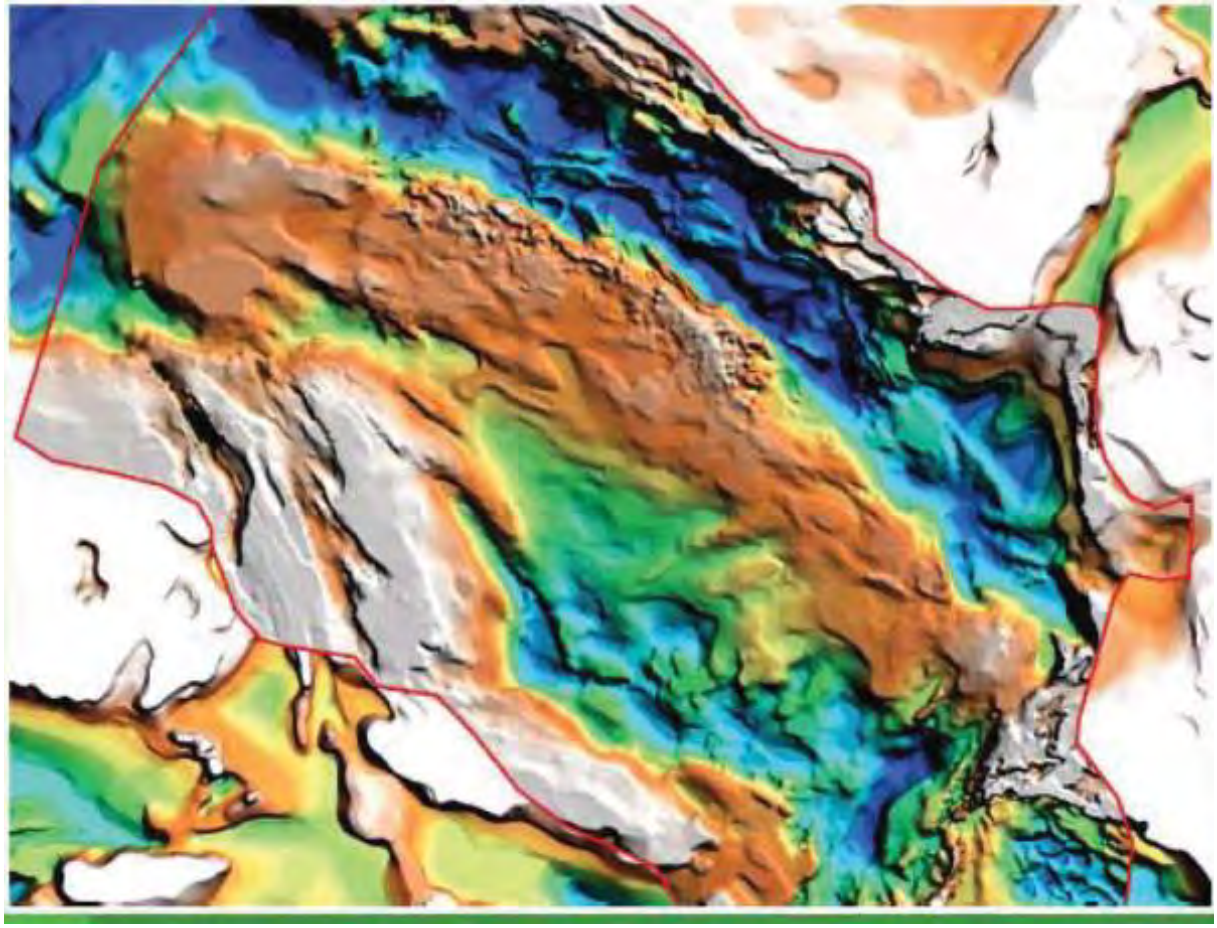


Figure 8.7: Seebase image of the Canning Basin derived from gravity data

Source: GSWA (Geological Survey of Western Australia 2017)

Warmer colours indicate gravity highs, associated with thinner sediments over basement highs



The present-day stress field places the Canning Basin in north west-south east compression. Recent studies by Geoscience Australia (Bailey & Henson 2018), interpreted stress magnitudes in the Canning Basin to indicate a strike-slip faulting stress regime. However, geomechanical models indicate a consistent transition from strike-slip to normal faulting with depth, as well as limited local transitions to both normal and thrust faulting.

Figure 8.8: Present day stress pattern in North-West Australia
Source: Rajabi et al. (Rajabi et al. 2017)

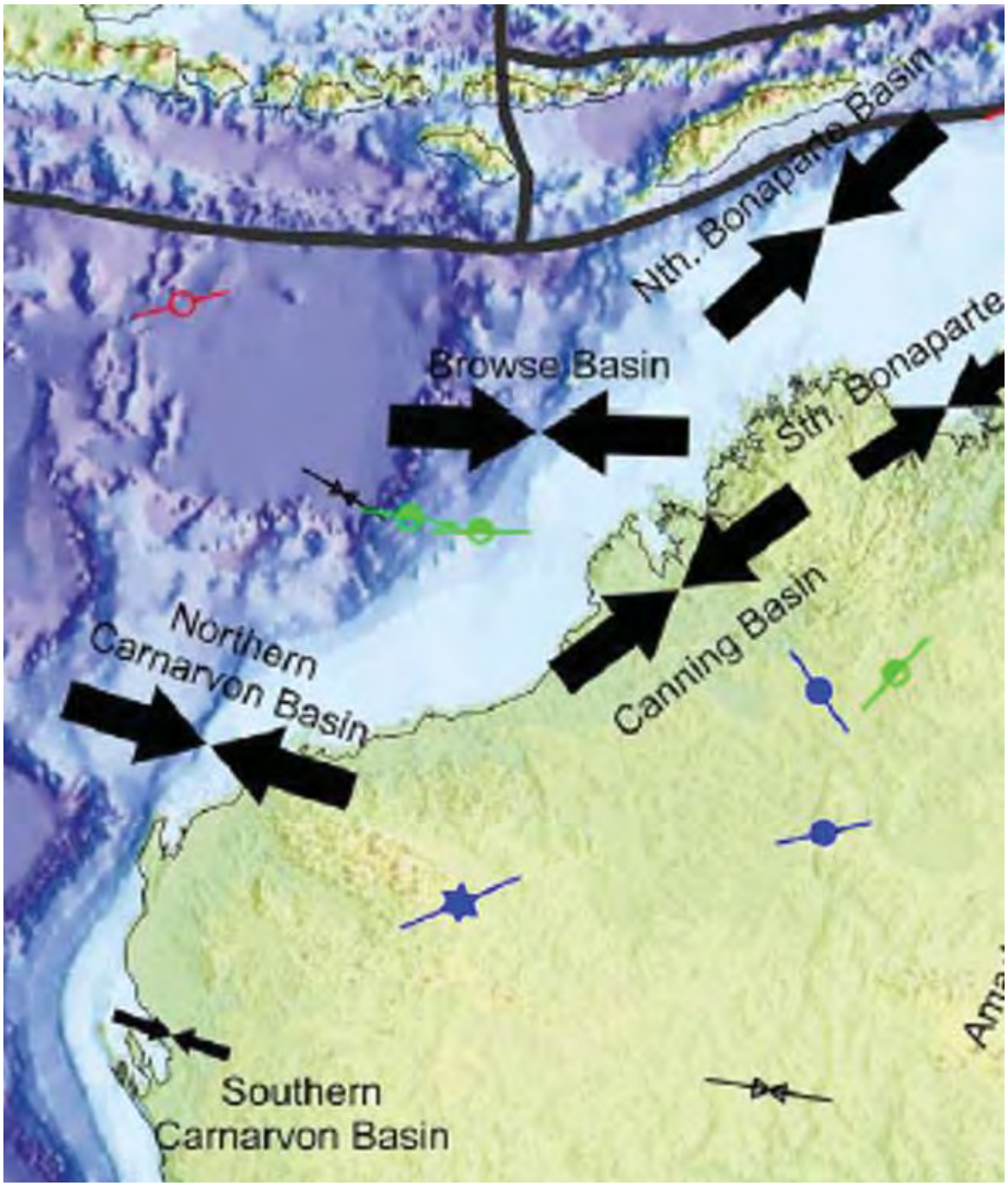


Figure 8.9: Analysis of stresses with depth in Canning Basin wells
Source: GA (Bailey and Henson 2018)

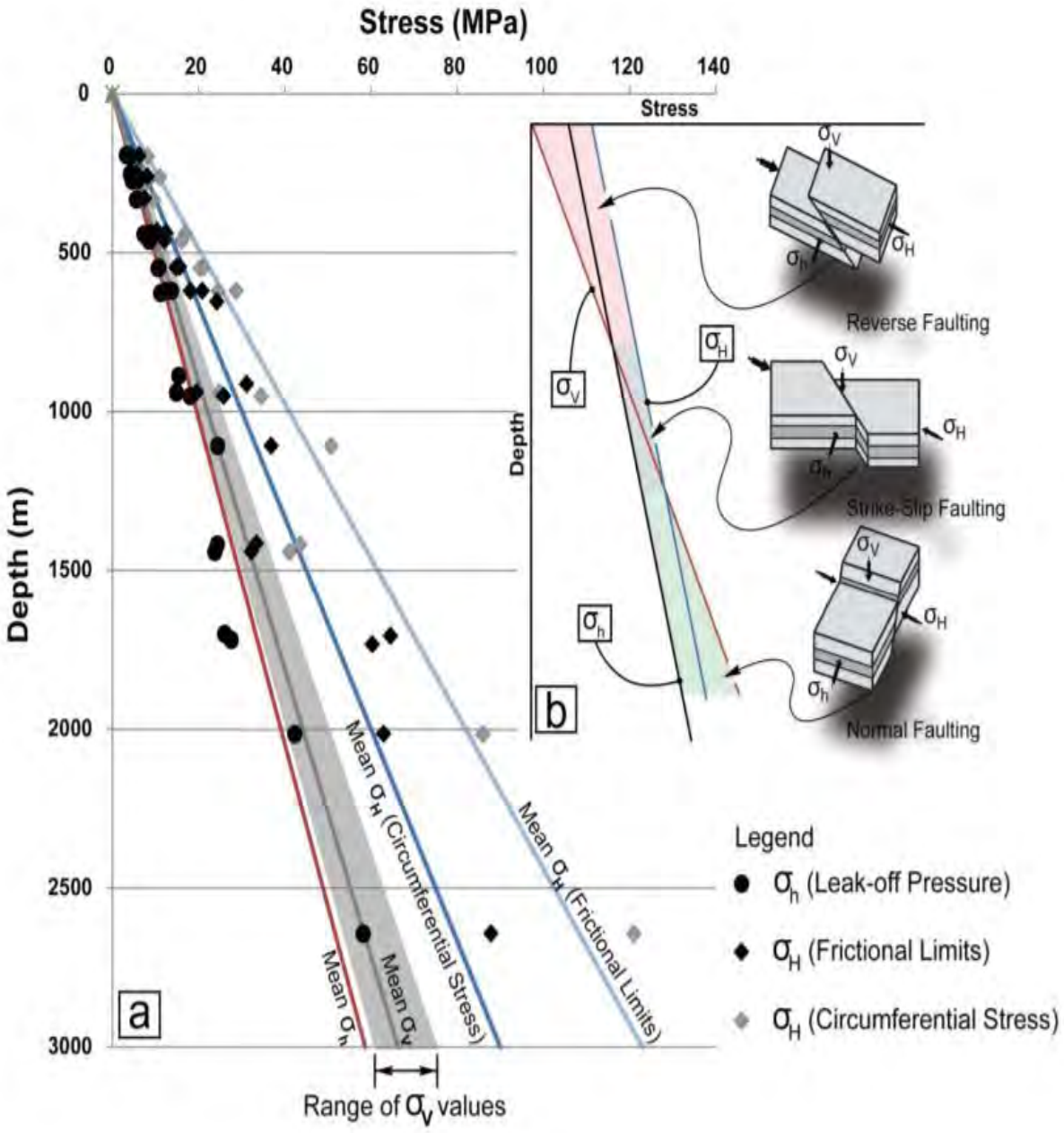
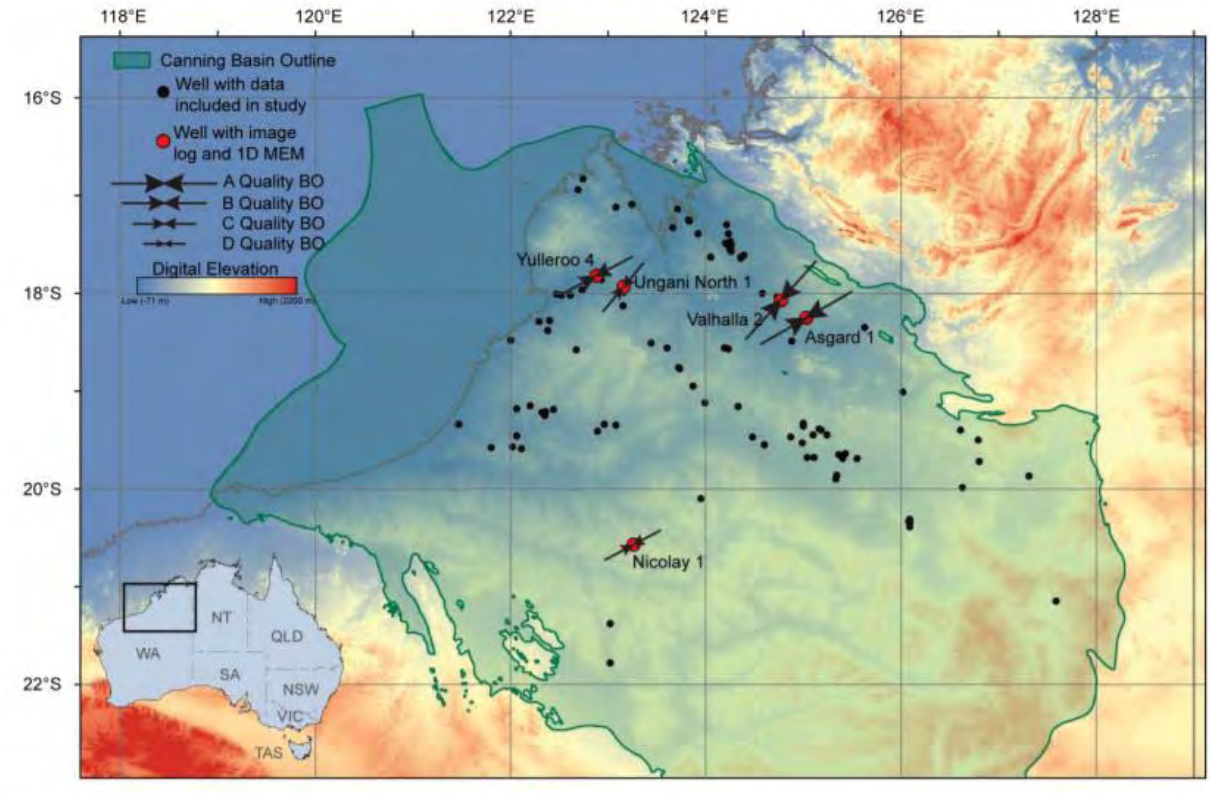


Figure 8.10: Petroleum well locations in the Canning Basin used to study present-day stress field and directions of the maximum horizontal compressive stress from borehole breakouts determined from borehole image logs

Source: GA (Bailey & Henson 2018)



The Canning Basin experiences a low background level of seismicity, quite typical of most of the Australian continent, although the paucity of seismic recording stations limits the number and magnitude of events that are recorded. There is rather more seismicity in the Fitzroy Trough and Crossland Platform than elsewhere in the basin.

Figure 8.11: Location of seismic receiving stations along the Great Northern Highway transect (CWASS) and ocean bottom seismometer transect offshore of the Canning Basin
Source: GA catalog events > M2.4

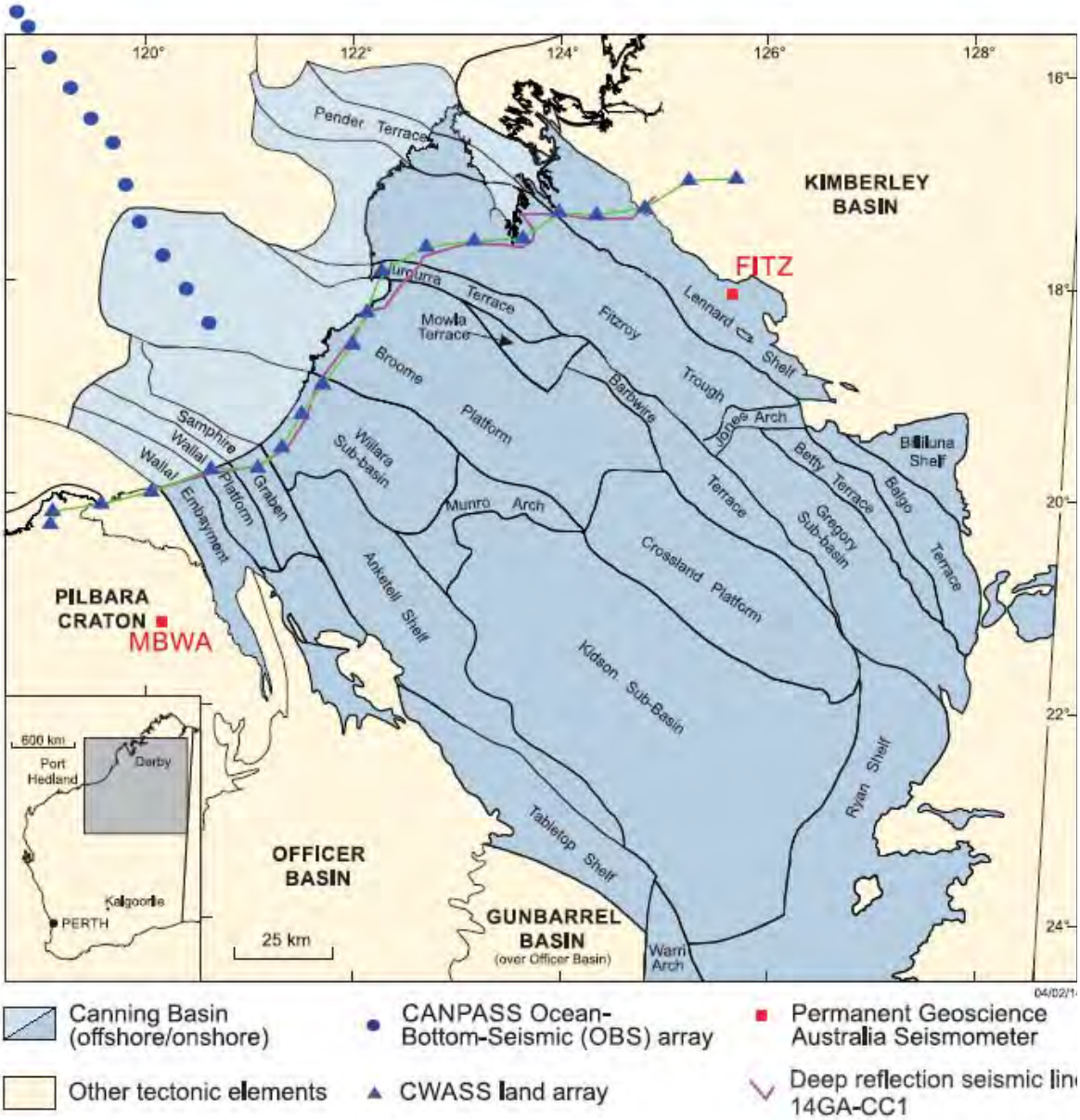


Figure 8.12: Historical record of earthquakes in the Canning Basin region

Source: GA catalog events > M2.4

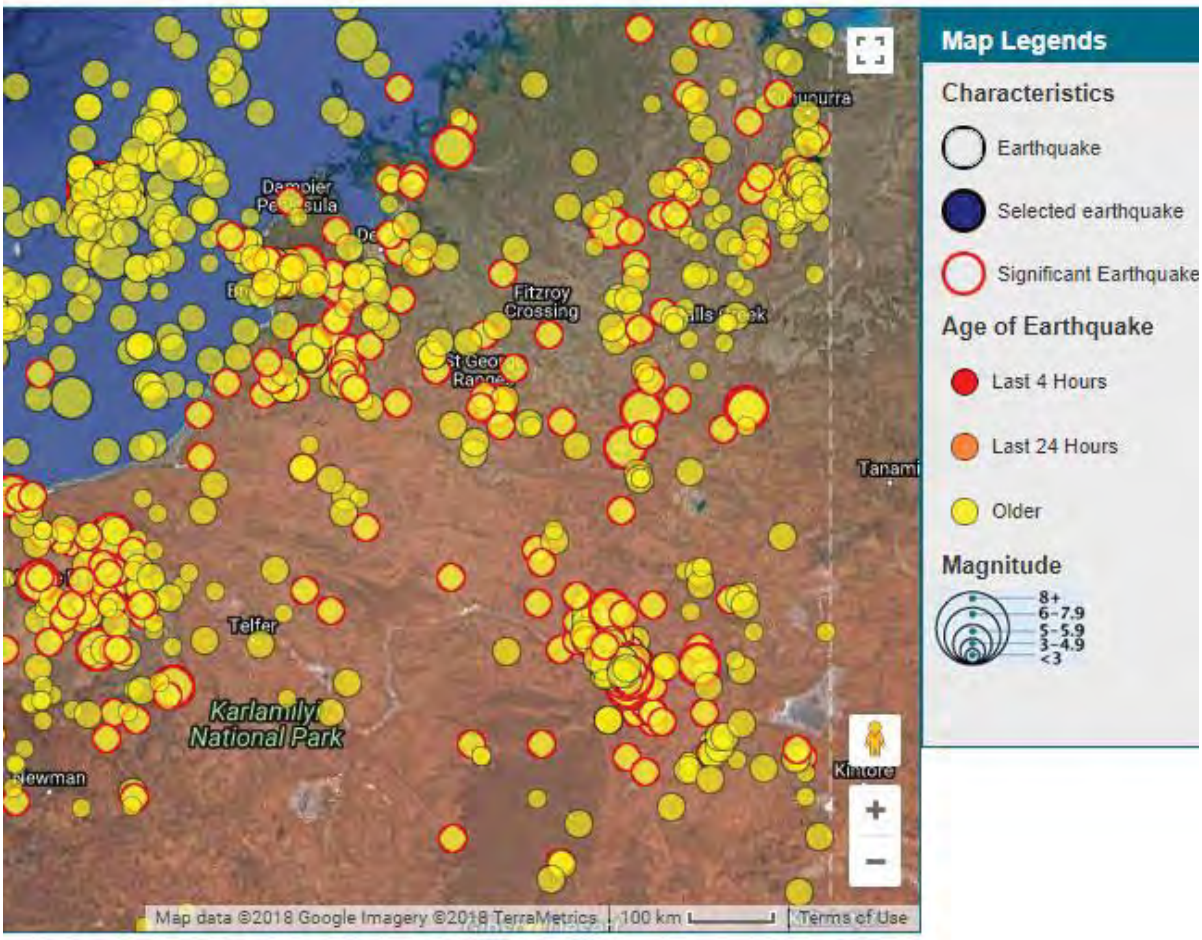
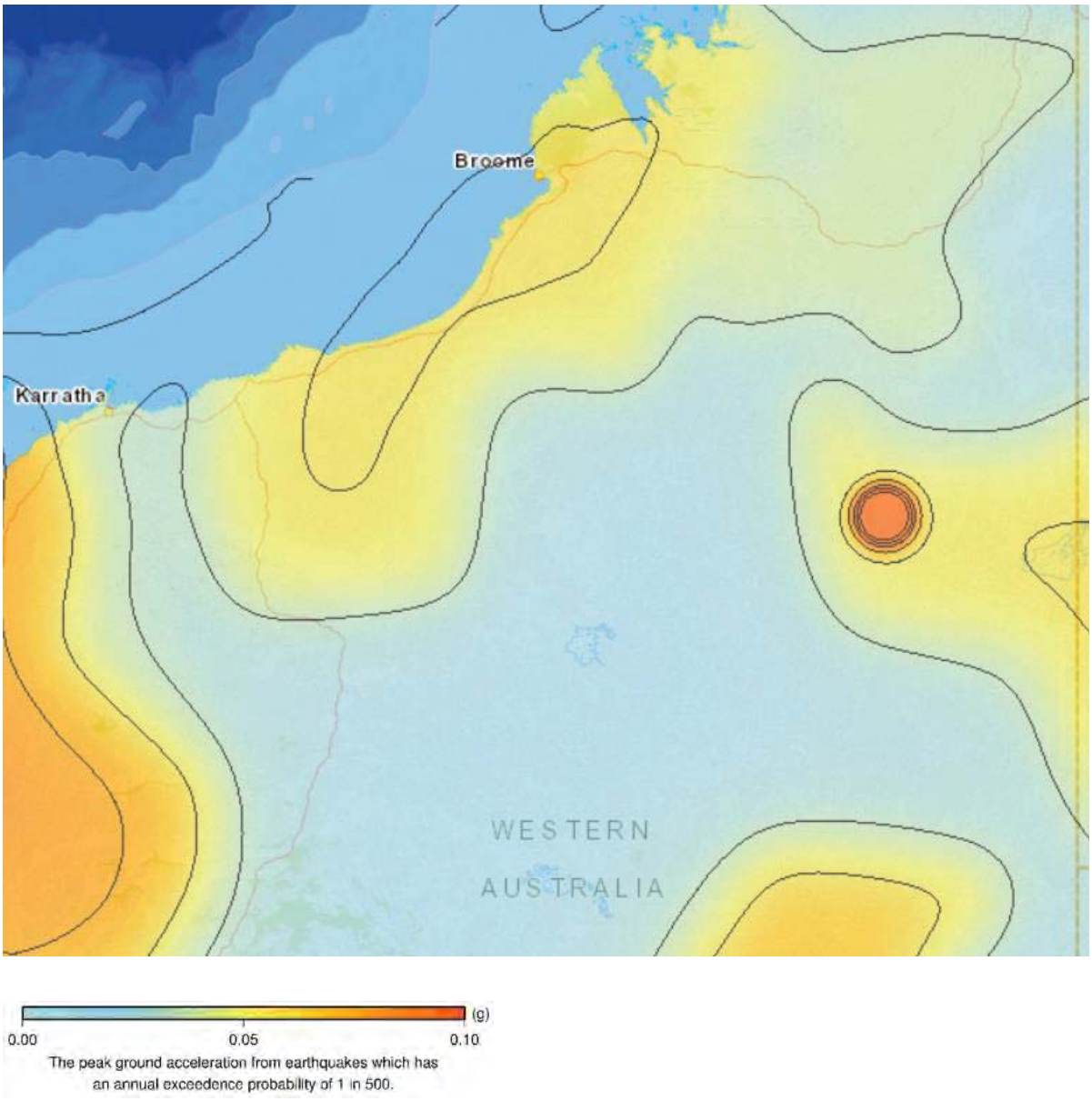


Figure 8.13: Map of seismic hazard in the region of the Canning Basin

Source: GA (Geoscience Australia 2017)



8.3.2 Perth Basin

The portion of the Perth Basin under consideration by the Inquiry comprises parts of the Swan IBRA Bioregion (IBRA sub-regions Perth (SWA02) and Dandaragan Plateau (SWA01)), and the Geraldton Sandplains IBRA Region (Lesueur Sandplain (GES02)). These regions correspond approximately to the Swan Coastal Plain, Arrowsmith Region, Dandaragan Plateau and Yarra Yarra physiographic regions (Playford, Cockbain & Low 1976), referred to in **Section 9** (Water) of this Report.

Together, these areas are characterised by a complex pattern of landforms and soils, a very high degree of plant endemism and extensive clearing for agriculture and other developments including town sites. Consequently, the region has a high number of threatened species and a significant number of areas are now reserved for nature conservation. The region also supports widespread agriculture, including land under irrigation, pasture and cropping. Tille et al. (Tille, Stuart-Street & van Gool 2013) identified and mapped the high quality agricultural land in the northern half of the prospective area considered in the Inquiry.

There are three TECs listed under the Australian EPBC Act in the bioregion:

- Banksia Woodlands of the Swan Coastal Plain (EPBC listed Endangered);
- Clay Pans of the Swan Coastal Plain (EPBC listed Critically Endangered); and
- Subtropical and Temperate Coastal Saltmarsh (EPBC listed Vulnerable).

Onshore terrestrial fauna, with the potential to occur in prospective oil and gas areas of the Perth Basin, based on EPBC species listings and their known ranges, include:

- Endangered:
    - The Western Swamp Tortoise *Pseudemydura umbrina* (only existing within hydraulic fracture stimulation ban area);
    - Western Spiny-tailed Skink *Egernia stokesii badia*;
    - Carnaby's Cockatoo *Calyptorhynchus latirostris*;
    - Woylie *Bettongia penicillata ogilbyi;*
    - Dibbler *Parantechinus apicalis*;
    - Red Knot *Calidris canutus* (coastal);
    - Curlew Sandpiper *Calidris ferruginea* (coastal); and
    - Bar-tail Godwit *Limosa lapponica menzbieri* (coastal).
- Vulnerable:
    - Carter's Freshwater Mussel *Westralunio carteri* (extreme southern extent of prospective area only);

- Lancelin Island skink *Ctenotus lancelini*;
- Forest Red-tailed Black Cockatoo *Calyptorhynchus banksii naso*;
- Chuditch *Dasyurus geoffroii*;
- Mallefowl *Leipoa ocellata*;
- Northern Bar-tail Godwit *Limosa lapponica baueri* (coastal);
- Australian Fairy Tern *Sternula nereis nereis* (coastal); and
- Australian Lesser Noddy *Anous tenuirostris melanops* (coastal).

Western Australia's listings of species at risk and wetlands of significance for each of these three IBRA sub-regions can be found in (Desmond 2002; Desmond & Chant 2001; Mitchell, Williams & Desmond 2002), and through the Department of Biodiversity Conservation and Attractions (DBCA) NatureMap portal.

The Western Australian Flora database lists 312 weed species found within the Geraldton Sandplain IBRA region and 890 weed species within the Swan Coastal Plain IBRA region. Most of the weeds are agricultural pastoral species for example, Buffel grass (*Cenchrus ciliaris*), Olive (*Olea europaea*), Radiata pine (*Pinus radiata*), Paterson's curse (*Echium plantagineum*), Cape tulip (*Moraea flaccida* and *M. miniata*), Spiny rush (*Juncus acutus*), Doublegee (*Emex australis*), Skeleton weed (*Chondrilla juncea*), African lovegrass (*Eragrostis curvula*), Prickly Paddy melon (*Cucumis myriocarpus*). Also present are Weeds of National Significance like Rubber vine (*Cryptostegia grandiflora*), Boneseed (*Chrysanthemoides monilifera*), Tamarisk (*Tamarix* spp.), Bridal creeper (*Asparagus asparagoides*), Broom (*Genista spp. Genista monspessulana*) and Blackberry (*Rubus fruticosus).*

At least seven feral or pest vertebrate species are present in the area, including fox, cat, dog, rabbits, rats, mice, and goats. Dieback (*Phytophthora* spp.) has been found and mapped across the region.

Figure 8.14 and **Figure 8.15** show the Beard vegetation systems and the native vegetation extent in the potentially prospective area of the Perth Basin.

Figure 8.14: Vegetation map in potentially prospective areas of the Perth Basin
Source: DWER

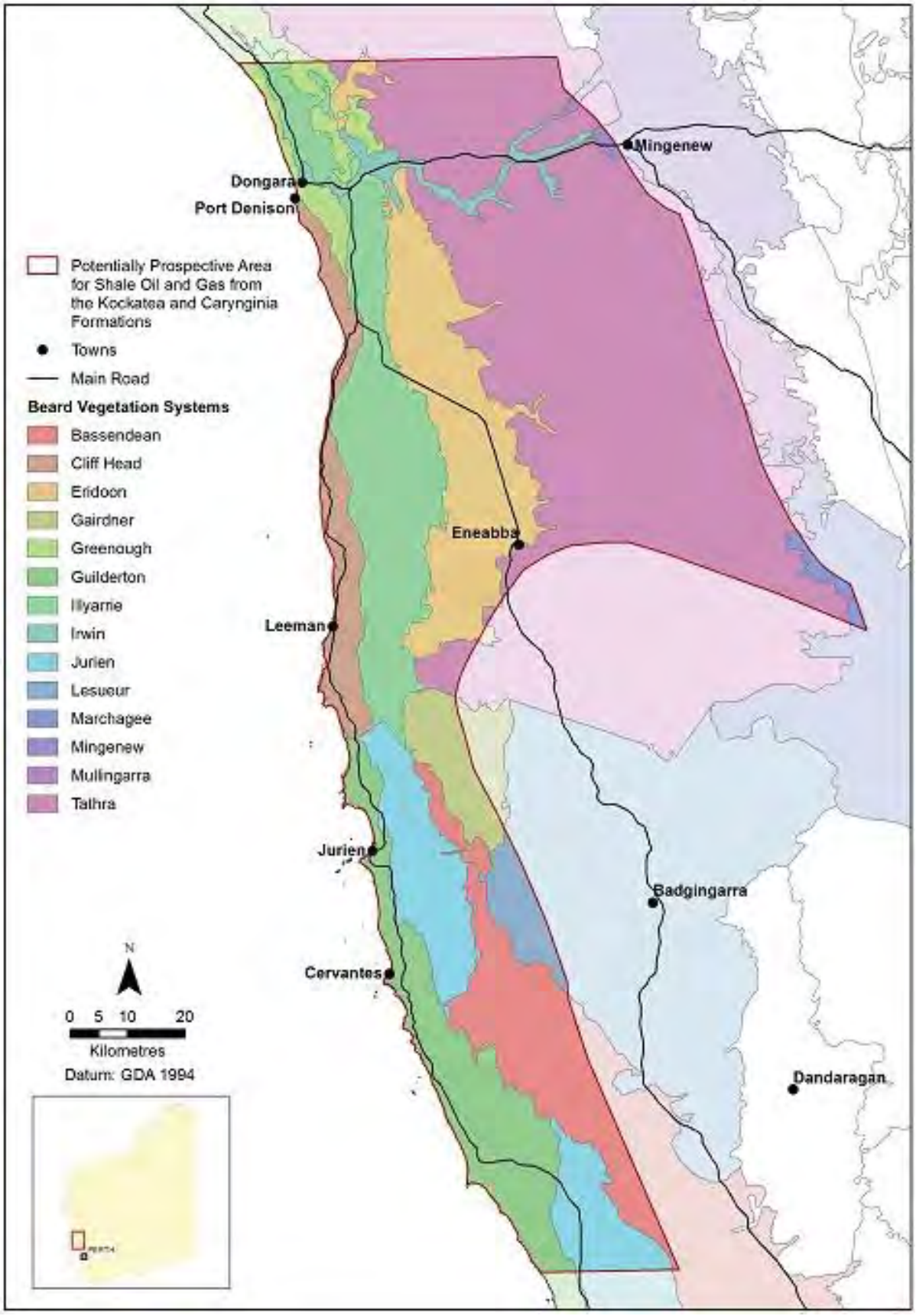
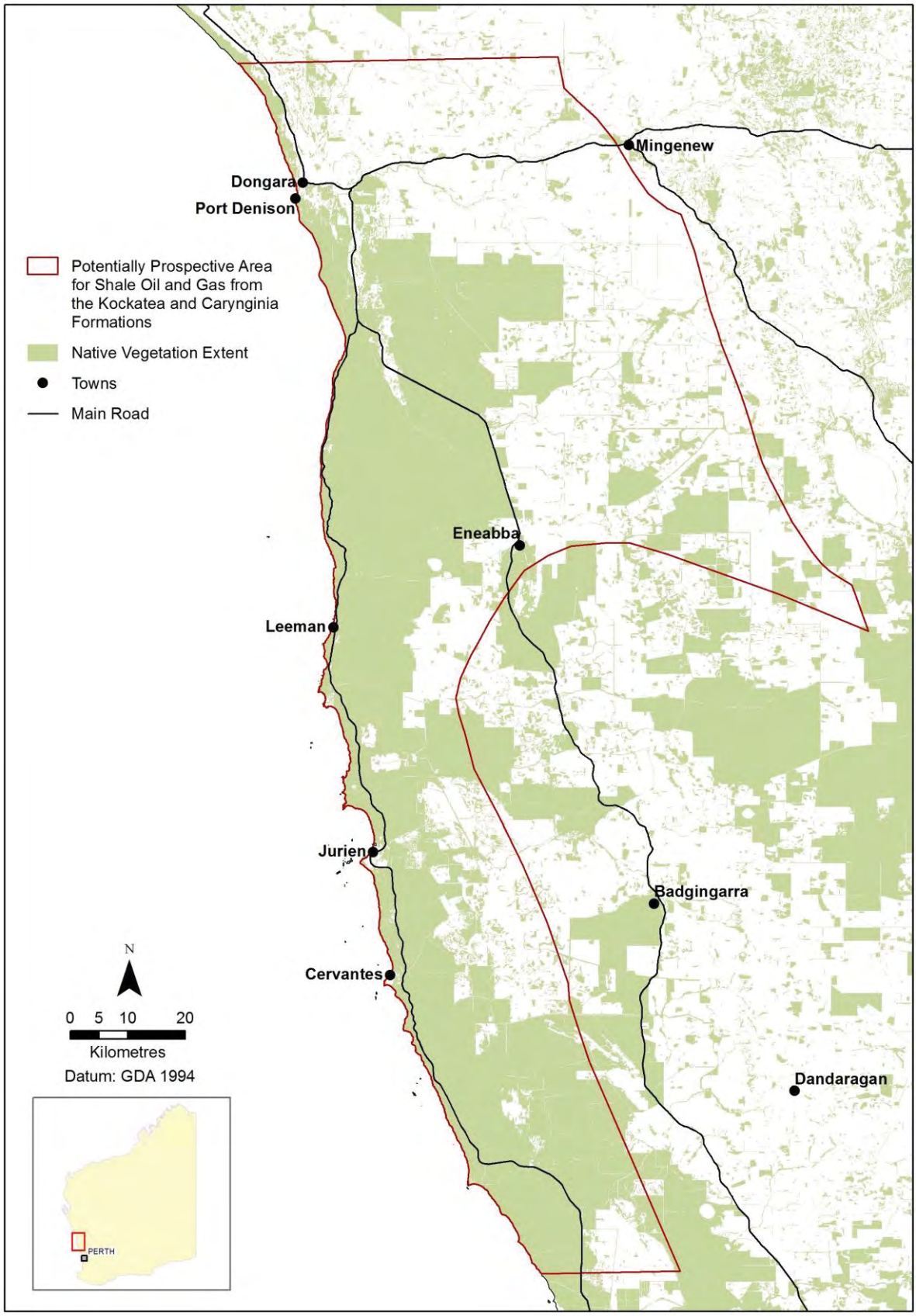


Figure 8.15: Remnant vegetation in potentially prospective areas for oil and gas in the Perth Basin

Source: DWER



8.3.2.1 Perth IBRA Sub-region

The Perth sub-region is composed of colluvial and aeolian sands, alluvial river flats, coastal limestone with heath or tuart woodlands on limestone, banksia and jarrah woodlands on Quaternary marine dunes of various ages and marri on colluvial and alluvials (Mitchell, Williams & Desmond 2002). Rainfall in this sub-region ranges between 600 mm and 1,000 mm annually (declining since the 1970s). The sub-region is part of the South West Botanical Province (Beard 1980), which has very high species diversity. The sub-region has areas of relatively high ecosystem or species diversity, notably on the eastern side of the coastal plain.

Of the 41 vegetation associations (Beard et al. 2013) found in the sub-region, seven have less than ten percent of their original extent remaining, with an additional 18 types with less than 30 percent of their original extent. Given the history of development of the Perth Basin, particularly agriculture, it is not surprising it has a very large legacy of weeds and introduced pests. Coates et al. (Coates et al. 2014) provide a recent description of the Kwongan (heath) component of this region's vegetation and the threatening processes of weeds, disease and fragmentation. Flora species of the Perth sub-region listed as threatened under State legislation include 66 Threatened and 44 Priority 1 flora species.

8.3.2.2 The Dandaragan Plateau IBRA sub-region

The Dandaragan Plateau is underlain by Cretaceous marine sediments and mantled by sands and laterites. The vegetation is characteristically banksia low woodland, jarrah - marri woodland, marri woodland, and scrub-heaths on laterite pavement and on gravelly sandplains. The annual rainfall is 700 mm.

More than 90 percent of the sub-region is cleared for agriculture, with about seven percent set aside for conservation.

Flora species of the Dandaragan Plateau sub-region listed as threatened under State legislation include 25 Threatened and 10 Priority 1 flora species.

8.3.2.3 The Lesueur Sandplain IBRA Subregion

The Lesueur Sandplains sub-region is composed mainly of proteaceous scrub-heaths, rich in endemics, on the sandy earths of an extensive, undulating, lateritic sandplain mantling Permian to Cretaceous strata (Desmond and Chant 2001). The sandplain is comprised of coastal limestones, and Triassic and Jurassic siltstones and sandstones (often heavily lateritised) of the central Perth Basin. Alluvials are associated with drainage systems, and there are extensive yellow sandplains in south-eastern parts, where the sub-region overlaps the western edge of the Yilgarn Craton. Heaths rich in endemics occur on a mosaic of lateritic mesas, sandplains, coastal sands and limestones, with heath on lateritised sandplains along the sub-region's north-eastern margins.

About 70 percent of this sub-region is cleared for agriculture, with about 17 percent in the conservation estate.

Flora species of the Lesueur Sandplain sub-region listed as Threatened under State legislation include 59 Threatened and 47 Priority 1 flora species.

8.3.2.4 The Conservation Estate in or near the prospective region of the Perth Basin

The region has a complex pattern of conservation estate including national parks and marine parks, as listed below:

- Alexander Morrison National Park;
- Tathra National Park;
- Nambung National Park;
- Jurien Bay Marine Park;
- Badgingarra National Park;
- Moore River National Park;
- Stockyard Gully National Park
- Drovers Cave National Park;
- Lesueur National Park;
- Watheroo National Park.

Nature reserves include:

- Beekeepers Nature Reserve
- Yardanogo Nature Reserve;
- Wilson Nature Reserve;
- Dookanooka Nature Reserve;
- Wotto Nature Reserve;
- Depot Hill Nature Reserve;
- Lake Logue Nature Reserve;
- South Eneabba Nature Reserve;
- Capamauro Nature Reserve;
- Pinjarrega Nature Reserve;
- Boothendarra Nature Reserve;
- Coomalo Nature Reserve;
- Hill River Nature Reserve;

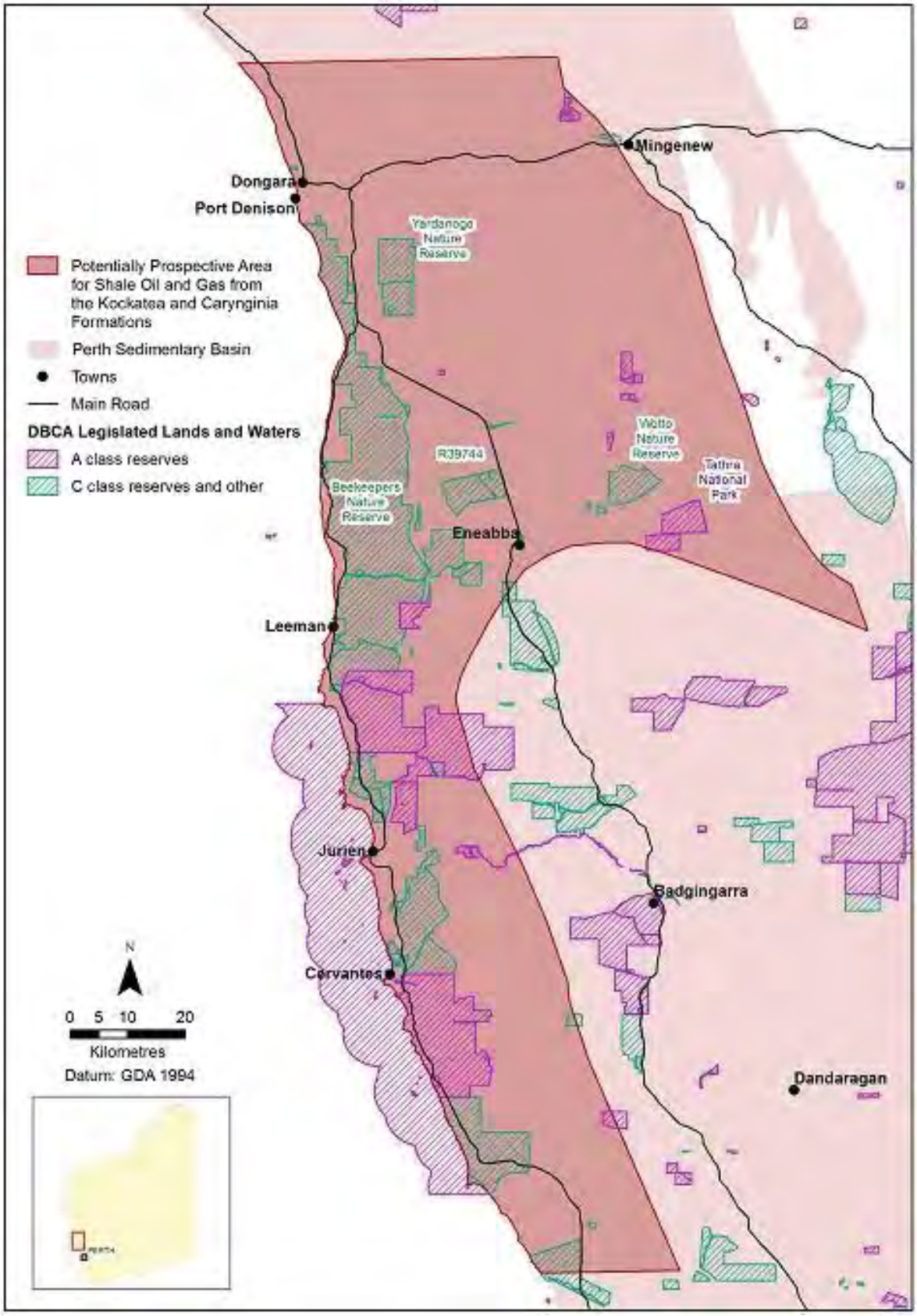
- Minyulo Nature Reserve;
- Wongonderrah Nature Reserve;
- Wanagarren Nature Reserve;
- Eneminga Nature Reserve;
- Bashford Nature Reserve;
- Nilgen Nature Reserve;
- South Mimegarra Nature Reserve;
- Namming Nature Reserve;
- Boonanarring Nature Reserve and large areas of the Gnangara -Moore River State Forest.

Collectively, the conservation estate covers a significant portion of the most prospective shale oil and gas formation, and as detailed below is subject to potential petroleum exploration and development. It is not unusual for resource exploration companies to request access to the conservation estate for broad scale exploration activities (such as seismic surveys) that may require environmental impact assessment and result in some environmental risks and impacts. Examples of such environmental assessments for this region are reflected in EPA reports associated with Ministerial Statements 159 (Coomallo), 119 (Watheroo National Park), 157 (South Eneabba Nature Reserve), 062 (Lesueur National Park) and 664 (Beekeepers Nature Reserve).

On 31 October 2014, the State Government granted Norwest Energy an Exploration Permit (492) that covered, among other areas, significant portions of Nambung National Park, including the iconic Pinnacles. Shortly thereafter, the company stated it had no intention of exploring or using hydraulic fracture stimulation at the Pinnacles or surrounding significant parts of the Park and formalised a variation to the permit that excluded significant areas including the Pinnacles, Red Desert, Little Painted Desert and Painted Desert.

Figure 8.16: The conservation estate in proximity to the potentially prospective areas of the Perth Basin

Source: DWER



8.3.2.5 Structures, stresses and seismicity of the Perth Basin

The Perth Basin is a north-south rift basin that contains a series of elongated, fault-bounded blocks uplifted and downthrown relative to one another (Norvick 2004). The major structures in the North Perth Basin are described by Mory et al.(Mory et al. 2005) and the Department of Water (Department of Water 2017a). Further details of the hydrogeology are discussed in the **Section 9** (Water) of this Report.

The high areas are denominated terraces or ridges, where older rocks are encountered near to the surface at the present day, following erosion. In the troughs between these high areas, thicker sediments accumulated and the rocks close to the surface are relatively younger (**Figure 8.17**). The main Darling Fault that bounds the Basin against the Yilgarn Craton to the east is, in places, overlain by sediments as old as upper Cretaceous in age, indicating that this major fault has not moved for tens of millions of years. Within the Basin, smaller faults have a range of orientations that may place them at a higher risk of potential reactivation **(Figure 8.18)**.

The present day state of stress in the Northern Perth Basin is described by King et al. (King, Hillis & Reynolds 2008) based on a compilation of well data. The Basin is generally under east-west compression, and the high value of the maximum horizontal stress compared with the vertical stress gives the Basin a strike slip stress regime, transitional to a thrust faulting regime. In this stress field, north-northwest striking faults with moderate dips and east-northeast and east-southeast oriented fracture sets, with shallow to steep dips, could potentially be reactivated. New faults and fractures will form with these orientations. Faults and natural fractures with east-west orientation and east-west orientation are least likely to reactivate in this stress regime.

In the offshore Perth Basin, studies by Geoscience Australia (GA) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) identified that some faults are actively leaking hydrocarbons from the Abrolhos Sub-basin area (Langhi et al. 2012). Thus, at least some faults in the basin may form permeable pathways for fluids and so are potentially hydrogeologically active. The leakage may be associated with episodes of fault movement, or more long lived, connected permeable pathways that are not closed by stresses. This is discussed in detail in **Section 9** (Water) of this Report.

Figure 8.17: Map of the main geological structures of the Northern Perth Basin

Source: Department of Water (DoW) (Department of Water 2017a)

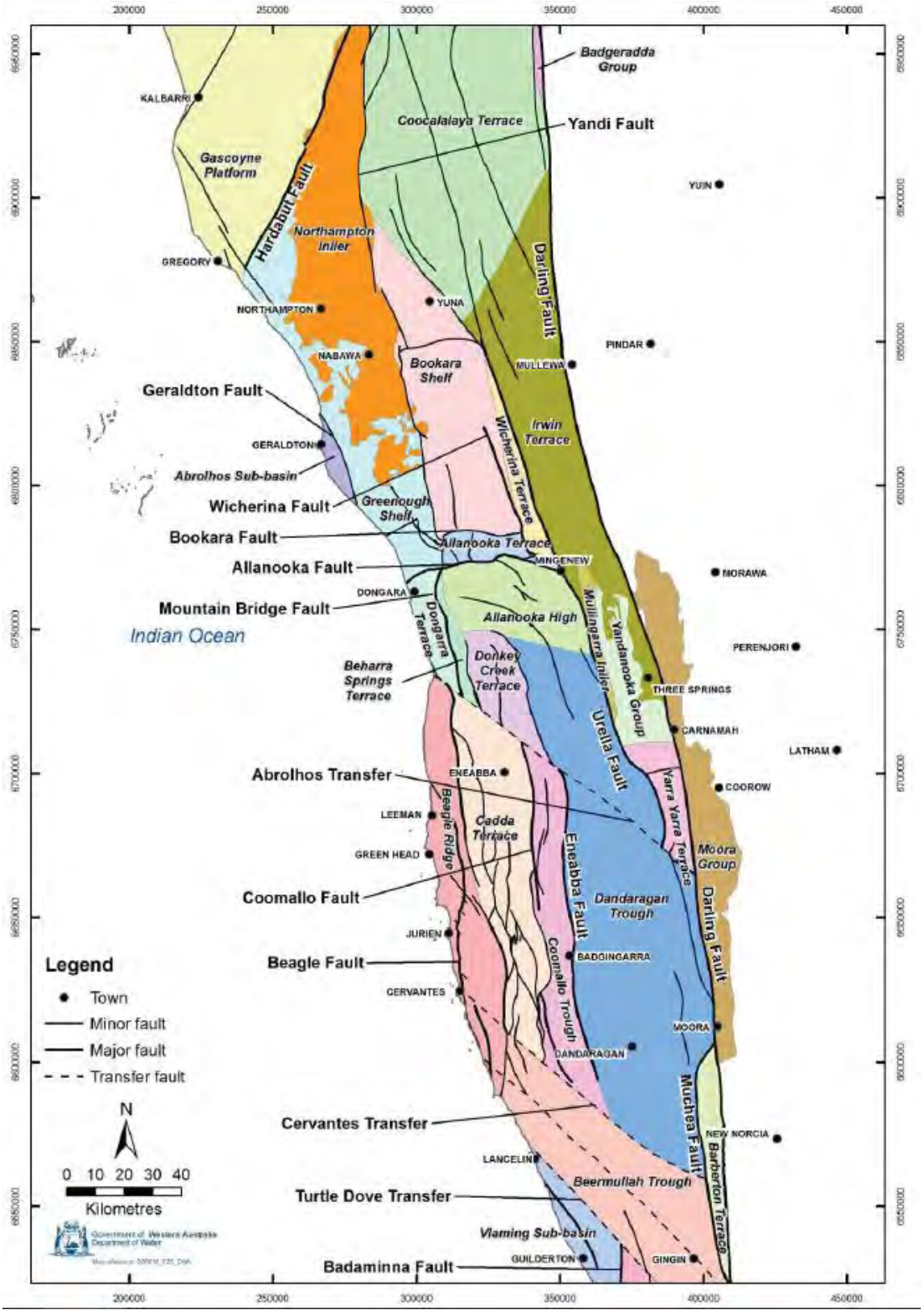


Figure 8.18: Geological map of the Northern Perth Basin

Source: DoW (Department of Water 2017a)

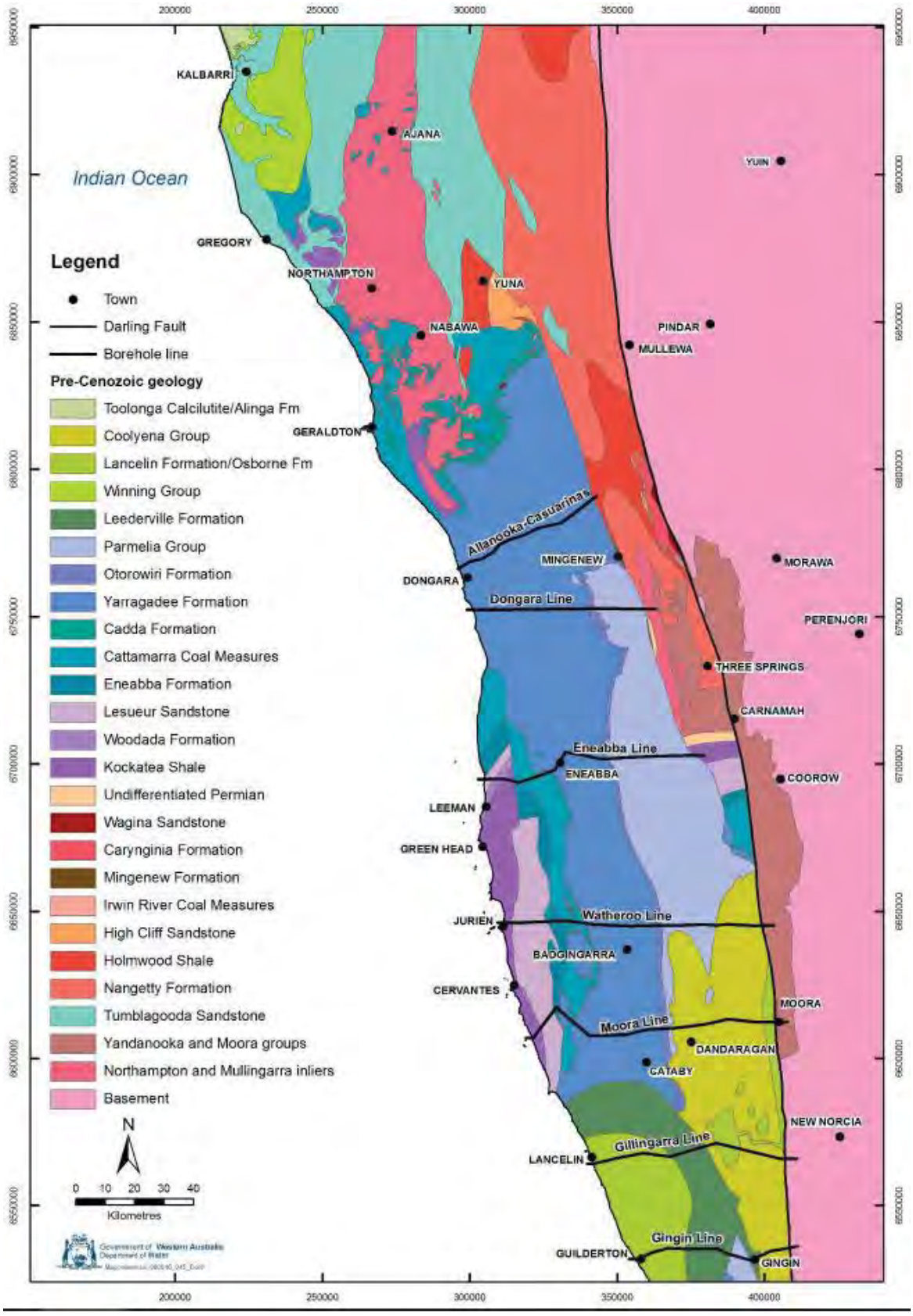


Figure 8.19: Principal stress directions of the maximum horizontal stress in the Perth Basin
Source: Rajabi et al. (Rajabi et al. 2017)

The Northern Perth Basin is relatively quiet in terms of historical seismicity with principle stress directions shown in **Figure 8.19**. It is identified as having low seismic hazard, being mapped as a 'background zone' by GA (**Figure 8.20**). There are more earthquakes in the offshore part of the Perth Basin than in the onshore region. To the east of the Perth Basin, there is an important zone of higher natural seismicity and seismic hazard in the Yilgarn Craton, where several larger earthquakes have been experienced in historical times (including the Meckering earthquake). As expected, from the scaling laws for earthquake sizes, the zone experiencing larger earthquakes in the Yilgarn also has a much higher number of small events.

Where the depth of events can be determined, most earthquakes in the Perth Basin are focussed within the basement rocks that lie beneath the sedimentary succession. Owing to

the small number of ground stations, earthquake locations are generally not determined with sufficient accuracy to relate them to a particular fault or zone of faulting, but there is no one area within the Basin that can be identified as having elevated seismic risk. Seismic recording stations within the Basin itself would enable better delineation of critically stressed and potentially hydrogeologically active faults.

Figure 8.20: Map of seismic hazard zones in South-West Western Australia
Source: GA (Jones 2004)

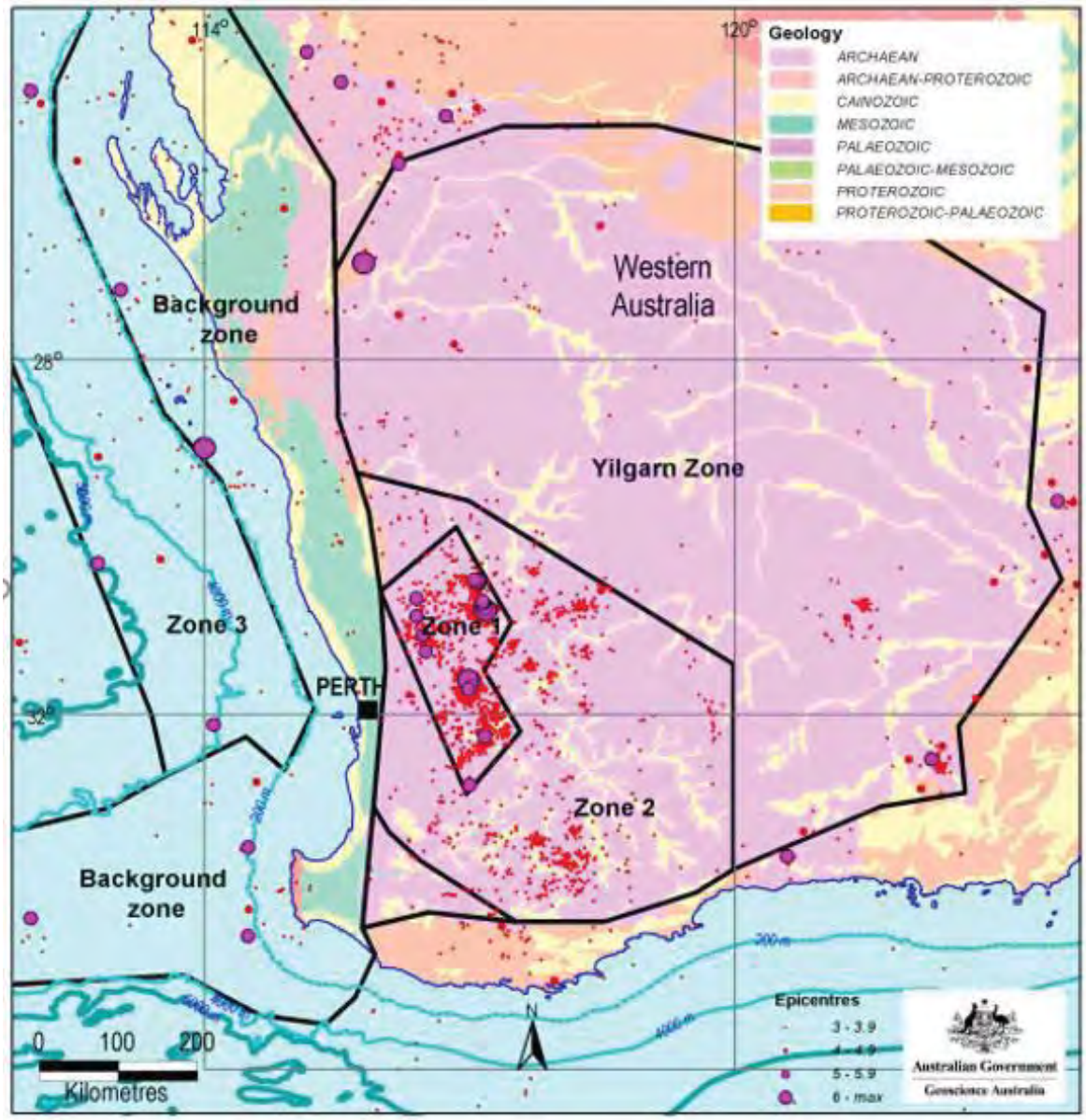
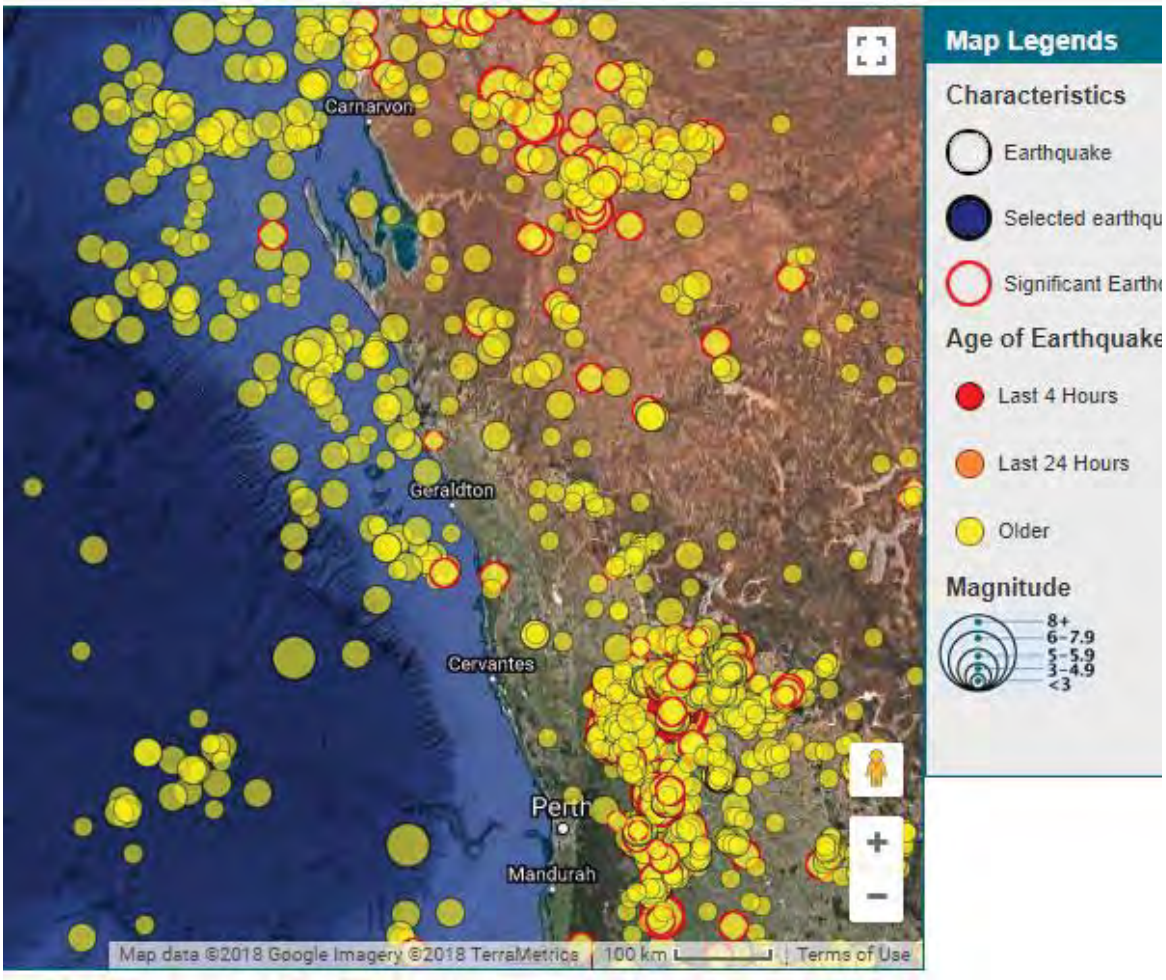


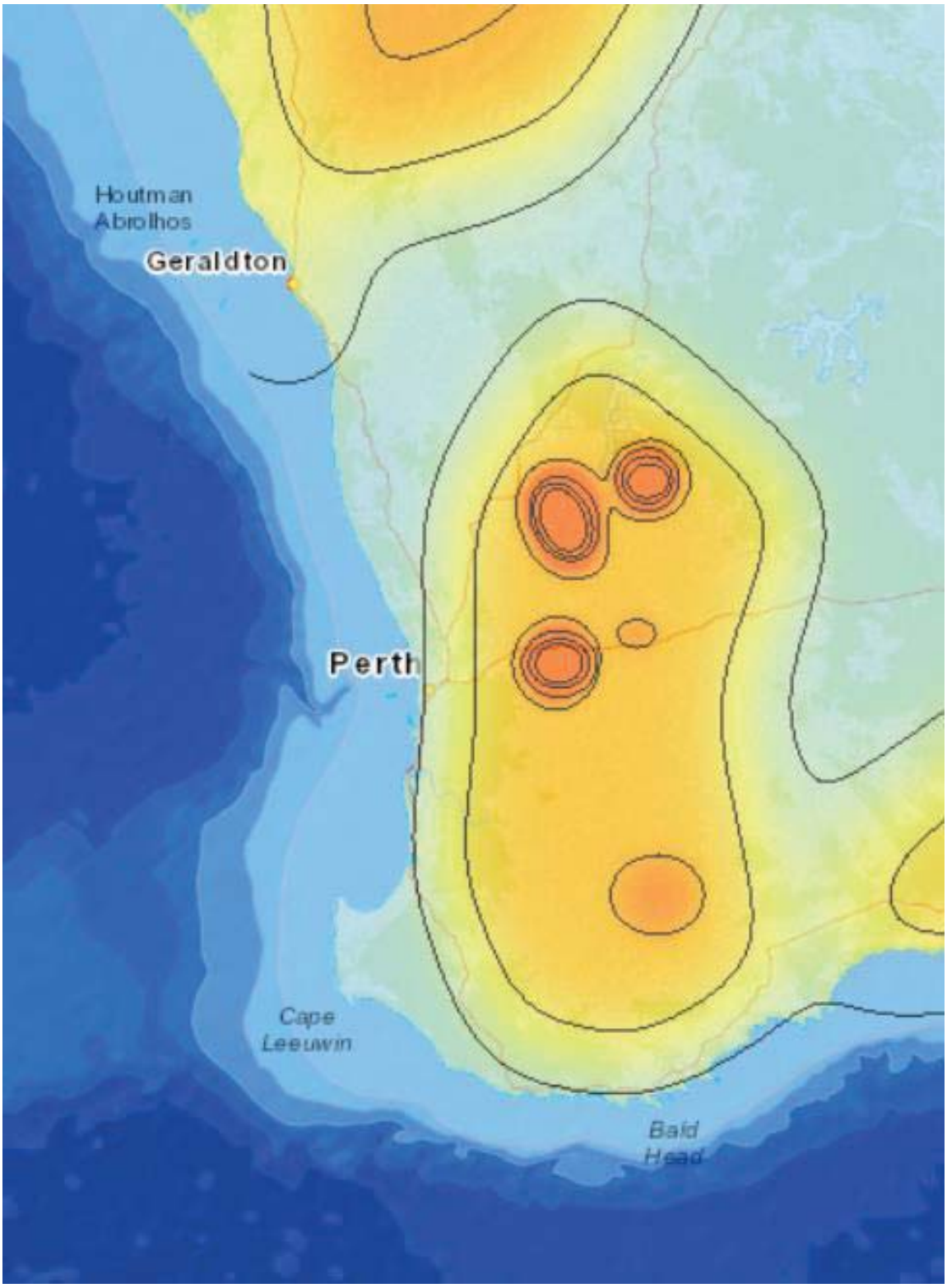
Figure 8.21: Record of historical earthquakes > Mw 2.4 in the Perth Basin area
Source: GA catalogue



http://www.ga.gov.au/earthquakes/searchQuake.do

Figure 8.22: Map of seismic hazard in the region of the Perth Basin

Source: GA (Geoscience Australia 2017)



8.4 Protection of environmental values associated with land in Western Australia

A range of Federal and State legislation govern the impacts an oil and gas development may entail. The principal Acts include the following.

8.4.1 The Petroleum and Geothermal Energy Resources Act 1967

The Petroleum and Geothermal Energy Resources Act 1967, and its subsidiary regulations, impose many requirements on proponents of oil and gas developments, including those intending to use hydraulic fracture stimulation as part of their operations. These requirements include detailed management plans aimed at reducing the risk to the environment, including local population centres and land uses. An overview of these regulations is presented in **Section 4** (Regulation) of this Report.

This documentation must extend to descriptions of the existing environment and consequences to that environment, including unplanned incidents like spills or fire, and must reflect consultation with relevant authorities and interested persons and organisations. Of particular note to the issue of protecting the environmental values of land from petroleum-related activities, is that the only specific cases where consent of the owner or trustee is required is: private land less than 0.2 hectares in size; cemeteries or burial places; reservoirs; places less than 150 metres from the aforementioned; or any 'substantial improvements'. The latter is determined by the Minister for Mines and Petroleum. There are no other prescriptive sections of the Act, or the derived regulations, that prescribe mandatory separation distances between petroleum development and other land uses or sensitive receptors (such as residences or settlements).

8.4.2 The Environmental Protection Act 1986

Additional State and Federal legislation directly protect the environmental values associated with land in general, and biodiversity and nature conservation in particular. The protection of Western Australia's environment is legislated primarily through the *Environmental Protection Act 1986* (EP Act). The object of that Act is to protect the environment of the State, with regards to a set of principles including precaution and the conservation of biological diversity and ecological integrity. Native vegetation clearing, for example, is governed by this Act, which requires that any person clearing native vegetation on private or public lands across the State must hold a permit, unless they qualify to clear under an exemption. The DWER administers the clearing of native vegetation under the EP Act; the Department of Mines, Industry Regulation and Safety (DMIRS) have a delegation to approve clearing for mining and petroleum activities, but are held to the same approval criteria. A detailed description of how clearing is regulated, with reference to the relevant laws, can be found at https://www.der.wa.gov.au/our-work/clearing-permits.

Where a proposal's potential environmental impacts may be significant, it is referred to (or called in by) the EPA for consideration to assess. In doing so, the EPA considers whether the

proposal has sufficiently applied the mitigation hierarchy to avoid, minimise, remediate and, potentially, offset impacts, for the proposal to meet the EPA's environmental objectives.

Under a 2016 Memorandum of Understanding between DMIRS and the EPA (http://www.epa.wa.gov.au/sites/default/files/Publications/OEPA-DMP-MOU-100216_0.pdf), all onshore proposals meeting any of the following criteria are to be brought to the EPA's attention for potential assessment:

- Environmentally sensitive areas including;
    - Within 500 m of World Heritage property;
    - Within 500 m of a Bush Forever site;
    - Within 500 m of a TEC;
    - Within 500 m of defined wetlands (including Ramsar wetlands, Australian Nature Conservation Agency (ANCA) wetlands, conservation category wetlands);
    - Area containing rare flora;
    - Area covered by an Environmental Protection Policy;
    - Within 500 m of a declared/proposed State Conservation Estate, including a National Park, Nature Reserve, Conservation Park or State Forest and Timber Reserves;
    - Within a Public Drinking Water Source Area (PDWSA);
    - Within 2,000 m of a declared occupied town site;
    - Hydraulic fracturing exploration and development activities;
    - Activities within the Strategic Assessment for the Perth Peel Region; and an
    - Area previously or currently subject to formal assessment by the EPA.

The EPA has developed general technical guidance to inform proponents and the assessment of their proposals; of note here is EPA Guidance Statement 3 - Separation Distances between Industrial and Sensitive Land Uses (Environmental Protection Authority 2005). Separation distances are the estimated distances recommended to separate a source of emissions from sensitive land uses, to ensure that the health and amenity of people are not adversely affected. Sensitive land uses, in this context, include residences, hospitals and nursing homes, short-stay accommodation, schools, child care facilities, shopping centres, playgrounds and some public buildings. Some commercial, institutional and industrial land uses that require high levels of amenity or are sensitive to particular emissions may also be considered 'sensitive land uses'. In EPA Guidance Statement 3, and in the absence of any further specific information, the recommended separation distances are generally considered sufficient to minimise harmful exposure. Developments proposed to be within

these distances are expected to provide evidence and analyses showing no resulting increase in risk. Oil and gas extraction, and processing and refining, all have a recommended separation distance of 2,000 m.

The EPA may choose to formally assess any such project, and in 2016 it indicated that it will assess projects involving hydraulic fracture stimulation, although none have been referred since that decision. It is also likely that major oil and gas infrastructure, such as large processing facilities or regional pipelines, would trigger a formal assessment by the EPA, while proposals for individual conventional oil and gas wells may not. The EPA has not had the opportunity to assess the environmental impacts of a gas field in toto, as this has not been part of the onshore oil and gas approval system to date. In that regard, the EP Act affords the EPA the option of anticipating the cumulative impacts of future proposals of a like kind across a region (a strategic assessment), and there is no reason, in principle, that this could not be done for unconventional gas fields.

8.4.3 Biodiversity Conservation Act 2016

The *Biodiversity Conservation Act 2016* of Western Australia has the objectives of:

> "(a) to conserve and protect biodiversity and biodiversity components in the State and (b) to promote the ecologically sustainable use of biodiversity components in the State"

The Act empowers the State to create biodiversity management programs to conserve or protect species, ecological communities, and habitats; to manage the sustainable use of native species; and to manage research and strategies relevant to biodiversity conservation.

8.4.4 Conservation and Land Management Act 1984

The Conservation and Land Management Act 1984 (CALM Act) defines the nature and vesting of the conservation estate of Western Australia, including national parks, conservations parks, State forest, marine parks, marine nature reserves, marine management areas, nature reserves and timber reserves. The CALM Act gives the management of the conservation estate to the Department of Biodiversity, Conservation, and Attractions (DBCA). It also specifies the kinds of activities that may not be permitted in the conservation estate, for instance, petroleum exploration or production is forbidden in a marine park sanctuary zone, but may be permitted in a general purpose zone. The CALM Act does not in general derogate from (limit) the operation of the *Mining Act 1978,* the *Petroleum and Geothermal Energy Resources Act 1967*, or any other Act relating to minerals or petroleum. Section 15A of the *Petroleum and Geothermal Energy Resources Act 1967* allows the Minister for Mines and Petroleum, in consultation with the Minister for Environment, to consent to enter the conservation estate 'for the purpose of mining and petroleum-related activities', including national parks and conservation reserves.

8.4.5 Environmental Protection and Biodiversity Conservation Act 1999

At the Federal level, the *Environmental Protection and Biodiversity Conservation Act 1999* (EPBC Act) has objectives including:

- Provide for the protection of the environment, especially matters of national environmental significance;
- Conserve Australian biodiversity;
- Provide a streamlined national environmental assessment and approvals process;
- Enhance the protection and management of important natural and cultural places; and
- Promote ecologically sustainable development through the conservation and ecologically sustainable use of natural resources.

If a development proposal threatens to impact any Matters of National Environmental Significance (MNES), it may trigger an assessment under the EPBC Act. The matters potentially relevant to this Inquiry extend to:

- World Heritage properties;
- National Heritage places;
- Wetlands of international importance (listed under the Ramsar Convention);
- Listed threatened species and ecological communities; and
- Migratory species protected under international agreements.

It is an option at present for the Western Australian EPA to undertake a bilateral assessment with the Department of the Environment and Energy (DoEE), which would inform independent and separate approval decisions by the State Environment Minister under the EP Act and the Federal Environment Minister under the EPBC Act.

8.5 Key issues raised

The Inquiry heard, through written submissions and presentations at public meetings, concerns about the impact hydraulic fracture stimulation (and the onshore expansion of an oil and gas industry that it would make possible) would have in relation to a number of risks to landscapes and biodiversity. These included:

- Fragmentation and loss of the landscape and habitat, including water course edge impacts;
- Spread of Phytophthora dieback, weeds, feral animals and increased fire risk;
- Impacts to fauna habitats directly associated with stormwater runoff and change of surface water flows;

- Impacts to stock, flora and fauna due to exposure to chemical and wastewater, including spills during transportation;
- Damage to public and private roads;
- Impacts to agricultural soil and crop productivity (including product safety and marketing certification) from soil or water contamination;
- Loss of agricultural productivity due to land degradation or restricted or disrupted access; and
- Induced seismic events.

8.6 Risk assessment

8.6.1 Overview

Peer-reviewed literature on the impacts of unconventional oil and gas development in Western Australia is lacking, and although some Australian impact literature is available, it is not well-developed. The Inquiry therefore looked internationally, where the relevant research is significantly more mature if, for no other reason, the unconventional oil and gas developments have been established for some time and at scale.

Overseas studies on the landscape footprints of unconventional oil and gas fields consider the cumulative and diverse impacts on the environment, including biodiversity, landscape amenity and ecosystem health. Some of these, for example as found by Burton et al. and McClung & Moran (Burton et al. 2014; McClung & Moran 2018) only point out the potential risks based on predictive ecology and call for more research. While others have looked at actual impacts, such as Donnelly et al.(Donnelly, Cobbinah Wilson & Oduro Appiah 2017) who evaluated the landscape impacts of shale gas developments in two forested systems and found in each that one percent of the area was cleared with additional implications from habitat fragmentation. Allred et al. (Allred et al. 2015) calculated the loss of net primary productivity across North America from all oil and gas developments and at the other extreme Copeland et al. (Copeland et al. 2009) looked at the impacts of oil and gas development on a single species of local concern.

From the general literature, the Inquiry concluded that for the landscape and biodiversity impacts of oil and gas development based on hydraulic fracture stimulation, there is limited potential risk to land and associated environmental values directly associated with the hydraulic fracture stimulation itself. These extend to: increased impacts from traffic; the potential for local soil contamination from chemical spills used in the process; the potential to increase seismicity; and the potential contamination of surface water from spills or leakage. The latter is considered in detail in **Section 9** (Water) of this Report.

More generally, however, the Inquiry agrees with Brittingham et al. (Brittingham et al. 2014) in concluding that the broader impacts of an unconventional oil and gas fields are largely of the same nature as other anthropogenic activities involving clearing, roads and other

infrastructure development, with those few exceptions specific to the hydraulic fracture stimulation technology such as the risk of surface chemical spills. Thus, the wider environmental and ecological literature is largely applicable in considering the potential landscape and biodiversity impacts of unconventional oil and gas development, as is the existing environmental impact framework for assessing those impacts. The Inquiry also agrees with the broad ecological literature regarding the principal determinants of those impacts, being scale and proximity to areas of high ecological sensitivity or value.

8.6.2 Pressures arising from developing onshore unconventional oil and gas

8.6.2.1 Infrastructure development

The general infrastructure associated with onshore oil and gas developments based on hydraulic fracture stimulation, are described in **Section 6** (Overview) of this Report, and in some very specific detail in industry submissions to this Inquiry. These include well pads, storage areas and wastewater ponds, lay-down areas for equipment, pipelines, water supply infrastructure, and gas processing facilities. Infrastructure also extends to the tracks and roads required for both exploration and operations. The potential environmental pressures that result from the use of this infrastructure extends to increased traffic, noise and light, land degradation (particularly erosion and contamination), spread of weeds and pests, and fire risk. To estimate the potential overall land footprint of onshore unconventional oil and gas development, the Inquiry considered both the generalised estimates available in the literature, as well as the specific infrastructure anticipated in development scenarios submitted by companies anticipating further operations in Western Australia and the regulatory environment that applies to them.

Generalised estimates of infrastructure footprints associated with the development of unconventional oil and gas are largely based on experience overseas, and some caution is needed in recognising significantly different settings to those in Western Australia, including how water is transported to and from sites, the degree that existing roads are used (and the degree that increases local traffic), the number of wells per well pad and their aerial coverage, the degree to which further land clearing is required, and the degree to which new infrastructure might be required to get the product to market.

Slonecker (Slonecker et al. 2012) evaluated total footprints of shale gas developments in two counties in Pennsylvania. This study found 0.5 – 0.8 percent of the counties were impacted, and where forested, the developments caused a loss of 0.12 to 0.42 percent of forest cover and reduced mean forest patch size by eight to twenty percent (noting that the forested landscape was already reduced to patches of mean size 35 to 40 ha by historic development). Donnelly et al. (Donnelly, Cobbinah Wilson & Oduro Appiah 2017) found shale gas developments in two formations in the United States, both disturbed less than one percent of the region, although noted the habitat fragmentation it caused. Wolaver et al.

(Wolaver et al. 2018) forecasted the impact of 17,000 to 45,500 wells across the Eagle Ford Shale Play would impact 0.73 to 1.96 percent of the region's vegetation.

The density of unconventional wells indicated in company submissions to this Inquiry is one well pad per 16 to 23 km^2, which is similar to the range of industry estimates quoted by the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory (one pad per 10 to 20 km^2). This is a lower density than existing conventional gas wells in the gasfields of the northern Perth Basin. In its first 25 years of operation, the 45km^2 Dongara field, for instance, had 27 wells drilled, of which 20 were completed for gas production; the small Mt Horner oilfield had 13 wells in 2 km^2 (Mory & Iasky 1996).

SKM (Sinclair Knight Merz 2013) estimated the need for about 1.5 km of connecting pipeline and roads per well pad whereas the Northern Territory used an industry estimate of 2.1 km at a width of 15m, with about another kilometre per well pad, required to connect processing facilities. In its submission to this Inquiry, the Australian Petroleum Production and Exploration Association (APPEA) reported an industry estimate of an unconventional oil and gas field footprint at about 14 ha (0.14 km^2) per well pad developed, which includes pipeline connections and access roads. Using the higher of all these estimates, the total footprint of an unconventional oil and gas development might extend to 1.5 to 2.5 percent of the development area prior to any subsequent rehabilitation and revegetation.

Finding 1: In the potentially prospective area for shale oil and gas in the Perth Basin, which encompasses existing gas fields between Eneabba and Dongara, the geology is most suitable for production from stimulated horizontal wells, with a density of well pads substantially lower than overseas unconventional gas fields with vertical wells.

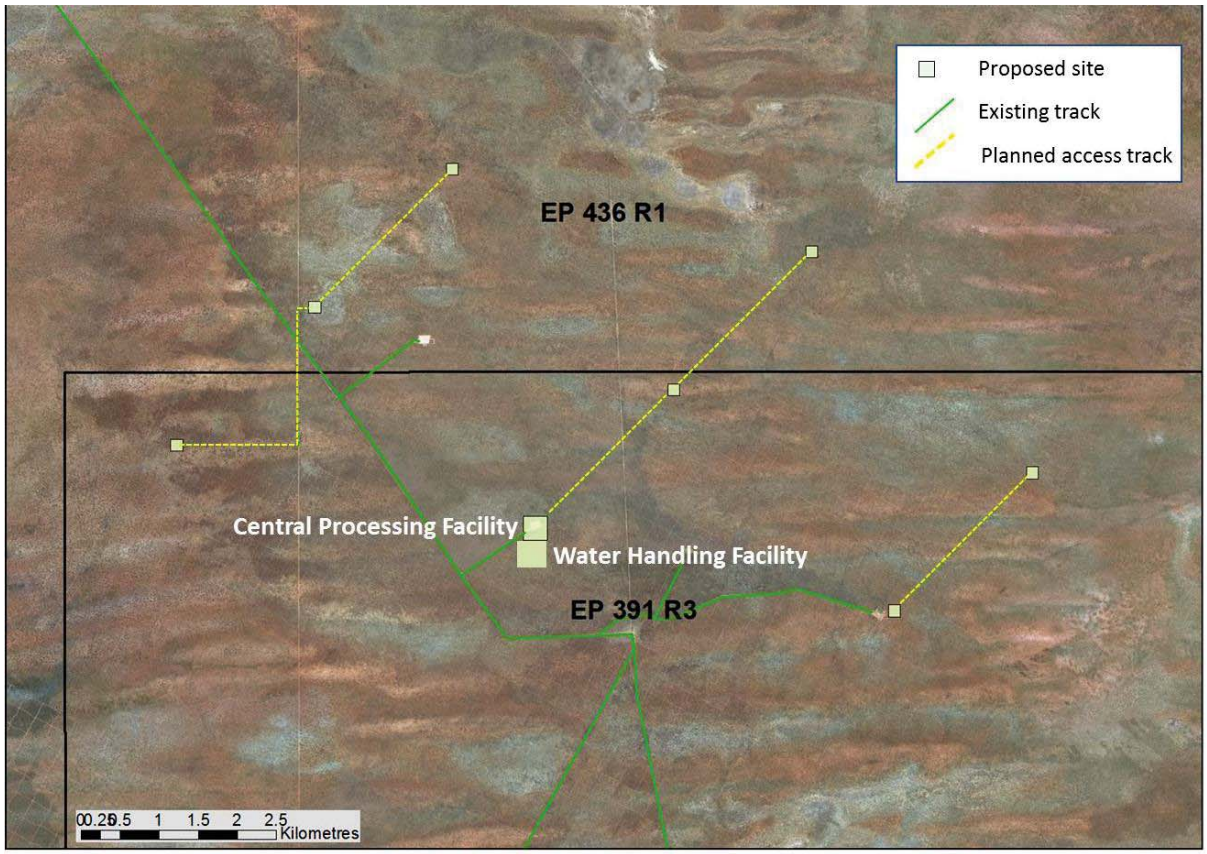
All Findings and Recommendations are consolidated in Section 14

The Inquiry notes that these collective estimates of well pad density do not accord with the many visual representations of unconventional oil and gas fields found elsewhere in the world, which were included in a number of the submissions to this Inquiry, showing a much higher density of well sites. Indeed, the descriptions of well site densities from elsewhere are in some cases higher than those anticipated above, whether for reasons of geology, advancing technology or both.

In its submission to this Inquiry, Buru Energy estimated its total development footprint at Yulleroo (producing a nominal 130 TJ/d) including roads, pipelines, gas processing and water treatments facilities to be about 1 km^2 in an area of more than 100 km^2 (1 percent). This does not include any previous clearing for exploration nor does it include a pipeline to market. A similar analysis was contained in MC Resources Australia's submission.

Figure 8.23: Proposed layout of infrastructure in support of a 130 TJ/d development in the Canning Basin by Buru Energy, involving the clearing of about 100 hectares of native vegetation

Source: Buru Energy Submission



In addition to the footprints of the developed oil and gas field, there may be additional footprints from any pipelines to connect the field to market. Connecting unconventional oil and gas development in the Canning Basin to anything other than a highly restricted local market would require a pipeline to Karratha more than 500 km long. At a nominal width of 10 m this would translate to a regional footprint of 5 km^2.

In the Canning Basin, any new infrastructure will almost entirely require clearing (and subsequent rehabilitation) of native vegetation, noting the existing condition of vegetation varies with previous land use, especially from grazing and fire regimes. The situation is quite different in the Perth Basin, which is already heavily cleared and existing pipeline infrastructure is available to get the gas to a large domestic market.

8.6.2.2 Broad scale exploration

The development of any onshore oil and gas field (conventional or otherwise) is normally preceded by a broad exploration of the region to identify the most prospective places. This typically involves on-ground seismic surveys, which in turn require vehicle access along an extensive set of seismic lines. As an example, the proposal by UIL Energy Ltd for a 2-D seismic survey within Exploration Permits 447, 488 and 489 in the Perth Basin (UIL Energy

2016) involved 264 km of seismic lines 4.5 m wide and spaced 2 km to 9 km apart. Because this survey would take place in a landscape already heavily cleared, the survey design only required the clearing of 24 ha of native vegetation. These lines are typically used just once. Regulations require flora and fauna surveys to inform impact avoidance and mitigation, the control of weed and pest introduction (especially dieback), and soil protection and rehabilitation. In this case, the company committed to cutting the vegetation above ground and green mulching in situ to protect the soil surface and seedbank, followed by a rehabilitation and offset program. A 3-D seismic EPBC referral from UIL Energy Ltd for Exploration Permit 495 (Perth Basin) indicates plans to acquire 237 km of data requiring 96 hectares of native vegetation clearing.

"Fracking, similar to other types of resource extraction, is often considered to have a relatively small development footprint. This is because the actual extraction pads cover a relatively small area. However, the assessment of the footprint and its impact needs also to take into account the linear infrastructure associated with the actual extraction infrastructure" – submission from Prof Richard J. Hobbs

An example of a more extensive seismic survey (and associated regulation and management) perhaps more typical for remote areas is the Santos survey plan for the Amadeus Basin (Santos 2016), which describes the design and environmental impacts, mitigations and restoration for 1,300 km of survey. Similarly, Buru Energy's environmental plan for the Kurrajong 3D seismic survey for Exploration Permits 391 and 436 of the Canning Basin detailed the flora and fauna surveys preceding the establishment of the survey lines, the quarantine protocols, the avoidance of sensitive areas, surface water features and large trees, rehabilitation and monitoring of recovery.

8.6.2.3 Increased traffic

Associated with the physical land footprint of onshore oil and gas development, is an increase in traffic, particularly in the development phase of an unconventional oil and gas field. The potential land impacts from increased traffic on landscapes are two-fold. The first is a decrease in landscape amenity (particularly at places with high natural or cultural heritage values). The second is direct impacts on fauna. Other traffic impacts on social surroundings are considered separately in **Section 12** (Social surroundings) of this Report.

The literature estimates of increased Heavy Duty Vehicle (HDV) traffic associated with hydraulic fracture stimulation vary widely, but for the most part focus on the traffic associated with the use and disposal of water and chemicals used in the hydraulic fracture stimulation process (Goodman et al. 2016). The focus on HDVs in particular is driven by their disproportionate annoyance arising from noise emissions when compared to lighter vehicles (Sandberg 2001). There is a great variation in HDV traffic estimates in the literature due to differences in the amount of water and sand (proppant) requiring transportation by truck, the number of stimulations required, and the need to transport flowback liquids by truck;

these features can comprise more than 75 percent of HDV movements. As an example, the assessment of natural gas impacts for New York City's Watershed estimated 800 to 1,000 truck trips per well, about half of which was to deliver water and another third was for the removal of flowback water. Broderick et al. (Broderick et al. 2011) used these estimates to consider whole-of-life traffic for a six-pad well and reported a range of 3,870 to 5,750 trips per well pad, including construction, water delivery and water removal.

In its submission to this Inquiry, Buru Energy provided traffic estimates and modelling for the conceptual gas field proposed at Yulleroo (nominal production 130 TJ/d for 17 to 20 years based on eight well pads each with ten wells). In this case, neither the water supply nor the flowback water would require trucking; most vehicle movements were associated with the delivery of sand (proppant). Buru Energy estimated that up to 190 return truck trips would be associated with each hydraulic fracture stimulation campaign (stimulating three to four wells), with perhaps two campaigns per year. Traffic movements would comprise approximately 30 truck movements associated with fracturing equipment, about 110 traffic movements associated with sand (proppant) and a further 50 movements associated with incidental traffic movements to site. These estimates are broadly consistent with equivalent traffic components as described in Broderick et al. (Broderick et al. 2011) but do not include traffic for site establishment and road construction, as there are largely existing developments at Yulleroo. The estimates are also consistent with those provided to this Inquiry by Condor Energy Services Ltd, which indicated that a medium to large hydraulic fracture stimulation project in Western Australia may require 25 to 35 heavy vehicle movements to and from the project site.

Based on these movements and the requirement for up to three stimulation campaigns per year, the number of heavy vehicle movements to and from the Yulleroo field is estimated by Buru Energy to be as high as 510 return trips per year (four to 20 of these return heavy vehicle trips per year associated with the transport of concentrated chemicals). Using reported traffic volumes from Main Roads, Buru Energy noted that the average number of vehicles and heavy vehicles on the Great Northern Highway near Yulleroo is between 360 and 790 per day (20 percent to 32 percent heavy vehicles). Consequently, Buru Energy assert that hydraulic fracture stimulation campaigns would contribute only minor increases in traffic movements, relative to existing levels, with no requirements for heavy vehicles to go into regional towns under ordinary circumstances, and that the proposal would substitute local gas for LNG currently supplied by road tanker from Karratha, requiring about 500 trips per year over 800 kilometres. Buru Energy also maintained it generally limits HDV movements to daytime operating.

At the other extreme, among oil and gas fields envisioned for development based on hydraulic fracture stimulation submitted to this Inquiry is that of Finder Shale Pty Ltd (see **Figure 6.7**). Finder Shale Pty Ltd's (approximately) 600 TJ/d scenario would develop 60 well sites supporting 480 wells over 20 years. Again, recognising the company proposes no

trucking of water as supply or flowback, a reasonable estimate based on Broderick et al. (Broderick et al. 2011) would be about 845 to 1,550 truck visits per year.

There is substantial literature on wildlife mortality associated with vehicular traffic in Australia and overseas, but not specific to oil and gas project areas (Eco Logical Australia 2013) and often only specific to species of concern that do not live in Western Australia, for example koalas and wombats. Some generalities that flow from this literature include:

- Mortality increases with the traffic volume and speed (Seiler & Helldin 2006);
- Most incidents commonly occur at night, or early morning and late afternoon (Seiler & Helldin 2006);
- Incidents may be greater in particular seasons, especially in relation to breeding and dispersal, or during periods of drought (Lee et al. 2004);
- Mortality is more acute in areas close to wetlands and ponds (Forman & Alexander 1998); and
- Mortality can be reduced through appropriate mitigation (Magnus et al. 2004).

In the Buru Energy supplement to EPA Referral for the Laurel Tight Gas Pilot Exploration Program (Buru Energy 2013), the company specified a traffic management plan that included speed limits on station and access tracks, no night driving except for emergencies, and restriction of traffic to operational areas only, all aimed at reducing impacts on fauna. AWE Limited's submission to this Inquiry also refers to mitigations including speed limits. Similar mitigations (speed limits; limited driving at night, dusk and dawn; maintaining and operating vehicles to minimise dust, smoke and noise in habitat areas) are found in Santos' Fauna Management Plan for its GLNG Project in Queensland and as well as components of the fauna management commitments by Chevron Australia at Barrow Island.

8.6.2.4 Increased noise and light

Noise and night time lighting have the potential not only to lessen amenity for people, but also fauna.

Jones et al. (Jones, Pejchar & Kiesecker 2015) identified the sources of noise within an oil and gas field to potentially include vehicle traffic, drill rigs, hydraulic fracture stimulation operations, production wells, pump jacks, aerial coolers, compressors, flare stacks, and generators. Noise level estimates in oil and gas fields range from 59 decibels (dB(A)) at drilling rigs to 70 dB(A) at large gas compressors (Blickley, Blackwood & Patricelli 2012). In its submission to the Inquiry, Condor Energy, indicated the sound pressure produced by its hydraulic fracturing equipment is typically 100-108 dB(A) at 1m, depending on the specific equipment being used at the time. Even without artificial noise dampening or attenuation (due to vegetation or ground forms) the noise is reduced to the mandated level for noise sensitive premises (that is, for human amenity) at less than 1,400 m distance. Condor Energy further noted that independent noise monitoring of its hydraulic fracturing activities in New

Zealand had shown that in real world conditions (with some attenuation due to vegetation and ground form) they meet the applicable Taranaki region noise limits at 800 m distance.

In its submission to the EPA for approval for operations at Yulleroo in 2013, Buru Energy committed to limiting loud (90 dB(A) at well site) operations to short durations (approximately one day) and only during daylight hours. The company also noted that flowback operations have low noise levels 'barely audible outside of the fence-line'. In its submission to this Inquiry, Buru Energy reported on noise monitoring during hydraulic fracture stimulation operations in 2016, finding source noise levels ranged from 89 and 108 dB(A) and were typically less than 65 dB(A) 800m away. As part of AWE Limited's submission, a consultant's report on noise complaints related to flaring were analysed in some detail. The report concluded that with the right prevailing winds, the noise from flaring at premises 2 km to 4 km distance could be heard and modelling suggested it was possible AWE exceeded the *Environmental Protection (Noise) Regulations 1997* at night, although no actual noise data was collected to verify this.

There is, of course, an interaction between increased traffic and noise. Goodman et al. (Goodman et al. 2016) found that modelled roadside noise associated with traffic supporting a hydraulic fracture stimulation operation was 'miniscule' (<1 dB(A)) when calculated as a long-term average, and consideration of short-term periods of noise were more appropriate to evaluating impacts; peak roadside noise levels approached 62 dB(A).

Light pollution can be a source of disturbance to people and to animals (Jones, Pejchar & Kiesecker 2015; Perkin et al. 2011). Night-time light from oil and gas fields may include gas flares, vehicle headlights, and temporary disturbance from 24-hour drilling infrastructure. The level of light pollution in oil and gas fields varies greatly, depending on the amount of human activity and necessity for flaring. Industry submissions to this Inquiry from AWE Limited and Buru Energy identify light minimisation measures at their operations including limiting direct lighting to operations areas only, inward-facing lighting, limiting night time operations and vehicle movements, and location of sites away from sensitive light receptors, including residences and highways.

There is no common framework for estimating impacts on fauna from the intensity, frequency, and timing of noise and light (Francis & Barber 2013), due in part to the challenge of assessing the impacts of noise or light from other influences associated with the underlying activity that is generating them (Francis, Ortega & Cruz 2011). One emerging generality is that the loudness of the noise or brightness of the light is less important than their constancy or regularity. A relatively irregular and unpredictable (but quiet) noise could be perceived by fauna as a threat. Although wildlife may habituate to a consistent noise, there may still be fitness costs to individuals (Francis & Barber 2013).

There is the potential for fauna to be attracted to well sites by lighting and thus at risk of entrapment or vehicle strike. The Inquiry was presented some limited evidence of a dead animal at a well site (photo included in Environs Kimberley's submission) as well as an

account at the public meeting in Broome of a dead dingo and a goanna at a well site. Industry submissions to this Inquiry from AWE Limited and Buru Energy, recognise this risk and indicate management strategies by means of fencing well sites, fencing open excavations and/or providing fauna egress paths, and by restricting vehicle speeds and movements at night.

8.6.2.5 Increased fire frequency

Changes in bushfire frequency does not largely feature in the international literature on the development of onshore oil and gas, but understandably is a matter for review in Western Australia. There is extensive literature on Australian fire ecology, with more recent studies forecasting increased fire frequencies as a result of our changing climate interacting with increased ignitions by people (mostly near settlements) (Cary et al. 2012). As a generality, the concern for Australian biodiversity and ecosystem health is that fires have become too frequent and too hot (Olsen & Weston 2005). This is apparently the case in the Dampier Bioregion (Canning Basin).

The infrastructure and operations of an oil and gas field potentially present greater risks of ignition due to increased access and industrial operations. An increased network of roads and other cleared areas that may serve as barriers to the spread of fires, and a local workforce properly equipped might be available to put fires out or manage them. The net effect (risk) of these factors could not be generalised by the Inquiry. Some standard industry practices and procedures related to fire management include: firebreaks around the well sites and camp; firefighting equipment at the well sites, camp and in vehicles with personnel trained in its use; only allowing flaring (if required) under permit from the Department of Fire and Emergency Services; only using diesel vehicles; designated smoking areas; restriction of vehicle and personnel access to operational areas to minimise chance of ignition; use of a gas detector; separation of fuel/hydrocarbon tank and separator at a minimum distance (Buru Energy, AWE Limited submissions).

According to Burrows (Burrows 2015), the original fire regime of the Canning Basin prospective areas was frequent patch-burning in the early dry season by Aboriginal people and lightning caused fires later in the dry season. Early dry season fires were low intensity, relatively small and patchy, and restricted the size and intensity of late dry season fires. The current fire regime is characterised by frequent large and intense bushfires in the mid to late dry season (August to December). These fires homogenise/simplify the vegetation growth stages and structures over large areas, with mid-storey vegetation particularly at risk. They also threaten fire sensitive ecosystems such as monsoon vine thickets and mound springs. As described above, fires were extensive throughout the Dampier bioregion between 1997 and 2001, and again in 2004. In each of those years 31 to 48 percent of the area was burnt (Bastin 2008). Burrows (Burrows 2015) recommended the following fire management principles for the region:

- Reduce the area burnt by late dry season fires by increasing the proportion of the area burnt in the early dry season and installing strategic fuel reduced buffers;
- Progressively reduce the size of late dry season fires by burning in the early dry season to establish a coarse-grain mosaic of burnt patches and by installing a strategic network of low fuel buffers; and
- Use prescribed fire mosaics to increase the level of protection to fire sensitive ecosystems.

The recommended fire regime for the tuart woodlands of the Swan bioregion is for regular, low intensity (cool season) fires (Mitchell, Williams & Desmond 2002). More generally for the Swan bioregion, fire regimes for remnant vegetation are currently set at exclusion, and are yet to be optimised for biodiversity outcomes (Mitchell, Williams & Desmond 2002).

8.6.2.6 Introduction and spread of weeds and pests

The large number of vehicle movements in and out of a developing oil and gas field has the potential to spread weeds and pests into areas where they do not already occur, including significant plant diseases like dieback. The soil disturbances associated with development also had the potential to increase weed presence in areas where they are already present. Introduced weeds have the potential to impact biodiversity through competition with the native flora as well as changing the fire regime, and to impact the beneficial use of land for cropping or grazing. Jones et al. (Jones, Pejchar & Kiesecker 2015) found few references to invasive species studies associated with the oil and gas industry, but noted that developers often identify and employ best management practices to prevent introductions and control invasions should they occur.

The weeds occurring in the Canning Basin have been introduced by other land users, in particular by pastoral activities. Buffel grass (*Cenchrus ciliaris*) is now well-established across the West Kimberley. This species is highly productive and an excellent fodder species; as a result, the species was widely introduced by pastoralists to improve pastoral quality. While this practice has now abated due to increased awareness of the threat that introduced species pose to native biodiversity, buffel grass occurs widely across the Canning Basin.

Weed management is principally governed by the *Agriculture and Related Resources Protection Act 1976*, administered by the Agricultural Protection Board of Western Australia. Other Western Australian legislation relevant to onshore oil and gas operations include:

- *The Plant Disease Act 1924*;
- *Plant Disease Regulations 1989*;
- *Biosecurity and Agricultural Management Act 2007*; and
- *Biosecurity and Agricultural Management Regulations 2013*.

Industry submissions to this Inquiry from Finder Shale, AWE Limited, APPEA, Condor Energy and Buru Energy all make reference to weed and/or quarantine management plans and practices associated with their developments. These extend to on-ground surveys in association with flora to identify weeds already present prior to development (for example, as described in the submission from Buru Energy).

The submission by the Western Australian Farmers Federation (WAFarmers) noted the potential impost on farm enterprises trying to meet biosecurity regulations and standards:

> *"Agriculture encounters regulation throughout all aspects of the business, with biosecurity becoming more critical to producers and increasingly regulated by government. Western Australia has rigorous biosecurity measures, which often require producers to keep a register of who comes on and off farm. These biosecurity plans and measures are what give WA agriculture a competitive edge when competing in a global market. Having increased vehicle and personnel movements' on-farm can lead to more administrative measures having to be undertaken by the farmer. This does take him or her away from their core duties which can lead to a loss of productivity"* – submission from Western Australian Farmers Federation

On the basis that feral animals are well-established throughout the regions, the Inquiry does not consider the development of an unconventional onshore oil and gas industry as materially adding to the existing impacts these animals are having or their spread.

8.6.2.7 Soil erosion, contamination and loss of beneficial use of land

Unconventional oil and gas field development, with the associated hydraulic fracture stimulation, has some potential to damage soil in two principal ways. The first is local contamination associated with surface spills of chemicals or product. The second is through physical damage to the soil itself, mainly erosion. There is not much literature specific to this industry and technology in this regard (Pichtel 2016). The available literature addressing the broader impacts of the industry on agriculture is focussed on competition for water for irrigation, land and crop contamination by irrigation with wastewater, direct contact of livestock with wastewater, and perceptions regarding the marketability of products if produced near gas fields (Farah 2016; Haswell & Bethmont 2016). The submission by WAFarmers to this Inquiry noted some concern among its members regarding the latter and is interested in more local research being undertaken on the potential for chemical contamination of final products.

The few studies that have been conducted on soil contamination from oil and gas development in Texas indicate that well pad development has an increased potential for erosion, and that soil contamination is possible from oil and gas production, however, these risks were not quantified. Lauer et al. (Lauer, Harkness & Vengosh 2016) measured soil contamination from wastewater spills in North Dakota, and found that in addition to the brine salts, there was a soil residuum of elevated radon (reflecting the relatively high concentrations of radon in the producing formation), and persistent traces of hydrocarbons

for up to four years after the spill; no reference is made to whether these sites had any remediation following the spills, which ranged in volume between 200 to 10,000 litres. There is additional literature relating to soil contamination from the surface disposal of wastewater, for example, as noted by Skalak (Skalak et al. 2014), but this practice is not permitted in Western Australia. Pichtel (Pichtel 2016) associated the principal impacts on soil from wastewater spills with increased salinity, and that the practices for remediation of soil contaminated with wastewater resulting from the production of oil and gas 'often tend to be straightforward'. Dong et al. (Dong et al. 2013) reported effective soil remediation techniques for treating contamination by petroleum hydrocarbons and heavy metals.

The risks associated with wastewater management, and their mitigation, are covered in **Section 6** (Overview) and **Section 9** (Water) of this Report. Buru Energy's submission specifies procedures to sample and analyse soil from their lease areas, before and after operations, in order to detect any impacts, and indicate that in the event of a spill the affected area is scraped up and removed for disposal at a licensed facility. The Inquiry found that this is a standard requirement and practice for petroleum production facilities in Western Australia.

The question of erosion risk can be addressed more generally through a broad literature on the impacts of roads specifically and clearing more generally. There is a fundamental relationship between baring the soil surface and the potential for it to erode. The actual degree of resistance to erosion that results is dependent on a large variety of factors, and the overall consequences to land is dependent on both scale (extent) and location. The limited scale and number of well pads associated with historic onshore oil and gas development, and the nature of the soils upon which they were built, may explain why this issue was not prominent among the concerns expressed to this Inquiry and perhaps why soil erosion has not figured prominently in other risk assessments of unconventional gas development.

There are, however, concerns based on the experience with the cumulative impacts of roads and additional land disturbance in other places, resulting from other industries. In his submission to this Inquiry, Professor Richard Hobbs drew attention to analyses done across the Great Western Woodlands on the extent and impacts of tracks and roads, particularly on landscape fragmentation and local surface hydrology and erosion (Raiter et al. 2017, 2014). Raiter et al. (Raiter et al. 2018) assessed local impacts on surface hydrology and erosion along 1,000 km of linear infrastructure (tracks) in the Great Western Woodlands, and found the likelihood of surface pooling and erosion to be five to six times more on minor and major tracks (not paved or maintained unpaved roads), compared to off-road, with the degree of impact dependent on a variety of factors including topography, local engineering, grazing, rainfall and inherent erosivity. These authors concluded that apart from minimising linear infrastructure, the impact could be mitigated by better design and the rehabilitation of unused tracks. In the prospective areas of the Perth and Canning Basins, however, there is

low runoff from sandy soils, and issues such as erosion and interception of sheetflow are generally absent.

Buru Energy has a requirement, as specified in their Canning Basin Seismic Survey Generic Environmental Plan (Buru Energy 2015), to monitor representative sites to measure the success of rehabilitation of seismic lines and camp sites in terms of vegetation and erosion, with the expectation that the vegetation is returned to its original species richness with no increase in weeds. In its submission to this Inquiry, Buru Energy indicated no observations or reports of erosion at any well sites on their lease associated with previous exploration activities.

Finder Shale indicated its requirement for a Soil and Erosion Management Plan, and all industry submissions indicated the requirement for a rehabilitation plan for all activities, including exploration tracks. At the public meeting at Noonkanbah, the Inquiry was informed by Traditional Owners that they had no concerns about erosion or the recovery of vegetation on survey tracks and other clearing for the unconventional gas developments near their town.

No evidence was presented to the Inquiry indicating substantial or unmanaged soil erosion or farmland degradation issues associated with onshore oil and gas development in the Perth Basin. The Panel did not observe any significant erosion on field visits to existing well pads in the Dongara region, noting that all but the last tens to hundreds of metres of access were on existing regional roads. However, the Panel noted the experiences shared by landholders with close experience with the onshore oil and gas industry accessing farmland. The Panel heard descriptions of poor land (well site) rehabilitation (for example, the submission from Rod Copeland). The Panel also heard statements from landholders, with oil and gas operations on their properties, who were satisfied with the condition their land was left in and/or benefited from infrastructure such as fences, gates or roads that were left behind by agreement. The Panel concluded there is the potential for long-term soil impacts or productivity losses on farmlands, limited to the degree that access tracks and infrastructure sites are not adequately restored to an agreed and acceptable level. The Panel notes submissions from the Pastoralists and Graziers Association of Western Australia (PGA) and the WAFarmers, where both organisations felt the issues of potential impacts were well-enough understood and regulated, and that it should be left to individual farmers to negotiate the terms of access.

"The PGA believes that individual landowners have the right to negotiate mutually agreeable and beneficial contracts with HFS companies… Each property is unique and each farming operation is unique and the property owner and farm manager are best placed to know what activities or issues proposed HFS operations are likely to impact on and how much. Furthermore, each stage of HFS operations – access agreement negotiations, exploration, drilling, production and rehabilitation may impact differently on the property and the farming operation" – submission from Pastoralists and Graziers Association of Western Australia

"WAFarmers represent members who predominantly operate on freehold land; it is for this reason why WAFarmers advocates for farmer choice. It is best left to individual property owners to decide what occurs on their land. There have been instances where agriculture and resources company co-existing well together, with the resources company investing in on-farm infrastructure. Of course, there are also examples where resource companies employ bullying tactics to gain entry, or may not behave in a collaborative manner once they have gained entry. WAFarmers advocates for a process to be put in place that informs all parties of their rights, entitlements, privileges and responsibilities when discussing land access arrangements" – submission from Western Australian Farmers Federation

Similarly, where pastoralism and prospective unconventional oil and gas development intersect in the Canning Basin, some concern was expressed over the potential impacts of an expanded onshore oil and gas industry on the operations of pastoral leases. The issues identified focused mainly on impacts on water resources and made little reference to other impacts on the productive use of land. Nevertheless, a common theme emerged on land access and protection of agriculture:

"whilst the KPCA has an open mind to the possibility of working collaboratively with petroleum companies, the KPCA would like to see a stronger land access regime for pastoralists which will include consent to entry requirements and compensation for restriction on land use/limitations to diversification, due to petroleum activities, being legally mandated as well as the right to veto activities should they ultimately not be compatible with the pastoralist's current land use and/or the full range of diversified pastoral land uses. This would also allow for consideration of the increasing biosecurity requirements that pastoralists need to meet to conduct operations" – submission from Kimberley and Pilbara Cattlemen's Association

8.6.2.8 Uncontained fracture growth, fault reactivation and increased seismicity

Canning Basin

Exploration targets for unconventional oil and gas in the Canning Basin include a number of areas where the overburden is relatively shallow and/or consists of brittle rock such as limestones, with relatively thin shale seals. This could present an elevated risk of uncontained fracture growth should the geomechanical conditions be unfavourable.

According to recent studies by Geoscience Australia, the changes in three principal stresses with depth in the Fitzroy Trough and Kidson Sub-basin are quite typical of many continental basins (**Figure 8.10**). In the near surface, reverse faulting is prevalent as the maximum principal stress is horizontal and the minimum principal stress is vertical. At intermediate depths, there is a transition to a strike-slip stress regime and below approximately two kilometres the maximum principal stress is vertical and a normal faulting stress regime prevails.

8.6.2.9 Analysis of stresses with depth in Canning Basin wells by Geoscience Australia (Bailey & Henson 2018)

In their submission to the Inquiry, Finder Shale Pty Ltd provided well data and geomechanical modelling results to indicate this pattern of stresses also prevails in the central part of the Canning Basin, where the lower Goldwyer Formation is the exploration target. The stress state acts to constrain the propagation of hydraulic fractures to be vertical at depths below about two kilometres in the productive part of the Goldwyer, whereas upwards growth is inhibited at shallow depths where the maximum compressive stress has rotated to be horizontal and limestones with relatively high cohesive strength are encountered.

The Inquiry was not made aware of, through submissions or otherwise, any studies that show an enhanced risk of fault reactivation, fault leakage or induced seismicity in any part of the Canning Basin. However, the risks from the geomechanical consequences of wells intersecting faults or hydraulic fracture stimulation inducing fault movements and leakage, was raised as a general concern at community consultations in Broome and in Perth, and companies were criticised for not providing detailed information about any wells that had intersected faults during drilling.

Concerning seismic monitoring, the Geological Survey of Western Australia (GSWA) (in collaboration with the University of Western Australia and Macquarie University) recently undertook a deployment of mobile seismic sensors along two transects in the onshore parts of the Canning Basin. At the same time, an array of seabed recorders was placed offshore with the collaboration of the Chinese Academy of Sciences. While these arrays are only temporary, the information gathered should improve understanding of the seismicity and

crustal structure of the region and also provide information to assist in the planning of future baseline surveys and monitoring activities of seismicity in the basin.

Finding 2: Given the paucity of studies on tectonics and seismic hazard in the Canning Basin, further data collection, permanent monitoring stations and independent studies of the stress state and neotectonic activity, such as those undertaken by Geoscience Australia, are warranted.

Perth Basin

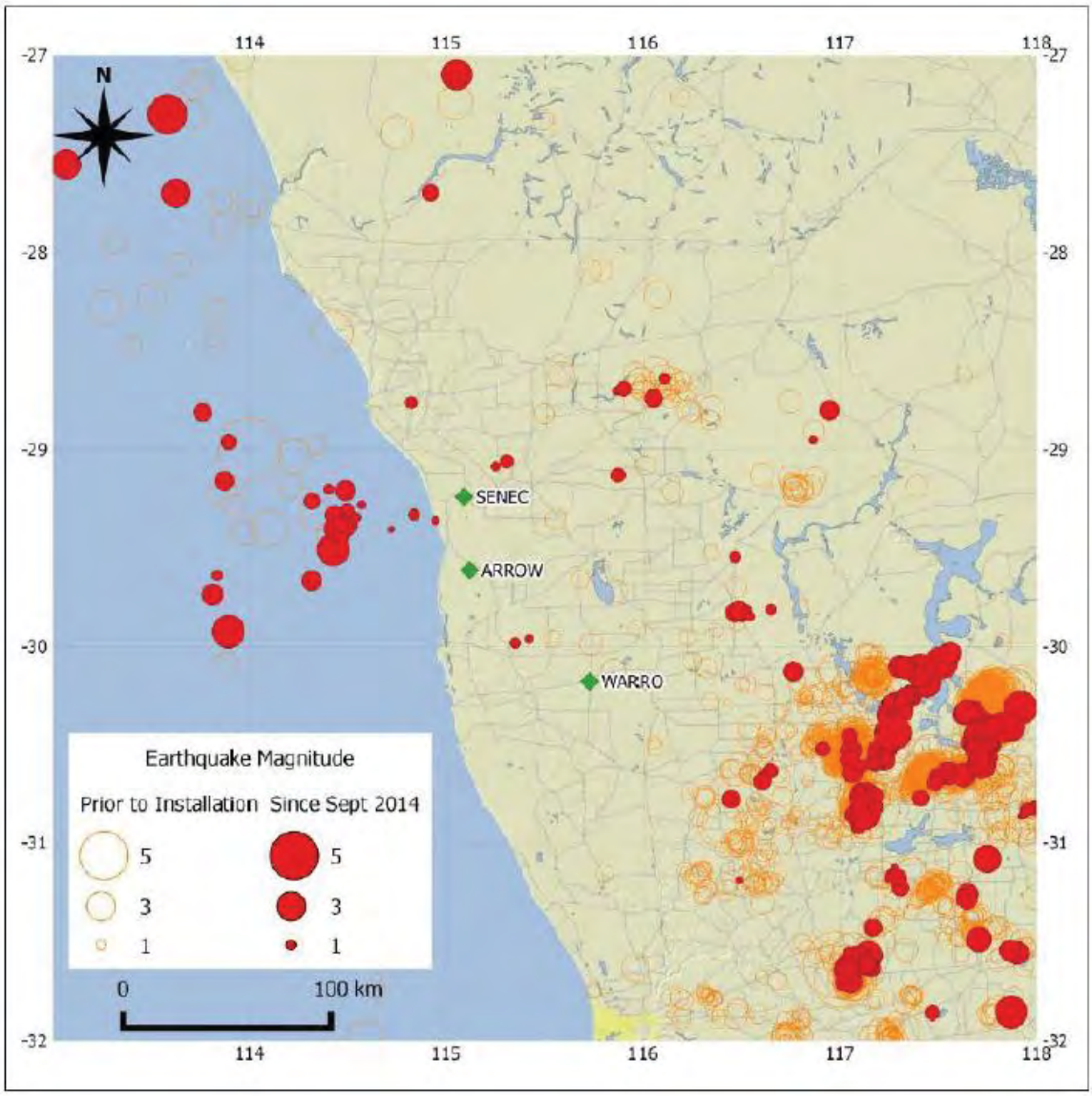
Submissions to the Inquiry from industry operators in the Perth Basin drew attention to geomechanical studies undertaken as part of well planning and hydraulic fracture stimulation operations. These studies included details of coupled mechanical modelling undertaken to predict subsurface stress distributions and fracture growth, and micro-seismic monitoring of the extent of fracture stimulations. The specific scenario of fault reactivation was not perceived as being of high-risk, according to these industry submissions.

In community consultations, the risks arising from uncontained fracture growth, geomechanical perturbations and induced seismicity in the subsurface were raised by a number of participants. Submissions from the Lock the Gate Alliance and the Conservation Council of Western Australia (CCWA), drew attention to these concerns with reference to the Perth Basin. The Inquiry was also made aware of recent research that indicates the potential for fault reactivation associated with hydraulic fracture stimulation in the area of the Cadda Terrace, conducted by Fiona Mullen at the University of Auckland. While we understand that some of this work is still undergoing scientific peer review, the Master's thesis of F. Mullen is publicly available and the findings are reviewed in **Section 9** (Water) of this Report.

In its submission to the Inquiry, AWE Limited described its contribution to a Midwest regional seismic monitoring project. The North Perth Basin Seismic Monitoring Network, installed by the Seismology Research Centre (SRC), comprises three seismic monitoring stations installed in mid-September 2014 throughout the northern Perth Basin (near the Senecio-2 well, Arrowsmith and the Warro Field site).

Figure 8.24: Background seismicity in the Northern Perth Basin showing location of baseline monitoring stations (green diamonds) at Senecio, Arrowsmith and Warro well locations.

Source: Submission from AWE Limited



8.7 Meeting the environmental objectives

Given the above pressures on land associated with the onshore development of an unconventional oil and gas industry, the Inquiry considered the risks to meeting the stated objectives of the EPA guidelines:

- Flora and fauna are protected so that regional biological and ecological integrity are maintained;
- The integrity of places of distinctive ecological and conservation value is preserved; and
- Soil and land health are maintained so that environmental values including beneficial use are protected.

The Inquiry also considered the risks associated with meeting the objective:

- Induced seismic activity causes no harm.

It is clear to the Inquiry that the key risk to meeting these objectives is the clearing of native vegetation for infrastructure, with the subsequent loss and fragmentation of habitat. The intactness of a landscape is its 'naturalness' and is influenced by the proportion of native vegetation remaining and its patchiness (Eco Logical Australia 2013). Intact landscapes, including the arid and semi-arid regions, possess a continuum of native vegetation cover with little or no degree of roadways, thus a high level of connectivity and relatively low degree of modification (McIntyre and Hobbs, 2001).

The three industry submissions detailing current and anticipated developments in the Canning Basin (MC Resources Australia, Buru Energy and Finder Shale) provide some indication of the degree to which regional biodiversity and ecological integrity (as indicated by landscape intactness) might be impacted, if onshore unconventional gas is developed in those prospective regions where the native vegetation is largely uncleared. It is clear that the cumulative area disturbed directly by developments based on multi-well sites (pads) and the anticipated spacing of well sites (one per 16 to 25 km^2) is limited to (at most) the clearing of one to two percent of the landscape (inclusive of access roads, survey tracks and pipeline easements). Virtually all of this is subject to a requirement to revegetate. Under the expectations of the current regulatory framework at both the State (for example, the EP Act) and Federal (for example, the EPBC Act) levels, the location of this infrastructure must be based on flora and fauna surveys and avoid listed flora and habitats and other ecologically sensitive areas.

For instance, in its submission to the Inquiry, Buru Energy offered a detailed example of the identification and subsequent avoidance and minimisation of the direct impacts of clearing for its operations. This extended to the identification of recognised ecologically sensitive areas (including those listed by the State or under the EPBC Act, EPA Redbook areas and National Heritage areas) and to other areas sensitive to disturbance (for example, drinking

water supplies and riparian vegetation). Buru Energy subsequently located its activities at significant distances from the nearest such areas (4 km away from Taylors Lagoon; 25 km away from the Camballin Floodplain; 25 km away from the West Kimberley National Heritage Place). For its proposed development at Yulleroo (130 TJ/d), clearing for the gas field infrastructure would impact 100 ha of Vegetation Association 7748, which extends over 4,744 km^2 of the region, or about 0.02 percent of the vegetation type associated with the area. Progressive rehabilitation is expected to reduce this area to 70 ha. Rehabilitation operations involve ripping and re-contouring the well sites, spreading stockpiled topsoil and vegetation to encourage regrowth, and periodic monitoring of rehabilitation success with annual reports to the regulator.

Similarly, in Finder Shale's submission, the company describes its pre-development surveys for its exploration program with no identification of any listed Ramsar wetlands flora or fauna species or habitat of conservation significance and no weed species. The nearest wetland of national significance is the Dragon Tree Soak Nature Reserve, 80 km to the south, and the nearest zone of ecological significance is Munro Springs, approximately 90 km to the south-west. Finder Shale's project area has no permanent surface water features, and the nearest landscape feature that contains ephemeral watercourses and a chain of waterholes is the Edgar Ranges, at the north-east corner of permit EP 493. There are no known groundwater dependent ecosystems.

Finding 3: The direct impacts of clearing for infrastructure on vegetation and ecological integrity from development proposals of the scales described in the industry submissions to the Inquiry (including access roads and even a regional pipeline) are sufficiently managed under the existing regulatory environment to pose a low risk.

The Inquiry recognises the potential indirect impacts of infrastructure development posed by the extensive development of tracks (for survey and access) including the fragmentation of the native vegetation cover (c.f. (Raiter et al. 2014, 2017)). The Inquiry notes the requirement to rehabilitate (revegetate) survey tracks under the current regulatory regime, but also recognises that access tracks and other linear infrastructure like pipelines may remain used (and thus unvegetated) for an extended time over the life (say, 20 years) of an oil and gas field. Information provided to this Inquiry (through submissions and public meetings) indicate that the substantial recovery of pindan vegetation following temporary clearing for surveys is relatively quick (one to five wet seasons), if not complete. Dawson (Dawson 2017) found no discernible difference in vegetation structure and community composition between control (reference) and seismic (impact) plots, between six and 12 months after disturbance in the West Kimberley, though differences in understorey height and density likely reflected the time taken for the vegetation to grow.

The same cannot be said for the native vegetation cleared for survey lines in the Perth Basin. While in situ mulching is apparently effective in protecting the soil and retaining seedbank, it

is not assumed by this Inquiry that the resulting recovery of native vegetation is complete with respect to the original structure and diversity.

Recommendation 1: The cumulative impacts of landscape clearing and fragmentation depend on scale and duration. Such impacts should be anticipated and assessed prior to development approval, with the eventual rehabilitation and restoration of redundant infrastructure clearing meeting the expectations of both regulators and the community.

Of the other indirect potential impacts on flora, fauna and ecological integrity, the introduction or spread of weeds and pests was a matter of concern raised in submissions to this Inquiry. Given the widespread establishment of weeds in those parts of the Canning Basin historically subject to pastoral use, and the protocols identified by both industry and regulation for quarantine, inspection and response, the Inquiry considers the residual risk under current regulations to ecological integrity as negligible in so far as the developments are required (a) to not introduce anything new, and (b) not increase the extent or density of weeds that are already there.

Finding 4: In the Canning Basin, the residual risk under current regulations from the spread of weeds is negligible in areas historically subject to pastoralism. For extensive areas free of weeds, the residual risk of impacting on ecological integrity is low.

The situation for remnant vegetation, including conservation reserves, across the prospective areas of the Perth Basin is to some extent different. The remnant vegetation is not generally subject to grazing by livestock and is often reasonably weed-free, while the surrounding farming country and road verges are weed-rich. Further, the native vegetation is susceptible to dieback, so quarantine and hygiene associated with any access is critical for its protection. Thus, the risks associated with the introduction of weeds by oil and gas development in this region is, in a sense, binary. Where activities take place on cleared land the risk under standard protocols is low. Where development requires access to native vegetation, it is material and can only be kept low by stringent and diligent quarantine and hygiene procedures.

Finding 5: In the Perth Basin, strict quarantine and hygiene procedures are necessary to protect native vegetation and agriculture, to keep the risk of introduction and spread of weeds low.

The risks to ecological integrity because of changed fire regimes as a result of unconventional oil and gas development can only be inferred indirectly, as there was no direct experience or evidence available to the Inquiry in this regard. While increased chance of ignitions might be higher, limited access, areas of active operation, firebreaks (by design or simply as access roads) and the self-interest of fire prevention, firefighting equipment and trained personnel argue for reduced fire risk overall.

Finding 6: The indirect impacts on fauna from traffic, noise and light pollution under the existing regulatory regime and industry practice are all considered to be low.

The Inquiry concludes that the overall risk to flora and fauna, and the maintenance of ecological integrity, is low provided that future unconventional oil and gas developments:

- Survey and identify areas of ecological sensitivity or significance, and avoid them;
- Survey flora and fauna, and avoid areas with species of conservation significance;
- Design the layout of infrastructure to minimise the clearing of native vegetation;
- Exercise progressive and effective revegetation and site rehabilitation at the earliest opportunity;
- Adopt and diligently maintain weed and pest quarantine, hygiene and, where necessary, control or eradication;
- Actively prepare for and commit to the prevention and control of fires;
- Adopt mitigations to direct fauna impacts, including traffic management, lighting design and use, and exclusion fencing; and
- Appropriately offset the residual environmental impacts on flora and fauna in accordance with the Western Australian State Environmental Offset Policy.

All the above are expectations under the existing State and Federal regulatory regimes. Crucial to the effective exercise of regulatory overview is the ongoing assessment of potential environmental impacts of new development proposals against the accumulated impacts to the flora, fauna and ecological integrity of a region. This has to be done with the explicit understanding that even with effective and progressive decommissioning, rehabilitation and offsetting, a region may reach a limit to the degree of cumulative impact (including landscape fragmentation) that society considers prudent.

Finding 7: The overall risk to flora and fauna, and the maintenance of ecological integrity, is low, if the current State and Federal regulatory and environmental approval processes are applied, including the consideration of cumulative impacts.

With respect to the risk in preserving the integrity of places of distinctive ecological and conservation value, the Inquiry concludes that the overall risk is low for the foreseeable unconventional gas developments in the Canning Basin, given their particular locations. However, it is possible that future developments (including extensive exploratory surveys) may encroach upon (or in fact enter) areas of conservation significance, or key areas of aesthetic value. In those cases, the consequences to conservation, the community and to tourism is high.

"Exclusion zones are an important part of minimising risk for especially sensitive environments. Many other regimes automatically exclude certain areas from possible tenure, where any risk is deemed unacceptable - for example, threatened ecological communities, sites of cultural heritage, public drinking water sources and residential or agricultural infrastructure" – submission from Environs Kimberley

Finding 8: For the Canning Basin, the risk to damaging the integrity of places of distinctive ecological and conservation value is low, so long as future developments do not encroach on areas of high conservation significance, cultural or aesthetic value.

In the Perth Basin, where remnant vegetation is already reduced to perhaps one-quarter of its original extent and mostly vested in the conservation estate already, the identification and recognition of places of conservation and aesthetic significance, and the preservation of their value in those regards, is of particular importance. By that same history and extent of clearing, the region affords more opportunity to avoid native vegetation (in general) and the conservation estate (in particular), in potentially accessing unconventional oil and gas resources.

Under current legislation, petroleum companies granted an exploration permit have the right to potentially gain access to the conservation estate as well as other places of aesthetic or conservation significance within the permit area. To an extent, the industry has anticipated the unacceptability of exercising that right through the relinquishments of leases covering some iconic natural features like Roebuck Bay and the Pinnacles (as described previously). To date, at least in the Canning Basin, the industry has generally located their early exploration and development projects well away from such places. However, it is the view of the Inquiry that such avoidance be formally regularised.

Finding 9: For the Perth Basin, the risk to damaging the integrity of places of distinctive ecological and conservation value is moderate as present regulations allow potential entry into the limited areas of native vegetation. This risk reduces to low if such entry is forbidden.

Recommendation 2: The Western Australian Government, in consultation with the community, should identify places of iconic natural heritage and exclude those places from future exploration and development for unconventional oil and gas associated with hydraulic fracture stimulation, sufficient to protect their values from direct development or by proximity to increased traffic, noise, light or visual impacts. These consultations should be a formal part of the process by which the Western Australian Government releases acreage for potential development.

Regarding this recommendation, the Inquiry is making perhaps a fine distinction between the impacts of unconventional versus conventional oil and gas development, and recognises the limits of its Terms of Reference.

The Inquiry concludes that the overall risk to soil and land health including beneficial use, is low if future unconventional oil and gas developments:

- Diligently and effectively remediate any sites following a contaminant spill;
- Design and maintain road infrastructure to minimise erosion and impact on local surface water flows;
- Close and effectively rehabilitate survey tracks and access roads at the earliest opportunity; and
- Where access is required on farmlands or pastoral leases, establish agreements with the landholder or leaseholder on the location of infrastructure, operations and completions to minimise or offset any impacts on beneficial (agricultural) use.

Finding 10: The overall risk to soil and land health including beneficial use, under the current regulations related to remediation, maintenance and rehabilitation, is low. However, the residual risk and impact can be further minimised through landholder consultation and compensation on residual impacts.

Recommendation 3: Access to productive land should require an agreement with the Traditional Owners, landholder or leaseholder regarding the location, maintenance, operation and remediation of infrastructure, as well as compensation for residual damage to the subsequent productive use of the land.

The Inquiry also considered the risk of induced seismicity against the following environmental objective:

- Induced seismic activity causes no harm.

Finding 11: Given the known low projected volumes of injected fluids and geomechanics of the Canning and Perth Basins, the risk to life or damage to property and infrastructure from induced seismicity is low. Owing to the incompressible nature of target formations and the relatively small volumes of fluids being withdrawn per unit volume of rock in unconventional oil and gas production, the risks of land subsidence or uplift at the surface associated with hydraulic fracture stimulation operations in Western Australia are negligible.

While the prevailing stress state does place many minor faults and fractures close to failure in the deeper subsurface, reactivation of these planes of weakness are highly unlikely to

propagate to a scale of movement that would result in a felt earthquake (magnitude Local of ~2.5 or greater). The risk of induced seismicity associated with future hydraulic fracture stimulation activities in Western Australia is further mitigated by a combination of geological factors and existing regulations and practices, such as:

- Risks of induced seismicity are closely related to large cumulative volumes of fluids injected into part of a basin over a period of years to decades. The cumulative volumes of fluids injected into the surface, under the likely development scenarios for tight gas, shale gas and tight oil in Western Australia, are expected to be very low. The number of wells and well density are both low compared with areas in North America, where induced seismicity has been experienced;
- The prohibition of the subsurface disposal of produced water or other waste fluids into wells in Western Australia removes the most significant risk factor for induced seismicity related to oil and gas operations;
- There are no development plans for areas where unconventional gas or tight oil accumulations are located close to basement faults. Typically the targets in the Perth and Canning Basins are underlain by several kilometres of older sediments, and therefore it is extremely unlikely that fluids would penetrate to basement structures; and
- While microseismicity is to be expected in association with any hydraulic fracturing stimulation activity, current industry best practice makes use of the measurement of these extremely small events, which can give an early warning of any unusual geomechanical events and reveal unmapped geological structures.

While we consider the risks of impacts to land from seismicity (induced by hydraulic fracturing stimulation) to be low, we note that tremors significantly larger than the usual size of microseismic events can occur, indicating that a pre-existing fault plane has been influenced by fluid pressure and/or stress changes. The Inquiry notes the best practice of oil and gas operations in jurisdictions such as Alberta and British Columbia in Canada, and precautionary measures advised by expert panels convened in the United Kingdom and the Northern Territory, involve a 'traffic light' warning system that makes use of on-the-ground monitoring of hydraulic fracture stimulation activities.

Recommendation 4: An early warning system based on a 'traffic light scheme' should be implemented to prevent adverse geo-mechanical events reaching a size of any consequence to land or hydrogeology.

The following steps are necessary to implement such an early warning system:

- Baseline monitoring using seismic ground stations to establish the background spatial distribution and magnitudes of natural earthquake activity across the sub-basin hosting the hydraulic fracturing stimulation activity;

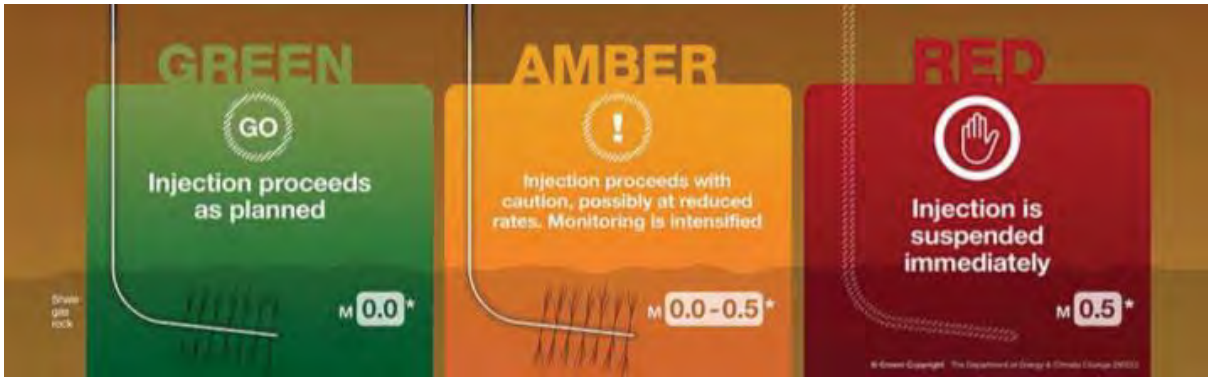
- Monitoring should extend tens of kilometres away from any likely well locations and include sensors located near to population centres that could be affected;
- Establishment of a permanent seismic array with coverage of areas undergoing hydraulic fracture stimulation, to enable the detection of all seismic events of magnitude Mw = .05;
- Microseismic monitoring of the near field of the well being stimulated, using a moveable array of sensors deployed at the surface or in a nearby well(s) to record activity during and immediately after the hydraulic fracture stimulation operations;
- Real time reporting of seismicity to a competent authority able to identify statistically meaningful patterns in activity that that may be a cause for concern;
- An agreed definition of earthquake magnitude and frequency to denominate 'green', 'amber' and 'red' status definitions and action levels; and
- Monitoring should continue for at least two years after the cessation of hydraulic fracture stimulation operations in an area.

The United Kingdom Oil and Gas Authority currently sets an action level at M_L of 0.5 to trigger a red condition, where injection is suspended. This level is far below the level of any felt seismicity, but considerably larger than typical microseismic events that accompany hydraulic fracture stimulation. A competent authority can establish the relevant action level for detected seismicity, with action levels for green, amber and red, based on moment magnitude, Mw as per Drummond's (Drummond 2016) definitions of official terminology at GA.

Figure 8.25: United Kingdom government guidance on developing shale gas

Source: Department for Business (Department for Business 2017)

Status	Green	Amber	Red
Actions:	Injection may proceed	Injection proceeds with caution, maybe at reduced rates	Injection is suspended immediately
Agreed Magnitude level (and definition of which scale) *	$M_{L^*} < 0$	$M_{L^*} = 0$ to 0.5	$M_{L^*} > 0.5$



Further recommendations regarding the maintenance of geomechanical integrity of subsurface formations are discussed in the **Section 9** (Water) of this Report.

9

Risk assessment: Water

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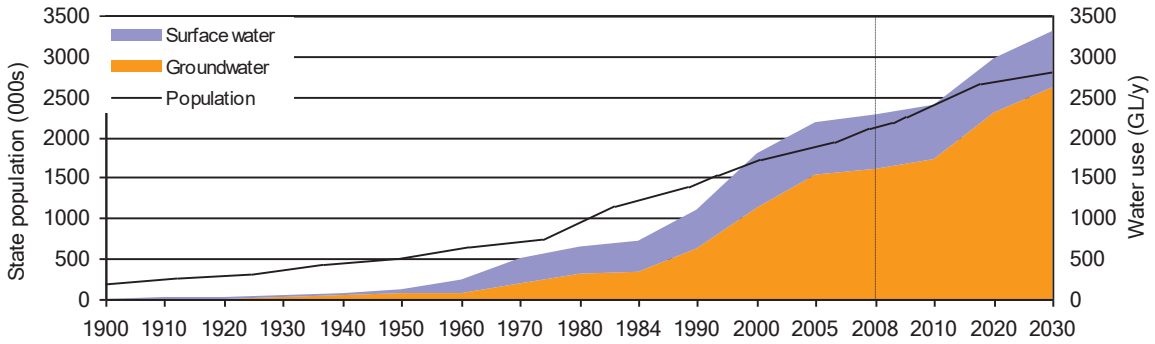
9 Risk assessment: Water

9.1 Introduction

Western Australia is heavily reliant on groundwater (**Figure. 9.1**) and the Western Australian public has a high awareness of groundwater issues. Groundwater is the major source of drinking water for the Perth metropolitan area, some 80 regional towns and for isolated communities throughout the State. It is used directly by one in four metropolitan households through garden bores, many farms and most pastoral leases depend on groundwater (in many cases of moderate salinity), and most horticulture is irrigated from groundwater. Surface water is only used for irrigation in the South-West, the Ord River Irrigation Area, for water supply to the Goldfields, (the agricultural region of the West Pilbara), and to augment public supply in the metropolitan area. There is on-farm use of dams for horticulture, particularly around Manjimup and Margaret River, and for stock water in areas where groundwater is too saline or not available.

Figure 9.1: Licensed groundwater and surface water use in Western Australia
Source: Department of Water and Environmental Regulation (DWER)



The main low salinity groundwater resources of the State are in sand, sandstone and limestone aquifers in the Perth and Canning Basins. Both the Northern Perth Basin and the North Eastern Canning Basin host conventional oil and gas deposits, and these are also the areas prospective for shale gas and tight oil.

Water conservation measures and campaigns since the last summer total sprinkler ban in 1977/1978 have increased public awareness and educated a whole generation in water issues. Ongoing sprinkler restrictions and winter bans in the metropolitan area provide a constant reminder to the public that local water supplies need to be conserved. It is often said that Perth would be one of the few places in the world where the population could name the major aquifers it draws its water from. A proposal to bring water from the South-West Yarragadee aquifer to Perth became a public issue in 2007 with demonstrations at Parliament house by 'Friends of the Yarragadee' against development of its resources to supply Perth. Yet there are still calls to develop and pipe water from the Kimberley, despite numerous studies showing that significantly lower cost alternatives are available. Myths still

abound about ‘groundwater – the hidden resource’, despite the significant increase in knowledge gained from systematic groundwater investigation over the last 60 years (Allen 1997). Many of the submissions to the Inquiry referred to Western Australia as ‘the driest state’, or even ‘our State is one of the driest places on earth’.

The need to protect groundwater quality was illustrated by the findings of the 1994 Select Committee on Metropolitan Groundwater Supplies of the Western Australian Parliament, which recommended protection of land use (on the Gnangara Mound) to maintain pristine groundwater quality for the Perth water supply. Perth residents have been led to expect to have naturally pristine water, though recent education campaigns have led to the acceptance of recharging treated wastewater into drinking water supply aquifers below Perth.

The sandy soils common to the Perth and Canning Basins provide a pathway for pollutants to reach and contaminate groundwater, and there is a legacy of contamination plumes from industry, horticulture and septic tanks in the Perth area.

The State has pronounced dry seasons in the South-West (summer) and Kimberley (winter) and highly variable rainfall in the North-West and interior. The drying climate in the South-West since the 1970s has seen a drastic drop in yield from metropolitan reservoirs and in water table levels on the Gnangara Mound.

Groundwater supports culturally and ecologically important wetlands on the Swan coastal plain and the Canning Basin, as well as contributes to the maintenance of Fitzroy River wetlands in the dry season.

Virtually all groundwater use in the State, other than for domestic and stock water, is licensed, and the quality of public drinking water sources is protected with land use controls around water supply bores. Groundwater quality in general is also protected by regulations on waste disposal.

9.2 Key issues raised

Groundwater was raised as an issue in the majority of the written submissions and by most participants in the public consultations. It was reiterated that Western Australia is a dry state, and its water a precious resource. Through the submissions and public meetings anxiety was raised over the level of water use in hydraulic fracturing stimulation, questioning whether it would compromise other uses, such as agriculture.

The main concern was over potential contamination in relation to the suite of chemicals used in hydraulic fracture stimulation fluids. There was general concern about the possible health effects of chemicals used as additives, and those that may come to the surface in flowback water. Contamination concerns particularly related to drinking water supplies, stock water and irrigation water.

The pathways for contaminants to enter water supplies mentioned above included: well-casing and cement grout integrity, both over the lifetime of gas extraction and over the long

term (hundreds or even thousands of years); leakage from surface retention ponds; and transport of fluids to or between sites.

These issues were comprehensively covered in the submission from Dr Ryan Vogwill.

A low level of trust was expressed by participants concerning the adequacy of regulations, observance by petroleum companies, and the ability of government to enforce them both during operations and over the long term, post-abandonment.

9.3 The water resources of prospective shale oil and gas regions

9.3.1 Introduction

Groundwater is replenished or recharged by rainfall, either directly through the soil or through stream beds. This recharge gives rise to meteoric groundwater flow systems, which are driven by rainfall recharge with groundwater flowing through permeable aquifers to discharge to surface waters, to groundwater dependent ecosystems or to the sea. Groundwater in the Perth and Canning Basins has been shown by carbon dating to flow slowly, typically at rates of a few metres (m) per year. Discharge from the aquifers in the Perth Basin is mostly offshore, though there is minor inland spring discharge. Discharge from aquifers in the Canning Basin supports dry season flows in the Fitzroy River.

Over most of Western Australia, annual evaporation far exceeds annual rainfall. Salts in rainfall are concentrated by evaporation from vegetation and the soil zone, hence groundwater in Western Australia generally has a significant salt content. Salt content typically increases along the groundwater flow path. In the Perth Basin, groundwater is commonly fresh in areas of outcrop at the surface, and meteoric groundwater flow extends downwards to basal aquicludes or to depths where the permeability is low. Where the aquifers become confined, groundwater typically becomes brackish or saline.

At depth in the Perth Basin, below the zone of meteoric flow systems in less permeable formations, groundwater is saline and stagnant. Groundwater in sediments of marine origin may be connate, reflecting the salinity of the sea at the time of deposition. Seawater may also have entered aquifers during periods of inundation by marine transgressions. Groundwater along the eastern margin of the Perth Basin is also saline owing to southward groundwater flow from the Yarra Yarra salt lakes which are fed from the paleodrainages on the Yilgarn Craton.

The chemical compositions of Western Australian groundwaters are predominantly sodium chloride, and it is salt content which constitutes the main constituent of Total Dissolved Solids (TDS) and generally limits beneficial uses (**Table 9.1**). The other major ions present are calcium, magnesium, potassium, sulfate and bicarbonate. Nitrate originating from native plants also occurs in groundwater of potable salinity at concentrations exceeding recommended drinking water levels for infants, particularly in central Western Australia.

Groundwater flow systems may be quite separate where geological strata are separated or compartmentalised by geological structures, such as faults (Bense et al. 2013). Groundwater

flow systems may also include more than one geological formation where they are in hydraulic connection.

An aquifer in a sedimentary basin is defined as a geological formation, group of formations, or part of a formation which can store and transmit water, having the properties of both porosity and permeability. Generally, the term aquifer is used to describe a formation which can yield useful quantities of water to a well or bore. A useful quantity may range from being able to run a centre pivot irrigator to a bore or well for stock watering. An aquifer may contain fresh, brackish, saline or hypersaline groundwater (**Table 9.1**). An aquifer may also be a reservoir for conventional oil and gas accumulations, though at the depths at which these accumulations occur, porosity and permeability are often much lower, and groundwater circulation very slow. By definition, unconventional oil and gas are found in very low permeability rocks that have very low flow potential when unfractured.

Table 9.1: Groundwater salinity categories

Source: Australian Water Resources Council and Department of Water (DoW) (Australian Water Resources Council 1988; Department of Water 2014)

Salinity (mg/L Total Dissolved Solids)	Description	Potential use
0 – 500	Fresh	All purposes, domestic and irrigation
500 – 1,000	Fresh –marginal	Most purposes
1,000 – 1,500	Fresh – marginal – brackish	Upper limit for drinking
1,500 – 3,000	Brackish	Livestock, some irrigation
3,000 – 7,000	Saline	Most livestock
7,000 – 14,0000	Saline	Some livestock (sheep)
14,000 – 35,000	Saline	Ore processing
35,000 – 100,000	Hypersaline	Ore processing
>100,000	Hypersaline – brine	Salt production; ore processing

Since much of the literature on the impacts of hydraulic fracture stimulation is from the United States, it is pertinent to note that the state of California refers to the protection of freshwater containing 3,000 milligrams per litre (mg/L) TDS or less, and United States Federal regulation defines underground sources of drinking water (USDW) as containing less than 10,000 mg/L TDS (California Council on Science and Technology 2015b).

Aquifers are currently named by their geological formation, which are defined on the basis of age and lithology (the type of rock they are dominantly composed of). These geological

divisions do not always reflect the hydrogeology. The main aquifers in the Perth Basin are mostly sands or sandstone, but these also contain significant portions of interbedded siltstone or shale. Locally, karst conditions, underground streams, also occur in the coastal Tamala Limestone, particularly between the Nambung and Arrowsmith Rivers. A distinction is made between unconfined aquifers, in which there is a water table open to recharge and contamination from the surface, and confined aquifers, which are overlain by other geological formations. An aquifer may be unconfined in one locality and confined elsewhere, where it is overlain by impermeable sediments.

The major confined aquifers in the Perth Basin are Triassic to Cretaceous in age. In outcrop, they are commonly lithified or ferruginised, but are generally loosely consolidated in the subsurface, with high permeability and porosity. These properties decrease with the depth and temperature of burial and increased consolidation. A rock formation that has good aquifer properties at a shallow depth may lose its storage and flow properties at greater depth, and therefore the use of geological names synonymously with aquifers can be misleading.

The submission to the Inquiry from Latent Petroleum, the operator of the Warro gasfield, stated that:

> *"the definition of aquifers, referring to the use of Yarragadee aquifer in the Department of Water and Environmental Regulation (DWER) water allocation system, was not satisfactory and further identification and classification was needed. The tight gas at Warro is in the lowermost part of the 4,000 m thick Yarragadee Formation, where the formation water is saline. The deepest water production bores in the Northern Perth Basin are 600 m deep in the Yarragadee aquifer at Eneabba. However, the Yarragadee Formation in the Warro hydrocarbon exploratory wells is sufficiently consolidated at a depth of 4,000 m so it holds tight gas reserves. This indicates that groundwater circulation at the base of the Yarragadee Formation is highly restricted"* – submission from Latent Petroleum

In Australia, the term water bore, or simply 'bore', is used for a drilled hole to produce or monitor groundwater and cased with steel, fibreglass or plastic casing. The term 'well' is usually restricted to dug wells, lined with brick, stone or timber. This distinction does not exist in North American usage where drilled holes are also 'wells' as in 'oil well' and 'water well'. The American usage is used worldwide in the oil industry. The wells drilled for the exploration and production of unconventional oil and gas extend typically from 2,000-4,500 m in depth and are lined with several strings of cemented in steel casing. They therefore pass well beyond the depth of any productive aquifers but may penetrate both confined and unconfined aquifers containing water of different salinities in their shallower section.

9.3.2 Canning Basin

9.3.2.1 Surface water

The Fitzroy and Lennard Rivers which discharge into King Sound are the only major rivers in the Canning Basin (**Figure 9.2**). Elsewhere there are short ephemeral drainages on ranges and to the east and west of the Dampier Peninsula. The Great Sandy Desert is occupied by the courses of former rivers (paleodrainages). The Mandora Palaeodrainage is the largest system and occasionally floods across the outlet at Mandora Marsh. Springs maintain permanent salt water at Salt Creek, 40 km inland. The Percival Salt Lakes occupy the Percival Palaeodrainage in the centre of the basin. Fresh water springs in the vicinity of the lakes have provided water and the Canning Stock Route passes along the lakes, being the only route across the desert where shallow wells can be constructed. Water also persists in interdunal swales after cyclonic rains.

The Fitzroy River is one of Australia's largest unregulated rivers, draining a catchment of 88,980 km^2 and having an average annual runoff of around 6,000 GL. It rises in the Precambrian rocks of the Halls Creek Belt and has an extensive floodplain below Fitzroy Crossing (Petheram et al. 2018). The Lennard River drains an area of 14,160 km^2 and has an annual average runoff of 1,500 GL.

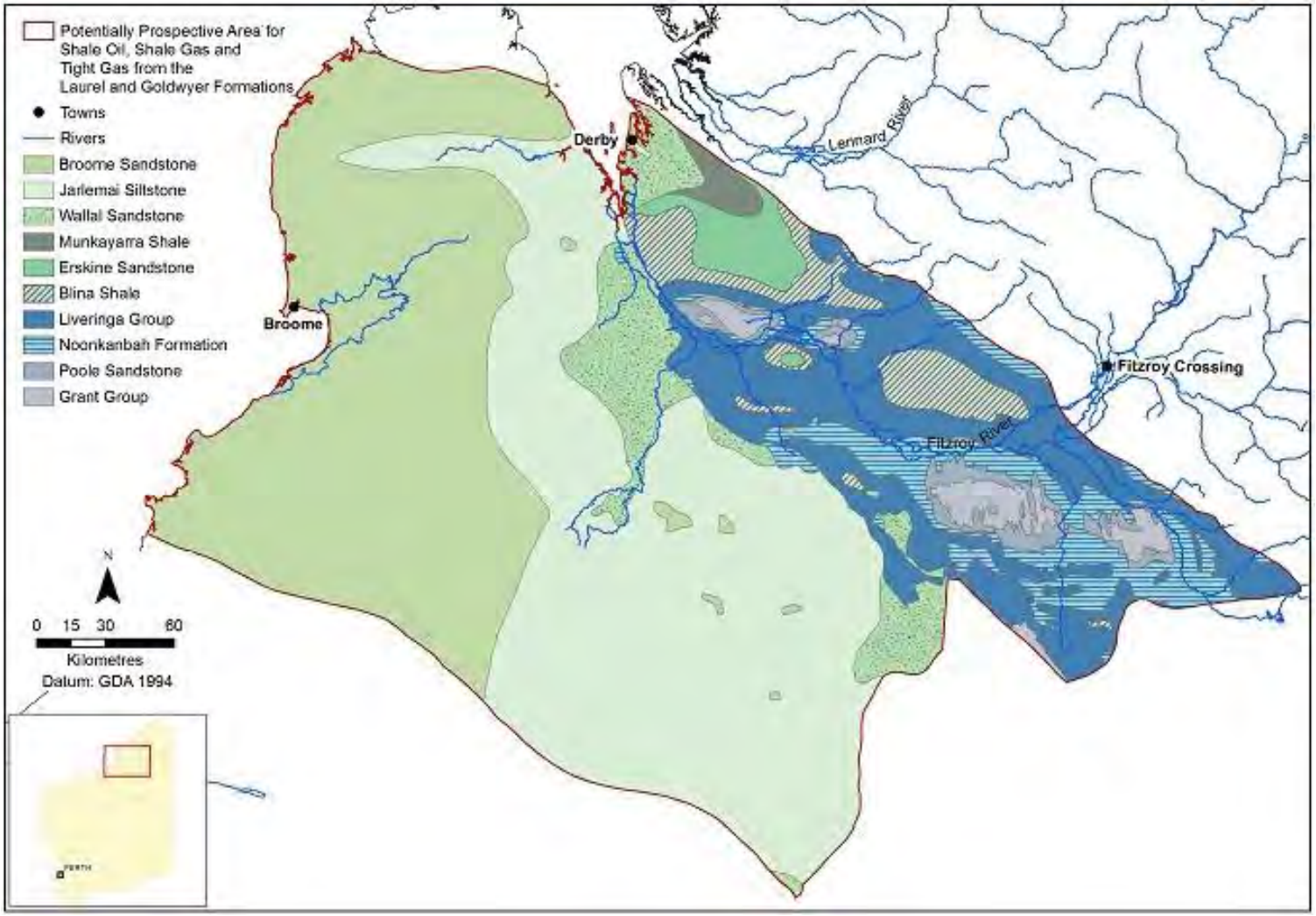
Annual discharge in the Fitzroy River at Fitzroy Crossing is highly variable, ranging from 300GL (1992) to 25,000 GL (2000) with most of the flow between December and March (Harrington et al. 2011). During the dry season, permanent pools are maintained by groundwater. Harrington et al. (Harrington et al. 2011) estimated from river chemistry profiles in May that 102 ML/day of groundwater discharged into a 100 km stretch of the river, of which 96 percent was from the alluvial aquifer and four percent from regional aquifers.

The salinity of wet season flows is less than 250 mg/L, but varies spatially and temporally during the dry season. Dry season salinity levels tend to reflect the underlying groundwater salinity, with lower salinity over the major Permian sandstones and higher salinity (up to 900 mg/L) over the Noonkanbah Formation and Blina Shale.

Water from the river, fed by a barrage across the river, and water from a dam on Uralla Creek was used for irrigation of rice, grain and fodder crops at Camballin between 1952 and 1983, when a major flood damaged the levee banks (Yuhun 1985). There has been renewed interest recently in irrigating fodder crops for cattle (Petheram et al. 2018). Potential dam sites were assessed by CSIRO (Petheram et al. 2014).

Figure 9.2: Geological map of the potentially prospective areas in the Canning Basin

Source: Lindsay and Commander (Lindsay & Commander 2006) from GSWA data and additional information from DWER



Waterbird usage of the floodplains, particularly Camballin, is listed with the Ramsar Convention on Wetlands and several species are protected under international agreements.

Under the Environmental Water Provisions Policy for Western Australia (Water and Rivers Commission 2000), provision must be made for the protection of water-dependent ecosystems, while allowing for the management of water resources for their sustainable use and development to meet the needs of current and future users. The sustainable yield for consumptive use must account for the Ecological Water Requirements (EWRs), which are water regimes required to maintain the ecological values at a low level of risk. The ecology of the river and knowledge gaps are described by Pusey and Kath (Pusey & Kath 2015). The Fitzroy River and its tributaries is a proclaimed surface water area and use of water is licensed. Licensed abstraction was 14.2 GL (2015), mainly to two pastoral enterprises (Harrington & Harrington 2015).

Toussaint et al. (Toussaint et al. 2001) emphasised that indigenous groups have expressed their dependence upon the river and the cyclical relationship of water, such as the importance of the *warramba*, or annual flood that cleans out the river system. The importance of water to local indigenous people is communicated by knowledge exchange, song, stories and film, and Traditional Owners constantly reaffirm that the Fitzroy Valley rivers, waters and riverine resources are central to their lives. Some communities supplement their food sources by fishing and gathering aquatic fauna.

There is also a deeply held belief among local communities that any controls on the natural flows or water level reduction induced by groundwater abstraction will negatively alter traditional food sources that some communities still rely upon (Toussaint et al. 2001). The indigenous communities consider permanent pools in the Fitzroy as ‘living water’. Ecologically, permanent pools are important refuges for aquatic species enabling them to survive the harsh dry season. Therefore, any process that impacts on pools (for example, infilling by sediment or lowering of water levels by abstraction) can have substantial impacts on fauna. The Traditional Owners emphasised that infilling made pools unsuitable for fishing and that floods are critical to flush these pools and ‘cleanse the country’. Overall, there is a clear linkage between ecological and cultural values of specific freshwater habitats, particularly the permanent pools.

Indigenous knowledge of water in the north-west of the Great Sandy Desert has been documented by Yu (Yu 1999) in a report to the then Water and Rivers Commission. The Karrijarri concept of ‘living water’ refers to permanent groundwater connecting various water sources. They distinguish ‘jila’, permanent water sources, from ‘iirri’, seasonal soaks, ‘pirapi’, claypans and ‘wirrkuja’, rockholes. Understanding the nature of these sources was critical to survival and Traditional Owners are responsible for looking after those water supplies.

9.3.2.2 Groundwater

Detailed groundwater studies have been carried out, only in the extreme South-West (West Canning Basin), along the coast and around Broome (LaGrange Sub-area and Dampier Peninsula), near Derby, and along the Fitzroy River. An extensive assessment of the LaGrange area has been carried out recently under the Water for Food Program (Department of Agriculture and Food 2016), involving 49 new bores at 24 sites. Currently DWER is finalising reports on drilling carried out at Mowanjum, Mt Anderson, Bunuba, Kimberley Downs, Knowsley and in conjunction with CSIRO at Brooking Springs and the Lower Fitzroy River (Clohessy 2017) as part of the Northern Australia Water Resource Assessment Program. Elsewhere conditions are inferred from pastoral bores in the Fitzroy Trough and along the coast, and inland from widely spaced petroleum exploration wells and shallow bores and wells (Harrington & Harrington 2015; Laws 1991a; Lindsay & Commander 2006). The basin contains some 10 km thickness of sediments ranging in age from Ordovician to Cretaceous, and can be subdivided structurally into the Fitzroy Trough and Gregory Sub-basin (extending south-east from Broome and encompassing the Fitzroy River Basin) and the Kidson and Willara Sub-basins (**Figure 8.6**), which underlie the Great Sandy Desert.

9.3.2.3 Fitzroy alluvial aquifer

An alluvial aquifer, consisting of up to 25 m of sands and gravels, stretches some 275 km along the Fitzroy River (Lindsay & Commander 2006). The alluvium is recharged by river flow and rainfall in the wet season, and discharges to river pools in the dry season. Discharge also takes place through the alluvium in the dry season from the underlying Permian aquifers, with groundwater of differing salinity (Harrington et al. 2011; Harrington & Harrington 2015). Groundwater discharge from the Liveringa and Grant Groups is relatively low salinity but from the Noonkanbah Formation and probably the Blina Shale, it is brackish or saline. Harrington and Harrington (Harrington & Harrington 2015) also suggest that groundwater from the Poole Sandstone discharges to the river up faults, based on helium-4 analyses. Groundwater from these confined aquifers is critical in maintaining the pools and their associated ecosystems at the end of the dry season.

The hydrogeology of the alluvium has not been investigated in detail, despite having been suggested as a major water source for local irrigation and even a canal supplying the Perth Region. The additional five monitoring bores recently drilled into the alluvium between Looma and the Fitzroy barrage show the alluvium to be very heterogeneous, and would not be considered a major or significant water source. Groundwater in three of these bores was saline, ranging from 9,700- 21,700 mg/L (Clohessy 2017).

The alluvial aquifer supports dry season river flows and permanent pools in the main channel, which persist until the commencement of wet season river flows. The aquifer may also support pools away from the main channels, such as Liveringa Pool. The pools in the dry season represent the only permanent water source for terrestrial, aquatic and avian wildlife,

and they also support fringing vegetation. The river and pools are culturally significant for the local communities.

9.3.2.4 Mandora and Percival Paleodrainages

The Great Sandy Desert is traversed by paleodrainages representing the courses of what were formerly major rivers (**Figure 9.3**). These depressions now contain shallow calcrete aquifers and shallow groundwater, which gives rise to springs, often fringing salt lakes.

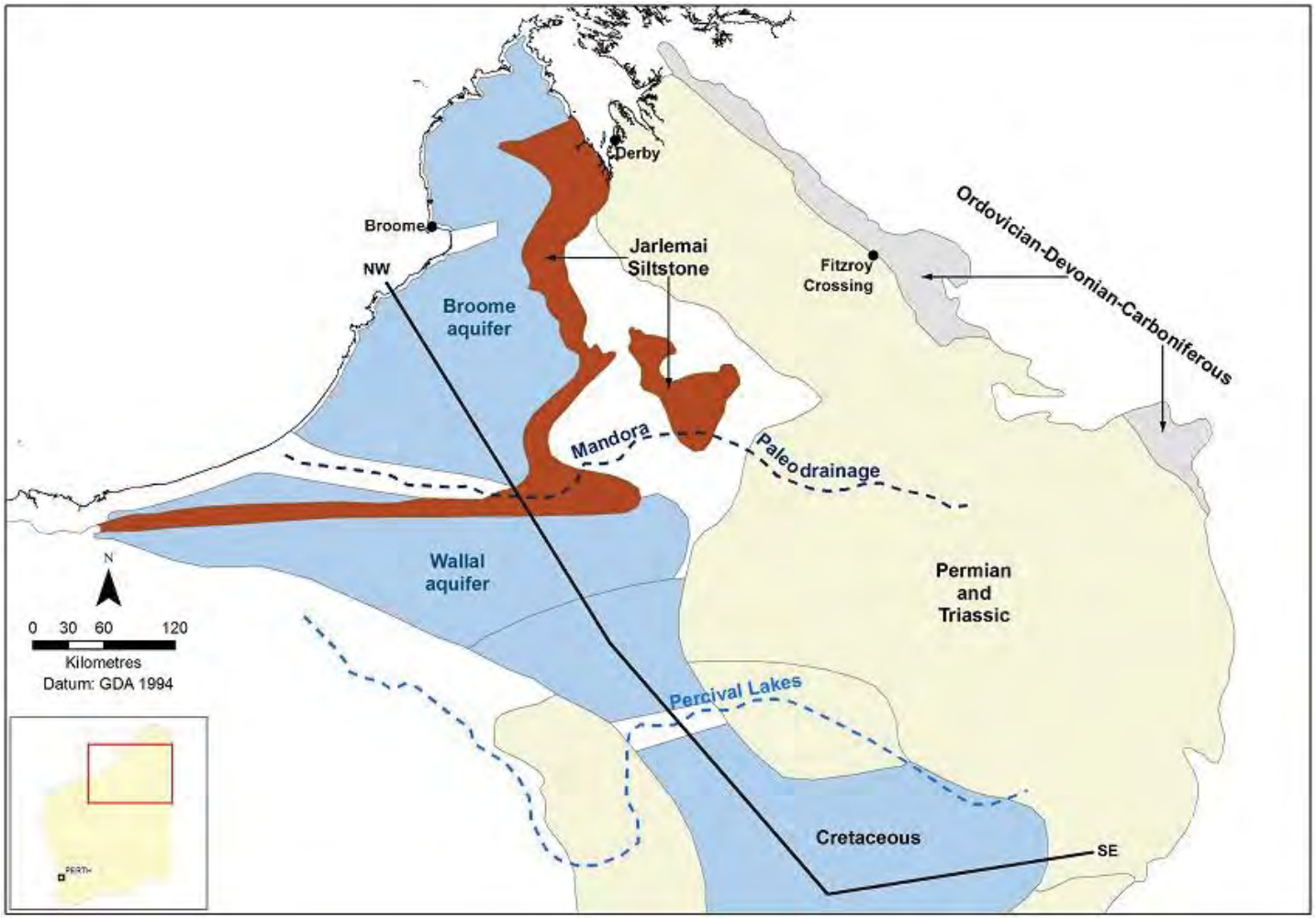
The greatest concentration of springs is in the Mandora Paleodrainage (English, Luu & Coote 2016) in the Walyarta Conservation Park, where there are spring fed raised peat mounds and saline discharge supporting mangroves at Salt Creek. The isolated Kurriji Pa Yajula (Dragon Tree Soak) is about 100 km to the east along the same paleodrainage.

The path of the Canning Stock route traverses the Percival Paleodrainage where the water table is shallow and there are springs around the salt lakes. The community at Punmu, 100 km south east of Telfer, owes its location to springs in the paleodrainage near Lake Dora (Commander 1985).

Saline groundwater in the Mandora Paleodrainage is probably partly responsible for the brackish groundwater in the Wallal Sandstone aquifer north of Mandora Marsh (also known as Samphire Marsh), although the relationship is not known. Groundwater with a salinity of 103,000 mg/L, presumably originating in the paleodrainage, is also present in the base of the Broome Sandstone aquifer near the Mandora Marsh (Department of Agriculture and Food 2016).

Figure 9.3: Canning Basin paleodrainages, and possible extent of low salinity groundwater (light blue) in the Broome and Wallal Sandstones and unassigned Cretaceous sediments. Section line refers to Figure 9.9.

Source: Commander (Commander 1989)

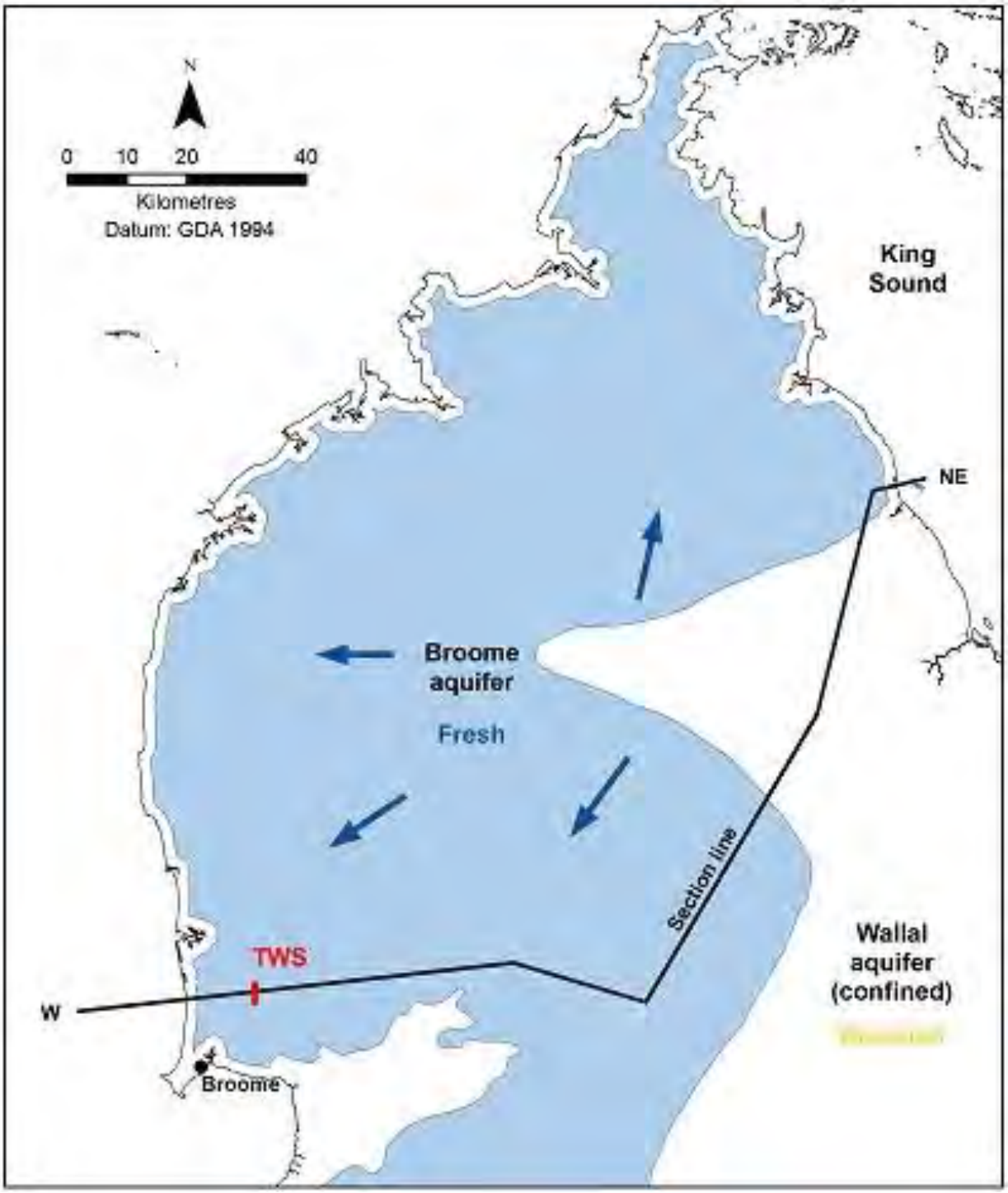


9.3.2.5 Broome Sandstone

The Cretaceous Broome Sandstone aquifer (Commander 1989; Department of Agriculture and Food 2016; Laws 1991a; Leech 1979) extends along the entire coast from the De Grey River to Cape Leveque, and inland by up to 150 km (**Figure 9.3**). It includes all the Cretaceous formations in that area stratigraphically above the Jurassic Jarlemai Siltstone. The aquifer generally thickens towards the coast, reaching a maximum thickness of around 250 m. The Broome Sandstone is an unconfined aquifer, recharged directly from rainfall and conformably overlies the largely impermeable Jarlemai Siltstone. In the centre of the Dampier Peninsula (**Figure 9.4**), the water table is deep, exceeding 100 m below surface (Laws 1991b). Groundwater is generally fresh, with salt water interfaces along the coast and around the fringes of Mandora Marsh and Roebuck Plains where groundwater discharge supports springs and phreatophytic vegetation. Springs are also common in water courses in the Coulomb Nature Reserve on the western Dampier Peninsula, and the aquifer also supports Munro Springs (Department of Agriculture and Food 2016). The aquifer is used for Broome town water supply, community water supply, for stock watering, and increasingly for irrigation on pastoral leases north of Mandora Marsh. Sheffield Resources Limited's Thunderbird mineral sand proposal also intends to dewater the orebody in the Broome Sandstone and use water for processing.

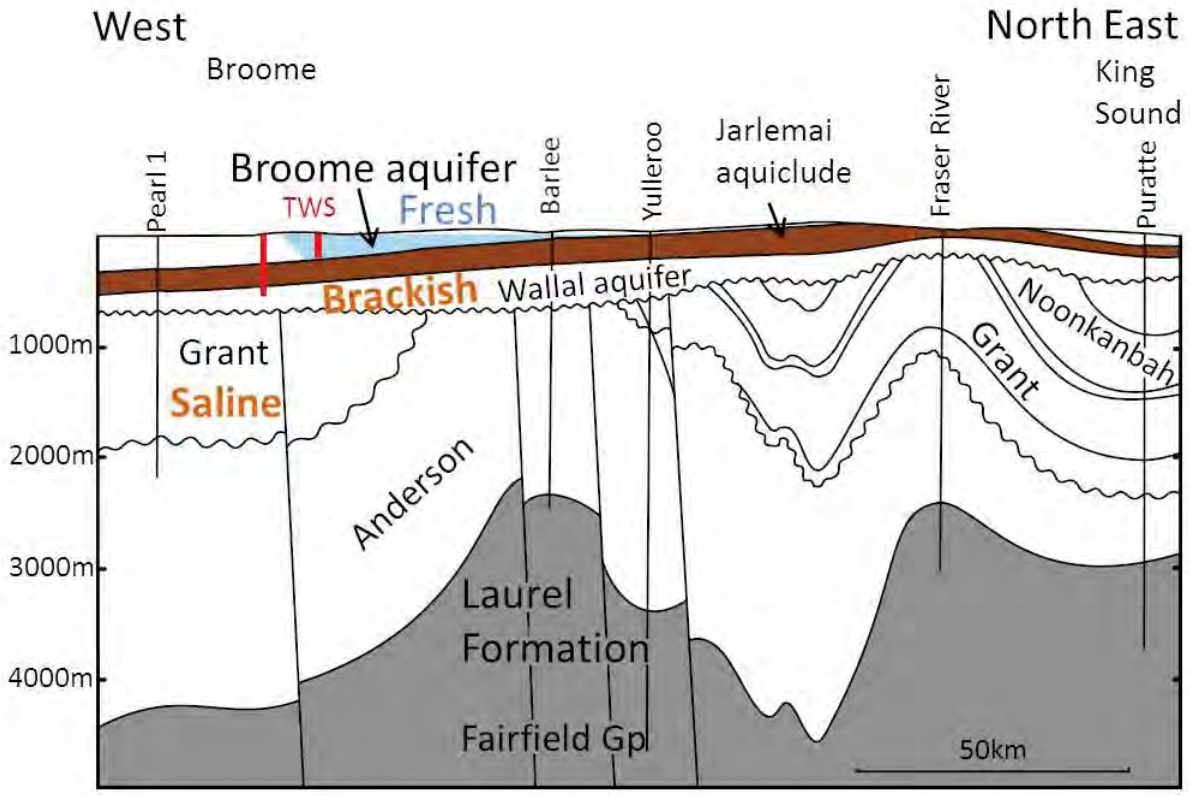
Figure 9.4: Distribution of the Broome Sandstone aquifer on the Dampier Peninsula; section line refers to Figure 9.5

Source: Commander and Laws (Commander 1989; Laws 1991b)



Cretaceous sediments equivalent to the Broome Sandstone crop out in the Kidson Sub-basin (**Figure 8.6, 9.3**) and may contain low salinity groundwater, but there is little information on the extent of fresh groundwater.

Figure 9.5: Geological cross-section showing low salinity groundwater in the Broome Sandstone (light blue) and prospective shale gas target (grey).
Source: GSWA



9.3.2.6 Wallal Sandstone aquifer

The Jurassic Wallal Sandstone underlies the Jarlemai Siltstone in the west of the basin (Leech 1979), and crops out beneath the Great Sandy Desert (**Figure 9.3**) (Commander 1985, 1989). It unconformably overlies various formations of Permian age. Together with the overlying Alexander Formation, it forms a 500 m thick aquifer, unconfined inland, and confined along the coast where it is overlain by the Jarlemai Siltstone and Broome Sandstone (**Figure 9.5**). It is recharged by direct rainfall on the outcrop, and groundwater flow is towards the coast, or locally to King Sound. Groundwater discharge is presumably a considerable distance offshore, as the potentiometric head along the coast is artesian (as at Broome), and up to 30 m above sea level at Cape Keraudren. Groundwater salinity in the extreme south-west of the basin is low, but salinity increases northwards along the coast to brackish north of Mandora Marsh, and is around 2,500 mg/L at Broome. There is very little information on salinity in the interior of the basin. In its submission to this Inquiry, Finder Shale reported a salinity of around 1,500 mg/L from its Theia well site 200 km south-east of Broome. The aquifer was investigated in the West Canning Basin for supply to Port Hedland, and is now being increasingly used between the De Grey River and Mandora Marsh for irrigation. Brackish groundwater is used for pastoral purposes on the east of the Dampier Peninsula.

9.3.2.7 Erskine Sandstone aquifer

The Triassic Erskine Sandstone occupies a syncline extending south east of Derby (**Figure 9.6 and 9.7**) (Laws & Smith 1989; Smith 1992). It is in contact with an overlying outlier of Wallal Sandstone at Derby where the intervening Munkayarra Formation is absent, and is bounded beneath, and around the margin by the underlying Blina Shale (Laws & Smith 1989; Smith 1992). Groundwater is recharged on the outcrop of the aquifer, with groundwater flow towards King Sound. Seawater interfaces occur in the aquifer around the Derby peninsula. Groundwater in the Erskine Sandstone away from the coast is fresh, generally less than 500 mg/L. The Erskine aquifer is used for Derby water supply and small scale horticulture, and the Wallal aquifer supports irrigation at Mowanjum, near Derby. Shallow groundwater in areas underlain by Blina Shale is generally saline.

Figure 9.6: Distribution of aquifers in the Derby area

Line of section refers to Figure 9.7

Source: Laws and Smith (Laws & Smith 1989; Smith 1992)

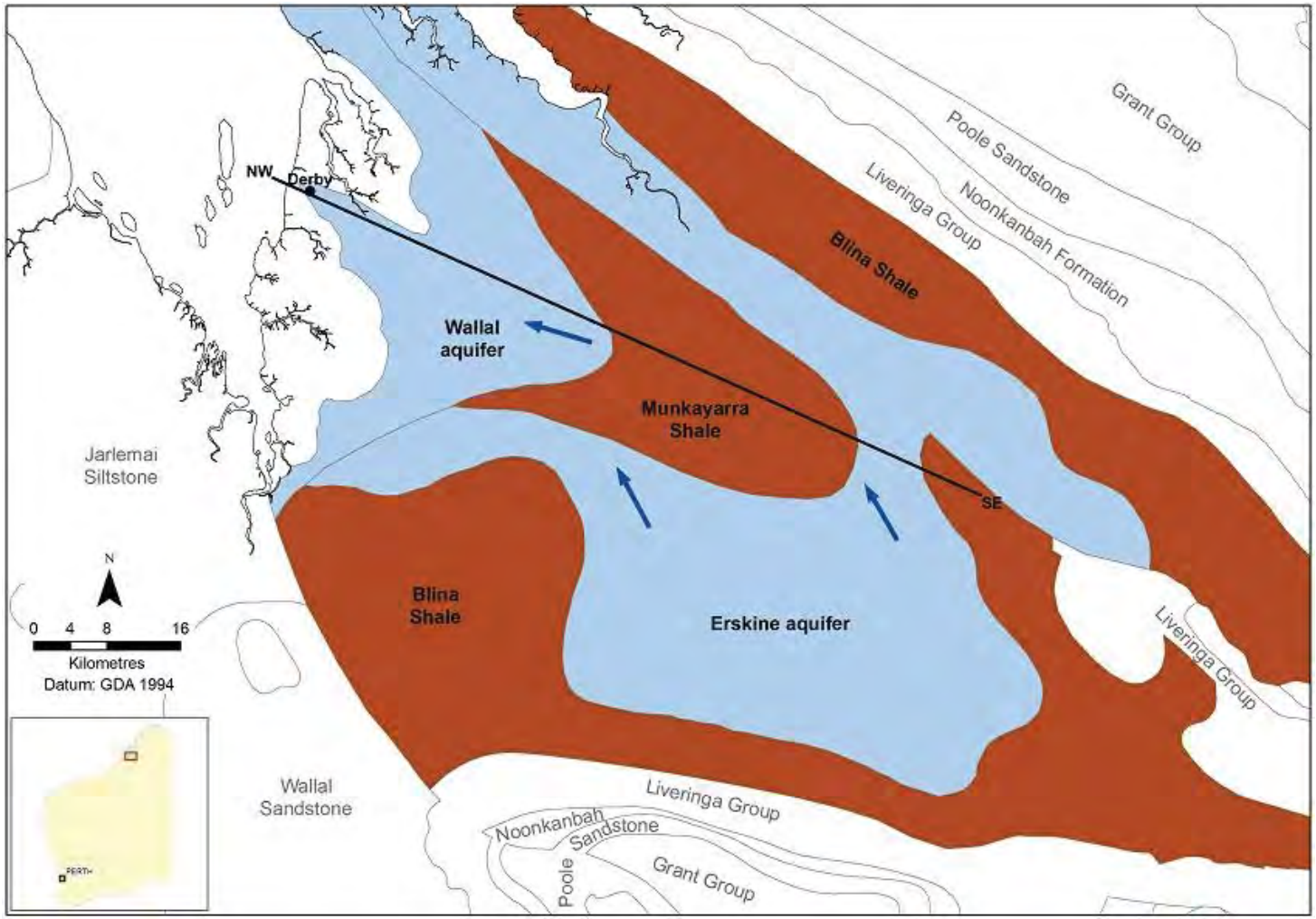
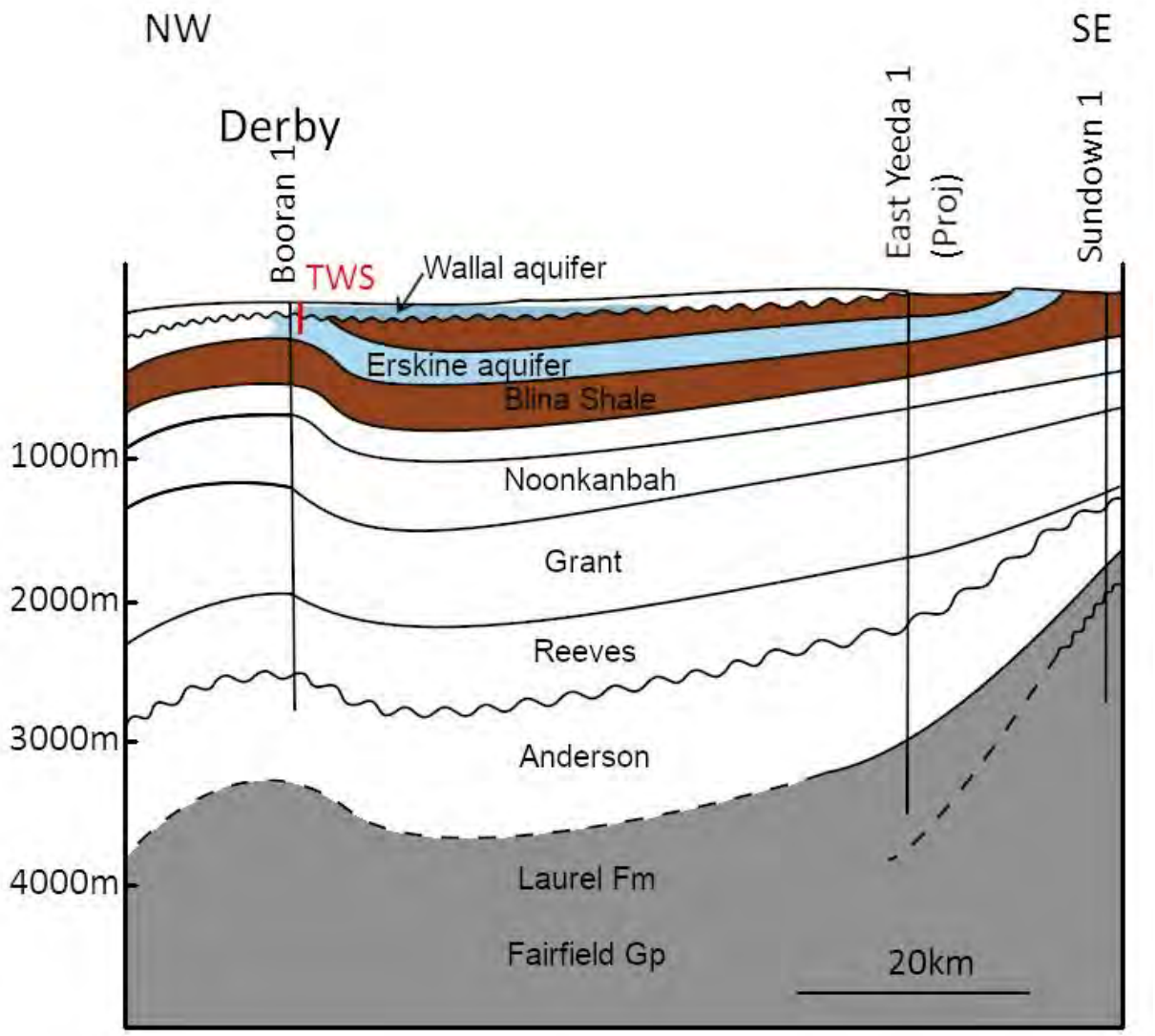


Figure 9.7: Geological cross-section showing low salinity groundwater in the Wallal and Erskine sandstones near Derby, and potential shale gas targets in the Laurel Formation and Fairfield Group (grey)

Source: GSWA (Unpublished data) and Laws and Smith (Laws & Smith 1989)



9.3.2.8 Liveringa Group

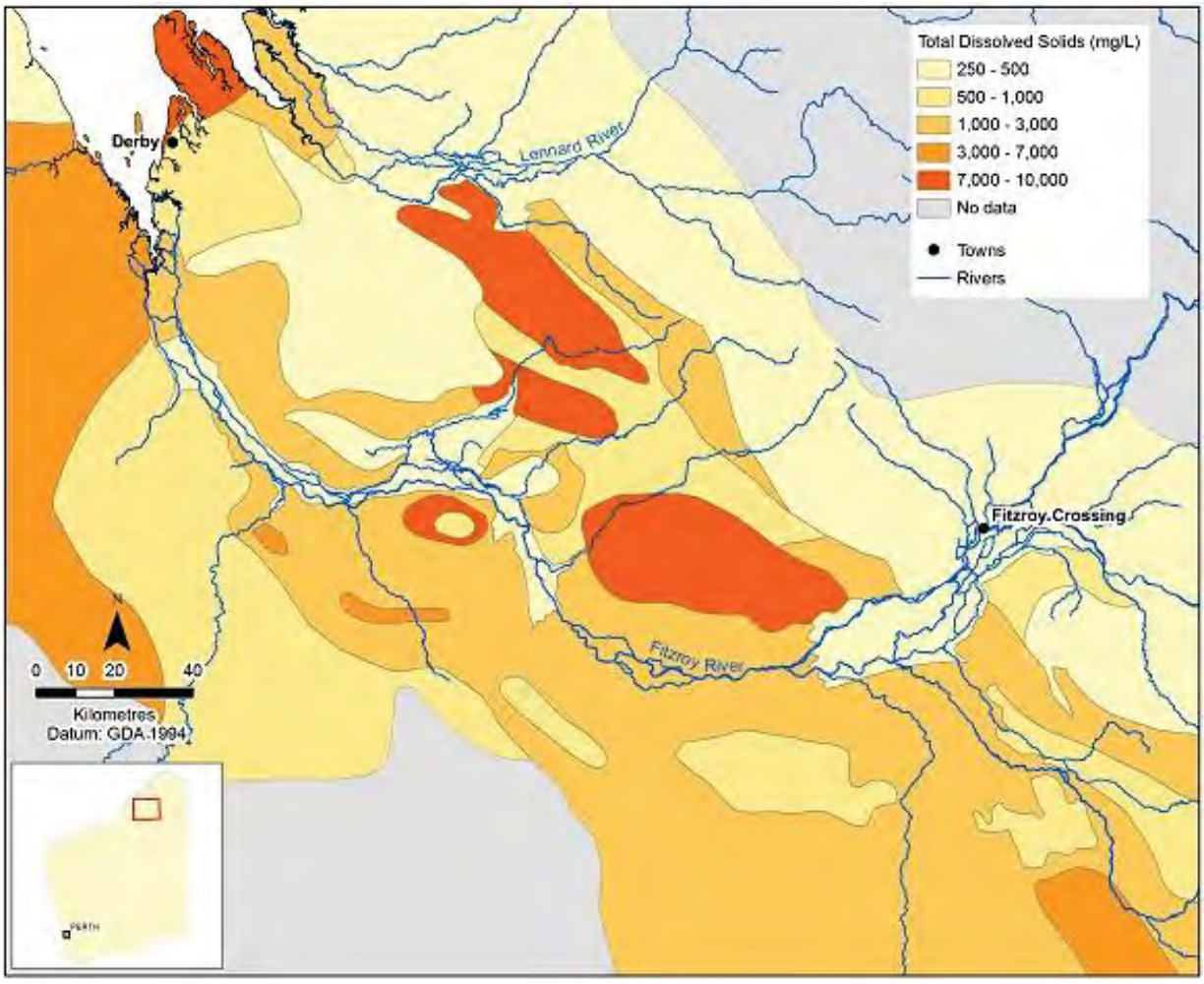
The Permian Liveringa Group contains 600 m of various sandstone aquifers and fine grained formations, and crops out in the Fitzroy Trough (**Figure 9.2**). It overlies the largely impermeable Noonkanbah Formation. Groundwater varies in salinity from marginal to brackish (**Figure 9.8**). It is used mainly for stock and domestic supply, and is also the aquifer used at the Valhalla and Asgard well sites. Bore yields are variable.

9.3.2.9 Grant Formation and Poole Sandstone

The Permian Poole Sandstone and Grant Group together form a major aquifer up to 2,100 m thick (Taylor et al. 2018). They crop out as inliers in the Fitzroy Trough, in the Grant and St Georges Ranges, and underlie the greater part of the Great Sandy Desert, stratigraphically below the Noonkanbah Formation (**Figure 9.9**). In the Great Sandy Desert, the Poole and Grant Group are in contact with overlying Cretaceous sandstones. In the Fitzroy Trough, groundwater is generally low salinity, but in the Willara and Kidson Sub-basins (**Figure 8.6**) groundwater in the Grant Group is as much as 37,000 mg/L (NaCl eq.) in Munro 1 (Ghassemi, Ferguson & Etminan 1991).

Groundwater from the Grant Group or Poole Sandstone has been used for irrigation at Camballin, mine supply at Ellendale, and for town water supply to Fitzroy Crossing. Large bore yields have been achieved at Camballin and Ellendale, but the aquifer at Fitzroy Crossing appears to be fractured and comparatively low-yielding (Department of Water 2008a).

Figure 9.8: Groundwater salinity distribution in the Fitzroy Trough, interpreted mainly from pastoral bores and wells.
Source: Lindsay and Commander (Lindsay & Commander 2006) and updated by DWER



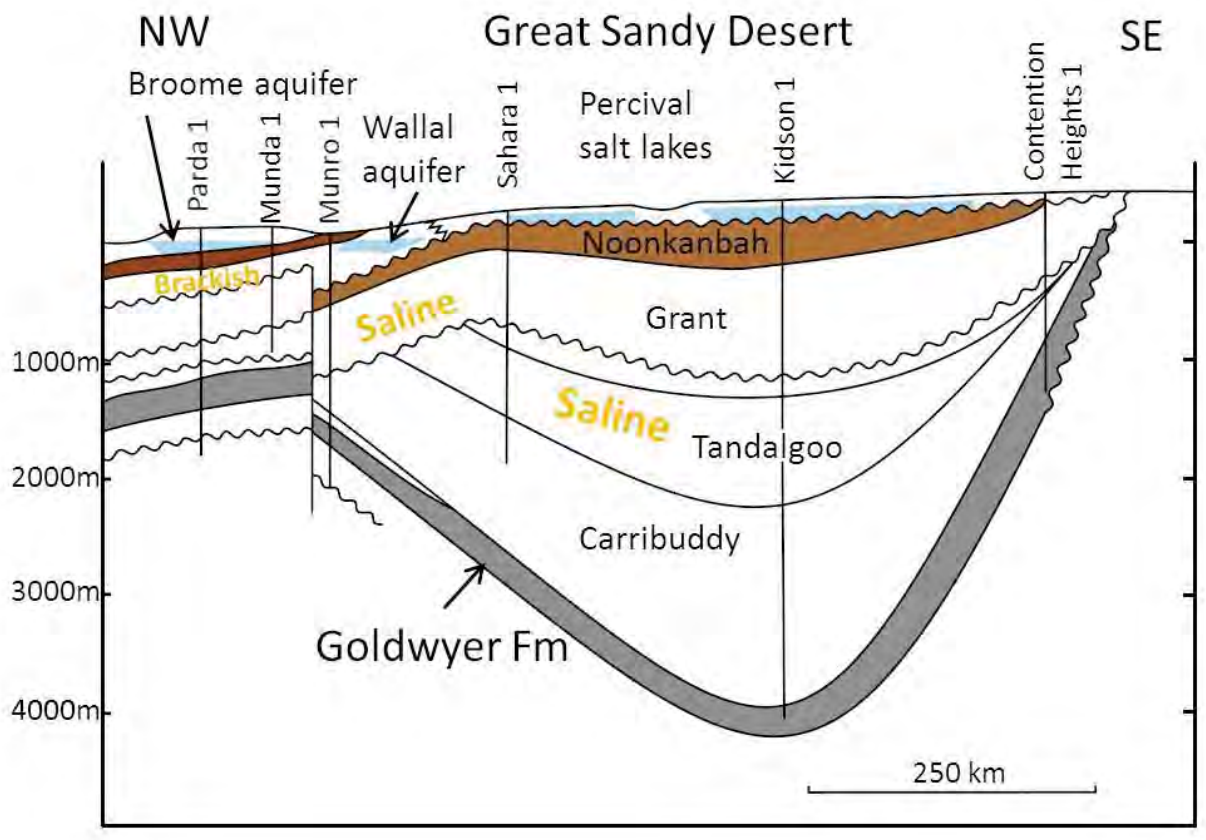
9.3.2.10 Carboniferous, Devonian and Ordovician formations

In the eastern Fitzroy Trough, there are various sandstones and the Devonian limestone reefs which generally contain fresh groundwater and probably represent local flow systems, discharging to the major rivers. Significant dewatering has been necessary at lead-zinc mines in the Devonian limestones.

Very little is known of the aquifers stratigraphically below the Grant Group in the Kidson and Willara Sub-basins. Ghassemi et al. (Ghassemi, Ferguson & Etminan 1991) quote salinities of 5,500 – 27,000 mg/L (NaCl eq.) in the Tandalgoo Formation in Kidson 1 (**Figure 9.9**). A factor affecting groundwater salinity in the Kidson and Willara Sub-basins is the dissolution of evaporites in the Carribuddy Group, particularly where salt domes have formed and intruded into overlying formations (Ghassemi, Ferguson & Etminan 1991).

Figure 9.9: Geological cross-section through the Kidson Sub-basin showing possible low salinity groundwater in the Broome and Wallal Sandstones (light blue) and potential shale gas target (grey)

Source: Ghassemi et al. (Ghassemi, Ferguson & Etminan 1991)



9.3.2.11 Existing water use

Most of the Canning Basin lies within the Canning–Kimberley Groundwater Area in which all groundwater extraction, apart from domestic and stock use, is licensed.

Groundwater use is at a low level, concentrated around Broome and Derby, with town water supply and horticultural activity. Formerly, groundwater was used for irrigation at Camballin. Bores supply stock water to pastoral leases. A small public water supply scheme supplies Fitzroy Crossing (**Table 9.2**), and groundwater also supplies indigenous communities (**Table 9.3**).

Investigations by the former Department of Agriculture and Food (Department of Agriculture and Food 2016) have identified suitable land in the LaGrange area south of Broome, envisaging development of 5,000 ha of irrigation using 50 GL/a from the Broome Sandstone aquifer. A 38 ha centre pivot irrigation system has recently been installed at Mowanjum to provide cattle grazing.

There has been groundwater use for mining purposes in the Fitzroy Trough at Ellendale (diamonds) and Blendevale/Pillara, Cadjubut and Narlala lead/zinc mines.

The proposed Thunderbird mineral sands mine on the Dampier Peninsula, east of Broome, is expected to extract up to 33 GL/a from the Broome Sandstone aquifer when operating below the water table, reinjecting 22 GL/a of this water back into the aquifer. This groundwater source is from the Canning-Pender sub-area of the Canning-Kimberley Groundwater Area, which currently has 95.4 percent of its available groundwater resources (50GL/a) available for allocation.

Table 9.2: Characteristics of town water supplies in the Canning Basin
Source: DoW drinking water source protection reports (Department of Water 2012, 2008b, 2008a)

Town water supply	Licensed allocation kL/a	Depth to water table (m)	Aquifer
Broome	5,4000,000	30	Broome Sandstone (unconfined)
Derby	800,000	10	Erskine Sandstone (confined)
Fitzroy Crossing	250,000	20-23	Grant Group sandstone (fractured, unconfined)

Table 9.3: Main Aboriginal communities in the study area with groundwater supplies from the Canning Basin

Source: Australian Bureau of Statistics 2016 Census

Community	Population (2016 Census)	Aquifer
Ardyaloon or Bardi (One Arm Point)	340	Broome Sandstone
Bayulu	322	Grant Group
Beagle Bay	305	Broome Sandstone
Bidyadanga (LaGrange)	617	Broome Sandstone
Djarindjin-Lombardina	395	Broome Sandstone
Djugerari	47	
Kunawarritji	76	
Jarlmadanga Buru	85	Grant Group
Joy Springs	59	
Looma (Camballin)	519	Grant Group (Poole)
Mowanjum	311	Wallal/Erskine
Muludja	154	
Pandanus Park	125	
Punmu	142	Triwhite Sandstone
Wangkatjungka	228	
Yakanarra	126	
Yungngora (Noonkanbah)	378	Grant Group

The locations of these communities are shown on **Figure 12.4**.

9.3.3 Northern Perth Basin

9.3.3.1 Surface water

In the prospective area for shale gas and oil, and tight gas in the Northern Perth Basin, only the Hill and Irwin Rivers reach the sea (**Figure 9.10**). A number of ephemeral internal drainages (Nambung River, Cockleshell Gully, Indoon-Logue including Stockyard Gully, Bindoon Creek and Eneabba Creek, and Arrowsmith River) pond up against the coastal limestone and discharge into cave systems, some of which may extend offshore. South-east of the area drains towards the Coonderoo River, a tributary of the Moore River, which occupies an area of salt lakes along the line of the Darling Fault.

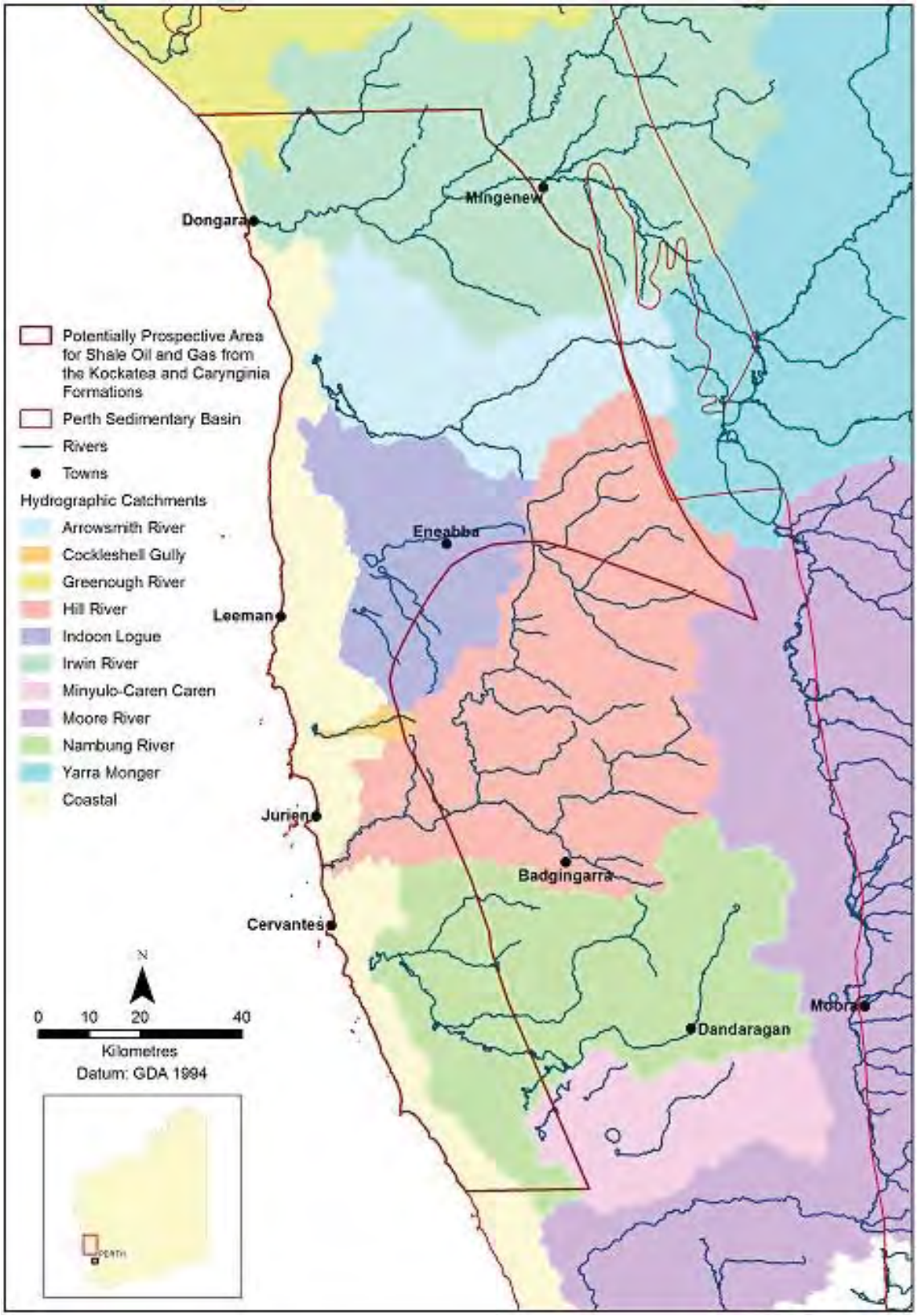
The Irwin is the only river which flows regularly, because of its large catchment extending east of the Perth Basin, and had a mean annual flow of around 40 gigalitres per annum (GL/a) in 1993-2002 (Mayer, Ruprecht & Bari 2005). Its largest recorded flood took place in March 1971. Owing to the sandy soils, runoff in many of the minor streams is highly seasonal and occurs only in exceptionally wet years such as 1974 (Commander, 1981) or following cyclonic events. Annual flow in the Arrowsmith River during the period 1972-2000 ranged from 0.1 GL/a in 1976 to 24 GL/a in 1999 (Department of Water 2017b). Spring discharge from groundwater also occurs into the Hill River (Lindsay 2004), Arrowsmith River (Barnett 1970; Commander 1981) and Irwin River (Allen 1980), but does not maintain significant flow.

The salinity of runoff is highly variable (**Table 9.4**). It is at its lowest following heavy rainfall and increases with time after a rainfall event. Salinity also depends on where the runoff is generated. Runoff from the Permian sediments and Precambrian rocks east of the Urella Fault is saline; runoff originating from areas underlain by Parmelia and Yarragadee Formations are generally fresh to brackish; runoff from the Leederville-Parmelia and Yarragadee aquifers is fresh; whereas runoff and base flow from areas underlain by the Cattamarra Coal Measures are brackish to saline.

Table 9.4: Runoff characteristics of rivers in the Northern Perth Basin
Source: DoW, Mayer, Ruprecht and Bari (Department of Water 2017b; Mayer, Ruprecht & Bari 2005)

	Station ID		Mean annual flow 2000-2015 (GL/a)	Salinity class	Mean salinity 1993-2002 (mg/L)
Irwin River	701-009		16	Brackish-saline	2300
Arrowsmith R	701-005		5	Brackish-saline	2900
Hill River	6117-002 617-017		- 5	Fresh-brackish Brackish	1100 -

Figure 9.10: Surface water catchments in the northern Perth Basin
Source: DWER



9.3.3.2 Groundwater

The Perth Basin contains Western Australia's most important groundwater resources. The northern part of the basin contains extensive Mesozoic (Triassic, Jurassic and Cretaceous) sandstone aquifers and locally significant superficial aquifers. There are extensive areas of fresh groundwater, the soils are sandy or gravelly allowing direct recharge from rainfall; and the water table is commonly deep below the surface. Groundwater is used for public water supply, mining, stock and domestic use on farms, and for irrigation (development of which has been hampered by the depth to water).

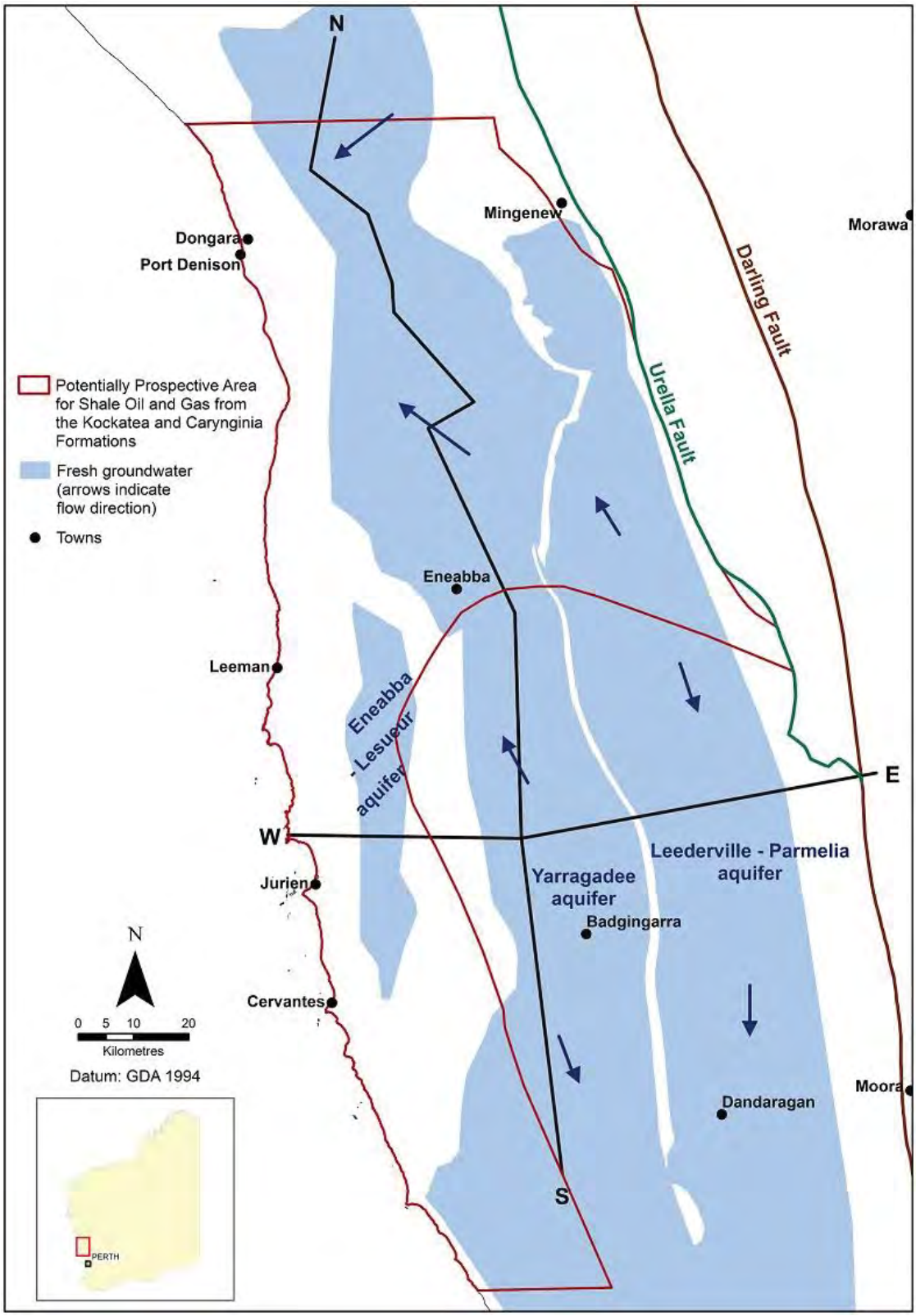
Occurrences of conventionally accessible oil and gas reserves, which have accumulated in structural and stratigraphic traps over millions of years, are associated with stagnant saline groundwater at depth. They are generally separate from the shallower potable fresh groundwater systems which are typically renewed on a scale of tens of thousands of years and from which any hydrocarbons are naturally flushed or escape as gases.

The hydrogeology of the Northern Perth Basin (**Figure 9.11**) is known at a regional scale from a network of widely spaced government exploratory bores, and from private bores and hydrocarbon exploration wells (Department of Water 2017b). The basin sediments are as much as 15 km thick close to the eastern margin along the Darling Fault near Dandaragan, and thin to around 2km at the coast near Jurien. Sedimentary rocks are relatively flat lying and undeformed close to the Darling Fault (which bounds the basin against the Yilgarn Craton to the East) but are increasingly faulted and tilted in the Hill River area, east of Jurien. The basin contains two major aquifers: the Leederville-Parmelia aquifer, and the Yarragadee aquifer in which low salinity groundwater extends to depths of around 3,000 m (**Figure 9.12**). The Lesueur Sandstone and Eneabba Formation also contain significant fresh groundwater resources where they crop out at the surface in the Hill River area east of Jurien.

Figure 9.11: Distribution of fresh groundwater in major aquifers of the Northern Perth Basin

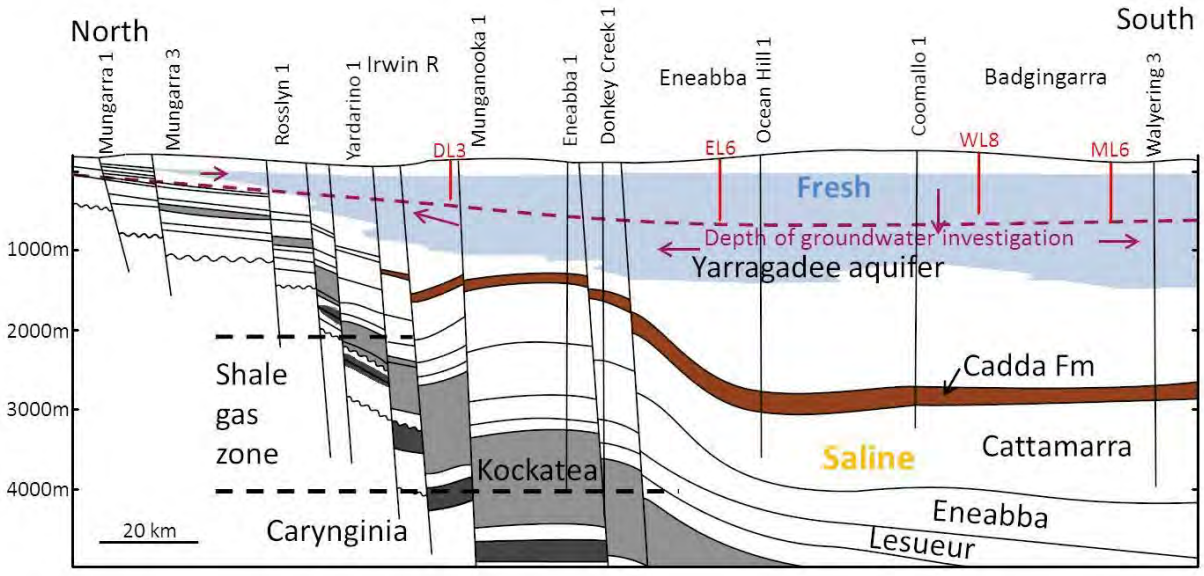
Section lines refer to Figures 9.12 and 9.14

Source: DoW (Department of Water 2017a) updated by DWER



These fresh, meteoric, groundwater systems are replenished mainly by rainfall falling on the outcrop of the aquifers. Groundwater flows slowly to discharge offshore at flow rates of around several metres per year, and groundwater ages sampled from bores range from thousands to tens of thousands of years. At depth, generally below the Cadda Formation that forms a continuous marine shale aquiclude, groundwater is saline and stagnant, and the brines may reflect sequestered seawater from previous periods of inundation.

Figure 9.12: North to south geological cross-section, showing depth of low salinity groundwater (light blue) and shale gas targets (grey), groundwater investigation bores (red) and petroleum exploration wells (black).
Source: Geological Survey Western Australia (GSWA)



9.3.3.3 Superficial aquifer

Superficial sands and limestone underlie the coastal plain and coastal dune systems, and form an aquifer up to 25 m thick (Department of Water 2017a; Kern 1993, 1997; Kern & Koomberi 2013; Nidagal 1995).

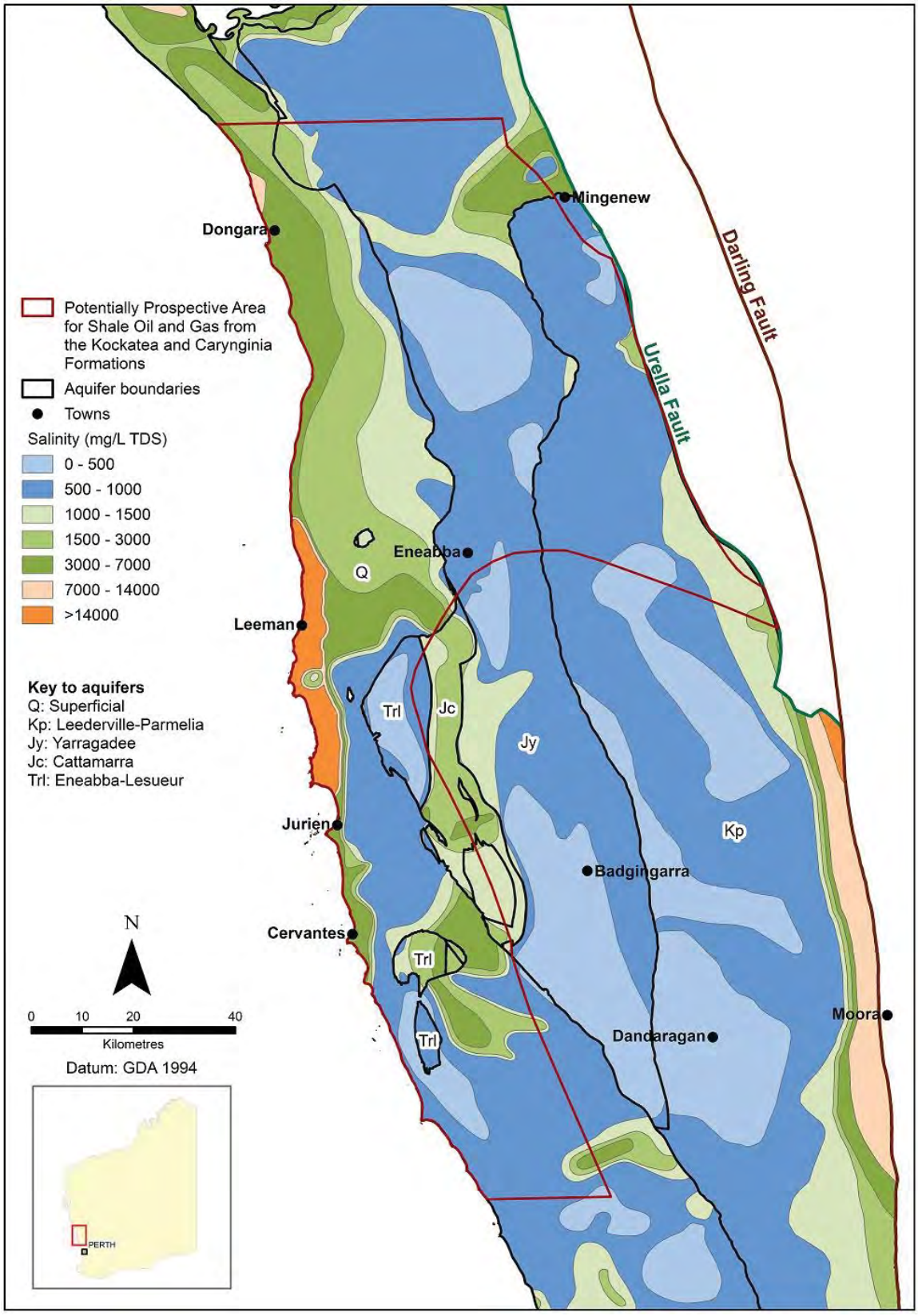
Groundwater is recharged by rainfall, ephemeral streams that pond up against the Spearwood Dunes, and there is also upward discharge in places from the underlying confined aquifers. The Tamala Limestone, making up the Spearwood Dunes, locally exhibits karst features, with caves, and underground river channels, though Smith et al. (Smith, Massuel & Pollock 2012) found that conduit flow in the Perth area is not typical of the formation. In the Bassendean Dune System, south of Jurien and south east of Dongara, the water table is generally shallow, supporting wetlands and phreatophytic vegetation. However, some areas, for example the eastern coastal plain north of Eneabba, are unsaturated, with the water table in the Mesozoic aquifers below, and many of the ephemeral wetlands (for example, Lake Logue) are perched and supported by ephemeral streamflow.

Groundwater in the superficial aquifer generally becomes increasingly brackish to saline northwards. Saline groundwater occurs near the coast between Cervantes and Leeman associated with salt lakes. Elsewhere, a seawater wedge occurs along the coast and may extend one or two kilometres (km) inland. Discharge from the aquifer is inferred to take place to the salt lakes and along the coast, above the sea-water edge, though karst conduits may extend some distance offshore. Rapid flow may occur in karst conduits when flood waters recharge the aquifer.

The superficial aquifer supports vegetation where the water table is shallow, south east of Dongara and south-east of Jurien. It supports saline coastal lakes, such as Lake Thetis near Cervantes, in which there are microbialites. The aquifer supports subterranean groundwater dependent ecosystems (Susac 2012).

Fresh groundwater resources are limited (see **Figure 9.13**), but are used for Jurien and Cervantes water supply and for standby in the Greenhead-Leeman town water supply scheme. The superficial aquifer also supports irrigated horticulture in the Dongara-Irwin area. Groundwater at the northern extent, on the Greenough Flats north of Dongara, is brackish to saline (Kern & Koomberi 2013).

Figure 9.13: Groundwater salinity near the water table in the Northern Perth Basin
Source: DoW (Department of Water 2017a) updated by DWER

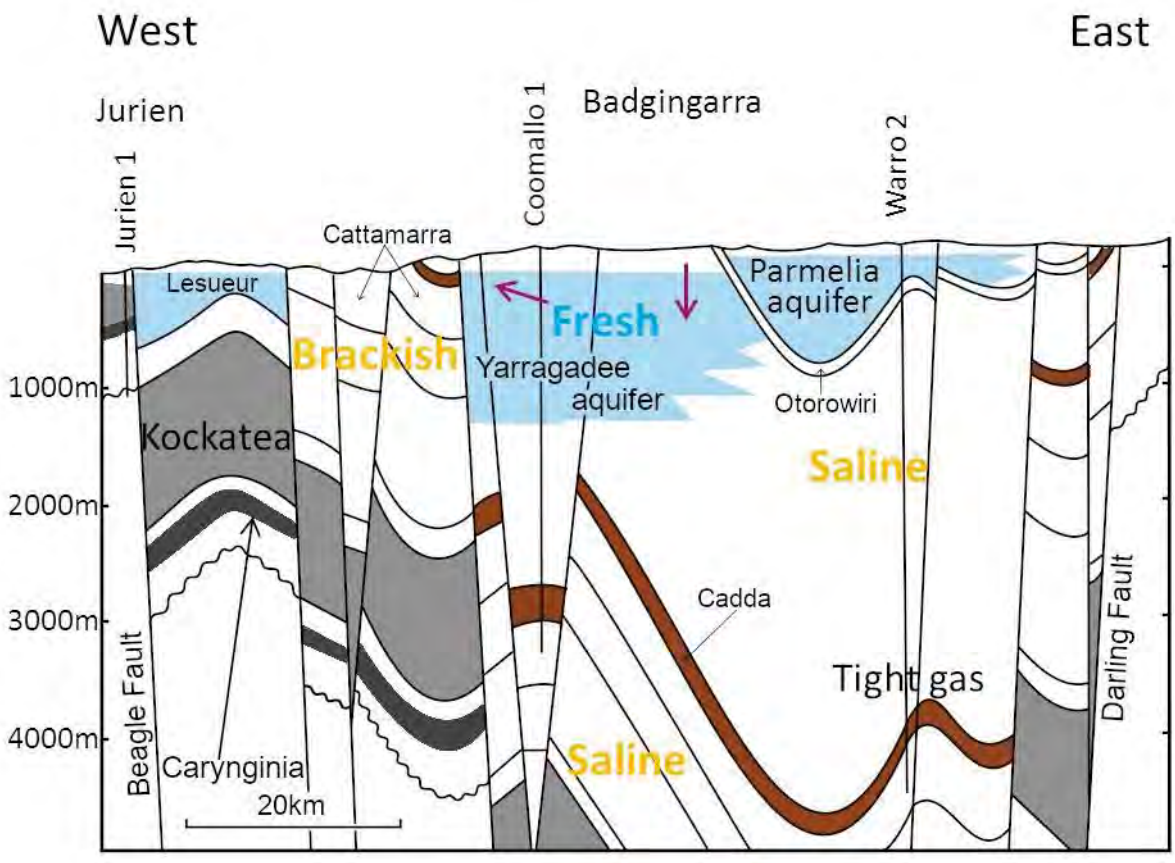


Groundwater levels in unconfined aquifers located under perennial vegetation have been falling in recent decades because of reduced rainfall and higher temperatures in the Perth Basin. Future climate scenarios indicate this decline will continue and accelerate under extreme dry conditions (CSIRO 2009).

9.3.3.4 Leederville-Parmelia aquifer

The Cretaceous Leederville-Parmelia aquifer (**Figure 9.14**) occurs below the Dandaragan Plateau (Balleau & Passmore 1972; Barnett 1970; Briese 1979; Commander 1978a, 1978b, 1981; Department of Water 2017b; Harley 1974a, 1974b; Irwin 2007) between the Dandaragan Scarp and the Darling and Urella Faults. It is up to 400 m thick and is bounded below by the Otorowiri Siltstone which crops out along the Dandaragan Scarp. In the south, near Dandaragan, the Parmelia Formation is directly overlain by the younger Cretaceous Leederville Formation, both formations making up the Leederville-Parmelia aquifer, consisting of weakly indurated interbedded sand and siltstone. This is confined by the Late Cretaceous Kardinya Shale, part of the Coolyena Group (**Figure 8.18**).

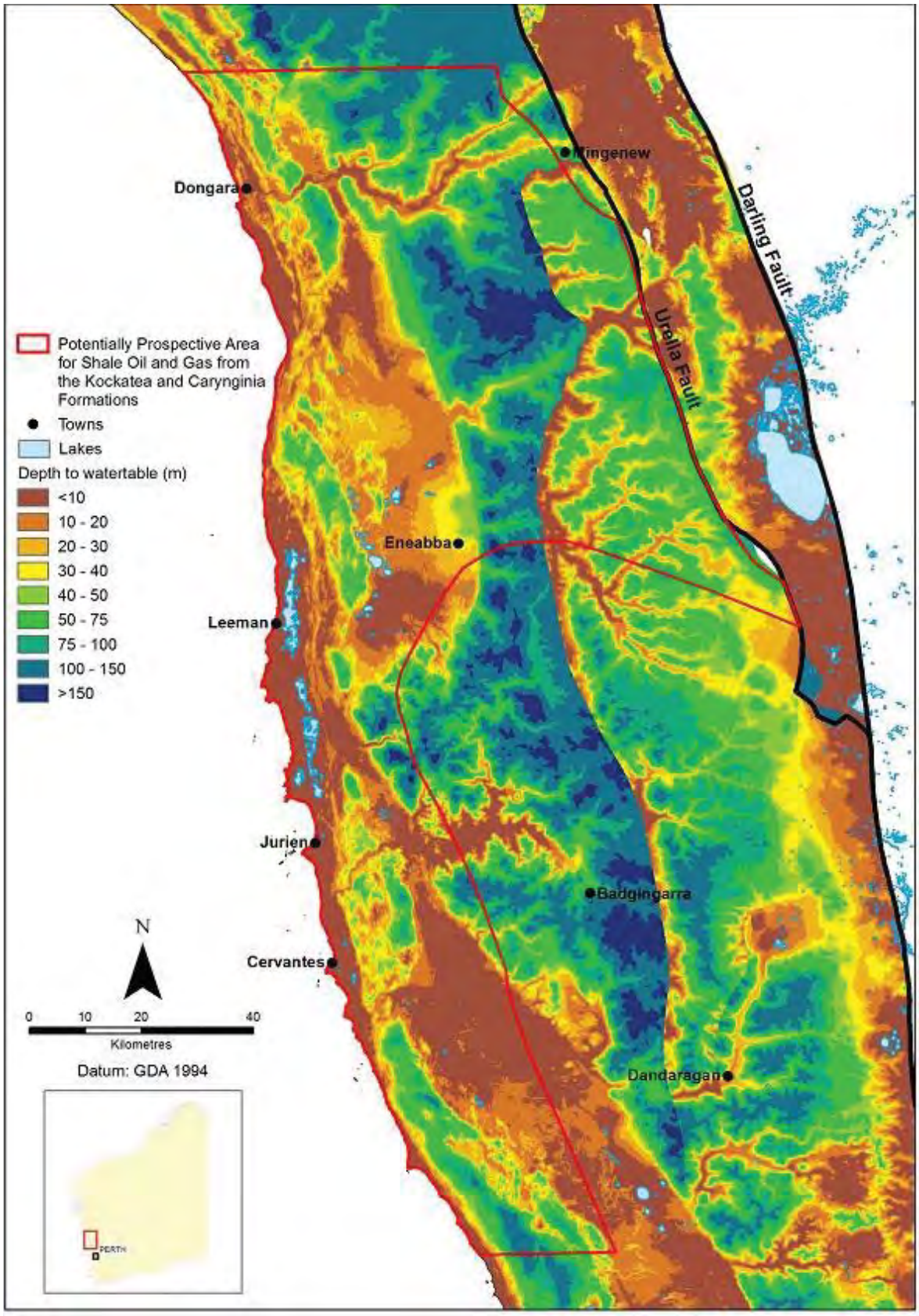
Figure 9.14: West-east cross section showing low salinity groundwater in the Leederville-Parmelia, Yarragadee and Lesueur aquifers (light blue) and shale gas targets in grey.
Source: Mory and Iasky (Mory & Iasky 1996)



Groundwater recharge takes place directly from rainfall infiltrating the sandy and gravelly soils. Groundwater flows south from a groundwater divide south east of Eneabba (**Figure 9.11**) and to the north of this, discharge occurs to the Arrowsmith River and springs along the Dandaragan Scarp. The water table is relatively flat and ranges up to 100 m below the surface (**Figure 9.15**). Groundwater levels have been rising by as much as 0.3m per year since clearing of the native vegetation for cereals and pasture (**Figure 9.16**). Levels are expected to continue to increase under cleared dryland agriculture, even under dry climate scenarios (CSIRO 2009). Bekele et al. (Bekele, Salama & Commander 2006a, 2006b) found pre-clearing recharge rates of < 12 mm/year have increased to 20-50 mm/year post clearing under pasture or cereal crops.

Figure 9.15: Depth to water table in the Northern Perth Basin

Source: DoW (Department of Water 2017b) and additional information from DWER



Carbon-14 dating has been performed on groundwater samples from investigation bores (Department of Water 2017b) and results ranged from 2,580 years (Arrowsmith River 22) to 21,090 years (Agaton 6), with a median of around 7,000 years in the Arrowsmith River area to 11,000 years in the Agaton borefield. Bekele et al. (Bekele, Salama & Commander 2006b) determined groundwater ages from nine shallow farm water supply bores west of Coorow, of which one was modern, seven ranged from 1,809-6,301 years, and one was 36,014 years old. They concluded that the Leederville-Parmelia aquifer is a 'sluggish groundwater flow system with low hydraulic gradients'.

The Leederville-Parmelia aquifer generally contains low salinity groundwater (**Figure 9.13**), (except along the eastern margin, close to the Darling Fault), especially along the chain of salt lakes by the Coonderoo River where groundwater discharge is inferred to take place.

The aquifer supports a number of springs and soaks along the Dandaragan Scarp, and an increasing amount of streamflow in the Arrowsmith River.

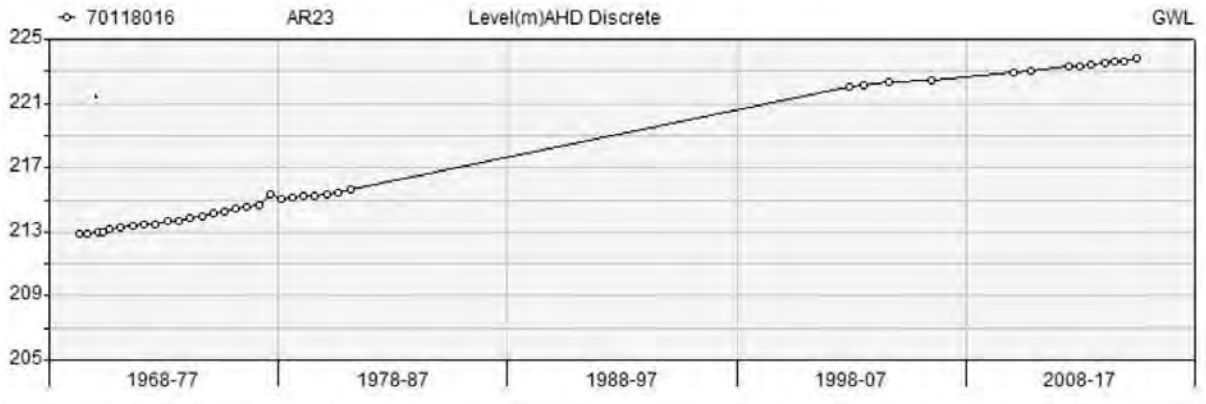
The aquifer is used for town supply to Mingenew, Morawa, Perenjori, Three Springs, Carnamah, Coorow, Moora and Dandaragan, for stock and domestic water on farms, and for irrigation, especially in the south. Five GL/a is also licensed to be taken from south of Mingenew for mineral processing at Karara Mining Limited's magnetite mine, 200 km south-east of Geraldton in the Midwest.

Figure 9.16: Groundwater level rise in the Leederville-Parmelia aquifer at (Arrowsmith 23, 15 km south-west of Arrino) and in the Yarragadee aquifer (Watheroo Line 7, 9 km north of Badgingarra)

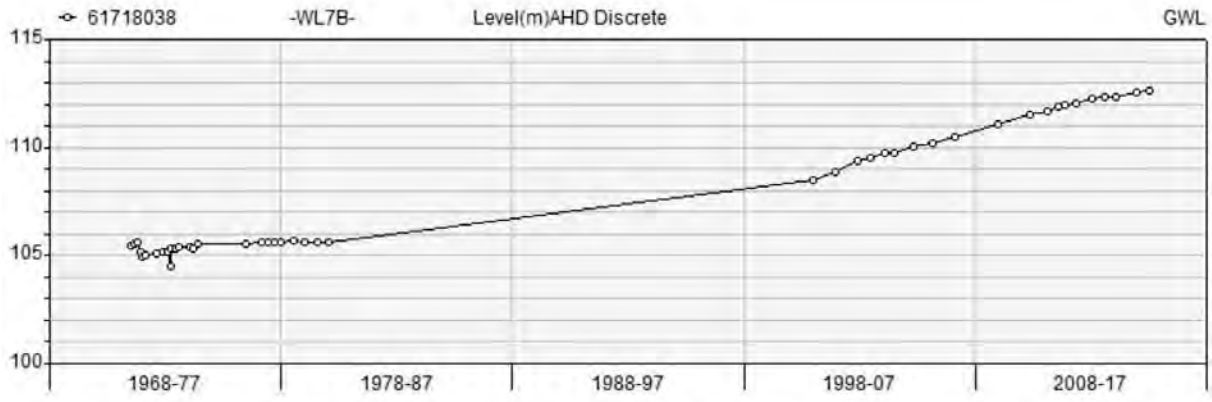
Vertical scale in m AHD

Source: DoW (Department of Water 2017b)

Arrowsmith 23



Watheroo Line 7B



9.3.3.5 Yarragadee aquifer

The Jurassic Yarragadee Formation is the most important and widespread aquifer in the Northern Perth Basin (**Figure 9.11**), extending from the Perth metropolitan area almost as far as the Greenough River (Allen 1980; Briese 1979; Commander 1978b, 1981; Department of Water 2017a; Harley 1974b; Irwin 2007; Schafer 2016). It is up to 4,000m thick, and crops out between the coastal plain and the Dandaragan Scarp (except in the Hill River area where older formations occur), extends below the coastal plain, and extends to the Darling and Urella Faults in the east below the Otorowiri aquiclude.

Groundwater in the Yarragadee aquifer is recharged by rainfall and local runoff on the outcrop. Groundwater flows north from a groundwater divide near the Hill River east of Jurien (**Figure 9.11**) to eventually discharge to the Superficial Aquifer and offshore south of

Dongara, and south to discharge to the ocean south of Ledge Point. Locally, north of the Irwin River, groundwater flow is south-westward towards the coast. Around Badgingarra, to the south and east of Eneabba, and on the Victoria Plateau north of the Irwin River, the water table is as much as 150 m below surface (**Figure 9.15**). On a local scale, groundwater is compartmentalised by faults (Commander 1974, 1981). Groundwater levels in areas where the native vegetation has been cleared for farming (**Figure 9.16**) are rising at similar rates to those in the Leederville-Parmelia aquifer, up to 0.4 m/year (Watheroo Line 8).

Carbon-14 dates from 13 samples from investigation bores in the Allanooka- Irwin View area ranged from 2,140-11,000 years, with a median of 7,050 years old (Department of Water 2017b). Lateral groundwater flow in the Yarragadee aquifer is likely to be very slow, comparable or lower than the 1m/yr rate found by Davidson in the Perth area (Davidson 1995).

Wireline logs from some oil exploration wells indicate that low salinity groundwater extends to the base of the aquifer which is formed by the Cadda Formation aquiclude, suggesting that the meteoric flow reaches depths of 3,000m (**Figure 9.12**). Commonly there is a sharp increase in salinity at the boundary with the Cadda Formation and in other wells this increase is several hundred metres above the base of the Yarragadee Formation. Glasson et al. (Glasson, Reid & Oldham 2011) found similar sharp salinity increases near the base of the Yarragadee Formation in oil exploration wells south of Gingin. This salinity increase may indicate a substantial decrease in permeability in the lower parts of the Yarragadee Formation. Groundwater in the upper part of the aquifer is generally fresh to marginal, but locally saline close to the Arrowsmith and Irwin Rivers, as a result of recharge from saline streamflow. Where the aquifer is confined by the overlying Otorowiri Formation, the groundwater is brackish, becoming progressively saline eastwards.

The aquifer supports Hill River Spring and its associated vegetation, and there is also discharge to Springy Creek and the Irwin River, though in general, the water table in the Yarragadee is deep below the surface.

Groundwater from the Yarragadee aquifer is used for town water supply to Geraldton, Dongara-Denison (from the Allanooka Scheme), Eneabba and Badgingarra; by the mineral sand industry at Cooljarloo and formerly Eneabba (still currently allocated 17.5 GL/a); for stock and domestic supply on farms; and for minor irrigated agriculture.

9.3.3.6 Cattamarra aquifer

The Early Jurassic Cattamarra Coal Measures crop out at the surface in the Hill River area where it is relatively intensely faulted (Briese 1979; Commander 1981; Harley 1974b, 1974a). Groundwater is likely to be compartmentalised by the faulting, and groundwater flow complex. Discharge takes place in the Hill River valley, and on the coastal plain flats east of Cervantes and south west of Eneabba.

The Cattamarra aquifer contains mainly brackish to saline groundwater (Commander 1981; Harley 1974b). On farms south west of Eneabba, where the Cattamarra aquifer is close to the surface, groundwater is commonly brackish to saline.

In the Dandaragan Trough, below the Cadda Formation, petrophysical logs and drill stem tests from petroleum exploration wells indicate high salinity, reaching 50,000 mg/L, indicating that the groundwater is stagnant and not connected to a meteoric groundwater flow system.

9.3.3.7 Eneabba and Lesueur aquifers

The Lesueur Sandstone (Harley 1974b) and overlying Eneabba Formation (Commander 1981), which consists of interbedded sand and shale, are considered as one aquifer system (Department of Water 2017b).

The aquifer is recharged by rainfall, local runoff and by leakage through the Superficial aquifer. Groundwater flows north and south away from a groundwater divide near Cockleshell Gully.

The Lesueur aquifer has been intensively investigated near Jurien (Baddock & Lach 2003). Carbon-14 dates ranged from 600 years to more than 30,000 years, the median value of 15 dates being 6,590 years. They inferred groundwater flow rates in the upper part of the aquifer of 3-8 m/year.

In the outcrop in the Hill River area, and east of the Beagle Fault on the Cadda Terrace near Jurien, groundwater in the Lesueur and Eneabba aquifers is generally fresh. Salinity rises northwards and becomes brackish in the Woodada gasfield, suggesting a degree of connection and groundwater flow (Mullen 2017). Elsewhere, at depth in the Dandaragan Trough, groundwater in both formations is saline, for instance at Arrowsmith 1, at a depth of 1,500m, salinity is 27,000 mg/L (Mullen 2017).

Groundwater discharges upwards into the base of the Superficial aquifer, and appears to give rise to Three Springs, near Stockyard Gully.

Groundwater from the Lesueur aquifer is used for Greenhead-Leeman town water supply and has been investigated for future supply to Jurien. Groundwater from the Eneabba and Lesueur aquifers is also used for irrigation, and stock and domestic supply.

9.3.3.8 Existing water use

Given the long dry summers and generally poor water holding capacity of the soils for dams in the Northern Perth Basin, farms in the area rely almost exclusively on groundwater for domestic and stock water. Rainwater tanks may be used in addition for drinking water, especially where the groundwater is brackish or saline. The west Midlands has previously been regarded as a problem area for farm water supply (Kelsall 1977), however, that is mainly due to the deep water table, which is more than 150 m below surface in some areas (**Figure 9.15**). In the early years of setting up the War Service Land Settlement Scheme in

Western Australia (in the 1950s), this necessitated deep bores and very large windmills. With rotary drilling technology and the availability of electric submersible pumps, this problem is largely overcome.

Irrigation of horticultural crops is best developed in the Irwin area where there are suitable soils, the water table is relatively shallow and the groundwater is low salinity. Large scale irrigation using centre pivot irrigators was also carried out south-west of Eneabba (from the Eneabba aquifer) and on the Dandaragan Plateau (from the Leederville-Parmelia aquifer) close to Moora. Groundwater from the Leederville-Parmelia aquifer is used for growing native flowers, tree crops, olives and potatoes. A number of areas have been identified with potential for irrigated agriculture as part of the State Government's Water for Food program (Hydroconcept 2015).

In 2013 (Department of Water 2015a), of the 48 GL/a licensed for irrigation in the Arrowsmith, Jurien and southern Gascoyne groundwater areas, only 15 GL/a was being used, mostly in the Dinner Hill, Dongara, Eneabba Plains and Twin Hills sub-areas (this figure also includes a small amount at Northampton). It was noted that 200 GL/a was unallocated and therefore still available for general use in the Jurien and Arrowsmith groundwater areas (Department of Water 2015a).

Farm dams are most common on the heavier soils overlying the Otorowiri Formation and the Cattamarra Coal Measures, where groundwater is brackish or saline, or bores low yielding. Farm dams have also been used for aquaculture to grow yabbies (*Cherax albidus*).

Public water supplies in the Northern Perth Basin are exclusively sourced from groundwater (**Table 9.5**). Dongara-Denison is connected to the Allanooka borefield (Geraldton Water Supply); Mingenew, Eneabba, Greenhead-Leeman, Badgingarra, Cervantes, Jurien and Dandaragan all have dedicated schemes. In addition, supplies for towns outside the basin, Morawa- Perenjori, Three Springs, Carnamah-Coorow and Moora are drawn from bores in the Leederville-Parmelia aquifer, just west of the Urella or Darling Faults.

Carbon-14 dates of water analysed from town water supply production bores in the Leederville-Parmelia and Yarragadee aquifers are several thousands of years before present (**Table 9.5**). While these are not unique ages, owing to mixing of young and old waters, it does suggest the groundwater in many of these bores in the confined aquifers is not easily contaminated from surface activities or affected by recent climate change.

Table 9.5: Northern Perth Basin town water supply characteristics

Source: DoW drinking water source protection reports (Department of Water 2007a, 2008d, 2013, 2017c, 2007c, 2008b, 2008c, 2008a, 2007b, 2009a, 2011a, 2012, Department of Water and Environmental Regulation 2017b, 2017a; Water and Rivers Commission 2002)

Town water supply scheme	Licensed abstraction (kL/a)	Depth to water level (m)	Aquifer	Carbon-14 date (years)
Arrowsmith (Morawa-Perenjori)	600 000	Artesian	Leederville-Parmelia	7120
Allanooka (Geraldton – Dongara)	14 000 000	12-80 20	Yarragadee Superficial	3650-7520 -
Badgingarra	50 000	145	Yarragadee	-
Dandaragan	70 000	26	Leederville	-
Dathagnoorara (Carnamah-Coorow)	400 000	90+	Leederville-Parmelia	6730
Dookanooka (Three Springs)	240 000	60+	Leederville-Parmelia	2300
Eneabba	200 000	30	Yarragadee	-
Jurien	420 000	3-8	Superficial	-
Kolburn (Moora)	650 000	Confined	Leederville-Parmelia	-
Mingenew	120 000	12-28	Leederville-Parmelia	5190
Mount Peron (Greenhead-Leeman)	470 000	15	Lesueur	-

Mining is the largest user by volume allocated, partly because groundwater needs to be extracted to access minerals below the water table. Licensed water entitlements for mineral sand mining total 22 GL/a, however only 5 GL/a (including a small amount from Port Gregory north of Geraldton) was consumed in 2013 (Department of Water 2015a). Mineral sand mining is carried out at Cooljarloo and was carried out at Eneabba between the mid-1970s and 2014. As part of this resource extraction process, groundwater is pumped to supply water to the mineral separation plants and to maintain water levels in dredge ponds. Mineral sands were formerly mined east of Jurien and further deposits have been identified along the Gingin Scarp north of Eneabba.

The Karara iron ore mine obtained a water licence in 2011 for 5 GL/a from the Leederville-Parmelia aquifer based on a bore field at Yandanooka and pipeline 136 km to the mine site.

The most significant use in the gas industry is for infrastructure related to the Cliff Head offshore gas development (Department of Water 2017b). The oil and gas industry had a licensed entitlement of 0.7 GL/a, of which use was reported to be less than 0.2 GL/a in 2013. The Mount Horner oil field was reported (Department of Water 2002) to yield 0.25 GL/a of produced water, which was used at that time to irrigate tree plantations.

The then Department of Water's Mid-West regional water supply strategy (Department of Water 2015a) acknowledged that hydraulic fracture stimulation for shale gas could use 20 ML per well, and noted that the relatively small volume of water needed for hydraulic fracture stimulation indicated that competition for groundwater resources between shale and tight gas developers and other water users would not be a significant issue.

9.3.3.9 Groundwater vulnerability to contamination

The Northern Perth Basin contains mainly sandy soils and sediments and therefore groundwater is at risk of contamination by surface activities. The vulnerability of the groundwater to contamination depends on a number of topographical, geological and climatic factors, and is especially dependent on the water table depth and on aquifer lithology (Appleyard 1993). The relative importance of these factors was taken into account to produce a 1:500 000 scale map of the Northern Perth Basin with a five-fold ranking of vulnerability to contamination (Appleyard, Commander & Allen 1993), based on the DRASTIC system (Aller et al. 1987). **Figure 9.17** is a simplified representation of this 1:500 000 scale vulnerability map.

The areas most susceptible to contamination are on the coastal plain where the water table is shallow. The plateaus and other upland areas are assessed to have a generally low vulnerability to contamination, owing to a deep water table.

Appleyard (Appleyard 1993) noted that the most severe occurrences of groundwater contamination usually result from the deliberate or accidental disposal of solid and liquid wastes in a small area. Leachate from these point sources of contamination moves

downwards through the unsaturated zone until it reaches the water table, where it mixes with and contaminates groundwater.

Groundwater with dissolved contaminants usually has a higher density than the surrounding uncontaminated groundwater, and so sinks towards the base of the aquifer. A 'plume', rather like an inverted smoke plume, may be formed and move along the top of underlying impervious sediments. The plume loses its identity at some distance downstream of the source as the contaminants are progressively diluted and dispersed over a large area of the aquifer. Contaminants may also interact chemically and physically with the aquifer medium, including being fixed or adsorbed to minerals, or precipitate as solids. Microbes can transform biological materials and oxidise metals to provide them energy.

Petroleum liquid hydrocarbon contaminants, including chlorinated hydrocarbons (called LNAPL – or Light Non-Aqueous Phase Liquids) may float on the water table, owing to low density and low miscibility with water. Other organic compounds, which are denser than and immiscible with water (called DNAPL or dense non-aqueous phase liquids), may settle in depressions at the base of the aquifer, and thus not flow with the groundwater.

A number of physical factors affect the degree to which groundwater is susceptible to contamination from surface land use. The most important of these factors are discussed below.

Depth to water table

The water table is a surface below which all pore spaces in a sediment are filled with water and the water is held at atmospheric pressure (that is water will flow into a well or bore below the water table). The depth of the water table below the ground determines the thickness of unsaturated sediment through which contaminants must pass to reach groundwater. Where this sediment thickness is large, there is greater potential for the removal of contaminants from the infiltrating water by a number of processes including adsorption by clay minerals, iron oxides and organic matter, and chemical or microbially assisted oxidation. Particles may also be physically filtered moving through a sand medium. The deeper the profile, the less likely mitigation processes will be overwhelmed and pollutants will break through and enter an aquifer.

The depth to the water table is the most important factor affecting the vulnerability of groundwater to contamination in the Perth Basin. The vulnerability to contamination is therefore highest on the coastal plains, where the water table occurs at a shallow depth. Vulnerability is also high where karst development allows direct access to the water table through solution openings. The vulnerability to contamination is conversely much lower on the major plateaus and other upland areas, where the water table is usually much deeper than on the coastal plains.

Sediment lithology

The grain size and sorting of sediments above and below the water table affects permeability and has a strong control on the susceptibility of groundwater to contamination. Contaminants are transported to the water table more easily through coarse-grained sediments (such as sand or gravel) than through fine-grained sediments (such as silt or clay). The degree to which contaminants are removed from infiltrating water is usually much less in coarse-grained than fine-grained sediments. The effect of lithology is a particularly important factor in the Perth Basin because a large proportion of the basin is medium-grained sandy sediments, which readily allow the infiltration of contaminants.

The mineral composition of the sediment is another important factor affecting the movement of contaminants in the unsaturated zone. Generally, quartz sand has a poor adsorptive capacity unless sand grains are coated with iron oxyhydroxides, whereas increasing proportions of clay minerals will give rise to a greater potential for contaminants to be removed by adsorption. Calcium carbonate in limestone has the ability to neutralise acids, and to reduce the movement of heavy metals and phosphorus.

The porosity, permeability and degree of stratification of sediments below the water table also affects the potential contamination impacts through an aquifer. Groundwater flow rates are generally low in fine-textured sediments, and contamination may be restricted to a much smaller area than in a plume containing the same mass of contaminants in coarse-textured sediments.

Contamination in fine-textured sediments is less likely to affect groundwater use, with the fewer bores drilled likely to be low yield. Also, the salinity of groundwater in these sediments in the Perth Basin is frequently brackish to saline. However, wetlands in areas underlain by silty or clayey sediments may still be affected by the slow discharge of contaminated groundwater.

Limestone areas with karst features pose special problems for the assessment of groundwater vulnerability. Limestone formed along the coastal margin of the Swan Coastal Plain. In most areas, only lithification has taken place, and the sedimentary sequence beneath the dunes consists of weakly cemented sandy limestone and unconsolidated sand. Locally, however, the dunes are lithified to limestone, and karst features such as dolines, caves and solution pipes may allow the direct access of surface water to depths greater than 30 m in rapid dispersal at the water table.

The presence of karst features can therefore greatly increase the vulnerability of areas that might otherwise have low or moderate vulnerabilities to contamination based solely on water table depth. Major cave locations are shown on the map (Appleyard, Commander & Allen 1993), and these indicate where some areas of intense karst development are located.

Climatic factors

The availability of water for groundwater recharge is an important factor for determining the degree to which contaminants are leached from the land surface and carried to the water table. With lower rainfall and higher evaporation rates in the northern part of the Perth Basin, it might be expected that the rate of recharge may be lower than elsewhere in the basin. However, the relationship between recharge and rainfall is not simple, and other factors such as intensity of rainfall, extent of runoff, sediment lithology and depth of water table also have a bearing on recharge rates. Chloride concentrations in groundwater are a good guide to long-term net recharge rates in a system, where there is no natural source of chloride.

Nature of contaminants

The chemical composition of potential contaminants is one of the most important factors affecting the susceptibility of groundwater to contamination. The mobility of chemical compounds in the unsaturated zone is affected by a large number of factors, including the degree to which these compounds are adsorbed by organic matter or minerals, viscosity, the solubility of the compounds in water and how rapidly they oxidize, volatilise or break down.

Some chemical compounds have a very low mobility in soils and although they may be highly toxic, they may not pose a great threat to groundwater quality. However, a large percentage of the compounds released to the environment as a result of human activities are mobile to some degree in soils. The relative mobility of potential contaminants has not been taken into account on the groundwater vulnerability to contamination map (Appleyard, Commander & Allen 1993).

The mapping is based on a semi-quantitative ranking of the vulnerability of groundwater to contamination. This was done using the DRASTIC numerical scheme developed by the U.S. EPA (Aller et al. 1987), whereby the vulnerability of groundwater to contamination is represented as a sum of individual factors, which are given ratings between one and 10 on the basis of their relative impact on contamination vulnerability. Each DRASTIC factor rating is multiplied by a weighting factor ranging between one and five, depending on its perceived importance in controlling vulnerability to contamination.

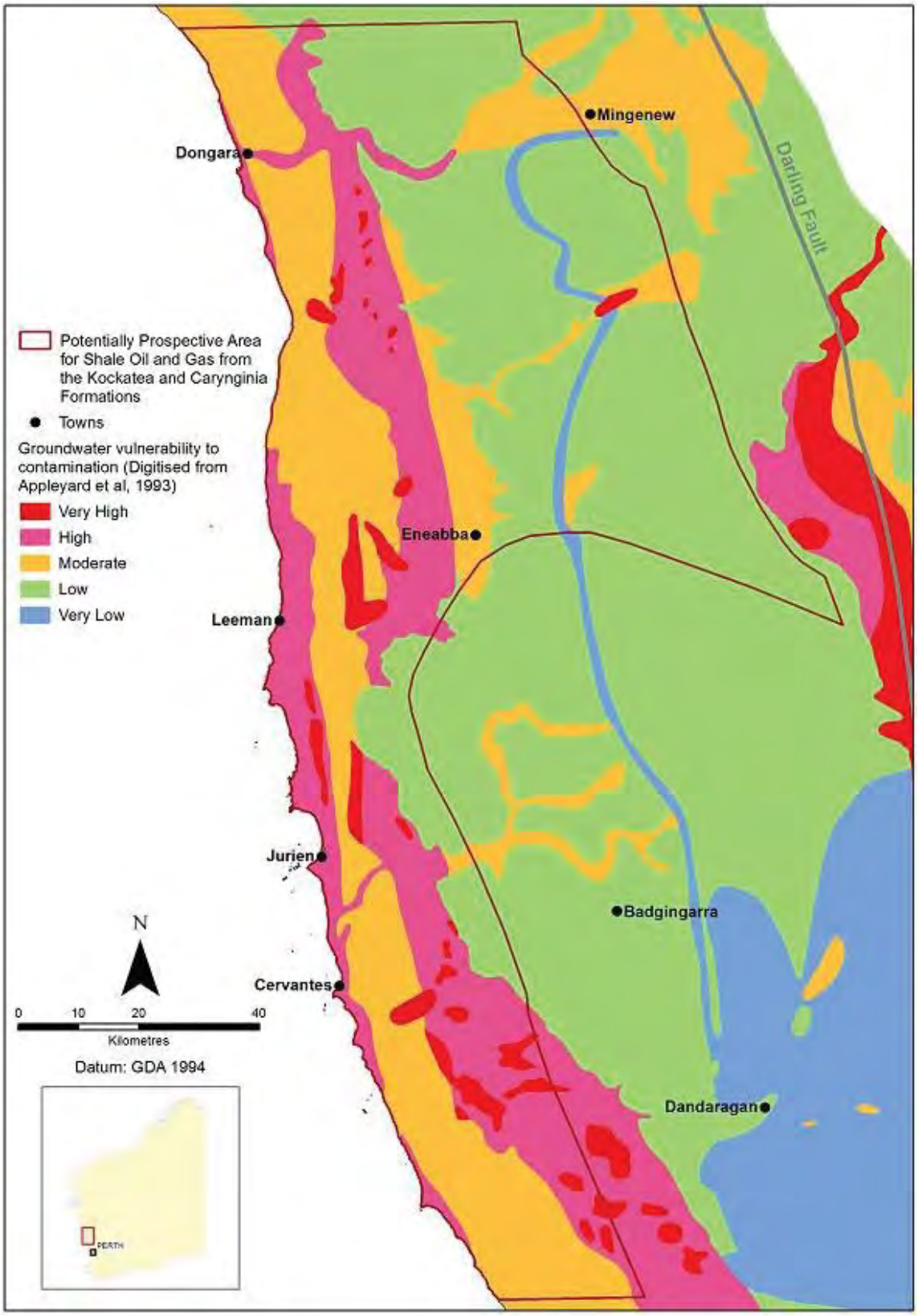
The DRASTIC score of an area is the sum of the weighted factors. DRASTIC is an acronym for the following factors:

- **D**epth to water table;
- **R**echarge (net);
- **A**quifer media;
- **S**oil media;
- **T**opography;
- **I**mpact of the vadose zone; and
- Hydraulic **C**onductivity of the aquifer.

The procedure used in compiling the map was to calculate DRASTIC scores along a number of east-west transects spaced at regular intervals in the Perth Basin. Within each transect, DRASTIC scores were calculated at two-kilometre intervals with a computer spreadsheet, and these scores were used to help define classes of common vulnerability based on geological, hydrogeological and geomorphological characteristics. The DRASTIC scores were used to generate five classes of vulnerability to contamination: very high; high; moderate; low; and very low. These are colour coded from red (one - very high vulnerability) to dark green (five - very low vulnerability) on the map.

Within each vulnerability class, sub-categories were created (designated by the letters a, b, c) to allow areas with the same vulnerability to contamination to be differentiated based on lithology and depth to the water table. A further stage of sub-division was carried out (designated by subscript numbers) to allow vulnerability classes to be related to a specific geological or physiographic setting, and these formed mappable units of common vulnerability (Appleyard, Commander & Allen 1993). On a regional scale, depth to the water table and lithology are the most important components of the DRASTIC score, and these factors were used to extrapolate mapped units between the calculated transects. The mapped vulnerability units were generally closely associated with geological formations and so formation names were used as the main descriptors of the vulnerability units (Appleyard, Commander & Allen 1993).

Figure 9.17: Northern Perth Basin groundwater vulnerability to contamination
Source: Appleyard et al. (Appleyard, Commander & Allen 1993) and additional information from DWER.



Areas of very high vulnerability

Tamala Limestone (where it is karstic)

Areas of pronounced karst development in the Tamala Limestone occur locally between the Nambung and Arrowsmith Rivers. The Tamala Limestone contains a large number of caves and other karst features, many of which are interconnected and associated with underground streams.

Karst development occurs in the Tamala Limestone along the Beagle Fault system between Cervantes and Dongara. The karst development in this area may be controlled by the position of the Beagle Fault, where discharge from confined aquifers to the base of the Tamala Limestone may occur.

Bassendean Sand (shallow water table)

Large areas of the Swan Coastal Plain are underlain by sand with a depth to water table of less than three metres. These areas are mostly in Bassendean Sand and are usually associated with wetlands.

Areas of high vulnerability

Bassendean Sand/ Tamala Limestone / Safety Bay Sand (intermediate water table)

Much of the Swan Coastal Plain is covered by sandy sediments with a water table 3 m to 30 m deep. This includes most of the Bassendean Sand, and low-lying areas of Tamala Limestone and Safety Bay Sand.

Areas of moderate vulnerability

Bassendean Sand/ Tamala Limestone/ Safety Bay Sand (deep water table)

The western parts of much of the Swan Coastal Plain are covered by high dunes where the water table is commonly more than 30 m deep. The dunal sediments consist of unconsolidated sand and calcarenite, and comprise the Safety Bay Sand, Tamala Limestone, and part of the Bassendean Sand. The lime in the Tamala Limestone and Safety Bay Sand reduces the vulnerability to many contaminants compared with the quartz dominated Bassendean Sand.

Undifferentiated Mesozoic formations

Formations underlying the Dandaragan Plateau have a moderate vulnerability to contamination where major drainages have incised the plateau surface and have reduced the depth of the water table to less than 30 m.

Areas of low vulnerability

Undifferentiated Mesozoic formations

The Dandaragan and Victoria Plateaus and the Arrowsmith Region are underlain by sandstone and minor shale of Triassic to Cretaceous age, with generally deep water tables. These areas are also intake areas for the extensive regionally important aquifers which contain confined groundwater beneath the Swan Coastal Plain.

Superficial sand

Superficial sands occur in dry valleys within the Dandaragan Plateau. These areas have a variable potential for the vertical percolation of contaminants, depending on the lithology of the underlying rocks and the depth to the water table.

Areas of very low vulnerability

Coolyena Group

The Coolyena Group on the Dandaragan Plateau consists predominantly of shale, with minor sandstone, chalk and glauconitic sandstone. These sediments generally have a very low permeability and they form a thick (>30 m) low permeability cover on the underlying Leederville Formation aquifer. A water table may be absent in these sediments, although local perched aquifers occur (not mapped), which discharge locally to springs. The Coolyena Group is classed as an area of very low vulnerability on its regional role as a confining bed to the Leederville Formation. There may be a high potential for contamination of local perched aquifers and rivers receiving runoff from low permeability soils.

Otorowiri Siltstone

The Otorowiri Siltstone outcrops along the Dandaragan Scarp on the western margin of the Dandaragan Plateau. This unit consists of siltstone and shale, has a very low permeability, and forms a regional hydraulic barrier that separates groundwater in adjacent aquifers into eastern and western flow systems.

Point and non-point sources of groundwater contamination

The distribution of likely point sources of groundwater contamination was investigated by the Geological Survey of Western Australia (Hirschberg 1993) , finding a low density of waste disposal sites and animal/food waste sources in the Northern Perth Basin. Hirschberg (Hirschberg 1993) considered the major impact on groundwater quality was more likely to come from the widespread application of fertilisers and pesticides as a consequence of both dry-land and irrigated agriculture. A baseline survey of non-point source groundwater contamination was carried out in 1992-3 (Hirschberg & Appleyard 1996), which involved sampling existing private water supply bores in the Northern Perth Basin screened within 10 m of the water table. The results were negative for pesticides and contamination from

fertilisers was only found in areas of intensive horticulture. It was noted that there are high nitrate concentrations in the Dongara area but that these may be natural.

The negative results should not lead to complacency, as the sampling was carried out on a grid pattern and at a time where no-till and minimum tillage cropping practices (which involve the heavy use of herbicides for weed control) had only been practised for a couple of decades. No studies have yet been carried out to specifically track the fate of pesticides or sample water from closer to the water table where water quality changes might be expected to be found. With increasing areas under intensive horticulture, contamination can be expected (see case study **Section 9.3.4** below).

9.3.4 Groundwater Management

Groundwater use in Western Australia is regulated by the *Rights in Water and Irrigation Act 1914* (RIWI Act).

The area of interest in the Northern Perth Basin falls within four legislatively proclaimed groundwater management areas: the Jurien and Arrowsmith Groundwater Areas, the southernmost part of the Gascoyne Groundwater Area, and the northernmost part of the Gingin Groundwater Area. DWER manages the Gingin, Jurien and Arrowsmith Groundwater Areas with allocation plans (Department of Water 2015b, 2010a, 2010b) which set the amount of groundwater that can be taken each year (the allocation limit). They guide how the department licenses groundwater use at the local scale, by defining the local rules to be applied for each aquifer by sub-area. DWER manages groundwater in the Gascoyne Groundwater Area using allocation limits and state-wide licensing policies without an allocation plan.

Allocation plans are designed to achieve specific water resource objectives and to contribute to broader, water related outcomes such as economic development or protecting environmental features. DWER establishes the objectives and outcomes of each allocation plan using a process of scientific assessment, policy analysis, consultation and considering (sometimes competing) water demands. At the most fundamental level, this means deciding how much water should remain in the system to maintain the integrity of the water resource and to support groundwater dependent ecosystems.

DWER regulates groundwater abstraction and provides advice to other regulators so that the integrity of the water resource, including the water-dependent environment, is maintained. It considers both the take and the use of water when assessing licence applications. This includes assessing environmental risk from abstracting and using water and whether this falls under the provisions of environmental legislation such as the Australian *Environmental Protection and Biodiversity Conservation Act 1999* (EPBC Act), and the Western Australian *Environmental Protection Act 1986* (EP Act), which cover social, cultural and heritage considerations, as well as ecological factors.

Proposals to abstract groundwater must demonstrate they:

- Can be met within exiting allocation limits;
- Maintain resource integrity and quality;
- Avoid impacts with other water users; and
- Avoid impacts to sites of high ecological, cultural or social value.

Where a groundwater activity (such as abstraction, excavation or managed aquifer recharge) poses risks to a water resource, other users or the environment, proponents are required to undertake a hydrogeological assessment (Department of Water 2009b). This assessment should predict impacts to the water resource and characterise or quantify the risks to other users and the environment.

Groundwater Areas are subdivided into groundwater sub-areas. Sub-areas generally have several groundwater resources, which are the major aquifers, each of which has an allocation limit. The allocation limits apply to low salinity groundwater. Generally, there have been no allocation limits set for the deep aquifers in which the groundwater is brackish or saline. To accommodate the needs of aquaculture, 'saline resources' have been created at the coast, to allow for pumping seawater from shallow coastal aquifers.

Allocation limits and water available for allocation are shown in **Tables 9.6 and 9.7** and illustrated in **Figure 9.18**.

Submissions to this Inquiry from Latent Petroleum, the operator of the Warro gasfield, and the Australian Petroleum Production Exploration Association (APPEA) questioned the classification of aquifers in the Warro area. The existing approach has been to treat any geological formation that can yield useful quantities of water as an aquifer. However, these submissions state that a large proportion of the Yarragadee is not a viable water source for most purposes, due to excessive depth and/or salinity, and both submissions suggest applying a water resource assessment approach that is in line with the resource definition approach applied to mineral and petroleum industries.

"A subject that requires consideration is the identification and classification of aquifers in the Warro area. In the resources description paper, an all-encompassing definition is used – any geological formation that holds and can yield useful quantities of water. Such a definition could be contrued to encompass not only the shallow water bearing units but suggest much of the Yarragadee should be considered an aquifer. As set out in a presentation on this subject in 2015 (see Appendix B), most of the Yarragadee cannot be considered to be a viable aquifer due to excessive depth and/or salinity. It is important to recognise that in an objective, scientific assessment not all water bearing sands would classified as viable aquifers. It is suggested that a water resource assessment approach akin to those used in the mineral and petroleum industries should be adopted to bring more discipline and scientific rigour to the identification of aquifers of interest" – submission from Latent Petroleum

In this area, knowledge of the Yarragadee aquifer is based on the Watheroo and Eneabba Lines that were drilled for groundwater investigation in the early 1970s. These bores are 6.4 km apart on the borelines and the borelines are 50 km apart. The bores only penetrate the uppermost 600 m of the Yarragadee, where it is unconfined, and only several hundred metres where it is confined. Hence, there is very limited data on the aquifer characteristics and groundwater salinity.

The DWER allocation system was designed to meet current needs in 2000, and at the time there was no reason to subdivide the Yarragadee, or to include deeper formations with saline formation water. The focus was on renewable groundwater resources, and there is provision to create new 'resources' as necessary. An example is the 'saline resource' created for the aquaculture industry to pump sea water from coastal aquifers.

Unlike mineral and petroleum resources, which may be developed and completely depleted, low salinity groundwater resources are managed on a sustainable basis. The major criterion for determining sustainable yield is the impact on other users and the environment. A sustainable yield is not therefore a quantity that can be uniquely determined.

Table 9.6: Allocation limits and water available for general use from major aquifers in the Northern Perth Basin (showing only resources over one GL/a allocation limit)

Source: DWER unpublished data, June 2018

Groundwater Area	Groundwater sub-area	Aquifer	Allocation Limit GL/a	Remaining volume GL/a
Gascoyne	Casuarinas	Yarragadee	4.6	4.5
	Casuarinas	Cockleshell Gully	5	4.3
Arrowsmith	Dongara	Superficial	6.9	2.7
	Dongara	Yarragadee	3.7	3.2
	Allanooka	Yarragadee	8.5	8.4*
	Twin Hills	Leederville-Parmelia	3.4	3.3
	Twin Hills	Yarragadee	42.8	23.5
	Eneabba Plains	Superficial	14.4	12.4
	Eneabba Plains	Yarragadee	20.4	5.8*
	Eneabba Plains	Eneabba	2	0.6
	Eneabba Plains	Lesueur	1.3	1.3
	Tathra	Leederville-Parmelia	29.9	13.9
	Morrison	Leederville-Parmelia	3.4	3.4
Jurien	Cervantes	Superficial	26	23.4
	Cervantes	Lesueur	3	0
	Nambung	Superficial	3.6	0.9
	Nambung	Yarragadee	8.8	6.3
	Nambung	Cattamarra	1.6	1.6
	Nambung	Lesueur	2.7	2.5
	Badgingarra	Yarragadee	26.5	21.1
	Dinner Hill	Leederville-Parmelia	10.4	1.4
Gingin	Cowalla	Leederville-Parmelia	17.6	0
	Wedge Island	Superficial	48.5	12.1
	Cataby	Yarragadee	4	0.02

*Applications pending

Figure 9.18: Groundwater resources and their availability status in 2012

(see **Table 9.6** and **Table 9.7** for updated Northern Perth Basin and Northern Canning Basin figures)

Source: DoW (Department of Water 2014)

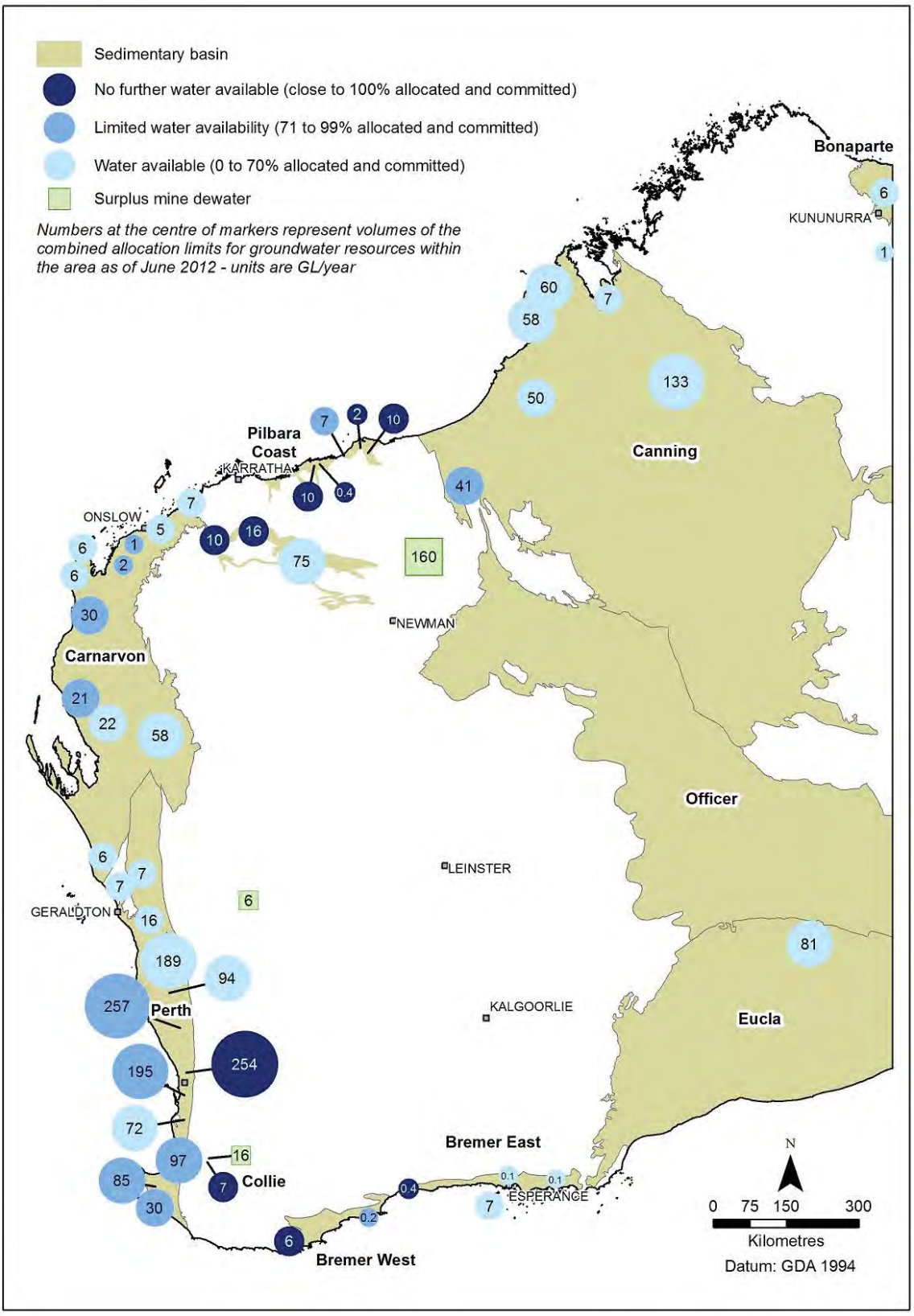


Table 9.7: Allocation limits and water available for general use from major aquifers in the northern Canning Basin (showing only resources over 1 GL/a allocation limit)

Source: DoW (June 2018)

Groundwater Area	Aquifer	Allocation Limit GL/a	Remaining volume GL/a
Broome	Broome Sandstone	28.8	24.1
	Wallal Sandstone	7	6.8
Canning-Kimberley	Broome Sandstone*	97	81.7**
	Wallal Sandstone*	20	18.8
	Erskine	5	4.5
	Liveringa Group	9.3	8.6
	Grant Group	99.6	98.8
Derby	Wallal	4.7	4.2
	Erskine	0.41	0.40

*Not including West Canning Sub-area **Applications pending

The protection of groundwater quality is discussed at length in the Guidelines for groundwater quality protection in Australia, published under the National Water Quality Management Strategy (NWQMS). The NWQMS's stated objective is:

> Achieving sustainable use of the nation's water resources by protecting and enhancing their quality while maintaining economic and social development.

The desired outcome of the guidelines is:

A consistent, high level approach to groundwater quality protection across Australia with the assignment of Environmental Values (beneficial uses) for all groundwaters, particularly where there is a risk of contamination, and development of protection plans incorporating quality protection measures for these areas.

The guidelines outline the following principles

- Ecologically sustainable development;
- Risk based approach;
- Polluter pays;

- Intergenerational equity; and
- Precautionary principle.

Protection of groundwater exists within three legislative frameworks:

- Groundwater management, which deals with entitlements and allocation;
- Land Use Planning, which controls decisions on land development; and
- Environmental protection, which deals with environmental maintenance and hazardous activities (Australian Government 2013)

The guidelines acknowledge that natural groundwater quality is highly variable, both laterally and vertically, in the same aquifer.

The guidelines endorse a risk based approach and acknowledge the attenuation zone in which contaminant concentrations may be reduced. The guidelines further distinguish between contamination, which changes the concentration of constituents, and pollution, which renders groundwater unfit for its previous beneficial use (a distinction not present in the EP Act).

Western Australian regulations mirror the above approach, as follows:

- Groundwater quality may be protected during the water licensing process, for instance to account for pumping affecting seawater intrusion or induced leakage from adjacent more saline aquifers;
- Public drinking water sources are subject to land use controls; and
- Hazardous activities are regulated under the EP Act.

Public Drinking Water Source Areas (PDWSAs) are proclaimed around the majority of public drinking water bores. Land use controls exist under three classifications (see list below) with land uses specified under DWER's Water Quality Protection Note 25 (Department of Water 2016):

- P1 areas are managed to ensure there is no degradation of water quality with the objective of *risk avoidance* (existing land uses have low risks; Crown Land, some private land);
- P2 areas are managed to maintain or improve the quality of the drinking water source with the objective *of risk minimisation* (for example, rural zoning); and
- P3 areas are managed to maintain the quality of the drinking water source for as long as possible with the objective of *risk management* (for example, land zoned urban or light industrial).

Additional protection is provided by well head protection zones (WHPZs) which are generally circular with a 500 m radius around each water production bore in P1 areas and 300 m radius in P2 areas.

Mineral processing with chemicals is listed as incompatible with P1, P2 and P3 areas (Department of Water 2016). Proposals for oil and gas exploration and production are subject to the administrative agreement between the Department of Mines, Industry Regulation and Safety (DMIRS) and DWER (Department of Mines and Petroleum and Department of Water 2015) and the Guide to the regulatory framework for shale and tight gas (Department of Mines and Petroleum 2015a).

Various protection measures have been taken for drinking water supplies to Aboriginal communities in Western Australia (Ketteringham et al. 2007) including WHPZs, water source protection and management plans. Ketteringham et al. (Ketteringham et al. 2007) reported that nitrate, uranium, arsenic and heavy metals had been detected at levels that require treatment to meet the Australian Drinking Water Guidelines. As in the case of public drinking water sources, DMIRS will consult DWER on any proposal for petroleum activities within five kilometres of a community water supply.

Contamination of drinking water supply – case study

Residents of Woodridge attended the Dandaragan community consultation to share their concerns about contamination of drinking water supplies. Woodridge is a rural residential development bordering the west side of Wanneroo Road, 10 km east of Guilderton. The land on the opposite side of the road is used for intensive horticulture. The original water supply (1979) was from bores into the superficial aquifer, in this location the highly permeable Tamala Limestone, in which the groundwater flow direction is from east to west. By 1997 (Bush 1997) water quality monitoring in the supply bores was showing increasing concentration of nitrates derived from the horticultural activities some 500 m away.

In 2006, a new bore was installed to a depth of 200 m in the confined Leederville aquifer, and on commissioning in 2010, the superficial water supply bores were abandoned (Department of Water 2011b).

The case illustrates the necessity of land use controls in the groundwater catchment, especially in a highly vulnerable superficial aquifer; the efficacy of regular monitoring of nitrate levels (which were rising but did not exceed the Australian Drinking Water Guidelines); and the rate of flow and attenuation of contaminants which allowed time for an alternative supply to be implemented.

9.4 Identification and regulation of potential hazards, issues and pathways

The security of groundwater supplies was raised in virtually all submissions to this Inquiry, and summed up by Frank Creagh:

> *"concern by the community for the safety of water resources with regard to fracking, and I can only hope that this new inquiry will regard the issue as the most important factor"* – submission from Frank Creagh

Availability of groundwater, and maintenance of water quality was a key issue raised by the farming community:

> *"water is the No 1 asset for our farming enterprise"* – submission from Kingsley Smith

The Environmental Protection Authority (EPA) has stated that understanding the function, condition and geology of hydrogeological systems at both a site specific and regional scale is critical to support the assessment of quantity and quality risks to groundwater resources.

A petroleum company is required by DMIRS to prepare an Environment Plan to address these issues.

DMIRS refers petroleum proposals to the DWER, where the proposals may pose a significant risk to water resources (Department of Mines and Petroleum 2015a). Current practice is that a report on the hydrogeology is undertaken by a suitably qualified hydrogeologist or other appropriate professional (Department of Mines and Petroleum and Department of Water 2016a).

The Guideline for groundwater monitoring in the onshore petroleum and geothermal industry (Department of Mines and Petroleum and Department of Water 2016a) specifies the following:

- Baseline groundwater monitoring is used to establish groundwater conditions before petroleum activities commence and, when transitioned into surveillance monitoring, can determine whether groundwater has been affected by petroleum activities.
- Groundwater monitoring requirements are determined on a case-by-case basis depending on the scale and nature of the petroleum activity, the level of risk and the sensitivity and values of the surrounding environment, including (aquifers). Petroleum activities with a higher risk of adversely impacting groundwater resources or sensitive environments will require a more intensive baseline and surveillance groundwater monitoring program.
- An intensive groundwater monitoring program is likely to be considered appropriate for petroleum activities in areas:
    - In proximity to town and community water supplies;

- In proximity to environmental sensitivities such as, groundwater dependent ecosystems, conservation category wetlands, reserves, national parks etc.;
- Where the geology has potential to rapidly mobilise groundwater contaminants, such as faults and karst features;
- Where the groundwater has important beneficial uses, such as for domestic, stock and irrigation;
- In proximity to populated or culturally significant areas;
- Where there is a known risk of groundwater contamination; and
- With higher operational risks, or where the proposed activity has a high level of complexity, uncertainty or risk.

The groundwater monitoring program follows a review of existing information aimed at allowing both the petroleum operator and the regulators to understand the existing groundwater quality, current and historical land uses, potential contamination pathways, and sensitive receptors. This review includes a description of aquifers that are intersected by the proposed activities, features with the potential to create pathways for dynamic groundwater flow in the context of population centres or properties, and the surrounding environment including surface waters, culturally important areas, sensitive areas (for example, groundwater dependent ecosystems such as wetlands and cave systems) and protected areas (for example, reserves and national parks).

A less intensive groundwater monitoring program may be appropriate for petroleum activities that pose low risks to groundwater, or where there are no sensitive or water-dependent environments or water users near the proposed activity.

Where specific concerns or risks remain, the operator may decide to seek expert advice from consultants or academics who will often prepare a technical hydrogeological report and recommendations. DMIRS will review any subsequent reports and the environmental risk assessment to determine whether the proposal is acceptable, whether additional information is required, or whether additional controls and/or monitoring is required. In assessing the proposal, DMIRS may also request additional expert advice from other Government agencies, such as DWER and water service providers.

Daily well reports as stipulated in the *Petroleum and Geothermal Energy Resources (Resource Management and Administration) Regulations 2012* require operators to report the discovery of groundwater, depth of the water and quantity produced during well operations.

The Guideline (Department of Mines and Petroleum and Department of Water 2016a) advocates a broad chemical parameter suite in undertaking baseline groundwater monitoring, with a more detailed chemistry suite follow-up if necessary. Ongoing surveillance monitoring may be decided by either the operator or DMIRS as necessary.

DMIRS has observed in recent years that a majority of petroleum operators are deciding to undertake groundwater monitoring to demonstrate a commitment to protection of groundwater and industry best practice.

Baseline groundwater monitoring and assessment has been carried out for recently established wells, including those undergoing hydraulic fracture stimulation:

- Rockwater (2013) Warro Project: Hydrogeological modelling of potential impacts. Report for Latent Petroleum;
- Rockwater (2013) Hydrogeology of the Ungani Wellfield Area. Prepared for Buru Energy;
- Rockwater (2013) Drover-1 Groundwater Study. Report for AWE Limited;
- Rockwater (2015) Hydrogeological Assessment of Project Areas. Report for Buru Energy Ltd (Asgard and Valhalla);
- Rockwater (2013) Senecio Groundwater Study. Report for AWE Limited; and
- Rockwater (2015) Hydrogeological Assessment of the Waitsia Reservoir Drilling Programme. Report for AWE Limited.

The Guideline further specifies:

Surveillance monitoring should continue for at least the duration of the petroleum activity. For petroleum wells where there has been an external well failure or a serious spill incident prior to decommissioning, then monitoring should continue for two years after well decommissioning to account for any potential lag in groundwater movement from the well to the monitoring bore (Department of Mines and Petroleum and Department of Water 2016a).

In an assessment of Buru Energy's groundwater monitoring program in 2014 (prior to publication of the DMP/DoW Guideline for Groundwater Monitoring), the Yawuru Expert Group stated:

> *"Buru Energy's baseline groundwater monitoring program for the upper aquifer system is considered comprehensive and consistent with internationally accepted standards"* – submission from Yawuru

Companies can use the American Petroleum Institute standard HF2: Water Management, and DMIRS refers to this standard when assessing operational plans (Department of Mines and Petroleum 2015a).

Before the production stage of an oil and gas development, a Field Management Plan must be submitted, including details of how produced formation water will be monitored, managed and disposed (Department of Mines and Petroleum 2016a).

Finding 12: Baseline groundwater quality monitoring is now part of onshore petroleum activities and surveillance groundwater monitoring is carried out during operations.

Recommendation 5: That baseline and routine surveillance groundwater quality monitoring, including methane concentrations, should be included in an enforceable Code of Practice and results made publicly available before commencement of drilling operations and thereafter.

9.4.1 Water use

The process of hydraulic fracture stimulation requires a significant amount of water that is injected into the shale target (along with various chemicals). This is mostly imbibed into the shale matrix, with a portion returning to the surface as flow-back water. The take of water could potentially compromise other uses and was raised by participants in the community consultation as a general concern that it is a poor use of Western Australia's scarce water resources, and a competitor to use in agriculture.

The quantity of water required for a hydraulic fracture stimulation operation depends on the length and orientation of the well bore, its depth and the local geology (Australian Academy of Technological Sciences and Engineering 2017). Estimates of water use in the hydraulic fracture stimulation process vary with the geological conditions. Average fluid use in hydraulic fracture stimulation in North America has been typically 20 ML per well, but can be as much as 48 ML (Edwards et al. 2017). A recent evaluation of water use trends across North America (Kondash, Lauer & Vengosh 2018) indicated a trend for increased water use per well in some (but not all) evaluated regions, with median values for 2016 ranging between 21 and 42 ML per well, partly reflecting the increased length of horizontal wells. These authors did not offer an explanation for why water use per well had increased over time in some regions, apart from increased well length. An estimate of 20 ML per well has been adopted by this Inquiry as being applicable to Western Australia (see **Section 6.11** of this Report), which is greater than that quoted in company submissions to this Inquiry. Further, we also consider potential water use per well over 20 years if re-stimulation was required every five years (effectively, 80 ML per well over its lifetime).

For comparison, 20 ML is often likened to the capacity of eight Olympic-sized swimming pools. This is typically the amount used to irrigate a market garden of one to two hectares of horticultural crop over a year, and is about one twenty-fifth the amount typically used annually to irrigate a golf course, or about one fortieth of the amount used annually by a typical centre pivot irrigation system.

These amounts appear astronomical to domestic consumers using around 300 kL/a, who are paying up to $3.17 per kL, and who have been exhorted to minimise water use. Many of the submissions referred to 'our precious water resources' and queried why oil and gas companies should not pay for water used.

In his submission, Dr Vogwill considered the published studies of water use and made estimates of the total amount of water required for an unconventional gas field development. He determined a range of 7.28 – 44.47 GL/a for the Northern Perth Basin, and between 18.34 and 172.60 GL/a for the Canning Basin for a range of gas field sizes. These scenarios envisaged a 29-59 trillion cubic feet (tcf) (30,000 to 60,000 petajoules) field in the Northern Perth Basin, which is comparable in size to the giant Gorgon gas development offshore Western Australia (40 tcf). As this is 75 to 150 times the annual domestic gas demand in Western Australia the Panel did not consider this size of development to be realistic (**Section 6.8**).

Source Energy News Bulletin, in reference to the much smaller offshore Equus field, stated:

> "The project design is based on an independently certified resource of 2 trillion cubic feet of gas and 42 million barrels of condensate, which is said to be sufficient to supply a quarter of Western Australia's domestic gas demand (or 2 million tonnes of LNG a year), for 20 years" - (Leibovitch 2018)

Based on the high case of Ultimate Recoverable Resource (URR) for the Northern Perth Basin set out in **Section 6.8** of this Report, a likely scenario would involve 18 well pads with eight horizontal wells each, making a total of 144 wells over a 20-year period. This translates to an initial water use of:

144 wells x 20 ML each = 2,880 ML = 2.88 GL.

If the wells required restimulation every five years, this increases to 11.5 GL over a 20-year period, or just over 0.5 GL/a.

For the low case of URR set out in **Section 6.8** of this Report, the scenario involves 80 well pads, leading to a water use, including restimulation, of 51 GL over a 20-year period, or 2.5 GL/a.

For comparison, 0.5 GL/a is equivalent to the annual use of a golf course; annual licensed abstraction for mineral sands mining at Eneabba is currently 14 GL/a.

Table 9.6 shows that there is water available from a number of aquifers in the Northern Perth Basin.

The likely scenarios set out in **Section 6.8** of this Report for the Canning Basin can similarly be translated into an initial water use:

- Buru Energy: 8 well pads x 10 wells x 20 ML = 1,600 ML = 1.6 GL
- MC Resources: 20 well pads x 10 wells x 20 ML = 4,000 ML = 4 GL

- Finder Shale: 60 well pads x 8 wells x 20 ML = 9,600 ML = 9.6 GL
- Giving a total water usage of around 15 GL.

These estimates are somewhat greater than those given in the submissions by Buru Energy (in which they state the expected water use over the 20-year lifetime of their proposal is 1.065 GL) and by Finder Shale (whose maximum water use over the same period is expected to be 6.720 GL). MC Resources did not give a projected water use.

None of the company submissions accounted for the possibility of re-stimulation during the lifetime of the project. If the wells are re-stimulated every five years, and not accounting for re-use, the overall water use would be around 60 GL over twenty years, or 3 GL/a. For comparison, this amount of water for the three proposals by each company listed above is about half the annual licensed abstraction for Broome Town Water Supply, or a quarter of the nett use at Sheffield Resources Limited's proposed Thunderbird mineral sand operation. Most of the water for Finder Shale and MC Resources' projects would be brackish or saline, and Buru Energy's project could also use brackish-saline groundwater, so its use does not compromise agriculture.

Groundwater is the only likely source for hydraulic fracture stimulation activities both in the Perth and Canning Basins (discounting seawater desalination). The DWER regulates the take of groundwater, and a proponent has to apply for a water licence and provided certain conditions are met, and if there is available water (that is, the allocation limit has not been reached) a licence can be issued.

Under DWER's Operational Policy 5.12, (Department of Water 2009b) an application for a significant quantity of groundwater also needs to be accompanied by a Hydrogeological Report, the level of analysis depending on the quantity involved. Such analysis includes performance of the aquifer, drawdown, impact on existing users and the environment.

An operating strategy may also be required under DWER's Operational Policy 5.08 (Department of Water 2011b). The intent of this policy is to effectively utilise the licensing process when granting access to the State's water resources to better manage the resources by:

- Adopting a flexible approach to the production of a water resources operating strategy to satisfactorily address issues related to the taking of water from a particular water resource at a specific location;
- Increasing the licensee's awareness of their responsibilities and their participation in managing the water resources and specifically managing the impacts of taking and using water;
- Utilising the licensee's knowledge of the local area and their industry to address site specific and operational issues related to the taking and use of water;

- Supporting the principle of water conservation where water taken is used in an efficient and productive manner; and
- Ensuring licensees have considered risk and contingency options should water shortages or unexpected impacts from water abstraction occur.

Allocation limits generally refer to low salinity groundwater (fresh to brackish). An application may be made for brackish or saline groundwater in deeper aquifers for which allocation limits have not been set, with such proposals being assessed on their merits.

A provision exists to licence the take of saline groundwater along the coastline. This provision has been made primarily for aquaculture, where filtered seawater is required. This is separate from the allocation of fresh groundwater, as the ultimate source is the ocean.

Mitigation of excessive water use may be achieved by:

- Minimising fresh water use;
- Using saline/brackish/non-potable water sources. Invariably, brackish or saline groundwater occurs between the near surface fresh groundwater (if present) and the shale gas target; and
- Recycling and reusing flow-back water.

Edwards et al (Edwards et al. 2017) quotes flowback water as ranging from 10 -30 percent of water used during hydraulic fracture stimulation, the balance being imbibed into the shale matrix. However, in his submission Dr Vogwill quoted Vengosh et al. (Vengosh et al. 2014) who points out that waste water may be highly saline (up to seven times the salinity of seawater) and contains a large number of toxic chemicals and gases making hydraulic fracture stimulation water reuse difficult.

There is currently groundwater available in the Northern Perth Basin (**Table 9.6; Figure 9.18**), however this may be taken up by industry or agriculture in the future. Allocation limits are generally set initially to be conservative and are based on the available information. As new investigation data becomes available, and with longer periods of water level monitoring of the effects of groundwater abstraction, allocation limits may be able to be revised upwards to approach a long-term yield that reflects the current or expected future climate.

The groundwater resources of the Fitzroy Trough in the Canning Basin are relatively undeveloped (**Table 9.7; Figure 9.18**). Only the Broome Sandstone (Broome) and Erskine Sandstone (Derby) are used significantly, which is for town water supply and peri-urban use. Notwithstanding, a water licence applicant must provide a hydrogeological report which proves the resource can be utilised without undesirable consequences. In this respect, an application for 33 GL/a for Sheffield Resources Limited's proposed Thunderbird mineral sands mine on the eastern Dampier Peninsula was supported by a hydrogeological study as it is a significant proportion of the 50 GL/a allocation limit for the Canning Pender Groundwater Sub-area.

Finding 13: Excessive groundwater use is not permitted under the Department of Water and Environmental Regulation (DWER) water licensing regime. Water quantities to be used for petroleum operations are licensed by DWER, and applications for significant quantities have to be justified by a hydrogeological report detailing likely impacts, and may be subject to further review and advice from the Environmental Protection Authority (EPA). Claims of excessive water use by hydraulic fracture stimulation operations are not borne out by the companies' planned use of water and likely use is modest compared with other existing licensed uses.

9.4.2 Chemicals used in hydraulic fracture stimulation

9.4.2.1 Issues of concern

A large number of submissions to this Inquiry identified the use of chemicals in hydraulic fracture stimulation as a key cause for concern, in particular, in relation to human health and environmental impacts, including impacts on irrigation water.

It is important to note we all interact with a wide range of chemicals on a daily basis. All chemicals have the potential to cause harm and this depends on the dose to which the public, workers or the environment is exposed. Hence, it is important to understand which chemicals are used in the process of hydraulic fracture stimulation, the toxicity of these chemicals, if there is the potential for the public or the environment to be exposed to these chemicals and what the concentration may be at the point of exposure.

A number of submissions to this Inquiry have criticised the way the petroleum industry presents chemical information, specifically the industry practice to compare the chemicals used to household or food products. This is perceived as trivialising risks that may be posed by the chemicals, however this information is commonly provided so the public has some contextual information on what the chemicals are and where they may also see these chemicals used. This sort of information does not replace any requirements to assess the suitability of these chemicals for the proposed use.

9.4.2.2 Why are chemicals used?

Chemicals are used in a wide range of petroleum related activities. This includes drilling, hydraulic fracturing stimulation, well testing, well production and maintenance, well closure or decommissioning and emergency scenarios (Department of Mines and Petroleum 2013a).

Hydraulic fracture stimulation requires large volumes of hydraulic fracture stimulation fluid to be pumped into the rock under high, but controlled, pressure to create fine fractures that radiate from the well to access the natural gas produced and stored within the rock. Fine sand granules, commonly referred to as proppants, are mixed into the hydraulic fracture stimulation fluid to prop open newly created fractures through which released gas and

hydraulic fracture stimulation fluid flow back through the well for collection and storage at the well-head (Department of Health 2015).

9.4.2.3 Typical make up of hydraulic fracture stimulation fluids

The hydraulic fracturing fluid is comprised mainly of water, representing between 75 and 99 percent of the total volume depending on the situation. Proppants usually represent five to eight percent, but may contribute up to 25 percent of the hydraulic fracturing fluid volume (Department of Health 2015). Other chemicals used in hydraulic fracturing fluids typically comprise around one percent of the total fluid, with the Buru Energy submission noting that the volume and number of chemicals used in hydraulic fracture stimulation has reduced significantly over the last few years.

In some situations, a variety of other substances may be added at very low concentrations which, when combined, are reported to represent no more than five per cent of the total volume (Department of Health 2015). These chemical additives carry out a number of different functions that include: (Department of Health 2015):

- Biocides to control microbial growth in the fluid;
- Corrosion inhibitors and oxygen scavengers to assist in maintenance of well integrity;
- Scale and iron control chemicals for maintenance of well integrity;
- pH stabilisers and buffers to maintain hydraulic fracturing stability and immobilise clays;
- Friction reducers to improve recovery of the fluids;
- Gelling agents to increase the viscosity to allow more sand to be carried into fractures;
- Clay stabilisers to minimise clay swelling in the well and rock formation;
- Surfactants to reduce the surface tension to improve fluid recovery; and
- Breakers to break down the gel to enable release of the proppant into the fractures and enhance recovery of the flowback fluid.

In its submission to this Inquiry Halliburton provided information on the development of innovative products for use in hydraulic fracture stimulation, which the company stated will provide economic and environmental/health benefits by reducing the volume of chemicals required as well as utilising lower toxicity chemicals or techniques that eliminate the need to use some chemicals (for example, bacterial treatment using ultraviolet light, which significantly reduced the need for chemical biocides).

Large volumes of fluids are used in hydraulic fracture stimulation, which can mean the loads of chemicals may be significant over time, even when they are present at low percentages in the fluids.

9.4.2.4 Existing regulatory process to evaluate chemicals

Chemical disclosure

Chemicals that are proposed to be used for hydraulic fracture stimulation, and other activities, associated with drilling and well maintenance (that is, all chemicals for 'down-hole' petroleum activities) are required to be disclosed under the *Petroleum and Geothermal Energy Resources (Environment) Regulations 2012.*

This information is required to be provided in the operator's Environment Plan, where it is necessary to detail all chemicals and other substances in, or added to, drilling or treatment fluids or introduced into a well, reservoir or subsurface rock formation, during an activity. This includes drilling, cementing or hydraulic fracture stimulation during exploration, proof of concept, production and well decommissioning. This information is made publicly available from the DMIRS website through the department's Environmental Assessment and Regulatory System (EARS) (Department of Mines, Industry Regulation and Safety 2018a). This system requires registration to access, however all Summary Environmental Plans since April 2012 (where included as a PDF) are available to be viewed.

Guidelines for the disclosure and assessment of chemicals are outlined in the following documents:

- Chemical Disclosure Guidelines Version 2: August 2013 (Department of Mines and Petroleum 2013a); and
- Environmental Risk Assessment of Chemicals used in WA Petroleum Activities Guideline (Department of Mines and Petroleum 2013b).

This requires the listing of chemicals that are commonly used or may be used (as a contingency). All chemicals to be used are required to be reported on a Chemical Disclosure Reporting Template. This template requires disclosure of the products including the trade name, supplier, purpose, percent of product in fluid, toxicity and ecotoxicity information, the inclusion of a material safety data sheet (MSDS) and chemicals within the product, Chemical Abstracts Service (CAS) number and percent mass fraction in the fluid. The toxicity and ecotoxicity information required to be disclosed relates to acute toxicity for mammals and ecotoxicity, chronic toxicity and whether the chemical is persistent, bioaccumulative or subject to biodegradation.

DMIRS is required to be notified and provided additional information when there are changes to the chemicals being used down-hole.

Chemical by-products or chemicals within flowback water do not need to be identified. However, chemical changes in flowback water are required to be submitted to DMIRS post approval (Department of Health 2015).

Chemical risk assessment

The 'Environmental Risk Assessment of Chemicals used in WA Petroleum Activities Guideline' (Department of Mines and Petroleum 2013b) provides a framework to assist in the assessment of chemicals proposed to be used. This guidance references the use of principles, framework and process for risk management as outlined in the Joint Australian/New Zealand Standard AS/NZS ISO 31000:2009: 'Risk management – Principles and guidelines' (Australian/New Zealand Standard 2009) and the AS/NZS Handbook HB 203:2012 'Managing environment-related risk' (Australian/New Zealand Standard 2012).

The criteria referenced in the document to determine potential consequences reference current Australian guidance for the protection of aquatic environments (Australian and New Zealand Environment and Conservation Council and the Agriculture and Resource Management Council of Australia and New Zealand 2000), terrestrial environments (National Environmental Protection Council 1999a amended 2013) and human health (National Environmental Protection Council 1999b; National Health and Medical Research Council 2011 updated 2017). General guidance is provided on assessing the toxicity of chemicals where there are no criteria or guidelines available.

The guidance has criteria for deciding if a chemical or substance can be considered a hazard, persistent and/or bioaccumulative, and when an environmental risk assessment is required to be completed.

Where an environmental risk assessment is required, the document provides general guidance on what needs to be considered. This includes reference to enHealth guidance 'Environmental Health Risk Assessment' (enHealth 2012). These guidelines are used for the assessment of health effects that may be associated with chemicals, which may be in the environment from all different types of industries (for example, industrial emissions and contaminated land).

Finding 14: There is currently no requirement for the information on chemicals proposed to be used and/or the environmental risk assessment to be reviewed by the Department of Health (DoH), which has the relevant expertise to assess this information. Currently the DoH only reviews information when asked by the Department of Mines, Industry Regulation and Safety (DMIRS) or the Environmental Protection Authority (EPA) when there is a specific issue/concern. To ensure public confidence that appropriate expertise is used to review such assessment, it would be appropriate for DoH to review all such assessments.

Concern has been raised in a number of submissions to this Inquiry in relation to the potential presence of specific chemicals considered to pose a greater hazard to public health.

Benzene, Toluene, Ethylbenzene and Xylenes (BTEX) in chemicals used in hydraulic fracture stimulation have not been banned by regulation in Western Australia. Submissions have

raised concerns about the risks posed by the use of BTEX, noting that the use of BTEX in drill and hydraulic fracture stimulation fluids is banned in New South Wales, Queensland and Victoria. It is noted that BTEX chemicals occur naturally, particularly in groundwater and have the potential to be present in produced or flowback water. Guidelines are available from NHMRC and ANZECC to assess the significance/risks posed by these chemicals that may be present in produced or flowback water.

Finding 15: Benzene, Toluene, Ethylbenzene and Xylene (BTEX) have not been proposed to be used for drilling of wells using hydraulic fracture stimulation in Western Australia since 2009. Hence, banning use for this purpose should not be of concern to the industry but would assist in alleviating community concern.

Much of the concern related to the use of BTEX is associated with the potential carcinogenic and mutagenic properties of benzene (in particular). Other concerns have also been raised in submissions in relation to chemicals that are developmental toxicants or endocrine disrupting chemicals.

Hazards posed by endocrine disrupting chemicals in hydraulic fracture stimulation have been similarly highlighted in a number of reviews (Bolden et al. 2018; Kassotis et al. 2014a, 2016, 2015), and is an issue also noted by other reviewers (Saunders et al. 2018) and in the DoH submission. However, at present there is little empirical data to determine if such effects are likely to occur and, if they could occur given the pathways of exposure at such sites, whether the existing guidelines would already be appropriately protective. The issue of ensuring appropriate consideration of the potential for endocrine disruption is a matter still being addressed in all types of chemical assessments. Similarly, issues associated with chemicals with developmental effects that may be used in hydraulic fracture stimulation, as a mixture, have also been highlighted (Boulé et al. 2018).

Finding 16: The current requirements for chemical disclosure do not require the identification of key chemical hazards such as whether the chemical is a known or suspected carcinogen, mutagen, developmental toxicant or endocrine disruptor. To address public concern in relation to these issues it would be appropriate for these characteristics to be included in the chemical disclosure and the use of carcinogenic, mutagenic, developmental or endocrine disrupting chemicals minimised or avoided.

9.4.2.5 Existing detailed assessments of chemicals

Western Australian Department of Health 2015

The DoH conducted a Human Health Risk Assessment (HHRA) on hydraulic fracturing for shale and tight gas in Western Australian drinking water supply areas (Department of Health 2015). This assessment utilised a risk assessment approach to evaluate the potential risks posed to drinking water, where hydraulic fracture stimulation activities were undertaken in Western Australia. The assessment considered a range of activities that might result in fracturing fluids or flowback water reaching drinking water supply areas. Activities such as the preparation and use of fluids at a site, storage of flowback and produced waters in ponds or the transport of chemicals or wastewater to and from a site, were all considered.

The assessment summarised regulatory and published information (available to 2015) of risks posed by hydraulic fracture stimulation (including activities from coal seam gas (CSG) activities) in Australia and internationally (including the United Kingdom, European Union, United States and Canada).

A risk assessment approach considers the potential or likelihood for the chemical to be present in drinking water supplies, the toxicity of the chemicals at the concentrations that may be present, and the risks posed to the public should the water be consumed as drinking water.

The assessment considered commonly used chemicals in hydraulic fracture stimulation fluids as well as chemicals commonly detected in flowback fluid.

The assessment identified that under the right conditions, hydraulic fracture stimulation can be successfully undertaken without compromising drinking water sources. The assessment provided further recommendations to assist in the protection of drinking water sources, namely:

- The application of the Australian Drinking Water Guidelines for chemicals found in drinking water, or the conduct of a more detailed HHRA, where no regulatory guidelines have been established;
- A communication plan for notification of incidents with potential to impact public health and drinking water sources to be incorporated into ongoing stakeholder engagement;
- Ongoing consultation and collaboration between all Government agencies with responsibilities related to potential impacts of hydraulic fracture stimulation; and
- The establishment of appropriate separation distances or buffer zones between unconventional gas developments (wells and associated infrastructure) and any drinking water source area (including a water reserve, water catchment and

groundwater protection area and declared or proposed water supply catchment area).

National Industrial Chemicals Notification and Assessment Scheme 2018

The National Industrial Chemicals Notification and Assessment Scheme (NICNAS) completed a National Chemicals Risk Assessment for chemicals used in the extraction of CSG (Department of the Environment and Energy 2017a).

The coal seams from which methane is extracted are shallower than the shales and tight sands to be used in Western Australia. Coal seams amenable to gas extraction (with the potential for hydraulic fracture stimulation) are usually less than 1,000 m below the ground surface. Suitable shales, like those in Western Australia, are generally 2,000 to 4,000 m below the ground surface. Also, coal seams often contain significant amounts of water which must be extracted as part of the process to access the gas. The same is not the case for shale and tight sand formations from which gas can be extracted, where significant amounts of water must be available at the surface to allow hydraulic fracture stimulation to be undertaken. These differences mean that different chemicals are used to assist the fracturing process.

The assessment of chemicals used in CSG hydraulic fracture stimulation, completed in collaboration with the CSIRO, is a qualitative assessment addressing occupational, public health and environmental risks associated with chemicals used in drilling and extraction of CSG in the Australian context. It is a large and complex assessment that considered the potential risks to the environment (surface and near surface water environments) of 113 chemicals identified as being used for CSG extraction in Australia, from the period 2010 to 2012. Risk factors addressed included the transport, storage and mixing of chemicals, and the storage and handling of water pumped out of CSG wells (flowback or produced water) that can contain residual amounts of the chemicals used. Although the extraction process for CSG differs from extraction of shale and tight gas, there are many similarities between the two types of gas extraction in the associated infrastructure and in the surface handling of chemicals and wastewater.

The Panel notes that geogenic chemicals (that is, those extracted from the coal seam and contained in the produced water) are not included as part of the NICNAS assessment. In addition, assessment of contamination of soil or impacts on terrestrial plants or animals by leaks or spills of chemicals or wastewaters are also not part of the scope of the NICNAS assessment.

The focus of the NICNAS review relates to the impacts of surface discharges (spills or leaks) on surface water and near-surface groundwater, extending to potential downgradient effects on surface water through overland flow or discharge of the shallow groundwater into surface waterways. The reason for this focus is that international studies have shown that the greatest risk to human health and the environment is from spills or releases of chemicals

during surface activities, such as transport, handling, storage, and the mixing of chemicals. This is a reasonable conclusion based on previous studies and reviews.

While the NICNAS assessment focused on CSG activities, the assessment of risks posed by chemicals used in these activities on surface water and near-surface groundwater are considered applicable to the shale and tight gas and oil industry.

The NICNAS assessment concluded that:

- For workers handling chemicals used for drilling or hydraulic fracture stimulation, the majority of the chemicals are of low concern for human health from long-term exposures. Some chemicals were identified as not having correct hazard classifications in the Hazardous Substances Information System (HSIS), the database which informs users of chemicals in the workplaces and what management is required when handling a chemical in the workplace. NICNAS recommended that the HSIS be updated to ensure the most relevant information was readily available for these chemicals;
- In relation to potential exposures to the public, the risk assessment identified a range of chemicals where there is a high degree of confidence that the chemicals are of low concern for human health. A number of other chemicals were identified where there is the potential for concern, however, these would need to be assessed on a site-specific basis. The highest risk identified for human health relates to a bulk spill during transportation that then impacts on a surface water body which is used for drinking, bathing and/or swimming;
- Australia has a robust and effective regulatory framework to manage and mitigate the risks of handling and transporting chemicals, so the hypothetical transport accident scenarios envisaged in this study are unlikely. Nevertheless, some CSG chemicals have the potential to impact the environment should such an accident occur;
- The assessment of potential impacts to the environment identified potential concern with boron, in particular where wastewater may be reused for irrigation or dust suppression; and
- Overall the NICNAS assessment highlights the importance of undertaking a site-specific chemical risk assessment to inform risk management and mitigation procedures.

It is also noted that the CSIRO and the Australian Department of Environment and Energy (DoEE) are currently preparing a similar review for chemicals being used in hydraulic fracture

stimulation in shale and tight gas developments. This review is not currently available for consideration here as it has not been completed[1].

There has been some discussion about the types of geogenic chemicals that could be present in flowback water in CSG developments in Technical report no 5 (Mallants et al. 2017). This review confirmed that the literature indicates a range of major and minor ions, naturally occurring organic chemicals, other trace elements and radioactive elements may be present in flowback water collected during CSG extraction. The review also noted that there is a need for more data on contaminant concentrations in flowback water and for mechanistic studies to better understand how hydraulic fracture stimulation may or may not mobilise chemicals in a coal seam.

Other aspects of the CSG industry were considered by the CSIRO and the DoEE in a range of reports (Department of the Environment and Energy 2017a, 2017c, 2017d, 2017e, 2017f, 2017g, 2017h, 2017i, 2017j, 2017k).

Following on from the NICNAS assessment, DoEE prepared a Draft Risk Assessment Guidance Manual: for chemicals associated with CSG extraction (Department of the Environment and Energy 2017l). This draft guidance draws on existing approaches and guidance on the assessment of human health and environmental risks in Australia (and internationally) and includes some more industry specific guidance. As follows:

- Assessing all chemicals associated with drilling activities, cementing and well completion, perforation propellants, acid clean out and pre-wetting chemicals, hydraulic fracturing and fluid management activities that include produced water and waste fluids. It should also include naturally occurring geogenic chemicals mobilised by these activities and found in drilling fluids, drilling muds, flowback and produced water, brines and treated water). At present the Western Australian requirements do not include assessment of flowback and produced water. The Buru Energy submission provides results of analysis of flowback water, including Naturally Occurring Radioactive Materials (NORMs), and comparison against Australian Drinking Water Guidelines and ANZECC Stock Water Guidelines. Radon was detected in flowback water but not determined, by Buru Energy, to exceed drinking water guidelines. Little other information is available on the level of NORMs in deep groundwater in the study area;
- Disclosure of all products and chemicals used, noting that the guidance is consistent with existing Western Australian chemical disclosure requirements (Department of Mines and Petroleum 2013a);

[1] Information about this work is available at https://www.bioregionalassessments.gov.au/geological-and-bioregional-assessment-program

- Information requirements to assess the potential for exposure to occur, and where it does what a predicted environmental concentration may be. This requirement is consistent with guidance provided by (Department of Mines and Petroleum 2013a); and
- Guidance on information that needs to be considered to evaluate the toxicity to human health and the environment. In particular, the guidance recommends that for complex mixtures or blends of chemicals, whole of effluent or direct toxicity testing data should be obtained.

The submission from Buru Energy, and additional information provided to the Panel for clarification, included an assessment of ecotoxicity of two hydraulic fracturing fluids used by Buru Energy, Condor Frac Fluid FRW and Condor Frac Fluid ASB. This was undertaken in 2015 using a mixture ecotoxicity test (using the eastern rainbowfish and test protocol ESA SOP 117). This is not a current regulatory requirement. The testing was undertaken on concentrations up to and including 1,000 mg/L, with no effects observed to that concentration. The Buru Energy submission also references that ecotoxicity testing was undertaken on the Halliburton CleanStim product where a No Observed Effect Concentration (NOEC) of 200 mg/L, and EC_{50} > 200 mg/L was determined. Based on the definitions for ecotoxicity (as provided by NICNAS) these products are classified as very slightly toxic (the lowest rating). The Buru Energy submission also provides a link to a video where the Executive Chairman of the company drinks the hydraulic fracturing fluid, namely Condor Friction Reduced Fluid System.

It is understood that for flowback and produced waters in the CSG industry, an industry wide study of the ecotoxicity of such waters is currently underway. Ecotoxicity tests are also being undertaken to compare the produced water with water that just has high salinity, to determine if any toxicity noted in the tests is due to the effects of salinity or due to other geogenic chemicals that have been mobilised in the coal seam. It would be useful if similar work was undertaken for produced waters from shale and tight oil and gas developments. This is addressed in Recommendation 6.

United States

The United States has established FracFocus (http://fracfocus.org/), which is the national hydraulic fracturing registry, managed by the Ground Water Protection Council and Interstate Oil and Gas Compact Commission. This provides reference to a number of publications relating to hydraulic fracture stimulation, as well as the ability to look up individual wells and obtain the list of chemicals used at that well. This specifically relates to operations in the United States.

The U.S. EPA has also undertaken a comprehensive assessment of potential risks posed by chemicals (U.S. Environmental Protection Agency 2016). The U.S. EPA found that approximately 1,100 different chemicals had been used in hydraulic fracture stimulation

between 2005 and 2013. The United States review has noted that hydraulic fracturing technology has evolved rapidly over the past decade, and much greater attention is now being paid to the potential for contamination of below-ground and surface environments, with a much smaller fraction of these chemicals now being routinely used in modern/more recent hydraulic fracturing practice. However, within the database of 381 chemicals, the identities have not been disclosed on the basis of confidential business information. Not disclosing chemical information on this basis reduces the completeness of the data sets and the level of confidence in any assessment of the toxicity of chemical used in hydraulic fracture stimulation.

Gradient 2013

A number of technical reviews and submissions have referenced a review conducted by Gradient for Halliburton: National Human Health Risk Evaluation for Hydraulic Fluid Additives (Gradient 2013). This review relates to chemicals used in the United States for hydraulic fracture stimulation activities that include shale gas, and the potential for impacts to drinking water. The review concluded:

- That where wells are properly installed it is implausible for hydraulic fracturing fluids to migrate upwards from the target formation to impact an upper drinking water aquifer; and
- Where an unintended surface spill scenario is considered, and water is used for drinking water, potential impacts to human health were determined to be insignificant.

The assessment addressed a range of conditions and operations in the United States and the review states the outcomes apply broadly in other parts of the world with similar environmental conditions and regulations to the United States.

9.4.2.6 Review of chemicals previously approved for hydraulic fracturing in Western Australia

DMIRS has provided a list of chemicals approved for use on past activities that have involved hydraulic fracture stimulation. This data relates to activities conducted at the following wells (and year of hydraulic fracture stimulation):

- Arrowsmith 2 – Norwest Energy (2012)
- Corybas 1 – AWE (2009)
- Senecio 2 – AWE (2012)
- Whicher Range 5 – Amity Oil (2004)
- Woodada Deep 1 – AWE (2012)
- Yulleroo 2 – Buru Energy (2009)

- Helios 1H – Finder Shale
- TGS 15 – Buru Energy (2012)
- Warro 3 – Latent Petroleum (2009)
- Warro 4 – Latent Petroleum (2011)
- Warro 5 & 6 – Latent Petroleum (2015)

It is noted that some of these wells were assessed prior to 2012 when the current requirements for chemical disclosure and assessment were introduced. Information provided by the relevant companies on more recent wells (Helios 1H, TGS 15 and Warro 5 and 6) are publicly available from the Environmental Assessment and Regulatory Systems (EARS 2) (Department of Mines, Industry Regulation and Safety 2018a). These documents include the products and chemicals used in drilling and other operations. Limited or no information is publicly available for the wells stimulated during or prior to 2012.

Use of chemicals in Australia

To be able to manufacture, import or use a chemical in Australia, the chemical must be listed, assessed or regulated by one of four agencies, depending on its end use. The Australian agencies that administer these assessments are:

- NICNAS – industrial chemicals;
- Australian Pesticides and Veterinary Medicines Authority (APVMA) – agricultural and veterinary ('agvet') chemicals;
- Therapeutic Goods Administration (TGA) – therapeutic (pharmaceuticals and medicines); and
- Food Standards Australia and New Zealand (FSANZ) – food additives.

Chemicals used for hydraulic fracture stimulation are largely classified as industrial chemicals (which are assessed by NICNAS), with some also used as food additives. Industrial chemicals are all chemicals to be introduced into Australia that are not regulated as an agvet chemical, a therapeutic chemical or a food additive. Food additive chemicals are assessed by FSANZ. Biocides are chemicals used to control bacterial growth and so are regulated as pesticides. Where such chemicals are to be used in hydraulic fracture stimulation they must have been assessed/registered by APVMA. Industrial chemicals permitted for use in Australia by NICNAS are listed on the Australian Inventory of Chemical Substances (AICS). It is illegal to manufacture, import or use a chemical that is not listed on the AICS (or has not been assessed by APVMA, TGA or FSANZ).

If an industrial chemical that is not listed on AICS is proposed for use, the company wanting to use the chemical needs to notify NICNAS and submit a new chemical application. NICNAS can then assess the chemical for use in Australia. The chemical is not permitted to be used in

Australia until the NICNAS assessment has been completed. This applies for industrial chemicals wherever they are to be used, for example, hydraulic fracture stimulation, formulation of cleaning products, glues, paints and some personal care products.

A listing on AICS does not mean the chemical has been assessed in detail by NICNAS. There is only a small number of chemicals listed on AICS that have been assessed in detail where concerns for public health, workplace health and environmental effects associated with cosmetic, domestic, industrial or a site-specific use were identified. For chemicals listed on the AICS, there is no requirement to notify NICNAS of their use in hydraulic fracture stimulation. The most recent NICNAS review (NICNAS 2018) has more specifically evaluated 113 chemicals commonly used in hydraulic fracture stimulation, so these chemicals have been assessed in detail for risks when used for this purpose.

The Agricultural and Veterinary Chemicals Code Regulations 1995 (amended 1 July 2013) made under the Federal *Agricultural and Veterinary Chemicals Act 1994* and administered by the APVMA has declared (Schedule 3 Part 3) that:

> "Biocides to control organisms in water, used for the purpose of maintaining equipment associated with the extraction of coal seam gas in serviceable condition are not agricultural chemical products and as such do not require registration by APVMA for use as outlined in this assessment".

The wording of the amendment relates to the extraction of CSG, not unconventional or shale or tight oil and gas. In addition, there is no definition of what is meant by CSG. For this exemption to apply to shale gas in Western Australia, an amendment to the Regulations, or ruling/clarification from APVMA on the definition of CSG as referenced in the Regulation is required.

Finding 17: Without an amendment, ruling or clarification, it is inferred that biocides used in shale or tight oil and gas production will need to be registered for this use by the Australian Pesticides and Veterinary Medicines Authority (APVMA).

Review of chemicals previously approved

A combined listing of chemicals previously approved for use in hydraulic fracture stimulation in Western Australia are included in **Appendix 11** (chemicals used in drilling fluids are not included). This list includes the chemicals used, the CAS numbers (where known), the well the chemical has been evaluated for use in, if the chemical is listed by NICNAS on AICS, if the chemical has been assessed for hydraulic fracture stimulation by NICNAS (2018) and if the U.S. EPA has reviewed the chemical as used for hydraulic fracturing. It is noted that the U.S. EPA review of chemicals used for hydraulic fracture stimulation has only identified if there is information available on the chemical in relation to toxicity (human and ecological), persistence and the potential for bioaccumulation. For many chemicals listed there is no data available, and where there is data available the U.S. EPA review has not made any determination on risk, and that the chemicals proposed to be used for any specific project are assessed on a site-specific basis.

Table 9.8: Summary of chemicals assessed in Western Australia

Type	Number of Chemicals	Comment/Findings
Chemicals approved for use in hydraulic fracture stimulation in Western Australia.	149	-
Chemicals approved for use in hydraulic fracture stimulation in Western Australia that cannot be specifically identified as no CAS number or similar identifier was provided (i.e. chemicals not disclosed due to being listed as 'trade secret' or 'proprietary').	17 (11% of all approved chemicals)	These chemicals only relate to older approvals provided before the current chemical disclosure requirements were in place.
Chemicals approved for use in hydraulic fracture stimulation in Western Australia that are listed on AICS.	97 (65% of all approved chemicals)	While there are a few chemicals also listed as food additives by FSANZ, there are no additional chemicals approved for use in Australia by APVMA, TGA or FSANZ.
Chemicals approved for use in hydraulic fracture stimulation in Western Australia that were evaluated in the recent review of chemicals used in hydraulic fracturing in Coal Seam Gas undertaken by NICNAS (NICNAS 2018).	41 (27.5% of all approved chemicals)	The low number of chemicals evaluated for this use by NICNAS reflects the focus of the NICNAS review on chemicals commonly used in the coal seam gas industry only. NICNAS is currently conducting a similar review on chemicals used in hydraulic fracture stimulation in shale and tight gas.
Chemicals approved for use in hydraulic fracture stimulation in Western Australia that are listed/considered by the U.S. EPA in its review of chemicals used in hydraulic fracturing or found in flowback fluid.	98 (65.8% of all approved chemicals)	-

Finding 18: Since 2012, all chemicals proposed to be used have been disclosed.

Finding 19: Currently, there is no requirement for the Department of Mines, Industry Regulation and Safety (DMIRS), nor any other regulatory agency involved in the assessment and approval of hydraulic fracture stimulation activities in Western Australia, to check if a chemical is approved for any use in Australia.

Finding 20: The current regulations in Western Australia require the full disclosure and assessment of chemicals used in hydraulic fracture stimulation, including the use of a site-specific risk assessment where relevant. However, there are some deficiencies with the current system that need to be addressed.

Recommendation 6: The regulations governing the use and assessment of chemicals associated with hydraulic fracture stimulation should be strengthened and clarified, specifically:

- All chemicals proposed for use must be approved for use in Australia. It should be the regulator's responsibility to check that all the proposed chemicals are listed on the Australian Inventory of Chemical Substances (AICS), Australian Pesticides and Veterinary Medicines Authority (APVMA), Therapeutic Goods Administration (TGA) or Food Standards Australia and New Zealand (FSANZ) inventories prior to approval being granted.
- That a ruling is sought from APVMA on the need to register biocides used for hydraulic fracture stimulation in Western Australia (in line with the existing ruling on the use of these chemicals in the extraction of coal seam gas).
- The use of Benzene, Toluene, Ethylbenzene and Xylene (BTEX) in drilling and hydraulic fracturing fluids should be banned.
- Chemicals that are known or suspected carcinogens, mutagens, developmental toxicants and endocrine disruptors should be identified as part of the information disclosed on chemicals. Use of chemicals with these properties should be minimised or avoided in all operations.
- An enforceable Code of Practice should include the requirement to test for, and assess the risk from, a comprehensive list of analytes in groundwater, produced and flowback water, including geogenic chemicals and radon.
- The use of ecotoxicity testing should be considered to better assess the potential for impacts from the mixture of chemicals present in produced or flowback water.
- The Western Australian Department of Health (DoH) should review and provide advice on information and risk assessments provided on chemicals proposed to be used in hydraulic fracture stimulation, or expected to be present in produced or flowback water, and determine a list of low risk chemicals for hydraulic fracture stimulation, where detailed assessment of risk is not required to be provided. This would encourage industry to use lower risk chemicals instead of other chemicals that require more detailed risk assessment.

9.4.3 Groundwater contamination

Potential contamination of freshwater aquifers, particularly those used for drinking water supplies, was raised as an issue by the majority of participants in the public meetings held as part of the Inquiry and in many of the submissions. This concern was shared by both private landholders, utilising their own bores, and by consumers of town water supplies, which are subject to the Australian Drinking Water Guidelines, and which have groundwater protection zones around borefields. Instances relating to contamination of groundwater and surface water due to hydraulic stimulation activities in the United States were repeatedly raised.

The U.S. EPA (U.S. Environmental Protection Agency 2016) has reported on a number of these instances and where a cause could be determined the incident was found to be due to one or more of the following:

- Inadequate length of surface casing;
- Inadequate annular cementing;
- Old uncemented wells;
- Hydraulic stimulation directly in an aquifer used for domestic supply;
- Unlined pits (containing drilling mud, hydraulic fracturing fluids, flow-back, and produced water); and/or
- Discharge to surface waters.

For groundwater contamination to occur, there needs to be a source, a receptor, a pathway, and a driving force. These potential pathways are:

- By fractures propagating upwards from the shale target into a more permeable horizon;
- Through hydraulic fractures intersecting permeable fault zones;
- Through hydraulic fractures intersecting abandoned wells and causing failure of the hit well containment;
- Leakage from poor well integrity; and
- Infiltration of contaminants from surface spills or discharges.

9.4.3.1 Propagation of fractures (see Section 6.12)

The Australian Academy of Technology and Engineering (ATSE) (Australian Academy of Technological Sciences and Engineering 2017, 2018) found wide support in international literature for the conclusion of the 2015 Report of the Standing Committee on Environment and Public Affairs of the Western Australian Parliament, that the likelihood of hydraulic fracture stimulation intersecting underground aquifers is negligible. Hawke similarly found that:

> "The risk of fracture propagation in deep shale gas formations causing hydraulic fracturing fluid, methane or brine to contaminate overlying aquifers is very low" (Hawke 2014)

Mallants et al. (Mallants et al. 2017) carried out a comprehensive review of the possibility for pathway formation due to hydraulic fracture stimulation, related to shale gas in the United States. They quote Flewelling et al. (Flewelling, Tymchak & Warpinski 2013) who evaluated the physical limits on hydraulic fracture growth or fault movement and how such limits might factor into an analysis of potential fluid migration to shallow aquifers. Edwards et al. (Edwards et al. 2017) concluded that it was not physically plausible for induced fractures to create a hydraulic connection between deep shales and other tight formations to overlying potable aquifers, based on the limited amount of height growth at depth, and the common rotation of the least principal stress to the vertical direction at shallow depths. Geomechanical analysis carried out by Schlumberger SIS Geomechanics for Finder Shale indicated that fractures would not propagate through natural carbonate barriers above and below the target Goldwyer Formation in the Canning Basin.

Edwards et al. noted that observational and modelling studies indicated that hydraulic fracturing fluids are very unlikely to migrate upwards through 1,000m or more of overlying strata. They further state:

> "that pressure drawdown in the formation due to gas production means that even if fractures extend out of the shale formation and contain mobile water, the direction of water flow will be into the shale, rather than out, until the formation pressure equilibriates in the very long term" (Edwards et al. 2017)

Where it is a potential target for tight oil development, the Goldwyer Formation in the Canning Basin is more shallowly buried but still lies below approximately 600-1,000 m of low permeability limestones and shales in the overburden before the deepest aquifer is encountered. In this case, validation of the geomechanical model of rocks resistant to fracturing and with unfavourable stress orientation is required to reduce the risk of fracture hydraulic connectivity to extremely low levels.

The risk is therefore very low where the target formation is overlain by a substantial thickness of saline formation water in the overlying formations, and separated from near

surface potable aquifers by 1,000m or more. This is generally the case in the Perth Basin (**Figures 9.4 and 9.6**).

In the Fitzroy Trough, in the Canning Basin, the target Laurel Formation is separated by a number of formations from the fresh groundwater in the Broome and Erskine Sandstones (**Figures 9.13 and 9.15**).

Finding 21: The risk of contamination of shallow fresh water aquifers by saline groundwater through hydraulically stimulated fractures is low, because the likelihood of fractures propagating and creating pathways which would contaminate overlying aquifers is very low. In the event that this occurred, the potential consequences are considered to range from insignificant to major, reflecting the importance of water quality in the upper aquifers in the development area.

9.4.3.2 Hydrogeological Faults

The possibility of hydraulic fracturing fluids flowing up permeable fault zones was raised by participants in the Inquiry's public meetings and in written submissions. The word 'fault' has a negative connotation, beyond the inconvenience met by miners and quarrymen. The need to avoid faults, especially hydrogeologically significant faults, in order to minimise risk, is recommended as standard practice in **Section 6.12**.

In a hard rock environment, and visible in the field, faults may be open, and indeed fault zones may be conduits and targets for water bores to produce groundwater. In a sedimentary environment, particularly in the near surface relatively unconsolidated Mesozoic formations in the Perth and Canning Basins, faults are rarely visible and faults are commonly barriers to lateral groundwater flow (Commander 1974).

Bense et al. (Bense et al. 2013) describe the process of smearing and drag of sand and clay along fault planes in unlithified siliciclastic sediment. They considered it an important mechanism to generate a strongly anisotropic fault core in which sand will act as along-fault conduits while the clay smear will strongly hamper across fault flow. They considered faults in unlithified siliciclastic sediments are likely to behave in a combined conduit-barrier system, though they depict very low permeability along the fault plane, but in lithified siliciclastic sediment, where cataclasis (fracture, crushing and rotation) plays an important role, fault planes are likely to have much reduced permeability and behave as efficient barriers to fluid migration.

The offset of siltstone or shale against sandstone may cause a barrier to lateral flow and maintain a horizontal seal, or it may lead to creation of a vertical pathway between different sandstone layers. The likelihood that clay smear is an important factor in the near surface sediments in the Northern Perth Basin is illustrated by the drilling difficulties encountered with swelling clays in the Cretaceous Otorowiri Siltstone at depths of several hundred metres (Commander 1978a).

While there is evidence of faults as lateral barriers to groundwater flow, proving or disproving vertical flow is likely to be very difficult. The low permeability of fault zones mean that a considerable time would be needed to transfer significant quantities of fluid. Crostella (Crostella 1995) described faulting associated with oil and gas traps in the Dongara, Yardarino and Beharra fields, implying that the faults have remained relatively impermeable for a considerable period of time. However, hydrocarbon seepages have been detected offshore, and geomechanical modelling suggests fault planes oriented North North-West to East South-East are more likely to be forced into failure under a north-west extensional stress field, while faults with a north-west trend are more prone to seal (Langhi et al. 2012). Mullen (Mullen 2017) suggested that at the Woodada gasfield, uncemented faults oriented west to north-west for both the strike slip and normal case are critically stressed, and that the subset of faults is likely to have been leaking gas into the deep aquifers pre-development. She further considered that a fault intersected by Woodada 4 in the Woodada Formation may be circulating saline water from deeper strata.

Timms et al. (Timms et al. 2012) in a study of the geothermal prospects in the Perth Basin by the Western Australia Geothermal Centre of Excellence, commented that the small size of hydrocarbon reservoirs, in comparison to other Australian examples, is thought to be due to fault induced permeability baffles, rather than the juxtaposition of seal rocks. In an analysis of core material from the Apium 1 well, south-east of Dongara, they found that siderite, pyrite and minor quartz cementation significantly reduced the porosity of fractures. They concluded it was therefore highly likely that fossil (or inactive) faults have impermeable fault cores and an interlocking network of impermeable structures in the damage zones, irrespective of their orientation to the present-day stress field. In summary, they concluded that 'most, if not all of the Mesozoic faults in rocks of similar mineralogy and grain size in the northern Perth Basin would be sealing'.

The question of faults and their hydrogeological properties is addressed in hydrogeological assessments, for example;

> *"Both quartz cementation and strong cataclasis have resulted in low permeability of the faults, with permeability estimates to be about 0.002 to 0.004 millidarcies (mD) from 3000 to 3500 m in depth, and less than 0.0005 mD in the reservoir rocks. The position of faults are known, and at least for the initial tests the test sites will be away from them"* - Rockwater 2013 Warro Project: Hydrogeological modelling of potential impacts, included in the submission from AWE Limited

In her Master of Science thesis 'Unconventional Mining Risk to Deep Aquifers, Cadda Terrace', Fiona Mullen (Mullen 2017) contends that the Lesueur aquifer, which contains fresh water in the major part of the Cadda Terrace between the Drover-1 well to the south and Arrowsmith-1 well to the north is potentially at risk from contamination from hydraulic fracturing fluids themselves, or from more saline groundwaters at depth should faults in the area be reactivated through the normally sealing Kockatea Shale during hydraulic fracturing

operations, leading to hydrogeological linkage in the subsurface. The following risk factors were identified:

- Higher concentrations of hydrocarbons present in deep groundwaters suggest a deep thermogenic origin meaning that some fracture pathways already exist for hydrocarbons to migrate vertically through the Kockatea Shale;
- The state of stress in the Arrowsmith and Woodada Deep wells are in the strike slip regime and close to the state where favourably oriented faults in a west-north-westerly orientation could be reactivated by sustained fluid injection, for example the stress perturbation required for reactivation of some faults subjected to fluid injection is significantly less than 10 MPa;
- The state of stress in the Drover-1 well is poorly determined and may not place nearby faults close to failure. However, there are mapped faults within 500 m of the well trajectory according to seismic data;
- The Kockatea Shale is deeply buried and well cemented, and therefore brittle, such that renewed fracturing or fault movement would likely lead to a high permeability conduit owing to the effects of dilation; and
- The strike slip state of stress of the Kockatea Shale and immediate overburden do not produce a stress barrier that naturally contains the upward growth of fractures.

In drawing attention to Fiona Mullen's research the Lock the Gate Alliance state in its submission to the Inquiry:

> *"Mullen's work suggests the need to understand and map existing fractures and faults, both large and small, prior to any plans to frack an area. It also points to the need to fully understand how much gas may already be seeping into fresh water aquifers as an indicator of existing pathways for contamination"* – submission from Lock the Gate

The Panel notes that AWE Limited undertook both geomechanical modelling prior to, and microseismic monitoring during the fracture stimulation operations of the Drover-1 well, as they have documented in their own submissions to the Inquiry. No incidents were recorded during the stimulation operations or have been recorded since. However, it is worth pointing out that micro-seismic monitoring can only detect brittle rupture episodes and not slower ductile deformation that may accompany renewed faulting and fracturing in softer shales.

According to Mullen (Mullen 2017):

> "Microseismic monitoring is used to monitor small scale earthquakes which may occur as a result of hydraulic fracturing. Vertical extent of microseismicity has generally been used to confirm that aquifers are not affected by hydraulic fracturing operations (Flewelling, Tymchak & Warpinski 2013). However, mass balance analysis of microseismic deformation shows the cumulative shear slip and damage can only account for a small fraction of the volumetric deformation implied by production from shale gas reservoirs (Warpinski, Du & Zimmer 2012). Slow aseismic slip in unconventional reservoirs with clay and organic content greater than 30% by weight may be common during hydraulic stimulation and this is likely to be contributing significantly to production" (Kohli & Zoback 2013).

Palat et al. (Palat et al. 2015) used a numerical model to simulate the spread of a hydraulic fracture stimulation plume along a fault, based on parameters from formations in the Northern Perth Basin. Their modelling showed that the hydraulic fracturing fluid is contained within the target formation, and that the fluid intersecting a fault of high transmissivity results in the concentrations of the hydraulic fracturing additives dissipating faster, with the maximum concentrations declining to less than human health guidelines within one year.

An investigation of a potential carbon dioxide storage site at the depleted Dongara and Woodada oil and gas fields by Varma et al. (Varma et al. 2012), examined the integrity of the Kockatea Shale as a seal for pressurised fluid containment. A significant hydraulic head difference across the Kockatea Shale in the areas was noted, indicating that it is an effective seal over geological time, consistent with the known hydrocarbon accumulations in the area that have remained intact for tens of millions of years. However, geomechanical risks to seal integrity were identified that would limit the maximum storage capacity. While a simplistic geomechanical analysis indicated that faults in the Kockatea Shale would remain intact during pressurisation up to at least eight Megapascal (MPa), it was found by Varma et al. (Varma et al. 2012) that when poroelastic transfer of stresses are accounted for in a more realistic mechanical model, the repressurisation capacity on some faults was much less. Certain faults in the Kockatea Shale seal could potentially be reactivated with injection pressures of only a few MPa.

Finding 22: The risk of contamination of shallow fresh water aquifers by saline groundwater through hydrogeological faults is moderate, however where activities are undertaken such that faults are avoided, the risk is considered to be low. This is based on the likelihood that the presence of these permeable faults to propagate and create pathways which could contaminate overlying aquifers is rare. Should this event occur, the potential consequences are considered to range from insignificant to major, reflecting the importance of preserving water quality in the upper aquifers in the development area.

The Inquiry has found that seismicity from hydraulic fracture stimulation is unlikely and can be further controlled with a traffic light reporting system shown in **Section 8** (Land) of this Report. However, there is a remaining concern about the reactivation of geological structures that could impact on well integrity and water resources through creation and reactivation of hydrogeological pathways. The Panel considers that further steps can be taken to reasonably eliminate or mitigate these consequential risks.

A comprehensive risk analysis should include the following aspects:

1 **Definition of the subsurface state of stress.** Measurement of the prevailing stress state, that is, the directions and magnitudes of the maximum, minimum and intermediate principal stresses, with depth from the surface to at least one kilometre below the maximum depth of drilling.

2 **Definition of the structural context.** Mapping of all major structures in the basin sediments and in the immediately underlying basement rocks that could potential lead to felt seismicity, or damage to infrastructure or to well integrity, if reactivated.

These recommendations flow from the risk assessment and mitigations for induced seismicity in the **Section 8** (Land) of this Report and are in line with the National Harmonised Regulatory Framework for Natural Gas From Coal Seams (COAG Energy Council 2016; Standing Council on Energy and Resources 2013). In addition:

3 **Identification of any hydrogeologically active faults or fracture zones.** Identification of any faults or fractures that if reactivated or connected to by growing fractures would be hydrogeologically significant, that is, potentially breach sealing rocks and form a pathway for contaminants from the zone of production or from the wellbore, into an overlying aquifer or to the surface. The risk analysis should extend to the delineation of any faults or fracture pathways that could link a saline aquifer to a potable water aquifer should it become a permeable pathway owing to stress changes including reactivation of fault movement.

4 **Assessment of seal effectiveness.** The target zones for hydraulic fracture stimulation in a project development plan should be assessed according to the risk that loss of hydrogeological containment could occur during hydraulic fracture stimulation. This depends on the geological isolation of the producing formation from the nearest potable water aquifer. The degree of hydrogeological isolation depends upon the effectiveness of the overburden rocks as a seal. The factors to be considered in this analysis must include the thickness and permeability of overlying sealing rocks, their mechanical strength to resist fracture growth and shear rupture, their brittleness and the density and interconnectedness of natural fractures and joint networks within them. An important consideration is whether the state of stress in the locality inherently resists upwards fracture propagation (the best case being that the maximum principal stress is horizontal and the minimum stress is vertical in the seal).

In the case where any one factor, or a coincidence of factors points to a low level of seal effectiveness, then hydraulic fracture stimulation activities should not proceed.

5 **Adequate tools and expertise.** The geomechanical modelling used for the assessment of containment risks should employ suitable 3D analysis tools and be undertaken by suitably qualified independent experts. The geomechanical model should be updated as improved information about subsurface stresses and structures becomes available, for example, if a well intersects an unmapped fault, or unexpectedly high or low formation pressures are encountered.

6 **Acceptable range of scenarios.** The risk assessment should look at a range of plausible scenarios, and take into account cumulative impacts on the subsurface stress state of the region containing the oil and gas field over the expected lifetime of operations, including any change to the groundwater pressures as a result of abstraction.

7 **No go zones.** Hydraulic facture stimulation should not proceed wherever hydrogeologically significant structures are identified within two kilometres of a well and should also be avoided where the structures are so complex or poorly determined that predictions of geomechanical behaviours and outcomes are highly uncertain.

8 **Frac hits/well intersections.** Steps should be taken to avoid well intersections during hydraulic fracturing operations (frac hits) and to mitigate the consequences of a well intersection should one occur. Mitigations can include a sufficient offset distance, limitation on the size of the fracture treatment used and monitoring of pressure in nearby wells during hydraulic stimulation of a new well.

Finding 23: While there is a concern about the reactivation of geological structures that could impact on well integrity and water resources through creation and reactivation of hydrogeological pathways, the likelihood of the transfer of significant quantities of fluids is low.

Recommendation 7: All hydraulic fracture stimulation operations should be preceded by a comprehensive geomechanical risk analysis according to an enforceable Code of Practice.

9.4.3.3 Intersection with abandoned well casings

The possibility of hydraulic fracture stimulation intersecting abandoned well casings is discussed in detail in **Section 6.9** of this Report.

Mallants et al. (Mallants et al. 2017) carried out a literature review, involving mainly studies from the United States, and concluded that the only significant environmental risk to deeper groundwater resources was when abandoned or suspended well casings are intersected by fracturing-fluids, during the high-pressure stage of fluid injection, but that the likelihood was either unlikely or very unlikely in an Australian context.

The situation in the Northern Perth Basin and the Canning Basin is quite different from American oil fields with a long history of intensive drilling, with many old wells not decommissioned to modern standards. Dusseault and Jackson (Dusseault & Jackson 2014) considered that producing wells situated in the same target formation as new wells involved with fracture stimulation may be affected by hydraulic fracturing fluids when inter-wellbore distance is within approximately 250 m.

Finding 24: The likelihood of hydraulic fracture stimulation intersecting decommissioned bores and contaminating deep groundwater is low, given the documentation on decommissioned wells, and provided that adequate separation is made.

9.4.3.4 Casing integrity

The question of casing integrity, and the potential consequences of barrier failure on groundwater, was raised by participants in the public meetings and in written submissions. A particular concern was the long-term stability of cement and steel casing, over thousands of years. This is also an issue common to conventional wells.

The U.S. EPA has identified a number of pathways where well integrity is breached (**Figure 9.19**). These pathways may be;

- casing break;
- uncemented annulus;
- microannulus between the casing and cement;
- gaps in cement; and
- microannuli between the cement and surrounding rock.

Standards for the construction and integrity of oil and gas exploration and production wells have been described in **Section 6.9** of this Report, together with measures to check integrity. A particular feature of wells drilled for hydraulic fracture stimulation is that they must withstand a high pressure, therefore, for the well to be successful, it has to be constructed to a high standard.

Further, the Western Australian regulatory regime requires surface casing to extend to the depth of potable groundwater (Department of Mines and Petroleum 2015a).

The U.S. EPA (U.S. Environmental Protection Agency 2016) has documented a number of cases where poor or inadequate well construction was responsible for methane contamination of drinking water sources. These included, insufficient depth of surface casing, continuation of hydraulic fracture stimulation in a well where the cementing was not completed, and probable connection with old uncemented wells.

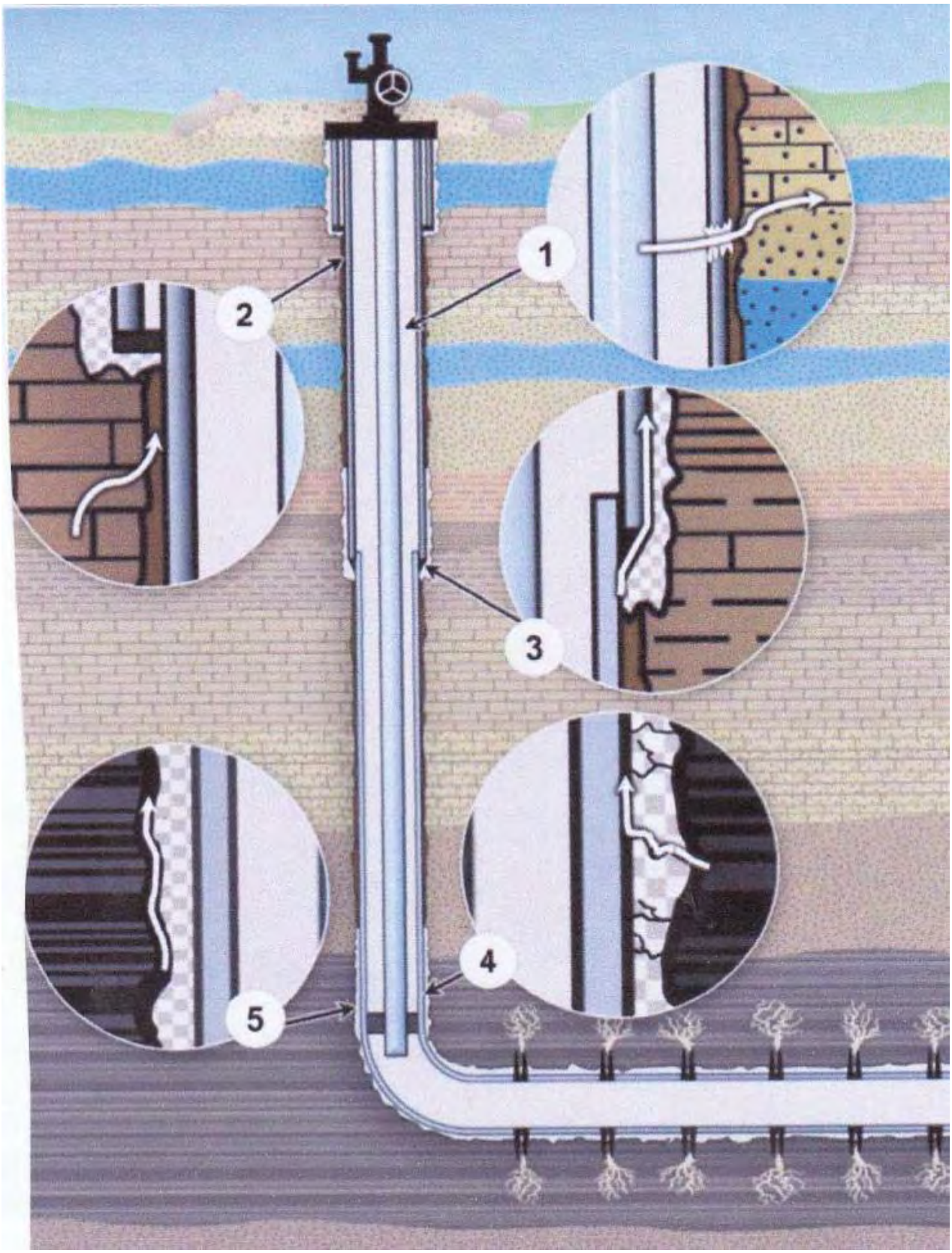
The following U.S. EPA figure (**Figure 9.19**) illustrates thick limestone beds, which is a feature of a number of North American basins. Problems with cement seal are most likely to occur in fissured limestone, although this factor was not explicitly dealt with by the U.S. EPA report.

Limestone is comparatively rare in the Mesozoic and Palaeozoic strata of the Perth Basin – occurring in thin horizons in the Holmwood Shale, Beekeeper Formation/Dongara Sandstone and Cadda Formations. In the Canning Basin, the thick reef limestones of the Devonian Fairfield Group are themselves a target for oil and gas exploration. The submission from Finder Shale refers to the carbonate overlying and underlying the Goldwyer Formation as being 'impermeable'.

The potential for transfer of fluids through these pathways depends on differential pressures.

Figure 9.19: Potential groundwater contamination pathways (white arrows) due to failure in well integrity.

Source: U.S. EPA (U.S. Environmental Protection Agency 2016)



Dusseault and Jackson concluded:

> "The quality of cement completions is a concern to future gas migration. Indeed, gas migration outside the casing is typically a result of incomplete cementing (in the case of older wells) or the formation of micro-annuli within or on the periphery of the cement sheath because of cement shrinkage. Gas-pressure gradients will promote the vertical ascent of gas slugs that will appear at the surface as pulsed gas flow. If such gas flows are not allowed to discharge to the atmosphere by shutting-in surface valves, potential for gas migration and subsequent groundwater contamination is exacerbated" (Dusseault & Jackson 2014)

Finding 25: The risk of contamination of shallow fresh water aquifers by saline groundwater and chemicals used in hydraulic fracture stimulation from well integrity failure is low. This is based on the likelihood of well failure occurring such that aquifers are interconnected in the study area being determined to be rare. Should this event occur, the potential consequences are considered to range from insignificant to major, reflecting the importance of water quality in the upper aquifers in the development area.

If standards of well construction are complied with, the risk of contamination of shallow fresh water aquifers is low.

9.4.3.5 Gases in groundwater

Concern was raised in public consultations about methane in groundwater supplies, drawing on reports from North America. The lighting of gas from a domestic water tap, depicted in the film 'Gasland', is a powerful image, drawing attention to the fact that dangerous levels of methane can persist in potable water.

There is an extensive literature on the subject in the United States, with conflicting findings. Many of these relate to the Marcellus Shale in Pennsylvania where there is a history of oil drilling back to the 1850s. The arguments revolve around whether the gas was there naturally, or as a result of leaking wells. Methane can be generated at depth (thermogenic), which is the gas sought to be produced, or at a shallow depth by biogenic processes. These two sources can be distinguished by isotopic analysis. What is generally lacking in the United States examples is baseline data on methane levels, collected before drilling.

A United States Geological Survey study (Heisig & Scott 2013) was carried out across the New York State Border where the Marcellus Shale comes close to the surface, but where hydraulic fracture stimulation is currently not permitted. The Marcellus Shale crops out in New York State and has previously been quarried for low grade roofing slate. The geology is characterised by fresh, glaciated, fractured bedrock, which includes black shale. The study found widespread gases (methane and ethane) in domestic water supply wells. The highest concentrations were found in wells in the valleys confined by valley sediments and this was

determined to be thermogenic methane, derived from deep in the bedrock. In upland areas, methane was also found, but determined to be biogenic.

A similar study was carried out by the Geological Survey of Canada in southern Quebec Province (Rivard et al. 2018). The area was known since the 1950s to have high methane levels in open domestic boreholes which produce groundwater from fractured black shales. Concentrations of as much as 80 mg/L were found, which far exceed the Quebec Province alert threshold of 7 mg/L to avoid risk of explosion. The methane was found to be mainly biogenic, with contribution of thermogenic methane in 15 percent of bores.

The U.S. EPA (U.S. Environmental Protection Agency 2016) reported on a number of cases in the United States where drinking water wells had been contaminated by methane. The causes were mainly attributed to poor well construction, insufficient depth of surface casing, poorly cemented wells and old abandoned uncemented wells. In a case in Pavillion, Wyoming, the same geological formation that is used to produce hydrocarbons also supplied the area's drinking water.

An experiment carried out over 72 days in Ontario (Cahill et al. 2017) with methane gas injected into shallow groundwater found lateral migration of gas beyond that expected by advection alone, and that methane persisted in groundwater despite active growth of methanotrophic bacteria.

There is broad agreement that hydraulic fracture stimulation itself is unlikely to contribute to significant vertical migration. Vidic et al. (Vidic et al. 2013) state the incidence rate of seal problems in unconventional gas wells is relatively low (one to three percent). However, there is substantial controversy over whether the methane detected in private groundwater wells in the United States, where drilling for unconventional gas is ongoing was caused by well drilling or by natural processes. They say it is difficult to resolve the issue because many areas have long had sources of methane unrelated to hydraulic fracturing, and pre-drilling baseline data is often unavailable. In his submission to this Inquiry, Dr Ryan Vogwill quotes Llewellyn et al. (Llewellyn et al. 2014) who conclude that the most likely explanation of the presence of natural gas and organic compounds in initially potable groundwater, one to three kilometres away from Marcellus Shale gas wells in Pennsylvania, was stray natural gas and drilling or hydraulic fracturing compounds, travelling through shallow to intermediate depth fractures.

In Western Australia, because of the long period of landscape stability, the rocks are commonly deep weathered and oxygenated, with reduced potential for methane generation and persistence. In the Northern Perth Basin, Commander (Commander 1981) and Harley (Harley 1974a) reported weathered sediments in the Yarragadee Formation extending to a maximum depth of 406 m. The Kockatea Shale, which is a black shale, and a gas and oil target at depth, is highly weathered where it crops out at the surface in the vicinity of the Northampton Block, with Playford et al. (Playford, Cockbain & Low 1976) describing the

outcrops as generally bleached white or pale yellow. Similarly, the Broome Sandstone in the Canning Basin is commonly oxidised to the base of the aquifer.

There are few documented occurrences of natural methane in Western Australian groundwaters, probably because of low levels, and the fact that black shales are rarely utilised for water supply. An exception occurs at Mia Station in the Carnarvon Basin (Condit 1935) where a driller reportedly lit gas from a waterbore in black shale of Permian age. Condit also mentioned other drillers' reports of gas in the Carnarvon Basin (presumably in water bores). The Merlinleigh and Byro Sub-basins have been identified as prospective for shale gas, but there is little information or exploration activity, and it has not been specifically considered by the Panel (**Section 5.7**).

Mullen (Mullen 2017) studied the gas measurements from deep exploratory gas wells on the Cadda Terrace (Woodada gasfield and neighbouring wells). She concluded that thermogenic gas had migrated into deep aquifers prior to any development and that faults may be the primary conduits. Methane levels in the Yarragadee Formation reached 2,800 parts per million (ppm) in East Lake Logue 1, and up to 9,500 ppm in the confined Lesueur Sandstone at a depth of 1,100m in Woodada 6. Generally, the Cattamarra Coal Measures, where it is a confining bed, acts to reduce methane biodegradation rates. She noted that the absence of methane in the Lesueur aquifer at the Gairdner well, where the aquifer is unconfined (and groundwater is low-salinity), may reflect increased rates of biodegradation of methane in a more oxidative environment.

In its submission, AWE Limited document analyses of water in two monitoring bores at its Drover site with 0.5 and 4 mg/L methane, which on subsequent analysis was determined to be of microbial origin and most likely related to drill muds and casing glue.

It is noted that methane and ethane, among other hydrocarbons, are listed as water quality parameters for laboratory analysis in Table 3 of the 'Guideline for groundwater monitoring' (Department of Mines and Petroleum and Department of Water 2016a).

Finding 26: The risk of contamination of shallow fresh water aquifers by methane as a result of hydraulic fracture stimulation activities is low. This is based on the available data, with likelihood of methane at depth migrating to upper aquifers assessed as rare. Should this occur, the potential consequences are considered to range from insignificant to moderate, reflecting the importance of the water resource.

This has been addressed in **Recommendation 5**.

Heisig and Scott (Heisig & Scott 2013) also record high radon values in groundwaters associated with high thermogenic methane in southern New York State. While radon levels in public water supplies drawn from the near-surface sedimentary formations in the Northern Perth Basin are low (Thorpe 1995), the submission from Ivan Quail brings to attention the likelihood of a significant radon content in flowback water. Radon gas is a potential health hazard, being linked to incidence of lung cancer. Uranium, radium and

thorium analyses from flowback water are documented (**Appendix 12 and 13**) but radon levels have not been measured.

Finding 27: There is a lack of information on radon in flowback water.

This has been addressed in **Recommendation 6**.

9.4.3.6 Groundwater contamination by on- or off-site spill of wastewater, produced water or chemicals

The potential for groundwater to be contaminated by spills of chemicals, hydraulic fracturing fluids, flow-back fluids and wastewater was a major issue raised by a majority of participants in the public meetings, especially in relation to drinking water.

A large amount of water, as much as 20 ML, may be required to be stored on site to provide the hydraulic fracture stimulation fluid, together with the added chemicals. A separate storage facility is also needed for flowback and produced water, which also contains chemicals derived from the formation.

Companies are specifically required to address the prevention of chemical spills and leaks at the surface through an Environment Plan and associated Oil Spill Contingency Plan:

> "The Oil Spill Contingency Plan should cover all potential spill sources and risks, including chemicals, drilling fluids, fuels and other substances. The plan should consider all potential spill scenarios including the type, volume, location and an assessment of impacts from each spill scenario. The plan must also detail how the operator will control and clean up any spill, and provide for ongoing monitoring" (Department of Mines and Petroleum 2015a)

Reportable Spills (those requiring DMIRS to be informed immediately) for the 2012 -2017 period and Recordable Spills (those which are recorded and reported to DMIRS later) are listed in **Appendix 10**. **Tables 9.9 and 9.10** illustrate the annual numbers of reportable and recordable spills for the 2013-2016 calendar years, and the volumes of liquids spilt. The type of fluids is described in **Table 6.3 and Appendix 10**, the major spills being drilling muds and produced fluids, while the smaller spills are fuel and machinery leaks. These statistics include unintended discharges into evaporation ponds, into the bunded area and onto hardstand.

Table 9.9: Annual number of reportable and recordable spills in petroleum activities
Source: DMIRS 2018

Calendar year	Reportable spills	Recordable spills
2013	5	70
2014	4	90
2015	3	123
2016	5	51

Table 9.10: Volume distribution of reportable and recordable spills in petroleum activities (6 October 2012 to 29 November 2017)
Source: DMIRS 2018

Volume (litres)	Number of Reportable Spills	Number. of Recordable Spills
>100,000	1	0
10,000 – 100,000	2	0
1,000 – 10,000	5	10
100 – 1,000	4	33
1 – 100	4	209
<1	0	115
Not specified	2	15

Spills may occur during transportation and on transfer from pond to well. Leakage may occur from ponds if double or triple liners are breached.

The consequences to groundwater quality depend on:

- The nature of the unsaturated zone (vulnerability);
- The nature of contaminants and whether they can be attenuated in the unsaturated zone by the processes of absorption, adsorption, oxidation or neutralisation; and
- The nature of the contaminants and whether they can be reduced in concentration in the groundwater by the processes of dispersion, dilution, adsorption and chemical change.

Once contaminants reach the water table, they may float, sink or disperse. Hydraulic fracturing fluids are mostly water and the density of the hydraulic fracturing fluids may depend on whether fresh or saline water has been used. Flowback water may be highly saline, and therefore much denser than local groundwater. The pathway depends on the relative density, direction of groundwater flow and stratigraphy.

Given these variables, it is sensible to account through a site water audit for the quantity of all fluids, that may lead to groundwater contamination. This would allow consideration of the quantity lost in any spill or leak, and if the loss was serious, allow for the design of an appropriate groundwater investigation program to determine the fate of contaminants, knowing the location, quantity, and composition of the lost fluid.

Mallents et al. (Mallants et al. 2017) modelled transport time and attenuation of contaminants for CSG basins in Queensland. They concluded that the calculated attenuation potential for organic compounds, based on degradation constants obtained from the literature indicated that for the long travel times typical of their two case study areas in CSG basins of eastern Australia, chemical/biological degradation processes together with sorption would easily reduce chemical concentrations to 'low concern'. Further, the calculated attenuation potential due to dilution and dispersion provided another line of evidence that for the large travel distances a significant decrease in chemical concentration can be expected (for both organic and inorganic chemicals).

In the Northern Perth Basin, there is a high risk of infiltration through the sandy soils. The time to reach groundwater depends on the amount of discharge, lithology and depth to water. There is a very high risk in the Tamala Limestone where the water table is shallow, and a lower risk where the water table is deep in interbedded weathered sand and shale of the Yarragadee or Parmelia Formations. Pathways are difficult to characterise, depending on strata and structural attitude (that is not necessarily vertical). Monitoring the water table is not simple in this situation, with difficulty in constructing, developing and sampling at the water table if it is deep.

Very slow groundwater flow rates are demonstrated by the carbon -14 analyses in major aquifers in the Northern Perth Basin (**Section 9.3.3.4**, **Table 9.5**). Davidson (Davidson 1995) estimates the rate of flow (seepage velocity) in the Yarragadee aquifer in the Perth area to be about 1 m/year, and 1 – 4 m/year in the Leederville aquifer. A rate of around 30 m/year was determined in the Leederville-Parmelia aquifer in the Dandaragan Water Reserve (Department of Water and Environmental Regulation 2017b).

In the Canning Basin, sites may vary in geology from shale (Noonkanbah Formation, Blina Shale and Jarlemai Siltstone) which have a low groundwater vulnerability, to sand (for example, the Broome Sandstone, and Erskine Sandstone) with a high groundwater vulnerability.

There is no legislated separation of oil and gas activities from sensitive receptors. The EPA 'Guidance for the assessment of environmental factors – Separation distances between

industrial and sensitive land uses No 3' specifies a buffer distance for oil and gas extraction of 2,000m (within which it has to be demonstrated that there is no unacceptable adverse impacts). The Guide to the Regulatory Framework for Shale and Tight Gas in Western Australia (Department of Mines and Petroleum 2015a) states

> "separation distances and potential contamination travel times between petroleum wells and PDWSA bores can be considered in PDWSA risk assessment processes by DoW".

In respect to private drinking water bore;

> "petroleum operators are required to consult landholders and relevant stakeholders".

By way of background, the State's regulatory framework has largely departed from prescriptive frameworks to outcomes and risk-based approaches, that is, risks must be considered specific to the activity and the local environment. As such, there is little prescriptive legislation and regulation administered by DMIRS that provides for prescriptive set-back distances from petroleum activities to residential properties. The location of petroleum activities in proximity to residential properties is largely regulated under the *Petroleum and Geothermal Energy Resources (Environment) Regulations 2012* under the outcomes and risk-based framework. However, referral to other agencies, principally the EPA, DWER, DBCA, DPLH and DoH may be undertaken. The roles of these agencies with regards to onshore oil and gas operations is detailed in the Guide to the Regulatory Framework for Shale and Tight Gas in Western Australia (Department of Mines and Petroleum 2015a).

Finding 28: The risk of contamination of near surface fresh water aquifers by drilling fluids, flowback water and chemical storage is moderate. This is based on the likelihood that spills and leaks do occasionally happen, as shown by the statistics. Given the generally low rates of groundwater flow expected in the prospective areas (with some exceptions, such as karst flow), the depth to water table, and the attenuation in the groundwater system, the consequence in the context of the prospective areas in the Northern Perth and Canning Basins is minor, provided there is adequate separation from private or public water supply bores. The risks are minimised by hardstand, bunding and lining of ponds, and by a stringent monitoring, reporting and recording regime. Early detection of leakage would further lessen risk by auditing the water cycle on a drill pad, accounting for fluids produced, disposed of or added to (for example, by rainfall) so as to identify significant unaccounted quantities.

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Finding 29: Fluid spills at the well site are the most serious threat to groundwater quality and there is a stringent reporting regime in place for spills. Consideration of groundwater vulnerability should be included in the Environmental Plan.

Recommendation 8: A site water audit should be required, accounting for water produced, evaporated and disposed, to detect significant leakage of fluids and determine whether remedial action to track any contaminants is warranted.

Recommendation 9: A separation of 2,000 metres from oil and gas wells associated with hydraulic fracture stimulation to bores used for Public Drinking Water Sources is warranted under the precautionary principle, as recommended by the Department of Health (DoH) and the Water Corporation. This is necessary for public confidence, irrespective of a low risk.

9.4.3.7 Disposal of waste

There are four main sources of waste produced during drilling, hydraulic fracture stimulation and gas production (Department of Mines and Petroleum 2015a):

- Drilling fluid;
- Rock cuttings;
- Flowback fluid; and
- Produced formation water.

Under the State Government's regulatory framework for shale and tight gas, the disposal of waste must be detailed in an operator's Environment Plan, which is subject to DMIRS approval.

Fluids are required to be stored in double or triple lined ponds constructed of customised High-density Polyethylene (HDPE) liners with interleaved geotextiles. Wastewater may be disposed of by evaporation from ponds, the solid residue being analysed for contaminants

and taken (with the plastic liners) to an appropriate licensed waste facility for disposal. Produced water may also be treated at site, or used in subsequent drilling operations.

Another technical option is for wastewater to be disposed by deep well injection. This option is regulated under the *Petroleum and Geothermal Energy Resources (Environment) Regulations 2012*. Historically, most reinjection has been into depleted hydrocarbon reservoirs, but this may not be feasible with shale gas wells. *The Health Act (Underground Water Supply) Regulations 1959* prohibits any disposal that may pollute or render unfit for human consumption the water in any well or other underground source of water supply, which water is used or intended or likely to be used for human consumption. Deep well disposal should not compromise beneficial use of the aquifer or pose a significant risk to the environment and would require a discharge licence under the EP Act.

In some overseas jurisdictions, at least in the past, wastewater from hydraulic fracture stimulations has been discharged onto land or into surface water bodies; much of the literature related to environmental contamination (including contamination of agricultural produce and harm to livestock and wildlife) arises from this practice. In Western Australia, the discharge of wastewater onto land or into surface waters would require a licence under the EP Act, and no such activities associated with onshore oil and gas development have been permitted, although there is no explicit ban under regulations.

From North American experience, the quantity of flowback water is in the range of 10 to 30 percent of injected hydraulic fracture stimulation fluid (Edwards et al. 2017). Most of this is produced in the first few months of production. As addressed in their submission, Buru Energy have set a goal of reusing 30 percent of flowback water.

A well site with eight horizontal wells may therefore have between 8 x 2,000 kL to 8 x 6,000 kL to dispose of, most in the first year of operation but also with an ongoing production rate.

Annual potential evaporation rates are two metres in the Northern Perth Basin to three metres in the Canning Basin, or nett 1.5 to 2.5 m, accounting for average rainfall. One and a half metres of evaporation represents a maximum loss of 15,000 kL/ha for low salinity water, as highly saline water evaporates at lower rates.

Solid wastes, residue from evaporation, which are likely to contain a high proportion of salts and NORMs, must be analysed and assessed for disposal at an appropriate waste disposal facility.

Finding 30: The risk of contamination of near surface fresh water aquifers by waste from petroleum drilling operations is low. This is based on the requirement for double or triple lined ponds and waste to be disposed in an approved waste disposal facility.

The Panel found that there were adequate regulations and practices in place to prevent disposal of fluids to surface or groundwaters; that evaporation in the Northern Perth and Canning Basins was sufficient to dispose of most excess water; and that there were

provisions in place for the disposal of residues and contaminated material (for example, pond liners).

9.4.3.8 Chemical spills during transportation

Chemicals used in hydraulic fracturing fluids, and fuel used to power the drilling operation, need to be transported to site. Generally, water is pumped from an on-site bore, and fluids disposed of by evaporation ponds. If hydraulic fracturing fluids (mainly water) were to be transported between sites, typically some 500 journeys by a 40 kL road tanker would be required to transport 20 ML of fluid needed for one hydraulic stimulation.

Detailed traffic management plans are required by DMIRS for transport of materials to and from well sites, and operators are required to work cooperatively with local government, the Department of Transport and the police (Department of Mines and Petroleum 2015a). Transportation of controlled waste on roads is regulated by DWER under the *Environmental Protection (Controlled Waste) Regulations 2004*.

The risk of spillage during transport is exacerbated by road access along gravelled tracks. The risk to surface water is heightened risk where transport routes cross drainage lines, and when runoff is occurring.

Finding 31: Transport spill plans and reporting requirements reduce the risks from spillage at critical points to surface water and to near surface groundwater to a low level.

Groundwater vulnerability factors – case studies

As previously described in Section 9.3.3.9 of this Report, the vulnerability of groundwater to contamination from surface spills is affected by a number of factors represented by the acronym DRASTIC (Aller et al. 1987). These are site specific and depend mainly on the geology and depth to water table.

A vulnerability ranking can be made on the basis of some of the more significant properties, being surface geology (how easy it is for vertical percolation to occur); depth to water table (how long it will take to drain vertically, affecting the attenuation which may take place in the unsaturated zone); the salinity at the water table (a low concentration of contaminant can have a significant impact on fresh groundwater, especially if it is drinking water quality, but not so great an impact on the use of saline groundwater); and rate for groundwater flow (how quickly contaminants may travel laterally). However, whereas limestone may be more vulnerable in terms of percolation time compared with sand, attenuation in calcareous sediment is far greater than in quartz sand.

The depth to water table is about the maximum experienced in the Perth Basin, and the range of natural groundwater flow rates, from 300 m/year in the Superficial aquifer, to 1

m/year in the Yarragadee aquifer, are taken from (Davidson 1995) relating to the Perth region.

	High vulnerability	Moderate vulnerability	Low vulnerability
Surface geology	Karst limestone	Sandstone	Shale
Depth to water table	<5m	50	150
Water table salinity mg/L	500 (drinking water)	1,000	2,000 + (brackish)
Groundwater flow rate m/a	300	10	1

For comparison, examples from recently drilled wells in the Perth and Canning Basin are given below:

Perth Basin	Woodada	Warro	Drover
Surface geology	Sand (Superficial)	Sandstone/siltstone (Parmelia)	Sandstone (Lesueur)
Depth to water table (m)	5-15	60-80	100
Water table salinity (mg/L)	1,000 -2,000	500 – 1,000	500-1,000
Groundwater flow rate (m/year)	Not available	30 (DoW) 4 (Rockwater)	Not available

Canning Basin	Yulleroo	Asgard/Valhalla	Theia
Surface geology	Sandstone (Broome)	Sandstone/ siltstone/shale (Liveringa)	Siltstone/ sandstone (Broome/ Jarlemai)
Depth to water table (m)	10-20	25-30	160 (depth to top of Wallal Sst.)
Water table salinity (mg/L)	<500	500-3,000	1,500 (confined) Wallal aquifer)
Groundwater flow rate (m/year)	30 (Rockwater)	2 (Buru-Rockwater)	Unconfined aquifer absent

The Theia site represents a very low risk to groundwater from surface contamination. The 40 m thick Broome Sandstone is unsaturated and separated from the confined Wallal Sandstone aquifer by 120 m of largely impermeable Jarlemai Siltstone. Groundwater in the Wallal sandstone aquifer is not drinking water quality, though it may have irrigation potential.

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Risk assessment: Greenhouse Gas Emissions

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10 Risk assessment: Greenhouse Gas Emissions

10.1 Environmental values at risk to Greenhouse Gas (GHG) emissions

It is clear from both the literature and submissions to this Inquiry there are concerns regarding the implications of hydraulic fracture stimulation for oil and gas production, related to the emissions of greenhouse gases (GHGs). While the principal GHG emissions associated with the industry, carbon dioxide (CO_2) and methane (CH4), pose no direct toxic threat to human health, there is an overwhelming volume of scientific evidence that the level of GHG emissions associated with the use of fossil fuels is harming the global environment, and therefore Western Australia's environment, by changing our climate. Thus, the Inquiry's risk assessment of GHG emissions is logically based on the following environmental value:

> GHG emissions associated with hydraulic fracture stimulation for developing Western Australia's oil and gas resources has a negligible impact on the environment through their influence on climate.

The form that environmental harm from a changing Western Australian climate may likely take is based on both historical observations of change and consensus modelling projections (Intergovernmental Panel on Climate Change 2014). As an example, since 1950 most of Western Australia has experienced an average rise of 0.10˚C to 0.20˚C in temperature per decade, with increased rainfall in much of the State but with significantly decreased rainfall in the State's South-West, where it has fallen by up to 50 mm per decade. At Fremantle, the relative sea level over 1897 to 2010 increased by 1.6 ± 0.1 mm/y, with a trend of 2.2 mm/y over 1920 to 1960, little trend from 1960 to 1990 and 4 mm/y over the last two decades (CSIRO and Bureau of Meteorology 2015). Sea surface temperatures increased by 0.6˚C off Ningaloo over recent decades (Feng, Meyers & Church 2005). Projections of climate, and their potential impacts into the future, depict serious consequences for Western Australia and its people (CSIRO and Bureau of Meteorology 2016). The projected impacts of climate change extend to human health (Australian Academy of Science 2015; Mora et al. 2017) and even to 'existential risk', that is a permanent, large and negative consequence to humanity.

10.2 The scope of the GHG risk assessment

The consideration of GHG emissions within this Inquiry is subject to some interpretation with respect to scope.

A narrow interpretation of the scope of this Inquiry, under its Terms of Reference, would only consider the risks of GHG emissions from the hydraulic fracture stimulation process per se. That is, it would not include emissions associated with the construction of the well, the production and processing of gas, and any leakage following abandonment (unless those

processes were directly influenced by the fracturing itself over and above the risks of GHG emissions from conventional gas wells).

Such an analysis of the risks posed by hydraulic fracture stimulation through GHG emissions would not be realistic or meaningful without considering the risks of impacts from those processes and developments logically and necessarily connected with its use. Thus, the Inquiry's risk analysis does explicitly consider the emissions associated with the upstream production of onshore gas employing hydraulic fracture stimulation. In this regard, this Inquiry is consistent with previous inquiries in Australia and overseas. These upstream emissions arise from the construction, production, transmission and delivery of products. For reasons explained later in this Section, an emphasis was placed on the estimation of fugitive methane emissions, including those from decommissioned (abandoned and plugged) wells.

The Inquiry's Terms of Reference and scope clearly do not extend to the consideration of the State's gas industry as a whole and its future, or how that gas might substitute for fossil fuels currently in use and whether gas is better or worse with respect to GHG emissions, or if the availability of such gas would have any bearing on gross consumption of fossil fuels at all. The environmental issues associated with the broader industry, specifically the emissions associated with the downstream use of gas (from any source) in Australia and overseas, are beyond the Inquiry's Terms of Reference.

Therefore, the most immediate GHG question central to this Inquiry, that the Panel directly addressed is: How much more GHG is associated with oil and gas production requiring hydraulic fracture stimulation over and above that emitted by conventional petroleum developments?

There is concern in sections of society that development of renewable fuel options will be delayed if shale gas provides an abundant and cheap source of energy into the future. This becomes an energy and climate change mitigation policy issue and is a higher-level matter which, while very important, sits above the mandate of this report (Cook et al. 2013)

This Inquiry, like the Australian Council of Learned Academies (ACOLA) review cited above (Cook et al. 2013), is not placed to forecast and assess the ultimate effects of developing Western Australia's oil and gas resources through hydraulic fracture stimulation on domestic or global gas consumption, the influence such development might have on the rate and direction of change in energy sources, or the relative emissions intensities of options other than gas. Given the strong likelihood (supported by submissions to this Inquiry) that for the foreseeable decade or two gas resources developed with hydraulic fracture stimulation are aimed at the domestic Western Australian market, that Western Australian gas demand is expected to have limited growth over the next decade, that the local market has limited

demand elasticity[2] (-0.35 as estimated by the Core Energy Group (Core Energy Group 2014)) and is likely a more expensive source to develop, then the most justified and straightforward assumption is that unconventional gas developed in Western Australia will substitute one-for-one with supplies currently produced conventionally and consumed in Western Australia. As such, the GHG risk reduces to the difference in emissions between those sources.

Some submissions to this Inquiry have expressed concern over the full lifecycle emissions associated with onshore gas developments, so the Panel has also provided estimates of lifecycle GHG emissions associated with development scenarios to further assist and inform the Western Australian Government in its future considerations regarding climate change mitigation.

"The Terms of Reference of the Inquiry are tightly cast, focusing particularly on the operational aspects of hydraulic fracturing. However, it is essential the climate risk implications, globally and locally, of such developments, be given full attention. This may sound extreme to those not close to the climate science and evidence, but it should be the primary concern of this Inquiry" – submission from Ian Dunlop, former Chair of the Australian Coal Association and former Chief Executive Officer of the Australian Institute of Company Directors

The GHG risk reported by this Inquiry is therefore presented from two very different perspectives:

1. The risks associated with the relative upstream emissions between unconventional and conventional gas assuming one directly substitutes for the other in the marketplace; and
2. The risk of not 'leaving it in the ground' with the implicit assumption that the consumption of any produced unconventional gas would be over and above (directly additive to) Australia's fossil fuel emissions, if this resource was not developed.

[2] how fast demand goes up if the prices goes down, as the ratio of percent change in demand to the percent change in price.

Finding 32: Much of the risk posed by greenhouse gas (GHG) emissions does not result directly from hydraulic fracture stimulation. However, it would be disingenuous not to recognise that this technology has the potential to open up large gas resources across Western Australia, with all the concomitant risks from the resulting emissions associated with gas field development.

Finding 33: The risks posed by greenhouse gas (GHG) emissions depends on whether, at one extreme, the gas directly substitutes for conventional gas sources, or at the other extreme, the gas adds to total fossil fuel consumption. It is the view of the Panel that for the foreseeable future in Western Australia, the former is far more likely than the latter. Emission values are presented for both cases.

10.3 Setting an objective for assessing GHG risk

To evaluate the risk to climate posed by oil and gas developments based upon hydraulic fracture stimulation, the Inquiry required an environmental objective that established a level of GHG emissions that pose a risk to the Western Australian environment and its people. This was not a straightforward exercise. In the first instance, to set a level of zero emissions is not only highly impractical, it is not consistent with the fact that all industries emit, and are allowed to emit, some level of GHG.

Ideally, the level would be set based on the harm that amount of GHG causes to Western Australia. This is a calculation beyond the current ability of science. This is because human-induced climate impacts operate through global atmospheric processes, and any realistic amount of GHG emissions from onshore unconventional oil and gas development in Western Australia will inevitably be a small fraction of worldwide emissions. The accuracy, precision and realism of current (and foreseeable) global climate models fall well short of being able to forecast the contribution to changes in Western Australia's climate resulting from changes in local emissions. Setting an environmental objective for GHG emissions strictly on this basis is highly problematic.

The Panel notes that unlike all other Australian States and Territories, Western Australia has no GHG emissions or climate change mitigation target that might provide a context for an objective for this Inquiry. The Panel also notes that Western Australia is the only Australian jurisdiction that has experienced a significant increase in GHG emissions since 2000, largely due to the predominance of the State's extractive industries (particularly conventional gas) as well as an increase in its population over that period. As the State's economy doubled over that same period, the emissions intensity of its economy (Million tonnes of carbon dioxide equivalent per billion dollars ($MtCO_2$-e/$b) Gross State Product) is about the same as

the national average, which in turn is almost twice that of the European Union and significantly higher than that of the United States.

The *Environmental Protection Act 1986* (EP Act), does compel due regard for the principal of waste minimisation such that 'all reasonable and practicable measures should be taken to minimise the generation of waste and its discharge into the environment'. Further, the EP Act defines pollution as 'direct or indirect alteration of the environment to its detriment or degradation or to the detriment of an environmental value…that involves an emission' and defines material environmental harm as 'environmental harm that is neither trivial nor negligible'.

GHG emissions are subject to consideration under these features of the EP Act. The Act also anticipates there may be limitations to how an environmental objective can be achieved, defining the concept of practicable as 'reasonably practicable having regard to, among other things, local conditions and circumstances (including costs) and to the current state of technical knowledge'.

Reasonably practicable levels of GHG minimisation, however, may not necessarily be acceptable or prudent. Some measure of emissions (above which the risk to our climate is materially harmed) is also needed to inform the assessment of risk.

One approach is to use a scenario for a gas field development, dependent on hydraulic fracture stimulation, and estimate the levels of GHG emissions, placing them in some context with global emissions and Australia's international commitments for mitigating climate change. In doing so, the implicit question is 'how big would emissions have to be to be considered significant at the global scale or in terms of Australia's commitments?'. As seemingly arbitrary as this might be, it is not inconsistent with implicit expectations under the Safeguard Mechanism of the Australian Government's Emissions Reduction Fund (Department of the Environment and Energy 2016). This is similar to the approach taken by the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory (Northern Territory Government 2018), which set the following environmental objective:

> "GHG and methane emissions from a new shale gas field must be minimised. The contribution to global anthropogenic GHG and methane emissions from a new gas field in the NT must be 0.1% or less" (Northern Territory Government 2018)

Such a level (<0.1 percent of global emissions) was considered to have a low consequence, with 0.5 percent and one percent of global emissions considered as serious and major, respectively. This objective recognises the principle that polluting waste should be minimised and complements that principle with a set of emission levels considered as having material consequences to our climate.

The Panel adopted this overall approach to setting an environmental objective for GHG emissions, noting that the scope of emissions considered through this Inquiry may differ from that considered as part of the Northern Territory Inquiry's Terms of Reference.

Further, this Inquiry recognises that the Australian Government has responsibility to meet its international agreements on GHG emissions, which presently commit the nation to reduce emissions by 26-28 percent on 2005 levels by 2030 (Department of the Environment and Energy 2015), translating to a reduction of 990-1055 Mt CO_2e in cumulative emissions between 2021 and 2030 and a 2030 target annual emission of about 592 Million tonnes per year carbon dioxide equivalent (Mt/y CO_2e). The Inquiry has established a GHG objective in this context. That is, the Inquiry evaluated the risks of GHG emissions levels as impacting on Australia's ability to meet its commitments and to minimise global warming. The Panel note that the recent report by Climate Analytics (Hare et al. 2018) also uses Australia's GHG (Paris) commitments as a benchmark for such an assessment. Thus, the Inquiry's GHG objective for risk assessment is:

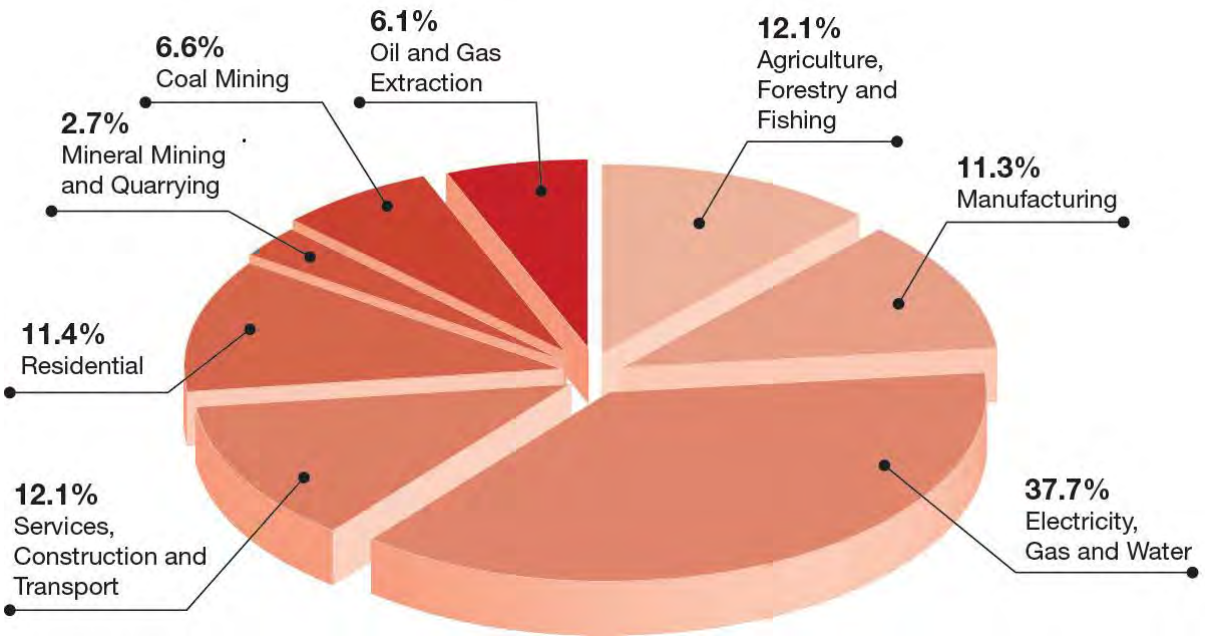
> "GHG emissions from onshore oil and gas fields developed with hydraulic fracture stimulation must be minimised. The contribution to Australian anthropogenic upstream GHG emissions from onshore fields in Western Australia must be 0.5 percent or less of 2016 Australian GHG emissions".

A value less 0.5 percent was considered to have a low consequence to Australia meeting its international GHG commitments and to the climate more generally, with 1.0 percent and 2.0 percent of 2016 Australian emissions considered as medium and high, respectively. For reference, equivalent emissions for the Gorgon (Phase 1) domestic gas project (design capacity 182 TJ/d) are estimated at 8.3 Mt/y CO_2e in the 2016 National Energy and Greenhouse Report's baseline determinations. This project equates to about 1.5 percent of Australia's 2016 GHG emissions. The value of 0.5 percent of Australia's 2016 GHG emissions equates to about 0.05 percent of current global emissions. A breakdown of 2016 GHG emissions by sector of the Australian economy is in **Figure 10.1**.

Figure 10.1: Australian GHG emissions by sector, 2016

Total national annual emissions were 550.2 Mt CO_2e. Coal mining and oil and gas sectors shown in this figure include both energy consumption and fugitive emissions.

Source: Department of Environment and Energy (Department of the Environment and Energy 2017b)



The risk associated with GHG emissions from gas production based on hydraulic fracture stimulation does not significantly differentiate between sources in the Canning Basin versus those from the Perth Basin. As such, the environmental GHG objective and subsequent risk analysis can be based on combined development scenarios across those regions.

10.4 Key issues raised

There is an extensive literature relating GHG emissions to oil and gas developments in general and those specifically employing hydraulic fracture stimulation. This reflects the scientific community's broad concerns over global warming. This literature is focussed, in the main, on emissions of methane.

For similar reasons, the Inquiry heard through many written submissions and presentations at public meetings an overall concern about the further development and use of fossil fuels more generally. These concerns extended well beyond the issues of hydraulic fracture stimulation, with the connection being the potential to access otherwise unavailable petroleum resources with a technology that has more GHG emissions than conventional developments (Tagliaferri et al. 2017).

Other specific concerns regarding GHG emissions that were raised through this Inquiry included the potential leakage of GHG (particularly methane) through well failures (both operational and decommissioned); purposeful venting and flaring associated with well construction and testing; ongoing flaring if production is focussed solely on tight oil; and the lack of adequate air emissions monitoring.

10.5 Upstream GHG emissions

The scientific literature and industry experience with upstream emissions associated with oil and gas fields developed with hydraulic fracture stimulation is extensive, but highly problematic in its interpretation and relevance to this Inquiry because it is confounded or inconsistent in several important ways:

- In any place, there are natural sources and background levels of both carbon dioxide and methane not attributable to gas development, and studies estimating industry emissions rarely enjoy comparison with baseline measurements prior to development (Moritz et al. 2015).
- GHG emissions from a well, or well field, are difficult to precisely determine. Published estimates of emissions are often based on measurements at differing scales, each having advantages and disadvantages, but rarely comparable and more rarely reconciled (Howarth 2015; Lafleur et al. 2016), but see Brandt et al. (Brandt et al. 2014).
- Studies report emissions from gas fields developed at different points in time, with older fields constructed with practices different to, and generally less environmentally stringent, than more recently developed fields (Howarth 2015; Roy, Adams & Robinson 2014; Schwietzke et al. 2014).
- There can be great variation in the potential emissions among wells (even within the same well field) making the characterisation of typical emissions problematic (Day et al. 2014; Omara et al. 2016; Robertson et al. 2017; Zavala-Araiza et al. 2015).
- Studies of emissions from gas fields associated with the use of hydraulic fracture stimulation can be in the context of Coal Seam Gas (CSG) or shale gas, which are inherently different in geologies and extraction technologies (but do share some common types of infrastructure).
- Some published estimates for projected Western Australian emissions from unconventional gas development are based on theoretical and implausible development scenarios (Bista, Jennings & Anda 2017; Frogtech 2013; Hare et al. 2018).
- All field estimates of emissions depend to some greater or lesser extent on the local geology and geography.

To maximise the relevance of literature on GHG emissions to this Inquiry, we relied most immediately on studies and emission estimates:

- Associated with practices like those required and adopted under the current regulatory arrangements in Western Australia;
- Associated with contemporary best practice worldwide, if different to those in Western Australia;
- Associated with geologies broadly like those in Western Australia; and
- As measured for onshore gas developments in Western Australia.

All activities associated with natural gas development result in GHG emissions, including site development, well construction, production, processing and transport. These gases mainly comprise carbon dioxide and methane but can also include hydrocarbons such as ethane and propane, as well as small amounts of nitrogen, water vapour and hydrogen sulphide. These emissions result from combustion engines and other energy usage, as well as direct venting or leaks.

Of the two main GHGs of significance to the Inquiry's risk analysis, carbon dioxide is associated with combustion and energy use, but can also be a waste product of natural gas processing if it is a component of the produced gas. Data from existing onshore gas-producing wells in Western Australia indicate typically low carbon dioxide content. For example, formation gas from the Corybas 1 well in the Northern Perth Basin had a carbon dioxide content of 1.9 percent, as assayed in gas samples taken at surface. Gas from type I and III Goldwyer shale in the Canning Basin has a mean carbon dioxide content of 3.4 percent from mud log gas samples taken over multiple depth intervals from the Theia 1 exploration well. Gas from Laurel (Canning) Basin-Centred System (Kingsley & Streitberg 2013) had a mean carbon dioxide content of 1.0 percent from mud log gas samples taken over a number of depth intervals from the Valhalla North 1 well (TGS 14).

Of far greater concern is the potential for methane emissions (see text box at the end of **Section 10.6**), and the preponderance of the scientific literature on the risks of unconventional (and conventional) gas development focuses on the emissions of methane. Most of this literature on the rates of GHG emissions differentiates among the following sources, recognizing that studies vary somewhat in what they include or not include in this differentiation (Allen 2016; Brandt et al. 2014)

- The purposeful combustion and vented emissions that arise during the upstream stage of gas production, including emissions from energy use and releases during well completions, processing, transmission and distribution;
- The purposeful but sporadic and unplanned emissions due to process upsets; and
- Leaks (the unplanned or 'fugitive' methane emissions) that occur through poor well containment (well failure), including from abandoned wells and emissions arising

from pathways to the surface created by the hydraulic fracturing itself, apart from those directly associated with the well containment failure.

In the Australian GHG inventory, fugitive emissions include most of the sources in the above list: leaks, venting and flaring, intentional and accidental releases, storage losses and so on. The only source not counted as a fugitive emission is energy combustion which includes gas or other fuels burnt in the course of constructing or operating the well (for example, gas powered engines to drive water pumps or compressors).

Modelling of gas fields in the United States by the National Energy Technology Laboratory (Skone et al. 2016) attributes about 40 percent of GHG emissions to the extraction process including methane emissions during well completion, 19 percent to processing (especially compression), and 41 percent to transport and distribution.

Estimates for GHG emissions from the various stages and components of shale gas well and gas field development were reviewed by the Inquiry and vary widely. Lafleur et al. (Lafleur et al. 2016) report a range of methane emissions of two percent to 17 percent of production volumes in the literature. The higher value is widely quoted and results from the study by Caulton et al. (Caulton et al. 2014) based on two estimates of emissions in the Marcellus region over two days using an instrumented aeroplane. The two estimates were 2.8 percent and 17.3 percent of production, with high uncertainty. A similar study by Peischl et al. (Peischl et al. 2015) of the same area (not cited in Lafleur et al. (Lafleur et al. 2016)), using essentially the same airborne methodology, was made about a year later and found emissions in a range of 0.18 percent and 0.41 percent of production. A second airborne study of this kind not cited in Lafleur et al. (Lafleur et al. 2016) is that of Karion et al. (Karion et al. 2015), who estimated emissions from the Barnett Shale region to be between 1.3 percent to 1.9 percent of production.

The current United States Environmental Protection Agency (U.S. EPA) methane emission factor (U.S. Environmental Protection Agency 2015c) is 1.4 percent of gross gas production, with a total full life cycle emissions factor of 1.8 percent. The basis for these emissions factors was called into question by Howarth (Howarth 2015) who concluded that, at best, the life cycle emissions factor for shale gas is about 3.8 percent of production. The work by Brandt et al. (Brandt et al. 2014) was one of the most comprehensive reviews and analyses of methane emissions from the production of natural gas available to the Inquiry, and included consideration of measured methane emissions resulting from hydraulically fractured wells. They concluded on the basis of measured methane changes in the atmosphere that there was an absolute upper limit of about seven percent methane leakage from natural gas production. Balcombe et al. (Balcombe, Brandon & Hawkes 2018) reported (on the basis of high-resolution measurements) median estimates of methane emissions across the entire natural gas supply chain at 0.8 to 2.2 percent of production.

In their revision of global fossil fuel methane emissions Schwietzke et al. (Schwietzke et al. 2016) concluded that the contribution from the production of natural gas had fallen from

eight percent during the 1980s to 1.9 percent currently, despite large increases in production and due to improved practices and replacement of older equipment. This latter value is similar to the best estimate in Brandt et al. (Brandt et al. 2014).

More recent field measurements and a large sample of other data sources for both conventional and unconventional wells fields analysed by Littlefield et al. (Littlefield et al. 2017) found that 1.7 percent of total methane production (95 percent confidence interval of 1.3 to 2.2 percent) was leaked between extraction and delivery. The field measurements in this study could not account for the source of about 19 percent of methane emissions on the basis of system component measurements. These 'unassigned' emissions pointed to a skewed distribution of leakage sources, consistent with previous studies of variability well leakage rates across well fields (Brandt et al. 2014; Lyon et al. 2016; Robertson et al. 2017; Zavala-Araiza et al. 2015). Field measurements of methane emissions across CSG fields in Queensland by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (Day et al. 2014) from 35 wells had a mean emissions rate from equipment on well pads (1.2 kilograms carbon dioxide equivalent per tonne (kg CO_2e/t)) consistent with the methane emissions factor under the National Greenhouse and Energy Reporting (NGER).

Regional-scale interpretations of airborne or satellite data ('top-down') offer the potential to provide an integrated measurement over time of all the methane emitted from an area, with the obvious challenge of differentiating natural sources from the emissions from oil and gas development. Published estimates of regional methane fluxes based on the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) sensor WFM-DOAS methane data produced by the Institute for Environmental Physics, University of Bremen or the IMAP-DOAS methane data produced by the Space Research Organization Netherlands (SRON) and Jet Propulsion Laboratory (JPL) NASA, vary in their interpretations and results. Schneising et al. (Schneising et al. 2014) used data from the SCIAMACHY platform and reported methane emissions from two United States regions with unconventional and conventional oil and gas developments at about nine to 10 percent of production, with an uncertainty of about $\pm$ 6-7 percent. Brandt et al. (Brandt et al. 2014) used data from the same platform for methane emission estimates for a region with a long history of coal, oil and gas development in the United States and reported values in excess of the U.S. EPA emissions inventory. By comparison, the airborne study of emissions from the Bakken region by Peischl et al. (Peischl et al. 2016) found GHG emissions of 6.3 percent ± 2.1 percent.

Day et al. (Day et al. 2015) reviewed the use of these findings and concluded that no definitive statement on 'fugitive' emissions could be made from these satellite data until four uncertainties had been addressed: (1) different retrieval algorithms giving entirely different results; (2) the impact of sensor degradation; (3) concomitant uncertainties in estimated methane fluxes; and, (4) the attribution of the estimated fluxes (for example, the split between natural seeps and industry emissions). In that same report, Day et al. (Day et al. 2015) describe a program to quantify methane emissions from the unconventional gas

fields in the Surat Basin using SCIAMACHY-derived methane data but in their examination of data covering the period between 2001 and 2011, they found no detectable difference in atmospheric methane concentrations over the Surat region, when compared to the remainder of Australia.

As well as satellite remote sensing, Day et al. (Day et al. 2015) also trialled higher spatial resolution airborne remote sensing, using an Airborne Laser Methane Assessment Generation 2 (ALMAG2), developed by Pergam, which uses a diode laser sensor to measure methane. These studies were complemented by two ground stations measuring methane fluxes and mobile measurements using vehicle mounted gas analysers within the Surat Basin.

Bruhwiler et al. (Bruhwiler et al. 2017) concluded that recent claims of significant increases in methane emissions from United States oil and gas production were 'inconsistent with observations by examining atmospheric inversions and observations from the NOAA aircraft monitoring program', and demonstrated atmospheric variability, sampling biases, and choice of upwind background can lead to spurious trends in atmospheric column average methane when using both in situ and satellite-based measurement. Cain et al. (Cain et al. 2017) demonstrated, by the use of simultaneous carbon isotope measurements, that a methane plume over the North Sea would have been attributed (on the basis of airborne monitoring alone) to an oil and gas operation, which it was not.

Data from the National Greenhouse Gas Inventory (NGGI) for 2014, as cited in Lafleur et al. (Lafleur et al. 2016), implied that 'fugitive' methane emissions from Australian oil and gas production was 0.5 percent of production. Lafleur et al. (Lafleur et al. 2016) considered this level inconsistent with measurements and estimates from a variety of sources, although their own review of the literature (and this review) show substantial uncertainty in the estimates. In its latest review of emissions factors, the Australian Department of Energy and Environment (DoEE) (Department of the Environment and Energy 2017m) reviewed the empirical evidence of 'fugitive' methane emissions associated with the unconventional gas industry, including data from Australian CSG fields and shale gas fields in the United States. In doing so, they noted the growing availability of 'top-down' and 'bottom-up' approaches to measurements in the United States that broadly supported the U.S. EPA emission factor of 1.4 percent of production, noting variation across facilities and significant remaining uncertainties. They concluded that Australian measurements were in broad agreement with the estimate provided to the U.S. EPA (15.5 g CO_2e/MJ).

Finding 34: In the absence of actual measurements, the emission rates typified for unconventional oil and gas production, associated with hydraulic fracture stimulation, as reflected in current United States Environmental Protection Agency (U.S. EPA) and Australian Government guidelines, are a justifiable basis upon which to estimate greenhouse gas (GHG) emissions from unconventional gas fields in Western Australia, noting the variation in estimates reported in the scientific literature.

The literature on 'super-emitters' of leaked methane offers both caution and opportunity for minimising GHG emissions from gas fields of any kind. History has shown such leaks can be of a very high order. In 2015, the blowout of a gas well connected to an underground storage facility in California resulted in a release of 97,100 tonnes of methane to the atmosphere, doubling the emissions of methane from the entire Los Angeles Basin for a period of more than three months (Conley et al. 2016). Robertson et al.(Robertson et al. 2017) found that 83 percent of methane leakage emissions in the Uintah Basin was from only 20 percent of well pads. Based on measured methane emissions for wells in the Barnett Shale, Rella et al. (Rella et al. 2015) reported that 30 percent of wells had no detectable methane emissions, and that six percent of wells accounted for 50 percent of emissions. Across a large, multi-basin sample Zavala-Araiza et al. (Zavala-Araiza et al. 2015) found that in general, 15 percent of well sites accounted for about 58 to 80 percent of total emissions. Detailed 'bottom-up' measurements of methane fluxes from a total of 67 CSG wells in New South Wales and Queensland by CSIRO (Day et al. 2014, 2017) indicated measured methane emissions from 88 percent of the wells produced less than 4.3 kilograms per day (kg/d) (equivalent to that produced by about 30 cows), with one percent of wells producing up to 63 kg/d. If this result holds in gas fields developed with hydraulic fracture stimulation in Western Australia, then there would clearly be a benefit from regularised monitoring, screening and intervention (repair) to minimise methane emissions. The Queensland Government's Code of Practice requires at least five-yearly inspection of gas wells for leaks, although some companies have much more frequent inspections.

Finding 35: Baseline monitoring of methane emissions from onshore gas infrastructure associated with hydraulic fracture stimulation, at appropriate scales, is essential for accounting and reporting on actual greenhouse gas (GHG) emissions. Following development, ongoing monitoring, screening and intervention (repair) to minimise emissions from leaking gas infrastructure would mitigate the risk to the climate and to public health.

Recommendation 10: Baseline measurements of atmospheric levels of greenhouse gas (GHG) should be acquired prior to the development of onshore wells employing hydraulic fracture stimulation, and should be the responsibility of the regulator. Atmospheric concentrations and process leakage of methane should subsequently be monitored over every well's entire life cycle, and detected leaks must be fixed by the operator, with GHG emission monitoring results publicly reported. These requirements should be part of an enforceable Code of Practice.

This is commensurate with the Findings (6) and (51) and Recommendations (2), (12) and (34) of the 2015 Report of the Standing Committee on Environment and Public Affairs of the Western Australian Parliament (the 2015 Western Australia Standing Committee Report) regarding transparency.

Subsequent work by CSIRO (Day et al. 2016) examined a much wider variety of methane emissions from sources at sites across New South Wales (including CSG gas infrastructure other than wellheads such as pipelines and compressors) and reported no emissions from the plugged, abandoned and suspended wells in the Casino gas field; very low emissions from production wells in the Camden and Gloucester gas fields; and a few instances of slightly elevated methane concentrations above background levels detected in the immediate vicinity of some well pads. The maximum emission rate detected from these wells was 0.03 grams of methane per minute (g CH4/min), while most of those examined showed no emissions, with some areas within the Camden gas field with significantly elevated methane concentrations compared to background levels on some sampling occasions. Two of the six wells examined in the Narrabri field showed emissions that appeared to be mainly related to the operation of gas-powered pneumatic equipment of the pads. The emission rates measured at these two wells ranged between 2.9 and 22.7 g CH4/min (4.2 and 32.7 kg/day), which were within the range of emissions measured previously on Australian CSG wells. Other work by CSIRO on CSG methane emissions (Day et al. 2017) found that the rates of methane emitted during well completions and workovers were less than half of the estimates for these emissions reported for United States shale operations by (O'Sullivan & Paltsev 2012).

Concerns have been expressed that 'fugitive' emissions may also arise from pathways to the surface created by the hydraulic fracturing itself, apart from those directly associated with the well. However, there is broad agreement that the fracturing of the rock itself is unlikely to contribute to significant vertical migration of gases to the atmosphere (Dusseault & Jackson 2014). Rather, the risk pathway is poorly-designed or poorly-constructed wells. For example, Osborn et al. (Osborn et al. 2011) found evidence of methane in a regional groundwater subject to gas well drilling and hydraulic fracturing. These findings were cited in the New York State Department of Health study (New York State Department of Health 2014) (New York State Department of Health 2014) that led to a ban on hydraulic fracture stimulation in that state. Schon (Schon 2011) subsequently argued that the interpretations by the New York State Department of Health lacked a baseline, did not recognise natural migration rates of methane and did not find any evidence of communication of fracturing fluids between the deep shales and shallow groundwater. Siegel et al (Siegel et al. 2015) re-examined the hypothesis in this same region with a much larger dataset (hundreds of times larger than previous studies) and found no relationship between methane levels in groundwater and its proximity to gas wells, most of which (92 percent) were hydraulically stimulated. None of these authors argued that hydraulic fracture stimulation per se

contributed to methane in groundwater; the arguments revolved around whether it was there naturally or as a result of leaking wells.

Boothroyd et al. (Boothroyd et al. 2017) considered the potential for methane to leak to the atmosphere along faults in hydrocarbon-bearing basins and concluded that there was some measured leakage from some faults, and shale basins had no more potential for this than non-shale hydrocarbon basins across the United Kingdom. Across all faults in the study, the mean methane leakage rate was 11.5 ± 6.3 t/km/y. The implication of these findings is there are natural sources of methane emissions and that faults can be (but are not always) a conduit to the atmosphere. They did not address the question of whether hydraulic fracture stimulation would increase this rate, noting that there is no evidence of overpressure in onshore United Kingdom basins, and thus the likelihood of gas migration along permeable pathways is reduced.

Finding 36: There is little risk of methane migration to surface aquifers or the atmosphere resulting from activities associated with hydraulic fracture stimulation, apart from those associated with pathways provided by the well itself (equivalent to the broader issue of containment of all fluids within the well).

10.6 Potential GHG emissions from decommissioned wells

There is a clear potential for oil and gas wells to leak methane to the atmosphere during the operational phase of the well. This risk continues beyond the time when the well is plugged and abandoned (decommissioned). Abandoned oil and gas wells represent potential conduits between hydrocarbon bearing formations and the atmosphere. If these conduits were not properly sealed upon abandonment, then leakage from formations could be occurring or develop over time.

Brandt et al. (Brandt et al. 2014) estimated that there are three million plugged and abandoned oil and gas wells in the United States, but could find no empirical data to characterise leakage rates. Recognising that little or no data existed on methane emissions from decommissioned wells, Kang et al. (Kang et al. 2014) measured methane at 19 abandoned wells (both plugged and unplugged) in Pennsylvania. They found little difference in methane rates between plugged and unplugged wells and a mean flux of methane of 0.27 kg/d but dominated by a few high emitters. Scaling these numbers as representative of all abandoned wells, this implied a contribution of four to seven percent of the total methane emissions for Pennsylvania, or an additional 0.1 to 0.2 percent of total 2011 gas withdrawals not included in U.S. EPA emission factors. The authors noted there was no regulatory requirement in the United States to monitor or account for methane emissions from abandoned wells. By contrast, Townsend-Small et al. (Townsend-Small et al. 2016) measured methane fluxes from 138 abandoned oil and gas wells and found that nine wells emitted

methane and eight of those were not plugged, concluding abandoned wells made up less than one percent of regional methane emissions.

Boothroyd et al. (Boothroyd et al. 2016) measured methane fluxes from 103 properly decommissioned (in-line with current best practice recommendations in the United Kingdom) gas wells in the United Kingdom, across four onshore basins with well ages up to more than eighty years old, with control site measurements for comparison. One well was obviously leaking gas at the surface. For 31 of the wells, methane measurements were significantly higher than ambient levels (maximum 147 percent of ambient). Thirty-nine wells had methane concentrations significantly lower than ambient levels (with the lowest 63 percent ambient). There was no correlation of methane levels with the age of the well. These authors noted the observation by Davies et al. (Davies et al. 2014) that some onshore wells in the United Kingdom were obviously not appropriately decommissioned. Davies et al. (Davies et al. 2014) noted that between 50 and 100 of the 2,152 onshore United Kingdom petroleum wells drilled between 1902 and 2013 were by companies that no longer exist and were not bought or merged by exiting companies ('orphaned'). Where the company that drilled the well no longer exists, or has been taken over or merged, (53 percent of wells in the United Kingdom), liability for any well integrity failures is unclear and it is possible that liabilities did not transfer to the new entities.

The Western Australian Government (Department of Mines and Petroleum 2015a) review of 1,035 wells in Western Australia that had not yet been decommissioned, found 122 (about 12 percent) to have had some form of failure (see **Section 6** of this Report for more detail). The review concluded that failure rates increased with age, noting the oldest wells in the study were 60 years old. Upon decommissioning, plugged and abandoned wells must be expected to maintain containment for thousands of years and there is no data available in Western Australia on the long-term performance of decommissioned wells. Western Australia has no research or monitoring program aimed at ensuring the long-term containment of decommissioned oil and gas wells.

Van der Kuip et al. (van der Kuip et al. 2011) considered that the diffusion of carbon dioxide in the cement matrix of plugged and abandoned wells forms the rate-controlling step in cement degradation, and the extrapolation of those results across a large range of regulatory requirements for the plugging of wells, and concluded that despite large variations in technical requirements for plug length (15 -100 m), they were all appropriate to the safe storage of carbon dioxide for thousands of years. Therefore, the risks of leakage due to poor mechanical integrity and placement of the plugs is of much greater significance. Reinforcing the importance of effective plugging (and testing) of wells is an observation by Day et al. (Day et al. 2015) of a gas well of unknown origin near Chinchilla, Queensland that was leaking substantial quantities of methane and subsequently plugged, but inadequately for preventing methane from continuing to diffuse around the well. New South Wales' Code of Practice for CSG wells requires abandoned wells to be sealed with concrete to the full depth of the hole.

Numerous standards, tools and technologies (now) exist for cement evaluating the effective cementing of wells.

Finding 37: It is essential that well abandonment includes sealing designed for long-term containment and that such sealing is tested for effectiveness and remedied if not effective. There is insufficient monitoring of the long-term methane containment of decommissioned oil and gas wells in Western Australia.

Recommendation 11: The Western Australian Government should implement an emissions monitoring program of decommissioned wells with respect to well integrity in general and methane emissions specifically, complemented by a research program to give further confidence to their long-term containment.

Why focus on methane emissions?

Methane is the major constituent of produced natural gas; it is effectively the target resource associated with onshore gas development whether hydraulic fracture stimulation is used or not. It is also a significant greenhouse gas, with its own unique natural cycle and residence time in the atmosphere. About 60 percent of total global methane emissions are anthropogenic and the rest is from natural sources (Saunois et al. 2016). Based on 2010 data, 16 percent of annual global anthropogenic emissions of GHG is in the form of methane, with 76 percent as carbon dioxide from fossil fuels and land uses (Edenhofer et al. 2014) More recent work by Aydin et al. (Aydin et al. 2011) concluded that the fossil fuel source of methane started to decline in the 1980s with an associated slowdown in the global growth rate of atmospheric methane which is now about 10 Mt/y (Saunois et al. 2016) with 2016 atmospheric concentrations at 257 percent of pre-industrial levels (World Meteorological Organization (WMO) 2017) Oliver et al. (Olivier, Schure & Peters 2017) noted that global methane emissions did not materially change between 2015 and 2016, and that the global cattle industry accounted for 23 percent of global emissions, with fossil fuel production and distribution accounting for 25 percent.

If methane is only a fraction of global GHG emissions, why is it such a focus for concern? This is because the potential for different GHGs to warm the atmosphere varies with both their ability to absorb energy and how long they persist in the air. To consider the warming equivalency of (on a mass basis) different GHGs, and to facilitate global climate modelling, the Global Warming Potential (GWP)(Solomon et al. 2007) was developed, and reflects both energy absorption and persistence relative to carbon dioxide. The warming impact of all GHGs together is then expressed as if were all carbon dioxide (CO2), expressed as 'CO2 equivalents' (CO2e). Thus, by definition, the GWP of carbon dioxide is one. The lifetime of

methane in the atmosphere is much shorter than the residence time for carbon dioxide and depends on complex feedbacks, but in general an input of methane to the atmosphere will have most of its warming effect over the first 10 years, and after 35 years more than 90 percent will have been oxidized to carbon dioxide. So emissions that were originally methane will still affect the atmosphere at a lower level over the hundreds of year lifetime of the carbon dioxide molecule (Jardine et al. 2003). Because methane (on a mass basis) has much higher energy absorption than carbon dioxide, and the net effect is a methane CO2e of 28-36 over 100 years (Edenhofer et al. 2014).

There is no agreed standard as to the GWP to apply to methane emissions. The Australian National Greenhouse Accounts Factors use a 100-year GWP of 25 (Department of the Environment and Energy 2017n), following a United Nations Framework Convention on Climate Change recommendation based on the Intergovernmental Panel on Climate Change Fourth Assessment Report (Intergovernmental Panel on Climate Change 2007). The IPCC Fifth Assessment Report(Edenhofer et al. 2014) specifies a 100-year GWP of 28-36. The IPCC Fifth Assessment Report (Intergovernmental Panel on Climate Change 2014) suggests that over a shorter period (20 years) a GWP of 84-86 is appropriate. Emissions calculations in this Report are presented with methane factors for 100-years (GWP = 25, 36) and 20 years (GWP = 87).

In short, per unit emitted, methane is a more powerful GHG than carbon dioxide and is the largest contributor to non-carbon dioxide GHG emissions. That is why methane emissions from gas developments is a focus of concern.

For example, according to the National Oceanic and Atmospheric Administration (NOAA), global carbon dioxide levels reached 405 ppm by late 2017, but the warming impact of all GHGs expressed as CO2e was calculated at 487 ppm by 2015, reflecting the effect of other GHGs, particularly methane. Based on estimates of global 'fugitive' emissions from fossil fuels (Saunois et al. 2016), an attribution of a third of these emissions to natural gas production, and a methane GWP of 36, the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory estimated methane's climate effect as 2.3 percent of global annual added greenhouse effect over the decade 2003-2012, concluding annual 'fugitive' emissions from global natural gas production is about 0.2 percent of the anthropogenic GHG warming effect of carbon dioxide and that recent 'fugitive' emissions from natural gas production is a small contribution to the current anthropogenic greenhouse effect.

"With respect to fugitive emissions from either conventional or unconventional natural gas extraction, leaks of methane – itself a potent greenhouse gas – add to community concerns over climate change. Ongoing public access to gas industry monitoring information could be used to increase transparency" - submission from Alan Finkel, Chief Scientist of Australia

10.7 Western Australian unconventional gas field development scenarios

More so than for any other potential environmental impact considered by this Inquiry, the climate risks posed by developing Western Australia's gas resources requiring hydraulic fracture stimulation scales with the size of the gas fields and how quickly they would be developed. Submissions to this Inquiry have made widely-varying assumptions in this regard.

At one extreme are emissions estimates based on a scenario of full exploitation of the entire onshore gas reserves of the State (*or the Canning Basin*). In some cases, such as the analysis by Hare et al. (Hare et al. 2018), the scenario requires a pipeline supplying half of Australia's needs. In another case (Bista, Jennings & Anda 2017), the full gas reserves of Western Australia are developed over 20 years. Beyond any debate over the emissions rates used in these scenarios, such scenarios are both implausible and highly misleading in any serious consideration of the likely risks posed by onshore gas development based on hydraulic fracture stimulation in Western Australia. Similarly, the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory considered emission estimates provided by the Australia Institute (Ogge & Campbell 2018) based on the full exploitation of the prospective resource, as 'unreliable' and 'highly inflated'.

The development scenarios considered by this Inquiry, as detailed in **Section 5.7** (Sedimentary Basins with Unconventional Oil and Gas Potential in Western Australia) of this Report, are based on:

- The historical rate of development of onshore wells;
- Plans for unconventional gas fields submitted to this Inquiry (all of which targeting the domestic Western Australian gas market); and
- The projected Western Australian domestic gas demand and the current and forecast capacities of existing suppliers.

As such, a new unconventional gas field in Western Australia, may produce as little as 100 TJ/d over twenty years. At the other extreme, combined production from gas fields may approach 500 – 1,000 TJ/d. The Inquiry considered a 1,100 TJ/d scenario in our GHG risk assessment as it meets the forecast Western Australian domestic demand out to at least 2022, even though it is not likely that onshore fields based on hydraulic fracture stimulation technologies would entirely supplant domestic supplies from conventional sources in the coming decades. The 1,100 TJ/d scenario equates to 400 PJ/y and is thus similar the 365 PJ/y scenario of gas production for the domestic market considered by the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory.

Finding 38: The risks posed by greenhouse gas (GHG) emissions associated with an onshore gas industry in Western Australia scale directly with the realised size of that industry. The future scale of the onshore unconventional gas industry (should the moratorium be lifted) cannot be forecast with certainty, but over the next decade or two it is likely to be limited, at the extreme, by the size of the domestic Western Australian gas market.

This accords with Finding (36) of the 2015 Western Australian Standing Committee Report regarding cumulative impacts.

"…the Inquiry should be aware that Geoscience Australia has described very large volumes of prospective petroleum liquids (shale oil) in Western Australia… The Inquiry should therefore report on the health, environment, and other risks associated with producing oil from unconventional reservoirs… for liquids-rich shales, the value of the liquids can greatly exceed the value of the gas. Indeed, gas can have zero value if markets are not found for the gas nor infrastructure put in place to collect, process, and transport the gas" - submission from Tim Forcey, Energy Advisor to the University of Melbourne

Finder Shale's submission to this Inquiry indicated potential to develop an oil-prospective formation far from existing gas transmission infrastructure, and the possibility that the early product to market from such a development might only be oil (with any produced gas vented or more likely flared). The Panel considered this is a distinctive scenario that could potentially have large emissions associated with it up to the time that the producer is able to also bring the gas to market. There is insufficient information to quantify the emissions from such a scenario, but clearly should such a scenario be proposed it should invite bespoke analysis and consideration of mitigation and offsets.

Finding 39: There is a distinctive greenhouse gas (GHG) risk associated with a tight oil development with no (initial) market for produced gas. Such a development bears unique and specific analysis of the resulting emissions, their mitigation and acceptability.

In constructing these scenarios, we acknowledge potential concerns that this scale of development might only be the start of larger fields in the longer term. However, these scenarios are realistic for the coming decades, and these calculations scale linearly if larger or smaller scenarios need to be considered. Further, it is highly likely that both markets and technologies will change over that time, as well as our understanding of the environmental performance (emissions) of developments based on hydraulic fracture stimulation.

10.8 GHG emissions for Western Australian unconventional gas field development scenarios

GHG emissions were calculated for development scenarios based on factors employed by the Australian Government (Department of the Environment and Energy 2017n) for upstream and lifecycle GHG emissions from a new shale gas field, assuming 100 percent domestic consumption of the gas. These emissions factors employ the official 100-year GWP (25). For completeness, the Panel also present emissions estimates based on a 100-year GWP of 36, and the 20-year GWP (87).

To place potential GHG emissions from gas field developments involving hydraulic fracture stimulation into context, the Panel compared them to national (Australian) and global emissions.

The Panel notes that these estimates do not necessarily translate to increases in Australia's emissions by these amounts, if this unconventional gas is only supplanting gas from conventional sources and domestic consumption does not change because of an increased alternative supply. Such modelling is beyond the scope of this Inquiry. One could well argue that the only increase in emissions in this case would be the increased emissions of producing unconventional versus conventional gas, and any differences in reservoir carbon dioxide across fields. In that regard, Stephenson et al. (Stephenson, Valle & Riera-Palou 2011) estimated that shale gas typically has an emissions intensity of 1.8 to 2.4 percent higher than conventional gas over the life-cycle of gas power generation, and even with extreme emissions assumptions, would be no more than 15 percent higher if flaring or reduced emissions recovery is employed. Their modelling study predicted that the development and completion of a shale gas well results in production emissions 1.2 to 1.5 grams of carbon dioxide equivalent per megajoule (g CO_2e/MJ) higher than conventional gas. Burnham et al. (Burnham et al. 2012) found the range of emissions estimates for shale gas and conventional gas lifecycle overlapped, and thus there was some statistical uncertainty in their finding that shale gas emissions were lower when conventional gas required liquid unloading. Weber and Calvin (Weber & Clavin 2012) found similar results, with the range in upstream emissions from conventional and unconventional sources largely overlapping and noting that about three-quarters of emissions are downstream and identical. Laurenzi and Jersey (Laurenzi & Jersey 2013) estimated that only 1.2 percent of lifecycle GHG emissions of gas from the Marcellus Shale was attributable to hydraulic fracture stimulation. A review of seven published analyses of lifecycle GHG emission comparisons, between shale gas and conventional gas (ICF Consulting Canada 2012), noted that all but that of Howarth et al. (Howarth, Santoro & Ingraffea 2011) who used different assumptions including a 20-year GWP, found only small (1.8 to 11 percent) increases in shale gas lifecycle emissions over conventional gas.

Finding 40: On balance, it is reasonable to expect some additional upstream greenhouse gas (GHG) emissions associated with the production of oil and gas using hydraulic fracture stimulation of shale or tight sands, when compared to upstream conventional oil and gas production. However, these additional emissions are typically smaller than differences in emissions arising from reservoir carbon dioxide, processing and transport between a given facility producing and delivering unconventional oil and gas and one doing so from conventionally developed resources.

Table 10.1: Upstream and lifecycle emissions for unconventional gas scenarios

Gas Production TJ/day	Additional GHG emissions over conventional development Mt CO2e/y[3]	Proportion of Australia's emissions for 2016[4] %	Upstream GHG emissions from unconventional development Mt CO2e/y	Proportion of Australia's emissions for 2016 %	Life Cycle GHG emissions[5][6] Mt CO2e/y	Proportion of Australia's emissions for 2016 %
	Based on a 100-year GWP (= 25)					
100	0.04	0.007	0.4	0.07	2.5	0.5
1100	0.4	0.07	4.4	0.8	24.7	4.5
	Based on a 100-year GWP (= 36)					
100	0.06	0.01	0.6	0.1	2.7	0.5
1100	0.6	0.1	6.3	1.1	26.7	4.8
	Based on a 20-year GWP (= 87)					
100	0.1	0.02	1.08	0.2	3.2	0.6
1100	1.3	0.2	11.88	2.1	31.6	5.7

[3] Based on increased upstream emissions from shale compared to conventional sources of 1.5 g CO_2e/MJ on a 100-year GWP (Stephenson, Valle & Riera-Palou 2011), also scaled to 20-year GWP, and no differences in reservoir CO_2 content.
[4] Australia's emissions for 2016-17 were 550.2 Mt CO_2e/y (Department of the Environment and Energy 2017n).
[5] Downstream emissions from combustion of gas assumed to be 57 g CO_2e/MJ (Steen 2001).
[6] No consideration for decreased emissions if gas substitutes for less efficient generation.

Full lifecycle emissions from a scenario of meeting all Western Australia's domestic gas demand (1,100 TJ/day), are about 0.05 to 0.06 percent of the world's 2016 GHG emissions (Olivier, Schure & Peters 2017). Again, this is under the assumption it does not displace any other fossil fuel usage.

The Inquiry recognises there are studies that argue for an upstream emissions factor two to three times greater than the U.S. EPA (and equivalent Australian Government) factors, for example, as described by Howarth (Howarth 2015). At the other extreme, Allen et al. (Allen & Torres 2013) reported an emission factor as low as 0.42 percent of total gas production. Adoption of reduced emissions completions technology is estimated to reduce the above emission factor by 23 percent (Skone et al. 2016).

The Inquiry found inconsistent and conflicting scientific literature regarding the net climate benefits of substituting unconventional gas for other fossil fuels. While beyond the Inquiry's scope to determine, the Panel suggests that given the variability in the literature as well as the real variation among production facilities and oil and gas fields, that such a determination can only be credible when based on actual local measurements of the performance of 'fugitive' emissions controls from a particular facility, and the facility-specific combustion emissions based on other fuels. This is consistent with the findings of McJeon et al. (McJeon et al. 2014).

Finding 41: Where regulations or approvals specify greenhouse gas (GHG) emission outcomes, the regulator must have and demonstrate sufficient capacity, competency, diligence and transparency to ensure that industry is achieving those outcomes. This is likely to require a combination of top-down and bottom-up monitoring, and thus technical partnership with agencies or institutions with advanced capabilities.

10.9 'Green completions' to reduce GHG emissions from stimulated gas wells

Historically, the gas component (mostly methane) of flowback from a hydraulically stimulated well was vented directly to the atmosphere, or at best flared for afety or to reduce its greenhouse warming potential to that of carbon dioxide. In 2012, the U.S. EPA introduced new regulations to minimise Volatile Organic Compound (VOC) emissions from the oil and gas industry, requiring the petroleum industry to reduce emissions from hydraulic fracture stimulation of wells by using reduced emissions completions (RECs) as well as other requirements to monitor and fix leaks. In May 2016, these regulations were updated with new performance standards to further reduce methane and other emissions across the production chain. This included the phasing in of 'green completion' to capture emissions from hydraulically stimulated wells, with a side benefit of this natural gas being brought to market. Skone et al. (Skone et al. 2016) modelled a 23 percent improvement to overall GHG emissions associated with shale gas development assuming implementation of these new performance standards. Day et al. (Day et al. 2017) reported measurements from a single

CSG well workover, which vented methane over the entire operation at a rate of 875 kg/h. Previously, O'Sullivan and Paltsev (O'Sullivan & Paltsev 2012) reported that by eliminating direct venting or flaring of flowback methane through capture technologies reduced the 'fugitive' emissions per well by 90 percent and 22 percent, respectively, reducing 'fugitive' emissions to between 0.39 percent to 0.99 percent of gas production.

Omara et al. (Omara et al. 2016) found that green completions on unconventional gas wells substantially reduced methane emissions. Allen et al. (Allen & Torres 2013) found that the lowest methane emissions per well (3 kg/hr) were from a well using the capture and separation technologies of green completions, as compared to measurements of more than 50 kg/hr from wells that directly flared or vented gas.

In their analysis and comparison of life-cycle emissions from a variety of electricity sources, Hardisty et al. (Hardisty, Clark & Hynes 2012) concluded that there were significant gains, and advantages, to investing in the minimisation of 'fugitive' methane from unconventional gas sources. The U.S. EPA (U.S. Environmental Protection Agency 2011) estimated that the capital costs of reduced emissions completion equipment, as required by regulation, would be recovered on the basis of the value of the captured gas within six months of use, under a program of 25 completions per year, at gas prices equivalent to those as of March 2018. ACOLA (Cook et al. 2013) concluded that the use of green completions, including the adoption of emission capture and/or flaring rather than venting, to be feasible to implement in Australia.

Calculations of the net economic benefits of reduced emissions completions by O'Sullivan and Paltsev (O'Sullivan & Paltsev 2012) (recognising that captured methane has value) indicated that even doubling the costs estimates of implementation would still have a net positive revenue for more than 80 percent of wells in the Barnett Shale gas fields. In December 2017, the United States Department of the Interior rescinded regulations aimed at reducing the environmental impact of hydraulic fracture stimulation for developing unconventional gas, including requirements for reduced emissions completions, stating it would save about $US 9,690 per well. At the time of writing this Report, an injunction maintaining enforcement of the regulation was in place ahead of litigation. Yacovitch et al. (Yacovitch et al. 2015) concluded on the basis of the distribution of 'fugitive' emissions across a range of sampled sites, that it was unlikely that the value of the lost product would be sufficient incentive for a producer to self-regulate with REC methane capture.

In Western Australia, Buru Energy implemented REC technologies for well completion and workovers (though not to the extent of full methane capture) as described in its Environmental Plan for Yulleroo:

"This is achieved in process engineering steps in which the flowback mixture passes through a sand trap, a three-phase separator removes natural gas liquids and water from the gas, which is then flared. Gas liquids will be sent to an onsite bunded condensate storage tank for subsequent shipment to a refinery. Flowback water is subsequently passed to the retention pond. Venting of gas to the atmosphere is to be avoided and when this is not possible for operational or safety reasons, it is to be kept to a minimum".

Under a tight oil scenario, where for a prolonged period gas would otherwise be vented or flared, REC technologies that incorporate gas collection into Compressed Natural Gas (CNG) for transport to market should be considered. Emerging and novel technologies may be, or may eventually become, feasible where other alternatives are not practical, such as small scale gas-to-liquids processing, for example as described by Glebova (Glebova 2013).

Western Australia has no regulatory requirement for reduced emissions (green) completions.

Finding 42: There is a global move toward reducing venting and flaring of gas across the petroleum sector. Reduced emissions completions are an established set of technologies that minimise greenhouse gas (GHG) and other harmful emissions and waste of product, and are both practical and environmentally responsible at the production phase of an oil and gas field.

Recommendation 12: Apart from the early exploratory phase of development, reduced emissions (green) completions should be a requirement, regulated and monitored as per the United States Environmental Protection Agency (U.S. EPA) New Source Performance Standards 2016.

10.10 Risk assessment

The Inquiry assessed the risks posed by hydraulic fracture stimulation in the development of oil and gas against the following environmental objective:

> GHG emissions from onshore oil and gas fields developed with hydraulic fracture stimulation must be minimised. The contribution to Australian anthropogenic upstream GHG emissions from onshore fields in Western Australia must be 0.5 percent or less of 2016 levels.

Under the regulatory environment preceding the moratorium:

- GHG emissions from the exploration phase of unconventional gas exploration present a negligible risk to the environment, even without RECs.
- A 100 TJ/day gas field (about 10 percent of Western Australia's domestic gas demand) developed with hydraulic fracture stimulation and modern techniques would pose a negligible to low risk to meeting Australia's international GHG commitments, or to the world's climate more generally, assuming the emission factors currently adopted by the Australian DoEE and U.S. EPA apply to a future industry in Western Australia.
    - On the basis of direct substitution for domestic supplies of conventional gas to the domestic Western Australian market, the risk is negligible.
    - On the basis of produced gas being completely additive to Australia's fossil fuel consumption, the risk is low. On this basis and using other (higher) estimates of emission factors from the scientific literature, these emissions would pose a moderate risk.
- An 1,100 TJ/day industry (Western Australia's domestic gas demand) developed with hydraulic fracture stimulation and modern techniques would pose a low to moderate risk to meeting Australia's international GHG commitments (or to the world's climate more generally) assuming the emission factors currently adopted by the DoEE and U.S. EPA apply to a future industry in Western Australia.
    - On the basis of direct substitution for domestic supplies of conventional gas to the domestic Western Australian market, the risk is low.
    - On the basis of produced gas being completely additive to Australia's fossil fuel consumption, the risk is moderate. On this basis and using other (higher) estimates of emission factors from the scientific literature, or with a materially larger industry, these emissions would pose a serious risk.
- In addition to the above, if decommissioned wells of future gas fields do not provide long-term containment of methane, the GHG risks posed by this scale of development are potentially significant and additional, and there is limited Western

Australian data directly informing the estimated magnitude of such emissions. This conclusion is at odds with Finding (40) of the 2015 Western Australian Standing Committee Report, which concluded that Western Australia has a robust system for monitoring abandoned wells.

- Estimates of GHG emissions based on fully developing all the potential shale and tight gas resources of Western Australia over a matter of decades (or ever) are neither plausible nor informative. In this regard, this Inquiry is in accord with Finding (35) of the 2015 Western Australian Standing Committee Report. However, such exaggerations do highlight the need for the State to forecast, plan, evaluate and approve (or reject) gas field developments of specified size and location, rather than leaving such envisioning to the community's imaginations.

If the above recommendations in this Section were fully implemented, then the residual risks to meeting the environmental objective for GHGs is reduced as follows:

- A 100 TJ/day gas field (about 10 percent of Western Australia's domestic gas demand) developed with hydraulic fracture stimulation and modern techniques would pose a negligible to low risk to meeting Australia's international GHG commitments, or to the world's climate more generally, under even less conservative scientific emission estimates.
- 1000 TJ/day from one or more gas fields (about 90 percent of Western Australia's domestic gas demand) developed with hydraulic fracture stimulation and modern techniques would pose a low to moderate risk.

The Panel notes that even with the implementation of the above recommendations, there is a residual GHG emission and consequent impact on climate. This impact would be further reduced if some or all of these emissions were offset, noting existing precedents for such requirements on (some) conventional gas projects in Western Australia.

Recommendation 13: Consideration should be given to offsetting the additional greenhouse gas (GHG) emissions from any onshore unconventional oil and gas production associated with hydraulic fracture stimulation. As a minimum, this should extend to the increase in 'fugitive' emissions over conventional upstream oil and gas production, plus reservoir carbon dioxide discharged to the atmosphere.

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11

Risk assessment: Public health

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11 Risk assessment: Public health

11.1 Introduction

Public health has been identified as an area of key concern in numerous submissions to this Inquiry. In particular, many submissions express sentiments consistent with the following:

> *"There is a rapid growing body of research that demonstrates that unconventional gas can have serious consequences for health and animal health"* - submission from Dr Bryan Whan

Many submissions also include reference to and provide summaries and extracts from the Concerned Health Professionals of New York and Physicians for Social Responsibility 'Compendium of Scientific, Medical, and Media Findings Demonstrating Risks and Harms of Fracking (Unconventional Gas and Oil Extraction' (Concerned Health Professionals of New York 2018) quoting their conclusions, including:

> "Findings to date from scientific, medical, and journalistic investigations combine to demonstrate that fracking poses significant threats to air, water, health, public safety, climate stability, seismic stability, community cohesion, and long-term economic vitality. Emerging data from a rapidly expanding body of evidence continue to reveal a plethora of recurring problems and harms that cannot be sufficiently averted through regulatory frameworks. There is no evidence that fracking can operate without threatening public health directly or without imperilling climate stability upon which public health depends".

In the Western Australian context, numerous submissions also quote conclusions from the work conducted by Dr Melissa Haswell (Haswell 2017), including:

> "The literature review identified increasing evidence of multiple potential hazards and exposure pathways posing credible risks to human health, via air emissions, water contamination, psychosocial stress and climate change. Increasing numbers of published studies report associations between negative health and developmental outcomes and nearness of residence to and/or intensity of unconventional gas operations. These significant risks, combined with substantial gaps in understanding, prevent confirmation of the safety of the industry to health and the environment".

It was important that the available science relevant to understanding potential impacts of unconventional gas activities on the health of the community be evaluated and considered by the Panel.

The purpose of investigating links between any environmental hazards and health impacts is to determine if a health effect can be attributed causally from an exposure to a hazard. For a health effect to be attributable to a specific hazard, a number of basic conditions must be met:

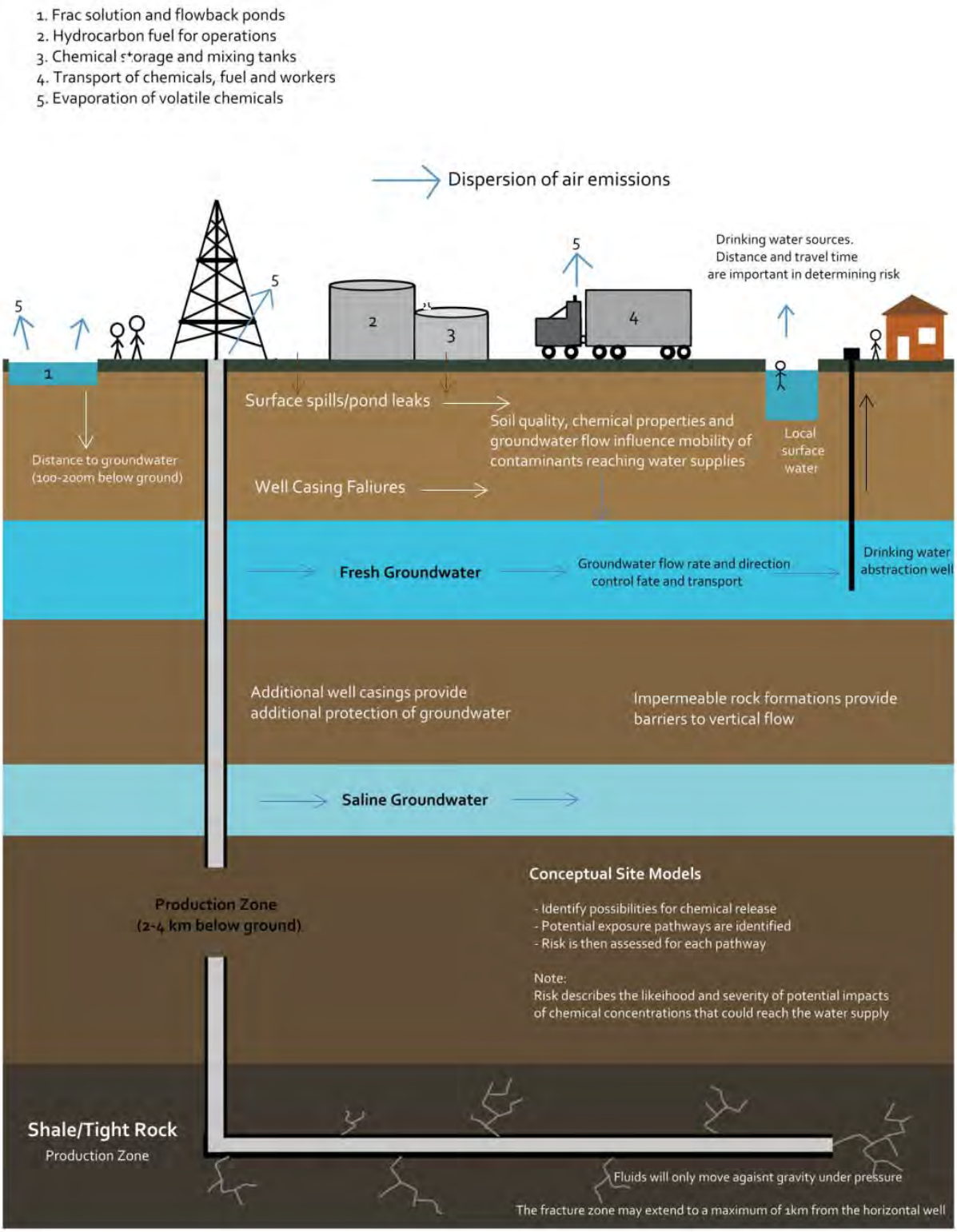
- There must be evidence of a hazard;
- The hazard has to be present in a sufficient amount (level or concentration) to be able to cause an adverse health effect; and
- Exposure to the hazard has to pre-date development of any associated health effect.
- Hazards are inherent in the activities undertaken and the chemicals that may be present in unconventional oil and gas developments. Particular concern has been raised in many submissions in relation to the hazards posed by the chemicals used in hydraulic fracture stimulation. These have been evaluated separately in **Section 9.4.2** (Water – Chemicals used in hydraulic fracture stimulation).

In relation to exposure, this depends on the characteristics of the chemical but also the media where the chemicals may be present, namely air, water or soil.

The following figure provides a generalised conceptual model of shale gas operations, coupled with the potential exposures that may need to be considered when evaluating public health risks.

Figure 11.1: Conceptual model – Potential pathways of exposure from shale gas activities, that may be relevant to assessing impacts to public health

Source: Western Australian Department of Health, modified by Inquiry Panel



To address these aspects, health professionals can use the following approaches:

- Obtain robust data on the hazard that may be present where exposure occurs, namely data on the concentrations that are present in air, water or soil, at the point where the public is exposed. Then, compare these exposure concentrations with guidelines that are based on the protection of human health, for all members of the public. This is a more traditional type of risk assessment and can provide a clear determination of whether exposures have the potential to be of concern to health, where the exposure concentrations exceed a health-based guideline.
- Conduct public health or epidemiological studies to identify if there is a link or association between a hazard and changes in health data. When conducting these studies, it is important to note that epidemiological studies require careful review to determine the quality of the study and reliability of the outcomes. In addition, there is an important difference between an association and causation that needs to be considered.

The following presents a review of the information available that is relevant to these types of health assessments.

The World Health Organisation (WHO 2016) defines health as:

> "a (dynamic) state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity".

Hence, the assessment of health should consider both the traditional medical definition that focuses on illness and disease as well as the broader social definition that includes the general health and wellbeing of a population, which is more specifically evaluated as mental health and wellbeing. Assessment of issues related to community health and impacts on mental health and wellbeing from hydraulic fracture stimulation in unconventional oil and gas activities are addressed in **Section 12** (Social surroundings).

11.2 Key issues raised

Many people commented that hydraulic fracture stimulation and its associated activities could have an adverse impact on human and animal health, specifically from:

- Exposure to potentially dangerous chemicals via soil and water contamination, especially water used for drinking, washing, stock watering and food production. While most chemicals used in hydraulic fracture stimulation have been assessed by the chemical safety regulator, the toxicity of many contaminants are not satisfactorily understood;
- Exposure to noxious gases and particles, including methane, ozone, hydrocarbons and Volatile Organic Compounds (VOC), and radon released from venting, flaring, use of drilling engines and compressors, and waste water evaporation;

- The risk of severe stress and mental health challenges for land owners, traditional owners and people living in adjacent communities, due to fears for their future health and their livelihoods; and
- The risks to public safety from transport accidents, induced earthquakes, fires and explosions.

11.3 Assessment of potential health effects based on data

11.3.1 General

The assessment of potential risks to human health associated with environmental hazards/contamination is commonly based on measurements of chemicals or hazards in different environmental media, where the public may be exposed via inhalation, ingestion or dermal contact. Such assessments involve the comparison of the concentrations reported with health-based guidelines, to determine if there is the potential for the hazard to be of concern and require management or mitigation. This approach, where the data is appropriately collected, provides a direct assessment of exposure.

With regard to hydraulic fracture stimulation, the issues most commonly evaluated include water quality and air quality, with some assessments also addressing other hazards such as noise, light, odours and traffic accidents.

Further discussion on the environmental pathways of exposure by which water quality may be impacted are discussed in more detail in **Section 9** (Water).

Limited data is available for hydraulic fracture stimulation and associated unconventional gas activities in Western Australia. This review has considered the data that is available, data which has been provided in submissions, as well as published reviews of international data such as those related to shale gas extraction in the United States, conventional oil and gas operations and coal seam gas (CSG) extraction (where relevant). It is noted that not all studies are of similar quality, therefore, this review has more heavily relied on robust reviews of the published data/studies.

11.3.2 Air quality

11.3.2.1 General

Unconventional gas developments and related activities release air pollutants to the atmosphere that may affect local and regional air quality (New York State Department of Environmental Conservation 2015). Sources of these emissions include dust from proppant materials, venting of gases during flowback, flaring and fumes (New Brunswick Commission on Hydraulic Fracturing 2016). Emissions from vehicles and equipment may also be an issue of concern (for example, Maryland Department of the Environment and Maryland Department of Natural Resources 2014; Scholes et al. 2016), although this is an issue related to resource development more generally, not only unconventional gas developments. Emissions from vehicles and equipment used for domestic and industrial purposes are subject to existing regulations relating to emissions.

Air pollutants associated with unconventional gas developments may include:

- Petroleum hydrocarbons, that include methane and other Volatile Organic Compounds (VOCs) such as benzene, toluene, ethylbenzene, and xylene (BTEX);
- Polycyclic aromatic hydrocarbons (PAH's);
- Pydrogen sulphide;
- Ozone and its precursors, including nitrogen oxides (NOx);
- Diesel emissions; and
- Particulate matter (PM), including silica dust.

Exposures to air pollutants are higher for workers involved in activities closer to the sources of these pollutants. Most air pollutants disperse as they move away from the source resulting in lower concentrations. Hence, much of the focus of monitoring and assessment relates to occupational exposures or monitoring close to the sources of air pollution, rather than community exposures.

11.3.2.2 Data from activities in Western Australia

There are limited requirements for monitoring air quality for unconventional gas operations in Western Australia. As a result, monitoring is undertaken on an ad-hoc basis.

Buru Energy submitted a report: *Fugitive Emissions Characterisation, Well Completion Emissions*, prepared by AECOM, dated 14 March 2014. This investigation involved the assessment of fugitive emissions during hydraulic fracture stimulation from one gas well in the Canning Basin (at Asgard 1). The program had also intended to look at emissions during well flowback (at Valhalla North 1), however, the data was not collected during flowback and so was not representative of that activity. Air data collected was analysed for gases as well as BTEX and naphthalene. The testing detected low levels of methane and toluene in air on the well pad. No comparison with health-based guidelines was undertaken in the report, however, it is noted that all concentrations reported were below public health-based air guidelines.

The AWE Limited submission referred to air monitoring conducted around the hydraulic fracture stimulation fluid retention ponds at Woodada Deep-01 well. The levels of BTEX reported (and included in the submission) were compared with the range reported in remote rural areas as well as industrial areas and at a service station. The concentrations reported were all noted as below the National Environmental Protection Measure (NEPM) Monitoring Investigation Levels. Air monitoring data collected close to Senecio-03 well was also provided in documents and given to the Panel at the Dongara public meeting. All concentrations were compared with workplace exposure standards (relevant to the exposures where the data was collected), with all concentrations well below these standards. No assessment of community exposures was included.

It is important to note that the health-based guidelines relevant for use in Australia (or as used in these investigations) are from the same sources as discussed in many of the studies reported in the international literature – including the United States Environmental Protection Agency (U.S. EPA) Integrated Risk Information System (IRIS) database, U.S. EPA Regional Screening Levels and Texas Center for Environmental Quality Effects Screening Levels. These health-based guidelines are designed to be protective of sensitive subpopulations like children, as well as the public more generally.

11.3.2.3 Data from international reviews

A number of papers have been published that include reviews of data and information related to characterising concentrations in air for the purpose of assessing potential risks to health from oil and gas operations. These reviews are summarised below.

McMullin et al (McMullin et al. 2017) provided a detailed review of data relevant to the potential impacts on health from oil and gas air emissions for people living near oil and gas operations in Colorado, with comparisons against health-based guidelines. In Colorado, oil is extracted from oil shale and natural gas is extracted from shales and tight gas formations. The review evaluated more than 10,000 air samples from Colorado (collected between 2008 and 2015) to estimate exposures for people living near oil and gas operations. Some of the monitoring data used in this review was collected very frequently (daily for a year or every 30 or 60 minutes over one month).

Other studies collected samples once every six to 10 days over a three month period. The sampling locations were all at least 150 metres from a well or production location. Samples were not aligned with particular types of facilities, so the measurements reflect impacts on air quality by a combination of oil and gas extraction and include contributions from other sources in the areas evaluated. The air concentrations were compared with published health-based air guidelines relevant for cancer and non-cancer effects, and short and long-term exposures. The study did not find any exceedances of the health-based guidelines. Data showed a low risk of harmful health effects from combined exposures to all substances.

A detailed systematic review of published data related to unconventional oil and gas activities was also undertaken by Health Protection Scotland (Health Protection Scotland 2016). In relation to airborne hazards, 10 studies were identified as of suitable quality to be included in the review, most of which related to United States shale activities. While there are limitations with the studies reviewed, three of these (Bunch et al. 2014; Swarthout et al. 2015; Zielinska, Campbell & Samburova 2014) concluded that concentrations of contaminants in air were not at sufficient levels to be of concern to public health. The other studies provided limited evidence to suggest that unconventional oil and gas activities resulted in airborne hazards at exposure levels in residential areas close to infrastructure that could pose a risk to health. The limited evidence relates to the potential for gaseous PAHs and tropospheric ozone across many thousands of sites (Saunders et al. 2018) to result in increased risks. These studies are specific to activities in the United States, where there

are a large number of wells in relatively small areas that may be close to residential areas. They are not considered to be relevant to the likely scale of activities in Western Australia. The potential for gaseous PAHs to be emitted from a particular well or for a well to impact regional ozone levels could be addressed in a site-specific risk assessment based on investigations of the geology and the type of well or other facilities to be used.

A review by Saunders (Saunders et al. 2018), included a larger range of papers relating to exposure than the one by Health Protection Scotland. This review did not consider the quality of the studies as part of its evaluation so treated all articles as equal. In relation to airborne hazards, there were a large number of gaps identified in the available studies. There is no question that chemicals involved in all stages of unconventional gas developments present a hazard. What is lacking is a distinction between hazard, the inherent danger posed by a chemical and the likelihood that people may be exposed to them while they are being used in unconventional gas developments. Most of the studies considered in this review rely on modelling or attribution of exposures, that is, the studies assume exposure occurs regardless, which introduces uncertainties and makes characterising actual exposure (and risk) difficult. This has precluded making credible conclusions in relation to airborne hazards. This is an issue also identified in other reviews where a range of hazards have been identified in relation to air quality (Adgate, Goldstein & McKenzie 2014; Werner et al. 2015).

Many of the submissions to this Inquiry focused on the hazards posed by chemicals that may be associated with all stages of unconventional gas activities, all of which are reasonable. However, without being able to understand whether exposure may occur, at what concentration that exposure occurs and the likelihood of such exposures occurring, it is not possible to make definitive conclusions on health impacts.

Hays & Shonkoff (Hays & Shonkoff 2016) reviewed a large number of studies related to different hazards posed by unconventional oil and gas activities. The review presented does not make any assessment of data quality and has included 46 original research studies, of which 87 percent indicate that unconventional gas developments have increased air pollutant emissions or atmospheric concentrations (above regional background or above emission inventory estimates) and 12 percent indicate no impact. Further review by Shonkoff et al (Shonkoff, Hays & Finkel 2014) has identified several of these studies suggesting that shale gas development contributes to pollutants in ambient air at concentrations known to be associated with increased risk of morbidity (Colborn et al. 2014; Kemball-Cook et al. 2010; McKenzie et al. 2012). Insufficient data is available to enable an assessment of the relevance of these studies to activities likely to be undertaken in Western Australia.

Given the lack of systematic tracking of exposure and health effects in communities, there is little data to inform risk mitigation and risk management activities. For air quality, key unknowns include: characterisation of baseline air quality prior to development in new

areas; how far away from a well concentrations could remain elevated; and characterisation of the variability in exposure during high emissions processes, specifically drilling, hydraulic fracture stimulation and well completion activities (Adgate, Goldstein & McKenzie 2014).

Overall, there is some limited data available that characterises concentrations of chemicals that may be present in air where the community may be exposed. However, the data that is available indicates that the concentrations in air within communities are likely to be below health based guidelines, so the consequence is likely to fall into the insignificant category. There may be some elevated concentrations close to the point of release where workplace exposures are of relevance, so the consequences in this regard may fall into the minor category. The likelihood that such impacts may occur during operations is difficult to characterise due to the limited data available, however, it may range from rare to almost certain, resulting in an overall risk that is low (in accordance with the risk assessment framework described in **Section 7** of this Report). There are uncertainties in this risk assessment due to the limited amount of data available for operations in Western Australia. With consideration of these uncertainties, risks have been considered to be medium.

Finding 43: There is limited compelling and definitive evidence linking public health effects to air emissions derived from unconventional gas developments associated with hydraulic fracture stimulation. The available data suggests risks may be considered to be low to medium, however, uncertainties within the available data limit the determination that air concentrations may exceed health-based standards near gas production facilities. Limitations with the available data on emissions to air can be addressed on a site-specific basis, with impacts assessed in a site-specific risk assessment.

11.3.2.4 Dust and traffic

Emissions to air will also occur from increased vehicular activity and the operation of plant and equipment at the site. There are no studies available that measure changes in air quality specifically related to emissions from vehicles and other plant and equipment for unconventional gas operations.

It should be noted that emissions to air from the generation of dust and combustion sources, in particular vehicle emissions, have been associated with a range of respiratory and cardiovascular diseases within the community (Hime, Marks & Cowie 2018).

Fine particulates from combustion sources are of particular importance within urban environments where traffic emissions are a significant contributor to air pollution and have negative impacts on mortality and morbidity health indicators in large populations (Hime, Marks & Cowie 2018). Health impacts from vehicle emissions in rural areas is less well studied but would be expected to be much lower than in urban areas. This would also be the case at remote locations where unconventional gas operations may occur in Western Australia.

The generation of dust has the potential to negatively affect the health and amenity of local residents living and working close to extraction activities. Tourist facilities and businesses in rural, regional and remote locations near hydraulic fracture stimulation activities may also be affected by increased dust. Therefore, minimising dust production and managing activities that generate dust is important.

Finding 44: Dust generated by hydraulic fracture stimulation activities and the movement of vehicles, as well as the emission of fine particulates from vehicle emissions, has the potential to negatively impact on community health.

Finding 45: There should be minimisation of dust generated by hydraulic fracture stimulation and/or vehicular movements especially in places within proximity to people and places with high amenity and cultural or aesthetic significance. Minimisation may include limiting land cleared for hydraulic fracture stimulation purposes, greening of areas around hydraulic fracture stimulation sites and prescient management of vehicular movements, especially in areas where roads are not bituminised or paved. The regular maintenance of heavy vehicles used in these operations can minimise exhaust emissions to air, in particular the fine particulates.

Recommendation 14: An enforceable Code of Practice should include measures to minimise the generation of dust throughout all operations and require the regular maintenance of all vehicles.

Recommendation 15: Baseline air quality monitoring for volatile organic compounds and dust, and ongoing monitoring of air quality should be incorporated into an enforceable Code of Practice and be made publicly available.

Recommendation 16: Potential impacts to air quality and human health should be assessed in a site-specific risk assessment.

11.3.3 Water quality

11.3.3.1 Data from activities in Western Australia

At present water impacts are generally required to be monitored through the collection of baseline and monitoring data during and after operations (*Petroleum and Geothermal Energy Resources (Environment) Regulations 2012*). This is discussed in **Section 9.4** (Water - Identification and regulation of potential hazards, issues and pathways.

The Buru Energy submission to the Inquiry included analysis of flowback water from Asgard 1 and Valhalla North 1, with comparison against relevant health-based guidelines, specifically the Australian Drinking Water Guidelines. The analysis included a range of inorganic compounds as well as radiological analysis for Naturally Occurring Radioactive Material (NORM). The data showed concentrations of inorganics and NORM complied with the drinking water guidelines at the point of measurement, in the dam, which is not a source of drinking water. Regardless of these analytes, the flowback water is not suitable for drinking due to elevated levels of total dissolved solids (TDS, a measure of salinity). In addition, elevated levels of chloride and sodium are reported, neither of which have a health-based guideline for comparison. The flowback water analysis data included in the submission did not include any results for organic compounds. As a result, it is not possible to make comment on the presence, or otherwise, of organic compounds in this water. The submission also included baseline groundwater monitoring data, as well as monitoring conducted post-hydraulic fracture stimulation at Asgard 1 and Valhalla North 1 well sites. The data showed no groundwater impacts (where evaluated against drinking water guidelines) associated with inorganics and NORM, from the operations.

The AWE Limited submission references work undertaken by an independent environmental consultant on soil beneath the double lined Woodada Deep-01 retention pond, which was used to temporarily store flowback fluids from hydraulic fracture stimulation. There were no concentrations reported above soil guidelines and no evidence of leakage or contaminated soil. The AWE Limited submission also references monitoring of flowback water and groundwater. While the submission notes there was no discernible influence on groundwater conditions near the site, the data was not provided and no comparison against public health guidelines was presented.

When considering exposures to chemicals in water, health-based guidelines are available for drinking water and for water used for recreational purposes. Australia has its own drinking water guidelines – the National Health and Medical Research Council (NHMRC) Australian Drinking Water Guidelines (National Health and Medical Research Council and National Resource Management Ministerial Council 2017). These guidelines are designed to be protective of sensitive subpopulations like children as well as the public more generally when consuming such water for a lifetime. The guidelines used in Australia are calculated in a similar fashion as those used in the United States or Europe.

Finding 46: The monitoring of chemicals in water does not always include analysis for a comprehensive list of analytes. This limits the assessment of baseline water quality and characterisation of impacts that may be of relevance to public health.

Section 9.4.2 (Water – Chemicals used in hydraulic fracture stimulation) provides further discussion in relation to chemicals that have been used for hydraulic fracture stimulation in Western Australia.

11.3.3.2 Data from international reviews

A number of papers have been published that include reviews of data and information that relate to characterising concentrations in water from unconventional oil and gas activities, for the purpose of assessing potential risks to health. These reviews are summarised below.

A detailed systematic review of published data has been undertaken by Health Protection Scotland (Health Protection Scotland 2016). While a large number of studies are available that consider unconventional oil and gas activities and water quality, only 10 studies were identified that included empirical data and were of suitable quality to evaluate. The assessment considered studies related to chemicals used in hydraulic fracture stimulation and chemicals present in flowback water, including the hydraulic fracture stimulation chemicals, geogenic chemicals from the shale formation and Naturally Occurring Radioactive Material (NORM) from the shale formations. The review concluded there was limited evidence to suggest that unconventional oil and gas activities resulted in the contamination of groundwater drinking wells to an extent that could pose a risk to health. The main issues that were identified included potential contamination of wells by saline water, metals or methane. The potential for such impacts will be different for each site as these contaminants arise from the geological formations rather than being introduced by people during hydraulic fracture stimulation or other aspects of well formation. The potential for salinity, metals or methane to be of concern for nearby groundwater wells would need to be addressed on a site-specific basis.

A review by Saunders (Saunders et al. 2018) included a larger range of papers relating to exposure, noting that the review did not consider the quality of the studies reviewed. The issues with the available studies for air discussed previously also relate to the studies and data available on water quality. This has precluded making credible conclusions in relation to impacts on water quality. This is an issue also identified in other reviews where a range of hazards have been identified in relation to water quality (Adgate, Goldstein & McKenzie 2014; Werner et al. 2015).

Hays & Shonkoff (Hays & Shonkoff 2016) considered studies related to different hazards posed by unconventional oil and gas. The review presented does not make any assessment of data quality and included 58 original research studies, of which 69 percent indicate a potential positive or actual incidence of water contamination and 31 percent indicate minimal potential, no association or rare occurrence of water contamination. There was

limited information provided in the review about what aspect of unconventional oil and gas production caused impacts on water quality in each of the studies reviewed. These limitations in the descriptions in each paper limit the confidence in applying the conclusions to hydraulic fracture stimulation in shale and tight gas formations in Western Australia. Further review by Shonkoff et al (Shonkoff, Hays & Finkel 2014) identified some evidence that supports theories of water contamination risks through a variety of pathways. Insufficient detail is provided to enable an assessment of the relevance of these studies to activities likely to be undertaken in Western Australia.

Most investigations have assessed the potential for impacts on water against guidelines for drinking water as this is the most sensitive use of water that could impact on human health. If water quality is compliant with relevant drinking water guidelines it will also be of an appropriate quality for recreational uses of the water (such as, swimming, bathing and boating).

Given the lack of systematic tracking of exposure and health effects in communities, there is little data to inform risk mitigation and risk management activities. For water quality, unknowns include characterisation of baseline water quality and impacts during each of the process steps that use water, that is, chemical mixing, hydraulic fracture stimulation flowback, and storage of flowback and produced water and wastewater treatment and disposal (Adgate, Goldstein & McKenzie 2014).

Finding 47: There is limited compelling and definitive evidence linking public health effects to contamination of water quality by unconventional oil and gas developments associated with hydraulic fracture stimulation elsewhere. There are uncertainties within the available data that limit the potential understanding of the likelihood that water concentrations may have exceeded health-based standards either close to oil and gas production facilities or at distance. Limitations with the available data on contamination of water can be addressed on a site-specific basis, with impacts assessed in a site-specific risk assessment.

Further assessment of the potential for the contamination of water and risks posed by hydraulic fracture stimulation are presented in **Section 9** (Water), which also provides recommendations relevant to the monitoring and management of water contamination.

11.3.4 Naturally Occurring Radioactive Material (NORM)

NORM is found everywhere in the environment including soil, rocks, water, air and vegetation. It is also present in the human body and all living tissues, typically in very low concentrations (SA EPA 2017). NORM primarily consists of uranium, thorium and potassium, which have been present since the formation of the earth approximately four and a half billion years ago. These radioactive elements spontaneously decay to produce a range of other radioactive elements known as decay products, such as radon and radium (SA EPA 2017).

Everyone receives a background radiation dose of NORM. The concern is that hydraulic fracture stimulation may have the potential to increase exposure via inhalation of radon gas (that may migrate through fissures in rock and porous materials, and be present in gas, wastewater or other wastes) and ingestion and dermal absorption of contaminated water. Health effects commonly associated with exposure to elevated levels of NORM include leukaemia and cancer (in particular, lung cancer), which has the potential to develop many years after exposure has occurred.

Limited information is available on NORM, including radon, in the submissions. However, information provided by Buru Energy indicates that NORM is monitored in groundwater and flowback water, with the levels evaluated against public health guidelines. The international literature includes studies undertaken in Pennsylvania (Casey et al. 2015), which indicated increased levels of radon within homes following unconventional gas development, with higher levels reported in counties where more than 100 wells have been drilled. Low levels of hydraulic fracture stimulation activities had radon levels no different (and sometimes lower) than in areas where there was no activity. Other researchers have also looked at radium levels in flowback water from Marcellus Shale in north-eastern United States (Nelson et al. 2014, 2015). These investigations reported the presence of naturally occurring radium isotopes in some flowback water from the Marcellus Shale. The authors noted that these isotopes could reach local environments if produced fluids at a site are managed poorly. In addition, the level of NORM in flowback water was found to have increased where it was stored in sealed containers. Where stored in open ponds, as is the case for operations expected in Western Australia, this is not expected to be an issue.

Risks from NORM in produced fluids at Western Australian sites are likely to be low given the scale of hydraulic fracture stimulation likely in Western Australia, the expected storage of flowback fluids in open ponds and the requirements imposed to ensure appropriate management of such fluids.

Finding 48: The amount of Naturally Occurring Radioactive Material (NORM) that could be present in produced fluids is likely to vary depending on the shale formation and very limited data is available for Western Australian shale formations. Hence it is important that NORM is monitored in groundwater and flowback water during hydraulic fracture stimulation operations. Consideration of the potential for hydraulic fracture stimulation to result in increased movement of gas (radon or methane) from the subsurface should be included in site-specific risk assessments for each development.

11.3.5 Other hazards

11.3.5.1 General

A detailed systematic review of published data has been undertaken by Health Protection Scotland (Health Protection Scotland 2016). The review found there was inadequate evidence to suggest that unconventional oil and gas activities results in noise, light or odours at exposure levels that would pose a risk to physical health. In addition, there was limited evidence to suggest that unconventional oil and gas activities are associated with increased vehicle accidents.

Research on other stressors, including noise and light, traffic, and other safety hazards needs to be conducted in the context of understanding the effect of the mixture of these chemical and physical stressors (that is, cumulative effects). The interaction with the stress created by rapid change and community disruption is a key research need for characterising health effects in locales where development is encroaching (Adgate, Goldstein & McKenzie 2014).

11.3.5.2 Noise

Constant and intermittent noise from hydraulic fracture stimulation activities but also from increased vehicle movement can be annoying and also disruptive, with potential impacts on mental health and other health outcomes for people living or working close to extraction activities. This is discussed in **Section 12** (Social surroundings). In addition, tourist facilities in a rural, regional or remote location near to hydraulic fracture stimulation could be adversely impacted by noise. Domestic animals in close proximity to sites generating persistent noise may also be negatively impacted.

Noise emitted from any premises/facility (which would include an unconventional oil and gas site) is required to comply with the noise levels under the *Environmental Protection (Noise) Regulations 1997*, established under the *Environmental Protection Act 1986* (EP Act). Rural and urban premises are defined as noise sensitive premises and, while there are exemptions for noise from the operation of farm equipment, noise from any unconventional oil and gas development activities would be required to comply with the regulations. Compliance with the noise regulations would be protective of health.

Information has been provided on noise levels by Condor Energy, Buru Energy and AWE Limited in their submissions to this Inquiry. This has been discussed in **Section 8** (Land) and generally the data indicated compliance with the noise requirements at sensitive premises within 1,400 metres of the operations. As part of the submission from AWE Limited, a consultant's report on noise complaints related to flaring were analysed in some detail; they concluded that with certain prevailing winds, the noise from flaring at premises two to four kilometres distance could be heard. Modelling suggested it was possible noise regulations could be exceeded at night, although no actual noise data was collected to verify this.

It is important that activities that generate noise are appropriately assessed and managed.

Finding 49: In areas with proximity to people and settlements, it is important to establish baseline noise levels before hydraulic fracture stimulation activities commence, and to undertake a site-specific noise assessment addressing all activities proposed, distances to sensitive receptors and/or mitigation measures required to demonstrate compliance with noise regulations. In addition, noise levels should be measured at regular intervals throughout the lifecycle of the development.

Recommendation 17: Baseline noise levels should be established, a site-specific noise assessment completed and ongoing noise monitoring conducted over the life of a project, with the aim of minimising noise generated by hydraulic fracture stimulation and/or vehicular movements, especially in places within proximity to people and domestic animals.

11.4 Assessment of potential health effects based on epidemiological data

11.4.1 Introduction

When reviewing data that is derived from public health or epidemiological studies, it is important that these studies are reviewed in a consistent and robust manner, and that the outcomes are carefully considered, particularly in terms of determining an association or causation.

11.4.2 Association and causation (Health Protection Scotland 2016)

Establishing a causal relationship first involves determining whether there is an adequate amount of sufficiently strong evidence linking a health effect to a specific hazard. The term 'association' is used to describe this linkage and is critical to the understanding of how to interpret the findings of scientific and epidemiological studies.

Association in environmental epidemiology refers to the statistical correlation between exposure to a hazard (which needs to be defined in the study) and the occurrence or frequency of a health effect. If exposure to a hazard and the development of a health effect are statistically correlated, then they can be said to be associated.

However, not all such associations are casual associations. Demonstrating a statistically significant association between a hazard and a health effect is not adequate alone to prove that a direct causal relationship exists, that is, that the health effect was directly caused by that exposure. An association could occur coincidentally by chance, or it could be a result of other confounding factors that are also correlated with both the exposure of interest and the health outcome of interest. Absolute causality is rarely established.

However, it is noted that even if no causal factor linked to an environmental exposure can be demonstrated, the mere perception of an exposure that is not well understood or observations of poor health in areas where a new or different activity may be undertaken

can be enough to create community anxiety and calls for action to be taken. Lay and media discussions of such events/situations are often based on the proposition that there was a real, but undefined, hazard out there somewhere that was causing the risk event (Stebbing 2010). This confirms that, real risk or not, consequences do occur because people respond to their perception of risk not to the risk itself, no matter how it is characterised (enHealth 2012). In this way, the social response to the perceived hazard may become enlarged or expanded beyond that expected by experts, institutions and media, and it indicates that risk cannot be studied or discussed in isolation from the social context of engaged stakeholders (enHealth 2012).

11.4.3 Reviewing adequacy of epidemiological studies

For public health medicine there is a standard approach to assessing epidemiological evidence. The quality of the evidence must be assessed, and this assessment should occur for each individual epidemiological study along with the collective assessment of all epidemiological studies that examine the same exposure and health outcome. Further, sources of evidence should preferably be published, peer reviewed, and critically appraised in articles and reports (a Dictionary of Epidemiology).

To ensure the epidemiological evidence is assessed in a systematic manner, a number of critical appraisal tools have been developed in the health sphere. These tools evaluate the quality of the studies and allow for an overall assessment of the evidence presented in these studies. The design of the study has a lot to do with its quality: studies that can 'control' for biases and exposures, such as randomised controlled trials, are of higher quality than those that cannot.

The 'gold standard' of critical appraisal tools has been developed by the Cochrane Collaboration, whose reviews have informed the implementation of better medical practise around the world. A downside to this tool is that it is primarily designed for assessing evidence from randomised control trials of medications but it is unable to be undertaken to assess the impact of a development such as an unconventional oil and gas development.

Acknowledging that epidemiological studies are of differing designs but still require systematic assessment, other critical appraisal tools have been developed for use in the public/environmental health sphere and can be found at the Enhancing the Quality and Transparency of Health Research Network website. http://www.equator-network.org/

11.4.4 Summary of health reviews of epidemiological evidence

11.4.4.1 General

To determine the state of evidence regarding potential health impacts from hydraulic fracture stimulation, peer reviewed papers and published government reports have been reviewed. This Inquiry has focused on those reviews that have adopted robust critical appraisals of the available studies.

11.4.4.2 Reviews adopting robust critical appraisal methods

Of the reports and papers reviewed, only three explicitly named the critical appraisal tool they used. McMullan et al (McMullin et al. 2017) used the adapted GRADE System, Health Protection Scotland (Health Protection Scotland 2016) used the Newcastle - Ottawa Scale, while Balise et al. (Balise et al. 2016) used the Office of Health Assessment and Translation Guidelines.

McMullin et al. 2017

This review involved the conduct of a systematic review of the epidemiological studies. A relatively small number of epidemiological studies (12) have been published that evaluate potential associations between oil and gas emissions and health outcomes. This includes a number of key references provided in submissions: (Casey et al. 2016; Fryzek et al. 2013; Hill 2013; Jemielita et al. 2015; McKenzie et al. 2017, 2014; Rabinowitz et al. 2015; Rasmussen et al. 2016; Stacy et al. 2015; Steinzor, Subra & Sumi 2013; Tustin et al. 2017; Werner et al. 2015). Two of these papers relate to studies conducted in Queensland in areas where coal seam gas (CSG) operations have been conducted.

The studies evaluated related to a wide range of health effects that included birth outcomes, birth defects, respiratory (eye, nose and throat (ENT) and lung), neurological (migraines and dizziness), cancer, skin (irritation and rashes), psychological (depression and sleep disturbances), cardiovascular, gastrointestinal (nausea and stomach pain), musculoskeletal (joint pain and muscle aches) and blood/immune effects.

The outcomes of the review were:

- There is limited evidence that exacerbation of existing asthma and self-reported dermal symptoms are associated with exposure to substances emitted from oil and gas operations;
- There is a lack of evidence or, in some cases, conflicting evidence concerning the relationship between other health outcomes and oil and gas operations;
- The majority of findings from the studies were ranked as low quality, primarily due to limitations of the study designs that make it difficult to establish clear links between exposures to substances emitted directly from oil and gas and the outcomes evaluated;

- A person's total exposure may reflect multiple substances from both oil and gas and non-oil and gas sources, from indoor and outdoor environments. For example, VOCs can be emitted from a variety of sources including oil and gas, other industrial operations, vehicle traffic and everyday consumer products such as nail polish, detergents, sealants, aerosol antiperspirants and deodorants;
- These epidemiological studies may also reflect the interactions of non-chemical stressors that may or may not be related to oil and gas operations that can contribute to adverse health outcomes in a population;
- Although these observational epidemiology studies alone are not sufficient to determine causality, they provide helpful information to direct further investigation into the public health implications of oil and gas activity near residential areas; and
- Studies of populations living near oil and gas operations provide limited evidence of the possibility for harmful health effects. This needs to be confirmed or disputed with higher quality studies.

The review recommended continued monitoring of exposures and evaluation of health risks using more comprehensive and representative exposure data.

Health Protection Scotland 2016

Health Protection Scotland undertook a critical review and appraisal of the available studies. All studies considered were reviewed and evaluated for quality and suitability for inclusion in the assessment. Included studies were subsequently evaluated using critical appraisal tools determined by the study type. Epidemiological studies were appraised using the Newcastle Ottawa Scale (Wells et al. 2014), adapted specifically for this review. Qualitative type studies and surveys were appraised using the Critical Appraisals Skills Programme (CASP) and the Centre for Evidence-based Management (CEBMa) checklists.

There were relatively few epidemiological studies available on the topic, with only six studies identified (Casey et al. 2016; Fryzek et al. 2013; Jemielita et al. 2015; McKenzie et al. 2014; Rabinowitz et al. 2015; Stacy et al. 2015).The small quantity of material available was of variable quality and was characterised by contradictory and inconsistent findings. This evidence base was therefore inadequate to determine if there was a general association between unconventional oil and gas activities and health impacts. Specific studies provided inadequate evidence of association between unconventional oil and gas activities and effects on reproductive and developmental health, and childhood cancer, or adverse neurological, cardiovascular or dermatological health outcomes. This included studies of self-reported health status.

Balise et al. 2016

This paper conducted a systematic review of evidence, using a standard search strategy and the Office of Health Assessment and Translation guidelines to assess the quality of evidence around conventional oil and natural gas extraction and human reproduction. The review identified and considered 45 original published papers that were suitable for inclusion in the review. The studies were noted to provide little actual measurement of exposure, rather they relied on distance to the source.

The results indicated there was moderate evidence for an increased risk of preterm birth, miscarriage, birth defects, decreased semen quality and prostate cancer. The quality of the evidence was low and/or inadequate for stillbirth, sex ratio, birth outcomes associated with paternal exposure, testicular cancer, female reproductive tract cancers and breast cancer. The evidence was inconsistent for an increased risk of low birth weight, therefore, no conclusions can be drawn for these health effects.

While this systematic review provides some evidence of negative impacts to human reproductive health from occupational and residential exposure to oil and gas activities, the exposure that relates to these effects is not clear.

Many of the 45 studies reviewed identified human health effects, with most of these focused on conventional oil and gas activities. There were only a few studies included in the review that related to unconventional oil and gas operations, however the paper suggests that the impacts may be greater, likely due to the assumed use of known endocrine-disrupting chemicals in hydraulic fracture stimulation. Refer to **Section 9.4.2** (Water – Chemicals used in hydraulic fracture stimulation) for further discussion on endocrine-disrupting chemicals.

11.4.4.3 Reviews adopting rigorous search strategy but no critical appraisal

Of the other reports and papers reviewed, six (Hays & Shonkoff 2016; Krupnick & Echarte 2017; Saunders et al. 2018; Shonkoff, Hays & Finkel 2014; Stacy 2017; Werner et al. 2015) specified a rigorous search strategy but failed to identify the critical appraisal tool for the assessment of the literature.

Krupnick and Echarte 2017

This review provides an assessment of the quality of the literature but does not detail the guidelines used to achieve this. The review considered epidemiology studies that are based on hospital reported data (Casey et al. 2016; Fryzek et al. 2013; Hill 2013; Jemielita et al. 2015; McKenzie et al. 2017, 2014; Rasmussen et al. 2016; Stacy et al. 2015) and self-reported health effects (Rabinowitz et al. 2015; Tustin et al. 2017); community based participatory research (Macey et al. 2014; Steinzor, Subra & Sumi 2013); health impact assessments and risk assessments (McKenzie et al. 2012; Witter et al. 2013); and occupational health studies (Bloomdahl et al. 2014; Durant et al. 2016; Esswein et al. 2013, 2014; Harrison et al. 2016;

Mason et al. 2015). The review also considered other papers relating to risk factors (including radon) and papers proposing various hypotheses (Aminto & Olson 2012; Bunch et al. 2014; Casey et al. 2015; Colborn et al. 2011, 2014; Elliott et al. 2017; Ferrar et al. 2013; Hays & Shonkoff 2016; Kassotis et al. 2014b; Mitchell, Griffin & Casman 2016; Saberi et al. 2014). The review also looked at literature reviews conducted by others (Adgate, Goldstein & McKenzie 2014; Finkel & Hays 2013; Shonkoff, Hays & Finkel 2014; Werner et al. 2015).

Overall, the review found that the literature does not provide strong evidence regarding specific health impacts from unconventional oil and gas development and is largely unable to establish mechanisms for any potential health effects.

As with other reviews, the lack of data and quality studies does not indicate a lack of health impacts. More rigorous study (addressing exposure and causation) is therefore needed to properly inform communities of risks and inform policymakers and oil and gas operators of methods for reducing these impacts on communities.

Stacy 2017

This review focused on unconventional natural gas developments and epidemiological studies examining health outcomes and proximity to these operations. The review does not outline the paper selection strategy or review criteria and has not involved a systematic review of the available data. The review considered seven studies (Casey et al. 2016; Fryzek et al. 2013; McKenzie et al. 2014; Rabinowitz et al. 2015; Rasmussen et al. 2016; Stacy et al. 2015; Tustin et al. 2017), all of which have been included in other more robust reviews.

To date, these studies have been primarily retrospective in design and used self-report of health symptoms or electronic health databases to obtain outcome information. Proximity to unconventional natural gas developments is often used as a surrogate for exposure. There is preliminary evidence linking respiratory outcomes, including asthma exacerbations, and birth outcomes, such as reduced foetal growth and preterm birth, to unconventional natural gas developments, however, results differ across study populations and regions. There are limitations with the studies undertaken and they should be considered as hypothesis generating, a view shared by Hays & Shonkoff (Hays & Shonkoff 2016). The use of proximity and density metrics of unconventional natural gas developments cannot identify specific exposures that could explain observed associations.

Although small, the current body of literature suggests that living near unconventional natural gas developments may have negative health consequences for surrounding communities. Future studies of the health effects of unconventional natural gas developments are required.

Saunders et al. 2018

This paper discusses the review of the public health impacts of unconventional natural gas development. It defined and quantified a search strategy, however the paper does not

provide an assessment of individual study quality in a systematic manner. Of the 953 papers initially identified, 156 were included in the review, of which 23 were health/epidemiological/population studies.

The epidemiology studies are limited and currently do not enable a definitive public health judgment to be determined, a position shared by the United States Centers for Disease Control (U.S. Centers for Disease Control 2012). Around half of the studies use derived hazard indices or self-reported symptoms, some subjects are self-referred or referred by activists, most involve very small sample sizes, some of the symptoms are of questionable plausibility, and very few use a credible exposure measure. As a result, this body of work is compromised by the real potential for exposure misclassification, bias, statistical unreliability and questionable spatial, temporal and biological plausibility.

It is worth noting that four of the five studies that use clinically confirmed cases and large sample sizes do report associations between residential proximity to unconventional gas development sites and increased risk of plausibly related adverse health outcomes, including three studies strongly suggesting adverse reproductive outcomes. The latter particularly requires further research given the evidence of the developmental and reproductive toxicity of many of the chemicals associated with the unconventional gas industry.

Hays and Shonkoff 2016

This review was a systematic search of all the peer-reviewed literature, however there was no systematic assessment of research quality. Based on the search criteria, the review included 31 original research studies relevant to unconventional gas developments and public health hazards, risks and health outcomes. Of these 31 studies, 26 (84 percent) contain findings that indicate public health hazards, elevated risks or adverse public health outcomes and five (16 percent) contain findings that indicate no significant public health hazards, elevated risks or adverse health outcomes. The vast majority of all papers on this topic identify limitations with the studies undertaken and indicate the need for additional study, particularly large-scale, quantitative epidemiologic research.

Werner et al. 2015

This review provided search criteria and a method for assessing ‘strength/relevance’ of evidence, although the method to determine relevance did not consider study design. The initial searches yielded more than 1,000 studies, but this was reduced to 109 relevant studies after the application of a ranking process. Of these, only seven studies (Fryzek et al. 2013; Hill 2012; McKenzie et al. 2014; Perry 2012; Steinzor, Subra & Sumi 2012, 2013; Texas Department of State Health Services 2010) were considered highly relevant based on strength of evidence, that is, these reviews provided evidence about direct associations between environmental health hazards related to unconventional gas development activities

and health outcomes. Of the remaining studies, 38 were considered relevant and 64 were considered not very relevant.

In reviewing available studies for strength of evidence, there are very few, if any, methodologically rigorous studies that have examined the potential cause-and-effect of unconventional oil and gas developments in the construct of hazard analyses, linked to exposure pathways and the actual health outcomes. In fact, the Panel's review shows that most of the peer-reviewed research was not very relevant in this context. Most of the highly relevant studies cannot be described as scientifically rigorous, due to methodological limitations, such as measurement and selection bias, as well as potential confusion.

Current scientific evidence that demonstrates direct associations between adverse health outcomes and environmental health hazards resulting from unconventional oil and gas development activities generally lack methodological rigour. Importantly, however, there is also no evidence to rule out such health impacts. While the current evidence in the scientific research reporting leaves questions unanswered about the actual environmental health impacts, public health concerns remain intense.

Similarly, the review by Shonkoff et al. (Shonkoff, Hays & Finkel 2014), despite not considering the quality of the studies or conducting a systematic review, identified the lack of sound epidemiological studies enabling understanding of the strength of associations between risk factors such as air pollution and water contamination, and health outcomes in individuals located in close proximity to shale gas developments.

11.4.4.4 Reviews with no rigorous search strategy and no critical appraisal

Of the other reports and papers reviewed, five reviews (Adgate, Goldstein & McKenzie 2014; Concerned Health Professionals of New York 2018; Finkel & Hays 2013; Haswell 2017; Haswell & Bethmont 2016) did not provide either the search strategy or any tools/methods for critically appraising the study quality and outcomes. There are also numerous other papers and reports that simply list out the findings of a range of epidemiological studies with no review of the study quality, suitability or outcomes. Such reviews imply credibility in the study outcomes by omitting such critical evaluation and should be considered with caution.

Adgate (Adgate, Goldstein & McKenzie 2014) and Haswell (Haswell 2017; Haswell & Bethmont 2016) identified a number of papers where health effects were identified in communities in the vicinity of unconventional oil and gas activities. While the reviews by Haswell (Haswell 2017; Haswell & Bethmont 2016) provided no critical review of the available studies, the Adgate review (Adgate, Goldstein & McKenzie 2014) identified a range of issues associated with the limited epidemiological studies available. In particular, this included a lack of spatial and temporal specificity in exposure and individual level risk factors, and how these relate to the health effects evaluated/identified. Other scientific limitations were also identified that included self-selected populations, small sample sizes, relatively short follow-up times and unclear loss to follow-up rates, limited exposure measurements and/or lack of access to relevant exposure data, and lack of consistently

collected health data, particularly for non-cancer health effects. Given these limitations, the lack of observational studies and the public's demand for answers, Adgate et al. (Adgate, Goldstein & McKenzie 2014) recommended that human health risk assessments will be needed to provide projections of potential future harm for both short-term and long-term human health risks.

The review by Adgate et al. (Adgate, Goldstein & McKenzie 2014) and Finkel & Hays (Finkel & Hays 2013) concluded that the absence of data does not imply that no harm is being done and that further research is required to quantify health risks for short-term and long-term exposures.

The report published by the Concerned Health Professionals of New York (Concerned Health Professionals of New York 2018) is cited in numerous submissions to this Inquiry. The report states it draws information from database searches but does not provide the search strategy used, including its inclusion and exclusion criteria. The report combines epidemiological evidence with investigative journalist reports and commissioned reports. It does not assess the quality of the evidence, as documented in the report, but rather encourages the reader to review the evidence provided and undertake their own assessment of its strength. As such, the statements made in this report should be vetted by the reader by seeking the original source of the statement and assessing the quality of the evidence that has led to the statement.

The report indicates that available peer-reviewed literature reveals both potential and actual harms. Specifically, Hays and Shonkoff (Hays & Shonkoff 2016) conducted a statistical analysis of the body of scientific literature available from 2009 to 2015 (again, noting that this did not include any review of the studies, the quality or strength of evidence) and reported 69 percent of original research studies on water quality found potential for, or actual evidence of, water contamination; 87 percent of original research studies on air quality found significant air pollutant emissions; and 84 percent of original research studies on human health risks found signs of harm or indication of potential harm.

Despite providing no review of the available studies, including the quality of the studies or the strength of the evidence or findings, this report has included a number of pre-determined outcomes that act as headings for some of the information and references provided. Hence, while the reader is directed to evaluate the information and studies for themselves, the report provides bias in the way it is presented. Regardless, the report provides a list of numerous studies and sources of information, mostly related to operations in the United States that can be reviewed in relation to a wide range of issues that may be associated with unconventional gas activities. These issues include air, water, health, public safety, climate stability, seismic stability, community cohesion and long-term economic vitality. The studies should be reviewed in detail to determine their reliability, suitability and relevance for consideration in any specific risk assessment that may be required for a state such as Western Australia, or any specific proposed hydraulic fracture stimulation activity.

11.4.5 Outcome of health and epidemiological studies and reviews

Although varying in their methods of review, all papers and reports similarly concluded that there was a lack of or limited epidemiological evidence regarding health impacts from unconventional oil and gas developments. In many cases the exposure pathways likely to be responsible for the observed health effects have not been identified, with most epidemiological studies using proximity to activities. This outcome is reinforced in the recent Scientific Inquiry into Hydraulic Fracturing in the Northern Territory (Northern Territory Government 2018), the Public Health England Review (Public Health England 2014), submissions by the Western Australian Department of Health and from Professor Bruce Armstrong to this Inquiry.

Most studies and reviews called for more research in the field with some highlighting a lack of evidence does not imply a lack of health impact. This outcome is consistent with that provided in the Department of Health (DoH) submission:

> *"The lack of conclusive evidence does not suggest that there is no effect and the DOH maintains that the precautionary principal be applied in considering future hydraulic fracturing stimulation projects in Western Australia. The DOH also holds the view that, if well managed and under the right conditions, public health risks can be minimised. However, in any regulatory framework public health risk needs to be considered"* – submission by the Department of Health

The limited epidemiological evidence should be of no surprise, given the nature of the situation and the limitations of epidemiological studies. The impact of environmental exposures over small populations are notoriously difficult to determine with current epidemiological science, a point highlighted by various health authorities who prescribe the use of risk assessment tools over epidemiological studies for the assessment of impacts on small populations (National Academies Press 2012; NSW Health 2017). This is also reinforced in one of the above reviews (Adgate, Goldstein & McKenzie 2014).

The lack of conclusive evidence does not mean no effect and the recommendation from the DoH that the precautionary principle be applied is appropriate, particularly given community concern about health and the lack of conclusive data on health issues identified in the literature.

Finding 50: To date, epidemiological studies have not provided general assurances regarding impacts on public health from the potential hazards associated with unconventional oil and gas development using hydraulic fracture stimulation due to inherent inferential weaknesses in that approach. Given the nature of the potential contaminants, the potentially severe or irreversible consequences to public health, and the uncertainty associated with the actual risk, the Precautionary Principle comes into consideration.

The DoH holds the view that if well managed and under the right conditions, public health risks can be minimised.

The most appropriate way to properly address potential health impacts is to complete a site-specific risk assessment process that addresses both short and long term health risks relevant to the community. This is required in existing regulations. However, the completion of a site-specific risk assessment is not always required for all developments. Closer consultation with the DoH should be undertaken to ensure site-specific risk assessments are conducted on sites where potential health impacts require additional consideration.

Finding 51: Site-specific health risk assessments would better inform the design and acceptability of unconventional oil and gas development associated with hydraulic fracture stimulation.

Recommendation 18: Site-specific health risk assessments, that have been peer-reviewed and provided to the Western Australian Department of Health, should be required for all unconventional oil and gas proposals associated with hydraulic fracture stimulation, addressing potential short and long-term health impacts.

The DoH submission presents a number of recommendations, one of which is adequate separation distances (buffer zones) between operations and human communities. The current EPA guideline for separation distances between oil and gas development and sensitive receptors (for example, residences and schools) is 2,000 metres (note that this is not embodied in regulation).

Recommendation 19: As a precautionary approach is justified, and in the absence of a local health risk assessment indicating otherwise, unconventional oil and gas wells associated with hydraulic fracture stimulation and processing plants should be located at least 2,000 metres from sensitive receptors such as residences, schools and settlements, as reflected in current Environmental Protection Authority (EPA) guidelines.

12

Risk assessment: Social surroundings

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12 Risk assessment: Social surroundings

12.1 Introduction

The development of onshore unconventional oil and gas reserves in Australia has stimulated a wide range of inter-related economic, social and environmental concerns. The perceptions of residents in both affected and unaffected localities intersect with the aspirations of resource companies and their contractors, and the public interest concerns of local, state and federal governments (Uhlmann et al. 2014).

The perceptions of many in Western Australia have been largely informed by the experiences of residents and communities elsewhere: from the coal seam gas (CSG) industry in Queensland and New South Wales, operational since the 1980s; and shale gas and oil development in the United States, dating from the early 1970s. Over five decades, technologies, legislation and the expectations of communities have all changed significantly (Jacquet 2014; Mayer 2017; Uhlmann et al. 2014). Nonetheless, it is the negative and deleterious impacts of resource extraction on people and communities that are the most pervasive in the social science, academic, social and popular literature. Poor governance structures around the management of resource extraction and its social impacts, and, at the ineffectual attempts by government to manage them has also been documented but to a lesser degree.

At the same time, businesses and communities in rural, regional and remote Australia are urged to engage with global market opportunities, and innovate and adapt wherever possible. Tensions occur at the nexus between ensuring current and future environmental values are not compromised, and promoting economic sustainability, prescient management of change and the inevitable cumulative impacts of change and innovation. As noted by Lai et al.:

> "Land use policies that encourage rural areas to accommodate multiple functions such as producing [agriculture and] mineral and energy resources while also maintaining cultural ecosystem services that support a sense of place[7] and identity ingrained in an image of rural landscapes desired by rural residents, can lead to land use conflicts and impose stress on community residents" (Lai et al. 2017)

It is also important to note that the most intense antagonism to recent CSG developments in in Australia - in the Surat Basin in Queensland and the Hunter River region in New South

[7] *Sense of place* and *place identity* refer to a variety of meanings and emotions associated with a location or place by individuals of groups. It is a sense of attachment and/or identity to a place that is more than a link to a physical space or particular geography (Devine-Wright 2009).

Wales - occurred during the frenetic construction phase (Moffat & Zhang 2014) from 2009 to approximately 2014. It is generally agreed that not enough was done to prepare or communicate with local communities that were likely to be affected by the multiple impacts imposed by the entry of a new industry sector, nor sufficient effort to win their trust (Franks et al. 2010; Franks, Brereton & Moran 2013; Queensland Gasfields Commission 2017). As a result, communities, services and infrastructure were overwhelmed with adverse impacts. Nor were communities properly prepared for the transition to the operational phase, which resulted in less people and fewer construction contracts in the local communities, causing further social and economic disruption. Since that chaotic period, it would appear that conflict and anger has dissipated (Queensland Gasfields Commission 2017; Scott 2016). More than the environmental impact, it was the social and economic disruptions that had a lasting influence on perceptions of how gas companies and governments interact with communities. The recent eastern Australian experience of rapid CSG development is a salutary lesson regarding the importance of the social surroundings and the costs of not paying sufficient attention to them.

In the definition of 'environment' in the *Environmental Protection Act 1986* (EP Act), subsection (1) stipulates that the 'social surroundings of man are his aesthetic, cultural, economic and social surroundings to the extent that those surroundings directly affect or are affected by his physical or biological surroundings'. In subsection (2), 'environment' means 'living things, their physical, biological and social surroundings, and interactions between all these'.

Therefore, the remit of the Panel conducting this Inquiry is to consider the potential impact of activities to social surroundings if an oil and gas industry carrying out hydraulic fracture stimulation proceeds in Western Australia, in so far as that harm is through the biological or physical environment, including harm to beneficial uses. Therefore, the considerations regarding the social surroundings for this Inquiry focus on:

- The risk of harm to current and future environmental values and those that benefit from them;
- Health status;
- Access to safe or fit-for-purpose water;
- The productive use of the land;
- 'Sense of place' or aesthetic values for the landscape; and
- Cultural heritage as impacted by changes to the physical or biological environment.

The Inquiry's Terms of Reference direct attention to 'community impacts', but the Inquiry's scope does not extend to social and economic benefits, nor to the broader consideration of industry's social licence to operate. Yet, these dimensions were prominent among the concerns and comments received in submissions to the Inquiry and raised at public

meetings. While the focus of consideration through this Report remains on potential impact on the community through harm to the environment, the Panel would be remiss if it did not also consider and report on these broader issues. We have endeavoured not to conflate them.

It is important to note that for every risk that is mitigated there are also opportunities and benefits, which can be valuable for rural, regional and remote communities. Therefore, finding the balance and remaining open minded is important.

Resource extraction presents an opportunity to diversify the local industry mix in some localities of Western Australia. The decline in population and businesses in many regional, rural and remote communities over the last 50 years and the implications for communities of this trend requires new industries and diversification strategies for future sustainability. Finding ways to co-exist can bring multiple benefits but the integration of new industries has to be done in a consultative and collaborative way from the outset, wherever possible, to avoid conflicts.

Unconventional oil and gas extraction has the potential to come into conflict with other industries for land and valued resources such as a productive labour force, potable water and aesthetically attractive and highly productive agricultural land. It therefore presents potential cause for tension. However, as a commodity, the oil and gas sector delivers high value products and an opportunity for economic and employment diversification in some localities, with potential flow-on benefits.

The literature on regional and community development rarely advocates a 'one size fits all' approach, particularly in relation to contentious issues. In the case of hydraulic fracture stimulation in a state like Western Australia, which has a vast geographic jurisdiction with variable population, industry distribution, natural assets and geology, it is inevitable the impacts will be variable, and case and place specific.

Resource extraction is not new to many parts of Western Australia although to date, unlike other parts of Australia, land use conflict particularly in relation to industry sector competition for land use, has been relatively modest or localised. However, Western Australian unconventional oil and gas resources are inferred to be present, in some cases in large quantities (particularly in relation to unconventional gas), in areas where other industry sectors are not only well established but also highly productive and high value (such as mining and agriculture), towns are established and high value commodities, such as water, are located.

Figure 12.1 and 12.2 show the proximity of wells that have undergone hydraulic fracture stimulation in relation to towns and Public Drinking Water Source Areas (PDWSAs) and other land uses in the Perth and Canning Basins.

Figure 12.1: Location of wells that have undergone hydraulic fracture stimulation in the Canning Basin in relation to towns, mines, PDWSAs and in relation to irrigation areas

Source: DWER

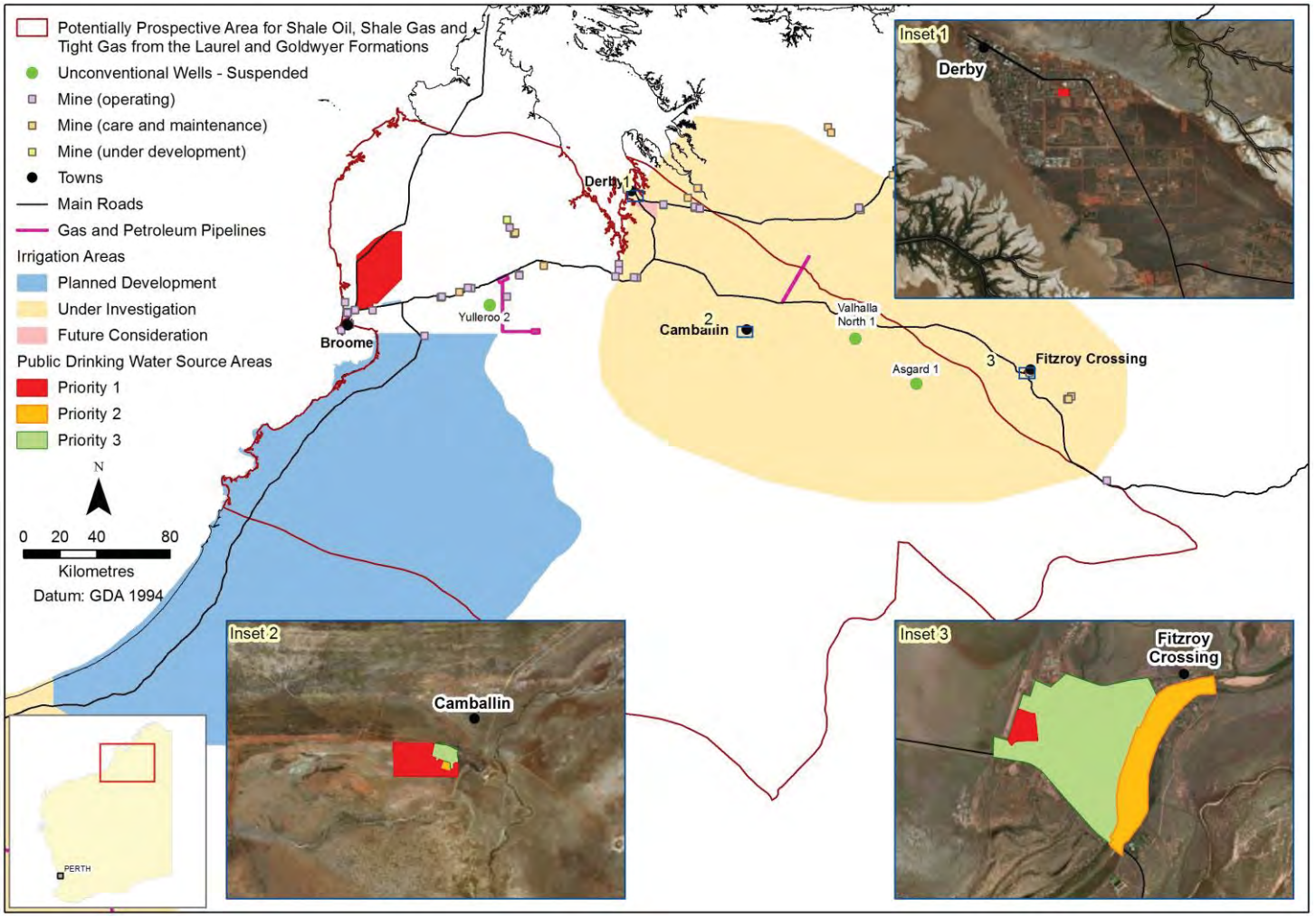
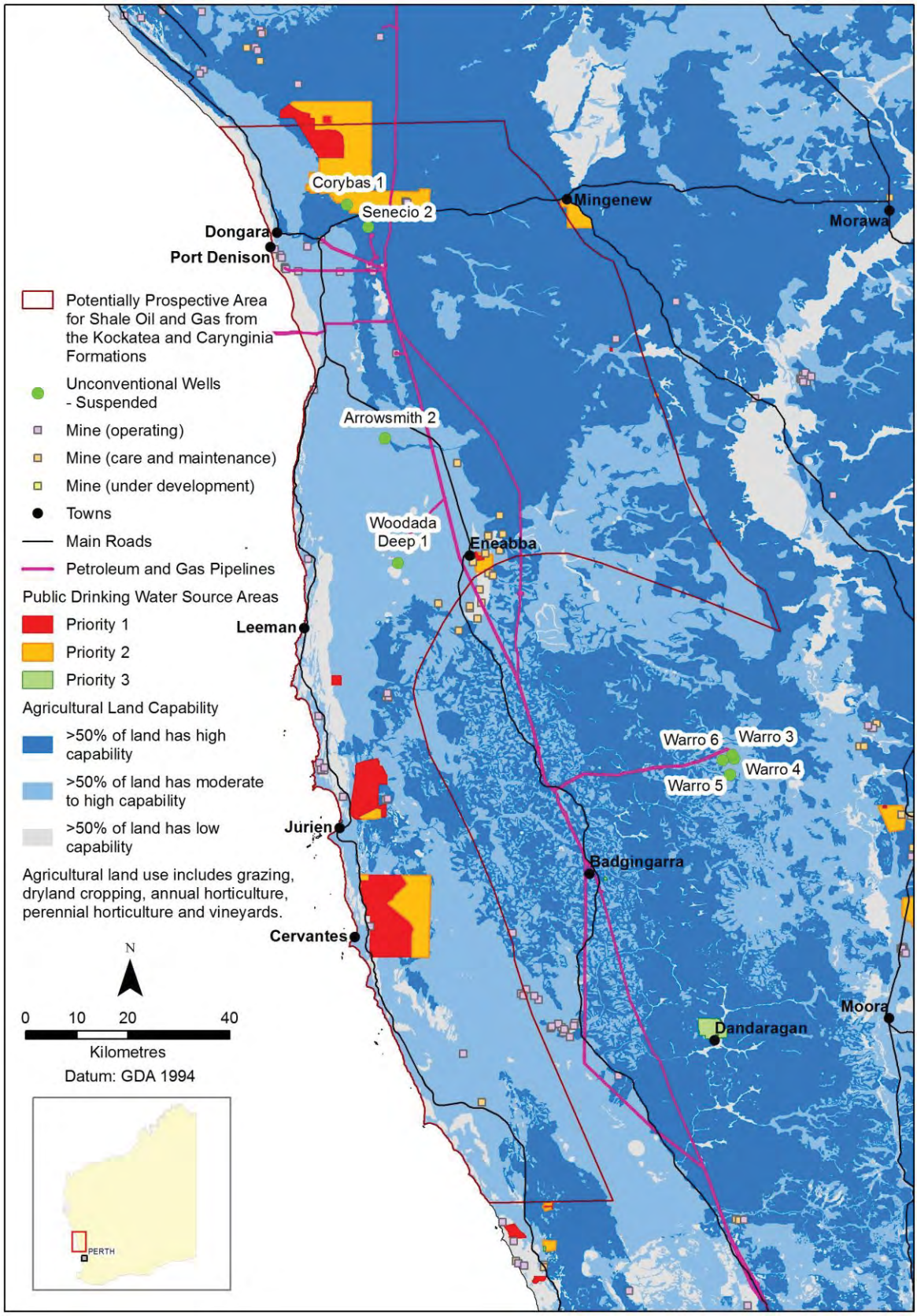


Figure 12.2: Location of wells that have undergone hydraulic fracture stimulation in the Perth Basin in relation to towns, mines, PDWSAs and in relation to agricultural land capability

Source: DWER



There is no Federal onshore mining or petroleum legislation that is applicable in the States or Territories that governs the relationship between resource development, communities and landholders. Each of the States and Territories has its own legislation regulating the exploration for and production of onshore minerals and petroleum. It is important to note that nowhere in Australia does the principle of the owner of the land owning the resources within it, apply.

12.2 Key issues raised

The majority of the submissions to this Inquiry addressed likely and perceived detrimental impacts from unconventional oil and gas extraction. However, there were also submissions noting benefits, not only from representatives and scientists who work within the resources industry, but also from community representatives and landowners, some of whose land has been accessed for unconventional oil and gas extraction (prior to the current moratorium). They made clear they had experienced or expected benefits from hydraulic fracture stimulation and they considered the environmental impacts were minimal or well managed. They also considered their interactions with industry representatives to be respectful and generally positive.

The key social impacts raised in the submissions to this Inquiry include issues already experienced by local residents as well as concerns raised regarding the threat of possible outcomes, which range from harmful and toxic, to annoying and causing displeasure. These submissions were generally based on what has been experienced elsewhere and subsequently documented by other inquiries and in other literature. Common concerns raised include:

- Health impacts for both people and animals based on experiences elsewhere;
- Poor governance controls of the extraction industry in other jurisdictions, particularly by government, and the threat of losing control of local land use and management;
- The scarring of the landscape by seemingly indiscriminate access tracks and roads to well sites and the potential loss of fauna and flora associated with landscape destruction;
- Increased vehicular movement to and from gas installations from employees and contractors increasing traffic noise and escalating the potential for accidents on often poorly maintained rural road networks;
- Competition for road access;
- Mental and physical health impacts from proximity to well sites and resource activities. This included eyes, nose and throat complaints, problems associated with isolation and stress engendered by concerns about living close to a gas site;
- The devaluing of property due to proximity to a well/gas resource site;

- Unpleasant odours and visual pollution emanating from gas installations, which restrict how people live and move around their properties;
- Water used for human and animal/stock consumption becoming unsafe;
- The amount of water used in hydraulic fracture stimulation interfering with the local water table and limiting local usage of water. This concern was particularly strong in the Dandaragan locality where high volume horticulture and stud stock enterprises operate;
- The unwillingness/inability of governments or other monitoring bodies to hold unconventional gas extraction proponents to account for well management during and after commissioning. There was disquiet around adequate ongoing monitoring if/when corporate and commercial entities changed ownership or divested; and
- The lack of economic and social benefits that flow to the communities closest to the resource extraction activities.

12.3 Social surroundings values

Sonter et al. (Sonter et al. 2014) identify four potential generalisations regarding land use change associated with resource extraction, which are potentially pertinent to the Western Australian onshore context if adverse outcomes are to be managed:

- The **direct footprint** of resource extraction, which is usually addressed by licensing conditions and agreements;
- The **offsite footprint**, which are often the ancillary impacts felt at the community level and not easily recognised at the beginning of a resource extraction process but quickly become evident as it is established in the community;
- The **indirect** outcomes, which are difficult to measure and cannot easily be attributed to any particular agent of change; and
- The **global footprint,** such as international demand, policy practices and trade agreements over which local landowners and residents rarely have control.

12.4 Risk management for social surroundings

Every day activities, ranging from the relatively mundane to the most complex, are associated with risk and it is important to assess the risk and make decisions based on credible information.

Risk assessment is a tool for informed decision-making. Addressing cumulative impacts or planning for mitigation of cumulative impacts is central to risk management. However, risk assessment for the social surroundings has additional complexities:

"recognition that the complex interactions characteristic of cumulative impacts require action by multiple sectors, not just multiple companies" (Porter, Franks & Everingham 2013).

This usually requires all spheres of government, companies, interest groups and community groups to be part of an ongoing commitment to collaborate, tolerate diversity and commit to broadly understood goals and outcomes. Uhlmann et al. (Uhlmann et al. 2014) also acknowledge the challenge of the different regulatory and/or economic power of participating stakeholders and the temptation to manipulate the collaborative process, revisiting the sense of losing control or being under-valued which can often lead to counter-productive outcomes.

Technical expertise is very important and the availability of reliable science to guide decisions regarding resource extraction, water and chemical management are accepted and relatively easily measured aspects of the risk management process. The regularity, reliability, transparency and credibility of monitoring activities also contributes to public confidence. However, while building trust and engendering a sense of sharing and mutual obligation appears to be at the centre of risk assessment, when it comes to the social surroundings, these aspects are usually subjective, not easily measured, take time to emerge and can be snuffed out very quickly.

Similarly, the determination of aesthetics and other social surroundings values, including beneficial uses of the environment, are locally subjective, with considerable variance among stakeholders. Therefore, determining the social surroundings is inherently provisional, incomplete and limited through this Inquiry. Understanding what is valued can best be ascertained or gauged through an ongoing dialogue with the local community and its established industries. This extends to the identification and appreciation of the cultural and heritage values of the environment. Rarely will quantitative and technical expertise alone, without qualitative judgements, be adequate.

Risk assessment of the social surroundings will likely be influenced by proximity, scale, visual impact and the recognition of significance of particular places in relation to hydraulic fracture stimulation activities. Therefore, the risk of impacts to social surroundings depends almost entirely on the specifics of the development, proximity to people and the environments they highly value. Perception of risk and measurable risk are often conflated; the relationship between the communities likely to be impacted and the relevant companies will influence perceived risk of impact.

Finding 52: Risk assessment of the social surroundings, particularly cumulative impacts, is necessary but complex and highly dependent on locale.

Recommendation 20: Risk assessments of impacts to the social surroundings from hydraulic fracture stimulation associated with unconventional oil and gas developments should be done on a case-by-case basis.

12.5 Communication and transparency

It is evident that recommendations for the regulation and monitoring of hydraulic fracture stimulation with regard to the social surroundings are complex and inter-related with the scientific and technical conditions of unconventional oil and gas extraction processes. The 2015 Report of the Standing Committee on Environment and Public Affairs of the Western Australian Parliament (the 2015 Standing Committee Report) stated that future exploitation of unconventional gas resources in Western Australia must be on the basis that it is socially acceptable, as well as economically and geologically possible and sound.

It is clear that site specific factors have varying impacts on the acceptability, safety and intensity of unconventional oil and gas extraction activities. Aside from the proximity to people and communities, the underlying geology will influence the level of risk, and determine the technical demands of any hydraulic fracture stimulation process required and the outputs of that process.

However, it is evident there are knowledge gaps that need to be addressed to improve predictions regarding potential impacts on humans, social networks, amenity and livelihood, in order to build trust in the industry and those who regulate it. Information gathering should be transparently undertaken regularly by qualified, reliable, credible and independent experts.

It is important the cultural and social dimensions of society, especially in communities in proximity to oil and gas extraction operations, are given equal weight and recognition to those of the technical, and often more easily measured, sciences.

As noted by the 2015 Western Australia Standing Committee Report:

> "A recent CSIRO report found that Australians broadly accept mining, with a reasonably positive acceptance of the industry. The same survey, however, revealed a low level of trust of the industry and regulators among the community" (Western Australia Legislative Council Standing Committee on Environment and Public Affairs 2015)

Achieving trust is a long-term process that can be quickly extinguished if people or communities perceive their trust has been misguided or undermined. An intrinsic feature of trust is knowledge, and it is clear from the literature that objective, measured data and knowledge regarding the social surroundings is largely absent. Trust is also closely linked to credible and understandable communication and engagement with people. The 2015 Standing Committee Report recommended engagement with affected communities at the earliest opportunity and at every stage of an unconventional oil and gas development. After

reviewing the submissions to this Inquiry and the transcripts from the community meetings, communication, or rather its lack or irregular nature, regarding hydraulic fracture stimulation activities and potential impacts is a common theme. Inadequate information and poor communication for all activities regarding unconventional oil and gas extraction, risk assessment and the social surroundings should be redressed as a priority.

Recommendation 21: Risk assessments and accountable disclosure of risks should be transparent, timely and publicly available as a guiding principle underlying an enforceable Code of Practice.

Regular communication from government and industry should therefore be conducted with the community, especially those in localities most likely to be impacted by hydraulic fracture stimulation activities, at the earliest opportunity and throughout the lifecycle of the development. Communication should convey information in a manner that can be broadly understood. It should be objective, informative, transparent and sufficiently regular to be effective without being overwhelming.

Building trust so that the resource development company is viewed as a part of the community is essential. It was evident in Dongara that the Community Roundtable Workshops (see submission by AWE Limited) and an independent community facilitator had played an important role in conveying information, airing concerns, tabling questions to be answered by the relevant stakeholder and public responses to concerns and questions. Inevitably, things change with a project and not everything goes to plan, but if regular information is trusted and expected, change is more easily accepted.

In his submission to the Inquiry, the Australian Government Chief Scientist, Alan Finkel, stated:

"By providing easily accessible data, the public will be in a better position to reach informed decisions" – submission from the Australian Government Chief Scientist

As noted at the Dongara public meeting, websites and intermittent email contact with the community 'just doesn't cut it'.

Finding 53: Regular communication with the community by both companies and government at the earliest opportunity is more likely to engender trust.

Recommendation 22: Communication and engagement with affected communities should be a priority at the earliest opportunity and at every stage of an unconventional oil and gas development associated with hydraulic fracture stimulation.

Recognising the importance of effective communication underpinning informed consent, the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory recommended interpreters be made available to those Aboriginal people for whom English is not their first language. This consideration should also be incorporated in Western Australia when communicating with Traditional Owners groups for whom English is not their first language.

Recommendation 23: Communication with Aboriginal people should be conducted by trusted informants in a language commonly used and understood by the local people. If English is not commonly used, then translators should be available to convey information.

12.6 Amenity and aesthetic impacts

Any change in the way land is used, especially on a large scale, is likely to interrupt the way that space is used and enjoyed. This may include land zonings, forms and spatial control of the built environment, and the emergence of changed landscapes (Everingham, Devenin & Collins 2015). Pipelines, telecommunication towers, mine tailings dumps and dams all interfere with amenity, especially in places where bucolic agricultural vistas and bushland have been the norm. A growing literature from elsewhere in Australia, focusing principally on the Surat Basin in Queensland and the Hunter River region in New South Wales, document land use conflict between rural residents, particularly farmers, and the CSG industry (Everingham, Devenin & Collins 2015; Fleming & Measham 2014; McManus 2008; Measham, Fleming & Schandl 2016). Bushland and the amenity associated with access to nature have also been reported to be compromised by resource extraction activities (Porter, Franks & Everingham 2013; Uhlmann et al. 2014). The pace and scale of gas production in Queensland in particular, with little consultation or communication from industry or government, took communities by surprise. Many long-standing community members felt their community and its amenity was violated by the gas industry. As explained by Everingham *et al*.:

> "The changes to the physical space of the Darling Downs … is accompanied by a sense of dispossession and disempowerment" (Everingham, Devenin & Collins 2015).

Increased vehicular movements, noise, dust and general 'busy-ness' changes how people enjoy particular places, especially if they have an aesthetic, cultural or heritage value. The rapid expansion of the gas industry in the Surat Basin reportedly changed the amenity of some towns, which previously were typical broadacre service towns.

In the case of the Hunter Valley, the gas industry was in conflict with the premium wine and premier horse breeding industries, both of which have considerable aesthetic appeal. A landmark ruling in 2013 in the New South Wales Land and Environment Court favoured local residents over the State Government and Rio Tinto because the judge could not be persuaded that the impacts on biological diversity and the social fabric of the small town of

Bulga in the Hunter Valley were exceeded by the potential economic outcomes of an expansion of a coal mine (ABC Radio 2013). The decision was later overturned (in 2016).

The local amenity and the livelihoods of the thoroughbred and wine industries in the Hunter Valley were cited as potentially compromised by the coal and CSG industries in New South Wales from dust and depletion of water supply (McManus 2008).

Experience shows that the **direct footprint** of resource extraction immediately impacts on the landscape and often expands over time (Huth et al. 2014; Phelan & Jacobs 2016; Porter, Franks & Everingham 2013). Although dependent upon the local quality and quantity of the resource and the regulations in place, basic economics dictate that economies of scale often drive expansion, particularly as the resource depletes. This results in more land being required to produce the same amount of resource and more land for waste management.

'Densification' is a term used to describe densely populated hydraulic fracture stimulation well pads across a landscape, which when viewed from air, incorporates a maze of tracks and roads accessing the well pads, as shown in **Figure 12.3** at Chinchilla, in the Surat Basin. As noted earlier in this Report (**Section 5.3**), the significant technologies associated with CSG result in much higher-density well pads than those expected in the development of shale or tight oil and gas resources within Western Australia. Experience from the Surat Basin may in part explain local concerns over potential land use conflicts arising from the development of unconventional resources in Western Australia, even if in fact such density of infrastructure is highly unlikely. The CSG well pads shown are located in productive and high value agricultural land, prized for intensive and broadacre agricultural production. Intense land use conflicts have occurred over the last decade between Queensland local farmers, environmental action groups and mining companies (Fleming & Measham 2014; Greer, Talbot & Lockie 2011; Petkova et al. 2009), with claims that quality agricultural land is 'locked up' by mining companies for non-productive uses. Pipes snaking across the landscape have reduced the availability of land for agriculture and complicated access to the landscape (Lacey & Lamont 2014; Measham & Fleming 2014). In addition, it is claimed that mining activities mar the aesthetic appeal of the landscape, which has been occupied by farmers for 150 years. A submission by a resident of Moora stated:

> *"There is strong evidence of pipelines, roads, traffic, weed contamination, gates being left open, stock getting caught up in drainage areas"* – submission from Juanita Farley

In the case of Queensland, many of these adverse impacts have been retrospectively addressed so that pipelines are now buried and follow fence lines, access roads are developed in collaboration with local landholders and agricultural specialists to minimise environmental impacts, and large tracts of productive land are not 'locked up' by the gas companies.

Figure 12.3: CSG wells near Chinchilla, Surat Basin, Queensland 2011
Source: ABC News (ABC News 2011)

Moran and Brereton (Moran & Brereton 2013) document the impact of 'densification' through the relationship between aggregate community complaints information and visual amenity over time in the Upper Hunter Valley in New South Wales. New road networks were perceived as 'scarring' the topography of the local landscape, especially by indiscriminate tracks made by exploration teams with little heed for the environmental or aesthetic impact they were having on the landscape.

'Desertification' in the Surat Basin (Queensland) and the Hunter Valley (New South Wales) was also recorded as an outcome of unconventional gas extraction due to the depletion of local water resources, creating dust issues but also a browning of the landscape (Greer, Talbot & Lockie 2011). By 2010, drought conditions abated and local water supplies were replenished. In 2018, water shortages are more to do with intermittent summer rains rather than interference with the water supplies through gas extraction (*pers. conv. 2018).* In Queensland, gas companies are increasingly cognisant of the sensitivity of water usage and there are examples of farmers and gas companies entering into shared water arrangements whereby the water used by gas companies is remediated and used for beef feedlots.

The introduction of pests, especially weeds, due to increased vehicular movement has been reported in the United States, marring the landscape (Bergquist et al. 2007) and adversely impacting on agricultural production (Uhlmann et al. 2014). Weed control has also been a concern in Queensland and New South Wales. Farmers and farm peak bodies have imposed

strict conditions for vehicle access, and it would appear farmers and gas company contractors and employees now consider these acceptable.

While it would be foolhardy to dismiss the experience and information about the impact of the CSG industry on communities and the social surroundings of other places, it is also scientifically inappropriate to extrapolate the outcomes of one industry in different contextual settings and presume that the same outcomes will be expected for another industry in entirely different environmental, social and geological conditions.

Finding 54: Coal Seam Gas (CSG) extraction and that of shale and tight oil and gas are materially different. The characteristics of the site, the resource, the location and numerous social conditions dictate the potential interface between the hydraulic fracture stimulation activities and the social surroundings.

Unconventional CSG extraction in Australia has occurred in relatively populated rural communities in the Surat Basin and the Hunter Valley and, as a result, the impacts of the industry have been felt more intensely. In Western Australia, onshore oil and gas extraction (with and without hydraulic fracture stimulation) has, to date, occurred in both rural and remote communities with mixed reception. While remote locations in the Kimberley region are noted for their extraordinary and unique beauty, the locations of gas wells are confined to geographic locations and pastoral leases with few people or domestic animals. However, the sites and potential sites in the Midwest and northern Wheatbelt are within close proximity to farms and towns (such as Dongara), and considerably more people are likely to notice and experience aesthetic and amenity changes.

Two companies that propose to extract unconventional oil and gas in Western Australia outlined in their submissions how they work to reduce the topographical scarring of the landscape by minimising well heads and locating well heads at significant distance from each other. In its submission, Buru Energy explain that by building 'superpads' with up to 40 wells drilled from one surface well head, which is achievable in the Kimberley, the topographical impact can be minimised. However, Buru Energy plans a less intensive development of up to 10 horizontal wells drilled from a single pad.

Finder Shale is also cognisant of the topographical and amenity impact of multiple surface well heads and plans to use a single eight horizontal well surface pad, with the stated intention of reducing surface impacts from access roads, flowlines and water storage facilities. The distance between Finder Shale well pads is expected to be a minimum of 3.3 km thus obviating the perception of 'densification'. It is intended that the reduced disturbance and smaller footprint have optimal rehabilitation outcomes when the wells are redundant. In contrast to the Queensland experience, Finder Shale claim that the use of multi-horizontal wells per single pad enables other land users such as pastoralists to comfortably co-exist with hydraulic fracture stimulation activities. The Finder Shale well site

is located in a particularly isolated location with no nearby populations, private properties, reserves, or national parks, in contrast to the Surat Basin and Hunter River region.

It is up to the regulators to monitor and ensure that companies abide by the agreements, and communicate to the community that the companies are held to account and do what they agreed to do.

Compromise of the amenity and attractiveness of the landscape by resource extraction activities is a risk if those activities are adversely experienced or observed by members of the public, particularly those not involved in the unconventional oil and gas industry. 'Densification' of oil and gas wells and the infrastructure around them, indiscriminate tracks and scarring of the topography, erosion and changing of the landscape are all potential risks to the amenity and aesthetic enjoyment of the landscape from hydraulic fracture stimulation.

It is important to note, and as was made clear in many submissions, local residents of a place consider their experiences, aspirations and knowledge should take precedence over those people who have opinions about unconventional oil and gas operations but do not have the connection to place. How this dilemma can be incorporated into risk assessment will take careful consideration.

Landscape features of particularly high aesthetic or cultural value become a particular focus for concern. Natural water features, such as waterholes and rivers, are relatively scarce in Western Australia and where they do exist they are often highly valued, not only for their utility but also for their amenity and aesthetic qualities. Riparian landscapes usually attract wildlife and an abundance of flora, which are important for biodiversity but they also have an aesthetic quality. These and other places have high visitations independent of mining and extraction activities so the potential for negative consequences to amenity and aesthetic enjoyment from resource development are high, and demand close consideration of measures to avoid or minimise impacts.

Recommendation 24: Amenity and what constitutes aesthetic enjoyment, or a sense of place, as determined by people who live in the communities proximate to hydraulic fracture stimulation activities, should be systematically and scientifically documented from the commencement of a hydraulic fracture stimulation project involving multiple well sites (moving from the exploration phase into the development and production phases). Baseline information and site-specific data collection should be a priority and systematically monitored and updated.

Reference to the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory and Risk Assessment

The terms of reference of the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory (Northern Territory Government 2018) were broad in scope and investigated a range of issues regarding the current and potential socio-economic impacts of hydraulic fracture stimulation and onshore gas extraction, not all of which are within the scope of this Inquiry. This Inquiry addresses the social surroundings as determined by the environmental protection legislation in Western Australia. Nonetheless, there are several conclusions and recommendations from the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory that overlap with the findings of this Inquiry:

- Site-specific factors can either increase or decrease the level of risk that can be posed by their use;
- Acknowledgement of the knowledge gaps that need to be addressed to improve predictions regarding potential impacts humans, social networks, amenity and livelihood;
- Aboriginal Dreaming about a place is holistic; there is no separation between subsurface sites and the topographical surface. Below ground water sources are as spiritually embedded as anywhere else. The Aboriginal spiritual connections and interpretation of place are an important consideration regarding beneficial use and aesthetic appreciation for the social surroundings; and
- How information is communicated to all stakeholders, most especially those whose land is more likely to be impacted by decisions regarding unconventional oil and gas extraction activities, must be easily understood and well documented. The services of a translator should be readily available for those for whom English is a second or alternative language. Developing trusted communication tools and practices underpin several recommendations regarding how people are given information about hydraulic fracturing activities, potential risks, risk management strategies and other stakeholders. Their recommendations are neither unique nor particular to unconventional oil and gas extraction activities, nor are they directed only at mining and/or unconventional gas companies. All stakeholders, including government, industry, land councils, activists, community 'locals' and land owners are relevant 'communities of interest' and therefore have a central role in strategic engagement, including prescient, appropriate, accurate and regular communication.

With regard to social impacts, the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory also highlighted the importance of early and regular engagement with affected communities and recommended regular, ongoing and systematic monitoring and measurement of social and cumulative impacts of a range of indicators, including many that fall into the category this Inquiry refers to as social surroundings.

12.7 Land access

Concerns have been raised by property owners in Western Australia (see the submission by the Kimberley Pilbara Cattlemen's Association submission) and elsewhere regarding the autonomy they have over their land and potential conflicts over land use (Everingham, Devenin & Collins 2015). Some Western Australian landowners look to the intrusive practices of resource company employees, particularly in New South Wales and Queensland, who have been granted exploratory licences and who access property with limited negotiation and little regard for livestock management, farm practices, topographical disturbance, weed and feral animal management or vehicular damage to land. The Queensland Gasfields Commission addressed this issue following the Scott Review (Scott 2016): regulations for improving the information available to landholders with regard to land access, negotiation with CSG companies and complaints against those companies were revised in 2017.

The Queensland Gasfields Commission, in their review of best practice regarding negotiations between landholders (usually farmers or pastoralists) and gas companies acknowledge that:

> "land access is a business-to-business relationship. Landholders enable resources to be developed on behalf of the community and there must be mutual knowledge of, and respect for, the businesses that are competing for access to and use of scare resources such as productive land and water" (Queensland Gasfields Commission 2017)

Weed control is increasingly standard practice for gas companies and farmers monitor access and weed control. Queensland peak agricultural organisation representatives report that the arrangements now are more respectful and workable.

Finding 55: There must be mutual knowledge of, and respect for, the businesses that are competing for access to and use of scarce resources such as productive land and water.

The Kimberley Pilbara Cattlemen's Association and Aboriginal groups in the Kimberley indicated their willingness to work collaboratively with petroleum industries but they were also keen to ensure autonomy (the right to veto activities) and stronger protection for their pastoral livelihoods, including access. Biosecurity was highlighted as a particular concern in the submission from Yawuru and also for some pastoralists.

Other submissions, many of which do not appear to have any direct link to the regions where hydraulic fracture stimulation activities occur or may occur in the future, raised concerns about the lack of control farmers and pastoralists have over their land, and who has access to it.

> *"Landholders may have no control as to where these structures are located on their property. Once this infrastructure is in place, restoring the natural landscape and restoring farm productivity is highly unlikely to occur"* – submission from Joan Sharpe

Some submissions were not factually correct, for example, one that implied that gas companies could displace farmers and Traditional Owners from their lands. There are farmers who want to engage with unconventional gas extraction companies and negotiate commercial access arrangements that offer business diversification opportunities and potential flow-on benefits for local communities. The Pastoralists and Graziers Association of Western Australia (PGA) submission to this Inquiry made it explicit that:

> *"entities have a fundamental right to access resources to which they have rights to under the law. In the case of post-Federation freehold primary producers, a HFS company with rights to a gas field have the right to access that gas field but must negotiate in good faith with the land owner for that access. The goal of such negotiations should be a mutually agreeable and beneficial contract"* – submission from Pastoralists and Graziers Association

The dimensions of some of the gas facilities are much bigger than some farmers envisaged, especially in the Surat Basin,(Everingham, Devenin & Collins 2015; Moffat & Zhang 2014; Queensland Gasfields Commission 2017). Initial pipelines hindered access and interfered with farming practices. Through negotiation and guidelines initiated through the Queensland Gasfields Commission, this has been addressed and remediated, where required.

In Western Australia, under the *Mining Act 1978*, landowners can also apply to have agricultural land (including private land under cultivation or other improvements) excised from a mining tenement application. For the specific details see Section 29(2) of the *Mining Act 1978*. The *Petroleum and Geothermal Energy Resources Act 1967* (PGER Act) does not have a provision requiring private land owner permission to enter land if the land is used for agricultural purposes (as described in the *Mining Act 1978*).

Finding 56: Broader excision provisions under the *Petroleum Geothermal Energy Resources Act 1967* (PGER Act) would give agricultural landowners, managers and leaseholders greater certainty as well as a greater sense of involvement in the licence process. For smaller scale operations or a well pad that may later be plugged and abandoned, a lease arrangement would seem the most appropriate arrangement.

A submission from Shane Love MLA, Member for Moore, noted the National Party of Western Australia (the Nationals WA) recommendation for amendments to the PGER Act to include a 'right of veto' to protect landholders' interests from exploration and production by commercial onshore oil and gas operators. This suggestion was also raised in submissions to the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory (Northern Territory Government 2018) but subsequently dismissed as legally unworkable.

12.8 Competition for social infrastructure

The offsite footprint of resource extraction has a social impact (Sonter et al. 2014). Competition for often unsealed roads in rural and regional settings has a social and economic cost, the latter often underwritten by local government authorities or individuals. As documented by Sonter et al. (Sonter et al. 2014) in the Bowen Basin coal region in Queensland, increased traffic transporting resource company needs and a growing workforce resulted in the need for significant upgrades of the region's road network. Similar impacts have been reported elsewhere (The Academy of Medicine Engineering and Science of Texas 2017). The Texas report acknowledges that the most intensive usage of roads is during the construction phase but the potential damage to road networks not built for the frequency and/or the weight of trucks, is dangerous for all traffic. School bus networks and the safety of children catching school buses on country roads are potentially compromised without strict management of increased road usage by resource companies and their employees and contractors. The experience in Texas, Queensland and northern New South Wales is that the demands on transportation infrastructure and the potential impacts on traffic safety from the oil and gas industry area is under-estimated and not addressed until significant damage is done.

Remediation of roads is an inconvenience for everyone and in the Texas experience, road infrastructure funding and compensation is low compared to the magnitude of the impact (The Academy of Medicine Engineering and Science of Texas 2017). There is evidence that gas companies in the Surat Basin are responsible for upgrading road infrastructure (Moffat & Zhang 2014) and work with local authorities to mitigate their impact. However, it is often the patchiness of responses to infrastructure pressures created by the resources industries, that causes greatest angst within the community (Measham, Fleming & Schandl 2016; Zhang & Moffat 2015). One community receiving road infrastructure while another misses out, depending upon companies and local conditions, causes unnecessary antagonism and resentment.

Finding 57: Increased demand for services and infrastructure, for example, transportation networks, both for product and workforce use has a physical and social impact.

The concerns regarding the competition for social infrastructure will be examined in more detail later in this Section.

12.9 Community health

Human health and potential impacts from hydraulic fracture stimulation are addressed in Section 11 (Public Health). This section addresses community health and considers the direct and indirect environmental and social impacts of resource development on communities. These impacts are often not easily captured by current management approaches or licensing conditions. As noted by Sonter et al. (Sonter et al. 2014) impacts caused by the direct footprint of resource extraction have received significant attention in the literature and they are the subject of impact assessments and licensing conditions, within which resource companies are required to avoid, minimise, rehabilitate or offset these impacts. However, some offsite, indirect impacts and even the threat of impacts have been shown to have a social impact, although these are not necessarily recognised or acknowledged as legitimate when mining or petroleum licences are granted. It is well documented (McGee 1999; Measham & Fleming 2014; Measham, Fleming & Schandl 2016; Norris et al. 2008) and also highlighted in the submission to this Inquiry from Professor Carmen Lawrence that widespread psychological stress can adversely affect individual and community wellness and adaptive capacity, undermining resilience and contributing to cumulative dysfunction (Norris et al. 2008). Furthermore, Sonter et al. considered that:

> "the challenges in managing these impacts are associated with assigning responsibility, since a direct link between cause and impact cannot always be easily established; however, overlooking them will have significant implications for achieving sustainable outcomes" (Sonter et al. 2014)

Similar sentiments were presented in the submission to the Inquiry from Peter Limb.

Part of the problem is because social and cultural impacts and/or quality of life concerns are often mentioned in community health literature, especially those connected with hydraulic fracture stimulation activities, but rarely are the impacts measured (Mayer 2017; Werner et al. 2015). The United States Centre for Disease Control (U.S. Centre for Disease Control 2016) defines quality of life as 'a broad, multidimensional concept that usually includes subjective evaluations of both positive and negative aspects of life'. While its subjectivity may compromise specificity, quality of life is accepted as an important function of mental health and increasingly, the links between a person's physical health and mental health are measurable (Lai et al. 2017; U.S. Centers for Disease Control and Prevention 2000). The submission to this Inquiry from Professor Carmen Lawrence states that:

> *"it is inherently difficult to assess the impact of unconventional gas exploitation (and similar resource exploitation) on human wellbeing, especially via changes to culture and community, since multiple influences are in play and effects are likely to take place over long time frames"* – submission from Professor Carmen Lawrence

Finding 58: Social and cultural impacts influence perceptions of quality of life. Quality of life is accepted as an important function of mental health.

At a community level, measurement of quality of life is more complex but no less important. Air and water pollution are relatively easily measured risks (Werner et al. 2015). More complex concepts are social capital, community trust, stress levels and sense of place, which are recognised as key elements for quality of community life (Britton & Denning 2006; Bureau of Transport and Regional Economics 2005; Mayer 2017) and for some, essential for a functional community (Edwards & Onyx 2007) and community health. However, these important social pillars are difficult to measure and as documented by Werner et al., (Werner et al. 2015) baseline data is not routinely collected for the purposes of measuring social impacts. Consequently, despite its accepted importance for community health, quality of life is rarely measured in a comprehensive way (Mayer 2017) and is often overlooked when planning a resource development life cycle.

The pace of development of unconventional gas in Australia and other countries over the last decade has caused considerable disquiet at local levels (Everingham, Devenin & Collins 2015; Kreuze, Schelly & Norman 2016; Queensland Gasfields Commission 2017). There is broad concern that the technical advances of the industry and the political and economic expediency of gas as an energy source have trumped social and health cautionary measures. As documented by Kreuze et al. (Kreuze, Schelly & Norman 2016) the expressed benefits of new resource extraction technologies such as horizontal drilling technologies usually focus on the economic and efficiency benefits and immediately measurable environmental impacts, but the longer term, cumulative outcomes, including human and community health, are often overlooked or the risk liability considered too esoteric. Cumulative impacts are discussed in more detail later in Section 12.14.

As noted earlier, in Queensland it is not only the scale of the unconventional gas industry that has made people and communities apprehensive but the rapidity of the change in the landscape; it has been described as ‘a tsunami of change’ (Queensland Gasfields Commission 2017; Walton et al. 2013). Lai et al. (Lai et al. 2017) document and measure the intensity of meanings associated with rural landscapes in particular, both at personal and community levels, through senses of identity, community cohesiveness and ecosystem health. In his submission, Peter Limb, cites examples in Queensland where farmers’ rural identity was not well understood by CSG staff from non-rural backgrounds, which caused dissention and even conflict. The United States literature, particularly that from Pennsylvania (Donnelly, Cobbinah Wilson & Oduro Appiah 2017; Jacquet 2012; Malin 2014) and Texas (The Academy of Medicine Engineering and Science of Texas 2017), document the sense of trauma some residents experienced as their communities transitioned from rural communities into an industrial landscape. Studies from the Surat Basin and Hunter River regions in Australia convey similar sentiments (Everingham, Devenin & Collins 2015; Fleming & Measham 2014; Moffat & Zhang 2014; Uhlmann et al. 2014).

"Residents' psychological stress can begin to overwhelm when a proposed use of land is perceived to threaten or harm the area and valued resources; and when such a perception continues unabated and coping strategies adopted by residents individually or collectively fail to result in desirable outcomes" (Lai et al. 2017)

Deleterious physical and social outcomes can ultimately have negative economic impacts. It is important to acknowledge the submissions to this Inquiry from people living in locations where hydraulic fracture stimulation already occurs, who feel they have been pressured and even bullied by others about their opinions regarding hydraulic fracture stimulation, causing considerable discomfort and even conflict. In his submission, Robert Locke, a local long-term resident of the Broome Shire wrote:

"I support hydraulic fracture stimulation. I do not support green activist groups coming into Broome, causing division and fear, spreading misinformation, and leaving the long term residents to put up with poor employment prospects and poor infrastructure that otherwise exists with a strong and robust economy" - submission from Robert Locke

In his submission to the Inquiry, George Morris wrote:

"environmental activists who have come here only recently, who do not pay shire rates, do not pay tax, do not employ people, do not invest in the town, and stir up considerable community angst about resource projects" – submission from George Morris

The Inquiry received a proforma from Broome residents that stated:

"anti-fracking antagonist groups target and prey upon vulnerable groups, such as remote Indigenous communities and remote pastoralists who may have limited knowledge of the industry and the science involved and be easily misled or influenced by misinformation intended to instil heightened fear and anxiety" – Broome residents proforma

In a presentation from the PGA, the Inquiry was told of farmers who had agreed to allow hydraulic fracture stimulation activities on their farms, and who were subsequently pilloried by activists and ostracised by neighbours and others in their communities for allowing it.

"They [activists] bully neighbours and spread misinformation causing divisions in small places [communities]. They [activists] don't have to live with the consequences of their actions" – submission from Pastoralists and Graziers Association

In their presentation, Lock the Gate told a similar story but about resource companies exerting pressure on landowners to allow hydraulic fracture stimulation on their properties, using legal tactics, and bullying and threatening language and behaviour to wear down property owners. In their submission, Lock the Gate recite numerous examples of landowners being intimidated and coerced by lawyers on behalf of gas companies, including

the experience of a Queensland farmer who was persistently bullied by gas companies causing considerable stress and a sense of 'invasion', behaviour which was ultimately blamed for his suicide. In the Kimberley, Lock the Gate document a Kimberley Aboriginal man's experience of 'intimidation and bullying from the fracking industry' and his sadness regarding indiscriminate clearing and fencing by gas companies on his people's land.

"Lock the Gate has spent time with Micklo on his country visiting the fracking wells and hearing the stories of intimidation and bullying from the fracking industry" – submission from Lock the Gate

Finding 59: The passionate and emotional debate and conflict regarding hydraulic fracture stimulation itself has potential psychological and physical ramifications to individual and community well-being.

Services and facilities have been recognised in community psychology and regional development literature as main drivers of community wellbeing (Moffat & Zhang 2014; Norris et al. 2008; Onyx & Bullen 2000; Walton, Williams & Leonard 2017; Zhang & Moffat 2015). Concerns regarding population influx from construction and extractive activities, and likely pressures on already under-resourced support and health services and facilities were raised at community consultation meetings and in numerous submissions to the Inquiry (see submission from Peter Limb).

A submission from Shane Love, MLA stated:

"the rate of change would be logarithmic as operations are scaled up" – submission from Shane Love MLA, Member for Moore

Increased demand for services without the commensurate increase in staff and resources were viewed as a potential threat to the personal health of residents and 'the thin end of the wedge'.

There were many submissions, like that provided by Catrina Scatena, which outlined fears that their local communities would experience conflict and irrevocable change from the inflow of people who are not 'local'.

At the Dandaragan meeting, some participants recounted warnings from visitors from the United States Midwest who told of the inconvenience and occasional social conflicts associated with hydraulic fracturing industry 'outsiders', whose expectations regarding services and facilities were urban-based. This aligns with the work undertaken by Everington et al. (Everingham, Devenin & Collins 2015) and Moffat and Zhang (Moffat & Zhang 2014; Zhang & Moffat 2015) measuring community spirit, cohesion and trust in the Surat Basin, and residents reporting they feel 'descended upon' and 'overwhelmed'. Jacquet (Jacquet

2012) and Krueze et al. (Kreuze, Schelly & Norman 2016) documented similar concerns across several states in the United States where the 'influx of newcomers can change social structure and community identity, which can lead to increased stress, tensions, disagreements and an overall reduced quality of life' (Kreuze, Schelly & Norman 2016).

The lived experience of people from the Kimberley where hydraulic fracture stimulation has occurred over an extended period does not appear to bear out some of the claims made in submissions. Furthermore, the submissions from industry groups suggest that the geology and environmental context of the resources in Western Australia do not support the intensive extraction activities suggested by many of the submission authors. Several submissions from individuals and Aboriginal groups overtly stated they wanted the hydraulic fracturing industry to expand so that more people would visit or reside locally and therefore increase demand for the services of local businesses. A submission from James Knight suggested that the hydraulic fracturing industry would be welcome in the Kimberley and especially Broome because it would mean more local jobs and improved local infrastructure.

A submission from the Yungngora Aboriginal Corporation noted the increased work opportunities and income derived from jobs offered by Buru Energy and Mitsubishi at Noonkanbah:

> *"we have had a good partnership with Buru and Mitsubishi on the project. Buru has done a lot of work on our country and have got our people involved. It has been good working alongside Buru, helping them out and keeping an eye on things. Our people like and are good at the work. Driving machines and working on site, keeping an eye on security and helping out in the camp. Having good jobs that are close to home so people can come home and see their families during their days off is important to us. Buru has also trained up some of our young people as rangers. They have been helping Buru out with water monitoring for a few years now……We need jobs and training for our young people so that Noonkanbah goes ahead"* – submission from Yungngora Aboriginal community

Research (Curran 2017; Moffat & Zhang 2014; Zhang & Moffat 2015) and experience (Queensland Gasfields Commission 2017) shows that many of the issues can be mitigated by early and consistent engagement with the community by government and gas companies.

> By addressing public demands for higher transparency and accountability standards, and greater community input into projects that impact them, social licence [8] helps operationalise corporate social responsibility in the mining industry (Curran 2017)

[8] Social licence to operate refers to the ongoing acceptance and approval of a development, project or action, by local community members and other relevant stakeholders.

To date, the scale of work and therefore workforce influx has not occurred in the places where hydraulic fracture stimulation has been carried out in Western Australia. However, the message that early, regular and consistent messaging, and contact with the relevant communities regarding intentions, future and current development and potential impacts is clearly one to be heeded if trust and social licence to operate are to be achieved. As noted by Norris et al. (Norris et al. 2008), unpredictability and 'surprise' erode community resilience. It is documented elsewhere in this Report and later in this Section regarding cumulative impacts, that in the absence of a clear understanding of a projected proposal's scale, infrastructure and context, community members and decision makers resort to experiences elsewhere. They draw on these experiences and an imagined project outcome to inform their perceptions of the project and its impacts, potentially leading to psychological stress and community opposition. This links to the earlier observation that knowledge gaps, particularly with regard to the social surroundings need to be addressed to improve predictions about the outcomes and impacts of hydraulic fracturing activity.

Finding 60: In the absence of a clear understanding of a projected proposal's scale, infrastructure and context, community members and decision makers resort to experiences elsewhere and an imagined project outcome to inform their perceptions of the project and its impacts, potentially leading to psychological stress and community opposition.

It is evident that community trust, social capital and sense of place all have the potential to mitigate stress at both the community and individual levels (Benham 2016; Jacquet 2014; Lacey & Lamont 2014; Lai et al. 2017; Mayer 2017). Again, the scale of change is an important determinant of distress and social dislocation.

It was evident at the public meetings and in some submissions that considerable emphasis is placed on the scientific dimensions of a hydraulic fracture stimulation and unconventional oil and gas project and not enough on the social aspects, particularly by government. The role of government as a trusted overseer of hydraulic fracture stimulation activities does not appear to be appreciated by all in the public domain. More effort must be made by both government and companies to accurately and regularly convey a projected proposal's scale, infrastructure and context and ensure that communication is indeed working. Too little information or information that can be misinterpreted provides opportunity for suspicion, fear and misinformation.

An integral feature of social capital is connectedness. Community leaders, government and companies all have a role to ensure there are opportunities for creating and bridging social capital:

> "bridging social capital are social ties across group boundaries, particularly differences in social status" (Mayer 2017)

The notion of 'social licence to operate' has a role to play in mitigating mental health and public safety issues. As noted at the beginning of this Section, this Inquiry's Terms of Reference, technically, does not extend to social benefits, and therefore to the broader consideration of industry's social licence to operate. Yet, these dimensions were prominent among the public concerns and comments received by the Panel. While the focus of considerations throughout this Report remain on potential impacts on the community through harm to the environment, the Panel considers it is important to also consider and comment on broader issues such as social licence to operate.

There is a vast literature regarding social licence to operate including considerable scientific assessment of its utility in Australia in communities associated with hydraulic fracture stimulation activities (Bice 2014; Cheshire, Everingham & Pattenden 2011; Everingham 2007; KPMG 2013; Lacey & Lamont 2014; Measham et al. 2013; Measham, Fleming & Schandl 2016; Moffat & Zhang 2014; Zhang et al. 2015; Zhang & Moffat 2015). The core thesis is that a social contract exists: a system of implicit and explicit principles and/rules determining how corporate partners and an entire community should treat each other and their expectations of each other. Importantly, social licence to operate is not a 'one-off' agreement but rather, it requires ongoing renewal and approval. More formally, consent has been used in relation to the resources industry with respect to the role of free, prior and informed consent. Social licence to operate however, tends to be less binding and is premised on a broad-based social agreement of procedural fairness and consensus.

With reference to community mental health, social licence to operate can only be achieved through an iterative process that takes time, regular and appropriate communication and mutual understanding. In New South Wales, an independent review of CSG and social licence to operate, showed that effective agreements were based on:

> "establishing comprehensive environmental baseline data prior to the commencement of large scale CSG projects and commissioning studies into landholder rights and compensation models, and potential health risks" (Lacey & Lamont 2014)

Another finding of this review found that the New South Wales Government also had to work harder to build trust with its citizens in its capacity to manage, monitor and regulate the industry (Engineer 2013).

In Queensland, social impact assessments (SIA) have been mandated to encourage social licence to operate but the outcomes have been contentious. The top-down approach has been criticised for being overly prescriptive and a forced process. SIA guidelines have been modified numerous times, none of which appear to have worked, with community and industry scepticism regarding their intent and efficacy (de Rijke 2013). The breakthrough came with the establishment of the Queensland Gasfields Commission in 2012 through the *Gasfields Commission Act 2013*. It is tasked with 'managing and improving sustainable co-

existence between rural landholders, regional communities and the onshore gas industry' (Queensland Gasfields Commission 2017). The Act enables the Commission to:

- Review the effectiveness of legislation and regulation;
- Obtain and publish factual information;
- Identify and advise on co-existence issues;
- Convene parties for the purpose of resolving issues;
- Promote scientific research to address knowledge gaps; and
- Make recommendations to government and industry.

Since its inception, there has been a positive response by the oil and gas industry and a significant decrease in the number of community and individual complaints. There has also been an increased confidence in the regulatory environment with oversight of the gas industry in Queensland. In 2016, there was an independent review of the Commission and the Queensland Government accepted 68 of the 69 recommendations to further refine the Commission's functions to ensure a harmonious relationship between the CSG industry and other land uses (Scott 2016).

It is clear that achieving social licence to operate is not a quick fix and requires investment in time and commitment to mutual obligations from the earliest opportunity. However, evidence shows that achieving social licence to operate has multiple benefits (Kapelus 2002; Lacey & Lamont 2014; Székely 2006). Even if mandating SIA and social licence to operate does not work, greater awareness of social licence to operate and public expectation of it would have significant benefit.

Discussions at the public meeting at Noonkanbah and submissions to this Inquiry show there is evidence of trust being developed between the Aboriginal people at Noonkanbah and the gas companies:

> *"Buru Energy have been around a long time and we trust them. … We have had a good partnership with Buru and Mitsubishi on the project. Buru has done a lot of work on our country and have got our people involved"* – submission from Yungngora Aboriginal Community

There are also signs there are efforts between Yawuru and other stakeholders to 'show respect and ask first'; slowly relationships are being built. The Native Title Tribunal have commended Yawuru on their approach to community engagement after attending a forum hosted by Yawuru leaders.

Finding 61: Social licence to operate is increasingly an expected part of the resource development lifecycle. Governments and other stakeholders, including activists, also have an obligation to demonstrate their commitment to social licence to operate.

Recommendation 25: Petroleum companies' commitment to building moral consent should be part of the assessment for licence procedures.

Recommendation 26: There should be a clear point of contact within Government for complaints or concerns to enhance social licence to operate.

12.10 Public safety

Maintaining water supplies and preserving water and air safety are concerns for almost all contributors to this Inquiry. Key issues around air and water quality are addressed in other Sections of this Report, specifically **Section 8** (Land), **Section 9** (Water) and **Section 11** (Public health). Nonetheless, there are issues associated with hydraulic fracture stimulation that may impact the social surroundings but which are not specifically addressed in the other Sections.

As noted by the Australian Government Chief Scientist, Dr Alan Finkel in his submission, the protection of water resources are a whole-of-society priority:

> *"I note the need for continued scientific work on water resources by Commonwealth agencies such as Geoscience Australia, CSIRO, and the Bureau of Meteorology, by State agencies, by university research groups, and by industry itself. I also note efforts by the Gas Industry Social and Environmental Research Alliance (GISERA) and the Queensland Office of Groundwater Impact Assessment to publish research on this topic"* – submission from the Australian Government Chief Scientist

In his submission, Finkel stressed the importance of information being readily available in language that is easily understood by the non-scientific community, thus reducing the risk of the dissemination of misinformation, fear and intimidation and therefore potentially contributing to stress. He also strongly advocated that information regarding the monitoring of resources should be easily accessible and easily understood by the public to enhance transparency and public confidence in the monitoring of hydraulic fracturing activities. This recommendation aligns with those suggested for Aboriginal heritage and reinforces the importance of timely, easily understood and pertinent communication for all stakeholders, particularly from government and unconventional oil and gas companies.

Social conditions may alter with the onset of particular environmental or economic changes contributing to vulnerability of industries and communities. The loss or diminished capacity of the community through the introduction or reduction of an industry sector has an impact on the community itself. In its submission, the Western Australian Department of Health makes the point that

"human health (epidemiological) studies have only used proximity as a surrogate for exposure" – submission from the Department of Health

As noted earlier, in Western Australia, the few hydraulic fracture stimulation activities in the Kimberley region currently operate in remote locations with limited human exposure. Scale of operations is also an important determinant of risk to public safety. On the overall risk profile, the small scale and remoteness of the activities and distance from human settlement gives them a low risk profile in relation to public safety

However, in the Midwest and northern Wheatbelt, there are higher population densities within proximity of hydraulic fracture stimulation activities and more intense agricultural production that depends on potable groundwater supply. The potential risk for public safety from increased hydraulic fracture stimulation activities is therefore higher in the Midwest and the northern Wheatbelt than is currently the case in the Kimberley region.

12.11 Noise, traffic and dust

The more people who live in proximity to hydraulic fracture stimulation sites, the higher the risk that the social surroundings will be impacted.

Increased vehicular activity, especially heavy duty vehicles associated with construction, drilling and hydraulic fracture stimulation operations is a potential risk to both amenity and safety, however context is clearly an important indicator of impact (see Department of Health Submission). Kreuze et al. (Kreuze, Schelly & Norman 2016) document that noise from trucks, drilling, generators, earth moving equipment and other well pad operations can disturb neighbours and in some cases animals. There is comprehensive literature regarding the potential social, physical and environmental impact of increased traffic, but many of the reports, particularly those linked with heavy trucks and industrial traffic, are highly variable in their results and estimates. For example, remoteness vis a vis proximity to a regional centre with a range of services and products, existing road infrastructure and the availability of groundwater for hydraulic fracture stimulation, (and hence the potential for less water transfer from elsewhere). It is also important to understand that traffic impacts are likely to vary considerably depending upon the stage of the development lifecycle. The construction phase is usually short-lived but likely to have intensive traffic activity that usually reduces significantly as the development shifts to the operational phase. Goodman et al. (Goodman et al. 2016) calculate that heavy vehicle movement noise levels effectively double at night in undeveloped areas, potentially affecting local residents' sleep patterns and comfort, therefore impacting on local amenity.

In Queensland's Surat Basin there have been concerns raised regarding compromised safety due to increased vehicular movements especially on unsealed or narrow country roads (Everingham, Devenin & Collins 2015). In numerous examples in the United States, increased heavy vehicle traffic has caused visible disruption and congestion on roads built for lighter traffic (Goodman et al. 2016; The Academy of Medicine Engineering and Science of Texas

2017). Delays and disruption to normal traffic patterns cause frustration and in some cases it was reported, dangerous situations as other road users use shortcuts and traffic violations to circumvent delays and traffic interruptions. Goodman et al. cite other issues including:

> "the increased incidence of [traffic] accidents involving direct injury and damage to property or accidental spillage of materials and/or chemicals" (Goodman et al. 2016)

As discussed earlier in this Section, heavy, over-width trucks present a hazard for other users and cause road infrastructure, especially surfaces and road edges to deteriorate quickly. Local governments, whose responsibility it is to maintain secondary and tertiary level roads, rarely have the resources to repair and maintain roads that are regularly degraded by heavy vehicles.

Recommendation 27: Baseline road use statistics measuring volumes of vehicle movements and the type of vehicles using road infrastructure should be undertaken before hydraulic fracture stimulation activities commence, and monitored at periodic intervals throughout the lifecycle of the development.

Local government usually has responsibility for the maintenance of roads, except main roads and arterial roads and bridges. Road maintenance is usually a major budgetary consideration for most rural and remote local government authorities, two thirds of which is unsealed (Department of Infrastructure and Regional Development 2013). Most local government authorities in rural, regional and remote localities are rarely able to afford the additional costs of maintenance associated with increased traffic generated by new resource extraction projects unless additional funds are sought from the proponents. In some cases, tracks and new roads are cut across land, damaging flora and creating dust and/or erosion unless properly maintained.

Recommendation 28: Roads regularly used by heavy vehicles should be upgraded (widened and sealed if necessary), with recompense from the proponent directed to local government authorities to assist with monitoring traffic usage of road infrastructure, road maintenance and upgrades.

The generation of excessive noise associated with hydraulic fracture stimulation is not limited to traffic. Werner et al. (Werner et al. 2015) identified noise pollution associated with engines, drilling, generators, radiator fans, pumps and compressors, which, in other jurisdictions (mainly in the United States), had caused problems for nearby residents. While for some, it was interference with amenity, for others there were health symptoms associated with low frequency noise exposure, which included headaches, stress, irritation, fatigue and disturbed sleep. In their submission to this Inquiry, Buru Energy has undertaken to limit the production of loud noise to daylight hours and only for short periods. Similarly,

Condor Energy suggest in their submission that noise levels at their proposed development will be well within acceptable levels, even without noise mitigation devices.

Vibration from hydraulic fracture stimulation activity has the potential to have a deleterious impact on the built environment and property. Dust generated from clearing, high vehicular traffic and lay-down areas are all potential risks associated with hydraulic fracturing activities. Dust has a nuisance factor but it can also have long-term detrimental effects on fauna and flora. Local residents living or working close to extraction activities are at risk, particularly those who suffer from respiratory complaints. See **Section 11** (Public health). Day-to-day amenity can be negatively impacted by dust intrusion. Werner et.al. (Werner et al. 2015) highlight in their review of environmental health impacts the stress induced by continuous illumination from vehicles and flaring for nearby residents.

Tourist facilities and businesses in a rural, regional and remote location near to hydraulic fracturing may also be adversely impacted by noise, dust and vibration.

Finding 62: Increased vehicular traffic associated with construction, drilling and hydraulic fracture stimulation operations is a potential risk to both amenity and safety. Noise, traffic and dust will increase from additional heavy and other vehicular traffic.

Finding 63: Proximity to people and the built environment heightens the risk of deleterious impacts from hydraulic fracture stimulation activities due to vibration, dust and noise.

Numerous submissions to this Inquiry cite examples, most based in the United States but also some from Queensland, where noise, traffic and dust have caused a disruption to the amenity of a locality and caused discomfort to people and in some cases their animals. In their submission, Lock the Gate provides a comprehensive citation of the impacts. Minimising the impacts and managing activities which generate these adverse outcomes is therefore a priority and regulations can address the deleterious impacts of noise, dust and traffic.

However, it is important to note that Werner et al., in their review of available studies for strength of evidence of environmental health impacts of unconventional natural gas development, found:

> "very few, if any, methodologically rigorous studies that have examined the cause-and-effect of unconventional natural gas development in the construct of hazard analyses, linked to exposure pathways and actual outcomes" (Werner et al. 2015)

They found that most of the 'highly relevant' studies cannot be described as scientifically rigorous due to methodological limitations such as measurement and selection bias. This is not to say that the social surroundings and other societal impacts should be dismissed or are

of secondary importance, but rather, their findings underscore the importance for baseline studies on infrastructure development, community resilience, amenity and quality of life to be conducted systematically from the commencement of, and scientifically monitored, throughout the resource development life cycle.

While the potential for direct impacts are more likely to be recognised early in the development life cycle, the indirect impacts are often less predictable and their outcomes less quickly measured and if necessary, addressed.

A potential indirect impact associated with increased traffic, especially in remote locations, is the competition for vehicle support services. For example, in Onslow in the North West of Western Australia, 90 kilometres from the main highway and 160 kilometres from the next nearest service station, the construction of onshore LNG infrastructure in the early 2000s caused the town's population to more than treble (Haslam McKenzie 2013). Petrol and other vehicle supplies regularly ran out, caused by intermittent increased demand, compromising residents' and visitors' safety and convenience.

A useful tool to assist communities and gas companies to measure and monitor impacts has been devised by the University of Queensland through their Boom Town Took Kit (see https://boomtown-toolkit.org/).

12.12 Heritage

Heritage includes a range of potential assets that are valued and in many cases contribute to a sense of community, identity and belonging. These assets may include architecture, artworks, objects, texts and music, as well as sites, places and even tastes. According to the Environmental Defender's Office of Western Australia, places of heritage significance have a cultural value or possess a special interest related to, or associated, with cultural heritage, and are of aesthetic, historic, scientific or social value for the present community and future generations (Environmental Defenders Office of Western Australia 2012).

Heritage crosses several government jurisdictions. A place can be registered with the *Heritage of Western Australia Act 1990*, which is linked with the Australian Government's Australian Heritage Council. Local government also has a role with the day-to-day planning protection of heritage sites through its planning schemes.

With regard to hydraulic fracture stimulation and unconventional oil and gas extraction, heritage legislation is likely to be invoked if there is a demonstrated threat to the aesthetic, historic, scientific or social value of a place. For example, induced seismicity, contamination or noise could all impact on a place of heritage significance.

Everingham et al. (Everingham, Devenin & Collins 2015) and McManus (McManus 2008) document agricultural heritage values in the Surat Basin and Hunter River regions, which are now being championed as social capital and used as a symbolic resource for regional identity, to recover some leverage from the increasing dominance of the resource industry.

Environments of cultural or archaeological significance in Western Australia are already protected by several different Acts including the EP Act (S 3A2(b)), the *Aboriginal Heritage Act 1972* (AH Act) and the *Heritage of Western Australia Act 1990*. A new Heritage Bill is currently in the Western Australian Parliament but not yet enacted. It advocates more transparency and directs that the Heritage Council (Western Australia) and Ministerial decisions on State Registration are published, thereby enhancing transparency. Importantly for risk assessment purposes, the *Heritage Bill 2017* provides better protection for archaeological and moveable objects situated in State Registered Places. These legislative protections ensure that destruction or damage to environments of cultural or archaeological significance will attract the relevant penalties. Hydraulic fracture stimulation and any other resource extraction is bound by these laws unless special consideration is granted within the guidelines of the respective laws.

Finding 64: Heritage is complex and includes a range of potential assets that are valued and in many cases contribute to a sense of community, identity and belonging.

12.13 Aboriginal heritage

O'Faircheallaigh (O'Faircheallaigh 2008) makes the point that 'for Aboriginal traditional owners of land or sea in Australia, the distinction between these two [physical] categories of 'cultural heritage' is artificial'. Knowledge, law, obligations, culture and people are all wrapped in a single English word, 'country', and connection through kinship is how knowledge is transmitted. As explained by Langton (Langton 2012) Aboriginal people have customary responsibilities to 'look after country' and protect and promote their cultural integrity and social vitality. Some sites and places, including water resources, have particular spiritual and cultural significance to all people, but especially Aboriginal people. They often also have aesthetic, recreational and in some cases, a beneficial use through tourism and/or bush and medicinal food purposes. Therefore, destruction or even change to the amenity value of those sites compromises cultural as well as beneficial uses derived from them. A key concern for many Aboriginal groups is the fear of displacement from their traditional homelands and the disruption to spiritual attachment they have to the land. There is a small body of literature focusing on Aboriginal cultural heritage and the potential dangers associated with the interference or removal of significant physical features or traditional places such as middens, hunting grounds and water holes due to interference from mining activities (Gillespie & Bennett 2012; Langton et al. 2004; Langton 2015; O'Faircheallaigh 2006, 2013). The Scientific Inquiry into Hydraulic Fracturing in the Northern Territory (Northern Territory Government 2018) also highlights the importance of subterranean sites, including aquifers, for Aboriginal people. In addition to their importance for physical wellbeing, water and water sources usually have cultural and spiritual values that are not limited to the surface. Their underground source and 'journey' are as spiritually significant as

the physical and topographical forms on the surface. In the submission from Yawaru, the assessment of risk is explained as:

"a holistic lens of country as a living cultural landscape, including the ecology and biodiversity; the hydrology and geomorphology; the history; the harvesting of resources; and the cultural story" – submission from Yawuru

A key tenet of the Australian *Native Title Act 1993* (NT Act) is the recognition in Australian law that some Aboriginal people continue to hold rights to their land and waters that come from their traditional laws and customs. O'Faircheallaigh describes Aboriginal heritage:

"as having two dimensions: the first, evidence of Aboriginal communities from earlier times, including burial sites, middens, rock and cave paintings and scatters of stone tools …; the second encompassing the places or landscapes that are of spiritual significance to living Aboriginal people"

Such areas are often associated with the actions of mythological beings during the creative period of the Dreaming, moving over the land and shaping the form it now takes and the laws and ceremonies that guide people's lives. These places and sites therefore have Aboriginal heritage value.

Finding 65: For Aboriginal people, there is no distinction between cultural and physical heritage. Preservation of these sites is important for a range of reasons including spiritual, cultural, aesthetic, recreational and amenity values.

Australian laws at the Federal and State levels recognise the importance and need for protection of Aboriginal heritage. International laws also recognise the rights of Aboriginal people to be informed and consulted in respect of development on their lands, some of which have been endorsed but not necessarily ratified by Australian governments. Nonetheless, these Declarations, Agreements and Conventions influence law-makers and decision-makers in Australia.

Legal protection of Aboriginal lands and spiritual sites is derived from the NT Act and at the State level, the AH Act and the EP Act all have some jurisdictional responsibility for the protection of particular sites and habitats. Resource companies are required to comply with each of these Acts. The AH Act provides the opportunity for relevant Aboriginal people to determine what activities, including resource extraction, can be conducted on land that is deemed for their traditional use, provided other legislation and provisions are satisfied.

The AH Act seeks to protect and manage places of cultural significance. Specifically, destruction, damage or alteration (impact) to an Aboriginal Site without the prior consent of the Minister for Aboriginal Affairs is an offence under Section 17 of the AH Act, with penalties for contravention. The Western Australian Department of Planning, Lands and Heritage maintains a Register of Aboriginal Sites that includes protected areas and all

Aboriginal cultural material. The Department also provides advice to the public and private sectors, and the community about Aboriginal heritage management (Department of Planning, Lands and Heritage 2017).

A hydraulic fracture stimulation proponent is obligated, as part of the licence process to consult and abide by the Register, and the relevant laws regarding Aboriginal heritage and places of cultural significance. However, it is evident to the Inquiry that reforms are required to strengthen Aboriginal rights over their lands. The AH Act is currently under review, nonetheless, this Inquiry reinforces the importance of empowering Aboriginal people through legislative frameworks to preserve Aboriginal heritage.

Mining agreements can be negotiated under the terms of the NT Act, however, if a negotiated outcome cannot be reached, particularly with regard to the protection of Aboriginal heritage, then the matter is referred to the National Native Title Tribunal. The Tribunal can refuse to grant a mining lease, grant it subject to conditions or grant it with no conditions (O'Faircheallaigh 2008). Rarely does the Tribunal block an application or attach conditions relating to cultural heritage protection.

Figure 12.4 and **Figure 12.5** show the location of wells that have previously undergone hydraulic fracture stimulation in relation to Aboriginal heritage sites in the Canning Basin and Perth Basin.

Figure 12.4: Location of wells that have undergone hydraulic fracture stimulation in the Canning Basin in relation to Aboriginal heritage sites

Source: Department of Water and Environmental Regulation (DWER)

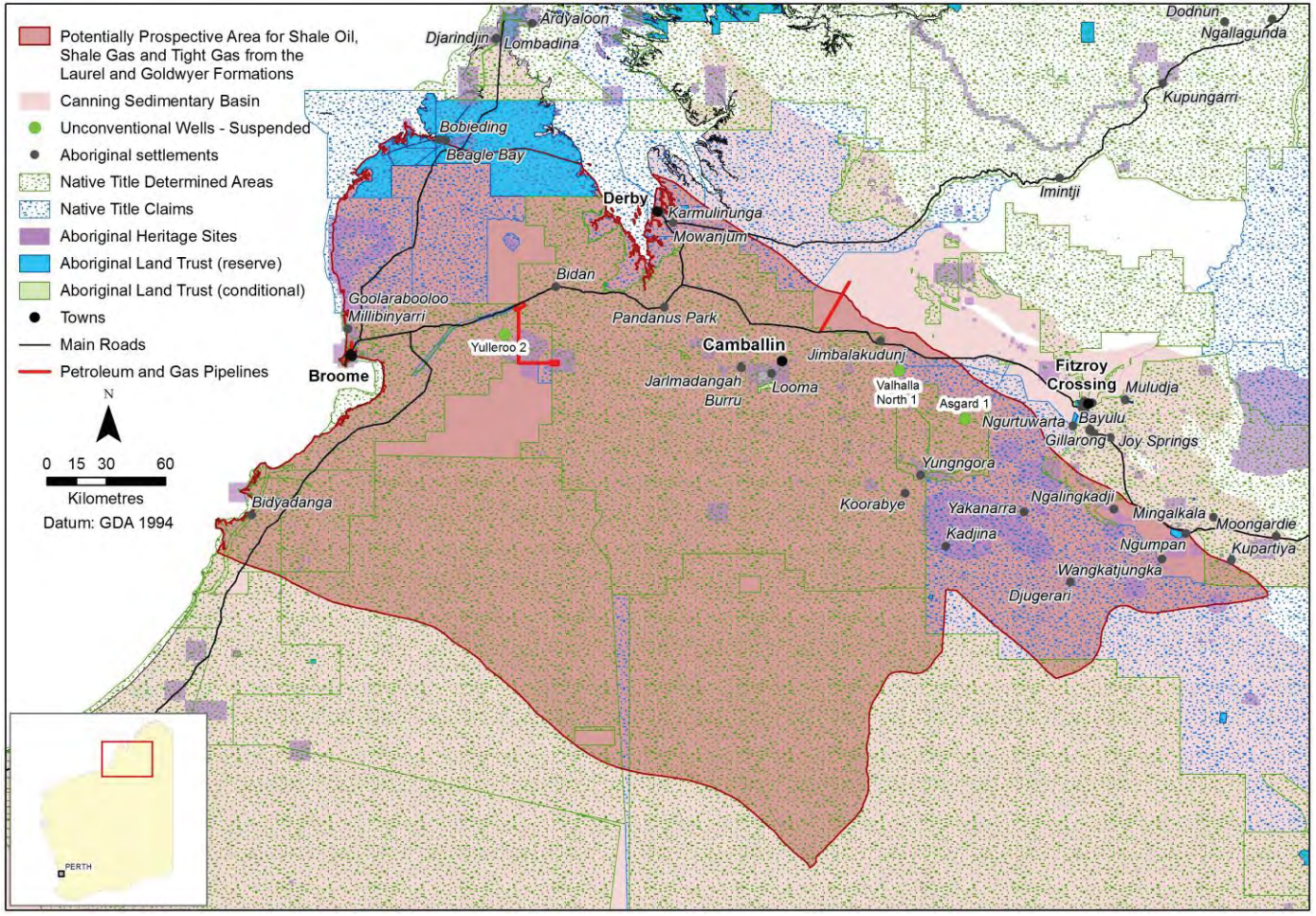
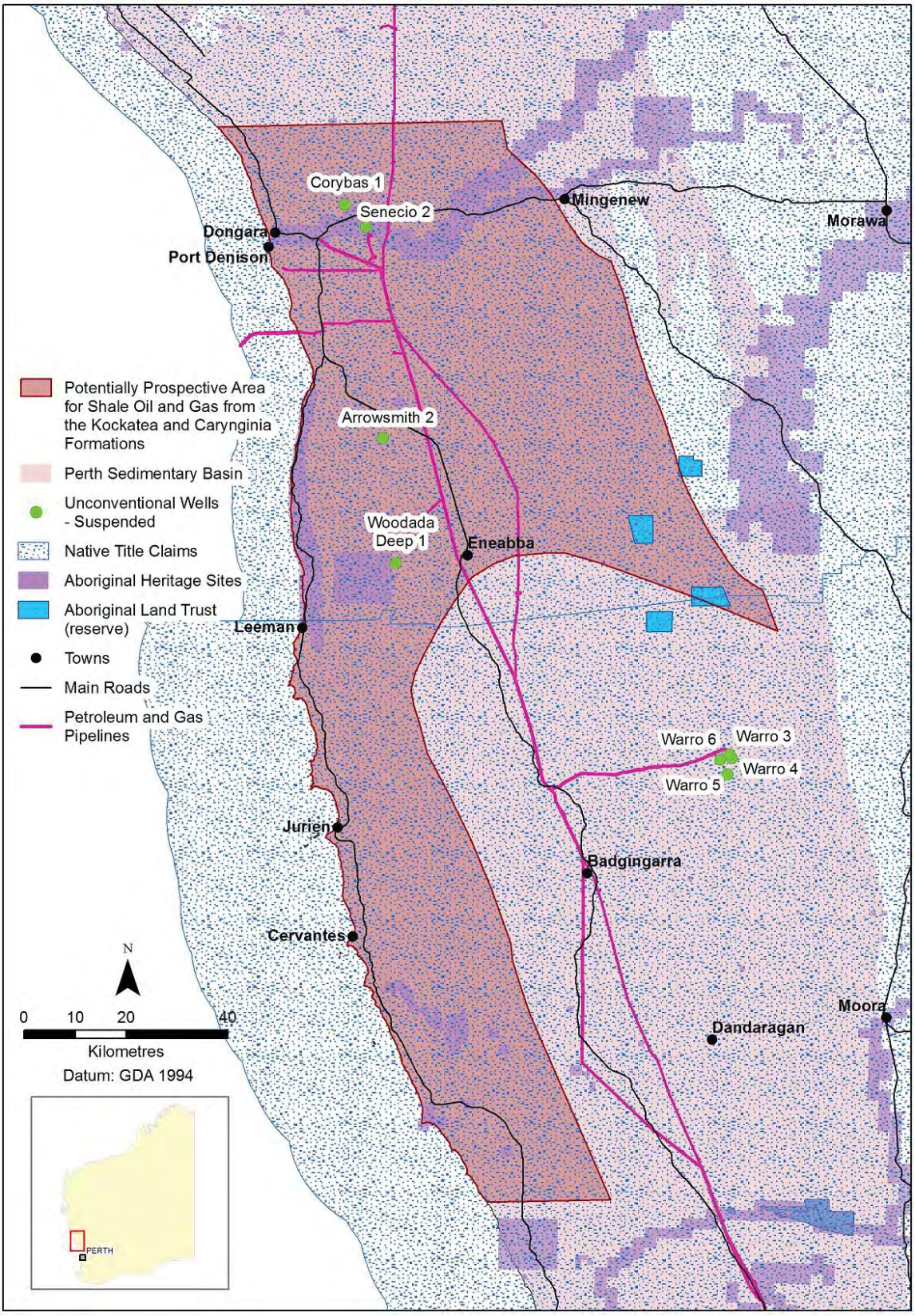


Figure 12.5: Location of wells that have undergone hydraulic fracture stimulation in the Perth Basin in relation to Aboriginal heritage sites

Source: DWER



As highlighted by Professor Carmen Lawrence in her submission to this Inquiry, both the 2011 and 2016 national State of the Environment reports warn of the precarious state of Aboriginal heritage protection in Australia. Knowledge and the transmission of information about particular places can be inadvertently shared with the culturally inappropriate people and thus cause damage to Aboriginal people. Furthermore, many Aboriginal cultural resources were destroyed before their value was broadly appreciated and properly recorded and documented. Wherever possible, it is therefore important to ensure Aboriginal heritage is preserved and not compromised by petroleum activities.

Finding 66: The progressive and cumulative destruction of Aboriginal cultural resources has disrupted Aboriginal knowledge and culture. Exploration and resource extraction can physically destroy or irrevocably alter physical and cultural sites.

O'Faircheallaigh (O'Faircheallaigh 2008) is of the view that government legislation has generally proved ineffective in protecting Aboriginal heritage. While an Aboriginal heritage assessment is typically required before mining permits, including exploration, are issued, Aboriginal heritage laws in Western Australia allow the responsible Minister to authorise destruction of sites (under Section 18 of the AH Act) for 'another purpose'. Agreements negotiated under the terms of the NT Act are also likely to put Aboriginal heritage in a weak position because development cannot be stopped if effective measures for protecting cultural heritage are not in place. Furthermore, Aboriginal groups are limited in their pursuit of compensation during the periods of negotiation, which applies considerable pressure to reach an agreement, regardless of the Aboriginal heritage outcome.

O'Faircheallaigh (O'Faircheallaigh 2008) goes on to argue that negotiated agreements have the potential to protect Aboriginal cultural heritage and reconcile potentially conflicting needs and aspirations but only where underlying weaknesses in the bargaining position of indigenous peoples are addressed. Enhancing Aboriginal bargaining power is therefore crucial for a more equitable arrangement, which also protects Aboriginal culture and heritage.

At the same time, Traditional Owners and Aboriginal leaders want their people to have the same employment opportunities and quality of life as other Australians (Langton et al. 2004; O'Faircheallaigh 2006). It is evident from some of the submissions to this Inquiry that Aboriginal groups who have had exposure to petroleum companies, particularly in the Kimberley region, have been generally satisfied with the manner by which agreements have been negotiated. The opportunities for local people to work while maintaining their land rights and the seriousness with which concerns raised with the company have been addressed has been particularly welcomed (see submissions from Buru Energy and the Yungngora Aboriginal Corporation). Cultural inductions have been made available for all contractors and Traditional Owners appear satisfied that their aspirations and responsibilities for preserving important sites and culture are properly respected. The

commitment to employ local people and overt engagement with cultural sensitivities mitigates the negative impacts associated with introduced labour force and exclusion.

The text box below shows an example of the dialogue between an oil and gas company and the local Traditional Owners.

The engagement between Traditional Owners and a company proposing oil and gas development involving hydraulic fracture stimulation is exemplified in the documented and highly detailed dialogue between the Yawuru Native Title Holders Aboriginal Corporation (YNTHAC) and Buru Energy. Buru's plans to develop and stimulate wells in the Laurel Formation of the Canning Basin is on land where Yawuru people hold exclusive possession Native Title rights. In July 2014, the YNTHAC resolved by majority:

> "Yawuru does not agree to the 2014/2015 fracking at Yulleroo, but if Buru Energy goes ahead with the fracking, Buru Energy must agree to meet environmental, social, cultural and economic conditions set by Yawuru and committed to negotiate strong conditions" (YNTHA media release 18 July 2014).

In 2014 Yawuru established a rigorous information and review process to assist the community on making an informed decision about the proposed development (http://www.yawuru.com/wp-content/uploads/2014/07/Background-re-Yulleroo-free-prior-and-informed-consent-process-.pdf).

On 15 April 2015, Buru Energy announced to the ASX that the Buru Energy/Mitsubishi Joint Venture had executed a Native Title Agreement with the Yawuru people that included a process for managing cultural, heritage and environmental matters. The agreement did not extend to specific consent for hydraulic fracture stimulation or extinguishment of native title. Buru Energy subsequently supported three independent specialist reviews of their activities and plans for using hydraulic fracture stimulation with the Yawuru people (as well as other native title holders in the region). Traditional Owner groups made their own selection of independent specialists to advise them on hydraulic fracturing activities, including 11 specialists from four different universities and the CSIRO. Buru Energy provided funding for the independent experts to reviews and made available all relevant approvals documentation. The reviews were undertaken independent of Buru Energy and included collaborative risk workshops, community meetings and information sessions. The resulting review for Yawuru was documented by (Yawuru Expert Group 2014) and is not only an extremely detailed, technical assessment of risk and compliance but also documents concerns and questions from Yawuru, Buru's responses and whether or not the issues were resolved to their mutual satisfaction.

While the Aboriginal groups in the Kimberley have been generally satisfied with the outcomes and practices companies employing hydraulic fracture stimulation, the

arrangements are nonetheless piecemeal and lack systematic evaluative criteria, governance transparency and consistency.

Finding 67: Cultural awareness and effective communication between the employees of companies, government and all landholders including Traditional Owners are an essential component of informed consent.

Recommendation 29: Cultural orientation should be made regularly available to hydraulic fracture stimulation employees including contractors in addition to relevant government employees to raise heritage awareness, including issues specific to Aboriginal heritage. Cultural orientation regarding Aboriginal matters should be conducted by local Traditional Owner groups or their approved cultural awareness providers.

O'Faircheallaigh (O'Faircheallaigh 2008) advocates the Northern Territory provisions in their Aboriginal Land Rights, whereby Aboriginal landowners have the right of veto over exploration and mining. There may also be an opportunity for Aboriginal groups to have the right of veto over environmental impact assessments of major projects, although to date, right of veto in relation to landowners has been dismissed as legally unworkable. A more transparent and workable option might be to bring about changes to the NT Act and the way it is currently administered by the National Native Title Tribunal.

Finding 68: Negotiated agreements have the potential to protect places of heritage value, including Aboriginal cultural heritage, and reconcile potentially conflicting needs and aspirations, provided the appropriate stakeholders are central to the negotiations.

Some of the submissions suggested activists and others who take it upon themselves to portray Aboriginal interests do not necessarily sit down with local Aboriginal people and get the local Aboriginal perspective on the potential risks and opportunities from hydraulic fracture stimulation and other economic diversification opportunities. For example, the submission from the Conservation Council of Western Australia makes the statement that:

"Aboriginal Traditional Owners are opposing fracking on their cultural lands, for they know that protecting their groundwater is critical to the health of their people and their country" – submission from the Conservation Council Western Australia

Yet, this statement has been contradicted numerous times by submissions made by Aboriginal Traditional Owners to this Inquiry (see for example submissions by Eric Yamera, James Knight, Robert Locke, Zac Fong and Fran Fong) and during public meetings.

It is also important to note that water taken from groundwater for use in hydraulic fracture stimulation may have an adverse impact on an aquifer, which provides water to springs and

waterholes. In the event that water holes with cultural significance deplete or dry up completely, then there is a direct impact on Aboriginal heritage. It is therefore necessary that water holes and other water resources with particular Aboriginal significance are acknowledged and properly monitored for adverse impacts from hydraulic fracture stimulation activity.

An Aboriginal heritage management plan, developed at the earliest opportunity in the development lifecycle could assist in preserving the integrity of Aboriginal heritage sites (Department of Planning, Lands and Heritage 2017).

Recommendation 30: An Aboriginal heritage management plan should be implemented at the earliest opportunity when potential risk is identified for a particular site of Aboriginal heritage or significance. The Aboriginal heritage management plan should have input from those Aboriginal people and groups whose land is under consideration for petroleum development using hydraulic fracture stimulation, and should identify the role Traditional Owners will play in monitoring the condition and protection of their cultural heritage. The Aboriginal heritage management plan should require the approval of local Traditional Owners.

12.14 Cumulative impacts

Franks *et al.* (Franks, Brereton & Moran 2013) and Porter *et al.* (Porter, Franks & Everingham 2013) explain cumulative impacts as the successive, incremental and combined impacts of one or more activities on society, the economy and the environment, which are not necessarily linear and accrue across time and space. Cumulative impacts also change, aggregate and interact over time and are therefore premised on uncertainty, incomplete knowledge, multiple perspectives and contested causality. There can be spatial and temporal separation of the source of change and the experienced impact. Impacts are often aggregated at varying levels and context can influence their intensity. For example, exogenous forces such as global prices for agricultural products, the availability of social infrastructure, weather conditions and local leadership can all mitigate or intensify how resource activities are experienced at the local level.

The footprints of resource extraction activities and their associated impacts are driven by global or external factors, many of which are uncontrollable by local landholders and communities (Sonter et al. 2014). The social and human spheres are at the centre of these impacts and mollifying them takes time, empathy and commitment. The sense of losing control can be intense and the senses of frustration, loss or even potential loss from imposed change can lead to obstruction and social action (Jacquet 2014; Moffat & Zhang 2014). Poor communication with local communities, lack of respect for residents' sense of place and identity and a lack of understanding of what is locally considered important leads

to mistrust and community action. Local stakeholders who are threatened by competing interests, incomplete knowledge of consequences (Uhlmann et al. 2014) and their perceived limited capacity or autonomy to mitigate change, use protests and community action to undermine the perceived opportunistic resource company whose activities are portrayed as potentially harmful or at the very least, likely to introduce considerable change. It would appear from submissions received to this Inquiry that many concerned residents expressed a sense of losing control and a fear of potential loss from imposed change. The submission from David Cook conveys these sentiments:

> *"to have our district industrialised with all the obstructive infrastructure of pipelines, roads, well heads"* – submission from David Cook

The submission from Maureen Diver conveys similar fears:

> *"I find the threat of fracking in our area leaves me very concerned for a future in farming. Without clean water soil and air then farming as we know it is lost. Our area has been earmarked as a food bowl region. We need to be left alone to get on with our job as primary producers. From invasion of privacy to potentially destroyed farmland"* – submission from Maureen Diver

A submission from Kingsley Smith states:

> *"unconventional fracking is also a 'slow violence'"* – submission from Kingsley Smith

An opposing view is the cumulative impacts if new industry opportunities are prohibited. A submission from Owen Finger, a Kimberley resident, says:

> *"In such a remote region with limited employment opportunities and industry, it would irresponsible for the inquiry to recommend and the state government to ban a process that could extract the tight gas, that could sustain an industry for up to 40 years. … The Kimberley has the highest unemployment rate in Western Australia and faces significant social challenges. A lot of these social issues are best addressed by providing people with meaningful employment"* – submission from Owen Finger

Another Broome resident offered similar views:

> *"When you are in Broome I encourage you to drive around and witness first-hand the social issues that occurs in Broome. There is high unemployment and significant social dysfunction. Without job opportunities and investment in the local economy the social issues in the Kimberley will only get worse. … A gas industry operating onshore in the Kimberley has the potential to benefit all people living in the region. I would like the Inquiry members to see the Kimberley, the vast distances, the small population and the social issues up here. We need opportunities up here, and I would be disappointed if the Inquiry made recommendations that would stop a safe industry from being established because of the noise and fear generated by loud activists"* – submission from Kelly Locke

These sentiments are not unique to the submitters to this Inquiry. As noted by the The Academy of Medicine Engineering and Science of Texas (TAMEST), local politicians in Texas communities where shale gas extraction occurs revealed they continuously:

> confronted a tension between encouraging and supporting energy development related economic growth and managing the associated negative social and environmental outcomes (The Academy of Medicine Engineering and Science of Texas 2017).

The history to date of onshore oil and gas development in Western Australia has been such that there is no opportunity for the community (or the regulators) to see the projected scale of an oil and gas field development across their region, or its impacts. Rather, development tends to proceed almost well by well. Thus, the community is left to imagine what it might eventually look like, how close to them it will be, and the cumulative impact across the landscape and on their community. Modelling outcomes technology for impact assessment has been adopted in Queensland but these techniques require reliable data. As noted elsewhere in this Section, data regarding the social dimensions is either incomplete or entirely absent, rendering modelling of social impact redundant until reliable and scientifically collected data is available.

Finding 69: Cumulative impacts of particular actions (including lack of action) have the potential to change, aggregate and interact over time. Uncertainty, incomplete knowledge, multiple perspectives and contested causality are often functions of conflict. Acknowledging cumulative impacts and managing them are important for the maintenance of community and individuals' quality of life.

Finding 70: Accurate data regarding the social dimensions are important and should be documented at the earliest opportunity of any development.

A shared theme in the content analysis of the literature regarding the social surroundings is the lack of power and opportunity for input by local community groups and authorities, including local government, regarding decisions and especially the regulation of activities that occur within their boundaries. A sense of powerlessness and frustration that local opinions have no influence was a common theme in the literature (Moffat & Zhang 2014; Zhang & Moffat 2015). Perhaps the most palpable example was the statement in the submission from Yawuru:

> *"By imposing a ban in some areas and not others the Government is effectively saying to the WA public who reside in the non-banned more remote areas - we do not value your environmental values as highly as in the banned areas and consequently we are prepared to risk fracking in your areas"* – submission from Yawuru

Kreuze et al., (Kreuze, Schelly & Norman 2016) document the frustrations and sense of powerlessness at the local level. In Michigan in the United States, in counties which until recently were dominated by agricultural industries, local residents were frustrated by their lack of recognition and inability to have input to the hydraulic fracture stimulation regulatory framework. Local government powers cannot conflict with state ordinances and they have no jurisdiction over permits for the location, drilling, completion, operation or abandonment of wells (Kreuze, Schelly & Norman 2016).

As noted earlier, the Australian experience in the Hunter Valley and the Surat Basin echoed these sentiments (see Everingham, Devenin & Collins 2015; Lai et al. 2017; Measham & Fleming 2014; Queensland Gasfields Commission 2017).

Arguably, good governance structures work against an appreciation of the cumulative impacts of the legacies of mining activities because it is the job of government officers to be impartial and not have the commitment to place, sense of community or community memory, which can only build over time. Consequently, unless the status of a range of community factors are scientifically measured and documented from the commencement of the resource development lifecyle, the cumulative impacts from hydraulic fracture stimulation activities on the social surroundings are less likely to be considered legitimate.

Finding 71: Systematic and scientific measurement of a range of social factors mitigate deleterious cumulative impacts.

Recommendation 31: Governments and resource companies should invest more in understanding and measuring the social dimensions of change and its links to mental health: A comprehensive local social impact analysis should be undertaken prior to the commencement of any activities associated with hydraulic fracture stimulation occurring.

12.15 Other considerations

While corporate social responsibility is not part of the Terms of Reference for this Inquiry, it was noted at public meetings that there was disquiet about the ability of unconventional oil and gas companies, to legally manipulate regulations regarding corporate ownership so that legal commitments and obligations, particularly around rehabilitation and legacy issues, can be avoided or at best, minimised by selling off or restructuring corporate entities, changing ownership or resorting to market failure and bankruptcy. There was also a strong perception that the direct benefits of hydraulic fracture stimulation more likely accrue to owners and employees connected to the energy industry, while the often negative direct and indirect impacts are experienced more keenly at the community and personal levels (Popkin et al. 2013). Furthermore, the recognised disadvantages associated with being a host community (see Haslam McKenzie 2016) in the iron ore industry, especially the lack of local resourcing (goods, services and jobs), population churn and the *hollowing out*[9] of local economies, makes communities cautious.

Consequently, communities are wary of unexpected consequences and a sense of powerlessness that once decisions are made about resource extraction activities, in this case, hydraulic fracture stimulation, there is no going back and little, if any opportunity to change course. 'Once the train has left the station there is little they can do to stop it'. Therefore, resistance is viewed as the safest option and local recourse is to add road blocks wherever they can (Kreuze, Schelly & Norman 2016).

The determination of aesthetics, and other social surroundings values including beneficial uses of the environment, can only be ascertained or gauged through a dialogue with the local community and its established industries. This extends to the identification and appreciation of the cultural and heritage values of the environment. Engagement, as discussed previously (see 'Social licence to operate') is not without cost. Maintaining the balance between the time needed to build relationships and the urgency required to advance solutions, and other time pressures pose a further challenge (Uhlmann et al. 2014). Consultation fatigue is a real challenge, especially in small communities and for particular community representatives, such as Traditional Owners and those who have the right, knowledge and capacity to speak on their behalf. Engagement is only as good as the participants involved and their commitment to the process. Common language and common goals will likely elicit positive results. Care has to be taken with a critical mass of representatives but not having so many representatives that meetings are hard to manage

[9] *Hollowing out* refers to resources companies' ability to outbid for local businesses and services so that the rest of the community is not able to easily access the services, or is forced to pay inflated prices.

and therefore do not achieve an outcome. Cultural obligations must be understood and observed to ensure meaningful participation.

Addressing the likely impact of hydraulic fracture stimulation on the social surroundings in Western Australia is complex. Western Australia is a large jurisdiction with different topographies, communities, industry sectors, resources, Aboriginal groups, climatic and geographic conditions. However, like everywhere else, the importance of community, livelihoods, connectivity, communication, cultural obligations and amenity are highly valued by all the communities who have contributed to this Inquiry. An assessment of potential risks to these important elements elicits passion; hence the commitment to scientific, evidence-based information to inform future, important decisions about hydraulic fracture stimulation in Western Australia in this Inquiry. It is therefore disappointing when information about the industry and the impacts of hydraulic fracture stimulation are misconstrued or evenly blatantly manipulated, and exaggerated claims were made at the public forums. Frogtech, in their submission, explicitly explain how their data from a report in 2013 has been persistently misquoted and misused by activist organisations. Another submission claimed water catches fire on her friends' property at Dandaragan and that the farm is ruined by unconventional gas extraction. This claim is patently incorrect. There has been no record of water catching on fire anywhere in Western Australia due to hydraulic fracture stimulation activities. These and many other fallacious claims serve to obfuscate rather than assist the process of accurately informing evidence-based advice.

Many submissions complained that interest groups from elsewhere were making claims about their community that were incorrect or mischievous, creating conflict and division within communities. Other submissions purported to speak about what they considered Aboriginal groups needed or wanted, without providing evidence they were speaking with Aboriginal authority. Lobbyists and activists have an important role in the debate but they should ensure their information is accurate and based on evidence, otherwise their voices and value are diminished.

13

Regulation and regulatory reform

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13 Regulation and regulatory reform

13.1 Introduction

The design, implementation and enforcement of regulation is the mechanism for government to ensure that, if it is permitted, hydraulic fracture stimulation is carried out in a manner that protects the environment, is safe for people and meets community expectations. Through the Terms of Reference, the Panel was asked to describe regulatory mechanisms that may be employed to mitigate or minimise risks to an acceptable level, where appropriate, and to recommend a scientific approach to regulating hydraulic fracture stimulation.

In the first instance, within a strict interpretation of the Terms of Reference, the Panel considered the regulations necessary to minimise risk from a strictly technical point of view, based on the available scientific evidence. However, over the course of the Inquiry it was clear that community concerns about the risks posed to those whose lives or livelihoods are potentially close to unconventional oil and gas developments might require additional changes to the regulatory framework to sufficiently reduce risk, or the perception of risk, to them or their community. The Panel's advice on recommended changes to regulation, should the moratorium be lifted, extends to this greater consideration, although the Panel has taken care to differentiate the strictly technically-driven advice from recommendations addressing broader concerns.

Section 4 of this Report provides an overview of the pertinent regulations and regulatory arrangements as they stood at the time of the moratorium. Much of this framework is summarised in 'A guide to the regulatory framework for Shale and Tight Gas in Western Australia - A whole of government approach 2015' (Department of Mines and Petroleum 2015a), and reflects significant changes to regulations since 2012. This guide describes each stage of the process to explore for and produce gas, as well as explaining how the agencies work together, using a set of Memoranda of Understanding (MoU) to regulate shale and tight gas in Western Australia. This framework – comprising legislation, regulation, standards, procedures and regulatory roles - is substantial, and if applied as designed and in full, provides the basis for environmental and public protection and the minimisation of risk.

13.2 Key issues raised

Through written submissions and at public meetings, the Inquiry heard concerns about the current regulatory framework for hydraulic fracture stimulation and suggestions for changes. These comments extended to:

- The engineering design, certification standards and operational procedures for wells and associated infrastructure;

- The sufficiency and effectiveness of the environmental approvals process;
- The requirements for monitoring and reporting;
- The accountability of industry;
- The independence of the regulator; and
- Land access.

The first three points fall into the domain of a scientific (technical) approach to risk avoidance, minimisation and mitigation, and many of the resulting recommendations in this regard arise from analyses in previous sections of this Report. The latter three points extend into non-technical areas of regulation that are seen as crucial to protecting the public interest and alleviating community concerns about the potential impacts of an onshore unconventional oil and gas industry based on hydraulic fracture stimulation.

In all cases, the Panel has resisted the temptation to over-specify or over-design any suggested changes to the regulatory environment; our recommendations are constructed as a guide to regulatory reforms that should reduce risk to acceptable levels. The Panel recognises that should the Government wish to advance these reforms, their implementation will require drafting with technical and legal expertise beyond the resources of the Inquiry.

13.3 Progress against the Western Australian Parliamentary Inquiry 2015 Recommendations

The Inquiry notes that the 2015 Report of the Standing Committee on Environment and Public Affairs of the Western Australian Parliament (the 2015 Western Australia Standing Committee Report) made a series of recommendations for regulatory reform associated with hydraulic fracture stimulation for oil and gas development. This is available in **Appendix 1**.

The purpose of that Report was to provide a comprehensive body of information and findings to assist the Parliament of Western Australia, future decision makers and the public in understanding the implications of hydraulic fracture stimulation for unconventional gas. That Committee considered the technical and geographic opportunities and challenges in developing unconventional gas resources with hydraulic fracture stimulation, including regulation of hydraulic fracture stimulation in Western Australia, access to land and land use, the chemicals used, and impacts on water resources, land, seismicity, air quality and human health.

The Standing Committee made 51 findings and 12 recommendations regarding the risks and management of hydraulic fracture stimulation, based on 117 submissions from agencies, industry, non-government organisations and the wider public.

Table 13.1 details the recommendations made and their implementation status to date, noting that not all of the recommendations were accepted by the State Government at the time.

Table 13.1: Implementation Status of the 2015 Western Australian Parliamentary Inquiry Recommendations

	Recommendation	Implementation Status
1	The Committee recommends that the Government amend section 153(3) of the *Petroleum and Geothermal Energy Resources Act 1967* to increase the maximum fines permitted in regulations made under the Act to a more appropriate level.	In Progress Penalty provisions under the current state petroleum Acts are currently being reviewed as part of the Petroleum 2020 project, which aims to combine and update existing state petroleum Acts into one Act by 2020.
2	The Committee recommends that regulation 83 of the *Petroleum and Geothermal Energy Resources (Resource Management and Administration) Regulations 2015* be amended, in particular the deletion of regulations 83(4) and 83(5).	In Progress Drafting instructions are currently with the Parliamentary Council's Office for amendment to the *Petroleum and Geothermal Energy Resources (Resource Management and Administration) Regulations 2015*. These instructions include the recommendation that Section 83(4) and 83(5) be deleted.
3	The Committee recommends that the Memorandum of Understanding between the Department of Mines and Petroleum and the Environmental Protection Agency be amended to require the Department of Mines and Petroleum to refer all proposals under section 38 of the *Environmental Protection Act 1986* to the Environmental Protection Agency.	Complete A revised Memorandum of Understanding between the then Department of Mines and Petroleum, now the Department of Mines, Industry Regulation and Safety with the then Office of the Environmental Protection Authority, now the Directorate of Environmental Protection Authority Services, was completed in early 2016. (Office of the Environmental Protection Authority and Department of Mines and Petroleum 2016) It includes a trigger that requires the Department of Mines, Industry Regulation and Safety to undertake a pre-referral consultation with the directorate Environmental Protection Authority Services on all hydraulic fracture stimulation proposals. All proposals that are determined to be significant proposals and all production licences will be referred to the Directorate of Environmental Protection Authority Services.

	Recommendation	Implementation Status
4	The Committee recommends that the Department of Mines and Petroleum develop a mechanism to consult with the Water Corporation (or, in the case of regional areas, with the relevant water provider) in relation to the regulation of hydraulic fracturing activities.	In Progress An Administrative Agreement with the then Department of Water, now the Department of Water and Environmental Regulation and the then Department of Mines and Petroleum, now the Department of Mines, Industry Regulation and Safety came into effect in January 2016. (Department of Mines and Petroleum and Department of Water 2016b) An informal mechanism to consult with the Water Corporation was developed, however this has not yet been finalised.
5	The Committee recommends that the Government establish a statutory body similar to the Queensland GasFields Commission to act as an independent arbiter for landowners and resource companies in land access negotiations involving onshore shale gas.	Activities discontinued The then Department of Mines and Petroleum established the Land Access Working Group, which first met on 15 December 2016. The working group included representatives from Government, farming groups, local government, industry and environmental groups. (Department of Mines and Petroleum 2016c) Activities of the Land Access Working Group were discontinued in mid-2017.
6	The Committee recommends that the Government establish a working group, including landowner representatives and community leaders, to draft legislation for a statutory framework for land access agreements between landowners and resource companies. The framework should include provisions for an agreement template, compensation for landowners and the enforcement of mandatory access conditions using Queensland's Land Access Code as a guide.	Activities discontinued The then Department of Mines and Petroleum established the Land Access Working Group, which first met on 15 December 2016. The working group included representatives from Government, farming groups, local government, industry and environmental groups. (Department of Mines and Petroleum 2016c) Activities of the Land Access Working Group were discontinued in mid-2017.

	Recommendation	Implementation Status
7	The Committee recommends that the Government ban the use of benzene, toluene, ethylbenzene and xylene during any hydraulic fracturing operations undertaken in Western Australia.	Complete The use of benzene, toluene, ethylbenzene and xylene (BTEX) compounds and products containing BTEX has continued to be regulated as per the Guidelines for the Development of Petroleum and Geothermal Environment Plans in Western Australia. (Department of Mines and Petroleum 2016a)
8	The Committee recommends that the Department of Mines and Petroleum's policy of public disclosure of chemicals used in any hydraulic fracturing activity be formalised in subsidiary legislation.	In Progress The ongoing Petroleum 2020 project is considering changes to the Act that would enable the full public disclosure of all chemicals used, as part of the public disclosure of an Environmental Plan, and the release of Environmental Plans in full.
9	The Committee recommends that resource companies in Western Australia be encouraged to explore the recycling of wastewater during hydraulic fracturing operations, where practicable.	Complete Agencies continue to encourage industry to reuse wastewater in accordance with existing policies.
10	The Committee recommends that baseline monitoring of aquifers and the subsequent publication of this data be a mandatory condition of all approvals for hydraulic fracturing operations in Western Australia.	Complete A guideline on groundwater monitoring in the onshore petroleum industry was implemented in August 2016. (Department of Mines and Petroleum and Department of Water 2016a) This guideline states that the operator is encouraged to provide the groundwater monitoring report to the landholder.
11	The Committee recommends that a fund similar to the Mining Rehabilitation Fund under the *Mining Rehabilitation Fund Act 2012* be established for activities governed by the *Petroleum and Geothermal Energy Act 1967.*	In Progress A discussion paper examining financial assurance options in the petroleum industry in Western Australia was completed and circulated internally and to the Minister. Consultation with stakeholders is planned for 2018.

	Recommendation	Implementation Status
12	The Committee recommends that any future consideration of hydraulic fracturing for unconventional gas in Western Australia be based on established facts, ascertained through baseline data and monitoring, with a view to strengthening the industry's social licence to operate.	Complete The Department of Mines, Industry Regulation and Safety continues to support evidence-based regulation, based on best available science. The Department has provided guidance material, created in consultation with other Western Australian agencies, to inform industry of Government's expectation for baseline monitoring and reporting, groundwater monitoring, chemicals and consultation. (Department of Mines, Industry Regulation and Safety 2018b)

This Inquiry has considered both the implemented as well as the unimplemented recommendations of the 2015 Western Australia Standing Committee Report in developing its advice on regulation.

13.4 Outcome-focussed verses prescriptive regulation, and As Low As Reasonably Practicable (ALARP)

Two characteristics at the centre of the existing regulatory framework for petroleum activities in Western Australia are (a) a risk-based, outcome-focussed approach, and (b) the use of ALARP (As Low As Reasonably Practicable) as a benchmark for sufficiency of practice. Each of these characteristics has been called into question through this Inquiry and bear consideration.

The Western Australian regulatory requirement for the application of best practice standards is largely based on a risk-based, outcome-focused regulatory regime. The move away from prescriptive regulation is to allow for local risk assessment and understanding of the local environment to inform the application of best practice. There is wisdom in this, recognising the great variation in geology, geography and infrastructure across Western Australia.

"Regulatory leading practice can be achieved when operators are required to identify and manage agreed risks consistent with the 'as low as reasonably practicable' (ALARP) principle. It is broadly accepted that a goal-based approach, where it is the operator's responsibility to identify all possible risks and how they are to be mitigated and demonstrably managed, is the most effective way to avoid damaging impacts on the environment and safety, and protect community interests and landowner rights, and help facilitate the achievement of a social license to operate" – submission from ATSE

The trade-off in this regard is less clarity and confidence around the interpretation of best practice and what can or should be considered sufficient standards to protect the

environment, as well as less clarity around compliance. Many submissions to this Inquiry indicated greater confidence in regulations if some aspects were explicitly defined, prescribed, proscribed or compelled. A useful regulatory model in this regard is the Australian *Offshore Petroleum and Greenhouse Gas Storage (Environment) Regulations 2009*, which takes a risk-based, outcome-focused approach overall but embodies some prescriptive elements (noting that these regulations only apply to Commonwealth offshore areas). For example, Regulation 10 not only specifies the requirement for an Environmental Plan, it also prescribes what it must contain and specifies the criteria by which it will be assessed and accepted. Even more prescriptively, it states specific and explicit considerations for places or species of environmental and heritage significance.

Finding 72: There is a place within an overall risk-based, outcome-focused regulatory framework for some prescriptive regulation. These prescriptions may extend to explicit requirements for consultation, exclusions, assessment, environmental standards, monitoring, disclosure and reporting.

The Panel encountered diverse understanding, and hence some discomfort, surrounding the meaning, interpretation and implications of ALARP. For many in the community, it is interpreted as leaving a great deal of discretion to both industry and the regulator with respect to the level of protection for the environment and public health.

"…the use of ALARP as a regulatory tool should be used with caution. In many circumstances it enables industry to establish its own standards with the primary driver being economics rather than environmental outcomes, acceptable or otherwise. The objective is uncertain in practice and risks favouring proponents' convenience over the environment and community. … the meaning and application of the ALARP principle is vague, and its definition varying even within the DMIRS' own resources. Its industry-facing Guidelines to the PAGER Resource Management and Administration Regulations state that 'ALARP defines the point where the investment costs required to further reduce the risks of an activity become disproportionate to the benefit gained, and may not be practically feasible or economically viable.' This economic emphasis contrasts with DMIRS' EP Guidelines, which provide that ALARP is: 'the point where the cost involved in further reducing the environmental impacts and risks of the activity would be highly disproportionate to the environmental benefit gained.' It is unclear from published materials which application of ALARP is used in the regulator's and Minister's determinations under the PAGER Act. In our view, without a consistent and transparent standard applied to fracking activities, the potential environmental impacts cannot be appropriately managed. The PAGER Act must provide for clear, measurable and prescriptive minimum standards with which any fracking activities would have to comply" – submission from the Environmental Defender's Office Western Australia

Alternatively, the Panel also heard interpretations from industry that ALARP embodies environmental acceptability, that is, ALARP requires environmental risks to be at an acceptable level.

> *"Opponents of the industry often criticise the ALARP process, stating that industry can just use cost as an excuse for not implementing suitable controls. This is a simplistic interpretation of the ALARP process and also ignores the equal requirement for risks to be of an acceptable level. It is possible for risks to ALARP, but not acceptable; in this situation, the activity would not go ahead without further risk reduction. The requirement to demonstrate ALARP and acceptable risk levels is recognised as best practice in the oil and gas and other industries"* – submission from Buru Energy

It is implicit rather than explicit under the existing regulatory framework that if the best practical and available means, in the eyes of the proponent, cannot sufficiently protect the environment, then no approval to proceed should be given. In contrast, regulation governing offshore petroleum development (*Offshore Petroleum and Greenhouse Gas Storage (Environment) Regulations 2009*) explicitly links ALARP with requirements for both the principles of ecologically sustainable development and environmental acceptability in the Act's object.

Finding 73: As Low As Reasonably Practicable (ALARP) is a useful working concept for the protection of the environment in the design and realisation of unconventional gas development. However, it should be explicitly linked to environmental acceptability through and within regulation.

13.5 Consideration of regulatory reform

13.5.1 An enforceable Code of Practice

The Inquiry encountered two fundamentally divergent and unreconciled depictions of the (nascent) onshore unconventional oil and gas industry with respect to environmental and public protection.

Multiple submissions to the Inquiry raised concerns that the existing regulatory regime, particularly as realised and prescribed under the *Petroleum and Geothermal Energy Resources Act 1967* (PGER Act) and subsidiary regulation, provides too much discretion regarding stakeholder consultation, the criteria by which an Environmental Plan or Well Management Plan is assessed, the environmental performance standards and procedures that apply, the monitoring and reporting required, the requirements for rehabilitation, the latitude on public disclosure, the execution of compliance auditing, and the consequences of poor operator performance.

The following submissions are broadly representative of this belief:

"Fracking is not covered in the list of 'prescribed premises' in the Environmental Protection Act 1984; thus is not subject to the normal pollution control regulations like other polluting industries (eg, requiring a pollution control license). Fracking companies cannot be successfully prosecuted if they pollute the environment if their activities are authorised by the DMP. Companies conduct their own Environmental Management Plans (EMPs), monitoring of the environment and compliance reporting. According to an independent review commissioned by the WA Government, EMPs are "legally unenforceable" Much very important information is not publicly available… information covered by 'commercial confidentiality' includes groundwater monitoring data, air quality monitoring data and well integrity and monitoring results" – submission from Nell Thayne

"From the outset of the PAGER Act… it is clear that this aspect of the regulatory framework does not make environmental protection a primary concern. As identified above, the PAGER Act does not contain any specific environmental requirements. There are some potentially relevant provisions relating to activities being carried out in a "proper and workmanlike manner and in accordance with good oil field practice"…. We respectfully submit that this vague, out-dated, and industry-oriented concept is entirely unacceptable as a mechanism for ensuring that best environmental practices are used in fracking activities. It is broad, vague, lacking in detail and unable to be measured or enforced… The lack of environmental provisions in the PAGER Act, coupled with its apparent exemption from the EP [Environmental Protection] Act…, means that environmental protection is largely relegated to an industry controlled, flexible environment plan" – submission from the Environmental Defender's Office Western Australia.

The Inquiry also received and reviewed the submissions and official documentation of actual practice and environmental performance of companies currently or recently developing conventional and unconventional onshore oil and gas resources in Western Australia. Through these investigations, the Panel identified environmental protections and protocols initiated and implemented over and above the apparent requirements specified under regulation (for example, submissions from Buru Energy and AWE Limited). These extend to extensive and intensive community consultation, environmental monitoring and research programs in the public domain, voluntary reporting of emissions, adoption of additional emission-reducing technology, funding independent third-party technical reviews of design and performance, and the adoption and further safety testing of more benign compounds used in hydraulic fracture stimulation.

"My company's environmental monitoring of HFS sites has taken the form of:

- *Monitoring of potential fugitive air emissions during HFS operations.*
- *Pre and post monitoring of soil chemical conditions within the footprint of on-ground HFS operations.*
- *Pre and post monitoring of groundwater chemical conditions within the superficial aquifer at the locations of the HFS operations.*

…From what we have observed the protections put in place by the Regulatory Departments (DMIRS and DWER) and the conduct of our client company are sufficient to mitigate the risk that these resources would be put at adverse risk pre- and post HFS operations. Our client company has adhered to not just the 'letter of the law' but has also been proactive [in] conducting the pre- and post HFS operations environmental monitoring and in requesting our input as to how best they go about fulfilling their obligations. To-date, my company's monitoring of the HFS sites has not shown any indication that the HFS operations have had a deleterious effect on the soil, groundwater or air quality at the locations subjected to HFS activities" – submission by Gemec Pty Ltd

"AWE co-sponsors ongoing seismic monitoring research by the Seismology Research Centre and has co-sponsored a baseline groundwater and air quality monitoring study undertaken by CSIRO. Results of these studies showed no impact from onshore petroleum activities and the baseline data assists with project planning to further mitigate any potential risks… Industry initiatives such as AWE's sponsorship of the independently facilitated community roundtables has proven to be helpful in ensuring local residents and other key stakeholders are kept up to date about project developments and also feel able to ask questions of subject matter experts. AWE's view is that the onshore petroleum regulatory and policy framework is appropriate. However, more needs to be done by both Government and Industry to broadly raise awareness of the comprehensive checks and balances in place, the safety and environmental performance record of the industry and its public benefits. This requires effective engagement with communities directly affected by onshore activities as well as those who are not. AWE sees itself as a leader in this area as it participates in the broader economic and social context of the Mid-West region" – submission from AWE Limited

"Buru Energy has made significant investments in research projects to increase the understanding of the Canning Basin environment, including: i) supporting a research project at Murdoch University investigating the disturbance ecology of the greater bilby, and ii) characterising the hydrogeology of project areas… Buru Energy's presence in the basin also has associated benefits as the many flora and fauna surveys undertaken… contributing valuable data and increasing the knowledge of the Canning Basin environments. Additional examples of Buru Energy's commitment to sustainable development of the Canning Basin include: refining seismic survey techniques to minimise ground disturbance; drilling slimhole exploration wells to minimise environmental footprints; and training of Traditional Owner Environmental Cadets in Conservation and Land Management" – submission from Buru Energy

It is clear that:

- at least some oil and gas companies are prepared and able to commit to higher standards of environmental protection and risk minimisation, monitoring, reporting and broader stakeholder consultation than is technically required under present regulations; and
- many stakeholders want higher environmental protection standards and associated processes explicitly defined and required through prescriptive regulation.

The resolution of these two broad observations logically leads to the creation of a Code of Practice, enforceable under regulation, that covers the range of environmental protections and associated issues such as consultation, design, performance standards, monitoring, rehabilitation, auditing, compliance and accountability.

Finding 74: An enforceable Code of Practice for hydraulic fracture stimulation in association with onshore unconventional oil and gas development, embodying necessarily prescriptive requirements and standards across the entire development lifecycle, is a useful mechanism to bring all such activities to an acceptable, high standard across the industry. Making adherence to this Code of Practice a regulatory requirement would provide greater assurance that the environment and public safety were being protected.

Such Codes of Practice are not unusual, and indeed the Australian Petroleum Production and Exploration Association (APPEA) has developed one for Western Australia onshore gas (Australian Petroleum Production and Exploration Association 2011). As drafted, it would not meet all of the expectations arising through this Inquiry with regards to prescriptive specification of consultation, environmental protections, standards, monitoring and reporting but it provides a framework and content that could be the basis for the development of a more complete Code.

It is also not unusual to have such a Code formalised under regulation: New South Wales has a *Code of Practice for Coal Seam Gas – Fracture stimulation activities* (NSW Department of Trade and Investment Resources & Energy 2012); and Queensland has a *Code of Practice for the construction and abandonment of coal seam gas wells and associated bores in Queensland* (Queensland Department of Natural Resources and Mines 2017). The Scientific Inquiry into Hydraulic Fracturing in the Northern Territory has recommended a similar Code of Practice be developed for that jurisdiction.

Submissions from Buru Energy, Finder Shale, APPEA and AWE Limited all identified the potential value in developing standard 'reference cases' (standard approaches) for specific activities, potentially for specific regions. These reference cases would be publicly available and used to inform and guide the design and expectations for procedures or operations aimed at minimising environmental risk to acceptable levels, and include operational standards and model conditions. These might initially be developed for low-risk activities such as airborne surveys. Such reference cases could become part of, or used in support of, codes of practice.

Finding 75: The development of reference cases to provide standard approaches to minimising the environmental impacts and risk for specific activities, including operational standards and model conditions, would be a useful addendum to an enforceable Code of Practice and could help focus efforts and attention on the design and assessment of higher risk aspects of unconventional oil and gas development proposals.

The construction of an enforceable Code of Practice for hydraulic fracture stimulation in association with onshore oil and gas development in Western Australia would also provide a mechanism to implement some of the prescriptive, technical recommendations made through this Report and some of the recommendations of the 2015 Western Australia Standing Committee Report. Section 153 (2a) of the PGER Act accommodates the application, adoption or incorporation of a Code of Practice or standards in regulations.

Recommendation 32: The Western Australian Government should develop a Code of Practice that adequately defines and prescribes the minimum standards and requirements for all onshore oil and gas activities involving hydraulic fracture stimulation, over the full development lifecycle. This Code of Practice should be made enforceable.

The specific concerns and issues raised through this Inquiry with respect to regulation may find their resolve and implementation, at least in part, through a comprehensive Code of Practice but are given further consideration and elaboration in the following section of the Report.

13.5.2 The engineering design, certification standards and operational procedures for wells and associated infrastructure

The engineering design, construction specifications and standards, and operating procedures for oil and gas wells, including those subject to hydraulic stimulation, are highly specified in a long series of international standards normalised as best practice and recognised under the current regulatory environment. This extends to standards such as those produced by the American Petroleum Institute (API), the worldwide leading standards setting body for the oil and natural gas industry. Accredited by the American National Standards Institute (ANSI), API has issued nearly 700 consensus standards governing all segments of the oil and gas industry. A fuller list of relevant API standards appears in **Appendix 14**. Many of the standards cited apply to petroleum operations more broadly and do not specifically address hydraulic fracture stimulation activities but they are applicable to unconventional oil and gas operations nonetheless. The Code of Practice for Western Australian Onshore Gas (Australian Petroleum Production and Exploration Association 2011) identifies 22 of the API standards as part of Western Australian petroleum regulation, five of which are specific to the process of hydraulic fracture stimulation.

The Inquiry neither found nor received compelling evidence that these API standards are insufficient for the purposes for which they were designed - as standards for best practice engineering – assuming that they are complied with and competently executed. The opportunity for further minimisation of risk to the environment and people through improving these particular standards is limited.

It should be noted that while these standards are designed to minimise the risks of environmental contamination and safety from an unconventional well, they are not accompanied by explicit standards on resulting emissions or discharges of pollutants. Reflecting concerns over the interpretation of ALARP, the Panel heard concerns about the lack of clear performance (outcome) criteria expected from an unconventional oil and gas well or field.

Finding 76: The global best practice standards for the design, construction and operation of oil and gas wells, including those relating to hydraulic fracture stimulation, are generally sufficient if competently executed and complied with. The opportunity for further minimisation of risk to the environment and people through improving these engineering-oriented standards is limited, although should be subject to some regulatory prescription.

The above Finding is particularly salient for the exploration phase of an unconventional oil and gas development, where activities are initially centred around a single or few wells. In this phase, the risks to the environment are localised and predominantly controlled through the effectiveness of the well and surface infrastructure to contain potential pollutants, and other avoidance and minimisation procedures and protocols largely embodied in the

standards. However, these petroleum-focused (that is, API) standards begin to lack sufficiency in environmental protection as the scale and footprint of the development extends to more gas fields through the production phase, when cumulative pressures on the environment from clearing, roads, water management, traffic and emissions increase.

The Panel received many comments recommending some form of prescription embodied in regulations at this level. That is, recommendations that would generally change some regulations to explicitly require, or explicitly forbid, certain activities or operations. These included:

- Specific design and testing requirements for well construction and commissioning with respect to the number of barriers and their extent through aquifers;
- Specific requirements for seismic monitoring and reporting;
- Specific plugging and testing requirements for decommissioning wells;
- Separation distance between wells and sensitive receptors;
- Prohibiting the use of BTEX chemicals;
- Prohibiting the use of potentially carcinogenic, endocrine-disrupting or mutagenic compounds;
- The requirement for reduced emissions completions and other limitations on venting;
- Prohibiting surface discharge of wastewater; and
- Prohibiting below-ground disposal of wastewater.

Findings and recommendations in this regard have arisen in **Section 8** (Land), **Section 9** (Water), **Section 10** (Greenhouse gas), **Section 11** (Public health) and **Section 12** (Social surroundings) of this Report.

It was clear through this Inquiry, as it has been through previous inquiries and reviews, that the issue of well integrity is central to environmental protection and public safety. Thus, regulator and public confidence in the competency of well design, construction, testing and commissioning such that they meet international standards is paramount. In this regard, since 1996 governing regulations for offshore petroleum wells in the United Kingdom required the examination and assurance by an independent, qualified, certified expert; this requirement now extends to onshore wells to ensure that 'the well is so designed and constructed, and is maintained in such repair and condition, that (a) so far as is reasonably practicable, there can be no unplanned escape of fluids from the well; and (b) risks to the health and safety of persons from it or anything in it, or in strata to which it is connected, are as low as is reasonably practicable'.

Directive 2013/30/EU of the European Parliament specifies a similar requirement for independent expert examination of well design. New Zealand Well Examination Guidelines, in contrast, allow for a well examiner to be identified either externally or within the operating company, if in the latter case the examiner is not in the immediate line management of operations. The Scientific Inquiry into Hydraulic Fracturing in the Northern Territory recommended that 'all wells be fully tested for integrity before and after hydraulic fracturing and that the results be independently certified'. In their referral of proposed tight gas drilling to the Environmental Protection Authority (EPA) in 2013, Buru Energy committed to providing additional test results (cement bond logging, pressure testing) on each gas well along with their specific drilling plans to an independent well examiner for final assessment and recommendations to the regulator.

Recommendation 33: To further ensure well integrity and thus environmental protection and public safety, well design, construction and testing should be assessed by an independent, certified expert well examiner, reporting to the regulator as a required part of commissioning, licensing and decommissioning.

13.5.3 The sufficiency and effectiveness of the environmental approvals process

Multiple submissions to the Inquiry asserted that the body of Western Australian regulations regarding onshore unconventional oil and gas development were wholly sufficient to protect the environment or overly onerous (for example, submissions from APPEA, Western Australian Chamber of Mines, Pastoralists and Graziers Association of Western Australia (PGA)).

"The regulatory framework for oil and gas in WA is sound and fit for purpose.

- *Many of the concerns raised about hydraulic fracturing are relevant to all petroleum exploration and drilling activities. They are well recognised by the industry and managed by adhering to high quality well construction and best practice in operations.*
- *The regulatory framework for the industry in WA has developed over 60 years and since 2011 been subject to independent review, a whole of government inter-agency assessment and a Parliamentary Inquiry in relation to the use of hydraulic fracturing.*
- *The current regulatory framework provides substantial protection for the environment and includes stringent checks and regulatory oversight"* - submission from MC Resources

"The resources industry is governed by more than 22 pieces of state and federal legislation and overseen by at least 8 government regulatory agencies. This has ensured that the industry operates within parameters that protect people and the environment while benefitting Western Australians… the resource industry is highly regulated and a positive contributor to the Kimberley region" – submission from G. Jenkins

"Our members have commented that they believe some aspects of the WA regulations are excessive. While many requirements such as baseline studies on soils, ground waters are well worthwhile, the chemicals reporting and pedantic nature of the process, is time and money wasting from both the company and the regulators perspective" – submission from The Norwood Resource

Through this Inquiry, the Panel also received a great deal of criticism and concern over the inadequacy of the PGER Act itself, and subsidiary provisions in the PGER (Environment) Regulations 2012, to adequately protect the environment. That is, the broader authorities and regulatory protections, for example, under the *Environmental Protection Act 1986 (*EP

Act) are not fully exercised under present arrangements, deferring to the PGER Act for governance of stakeholder consultation, environmental assessment, approval of environmental management plans and compliance.

We consider that the environmental impact assessment, licensing, native vegetation clearing and pollution control provisions in the EP [Environmental Protection] Act should apply to all fracking activities. … the EP [Environmental Plan under the PGER Act] is an inherently flexible instrument which is open to variation by DMIRS and the proponent in its content and scope. It is also an instrument that does not involve the stringent environmental impact assessment processes and protections contained within the EP [Environmental Protection] Act regime. From the outset of the PAGER Act… it is clear that this aspect of the regulatory framework does not make environmental protection a primary concern. The lack of environmental provisions in the PAGER Act, coupled with its apparent exemption from the EP Act…, means that environmental protection is largely relegated to an industry controlled, flexible environment plan - submission from the Environmental Defender's Office

The Panel noted that assessment and conditioning of all environmentally-significant mining proposals in Western Australia (and other major developments, for that matter) are normally assessed under Part IV of the EP Act against a well-established and tested set of environmental standards and guidelines, with an established consultation and appeals process, and become subject to a set of Ministerial conditions related to environmental protection and performance, extending to conditions requiring site rehabilitation and environmental offsets, if appropriate. These conditions are subject to audit by the Department of Water and Environmental Regulation (DWER) and infringement penalties embodied in the Act.

Finding 77: Environmental and public health assessment, approval, conditioning and compliance would be strengthened if executed through the *Environmental Protection Act 1986*, and this would go some way toward alleviating public concern over consultation, environmental protection standards, cumulative impacts and compliance.

The existing MOU between Department of Mines and Petroleum (DMIRS) and the Environmental Protection Authority (EPA) Services of DWER requires consultation on the referral of any proposal to employ hydraulic fracture stimulation to the EPA for its consideration. Under the EP Act, the EPA may choose not to assess such a proposal if it does not deem it to be environmentally significant, although the EPA publicly stated in 2016 that all such referrals would now be assessed. Further, the EPA's discretion is subject to appeal and it is the prerogative of the Minister for the Environment to direct the Authority to assess.

Through its assessment process, the EPA has regard to State policies as well as its own internal guidelines and policies. All of these may come into consideration in assessing an

unconventional oil and gas proposal, including Environmental Protection Bulletin No. 22, Hydraulic fracturing for onshore natural gas from shale and tight rocks (Environmental Protection Authority 2014). Should a Code of Practice (formalised under regulation) for developing onshore unconventional oil and gas become available, it would serve as a crucial touchstone informing any EPA assessment.

It is not unusual for the EPA to recommend that the Ministerial Statement granting approval for a proposal include one or more management plans that give effect to environmental protections, and that the EPA make the consideration of such plans part of its assessment. This would logically extend to the Environmental Plan and potentially the Well Management Plan and Field Management Plan required under the PGER Act. It is also a normal part of EPA advice that the Ministerial Statement extends to the required monitoring and environmental performance standards, the requirements for site closure and rehabilitation, and potential environmental offsets. DWER is responsible for auditing and compliance monitoring associated with a Ministerial Statement authorising a proposal.

Recommendation 34: The Environmental Protection Authority (EPA) should assess all onshore unconventional oil and gas developments associated with hydraulic fracture stimulation. To ensure issues of scale and cumulative impact are adequately considered, this should extend not only to individual wells during the exploratory phase of a development, but to the environmental assessment of proposed unconventional oil and gas fields if development may go forward.

This recommendation is consistent with Findings (8) and (9) and Recommendation 3 of the 2015 Western Australia Standing Committee Report.

The PGER Act includes a provision (s 101) affording Ministerial discretion on requirements for an oil and gas permittee to remove any infrastructure ('property'), close off wells, conserve local natural resources and 'make good any damage to the Earth's crust'. The PGER (Environment) Regulations 2012 makes no specific reference to any requirement for environmental site remediation. Submissions to the Inquiry noted that the only explicit requirement for rehabilitation of oil and gas developments are in DMIRS Guideline for the Development of Petroleum and Geothermal Environment Plans in Western Australia (the Environmental Plan Guidelines) (Department of Mines and Petroleum 2016a). These guidelines outline the need for infrastructure removal, site testing and rehabilitation. They do not specify the criteria or standards that would apply; a detailed plan in this regard is not required prior to commencement of the development and the operator establishes their own rehabilitation criteria (Department of Mines, Industry Regulation and Safety 2017a). Further, the duration and nature for monitoring post-closure (decommissioning) of sites is not specified in regulation but rather is determined on a case-by-case basis without explicit criteria.

"If the moratorium were lifted today, there would be no requirements on fracking proponents within the PAGER Act or associated regulations to remediate environmental impacts. Rather this is left to the general "ALARP" principle of project management. Alternatively, if a fracking proposal was assessed by the EPA pursuant to Part IV of the EP Act (see below), then if implementation of that proposal was authorised, there would be an opportunity to impose conditions on that proposal requiring remediation and rehabilitation of the site (including a process for responsible well abandonment), as well as monitoring compliance with those requirements" - submission from the Environmental Defender's Office

"Closure of hydraulic fracturing sites should be subject to the implementation of post closure management plan which includes a requirement for ongoing monitoring of closed site" – submission from the Western Australian Department of Health

A regular component of an EPA advice for mining proposals, and the resulting Ministerial Statements authorising a development, is the requirement for a rehabilitation and decommissioning plan. In some cases, this includes specific requirements for the restoration of key environmental values (for example, a species of concern, or a flow regime of a stream) or staging of the implementation and rehabilitation. More generally for mining developments, the EPA makes reference to guidelines for preparing mine closure plans (Office of the Environmental Protection Authority and Department of Mines and Petroleum 2015), the aim of which is to:

"ensure that, for every mine in Western Australia, a planning process is in place so that the mine can be closed, decommissioned and rehabilitated to meet DMP and EPA's objectives for rehabilitation and closure. Mine closure planning should be an integral part of mine development and operations planning. As such, the level of information required will correspond to the life span of the mine and reflect the various stages of the life cycle of the project".

Finding 78: There is no logical basis for any differences in regulatory expectations and arrangements for site rehabilitation between mining in general and onshore unconventional oil and gas developments associated with hydraulic fracture stimulation specifically. There is an opportunity to improve the efficiency and effectiveness of governance through uniform rehabilitation standards and procedures embedded within an enforceable Code of Practice under the *Petroleum and Geothermal Energy Resources Act 1967* (PGER Act) and available as guidance for assessments under Part IV of the *Environmental Protection Act 1986* (EP Act).

Recommendation 35: Appropriate standards for site rehabilitation and post-closure monitoring should be included in an enforceable Code of Practice.

13.5.4 The requirements for monitoring and reporting

In previous sections of this Report, based on submissions, the literature and global best practice, the Inquiry has made Findings and Recommendations with respect to monitoring. These extend to baseline monitoring of environmental conditions (for example, groundwater quality, land quality, seismicity, air quality [including methane], noise and traffic) as well as regular monitoring of how those qualities change over the life of an unconventional oil and gas development, including following closure and decommissioning.

Finding 79: The full specification and implementation of prescribed baseline and regularised monitoring may be specified within an enforceable Code of Practice.

In addition to what is monitored and when, the Inquiry received multiple submissions on the issue of public availability of environmental monitoring data, with many calling for the unconditional release of all such monitoring data.

"These baseline assessments must be transparent, legally verifiable and publicly available. If unconventional gas developments are to proceed in any areas of WA into the future, these publicly held baseline assessments will be critical for ensuring any future pollution can be quantified and responsible companies can be held to account. Baseline assessments must be accompanied by systematic monitoring of each of the attributes listed above to assess change against baseline. All baseline assessments and monitoring should be conducted independently, be made publicly available, and be paid for by a levy imposed on the industry" – submission from Lock the Gate

DMIRS has a Transparency Policy (Department of Mines and Petroleum 2011) that gives formal effect to overarching government policy in relation to transparency and the

community benefit of access to information. This includes 'easy access to the data, documents and information in relation to administration, regulation and investment attraction', and states,

> "We keep stakeholders informed of issues that affect them by providing transparent, timely, consistent and accessible information."

The principles guiding the release of data, documents and information are:

- promoting open government by treating information as a resource that should be accessible for the community to access and use;
- timeliness and accessibility;
- enhancing community awareness, understanding and engagement; and
- providing clarity around regulatory and decision making processes.

The Policy goes on to conclude that it will adhere to the position that if there is no legal reason to protect the information, it should be open to public access.

Finding 80: The default treatment of environmental monitoring data required by regulation or Ministerial Statement should be that it is not subject to commercial confidentiality and should be made public, and that availability be regularised through open publication by government (as opposed to simply available through the procedures of the *Freedom of Information Act 1992* (FOI Act)). This is consistent with the stated intent and principles of government transparency.

This is entirely consistent with Recommendations 10 and 12 of the 2015 Western Australia Standing Committee Report.

Recommendation 36: Baseline and subsequent environmental monitoring data collected as a regulatory requirement in the licensing, approval and auditing of unconventional oil and gas developments associated with hydraulic fracture stimulation should be made publicly and easily available, by default.

The Panel also received submissions suggesting who, other than the proponent, should be responsible for environmental monitoring, with some suggesting either third-party monitoring or monitoring by an agency other than DMIRS. To some extent, Findings and Recommendations in other sections of this Report have considered this for specific issues. In general, the wide-scale practice across all industries in Western Australia is for industry monitoring and reporting, with agency auditing of the quality and sufficiency of the reported data.

"As well as technical competence of the drilling companies, the major issue in ensuring damage to the environment is minimised, is appropriate Government regulation and adequate technical staff capacity to assess mandated self reporting by the UG companies of "incidents" and the data from any required regular monitoring of the well integrity, water and contaminant movement and methane fugitive emissions. Self reporting needs to be quality controlled by continuing Government inspections of the facilities and the companies event recording books. As well as staff capacity to assess and regulate EIS issues and reports from the shale gas companies, the WA Government also needs the costly and difficult to obtain expertise to monitor the shale gas and oil field operations" – submission from Professor Peter Dart

Finding 81: Apart from some highly technical or regional-scale monitoring (for example, regional methane emissions, regional seismic monitoring), environmental monitoring required by regulation or licence is generally the responsibility of the proponent. It is in their interest to do it well and to the specifications required. It is the responsibility of government to ensure it meets requirements and standards through auditing.

The issue of monitoring post-decommissioned wells remains. While the operator may be required, for a time determined on a case-by-case basis, to monitor sites and infrastructure following decommissioning and cover those costs, once the Minister accepts that all conditions have been met, the production licence is surrendered and all monitoring responsibilities of the operator cease. Any subsequent liabilities revert to the State.

The Western Australian Petroleum Information Management System (WAPIMS) lists every petroleum well in the State and its status. However, following surrender of the production licence, there is no monitoring program of well integrity by government, nor is there any government program researching or testing the long-term integrity of wells. While no evidence was presented to this Inquiry of post-decommissioning pollution from a stimulated and then decommissioned well, experience overseas suggests there is a potential residual risk. **Section 10** (Greenhouse gas) of this Report makes a Finding (Finding 37) and Recommendation (Recommendation 11) in this regard.

There is also the much broader and complex issue of the public availability of plans and compliance reports, centring on the public's right to know how the environment is being protected, versus commercial confidentiality. The Inquiry received a number of submissions, covering diverse views on this issue. There is no provision under the PGER Act that requires plans to be made public and, at present, only a summary of the Environmental Plan is provided for public disclosure; the full Plan can only be released with the consent of the operator. The summary is only required to provide a general description of the existing environment that may be affected and a summary of details for proposed facilities, operations, impacts, risks, implementation and consultation.

"Throughout the PAGER Act regime there is a lack of transparency which in turn undermines public trust and accountability that is important in environment and resource development decisions. From the outset, the applications process is private, with direct prohibitions on publishing certain information. There is no opportunity for the public to comment on an application for tenure, or any provision for objections to be made on public interest grounds at this important formative stage. This contrasts with other jurisdictions, and other resource legislation in WA (which allows public interest objections to be made). In our view there is a lack of transparency in the EP [Environmental Plan] framework that is not appropriate for modern regulation. The undefined level of detail required in the published EP summary could produce inconsistent levels of transparency across operations, and leaves open the possibility of very low provision of information that is of high importance to the community. Leaving this element of transparency to proponent and Department policy is not a robust regulatory approach. Other jurisdictions provide for publication of the full EP" - submission from the Environmental Defender's Office

"As a minimum there should be: public release of all other information relating to environmental management and compliance by the fracking industry, including proponent documentation, management plans, compliance reports and groundwater and environmental monitoring data" – submission from Judy Blyth

An alternative view on full public disclosure of plans came from other submissions, largely from industry:

"Increased transparency of petroleum activities has been seen by government agencies as a key aspect for increased confidence and trust in the community through greater understanding and awareness and is reflected in DMIRS' Transparency Policy. This is reflected by DMIRS considering full public disclosure of Environment Plans, monitoring data and compliance reports. Making all environmental information publicly available assumes opposition to the petroleum industry by activist groups is premised on protecting the local environment and groundwater in particular. Increasingly, it is becoming apparent that opposition to the petroleum industry reflects anti-fossil fuels positions that have been adopted by these activist groups. In this case, increasing transparency of environmental documentation and associated data will not increase public confidence in the petroleum industry. In certain instances, when environmental and other information has been publicly released, activist groups have taken selective parts of the released information and used it out of context to suggest that a problem might exist when that is not the case. The selective use and publication of environmental information can lead to further erosion in public confidence in the petroleum sector as well as with the regulator" – submission from Buru Energy

"…there is an increasing desire on the part of local communities and the public at large for even greater transparency and access to information. At the same time, laws and regulations that protect innovative technology and proprietary information enable the development of greener chemistry and products that deliver greater environmental and production benefits. Accordingly, Halliburton supports public disclosure of ingredient information related to its HF chemical products, provided that proprietary information of Halliburton and other innovator companies is protected" – submission from Halliburton

The Panel understands that some of the technical documentation provided as plans for consideration and approval by the regulator are inherently commercially-sensitive. This may extend to commercial arrangements, details of resource assessment and prospectivity, and certain engineering approaches and innovations. However, it is widespread, standard practice in other jurisdictions, as well as with proposals submitted for approval under the EP Act in Western Australia, that the documentation describing the proposal, the local environmental values at risk and the predicted impact on those values are described in detail and made publicly available. In this case, the Environmental Plan under the PGER Act serves this function and the Panel could not differentiate in general between the inherent need for commercial confidentiality involved in unconventional gas versus resource developments more generally.

Finding 82: Environmental Plans for unconventional oil and gas developments associated with hydraulic fracture stimulation broadly serve the equivalent function of environmental review documents provided to environmental agencies under other environmental regulatory regimes, and similar expectations on their availability for public review apply.

Recommendation 37: Once the Environmental Plans required under the *Petroleum and Geothermal Energy Resources Act 1967* (PGER Act) are deemed sufficient for consideration, they should be published in full at the time of assessment.

This recommendation is consistent with Recommendations 2 and 8 of the 2015 Western Australia Standing Committee Report.

The Inquiry considered the separate issue of the publication of compliance reports, and associated reports on the investigation of breaches. It is not standard practice for any of the State's environmental regulators to publish routine compliance reports (for example, quarterly or annual reports required under a plan or licence). More specifically, however, there is the question of whether reports indicating environmental non-compliance, reportable incidents or environmental audits should be made routinely and publicly available. Currently, Annual Environmental Reports, reportable and recordable environmental incident reports, emissions and discharge reports, and rehabilitation reports

submitted to DMIRS and can be requested through Freedom of Information (FOI). This information is otherwise routinely available to the public only through summarised statistics and information in the Department's annual reports.

"A lack of transparency is also evident in the "reportable incident" and compliance framework. A lack of transparency around environmental impacts and other regulatory contraventions is not appropriate for regulating the impacts of fracking. Any regulatory framework must provide for accountability to the community by making this information public, or risk undermining effectiveness of and public confidence in the regime. There are numerous examples of reporting of incidents and public reporting of environmental performance and compliance under approvals. The publication of this information would also further incentivise compliance by proponents" – submission from the Environmental Defender's Office

The DMIRS made available to the Inquiry a compilation of all the reported spills associated with hydraulically stimulated wells since 2012. This is available in **Appendix 10**. This information would have otherwise been available in principle through the *Freedom of Information Act 1992* (FOI Act) but not routinely published. With respect to the availability of incident reports and subsequent investigations, investigations remain confidential in situations where there is potential for prosecution. There are currently no provisions in the PGER Act for public release of information regarding incidents. However, reports can be accessed through the provisions of the FOI Act.

In response to questions to DMIRS from the Panel in this regard, DMIRS stated that it is striving to improve public reporting, through its ongoing transparency initiatives and the Petroleum 2020 legislative reform project.

In principle, reports that would otherwise be available under FOI should ideally be made publicly available. As stated by the Western Australian Office of the Information Commissioner:

"FOI is not a tool for agencies to prevent disclosure of documents because of embarrassment or unwelcome attention by the public. Conversely, neither is FOI intended to be used to disclose sensitive personal or business information about third parties (for example, trade secrets), or information that is currently deliberative or subject to lawful investigation".

Recommendation 38: Reports of environmental and public safety non-compliance, incidents and their investigation, and government environmental performance audits, should be made routinely publicly available once they would otherwise be reasonably subject to a Freedom of Information request.

13.6 Other regulatory advice

As stated in the introduction to this Section, the Terms of Reference and scope of the Inquiry focus on an evidence-based assessment of risk related to hydraulic fracture stimulation activities and what further regulation within a science-based approach might be useful in further reducing risk to an acceptable level. The Panel believes that the above considerations and recommendations are all clearly within that scope.

The Panel also heard concerns and suggestions for regulatory reform that extend beyond technical, science-based protections of the environment and public health. Such issues and reforms merge into greater considerations of public liability, administrative arrangements of government, procedural fairness and social equity. While the Inquiry was clearly not established to fully explore and advise on such matters, it was equally clear that such matters weigh heavily in the minds of many of those making submissions and statements to the Inquiry. Some of these matters are considered in detail in **Section 12** (Social surroundings) of this Report. It was the Panel's view that it held an obligation to consider and reflect on these matters, and that it is in the public interest to report on those considerations. In providing this advice, the Panel is conscious that while it is targeted at issues associated with unconventional oil and gas development based on hydraulic fracture stimulation, the issues often do not entirely differentiate between that industry, the conventional onshore oil and gas sector, and resource development more generally.

13.6.1 Industry accountability

The Panel heard through many submissions concerns about the potential risk that the public will hold liability for environmental and health impacts from unconventional oil and gas developments that should properly rest with the operator (industry). These concerns extend to assertions that the financial assurances, insurances or non-compliance penalties are too small to either cover these liabilities or deter poor practice over the operating life of an unconventional gas project. They also extend to the liabilities associated with site remediation and rehabilitation, including those that may emerge after decommissioning.

With respect to the financial assurance against environmental liabilities that may emerge over the life of an unconventional oil and gas development, there is apparently no bonding or other financial assurances required from an operator, even discretionary ones such as the Unconditional Performance Bonds provided for under the *Mining Act 1978* (Mining Act). Neither is there any equivalent to the Mining Rehabilitation Fund (established by legislation in 2012) that requires annual reporting of environmental disturbance and annual contributions to a Fund, the purpose of which is to offset the public liability for rehabilitating abandoned mine sites where the tenement holder/operator has failed to meet rehabilitation obligations and from whom the costs cannot be recovered.

"Regulations must require bonds to be paid to government to be used to remediate environmental damage" - submission from Sustainable Energy Now

"…in consideration of the long time frames for some impacts to be revealed, a trust fund approach would ensure that resources are available for post abandonment monitoring and well failure remediation" – submission from Nell Thayne

"Companies must be liable for compensation for environmental damage. Questions of how this could be assessed or calculated should be predetermined, and not left to chance" – submission from Buddhists for the Environment Western Australia (BFEWA)

Following Recommendation 11 of the 2015 Western Australia Standing Committee Report, it is the Panel's understanding that DMIRS has undertaken some preliminary work to assess the feasibility of options regarding financial assurance for environmental liability in the petroleum industry, including establishing a Petroleum Rehabilitation Fund or extending the Mining Rehabilitation Fund to petroleum related activities (as well as other models), in consultation with industry and community stakeholders. A discussion paper 'Examination of Financial Assurance for Petroleum in Western Australia' has been written for circulation among industry and government stakeholders, with the aim of progressing financial assurance options for the petroleum industry. The EP Act also contains a provision (s86) for establishing financial assurances, which may provide an alternative means to minimise public liability for remediation.

Finding 83: Site rehabilitation and the long-term environmental performance of wells is the clear responsibility of the operator. Appropriate financial assurance is required to ensure that any necessary remediation of impacts to the environment can be funded. Additionally, industry contributions to fund the remediation of legacy issues associated with the industry would further protect the State from future liability.

Recommendation 39: The Western Australian Government should require appropriate financial assurances or insurances to cover potential environmental liabilities, as well as contributions to a fund to cover liabilities defaulted by other unconventional oil and gas operations associated with hydraulic fracture stimulation in Western Australia.

The above Finding and Recommendation are entirely consistent with Findings (5) and (41) and Recommendation 11 of the 2015 Western Australia Standing Committee Report.

There was also a concern expressed to the Panel regarding the transfers of liability when a lease is transferred to another holder, specifically, that any existing or latent damage to the environment does not become the responsibility of the new leaseholder.

Under current legislation and regulation, when the ownership of a production licence changes hands, the responsibilities with respect to the forward management of the licence transfer to the new registered holders, jointly and severally, including all liabilities pertaining to decommissioning obligations. Change of ownership is conditional on the new registered holder accepting any residual responsibilities and liabilities attached to that licence. The new registered holder must demonstrate, to the Minister's satisfaction, that it has the technical expertise and financial competency and assurances to comply with the regulatory requirements for managing and decommissioning the fields included in the licences proposed for transfer. The registered holder is responsible for ensuring that, throughout the entire decommissioning and rehabilitation process, there is an accepted safety system in accordance with relevant legislation. The scope of coverage of the safety system includes all activities undertaken by the registered holder/operator and any contractors that are necessary to fulfil the registered holders' obligations and commitments to DMIRS. The safety system is required to be managed, controlled and updated throughout the entire decommissioning and rehabilitation process. With respect to the financial capacity of changing corporate entities (that is, corporate buy-outs or takeovers of companies), details of the registered holders of a petroleum title or licensed area are required to be correct and current at all times. Any changes to registered holders' interests on titles and licensed areas must be made available to DMIRS and approved by the Minister or his delegate. Presently, DMIRS does not have legislative powers that would limit or prohibit transactions.

The above assurances do not extend to issues of non-compliance and associated penalties. The Panel heard and read a number of views on this matter in the course of the Inquiry. These concerns included penalties being either too low or not appropriately scaled to the level of environmental impact resulting from the breach and to presumptions of responsibility for contamination or harm. Under current PGER legislation and regulation, the maximum penalty for non-compliance with regulations for all three petroleum Acts is $10,000, and DMIRS has guidelines for enforcement (Department of Mines and Petroleum 2015c) and prosecution (Department of Mines and Petroleum 2015d).To date, DMIRS has never fined or prosecuted an operator for any environmental breaches or lack of compliance.

There are no explicit offences relating to environment impacts under the PGER Act, although it is an offence to inject petroleum into a natural underground reservoir without Ministerial consent. Some offences are found among the PGER environmental regulations, mostly relating to the requirement for an Environmental Plan or complying with it.

"…the comparatively low penalties provided for in the PAGER Act regime are inappropriate for managing the environmental impacts of fracking... Under its subsidiary legislation the highest maximum penalty is only $10,000. This is in stark contrast to other Australian jurisdictions. For example, in Queensland non-compliance with their EP [Environmental Plan] equivalent carries a maximum penalty of $567,675… The extent of penalties must also be viewed with the financial capacity of fracking proponents, which are known to spend hundreds of millions on exploration and development in a single State. Clearly the penalties in WA's current regulatory regime are not considered sufficient to disincentivise environmentally harmful practices in fracking" – submission from the Environmental Defender's Office

Other legislation that defines environmental offences and associated penalties (most notably the EP Act) embody these provisions in an Act, as opposed to subsidiary regulations, and recognise that offence provisions and penalties should scale with the degree of environmental harm and how deliberate the contravention. For instance, the EP Act has a system of tiered penalties, with high penalties for bodies corporate.

DMIRS has previously sought legal advice and review regarding statutory penalties, and these were circulated for stakeholder comment in December 2013. For petroleum and geothermal legislation, it was concluded that:

- Penalty amounts should be increased, proportionate to the offence and structured to be applied in a consistent manner;
- Consideration should also be given to the introduction of corporate level penalties; and
- Penalty increases would be undertaken at the next opportunity for legislation review, but would require further consideration of the options and stakeholder consultation.

Finally, the issue of operator suitability was raised. It was noted that the process for an application for tenure (or an application for increasing or extending tenure) covers the applicant's technical and financial capacity; it asks no information on the company's environmental record. Environmental protection or resource legislation in other States (Victoria, New South Wales) and Federally allow for the consideration of an applicant's history of environmental compliance and this is a recommendation in the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory. The argument in favour of this is the incentive for long-term compliance as well as community confidence in both the industry and the regulators.

Finding 84: With adequate baseline, environmental monitoring, and appropriate monitoring over the whole lifecycle of an unconventional oil and gas development associated with hydraulic fracture stimulation, a presumption that a company employing hydraulic fracture stimulation is responsible for any local contamination event without evidence of attribution is not justified.

Finding 85: The penalties available for environmental offences under the *Petroleum and Geothermal Energy Resources Act 1967* (PGER Act) and subsidiary legislation are too low to provide an effective incentive for compliance.

Finding 86: Greater protections to the environment would be secured if environmental offences were clearly identified within the *Petroleum and Geothermal Energy Resources Act 1967* (PGER Act), along with a tiered system of penalties reflecting the seriousness of harm and intent.

Finding 87: An application for tenure (or to increase or extend tenure) does not include a requirement to disclose the applicant's environmental record.

Recommendation 40: Environmental offences, and a system of penalties scaled for seriousness of harm and degree of deliberate intent, as per the *Environmental Protection Act 1986* (EP Act), be incorporated into the *Petroleum and Geothermal Energy Resources Act 1967* (PGER Act). These penalties should extend to both the company and its directors.

Recommendation 41: Future access to tenements should consider the past environmental record of the applicant.

The need to increase the maximum fines permitted under the PGER Act to a more appropriate level is in accordance with Recommendation 1 of the 2015 Western Australia Standing Committee Report.

13.6.2 The independence of the regulator

More than any other single issue regarding the regulatory regime for hydraulic fracture stimulation, the Panel heard numerous concerns regarding trust in the regulator's independence and commitment to environmental compliance. Generally, this concern was focused on the conflict of interest inherent in a regulator being responsible for both promoting the industry and protecting the public interest in their health and their environment. These concerns came not only from the community and environmental Non-Government Organisations (NGOs), but also through industry submissions concerned about public confidence.

"The dual responsibility of the regulator as both a promotor and regulator of the industry has led to statements that the 'fox is guarding the henhouse' and led to some public distrust of the regulator. While this is unwarranted given the separation of the respective functions within DMIRS, this perception is widely propagated by opponents to hydraulic fracturing and is now an issue of concern amongst some members of the general public. If it can be demonstrated that separation of the promotion and regulatory functions would lead to an increase in public confidence in the regulator, Buru Energy would support this change" - submission from Buru Energy

"While we do not criticise the professionalism and expertise of staff within DMIRS, we strongly submit that it is not appropriate for one agency to have the responsibility for both promoting an industry and pursuing its development and expansion, while at the same time being the "lead agency" charged with its regulation. Any regulatory regime for fracking in WA should ensure that regulation and promotion responsibilities are clearly separated to ensure integrity and public confidence in the system. Recommendation: the responsibility for regulating the environmental impacts of fracking should reside with an environmental regulator under the EP Act. This would include decision-making involvement in the grant of tenure, the assessment process, the setting of the environmental conditions on any proposals, and enforcement for any non-compliance" – submission from the Environmental Defender's Office

"DMIRS is a major advocate for fracking, both within government and the community, and does all it can to (a) facilitate the expansion of the industry; (b) help the industry avoid the full costs and liabilities of its activities, and (c) shield it from proper public scrutiny" – submission from Peter Robertson

"A truly independent body should be involved in the full assessment of the unconventional gas industry and in its regulation" – submission from No Fracking WAy

"The Environment Plans are assessed and approved by a proponent for industry – the Department of Mines and Petroleum (DMP). This is an inherent conflict of interest within the DMP as the environmental regulator. The circumstances in which the Environment Protection Authority approve oil and gas developments or may impose conditions on the management of any part of the petroleum operation, (including produced water) must be toughened to protect the environment first and foremost" – submission from Hon Robin Chapple, MLC

"I believe there is a need for independence in the assessment of petroleum exploration and production licenses. It is not appropriate that the Department of Mines & Petroleum - the Ministry charged with securing the state's energy security - should assess exploration and production license applications submitted by petroleum companies and conduct environmental compliance audits. The Environmental Protection Authority offer the level of independence required in carrying out audits and inspections and the ongoing monitoring during the production phase, through to abandonment. The EPA should ensure that the Environmental Management Plan is executed with adequate follow up once a well is decommissioned" - submission from Shane Love MLA

Other submissions to the Inquiry and participants at public meetings suggested that monitoring and auditing of compliance should be undertaken by an independent organisation, separate from the government department that issues licences and operationalises the regulations. It was suggested any organisation tasked with monitoring should have sufficient powers to ensure compliance is taken seriously by proponents and the communities within which mining activities occur.

It is a general matter of good governance that there be clear separation between industry promotion (including the awarding of tenure and leases), and compliance. DMIRS administers petroleum titles and applications, releasing areas for competitive bidding, exploration and resource management. At the same time, it also administers environmental health and safety provisions and compliance. DMIRS has a clear role in supporting sustainable growth in the Western Australian economy.

It is not unique that a State department both allocates and regulates a resource, particularly renewable resources, such as water or fisheries. However, in such cases there are

frameworks in place to ensure sustainability of the industry, the environment and the community they support.

The new DMIRS (formed on 1 July 2017) adopted a new structure from 22 January 2018. Many of the activities of the former DMP now reside within the Resource and Environmental Regulation (RER) Group of the Department. The new structure is more strictly aligned along 'function' and, as a result, the Petroleum Division and Mineral Titles Division were abolished. All matters related to grant of title (minerals and petroleum) are now dealt with by the Resources Tenure Division. All compliance matters (minerals and petroleum) are now dealt with by the Resource and Environmental Compliance Division. The third division within the RER Group is the Geoscience and Resource Strategy Division, which consists of the former Geological Survey as well as policy officers dealing with the resources industry and legislation. All three of these Divisions, including the compliance function, answer to the leader of the RER Group, who reports to the Director-General (submission from the Department of Mines, Industry Regulation and Safety).

Finding 88: Clear and demonstrable separation of the function of ensuring environmental compliance of unconventional oil and gas developments associated with hydraulic fracture stimulation from the promotion and allocations of tenure to the industry would better conform to best practice in government, and would greatly increase public, and industry confidence in environmental protection and public safety. This is not adequately achieved through the current structure and roles of the Department of Mines, Industry Regulation and Safety (DMIRS).

There are multiple alternative models of governance that might better ensure independent environmental auditing and compliance. One would be to separate out the DMIRS compliance group and have it report directly to the Director-General, who then becomes personally (and visibly) responsible. An alternative would be that all environmental performance auditing and compliance be done under the EP Act and given effect by DWER. At the extreme, an entirely new agency could be established to fulfil this function. Each of these alternatives comes with considerations of cost, efficiency and capability.

Finding 89: An efficient and effective auditing and compliance model of governance for unconventional oil and gas development associated with hydraulic fracture stimulation is to exercise these duties under the *Environmental Protection Act 1986* (EP Act), employing the environmental science and regulatory capabilities of the Department of Water and Environmental Regulation.

Recommendation 42: The Western Australian Government should consider better separating environmental auditing and compliance of unconventional oil and gas development employing hydraulic fracture stimulation from the department that promotes and allocates resources to that industry.

It was also noted in submissions that whatever the regulatory arrangements, any regulator needs adequate capacity and capability to competently and effectively execute their duties, and some compassion was expressed for current staff with respect to meeting the expectations of the community and industry.

"The panel should consider the benefits of having independent regulators and that regulatory bodies should include appointments of qualified geologists, suitably skilled to assess the risks local geologies may have on unconventional exploration and production" – submission from Frogtech

"An equally important matter is whether governments are adequately staffed to carry out their duties in monitoring, audit and compliance of approved projects. In my experience, governments in Australia are not adequately resourced to do this. In my preliminary experiences with the WA Government I believe the problem is certainly at home here. A much greater investment in environmental departments in WA would be required if an unconventional gas industry were to develop in the state" – submission from Jessica Miller

The Yawuru, on whose land there have been hydraulic fracture stimulation activities, also raised concerns about the regulatory mechanisms in Western Australia being ill-equipped to cope with the pace, complexity and scope of the emerging hydraulic fracturing industry. In addition, concerns were raised in their submission that government monitoring bodies do not have sufficient resources to enforce regulations, and remoteness adds to the complexity and cost of assiduous monitoring. This was borne out at the Fitzroy Crossing public meeting where a participant claimed the regulator is not actually checking wells ('no visits, no inspections'), but local people go and check up on what is going on as observers. In short, many were satisfied with the regulations but were worried that these were not being enforced.

Finding 90: If the onshore unconventional oil and gas industry is to proceed and grow, then inadequate resourcing of environmental auditing and compliance will erode public confidence in the protection of the environment and safety.

Recommendation 43: The capability and capacity for the environmental auditing and compliance functions of government must be sufficient to assure environmental protection and safety, so this must be adequately resourced and include cost recovery from industry.

13.6.3 Access to land

An important issue driving concerns about, and opposition to, hydraulic fracture stimulation and the development of an onshore oil and gas industry in Western Australia are the arrangements and legislations surrounding access to land. This issue extends across freehold, pastoral leasehold and Aboriginal lands. It raises fundamental social and legal issues that go well beyond the Terms of Reference of this Inquiry and well beyond the specific case of unconventional oil and gas development. And yet, for the Inquiry not to acknowledge the issue and offer some reflection through this Report would, in the view of the Panel, do a disservice to those that have engaged with this Inquiry as well as those who commissioned it.

To some extent, this issue has been considered in part in other sections of this Report, particularly within **Section 12** (Social surroundings).

Some views expressed to the Panel, such as those from the PGA and the Western Australian Farmers Federation (WAFarmers), see the value in preserving the opportunity for individual and mutually-beneficial negotiations between a petroleum company and a landholder, noting concerns from pastoral leaseholders (for example, the Kimberley Cattlemen's Association) that leaseholders may be in a weaker position in that regard than owners of private land.

Many held views that there should be a right to deny or veto access to land, be it private, leasehold or under Native Title. In a statement to the Panel, a spokesperson for Lock the Gate suggested that if this one change were made, much of the organised opposition to hydraulic fracture stimulation would ease.

Others noted that access provisions, at least for private land, are significantly different between the PGER Act and the Mining Act. Under the former, access cannot be denied (apart from small parcels, cemeteries, reservoirs and places with substantial improvements), although compensation is required. Under the latter, access can be objected to and if consent is not granted by the Mining Warden, no mining can take place on or near the surface of the property. For some people representing views to the Panel, this was an important difference in the protection of property rights, particularly for agricultural enterprises. DMIRS Land Access Information Paper (Department of Mines, Industry Regulation and Safety 2017b) provides a clear summary of the differences in land access under the two Acts.

It was not clear to the Panel why these access provisions differ between the two Acts. Perhaps it is an artefact of history and a time when petroleum was treated as a strategic resource, as reflected in provisions for the Governor to pre-empt all petroleum production in case of a national or State emergency under the original *Petroleum Act 1936*. Other rationales are given in the Land Access Information Paper.

Through consideration of submissions, the Panel identified three basic approaches to facilitating land access in a fair and equitable manner. The first of these is through an enforceable Code of Practice that defines appropriate consultation, representation, access to expert advice, terms of compensation and conditions of access. A framework such as this was agreed among APPEA, WAFarmers, the PGA and Vegetables WA (VWA) in 2015. This framework includes a template for a Farming Land Access Agreement. In addition, individual petroleum companies have shared with the Inquiry their own processes and arrangements for accessing private land, pastoral land and Aboriginal lands, and the Panel heard expressions of satisfaction from many of those stakeholders with the consultations and outcomes.

A second approach is to establish a statutory body to act as an independent arbiter for landowners (in the broadest sense) and resource companies regarding access arrangements for developing onshore unconventional oil and gas. This approach has been adopted in Queensland (the Queensland Gasfields Commission) and recommended for the Northern Territory by the recent Inquiry. This would be accompanied by the establishment of a statutory framework for land access agreements; a formalisation of the kind of framework reflected in the APPEA/WAFF/PGA/VWA agreement. Such an approach was called for in Recommendations 5 and 6 of the 2015 Western Australia Standing Committee Report.

The Panel also heard dissatisfaction and doubts over the equitability and fairness of land access arrangements, with calls ranging from a requirement for 'prior, informed and written consent', to an absolute right of veto of access. The Panel does not underestimate the legislative complexity involved in providing for such rights across private, leasehold and Aboriginal lands, and how that could be made specific to unconventional oil and gas as opposed to any and all resource developments.

Separate to those frameworks or legislative changes regarding the fundamentals of access, the establishment of basic separation distances between unconventional oil and gas infrastructure and town sites, residences, water supply bores and places of iconic natural or cultural heritage has been considered in this Inquiry, with some recommendations for their adoption and treatment. Beyond that, submissions to the Inquiry raised the broader consideration of exclusions zones. The PGER Act does not facilitate the ability to excise areas from potential tenure, in contrast to the Mining Act, which specifies that graticular (tenure) blocks are fixed as 5' latitude and 5' longitude (about 80 km^2 each). Thus, places of iconic or sensitive value are not easily excluded from the granting of tenure for petroleum development. Such exclusions would at least in part reduce some public concerns about the

risks associated with hydraulic fracture stimulation and associated activities, and this is reflected in Recommendations in this Report. Public review with an opportunity to comment on the extent of proposed onshore oil and gas titles prior to them being finalised and awarded would afford the community a chance to identify areas that might be excluded from the titles, and the reasons why. It is the Panel's understanding that more recently, DMIRS has undertaken targeted stakeholder consultation on potential releases of acreage for petroleum development and accommodating the exclusion of areas deemed inappropriate for resource development.

Finding 91: The consideration and spatial definition of new petroleum titles should include stakeholder consultation regarding the exclusion of areas of high environmental, social or cultural sensitivity and value.

Recommendation 44: Stakeholder consultation on proposed releases of acreage for onshore unconventional oil and gas development should become a formalised and regular requirement.

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14 Findings and Recommendations

14.1 Land

Finding 1: In the potentially prospective area for shale oil and gas in the Perth Basin, which encompasses existing gas fields between Eneabba and Dongara, the geology is most suitable for production from stimulated horizontal wells, with a density of well pads substantially lower than overseas unconventional gas fields with vertical wells.

Finding 2: Given the paucity of studies on tectonics and seismic hazard in the Canning Basin, further data collection, permanent monitoring stations and independent studies of the stress state and neotectonic activity, such as those undertaken by Geoscience Australia, are warranted.

Finding 3: The direct impacts of clearing for infrastructure on vegetation and ecological integrity from development proposals of the scales described in the industry submissions to the Inquiry (including access roads and even a regional pipeline) are sufficiently managed under the existing regulatory environment to pose a low risk.

Recommendation 1: The cumulative impacts of landscape clearing and fragmentation depend on scale and duration. Such impacts should be anticipated and assessed prior to development approval, with the eventual rehabilitation and restoration of redundant infrastructure clearing meeting the expectations of both regulators and the community.

Finding 4: In the Canning Basin, the residual risk under current regulations from the spread of weeds is negligible in areas historically subject to pastoralism. For extensive areas free of weeds, the residual risk of impacting on ecological integrity is low.

Finding 5: In the Perth Basin, strict quarantine and hygiene procedures are necessary to protect native vegetation and agriculture, to keep the risk of introduction and spread of weeds low.

Finding 6: The indirect impacts on fauna from traffic, noise and light pollution under the existing regulatory regime and industry practice are all considered to be low.

Finding 7: The overall risk to flora and fauna, and the maintenance of ecological integrity, is low, if the current State and Federal regulatory and environmental approval processes are applied, including the consideration of cumulative impacts.

Finding 8: For the Canning Basin, the risk to preserving the integrity of places of distinctive ecological and conservation value is low, so long as future developments do not encroach on areas of high conservation significance, cultural or aesthetic value.

Finding 9: For the Perth Basin, the risk to damaging the integrity of places of distinctive ecological and conservation value is moderate as present regulations allow potential entry into the limited areas of native vegetation. This risk reduces to low if such entry is forbidden.

Recommendation 2: The Western Australian Government, in consultation with the community, should identify places of iconic natural heritage and exclude those places from future exploration and development for unconventional oil and gas associated with hydraulic fracture stimulation, sufficient to protect their values from direct development or by proximity to increased traffic, noise, light or visual impacts. These consultations should be a formal part of the process by which the Western Australian Government releases acreage for potential development.

Finding 10: The overall risk to soil and land health including beneficial use, under the current regulations related to remediation, maintenance and rehabilitation, is low. However, the residual risk and impact can be further minimised through landholder consultation and compensation on residual impacts.

Recommendation 3: Access to productive land should require an agreement with the Traditional Owners, landholder or leaseholder regarding the location, maintenance, operation and remediation of infrastructure, as well as compensation for residual damage to the subsequent productive use of the land.

Finding 11: Given the known low projected volumes of injected fluids and geomechanics of the Canning and Perth Basins, the risk to life or damage to property and infrastructure from induced seismicity is low. Owing to the incompressible nature of target formations and the relatively small volumes of fluids being withdrawn per unit volume of rock in unconventional oil and gas production, the risks of land subsidence or uplift at the surface associated with hydraulic fracture stimulation operations in Western Australia are negligible.

Recommendation 4: An early warning system based on a 'traffic light scheme' should be implemented to prevent adverse geo-mechanical events reaching a size of any consequence to land or hydrogeology.

14.2 Water

Finding 12: Baseline groundwater quality monitoring is now part of onshore petroleum activities and surveillance groundwater monitoring is carried out during operations.

Recommendation 5: That baseline and routine surveillance groundwater quality monitoring, including methane concentrations, should be included in an enforceable Code of Practice and results made publicly available before commencement of drilling operations and thereafter.

Finding 13: Excessive groundwater use is not permitted under the Department of Water and Environmental Regulation (DWER) water licensing regime. Water quantities to be used for petroleum operations are licensed by DWER, and applications for significant quantities have to be justified by a hydrogeological report detailing likely impacts, and may be subject to further review and advice from the Environmental Protection Authority (EPA). Claims of excessive water use by hydraulic fracture stimulation operations are not borne out by the companies' planned use of water and likely use is modest compared with other existing licensed uses.

Finding 14: There is currently no requirement for the information on chemicals proposed to be used and/or the environmental risk assessment to be reviewed by the Department of Health (DoH), which has the relevant expertise to assess this information. Currently the DoH only reviews information when asked by the Department of Mines, Industry Regulation and Safety (DMIRS) or the Environmental Protection Authority (EPA) when there is a specific issue/concern. To ensure public confidence that appropriate expertise is used to review such assessment, it would be appropriate for DoH to review all such assessments.

Finding 15: Benzene, Toluene, Ethylbenzene and Xylene (BTEX) have not been proposed to be used for drilling of wells using hydraulic fracture stimulation in Western Australia since 2009. Hence, banning use for this purpose should not be of concern to the industry but would assist in alleviating community concern.

Finding 16: The current requirements for chemical disclosure do not require the identification of key chemical hazards such as whether the chemical is a known or suspected carcinogen, mutagen, developmental toxicant or endocrine disruptor. To address public concern in relation to these issues it would be appropriate for these characteristics to be included in the chemical disclosure and the use of carcinogenic, mutagenic, developmental or endocrine disrupting chemicals minimised or avoided.

Finding 17: Without an amendment, ruling or clarification, it is inferred that biocides used in shale or tight oil and gas production will need to be registered for this use by the Australian Pesticides and Veterinary Medicines Authority (APVMA).

Finding 18: Since 2012, all chemicals proposed to be used have been disclosed.

Finding 19: Currently, there is no requirement for the Department of Mines, Industry Regulation and Safety (DMIRS), nor any other regulatory agency involved in the assessment and approval of hydraulic fracture stimulation activities in Western Australia, to check if a chemical is approved for any use in Australia.

Finding 20: The current regulations in Western Australia require the full disclosure and assessment of chemicals used in hydraulic fracture stimulation, including the use of a site-specific risk assessment where relevant. However, there are some deficiencies with the current system that need to be addressed.

Recommendation 6: The regulations governing the use and assessment of chemicals associated with hydraulic fracture stimulation should be strengthened and clarified, specifically:

- All chemicals proposed for use must be approved for use in Australia. It should be the regulator's responsibility to check that all the proposed chemicals are listed on the Australian Inventory of Chemical Substances (AICS), Australian Pesticides and Veterinary Medicines Authority (APVMA), Therapeutic Goods Administration (TGA) or Food Standards Australia and New Zealand (FSANZ) inventories prior to approval being granted.
- That a ruling is sought from APVMA on the need to register biocides used for hydraulic fracture stimulation in Western Australia (in line with the existing ruling on the use of these chemicals in the extraction of coal seam gas).
- The use of Benzene, Toluene, Ethylbenzene and Xylene (BTEX) in drilling and hydraulic fracturing fluids should be banned.
- Chemicals that are known or suspected carcinogens, mutagens, developmental toxicants and endocrine disruptors should be identified as part of the information disclosed on chemicals. Use of chemicals with these properties should be minimised or avoided in all operations.
- An enforceable Code of Practice should include the requirement to test for, and assess the risk from, a comprehensive list of analytes in groundwater, produced and flowback water, including geogenic chemicals and radon.
- The use of ecotoxicity testing should be considered to better assess the potential for impacts from the mixture of chemicals present in produced or flowback water.
- The Western Australian Department of Health (DoH) should review and provide advice on information and risk assessments provided on chemicals proposed to be used in hydraulic fracture stimulation, or expected to be present in produced or flowback water, and determine a list of low risk chemicals for hydraulic fracture stimulation, where detailed assessment of risk is not required to be provided. This would encourage industry to use lower risk chemicals instead of other chemicals that require more detailed risk assessment.

Finding 21: The risk of contamination of shallow fresh water aquifers by saline groundwater through hydraulically stimulated fractures is low, because the likelihood of fractures propagating and creating pathways which would contaminate overlying aquifers is very low. In the event that this occurred, the potential consequences are considered to range from insignificant to major, reflecting the importance of water quality in the upper aquifers in the development area.

Finding 22: The risk of contamination of shallow fresh water aquifers by saline groundwater through hydrogeological faults is moderate, however where activities are undertaken such that faults are avoided, the risk is considered to be low. This is based on the likelihood that the presence of these permeable faults to propagate and create pathways which could contaminate overlying aquifers is rare. Should this event occur, the potential consequences are considered to range from insignificant to major, reflecting the importance of preserving water quality in the upper aquifers in the development area.

Finding 23: While there is a concern about the reactivation of geological structures that could impact on well integrity and water resources through creation and reactivation of hydrogeological pathways, the likelihood of the transfer of significant quantities of fluids is low.

Recommendation 7: All hydraulic fracture stimulation operations should be preceded by a comprehensive geomechanical risk analysis according to an enforceable Code of Practice.

Finding 24: The likelihood of hydraulic fracture stimulation intersecting decommissioned bores and contaminating deep groundwater is low, given the documentation on decommissioned wells, and provided that adequate separation is made.

Finding 25: The risk of contamination of shallow fresh water aquifers by saline groundwater and chemicals used in hydraulic fracture stimulation from well integrity failure is low. This is based on the likelihood of well failure occurring such that aquifers are interconnected in the study area being determined to be rare. Should this event occur, the potential consequences are considered to range from insignificant to major, reflecting the importance of water quality in the upper aquifers in the development area.

Finding 26: The risk of contamination of shallow fresh water aquifers by methane as a result of hydraulic fracture stimulation activities is low. This is based on the available data, with likelihood of methane at depth migrating to upper aquifers assessed as rare. Should this occur, the potential consequences are considered to range from insignificant to moderate, reflecting the importance of the water resource.

Finding 27: There is a lack of information on radon in flowback water.

Finding 28: The risk of contamination of near surface fresh water aquifers by drilling fluids, flowback water and chemical storage is moderate. This is based on the likelihood that spills and leaks do occasionally happen, as shown by the statistics. Given the generally low rates of groundwater flow expected in the prospective areas (with some exceptions, such as karst flow), the depth to water table, and the attenuation in the groundwater system, the consequence in the context of the prospective areas in the Northern Perth and Canning Basins is minor, provided there is adequate separation from private or public water supply bores. The risks are minimised by hardstand, bunding and lining of ponds, and by a stringent monitoring, reporting and recording regime. Early detection of leakage would further lessen risk by auditing the water cycle on a drill pad, accounting for fluids produced, disposed of or added to (for example, by rainfall) so as to identify significant unaccounted quantities.

Finding 29: Fluid spills at the well site are the most serious threat to groundwater quality and there is a stringent reporting regime in place for spills. Consideration of groundwater vulnerability should be included in the Environmental Plan.

Recommendation 8: A site water audit should be required, accounting for water produced, evaporated and disposed, to detect significant leakage of fluids and determine whether remedial action to track any contaminants is warranted.

Recommendation 9: A separation of 2,000 metres from oil and gas wells associated with hydraulic fracture stimulation to bores used for Public Drinking Water Sources is warranted under the precautionary principle, as recommended by the Department of Health (DoH) and the Water Corporation. This is necessary for public confidence, irrespective of a low risk.

Finding 30: The risk of contamination of near surface fresh water aquifers by waste from petroleum drilling operations is low. This is based on the requirement for double or triple lined ponds and waste to be disposed in an approved waste disposal facility.

Finding 31: Transport spill plans and reporting requirements reduce the risks from spillage at critical points to surface water and to near surface groundwater to a low level.

14.3 Greenhouse gas

Finding 32: Much of the risk posed by greenhouse gas (GHG) emissions does not result directly from hydraulic fracture stimulation. However, it would be disingenuous not to recognise that this technology has the potential to open up large gas resources across Western Australia, with all the concomitant risks from the resulting emissions associated with gas field development.

Finding 33: The risks posed by greenhouse gas (GHG) emissions depends on whether, at one extreme, the gas directly substitutes for conventional gas sources, or at the other extreme, the gas adds to total fossil fuel consumption. It is the view of the Panel that for the foreseeable future in Western Australia, the former is far more likely than the latter. Emission values are presented for both cases.

Finding 34: In the absence of actual measurements, the emission rates typified for unconventional oil and gas production, associated with hydraulic fracture stimulation, as reflected in current United States Environmental Protection Agency (U.S. EPA) and Australian Government guidelines, are a justifiable basis upon which to estimate greenhouse gas (GHG) emissions from unconventional gas fields in Western Australia, noting the variation in estimates reported in the scientific literature.

Finding 35: Baseline monitoring of methane emissions from onshore gas infrastructure associated with hydraulic fracture stimulation, at appropriate scales, is essential for accounting and reporting on actual greenhouse gas (GHG) emissions. Following development, ongoing monitoring, screening and intervention (repair) to minimise emissions from leaking gas infrastructure would mitigate the risk to the climate and to public health.

Recommendation 10: Baseline measurements of atmospheric levels of greenhouse gas (GHG) should be acquired prior to the development of onshore wells employing hydraulic fracture stimulation, and should be the responsibility of the regulator. Atmospheric concentrations and process leakage of methane should subsequently be monitored over every well's entire life cycle, and detected leaks must be fixed by the operator, with GHG emission monitoring results publicly reported. These requirements should be part of an enforceable Code of Practice.

Finding 36: There is little risk of methane migration to surface aquifers or the atmosphere resulting from activities associated with hydraulic fracture stimulation, apart from those associated with pathways provided by the well itself (equivalent to the broader issue of containment of all fluids within the well).

Finding 37: It is essential that well abandonment includes sealing designed for long-term containment and that such sealing is tested for effectiveness and remedied if not effective. There is insufficient monitoring of the long-term methane containment of decommissioned oil and gas wells in Western Australia.

Recommendation 11: The Western Australian Government should implement an emissions monitoring program of decommissioned wells with respect to well integrity in general and methane emissions specifically, complemented by a research program to give further confidence to their long-term containment.

Finding 38: The risks posed by greenhouse gas (GHG) emissions associated with an onshore gas industry in Western Australia scale directly with the realised size of that industry. The future scale of the onshore unconventional gas industry (should the moratorium be lifted) cannot be forecast with certainty, but over the next decade or two it is likely to be limited, at the extreme, by the size of the domestic Western Australian gas market.

Finding 39: There is a distinctive greenhouse gas (GHG) risk associated with a tight oil development with no (initial) market for produced gas. Such a development bears unique and specific analysis of the resulting emissions, their mitigation and acceptability.

Finding 40: On balance, it is reasonable to expect some additional upstream greenhouse gas (GHG) emissions associated with the production of oil and gas using hydraulic fracture stimulation of shale or tight sands, when compared to upstream conventional oil and gas production. However, these additional emissions are typically smaller than differences in emissions arising from reservoir carbon dioxide, processing and transport between a given facility producing and delivering unconventional oil and gas and one doing so from conventionally developed resources.

Finding 41: Where regulations or approvals specify greenhouse gas (GHG) emission outcomes, the regulator must have and demonstrate sufficient capacity, competency, diligence and transparency to ensure that industry is achieving those outcomes. This is likely to require a combination of top-down and bottom-up monitoring, and thus technical partnership with agencies or institutions with advanced capabilities.

Finding 42: There is a global move toward reducing venting and flaring of gas across the petroleum sector. Reduced emissions completions are an established set of technologies that minimise greenhouse gas (GHG) and other harmful emissions and waste of product, and are both practical and environmentally responsible at the production phase of an oil and gas field.

Recommendation 12: Apart from the early exploratory phase of development, reduced emissions (green) completions should be a requirement, regulated and monitored as per the United States Environmental Protection Agency (U.S. EPA) New Source Performance Standards 2016.

Recommendation 13: Consideration should be given to offsetting the additional greenhouse gas (GHG) emissions from any onshore unconventional oil and gas production associated with hydraulic fracture stimulation. As a minimum, this should extend to the increase in 'fugitive' emissions over conventional upstream oil and gas production, plus reservoir carbon dioxide discharged to the atmosphere.

14.4 Public Health

Finding 43: There is limited compelling and definitive evidence linking public health effects to air emissions derived from unconventional gas developments associated with hydraulic fracture stimulation. The available data suggests risks may be considered to be low to medium, however, uncertainties within the available data limit the determination that air concentrations may exceed health-based standards near gas production facilities. Limitations with the available data on emissions to air can be addressed on a site-specific basis, with impacts assessed in a site-specific risk assessment.

Finding 44: Dust generated by hydraulic fracture stimulation activities and the movement of vehicles, as well as the emission of fine particulates from vehicle emissions, has the potential to negatively impact on community health.

Finding 45: There should be minimisation of dust generated by hydraulic fracture stimulation and/or vehicular movements especially in places within proximity to people and places with high amenity and cultural or aesthetic significance. Minimisation may include limiting land cleared for hydraulic fracture stimulation purposes, greening of areas around hydraulic fracture stimulation sites and prescient management of vehicular movements, especially in areas where roads are not bituminised or paved. The regular maintenance of heavy vehicles used in these operations can minimise exhaust emissions to air, in particular the fine particulates.

Recommendation 14: An enforceable Code of Practice should include measures to minimise the generation of dust throughout all operations and require the regular maintenance of all vehicles.

Recommendation 15: Baseline air quality monitoring for volatile organic compounds and dust, and ongoing monitoring of air quality should be incorporated into an enforceable Code of Practice and be made publicly available.

Recommendation 16: Potential impacts to air quality and human health should be assessed in a site-specific risk assessment.

Finding 46: The monitoring of chemicals in water does not always include analysis for a comprehensive list of analytes. This limits the assessment of baseline water quality and characterisation of impacts that may be of relevance to public health.

Finding 47: There is limited compelling and definitive evidence linking public health effects to contamination of water quality by unconventional oil and gas developments associated with hydraulic fracture stimulation elsewhere. There are uncertainties within the available data that limit the potential understanding of the likelihood that water concentrations may have exceeded health-based standards either close to oil and gas production facilities or at distance. Limitations with the available data on contamination of water can be addressed on a site-specific basis, with impacts assessed in a site-specific risk assessment.

Finding 48: The amount of Naturally Occurring Radioactive Material (NORM) that could be present in produced fluids is likely to vary depending on the shale formation and very limited data is available for Western Australian shale formations. Hence it is important that NORM is monitored in groundwater and flowback water during hydraulic fracture stimulation operations. Consideration of the potential for hydraulic fracture stimulation to result in increased movement of gas (radon or methane) from the subsurface should be included in site-specific risk assessments for each development.

Finding 49: In areas with proximity to people and settlements, it is important to establish baseline noise levels before hydraulic fracture stimulation activities commence, and to undertake a site-specific noise assessment addressing all activities proposed, distances to sensitive receptors and/or mitigation measures required to demonstrate compliance with noise regulations. In addition, noise levels should be measured at regular intervals throughout the lifecycle of the development.

Recommendation 17: Baseline noise levels should be established, a site-specific noise assessment completed and ongoing noise monitoring conducted over the life of a project, with the aim of minimising noise generated by hydraulic fracture stimulation and/or vehicular movements, especially in places within proximity to people and domestic animals.

Finding 50: To date, epidemiological studies have not provided general assurances regarding impacts on public health from the potential hazards associated with unconventional oil and gas development using hydraulic fracture stimulation due to inherent inferential weaknesses in that approach. Given the nature of the potential contaminants, the potentially severe or irreversible consequences to public health, and the uncertainty associated with the actual risk, the Precautionary Principle comes into consideration.

Finding 51: Site-specific health risk assessments would better inform the design and acceptability of unconventional oil and gas development associated with hydraulic fracture stimulation.

Recommendation 18: Site-specific health risk assessments, that have been peer-reviewed and provided to the Western Australian Department of Health, should be required for all unconventional oil and gas proposals associated with hydraulic fracture stimulation, addressing potential short and long-term health impacts.

Recommendation 19: As a precautionary approach is justified, and in the absence of a local health risk assessment indicating otherwise, unconventional oil and gas wells associated with hydraulic fracture stimulation and processing plants should be located at least 2,000 metres from sensitive receptors such as residences, schools and settlements, as reflected in current Environmental Protection Authority (EPA) guidelines.

14.5 Social surroundings

Finding 52: Risk assessment of the social surroundings, particularly cumulative impacts, is necessary but complex and highly dependent on locale.

Recommendation 20: Risk assessments of impacts to the social surroundings from hydraulic fracture stimulation associated with unconventional oil and gas developments should be done on a case-by-case basis.

Recommendation 21: Risk assessments and accountable disclosure of risks should be transparent, timely and publicly available as a guiding principle underlying an enforceable Code of Practice.

Finding 53: Regular communication with the community by both companies and government at the earliest opportunity is more likely to engender trust.

Recommendation 22: Communication and engagement with affected communities should be a priority at the earliest opportunity and at every stage of an unconventional oil and gas development associated with hydraulic fracture stimulation.

Recommendation 23: Communication with Aboriginal people should be conducted by trusted informants in a language commonly used and understood by the local people. If English is not commonly used, then translators should be available to convey information.

Finding 54: Coal Seam Gas (CSG) extraction and that of shale and tight oil and gas are materially different. The characteristics of the site, the resource, the location and numerous social conditions dictate the potential interface between the hydraulic fracture stimulation activities and the social surroundings.

Recommendation 24: Amenity and what constitutes aesthetic enjoyment, or a sense of place, as determined by people who live in the communities proximate to hydraulic fracture stimulation activities, should be systematically and scientifically documented from the commencement of a hydraulic fracture stimulation project involving multiple well sites (moving from the exploration phase into the development and production phases). Baseline information and site-specific data collection should be a priority and systematically monitored and updated.

Finding 55: There must be mutual knowledge of, and respect for, the businesses that are competing for access to and use of scarce resources such as productive land and water.

Finding 56: Broader excision provisions under the *Petroleum Geothermal Energy Resources Act 1967* (PGER Act) would give agricultural landowners, managers and leaseholders greater certainty as well as a greater sense of involvement in the licence process. For smaller scale operations or a well pad that may later be plugged and abandoned, a lease arrangement would seem the most appropriate arrangement.

Finding 57: Increased demand for services and infrastructure, for example, transportation networks, both for product and workforce use has a physical and social impact.

Finding 58: Social and cultural impacts influence perceptions of quality of life. Quality of life is accepted as an important function of mental health.

Finding 59: The passionate and emotional debate and conflict regarding hydraulic fracture stimulation itself has potential psychological and physical ramifications to individual and community well-being.

Finding 60: In the absence of a clear understanding of a projected proposal's scale, infrastructure and context, community members and decision makers resort to experiences elsewhere and an imagined project outcome to inform their perceptions of the project and its impacts, potentially leading to psychological stress and community opposition.

Finding 61: Social licence to operate is increasingly an expected part of the resource development lifecycle. Governments and other stakeholders, including activists, also have an obligation to demonstrate their commitment to social licence to operate.

Recommendation 25: Petroleum companies' commitment to building moral consent should be part of the assessment for licence procedures.

Recommendation 26: There should be a clear point of contact within Government for complaints or concerns to enhance social licence to operate.

Recommendation 27: Baseline road use statistics measuring volumes of vehicle movements and the type of vehicles using road infrastructure should be undertaken before hydraulic fracture stimulation activities commence, and monitored at periodic intervals throughout the lifecycle of the development.

Recommendation 28: Roads regularly used by heavy vehicles should be upgraded (widened and sealed if necessary), with recompense from the proponent directed to local government authorities to assist with monitoring traffic usage of road infrastructure, road maintenance and upgrades.

Finding 62: Increased vehicular traffic associated with construction, drilling and hydraulic fracture stimulation operations is a potential risk to both amenity and safety. Noise, traffic and dust will increase from additional heavy and other vehicular traffic.

Finding 63: Proximity to people and the built environment heightens the risk of deleterious impacts from hydraulic fracture stimulation activities due to vibration, dust and noise.

Finding 64: Heritage is complex and includes a range of potential assets that are valued and in many cases contribute to a sense of community, identity and belonging.

Finding 65: For Aboriginal people, there is no distinction between cultural and physical heritage. Preservation of these sites is important for a range of reasons including spiritual, cultural, aesthetic, recreational and amenity values.

Finding 66: The progressive and cumulative destruction of Aboriginal cultural resources has disrupted Aboriginal knowledge and culture. Exploration and resource extraction can physically destroy or irrevocably alter physical and cultural sites.

Finding 67: Cultural awareness and effective communication between the employees of companies, government and all landholders including Traditional Owners are an essential component of informed consent.

Recommendation 29: Cultural orientation should be made regularly available to hydraulic fracture stimulation employees including contractors in addition to relevant government employees to raise heritage awareness, including issues specific to Aboriginal heritage. Cultural orientation regarding Aboriginal matters should be conducted by local Traditional Owner groups or their approved cultural awareness providers.

Finding 68: Negotiated agreements have the potential to protect places of heritage value, including Aboriginal cultural heritage, and reconcile potentially conflicting needs and aspirations, provided the appropriate stakeholders are central to the negotiations.

Recommendation 30: An Aboriginal heritage management plan should be implemented at the earliest opportunity when potential risk is identified for a particular site of Aboriginal heritage or significance. The Aboriginal heritage management plan should have input from those Aboriginal people and groups whose land is under consideration for petroleum development using hydraulic fracture stimulation, and should identify the role Traditional Owners will play in monitoring the condition and protection of their cultural heritage. The Aboriginal heritage management plan should require the approval of local Traditional Owners.

Finding 69: Cumulative impacts of particular actions (including lack of action) have the potential to change, aggregate and interact over time. Uncertainty, incomplete knowledge, multiple perspectives and contested causality are often functions of conflict. Acknowledging cumulative impacts and managing them are important for the maintenance of community and individuals' quality of life.

Finding 70: Accurate data regarding the social dimensions are important and should be documented at the earliest opportunity of any development.

Finding 71: Systematic and scientific measurement of a range of social factors mitigate deleterious cumulative impacts.

Recommendation 31: Governments and resource companies should invest more in understanding and measuring the social dimensions of change and its links to mental health: A comprehensive local social impact analysis should be undertaken prior to the commencement of any activities associated with hydraulic fracture stimulation occurring.

14.6 Regulatory Reform

Finding 72: There is a place within an overall risk-based, outcome-focused regulatory framework for some prescriptive regulation. These prescriptions may extend to explicit requirements for consultation, exclusions, assessment, environmental standards, monitoring, disclosure and reporting.

Finding 73: As Low As Reasonably Practicable (ALARP) is a useful working concept for the protection of the environment in the design and realisation of unconventional gas development. However, it should be explicitly linked to environmental acceptability through and within regulation.

Finding 74: An enforceable Code of Practice for hydraulic fracture stimulation in association with onshore unconventional oil and gas development, embodying necessarily prescriptive requirements and standards across the entire development lifecycle, is a useful mechanism to bring all such activities to an acceptable, high standard across the industry. Making adherence to this Code of Practice a regulatory requirement would provide greater assurance that the environment and public safety were being protected.

Finding 75: The development of reference cases to provide standard approaches to minimising the environmental impacts and risk for specific activities, including operational standards and model conditions, would be a useful addendum to an enforceable Code of Practice and could help focus efforts and attention on the design and assessment of higher risk aspects of unconventional oil and gas development proposals.

Recommendation 32: The Western Australian Government should develop a Code of Practice that adequately defines and prescribes the minimum standards and requirements for all onshore oil and gas activities involving hydraulic fracture stimulation, over the full development lifecycle. This Code of Practice should be made enforceable.

Finding 76: The global best practice standards for the design, construction and operation of oil and gas wells, including those relating to hydraulic fracture stimulation, are generally sufficient if competently executed and complied with. The opportunity for further minimisation of risk to the environment and people through improving these engineering-oriented standards is limited, although should be subject to some regulatory prescription.

Recommendation 33: To further ensure well integrity and thus environmental protection and public safety, well design, construction and testing should be assessed by an independent, certified expert well examiner, reporting to the regulator as a required part of commissioning, licensing and decommissioning.

Finding 77: Environmental and public health assessment, approval, conditioning and compliance would be strengthened if executed through the *Environmental Protection Act 1986*, and this would go some way toward alleviating public concern over consultation, environmental protection standards, cumulative impacts and compliance.

Recommendation 34: The Environmental Protection Authority (EPA) should assess all onshore unconventional oil and gas developments associated with hydraulic fracture stimulation. To ensure issues of scale and cumulative impact are adequately considered, this should extend not only to individual wells during the exploratory phase of a development, but to the environmental assessment of proposed unconventional oil and gas fields if development may go forward.

Finding 78: There is no logical basis for any differences in regulatory expectations and arrangements for site rehabilitation between mining in general and onshore unconventional oil and gas developments associated with hydraulic fracture stimulation specifically. There is an opportunity to improve the efficiency and effectiveness of governance through uniform rehabilitation standards and procedures embedded within an enforceable Code of Practice under the *Petroleum and Geothermal Energy Resources Act 1967* (PGER Act) and available as guidance for assessments under Part IV of the *Environmental Protection Act 1986* (EP Act).

Recommendation 35: Appropriate standards for site rehabilitation and post-closure monitoring should be included in an enforceable Code of Practice.

Finding 79: The full specification and implementation of prescribed baseline and regularised monitoring may be specified within an enforceable Code of Practice.

Finding 80: The default treatment of environmental monitoring data required by regulation or Ministerial Statement should be that it is not subject to commercial confidentiality and should be made public, and that availability be regularised through open publication by government (as opposed to simply available through the procedures of the *Freedom of Information Act 1992* (FOI Act)). This is consistent with the stated intent and principles of government transparency.

Recommendation 36: Baseline and subsequent environmental monitoring data collected as a regulatory requirement in the licensing, approval and auditing of unconventional oil and gas developments associated with hydraulic fracture stimulation should be made publicly and easily available, by default.

Finding 81: Apart from some highly technical or regional-scale monitoring (for example, regional methane emissions, regional seismic monitoring), environmental monitoring required by regulation or licence is generally the responsibility of the proponent and it is in their interest to do it well and to the specifications required. It is the responsibility of government to ensure it meets requirements and standards through auditing.

Finding 82: Environmental Plans for unconventional oil and gas developments associated with hydraulic fracture stimulation broadly serve the equivalent function of environmental review documents provided to environmental agencies under other environmental regulatory regimes, and similar expectations on their availability for public review apply.

Recommendation 37: Once the Environmental Plans required under the *Petroleum and Geothermal Energy Resources Act 1967* (PGER Act) are deemed sufficient for consideration, they should be published in full at the time of assessment.

Recommendation 38: Reports of environmental and public safety non-compliance, incidents and their investigation, and government environmental performance audits, should be made routinely publicly available once they would otherwise be reasonably subject to a Freedom of Information request.

Finding 83: Site rehabilitation and the long-term environmental performance of wells is the clear responsibility of the operator. Appropriate financial assurance is required to ensure that any necessary remediation of impacts to the environment can be funded. Additionally, industry contributions to fund the remediation of legacy issues associated with the industry would further protect the State from future liability.

Recommendation 39: The Western Australian Government should require appropriate financial assurances or insurances to cover potential environmental liabilities, as well as contributions to a fund to cover liabilities defaulted by other unconventional oil and gas operations associated with hydraulic fracture stimulation in Western Australia.

Finding 84: With adequate baseline, environmental monitoring, and appropriate monitoring over the whole lifecycle of an unconventional oil and gas development associated with hydraulic fracture stimulation, a presumption that a company employing hydraulic fracture stimulation is responsible for any local contamination event without evidence of attribution is not justified.

Finding 85: The penalties available for environmental offences under the *Petroleum and Geothermal Energy Resources Act 1967* (PGER Act) and subsidiary legislation are too low to provide an effective incentive for compliance.

Finding 86: Greater protections to the environment would be secured if environmental offences were clearly identified within the *Petroleum and Geothermal Energy Resources Act 1967* (PGER Act), along with a tiered system of penalties reflecting the seriousness of harm and intent.

Finding 87: An application for tenure (or to increase or extend tenure) does not include a requirement to disclose the applicant's environmental record.

Recommendation 40: Environmental offences, and a system of penalties scaled for seriousness of harm and degree of deliberate intent, as per the *Environmental Protection Act 1986* (EP Act), be incorporated into the *Petroleum and Geothermal Energy Resources Act 1967* (PGER Act). These penalties should extend to both the company and its directors.

Recommendation 41: Future access to tenements should consider the past environmental record of the applicant.

Finding 88: Clear and demonstrable separation of the function of ensuring environmental compliance of unconventional oil and gas developments associated with hydraulic fracture stimulation from the promotion and allocations of tenure to the industry would better conform to best practice in government, and would greatly increase public, and industry confidence in environmental protection and public safety. This is not adequately achieved through the current structure and roles of the Department of Mines, Industry Regulation and Safety (DMIRS).

Finding 89: An efficient and effective auditing and compliance model of governance for unconventional oil and gas development associated with hydraulic fracture stimulation is to exercise these duties under the *Environmental Protection Act 1986* (EP Act), employing the environmental science and regulatory capabilities of the Department of Water and Environmental Regulation.

Recommendation 42: The Western Australian Government should consider better separating environmental auditing and compliance of unconventional oil and gas development employing hydraulic fracture stimulation from the department that promotes and allocates resources to that industry.

Finding 90: If the onshore unconventional oil and gas industry is to proceed and grow, then inadequate resourcing of environmental auditing and compliance will erode public confidence in the protection of the environment and safety.

Recommendation 43: The capability and capacity for the environmental auditing and compliance functions of government must be sufficient to assure environmental protection and safety, so this must be adequately resourced and include cost recovery from industry.

Finding 91: The consideration and spatial definition of new petroleum titles should include stakeholder consultation regarding the exclusion of areas of high environmental, social or cultural sensitivity and value.

Recommendation 44: Stakeholder consultation on proposed releases of acreage for onshore unconventional oil and gas development should become a formalised and regular requirement.

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