Hydraulic fracturing and well integrity review for the GBA regions

Technical appendix for the Geological and Bioregional Assessment: Stage 2

2020

A scientific collaboration between the Department of Agriculture, Water and the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia

The Geological and Bioregional Assessment Program

The Geological and Bioregional Assessment Program will provide independent scientific advice on the potential impacts from development of selected unconventional hydrocarbon plays on water and the environment. The geological and environmental data and tools produced by the Program will assist governments, industry, landowners and the community to help inform decision making and enhance the coordinated management of potential impacts.

The Program is funded by the Australian Government Department of the Environment and Energy. The Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia are collaborating to undertake geological and bioregional assessments. For more information, visit http://www.bioregionalassessments.gov.au.

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Authorship is listed in relative order of contribution.

On 1 February 2020 the Department of the Environment and Energy and the Department of Agriculture merged to form the Department of Agriculture, Water and the Environment. Work for this document was carried out under the then Department of the Environment and Energy. Therefore, references to both departments are retained in this report.

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Cover photograph

Santos Baryulah field gas well, Cooper Basin, October 2018
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Executive summary

Well integrity and hydraulic fracturing are important topics for government, industry and the community. This review presents a qualitative assessment of the findings from nine domestic and international inquiries and of data from the Cooper, Isa and Beetaloo GBA regions considered against the impact modes relating to hydraulic fracturing (three impact modes) and well integrity (five impact modes). The outcome of this review is a qualitative likelihood of occurrence for each impact mode in each GBA region. These outcomes are presented in the Cooper, Isa and Beetaloo GBA Program Stage 2 Synthesis reports.

Contents

Figures

Tables

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- Internal Peer Review Group: CSIRO: Luke Connell and Cameron Huddlestone-Holmes
- Technical Peer Review Group: Andrew Boulton, Peter McCabe, Catherine Moore and Jenny Stauber
- State Government Science Technical Review: This group includes scientists from the Northern Territory, Queensland and South Australian governments.

Abbreviations and acronyms

Abbreviation/acronym	Definition
API	American Petroleum Institute
CBL	Cement bond log
CO_2	Carbon dioxide
CSG	Coal seam gas
GAB	Great Artesian Basin
GBA	Geological and Bioregional Assessment
IEA	International Energy Agency
ISO	International Organization for Standardization

Units

Unit	Description
mm	millimetre
m	metre
km	kilometre
L	litre
ML	megalitre

The Geological and Bioregional Assessment Program

The $35.4 million Geological and Bioregional Assessment (GBA) Program is assessing the potential environmental impacts of shale and tight gas development to inform regulatory frameworks and appropriate management approaches. The geological and environmental knowledge, data and tools produced by the Program will assist governments, industry, landowners and the community by informing decision making and enabling the coordinated management of potential impacts.

In consultation with state and territory governments and industry, three geological basins were selected based on prioritisation and ranking in Stage 1: Cooper Basin, Isa Superbasin and Beetaloo Sub-basin. In Stage 2, geological, hydrological and ecological data were used to define 'GBA regions': the Cooper GBA region in Queensland, SA and NSW; the Isa GBA region in Queensland; and the Beetaloo GBA region in NT. In early 2018, deep coal gas was added to the assessment for the Cooper GBA region, as this play is actively being explored by industry.

The Program will assess the potential impacts of selected shale and tight gas development on water and the environment and provide independent scientific advice to governments, landowners, the community, business and investors to inform decision making. Geoscience Australia and CSIRO are conducting the assessments. The Program is managed by the Department of the Environment and Energy and supported by the Bureau of Meteorology.

The Program aims to:

- inform government and industry and encourage exploration to bring new gas supplies to the East Coast Gas Market within five to ten years
- increase understanding of the potential impacts on water and the environment posed by development of shale, tight and deep coal gas resources
- increase the efficiency of assessment and ongoing regulation, particularly through improved reporting and data provision/management approaches
- improve community understanding of the industry.

The Program commenced in July 2017 and comprises three stages:

1. **Stage 1 Rapid regional basin prioritisation** identified and prioritised geological basins with the greatest potential to deliver shale and/or tight gas to the East Coast Gas Market within the next five to ten years.
2. **Stage 2 Geological and environmental baseline assessments** is compiling and analysing available data for the three selected regions to form a baseline and identify gaps to guide collection of additional baseline data where needed. This analysis includes a geological basin assessment to define structural and stratigraphic characteristics and an environmental data synthesis.
3. **Stage 3 Impact analysis and management** will analyse the potential impacts to water resources and matters of environmental significance to inform and support Commonwealth and State/Territory management and compliance activities.

The PDF of this report and the supporting technical appendices are available at https://www.bioregionalassessments.gov.au/geological-and-bioregional-assessment-program.

About this report

In this technical appendix a review of knowledge about well integrity and hydraulic fracturing is presented that is relevant for the Cooper, Isa and Beetaloo GBA regions. It provides a qualitative review of available data from historical hydraulic fracturing and relevant reviews. The structure and focus of the synthesis report and technical appendices reflect the needs of government, industry, landowners and community groups.

Technical appendices

Other technical appendices that support the geological and environmental baseline assessment for the Cooper GBA region are:

- Owens R, Hall L, Smith M, Orr M, Lech M, Evans T, Skeers N, Woods M and Inskeep C (2020) Geology of the Cooper GBA region.
- Lech ME, Wang L, Hall LS, Bailey A, Palu T, Owens R, Skeers N, Woods M, Dehelean A, Orr ML, Cathro D and Evenden C (2020) Shale, tight and deep coal gas prospectivity of the Cooper Basin.
- O'Grady AP, Herr A, MacFarlane CM, Merrin LE and Pavey C (2020) Protected matters for the Cooper GBA region.
- Kirby JK, Golding L, Williams M, Apte S, Mallants D and Kookana R (2020) Qualitative (screening) environmental risk assessment of drilling and hydraulic fracturing chemicals for the Cooper GBA region.
- Evans TJ, Martinez J, Lai ÉCS, Raiber M, Radke BM, Sundaram B, Ransley TR, Dehelean A, Skeers N, Woods M, Evenden C and Dunn B (2020) Hydrogeology of the Cooper GBA region.

Other technical appendices that support the geological and environmental baseline assessment for the Isa GBA region are:

- Orr ML, Bradshaw BE, Bernardel G, Palu TJ, Hall LS, Bailey AHE, Skeers N, Dehelean A, Reese B and Woods M (2020) Geology of the Isa GBA region.
- Bailey AHE, Bradshaw BE, Palu TJ, Wang L, Jarrett AJM, Orr ML, Lech M, Evenden C, Arnold D, Reese B, Skeers N, Woods M, Dehelean A, Lawson C and Hall LS (2020) Shale gas prospectivity of the Isa GBA region.
- Buchanan S, Dixon-Jain P, Martinez J, Raiber M, Kumar PR, Woods M, Arnold D, Dehelean A and Skeers N (2020) Hydrogeology and groundwater systems of the Isa GBA region.
- MacFarlane CM, Herr A, Merrin LE, O'Grady AP and Pavey C (2020) Protected matters for the Isa GBA region.
- Kirby JK, Golding L, Williams M, Apte S, Mallants D and Kookana R (2020) Qualitative (screening) environmental risk assessment of drilling and hydraulic fracturing chemicals for the Isa GBA region.

Other technical appendices that support the geological and environmental baseline assessment for the Beetaloo GBA region are:

- Hall LS, Wang L, Bailey AHE, Orr ML, Owens R, Jarrett, A, Lech ME, Skeers N, Reese B and Woods M (2020) Petroleum prospectivity of the Beetaloo Sub-basin.
- Evans TJ, Radke BM, Martinez J, Buchanan S, Cook SB, Raiber M, Ransley TR, Lai ÉCS, Skeers N, Woods M, Evenden C, Cassel R and Dunn B (2020) Hydrogeology of the Beetaloo GBA region.
- Pavey C, Herr A, MacFarlane CM, Merrin LE and O'Grady AP (2020) Protected matters for the Beetaloo GBA region.
- Kirby JK, Golding L, Williams M, Apte S, Mallants D, King J, Otalega I and Kookana R (2020) Qualitative (screening) environmental risk assessment of drilling and hydraulic fracturing chemicals for the Beetaloo GBA region.
- Orr ML, Bernardel G, Owens R, Hall LS, Skeers N, Reese B and Woods M (2020) Geology of the Beetaloo GBA region.

Maps for the Cooper GBA region and the Isa GBA region use the Map Grid of Australia (MGA) projection (zone 54) and maps for the Beetaloo GBA region use the MGA projection (zone 53) the Geocentric Datum of Australia 1994 (GDA 1994).

1 Causal pathway overviews for hydraulic fracturing and compromised well integrity

This technical appendix presents an initial review of the likelihoods of causal pathways relating to hydraulic fracturing operations and compromised well integrity. The outcomes of this review are presented in the GBA Stage 2 synthesis reports for the Cooper, Isa and Beetaloo GBA regions. The findings of the qualitative likelihoods of impact modes relating to hydraulic fracturing and compromised well integrity causal pathways from this review serve to compliment the outcomes from the Stage 2 hazard prioritisation for each GBA region. This work will be followed, where applicable by a more detailed analysis of the impact modes prioritised for each GBA region in Stage 3.

The subsurface flowpaths causal pathways relating to hydraulic fracturing operations and well integrity considered in this technical appendix are similar in concept to those considered in the conceptual modelling for the Bioregional Assessment Program (Henderson et al., 2016).

1.1 Hydraulic fracturing – causal pathway overview

Hydraulic fracture stimulation is used to increase the productivity of a petroleum well by injecting fluid at sufficient pressure and flow rate to propagate hydraulic fractures into the reservoir. Once the hydraulic fracture fluid pressure is released at the end of the treatment, proppant (sand, or artificial ceramics) remains in the created hydraulic fractures to increase the effective permeability in the reservoir and ultimately the flow of gas to the well.

The hydraulic fracture stimulation techniques applied to produce shale and tight gas have advanced over recent years and build upon technologies and processes invented for exploiting conventional oil and gas resources (Golden and Wiseman, 2015; Hatton et al., 2018). In all cases the design objective is to create fractures in the target interval of oil and gas-bearing rock that maximise the flow of gas to the well (Hatton *et al.*, 2018).

Over the last decade, the potential environmental risks of hydraulic fracturing have been the focus of active discussion and investigation across industry, government and academic agencies. This recent focus on hydraulic fracturing of shale and coal seam gas wells has led to the commissioning of a number of significant domestic and international scientific inquiries to investigate potential impacts of hydraulic fracturing and related onshore petroleum development activities. The findings of these inquiries relating to the likelihood of impact modes from the hydraulic fracturing causal pathway are a key line of evidence considered in this technical appendix and are summarised in Table 4.

Where these inquiries conducted community consultations or invited submissions from the public, the most consistently raised concern was the potential impact of hydraulic fracture stimulation and its associated activities on groundwater. The following submission to the West Australian Inquiry (Hatton et al., 2018) was quoted verbatim in the report as being representative of the community concern of groundwater contamination:

> “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 to the Independent Scientific Panel Inquiry into Hydraulic Fracture Stimulation in Western Australia (Hatton et al., 2018).

Considering this community concern and following the focus of many of the scientific inquiries, three impact modes were assessed for the hydraulic fracturing causal pathway. These impact modes consider theoretical situations where hydraulic fracture propagation has extended beyond the designed area and in doing so may have dilated a subsurface flow path between geological layers in a way which was not intended. Table 1 shows the three impact modes relating to hydraulic fracturing which have been qualitatively assessed using historical data from each GBA region and findings from international and domestic scientific inquiries.

Table 1 Impact modes relating to hydraulic fracturing causal pathway

	Impact mode	Description
F.1	Hydraulic fracture growth into aquifer	**Description** Unintended vertical hydraulic fracture growth from the target interval into an overlying aquifer creating a subsurface fluid flow path. **Major activity** • Drill and hydraulic fracture **Potential effects** • Changed groundwater quality • Changed groundwater levels or pressures **Impact cause** • Poor hydraulic fracture treatment design • Poor well construction **Current controls** • Regulated well construction methods and verification of proper well completion • Knowledge of geology from seismic program works conducted prior to exploration and appraisal activities • Incorporation of additional geology knowledge from drilling and hydraulic fracturing operations in nearby wells • Hydraulic fracture treatment design • Hydraulic fracture monitoring (seismic / tiltmeter) • Good management and operator procedures

	Impact mode	Description
F.2	Hydraulic fracture growth into well	**Description** Unintended hydraulic fracture growth into another well which was not designed to handle high fluid pressures causing well integrity failure creating a subsurface fluid flow path. **Major activity** • Drill and hydraulic fracture **Potential effects** • Soil, groundwater and / or surface water contamination • Changed groundwater quality • Changed groundwater levels or pressures **Impact cause** • Poor hydraulic fracture treatment design • Poor well construction **Current controls** • Regulated well construction methods and verification of proper well completion • Knowledge of geology from seismic program works conducted prior to exploration and appraisal activities • Protocols to identify and remediate nearby old wells prior to undertaking hydraulic fracturing • Incorporation of additional geology knowledge from drilling and hydraulic fracturing operations in nearby wells • Hydraulic fracture treatment design • Hydraulic fracture monitoring (seismic / tiltmeter) • Good management and operator procedures
F.3	Hydraulic fracture growth into fault	**Description** Unintended hydraulic fracture growth into a fault causing dilation or slippage and creating a subsurface fluid flow path. **Major activity** • Drill and hydraulic fracture **Potential effects** • Changed groundwater quality • Changed groundwater levels or pressures • Fault reactivation and induced seismicity **Impact cause** • Poor hydraulic fracture treatment design • Poor well construction **Current controls** • Regulated well construction methods and verification of proper well completion • Knowledge of geology from seismic program works conducted prior to exploration and appraisal activities • Incorporation of additional geology knowledge from drilling and hydraulic fracturing operations in nearby wells • Hydraulic fracture treatment design • Hydraulic fracture monitoring (seismic / tiltmeter) • Good management and operator procedures

1.2 Compromised well integrity – causal pathway overview

Petroleum wells are constructed such that fluids are not able to pass from outside the well to the inside or to travel along the outside of the well between different geological layers or to the surface. Maintaining this leak-tight seal (well integrity) is a core focus of both governments and industry and well integrity industry standards are regularly updated to reflect developments in technology and best practice (International Organization for Standardization, 2013, 2017).

In order to create well integrity, components known as well barrier elements are arranged in such a way that a leak-tight seal is formed between the well and the rock. Often a minimum of two independent well barriers are required by regulation (e.g. Northern Territory Government, 2019) or recommended in industry standards (e.g. International Organization for Standardization, 2017) to provide redundancy such that a failure in one well barrier does not lead to unintended fluid infiltration into geological layers or to the surface. This practice of designing, constructing, operating and decommissioning wells in such a way to prevent unintended fluid movement is known as maintaining well integrity (International Organization for Standardization, 2017).

Well barrier elements can potentially be degraded or damaged by operational and environmental factors including exposure to formation fluids, drilling and hydraulic fracturing fluid pressure, mechanical stresses, poor well construction, degradation of the cement or steel casing or thermal cycling. This damage to the well barrier elements can potentially result in a failure of well integrity (USEPA, 2016).

The terminology around well integrity failures is not consistently applied across the industry or academic publications. It has been noted that mistrust and confusion in the community is in part due to different terminology and definitions of well failure (e.g. Cook et al., 2013; Pepper et al., 2018). A well failure or failure of a single well barrier does not necessarily result in a leak to the external environment, therefore it is incorrect to equate all well failures with environmental impacts (O'Brien, 2015). Similarly, a failure of all well barriers (compromised well integrity) may also not lead to negative environmental impacts as there may be no driver to cause fluids to flow vertically along a subsurface flow path along a well (Council of Canadian Academies, 2014; Huddlestone-Holmes et al., 2017; Hatton et al., 2018).

However, compromised well integrity could conceptually result in the unintended underground flow of fluids and gases into overlying stratigraphic units which could lead to an environmental impact. There has been significant work to understand the likelihood of those impacts occurring and they are generally considered manageable to a suitably low level given appropriate regulatory controls, sufficient understanding of the baseline geological and environmental systems, and implementation of best industry practices as summarised in Huddlestone-Holmes et al. (2017).

Data collection and monitoring limitations make it difficult to assess the rates which well integrity failures have caused impacts to underground resources e.g. Jackson et al. (2013); Vidic et al. (2013); Council of Canadian Academies (2014); USEPA (2016); and Jeffrey et al., (2017). These limitations are compounded if baseline studies are not conducted prior to commencement of operations (Council of Canadian Academies, 2014; Hawke, 2014). This uncertainty caused by the lack of validation data cannot be overcome by the scope of the GBA Program.

Table 2 Potential impact modes related to the compromised well integrity causal pathways reviewed in GBA Stage 2

	Impact mode	Description
W.1	Well rupture or failure across well barriers	**Description** Unintended fluid flow from outside the well to inside the well casing or vice versa **Major activities** • Drill and hydraulic fracture • Production and processing **Potential effects** • Changed groundwater quality **Impact cause** • Well integrity failure (failure of all barriers) **Current controls** • Knowledge of geology and supplementary seismic data, • Regulated well construction methods and verification of proper well completion • Well design considering site-specific factors, • Prescriptive work methods and subsurface integrity testing, • Good management, • Regulations and industry standards, • Operator procedures and including specialist engineers on-site during drilling and hydraulic fracturing.
W.2	Migration along casing annulus from reservoir to surface	**Description** Unintended fluid and/or gas flow from reservoir to surface along the annulus outside the well casing **Major activity** Production and processing **Potential effects** • Soil, groundwater and / or surface water contamination • Changed air quality **Impact cause** Well integrity failure (failure of all barriers) **Current controls** • Knowledge of geology and supplementary seismic data, • Regulated well construction methods and verification of proper well completion • Well design considering site-specific factors, • Prescriptive work methods and subsurface integrity testing, • Good management, • Regulations and industry standards, • Operator procedures and including specialist engineers on-site during drilling and hydraulic fracturing.

	Impact mode	Description
W.3	Migration along casing between rock layers	**Description** Unintended fluid flow between geological layers along the annulus outside the well casing **Major activity** • Production and processing **Potential effects** • Changed groundwater quality • Changed groundwater levels or pressures **Impact cause** • Well integrity failure (failure of all barriers) **Current controls** • Knowledge of geology and supplementary seismic data, • Regulated well construction methods and verification of proper well completion • Well design considering site-specific factors, • Prescriptive work methods and subsurface integrity testing, • Good management, • Regulations and industry standards, • Operator procedures and including specialist engineers on-site during drilling and fracturing.
W.4	Migration along decommissioned / abandoned wells	**Description** Unintended fluid flow along decommissioned petroleum wells **Major activity** • Decommissioning and rehabilitation **Potential effects** • Changed groundwater quality • Changed air quality **Impact cause** • Well integrity failure (failure of all barriers) **Current controls** • Knowledge of geology and supplementary seismic data, • Regulated well decommissioning methods and verification of proper well completion • Well design considering site-specific factors, • Prescriptive work methods and subsurface integrity testing, • Good management, • Regulations and industry standards, • Operator procedures and including specialist engineers on-site during decommissioning.

	Impact mode	Description
W.5	Loss of well control (blowout)	**Description** Uncontrolled fluid flow from the wellhead at the surface **Major activity** • Drill and hydraulic fracture **Potential effects** • Soil, groundwater and / or surface water contamination **Impact cause** • Well integrity failure (failure of all barriers) **Current controls** • Knowledge of geology and supplementary seismic data, • Regulated well construction methods and verification of proper well completion • Well design considering site-specific factors, • Prescriptive work methods and subsurface integrity testing, • Good management, • Regulations and industry standards, • Operator procedures and including specialist engineers on-site during drilling and fracturing.

1.3 *Qualitative review method*

The impact modes related to hydraulic fracturing and compromised well integrity causal pathways have been reviewed for each of the three GBA regions. The use of causal pathways is common in recent investigations and inquiries into the impacts of hydraulic fracturing on water resources (Wu et al., 2016; Huddlestone-Holmes et al., 2017; Mallants et al., 2017; Pepper et al., 2018). This report follows the causal pathway methodology from Henderson et al., (2016) and an approach similar to Mallants et al., (2017) in using multiple lines of evidence to evaluate the likelihood of each pathway.

The hydraulic fracturing and well integrity findings presented in the GBA Stage 2 GBA synthesis reports (Frery *et al.*, 2020; Holland *et al.*, 2020; Lewis *et al.*, 2020) are underpinned by the analysis of two existing lines of evidence. The likelihood of each impact mode has been qualitatively reviewed against these two existing lines of evidence with the results presented for comparison to the likelihood outcome from the GBA hazard workshops. Upon consideration of these findings, the hazards are prioritised for further evaluation (through generation of additional evidence) in GBA Stage 3.

The risks related to constructing and operating petroleum wells and to conducting hydraulic fracturing stimulation are minimised and managed by regulation (e.g. Queensland Department of Natural Resources and Mines, 2017; Queensland Department of Natural Resources Mines and Energy, 2018) and industry standards (e.g. American Petroleum Institute (API), 2014; International Organization for Standardization, 2017) which require or recommend operators conduct their operations in certain ways. An assessment of the effectiveness of the current regulatory framework and industry best practices and approaches to managing the impacts of well integrity failures and hydraulic fracturing operations is outside the scope of this review. However, Stage 3 risk assessments will consider key existing controls including the regulatory framework and approval process.

1.3.1 Lines of evidence to evaluate hydraulic fracturing and well integrity

This report follows an approach where multiple lines of evidence are used to evaluate the likelihood of each impact mode. The lines of evidence assessed in GBA Stage 2 that most closely relate to hydraulic fracture and compromised well integrity causal pathways are:

Line of evidence 1 (GBA Stage 2): Analysis of available data on historical GBA region hydraulic fracturing treatments and well integrity events

Potential data include:

- Remote hydraulic fracture growth monitoring (micro seismic or tiltmeter)
- Operator data on hydraulic fracture treatment design and modelling
- Interpretation of hydraulic fracture treatment pressure
- Publicly available data on well integrity failures.

The findings of the review of line of evidence 1 for each GBA region are presented in the Cooper, Isa and Beetaloo addenda to this report.

Line of evidence 2 (GBA Stage 2): Review of findings from relevant international inquiries

Information from international and domestic inquiries is of broad relevance to unconventional petroleum development in each GBA region. Nine inquiries were selected as the most relevant to the GBA regions and a qualitative assessment of the technical information and findings was undertaken for each impact mode and are presented in Section 2.

Output from GBA Stage 2 hydraulic fracturing and well integrity review

The output of this Stage 2 hydraulic fracturing and well integrity review is a qualitative likelihood score for each impact mode to inform identification of prioritised subsurface flow path impact modes for investigation in GBA Stage 3.

Line of evidence 3 (as required GBA Stage 3): hydraulic fracture growth modelling using parameters representative of the GBA regions (undertaken as part of Stage 3)

Line of evidence 4 (as required GBA Stage 3): physical evidence or data relating to contaminants entering key receptors from international literature, reports and bulletins, and field investigations (undertaken as part of Stage 3)

- Identification of hydraulic fracturing fluid or shale pore water components in samples taken from monitoring / water bores.
- Review pressure and flow profiles relative to model responses to determine the potential of vertical propagation.

Output from GBA stage 3 hydraulic fracturing and well integrity investigation

The outputs of the Stage 3 investigation will include potential effects of each impact mode which will compliment other GBA work such as contaminant transport modelling.

1.3.2 Qualitative likelihood categorisation

On consideration of lines of evidence 1 and 2 in this Stage 2 review, each hydraulic fracturing and compromised well integrity causal pathway impact mode has been assigned a qualitative likelihood. The likelihood descriptors used in this review are consistent with the hazard identification scores from the GBA Stage 2 synthesis reports (Frery *et al.*, 2020; Holland *et al.*, 2020; Lewis *et al.*, 2020) and the Independent Scientific Panel Inquiry into Hydraulic Fracture Stimulation in Western Australia (Hatton et al., 2018) as shown in Table 3.

Table 3 Likelihood definitions as used in this report related to other related likelihood definitions and ranking methods

Likelihood descriptor	Qualitative definition as used in this report to summarise qualitative findings from review of GBA region historical data	GBA likelihood score as used in the hazard identification workshops	Quantitative frequency of recurrence as used in the hazard identification workshops	Qualitative definition from (Hatton et al., 2018)
Very rare	Near-zero chance of occurring in the area of study	-2.5		
Rare	Very improbable to occur in the area of study given local geology, existing operational controls and/or regulatory conditions	-2.0	One event in 100 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.
Very unlikely	Very unlikely to occur in the area of study given local geological, operational and/or regulatory conditions	-1.5	One event in 33 years	
Unlikely	Possible but unlikely to occur in the area of study given local geological, operational and/or regulatory conditions	-1.0	One event 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	May occur or there is some evidence to support it will occur in the area of study	-0.5	One event in 3 years	The event should occur at some time as there is a history of casual occurrence of similar issues with past projects/activities.
Likely	Expected to occur in some activities in the area of study	0	One event in 1 year	The event is expected to occur as there is a history of frequent occurrence with past projects/activities.
Most certain		1.0	Ten events in 1 year	The event will occur in most circumstances as there is a history of continuous occurrence with past projects/activities.

2 Line of evidence 2: Findings from relevant reviews and inquiries

Several prominent international and domestic inquiries have conducted reviews of the risks of hydraulic fracturing activities including considering the potential likelihoods of many of the impact modes in their local contexts. Although geological properties, in-situ stresses and applied hydraulic fracture techniques will impact local risk profiles, these inquiries provide an important line of evidence in assessing the relative likelihood of each impact mode in each GBA region. The findings from nine inquiries have been analysed (with key excerpts presented in Sections 2.1 to 2.9) and categorised against the likelihood descriptions in Table 4 and Table 5 to distil, where possible, a relative qualitative likelihood of occurrence for each impact mode.

The arithmetic mode of these qualitative likelihoods across the domestic and international inquiries is presented as an indication of the current state of scientific understanding for each impact mode. The range of assessed likelihoods is also presented as a coarse indicator of either the level of alignment between the inquiries and/or the differences between the local subsurface conditions and industry operational practices. The findings from each of the nine reviewed inquiries are summarised in tables Table 4 and Table 5 and presented in the Stage 2 synthesis reports for each of the GBA regions (Frery *et al.*, 2020; Holland *et al.*, 2020; Lewis *et al.*, 2020). Key excerpts from each inquiry are presented in the subsequent sections:

- Section 2.1 Hydraulic fracturing for oil and gas: Impacts from the hydraulic fracturing water cycle on drinking water resources in the United States (USEPA, 2016)
- Section 2.2 Report of the independent inquiry into hydraulic fracturing in the Northern Territory (Hawke, 2014)
- Section 2.3 Engineering Energy: Unconventional Gas Production. Report for the Australian Council of Learned Academics (Cook et al., 2013)
- Section 2.4 Shale gas extraction in the UK : a review of hydraulic fracturing (The Royal Society and The Royal Academy of Engineering, 2012)
- Section 2.5 Drilling for oil and gas in New Zealand: Environmental oversight and regulation (Wright, 2014)
- Section 2.6 Environmental Impacts of Shale Gas Extraction in Canada (Council of Canadian Academies, 2014)
- Section 2.7 Report of the Nova Scotia Independent Panel On Hydraulic Fracturing (Atherton et al., 2014)
- Section 2.8 Final Report of the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory (Pepper et al., 2018)
- Section 2.9 Independent Scientific Panel Inquiry into Hydraulic Fracture Stimulation in Western Australia (Hatton et al., 2018).

Hydraulic fracturing causal pathway impact modes

Table 4 Summary of the findings of the likelihoods of each hydraulic fracturing causal pathway impact mode from key domestic and international works along with the description of the likelihood scores

	Impact mode	US Environmental Protection Agency, (2016)	Hawke, (2014)	Cook et al. (2013)	The Royal Society and The Royal Academy of Engineering (2012)	Wright, (2014)	Council of Canadian Academies (2014)	Atherton et al., (2014)	Pepper et al., (2018)	Hatton et al., (2018)	Description of likelihood scores
F.1	Hydraulic fracture growth into aquifer	Unlikely	Rare	Unlikely	Rare	Not assessed	Rare	Rare	Rare	Rare	**Rare**: Hydraulic fractures could conceivably grow in height to a maximum of approximately 400-500 m however this would be insufficient to intersect aquifers in the jurisdiction / study area **Unlikely:** Hydraulic fractures could conceivably grow in height to a maximum of approximately 400 m and this may be enough to intersect aquifers in the jurisdiction / study area
F.2	Hydraulic fracture growth into well	Unlikely	Not assessed	Not assessed	Not assessed	Not assessed	Unlikely	Unlikely	Not assessed	Rare	**Rare:** Fracture growth into other wells has been suggested as a possible cause for changes to nearby water quality but this has not been conclusively linked or is not considered probable in the area of study **Unlikely:** Hydraulic fracture Intersection and changes in fluid flow in other bores or wells has been observed in the area of study
F.3	Hydraulic fracture growth into fault	Rare	Unlikely	Unlikely	Unlikely	Not assessed	Rare	Not assessed	Rare	Unlikely	**Rare:** Fracture mechanics make it impossible for a hydraulic fracture to grow to a height greater than approximately 500 m **Unlikely:** Operators must characterise local stresses and faults to prevent hydraulic fractures from enhancing the conductivity of any intersected vertical faults

Compromised well integrity causal pathway impact modes

Table 5 Summary of the findings of the likelihoods of each compromised well integrity causal pathway from key domestic and international works along with the description of the likelihood scores

	Impact mode	US Environmental Protection Agency, (2016)	Hawke, (2014)	Cook et al. (2013)	The Royal Society and The Royal Academy of Engineering (2012)	Wright, (2014)	Council of Canadian Academies (2014)	Atherton et al., (2014)	Pepper et al., (2018)	Hatton et al., (2018)	Description of likelihood scores
W.1	Well rupture or failure across barriers	Rare	Rare	Rare	Not assessed	Rare	Rare	Very rare	Rare	Rare	**Very rare**: Fracture rupture would be detected immediately, and operations halted **Rare**: Well rupture or failure of well barriers has been observed or is possible in jurisdiction / study area but human error rather than mechanical failure is the failure mode
W.2	Migration along casing from reservoir to surface	Unlikely	Rare	Not assessed	Rare	Rare	Unlikely	Rare	Rare	Not assessed	**Rare**: Large vertical distance and good well construction practices will supress the likelihood of this causal pathway **Unlikely**: Risks are variable and poorly quantified but annular migration is the most likely pathway for methane. Liquid migration is not expected

	Impact mode	US Environmental Protection Agency, (2016)	Hawke, (2014)	Cook et al. (2013)	The Royal Society and The Royal Academy of Engineering (2012)	Wright, (2014)	Council of Canadian Academies (2014)	Atherton et al., (2014)	Pepper et al., (2018)	Hatton et al., (2018)	Description of likelihood scores
W.3	Migration along casing between rock layers	Unlikely	Very rare	Unlikely	Not assessed	N/A	Unlikely	Rare	Unlikely	Rare	**Very rare**: Vertical migration of fluids along the outside of the well casing between permeable formations is estimated as occurring in less than 0.1% of wells **Rare:** Vertical migration of fluids along the outside of the well casing between permeable formations is estimated as occurring in less than 1% of wells **Unlikely**: Vertical migration of fluids along the outside of the well casing between permeable formations is estimated as occurring in less than 3% of wells
W.4	Migration along decommissioned / abandoned wells	Unlikely	Unlikely	Unlikely	Unlikely	Unlikely	Unlikely	Likely	Unlikely	Unlikely	**Unlikely:** Some decommissioned wells are likely to leak methane and some level of monitoring is required **Likely:** Methane leakage from decommissioned / abandoned wells is certain
W.5	Loss of well control	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed	Rare	Not assessed	Not assessed	

2.1 *Qualitative review of the findings from: Hydraulic fracturing for oil and gas: Impacts from the hydraulic fracturing water cycle on drinking water resources in the United States (US Environmental Protection Agency, 2016)*

Background and scope

In 2010, the US Environmental Protection Agency (EPA) initiated a study of the potential impacts of hydraulic fracturing activities on drinking water resources. The EPA defined the scope of its study to focus on the acquisition, use, disposal, and reuse of water used for hydraulic fracturing. This was done in recognition that concerns raised about potential impacts were not limited to the relatively short-term act of fracturing rock, but can include impacts related to other activities associated with hydraulic fracturing. The report represents the capstone product of the EPA's hydraulic fracturing drinking water study. It captures the state-of-the-science concerning drinking water impacts from activities in the hydraulic fracturing activities water cycle and integrates the results of the EPA's study of the subject with approximately 1,200 other publications and sources of information.

Study area

United States of America

Authors

US EPA (US Environmental Protection Agency) staff and consultants

Focus

The goals of this report were to assess the potential for activities in the hydraulic fracturing water cycle to impact the quality or quantity of drinking water resources and to identify factors that affect the frequency or severity of those impacts.

Key findings

Each stage of the hydraulic fracturing water cycle was assessed to identify firstly the potential for impacts on drinking water resources and secondly, factors that affect the frequency or severity of impacts.

The report found that the primary factors that can affect the frequency or severity of impacts are:

1. the construction and condition of the well that is being hydraulically fractured,
2. the amount of vertical separation between the production zone and formations that contain drinking water resources, and
3. the location, depth, and condition of nearby wells or natural faults or fractures.

Qualitative review of the report findings for each impact mode

A qualitative review of the findings from US Environmental Protection Agency, (2016) has been undertaken though analysis of key excerpts from the text. The qualitative review (based on the likelihood descriptions in Table 4 and Table 5) provides a likelihood score for each impact mode. The likelihood score for each impact mode with related supporting excerpts are shown below in Table 6.

Table 6 Excerpts from US Environmental Protection Agency, (2016) related to each impact mode

	Impact Mode	Likelihood score	Key excerpts from: Hydraulic fracturing for oil and gas: Impacts from the hydraulic fracturing water cycle on drinking water resources in the United States (US Environmental Protection Agency, 2016)
Hydraulic fracture growth			
F.1	Hydraulic fracture growth into aquifer	Unlikely	"Fracture growth from a deep formation to a near-surface aquifer is generally considered to be limited by layered geological environments and other physical constraints." p6-55 "In some parts of the United States (e.g., the Powder River Basin in Montana and Wyoming), there is no vertical distance between the top of the hydraulically fractured oil- or gas-bearing rock formation and the bottom of treatable water. When hydraulically fractured oil and gas production wells are located near or within drinking water resources, there is a greater potential for activities in the hydraulic fracturing water cycle to impact those resources." pES-8 "Hydraulic fracturing can occur at or near the bottom of a production well or it may take place at different intermediate depths depending on the location of economically producible oil and gas, and thus the total vertical depth of a production well does not necessarily correlate to the depth at which hydraulic fracturing occurs." p2-16 "Fisher and Warpinski, (2012) and Davies et al., (2012) indicate 1% of fractures had a fracture height greater than 350 meters, and the maximum fracture height among all of the data reported was 588 meters. These reported fracture heights suggest that some fractures can grow out of the targeted rock formation and into an overlying formation." pES-27 "Because fluids travel through the newly-created hydraulic fractures, the location of these fractures relative to underground drinking water resources is an important factor affecting the frequency and severity of potential impacts on drinking water resources." pES-30 "Without data on relative location of induced fractures to underground drinking water resources we were often unable to determine with certainty whether fractures created during hydraulic fracturing have reached underground drinking water resources. Instead, we considered the vertical separation distance between hydraulically fractured rock formations and the bottom of underground drinking water resources." pES-30 "Microseismic data and modeling studies suggest that, in deep shale formations, fractures created during hydraulic fracturing are unlikely to grow through thousands of feet of rock into underground drinking water resources." pES-31

			"…hydraulic fracturing has occurred within underground drinking water resources in parts of the United States." pES-32 "…the vertical separation distance between the targeted rock formation and underground drinking water resources are important factors that affect the frequency and severity of impacts on drinking water resources." pES-32 "…thousands of feet of rock between hydraulically fractured rock formations and underground drinking water resources can reduce the frequency of impacts on drinking water resources during the well injection stage of the hydraulic fracturing water cycle." pES-33 "There is limited publicly available information (in the USA) to determine the vertical distance separating the shallowest hydraulic fracturing initiation point in a production well from the deepest drinking water resource." p2-8 "The primary factors that can affect the frequency or severity of impacts to drinking water associated with injection for hydraulic fracturing are: …(2) the vertical separation between the production zone and formations that contain drinking water resources,…" p6-1 [Data limits on well integrity, pre- and post-hydraulic fracturing groundwater quality, and fracture extent] "…in combination with the geologic complexity of the subsurface environment and the fact that these processes cannot be directly observed, make determining the frequency of such impacts challenging." p6-1 "…hydraulic fracturing operations are unlikely to generate sufficient pressure to drive fluids into shallow drinking water zones." p6-52 "Vertical separation between the zone where hydraulic fracturing operations occur and drinking water resources reduces the potential for fluid migration to impact the quality of drinking water resources." p6-71
F.2	Hydraulic fracture growth into well	Unlikely	"Regardless of the vertical separation between the targeted rock formation and the underground drinking water resource, the presence of other wells near hydraulic fracturing operations can increase the potential for hydraulic fracturing fluids or other subsurface fluids to move to drinking water resources. Frac hits have also been observed at wells up to 8,422 feet (2,567 meters) away from a well undergoing hydraulic fracturing." pES-32 "Abandoned wells near a well undergoing hydraulic fracturing can provide a pathway for vertical fluid movement to drinking water resources if those wells were not properly plugged or if the plugs and cement have degraded over time. For example, an abandoned well in Pennsylvania produced a 30-foot (9-meter) geyser of brine and gas for more than a week after hydraulic fracturing of a nearby gas well." pES-32 "To produce a consistent measure of proximity between these hydraulically fractured oil and gas production wells and drinking water resources during this time frame, the EPA counted the number hydraulically fractured oil and gas production wells located within 1 mile of public drinking water sources, and performed a count of the counties with a relatively high reliance on self-supplied drinking water that also contain one or more of these hydraulically fractured production wells. Between 2000 and 2013, approximately 3,900

			public water systems had between one and 144 wells hydraulically fractured within 1 mile of their water source…" p2-18 "The primary factors that can affect the frequency or severity of impacts to drinking water associated with injection for hydraulic fracturing are: (1) the condition of the well's casing and cement and their placement relative to drinking water resources, …and (3) the presence/proximity and condition of wells near the hydraulic fracturing operation." p6-1 "Anomalies in operational monitoring data can also indicate whether an unexpected event has occurred, such as communication with another well (USEPA, (2016) Section 6.3.2.3)." p6-43 "Frac hits (hydraulic fractures propagate to other existing hydraulic fractures) can be a particular concern in shallower formations, where the local least principal stress is vertical (resulting in more horizontal fracture propagation), and in situations where there are drinking water wells in the same formation as wells used for hydraulic fracturing." p6-58 "While the subsurface effects of frac hits have not been extensively studied, these cases demonstrate the possibility of fluid migration via communication with other wells and/or their fracture networks. More generally, well communication events can indicate fracture behavior that was not intended by the treatment design." p6-59 "…results indicate that the subsurface interactions of well networks or complex hydraulics driven by each well at a densely populated (with respect to wells) area are important factors to consider for the design of hydraulic fracturing treatments and other aspects of oil and gas production." p6-61 "The key factor affecting the likelihood of a well communication event and the impact of a frac hit is the location of the offset well relative to the well where hydraulic fracturing was conducted (Ajani and Kelkar, 2012). In the Ajani and Kelkar (2012) analysis, the likelihood of a communication event was less than 10% in wells more than 4,000 ft (1,000 m) apart, but rose to nearly 50% in wells less than 1,000 ft (300 m) apart. Well communication was also much more likely with wells drilled from the same pad. The affected wells were found to be in the direction of maximum horizontal stress in the field, which correlates with the expected direction of fracture propagation. Modeling work by Myshakin et al., (2015) is generally consistent with these results, indicating that the risk of fluid movement through pre-existing wellbores or open faults is negligible unless hydraulic fractures are located very close to these features." p6-61 "Well communication may be more likely to occur where there is less resistance to fracture growth. Such conditions may be related to existing production operations (e.g., where previous hydrocarbon extraction has reduced the pore pressure, changed stress fields, or affected existing fracture networks) or the existence of high-permeability rock units - tendency for asymmetric fracture growth toward depleted areas in low-permeability gas reservoirs due to pore pressure depletion from production at offset wells." p6-61 "…the potential for impact on a drinking water resource also depends on the condition of the offset well…. If the cement in the annulus between the casing and the formation is intact and the well components can withstand the stress exerted by the pressure of the fluid, nothing more than an

			increase in pressure and extra production of fluids would occur during a well communication event. However, if the offset well is not able to withstand the pressure of the hydraulic fracturing fluid, well components could fail (USEPA, (2016) Figure 6-4), allowing fluid to migrate out of the well." p6-62 "In older wells near a hydraulic fracturing operation, plugs and cement can degrade over time; in some cases, abandoned wells may never have been plugged properly." p6-62 "Based on the available information, frac hits most commonly occur on multi-well pads and when wells are spaced less than 1,100 ft (340 m) apart, but they have been observed at wells up to 8,422 ft (2,567 m) away from a well undergoing hydraulic fracturing." p6-71
F.3	Hydraulic fracture growth into fault	Rare	"…pressure data from previous hydraulic fracturing operations can indicate whether a geologic barrier to fracture growth exists and whether the barrier has been penetrated, or whether fractures have intersected with natural fractures or faults (American Petroleum Institute, 2015)." p6-43 "A statistical analysis of microseismic data by (Shapiro et al., 2011) found that fault rupture (movement along a fault) from hydraulic fracturing is limited by the extent of the stimulated rock volume and is unlikely to extend beyond the fracture network." p6-67 "In the Fisher and Warpinski, (2012) data set (USEPA, (2016) Section 6.3.2.2), the greatest fracture heights occurred when the hydraulic fractures intersected pre-existing faults." p6-67 "(Hammack et al., 2014) reported that fracture growth seen above the Marcellus Shale is consistent with the inferred extent of pre-existing faults at the Greene County, Pennsylvania, research site (USEPA, (2016) Section 6.3.2.2 and Text Box 6-6)." p6-67 "At a site in Ohio, (Skoumal, Brudzinski and Currie, 2015) found that hydraulic fracturing induced a rupture along a pre-existing fault approximately 0.6 mi (1 km) from the hydraulic fracturing operation." p6-67 "Lacazette and Geiser, (2013) also found vertical hydraulic fracturing fluid movement from a production well into a natural fracture network for distances of up to 0.6 mi (1.0 km). However, Davies et al. (2013) questioned whether this technique actually measures hydraulic fracturing fluid movement." p6-68 "…as demonstrated by microseismic data presented by (Vulgamore et al., 2007), in some settings [Woodford shale], the fracture network—and, in this case, the possibility of fault rupture— [hydraulic / stimulated natural fracture network] could extend laterally for thousands of feet [~1 km]." p6-67 [Related excerpt from (Vulgamore et al., 2007)] "The interaction with local structural features (faults, fracture swarms) had a significant effect on fracture treatment geometry. They can completely dominate fracture growth as subsequent stages may continue to grow into the previously intersected fault. This can prevent the full length of the lateral from being stimulated and may cause the well to underperform." [Appears to be ~500 m Hydraulic Fracture and ~500 m in natural fracture]

			"Lacazette and Geiser (2013) also found vertical hydraulic fracturing fluid movement from a production well into a natural fracture network for distances of up to 0.6 mi (1.0 km). However, Davies et al., (2013) questioned whether this technique actually measures hydraulic fracturing fluid movement." p6-68 "(Rutledge and Phillips, 2003) suggested that, in East Texas, pressurizing existing fractures (rather than creating new hydraulic fractures) was the primary process that controlled enhanced permeability and fracture network conductivity at the site (Ciezobka and Salehi, 2013) concluded in the Marcellus Shale that fracture treatments are more efficient in areas with clusters or "swarms" of small natural fractures,…" p6-67 "…other conditions in addition to the physical presence of a permeable fault or fracture would need to exist for fluid migration to a drinking water resource to occur. if such a permeable feature exists, the transport of gas and fluid flow would strongly depend upon the production regime and, to a lesser degree, the features' permeability and the separation between the reservoir and the aquifer. In addition, the pressure distribution within the reservoir (e.g., over-pressurized vs. hydrostatic conditions) will affect the fluid flow through fractures/faults. As a result, the presence of multiple geologic and well-related factors can increase the potential for fluid migration into drinking water resources." p6-67
Compromised well integrity			
W.1	Well rupture or failure across barriers	Rare	"The following combinations of activities and factors are more likely than others to result in more frequent or more severe impacts: …Injection of hydraulic fracturing fluids into wells with inadequate mechanical integrity, allowing gases or liquids to move to groundwater resources;…" pES-3, p10-3 & p10-23 "Because the well can be a pathway for fluid movement, the mechanical integrity of the well is an important factor that affects the frequency and severity of impacts from the well injection stage of the hydraulic fracturing water cycle." pES-28 "…an inner string of casing burst during hydraulic fracturing of an oil well near Killdeer, North Dakota, resulting in a release of hydraulic fracturing fluids and formation fluids that impacted a groundwater resource." pES-30 & p10-27 "…mechanical integrity failures have allowed gases or liquids to move to underground drinking water resources." pES-32 "…the mechanical integrity of the well is an important factor that affects the frequency and severity of impacts from the well injection stage of the hydraulic fracturing water cycle." pES-28 "…multiple layers of cemented casing…can reduce the frequency of impacts on drinking water resources during the well injection stage of the hydraulic fracturing water cycle." pES-32 "One way to ensure that the strength of the casing is sufficient to withstand the stresses imposed by hydraulic fracturing operations is to pressure test the casing. The casing can be pressurized to the pressure anticipated during hydraulic fracturing operations and shut-in periods; if the well can hold the

			pressure, it is considered to be leak-free and therefore should be able to withstand the pressures of hydraulic fracturing." p6-9 "Corrosion in uncemented zones is the most common cause of casing failure." p6-19
W.2	Migration along casing from reservoir	Unlikely	"A well with insufficient mechanical integrity can allow unintended fluid movement, either from the inside to the outside of the well or vertically along the outside of the well. The existence of one or more of these pathways [impact modes] can result in impacts on drinking water resources if hydraulic fracturing fluids reach groundwater resources." pES-29 "…hydraulic fracturing of an inadequately cemented gas well in Bainbridge Township, Ohio, contributed to the movement of methane into local drinking water resources." pES-30 "The primary factors that can affect the frequency or severity of impacts to drinking water associated with injection for hydraulic fracturing are: (1) the condition of the well's casing and cement and their placement relative to drinking water resources…." p6-1 "…temperature-related stresses [cooling to ~20 degrees] associated with hydraulic fracturing [fluid] remain as factors that can affect the integrity of the well casing." p6-22 "Improper placement of cement can lead to defects in external mechanical integrity. For example, an improper cement job can be the result of loss of cement during placement into a formation with high porosity or fractures, causing a lack of adequate cement across a water- or brine-bearing zone." p6-27 "Cementing in horizontal wells, which are commonly hydraulically fractured, presents challenges that can contribute to higher rates of mechanical integrity issues." p6-32 "Risk evaluation studies of a limited number of injection wells show that, if the surface casing is not set deeper than the bottom of the drinking water resource, the risk of aquifer contamination increases a thousand-fold." p6-73 "Cement integrity problems can arise as a result of challenges in centring the casing and placing the cement in [Deviated and horizontal] wells. Absent efforts to ensure the emplacement of sufficient cement that is of adequate integrity, the increased use of these wells in hydraulic fracturing operations has the potential to increase the frequency at which associated cementing problems occur. This, in turn, has the potential to increase the frequency of impacts to the quality of drinking water resources." p6-73 "In areas where there is little or no vertical separation between the production zone and drinking water resources, there is a greater potential to increase the frequency or severity of impacts to drinking water quality." p6-74
W.3	Migration along casing between rock layers	Unlikely	"A well with insufficient mechanical integrity can allow unintended fluid movement, either from the inside to the outside of the well or vertically along the outside of the well. The existence of one or more of these pathways can result in impacts on drinking water resources if hydraulic fracturing fluids reach groundwater resources." pES-29

			“The primary factors that can affect the frequency or severity of impacts to drinking water associated with injection for hydraulic fracturing are: (1) the condition of the well’s casing and cement and their placement relative to drinking water resources.” p6-1 “…the pressure- and temperature-related [cooling to ~20] degrees stresses associated with hydraulic fracturing remain as factors that can affect the integrity of the well casing.” p6-22 “In the study by Darrah et al. (2014) (USEPA, (2016) Section 6.2.2.1), using isotopic data, four clusters of gas contamination were linked to poor cementing. In three clusters in the Marcellus and one in the Barnett, gas found in drinking water wells had isotopic signatures consistent with intermediate formations overlying the producing zone. This suggests that gas migrated from the intermediate units along the well annulus, along uncemented portions of the wellbore, or through channels or microannuli.” p6-27 “(Watson and Bachu, 2009) found that regulations requiring monitoring and repair of sustained casing vent flow or sustained casing pressure had a positive effect on lowering leak rates. The authors also found injection wells initially designed for the higher pressures associated with injection (vs. production) experienced sustained casing pressure less often than those that were retrofitted (Watson and Bachu, 2009).” p6-37 “…Fleckenstein et al. (2015) found that placing the surface casing below all potential sources of drinking water and cementing intermediate gas zones significantly reduced sustained casing pressure.” p6-37
W.4	Migration along decommissioned/ abandoned wells	Unlikely	“…in South-Eastern Bradford County, Pennsylvania (discussed in USEPA, (2016) Section 6.2), where natural fractures intersected an uncemented casing annulus and allowed gas to flow from the annulus into nearby domestic wells and a stream (Llewellyn et al., 2015).” p6-68
W.5	Loss of well control	Not assessed	

References contained within Table 6 Excerpts from US Environmental Protection Agency, (2016) related to each impact mode

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2.2 Qualitative review of the findings from: *Report of the independent inquiry into hydraulic fracturing in the Northern Territory* (Hawke, 2014)

Background and scope

The Northern Territory Government (NTG) established an Inquiry on 14 April 2014 to undertake a thorough investigation into hydraulic fracturing for hydrocarbon deposits in the Northern Territory (NT) and the potential effects on the environment.

Among other things, the Chief Minister asked the Inquiry:

- … to separate the proven evidence about environmental risk from the myths and to give an accurate picture based on science; and
- … to provide recommendations on whether steps should be taken to mitigate any potential impacts from fracking.

263 submissions to the inquiry were received and posted on the Inquiry website to inform interested parties and facilitate information exchange. Community meetings and consultations in Alice Springs, Darwin and Katherine attracted a combined attendance of around 150 people.

Study area

NT, Australia

Authors

Dr Allan Hawke

Focus

The Inquiry set out to:

- respond to the Terms of Reference using evidence-based, factual research to explore the topics and to provide a solid foundation for the recommendations and findings;
- provide opportunities for the community, industry, peak groups and any interested party to submit information and thoughts for consideration;
- draw on existing research and case studies in addition to information gained through submissions and meetings; and
- ensure information sources were identified and examined.

Key findings

This Inquiry's major recommendation, consistent with other Australian and international reviews, is that the environmental risks associated with hydraulic fracturing can be managed effectively subject to the creation of a robust regulatory regime.

The most likely mechanisms for contamination are poor well integrity, leaks from abandoned wells or surface spills - issues common to the oil and gas industry, whether conventional or unconventional.

Qualitative review of the report findings for each impact mode

A qualitative review of the findings from Hawke (2014) has been undertaken though analysis of key excerpts from the text. The qualitative review (based on the likelihood descriptions in Table 4 and Table 5) provides a likelihood score for each impact mode. The likelihood score for each impact mode with related supporting excerpts are shown below in Table 7.

Table 7 Excerpts from Hawke (2014) related to each impact mode

	Impact Mode	Likelihood score	Key excerpts from: *Report of the independent inquiry into hydraulic fracturing in the Northern Territory* (Hawke, 2014)
Hydraulic fracture growth			
F.1	Hydraulic fracture growth into aquifer	Rare	“Fractures in the rock radiate out from the casing, with the greatest amount of fracturing aligned with the direction of maximum principal stress in the rock strata. At depths greater than 600 m, the vertical stress or overburden is generally the largest single stress, so the principal fracture orientation is likely to be vertical.” p97 “[Fisher and Warpinski, 2012]…showed that fracture height growth is generally greatest in the deepest wells; that most fracture growth is contained within 100-200 m; and that occasionally there are spikes of longer fractures, to a maximum of approximately 500 m.” p97 “The pressure required to propagate fractures across thousands of metres of rock can neither be achieved nor sustained.” p97 “Even if a pathway is created during fracturing between deep and shallow formations, this does not mean that fracturing fluid, gas or brine would necessarily flow into shallow aquifers. This would require suitable pressure and permeability conditions, as well as sustained hydraulic pressure once fracturing is completed. Analyses suggest upward flow of fluids via fractures to the shallow fresh water zone is highly unlikely.” p98 “Several studies and reviews have concluded that there is no unequivocal evidence of ground water contamination directly attributable to fracture propagation from hydraulic fracturing at “normal depths” (below 1200 m), and no evidence of chemicals from fracturing fluids in contaminated water wells (Groat and Grimshaw, 2012; The Royal Society and The Royal Academy of Engineering, 2012).” P100 “One exception may be ground water contamination at Pavillion, Wyoming. The suspected source of contamination were two conventional gas wells in the Wind River Basin which had been fractured to increase production - in this case, fracturing occurred within 372 meters of the surface, with water bores extending to as deep as 244m.” p100 “Detailed monitoring during a fracture treatment provides additional data about the performance of the fracture which feeds back to iteratively improve the fracture growth models for future stages, or other wells in the same target formation. Microseismic and tiltmeter monitoring (see above) provide the most information about fracture extent and geometry, but are

			relatively expensive to implement, particularly microseismic monitoring that requires an offset well of similar depth to the fracture operation. Therefore, these technologies are mostly applied during exploratory drilling and early development phases until fracture dynamics within that area are relatively well understood (King, 2012 p29).” p101 “Pressure sensors in the cemented annular region between casing strings can also detect any breakdown in well integrity during fracturing. Other monitoring methods during and after the fracture operation may be informative about fracture performance, including proppant tagging, chemical tracers, temperature measurement and fibre-optic sensors (All Consulting, 2012 pp63-66; King, 2012 Table 4; Cook et al., 2013 p62). The use of fibre optic sensors is a potential alternative to electronic gauges in high temperature conditions and increasingly detailed real-time fracturing diagnostics is an area of rapid technological development within the industry.” p101 “It should be noted that fracture modelling depends on estimating a large number of variables which “make the first estimates of computer modelling less than ideal” (King, 2012 p30), so that the maximum fracture heights from modelling within relatively poorly known NT basins must be treated cautiously, at least in the early stages of exploration and development.” p102 “The Inquiry finds with respect to Fracture Propagation, that the risk of fracture propagation in deep gas shale formations causing hydraulic fracturing fluid, methane or brine to contaminate overlying aquifers is very low, and may be minimised by requiring leading practice in fracture operations, including fracture modelling and real-time and post-fracture monitoring;…” p103
F.2	Hydraulic fracture growth into well	Not assessed	
F.3	Hydraulic fracture growth into fault	Unlikely	“…tracking bottom hole pressure shows a characteristic signature associated with fracture initiation, breakdown and propagation (e.g. Cook et al., 2013 Diagram 2, p70) and deviation from this may indicate intersection with a fault and prompt remedial action.” p101 “The larger spikes in fracture growth in the data of (Fisher and Warpinski, 2012) are interpreted as a result of hydraulic fractures intercepting faults, and this appears to be the greatest area of risk with fracture propagation.” p98 “(Davies et al., 2012) cited a maximum observed fracture height of 588m for a hydraulic fracture that extended into a pre-existing fault.” p98 “…real-time monitoring during the fracturing process can alert the operator to any anomalous events - such as fracturing intercepting a fault - and remedial action taken…” p98
Compromised well integrity			
W.1	Well rupture or failure across barriers	Rare	“Ensuring well integrity is a key aspect of reducing the risk of environmental contamination from unconventional gas extraction. Application of leading practice in well construction combined with rigorous integrity testing and effective regulatory oversight should result in a very low probability of well failure, but a ground water monitoring regime that can detect contamination attributable to unconventional gas activities is also desirable.” pES-xiv, p95 & p188

			“Many reported incidents that underlie public concern about ground water contamination may be linked to poor well construction techniques in the earlier stages of the unconventional gas and oil industry, and the risks are likely to be much lower for a developing industry in the NT using modern (and future) technology and subject to good regulatory practice. Nevertheless, the risks cannot be reduced to zero and some areas of uncertainty remain, particularly the very long term integrity of wells.” p85 “After each stage of casing and cementing is completed, well integrity can be tested by: • “cased-hole logging”, which includes a cement bond log (CBL) or similar evaluation logs from an acoustic device run inside the casing, that transmits and receives a sound signal to test the completeness and quality of the cement bond between the casing and formation wall; and • pressure testing, to ensure that a seal has been achieved and that casings have the required mechanical integrity and strength. Pressurising the well bore with water up to ~ 700 atmospheres (70 megapascals) for hold times of ten minutes is typical, but may be higher to exceed maximum expected hydraulic fracturing pressure (Cook et al., 2013, p56).” p88 “In the production phase, it is common for a thinner steel pipe (production tubing) to be inserted within the production casing and all fluids being produced will flow through this tubing. The annulus between the production tubing and the production casing can be monitored during the production lifespan of the well for any pressure change that might indicate a loss of pressure integrity.” p89 “…the length of time over which sealed well integrity will be maintained cannot yet be fully known, as modern well cementation practices are globally only 60 years old, and that this is a complex question that requires further investigation.” p89 “Aside from emphasising the primary importance of well integrity, a key learning for the developing Australian shale gas industry from these debates is that resolving the source of methane (or other chemical) contamination of ground water in these contested areas was greatly hampered by a lack of comprehensive pre-drilling baseline water quality samples and studies.” p90 “Moreover, if good practice and strong regulation are enforced, then monitoring should ensure that leaks are quickly detected and remedial action taken.” p92 “The Inquiry finds …ensuring well integrity is a key aspect of reducing the risk of environmental contamination from unconventional gas extraction. Application of leading practice in well construction combined with rigorous integrity testing and effective regulatory oversight should result in a very low probability of well failure, but a ground water monitoring regime that can detect contamination attributable to unconventional gas activities is also desirable;…” pES-xiv, p95 & p188
W.2	Migration along casing from reservoir	Rare	“During fracturing operations, pressure sensors in the annular regions between casing strings and inside the production casing are used to track pressure changes and detect any breakdown in well integrity.” p88

W.3	Migration along casing between rock layers	Very Rare	“The key to well integrity is constructing the well to ensure that it is reliably isolated from subsurface formations, other than those targeted for gas extraction, and there is “zonal isolation” between significant segments of the well profile. This is done by constructing the well with a series of concentric steel casings of decreasing diameter and increasing depth, with a cement seal between the outer casing and rock, and between casings.” p85 “Well integrity is influenced by the number of casings and the extent of cementing. Leading practice is for a minimum of three casings, and for all casings to be cemented to the surface. Integrity also depends on the quality of casing and cementing materials and the standard to which casing is joined, installed and cemented. Casings are joined carefully at a specified torque, ensuring that threads are in good condition. “Centralizers” are typically attached to the steel casing as it is assembled and lowered into the borehole, in order to keep the casing central in the hole.” p87 “The well cement slurry used is specifically engineered for this purpose taking into account local geological and hydrogeological conditions. Good cementation is harder to achieve in horizontal wells.” p88 “The high alkalinity of the cement protects steel casing from potential deterioration due to contact with acidic rock or water with high levels of CO_2 or H_2S.” p88 “…the products of steel corrosion and cement degradation are solid material, so deterioration over long periods would not simply result in wide open channels to the surface; and that liquid seepage was far less probable through narrow pathways resulting from long term deterioration than gas.” p89 “These data have been used to infer a probability of casing failure leading to aquifer contamination of 0.03%.” p91
W.4	Migration along decommissioned / abandoned wells	Unlikely	“It is not necessarily appropriate to extrapolate estimated leakage rates in older wells to predicted outcomes for wells constructed using modern casing and cementing materials and practices.” p131 “Cemented wells can maintain good integrity after 40 years, despite large variation in reservoir pressure (King, 2012, p21), and industry proponents maintain that if properly constructed and decommissioned “the well essentially becomes part of the rock and will afford protection in perpetuity” (Santos submission, p 25). There is, however, some evidence of surface casing vent flow from recent wells (citations in Council of Canadian Academies, 2014, p58), and the CCA Report [Council of Canadian Academies, 2014] concluded that the degree of improvement claimed (in cementing and other practices to ensure well integrity) has not been independently tested or verified. Cook et al. (2013, pp128-129) stated that the longevity of integrity of decommissioned wells remains poorly understood and noted this as a topic where more information is essential, and where careful attention in terms of regulation and governance is required.” p131 “The (The Royal Society and The Royal Academy of Engineering, 2012 p30) noted that if well abandonment in the UK is completed without unusual or adverse developments, no subsequent monitoring is currently required, and recommended that monitoring arrangements should be developed to detect possible well failure post abandonment. (Atherton et al., 2014, pp212-213) also noted the development of slow gas leakage can take place years after

			well decommissioning and that this may be difficult to detect, particular if there is subsurface leakage into shallow strata." p132 "The Inquiry found with respect to Well Closure and Site Rehabilitation, that… application of leading practice for construction and closure can minimise environmental risks associated with decommissioned wells, but the longevity of long-term integrity of decommissioned wells remains poorly understood;" pES-xvi, p134 & p193
W.5	Loss of well control	Not assessed	

References contained within Table 7 Excerpts from Hawke (2014) related to each impact mode

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2.3 Qualitative review of the findings from: Engineering Energy: Unconventional Gas Production. Report for the Australian Council of Learned Academics (Cook et al., 2013)

Background and scope

A three-year research program funded by the Australian Research Council and conducted by the four Learned Academies through the Australian Council of Learned Academies for PMSEIC, through the Office of the Chief Scientist. Securing Australia's Future delivers research-based evidence and findings to support policy development in areas of importance to Australia's future.

A study of shale gas in Australia which looks at: resources, technology, monitoring, infrastructure, human and environmental impacts, issues communication, regulatory systems, economic impacts, lessons learned from the coal seam gas industry, and impacts on greenhouse gas reduction targets

Study area

Australia

Authors

Peter Cook (Chair), Vaughan Beck, David Brereton, Robert Clark, Brian Fisher, Sandra Kentish, John Toomey, John Williams

Focus

Review focused on shale gas which could potentially fill knowledge gaps, identify and consider community concerns; and address both the opportunities and the challenges that might arise from shale gas.

Key findings

Because of the way shale gas is produced it has the potential to impact on the landscape, on ecosystems, on surface and groundwater, on the atmosphere, on communities, and rarely may result in minor induced seismicity. Many impacts are possible, but the likelihood of many of them occurring is low and where they do occur, other than in the case of some biodiversity impacts, there are generally remedial steps that can be taken. However, most can be minimised where an effective regulatory system and best monitoring practice are in place and can be remediated where they do occur. If preferential pathways (e.g. faults) are stimulated from the hydraulic fracturing process, travel time for contaminants to reach the surface can be reduced by 1-2 orders of magnitude (Myers, 2012; Frogtech, 2013).

Under normal conditions, risks of consequences from shale gas production to groundwater ecology and groundwater dependent ecosystems are low to moderate, although uncertainty about groundwater impacts is high largely because of lack of detailed information on deep stratigraphy, faults, discontinuities, stress distribution and lack of understanding of deep hydrogeological processes. Most gas wells can be expected to pass through aquifers ranging from freshwater to saline and at depths ranging from very near surface (tens of metres) to deep (hundreds to thousands of metres), and are subject to well integrity regulation.

Australian basins such as the Cooper-Eromanga Basin, in addition to surface aquifers, shale gas wells (like conventional gas wells) pass through deep aquifers of the Great Artesian Basin. To minimise the risk to this vital groundwater resource, best practice should be adopted in both well integrity and the use of sensing technology to monitor the hydraulic fracturing process, particularly when there is any potential for extended vertical growth of fractures.

Qualitative review of the report findings for each impact mode

A qualitative review of the findings from Cook et al. (2013) has been undertaken though analysis of key excerpts from the text. The qualitative review (based on the likelihood descriptions in Table 4 and Table 5) provides a likelihood score for each impact mode. The likelihood score for each impact mode with related supporting excerpts are shown below in Table 8.

Table 8 Excerpts from Cook et al. (2013) related to each impact mode

	Impact Mode	Likelihood score	Key excerpts from: Engineering Energy: Unconventional Gas Production. Report for the Australian Council of Learned Academics (Cook et al., 2013)
Hydraulic fracture growth			
F.1	Hydraulic fracture growth into aquifer	Unlikely	"In important Australian basins such as the Cooper-Eromanga Basin, in addition to surface aquifers, shale gas wells (like conventional gas wells) pass through deep aquifers of the Great Artesian Basin. To minimise the risk to this vital groundwater resource, best practice should be adopted in both well integrity and the use of [remote] sensing technology to accurately and closely monitor the hydraulic fracturing process, particularly the potential for extended vertical growth of fractures." p25 "…it is difficult to propagate a fracture further than a few tens of metres, other than where a transmissive fault is intersected." p125 "Microseismic monitoring of shale gas operations will not provide the location or transmissibility of all fractures." p135
F.2	Hydraulic fracture growth into well	Not assessed	
F.3	Hydraulic fracture growth into fault	Unlikely	"These few events have been linked to the intersection of active fault structures by hydraulic fractures. Best practice mitigation involves the identification and characterisation of local fault structures, avoidance of fracture stimulation in the vicinity of active faults, real-time monitoring and control of fracture growth through available sensing technologies and the establishment of 'cease-operation' triggers based on prescribed measured seismicity levels. Such best practice approaches will need to be utilised in Australia." p25 "Faults can connect deep shale reservoirs to aquifers and the intersection of faults by high pressure fluid from either hydraulic fracturing, or the disposal of large volumes of produced water from shale gas plays via deep injection in wastewater wells requires caution with regard to aquifer contamination and induced seismicity, respectively." p61

			"There may also be a risk of propagating fractures towards the aquifers of the GAB along pre-existing faults (Report to this Review Cooke, 2013) though it is difficult to propagate a fracture further than a few tens of metres, other than where a transmissive fault is intersected." p125
Compromised well integrity			
W.1	Well rupture or failure across barriers	Rare	"Contamination can also potentially occur via leakage from a borehole into a freshwater aquifer, due to borehole failure, particularly from abandoned bores, or (though less likely) from an incorrect hydraulic fracturing operation." p16 "These are unlikely to occur if best practice is followed, but regulations need to be in place and enforced, to help to ensure this." p16 "Contamination of freshwater aquifers can occur due to accidental leakage of brines or chemically-modified fluids during shale gas drilling or production; through well failure; via leakage along faults; or by diffusion through over-pressured seals." p24 "At the moment there appears to be a lack of comprehensive data and analysis on the matter upon which a judgement can be formulated or even an agreed definition of what constitutes a "failed" well." p128
W.2	Migration along casing from reservoir	Not assessed	"As a summary, the key risks relate to on-site spills and well integrity issues induced by the hydraulic fracturing process, with the highest frequency risk being emissions of methane." p61 "There is also a need to research the applicability of emerging techniques such as fibre optics to long term downhole monitoring of well integrity." p181
W.3	Migration along casing between rock layers	Unlikely	
W.4	Migration along decommissioned/ abandoned wells	Unlikely	"There are effective regulations in place covering abandonment for conventional gas wells, but shale gas regulations will need to take account of the fact that there could be hundreds of abandoned wells, many of them penetrating major aquifers; long term monitoring will be needed." p28 "Well abandonment is not just a regulatory issue but is also an issue that requires more research and development in areas such as the very long-term behaviour of cements and extended monitoring under hostile subsurface conditions." p29 "The very long-term integrity of a cemented and plugged abandoned well (beyond 50 years) is a topic where more information will be essential. Cement and steel do not have the very long-term integrity of geological materials. If shale gas fields develop to the size and extent in Australia as in the United States, there will be a legacy of abandoned gas wells, which will need to retain integrity if we seek to avoid connections across stratigraphy over many thousands of metres, including confined aquifers and strata of water-bearing material with very different chemistry." p128 "The Expert Working Group found it difficult to obtain information on long term well integrity and on the rate of well failure. It concluded that there is a

			need to study well integrity in Australia, in conjunction with industry, in order to confirm whether or not this is a major issue for the shale gas industry in the longer term." p181 "Associated with this issue is that of abandoned wells, including both the issue of well remediation to avoid contamination of aquifers and of orphan wells. This issue is not yet a major problem in Australia, but in time it is **likely to become one**. There is a need for Australian and international industry, governments and researchers, to jointly study the issue in order to establish a way forward." p181
W.5	Loss of well control	Not assessed	

2.4 Qualitative review of the findings from: *Shale gas extraction in the UK: a review of hydraulic fracturing* (The Royal Society and The Royal Academy of Engineering, 2012)

Background and scope

The UK Government's Chief Scientific Adviser asked the Royal Society and the Royal Academy of Engineering to carry out an independent review of the scientific and engineering evidence relating to the technical aspects of the risks associated with hydraulic fracturing to inform government policymaking about shale gas extraction in the UK.

The Terms of Reference of this review were:

- What are the major risks associated with hydraulic fracturing as a means to extract shale gas in the UK, including geological risks, such as seismicity, and environmental risks, such as groundwater contamination?
- Can these risks be effectively managed? If so, how?

This report has analysed environmental and health and safety risks. Climate risks have not been analysed. The risks addressed in this report are restricted to those associated with the onshore extraction of shale gas. The subsequent use of shale gas has not been addressed.

Study area

Shale gas in the United Kingdom

Authors

The Royal Society and The Royal Academy of Engineering

Key findings

Risks associated with hydraulic fracturing for shale gas can be managed effectively in the UK if operational best practices are implemented and enforced through regulation.

The available evidence indicates that the risk of fractures propagating from shale formations to reach overlying aquifers is very low provided that shale gas extraction takes place at depths of many hundreds of metres or several kilometres.

Ensuring well integrity must remain the highest priority to prevent contamination.

Monitoring should be carried out before, during and after shale gas operations to inform risk assessments. Methane and other contaminants in groundwater should be monitored, as well as potential leakages of methane and other gases into the atmosphere. The geology of sites should be characterised and faults identified. Monitoring data should be submitted to the UK’s regulators to manage potential hazards, inform local planning processes and address wider concerns.

Monitoring of any potential leaks of methane would provide data to assess the carbon footprint of shale gas extraction.

Qualitative review of the report findings for each impact mode

A qualitative review of the findings from The Royal Society and The Royal Academy of Engineering (2012) has been undertaken though analysis of key excerpts from the text. The qualitative review (based on the likelihood descriptions in Table 4 and Table 5) provides a likelihood score for each impact mode. The likelihood score for each impact mode with related supporting excerpts are shown below in Table 9.

Table 9 Excerpts from The Royal Society and The Royal Academy of Engineering (2012) related to each impact mode

	Impact Mode	Likelihood score	Key excerpts from: *Shale gas extraction hydraulic a review of in the UK: fracturing* (The Royal Society and The Royal Academy of Engineering, 2012)
Hydraulic fracture growth			
F.1	Hydraulic fracture growth into aquifer	Rare	"The available evidence indicates that the risk of fractures propagating from shale formations to reach overlying aquifers is very low provided that shale gas extraction takes place at depths of many hundreds of metres or several kilometres." p4 "Geological mechanisms constrain the distances that fractures may propagate vertically." p4 "Even if communication with overlying aquifers were possible, suitable pressure conditions would still be necessary for contaminants to flow though fractures." p4
F.2	Hydraulic fracture growth into well	Not assessed	
F.3	Hydraulic fracture growth into fault	Unlikely	"Recommendation 3: To mitigate induced seismicity: BGS or other appropriate bodies should carry out national surveys to characterise stresses and identify faults in UK shales. Operators should carry out site-specific surveys to characterise and identify local stresses and faults." p6
Compromised well integrity			
W.1	Well rupture or failure across barriers	Not assessed	
W.2	Migration along casing from reservoir	Rare	"More likely (than fracture growth into aquifer) causes of possible environmental contamination include faulty wells." p4 "Ensuring well integrity must remain the highest priority to prevent contamination." p4 "The probability of well failure is low for a single well if it is designed, constructed and abandoned according to best practice." p4 "Recommendation 2 To ensure well integrity: • Guidelines should be clarified to ensure the independence of the well examiner from the operator. • Well designs should be reviewed by the well examiner from both a health and safety perspective and an environmental perspective.

			• The well examiner should carry out onsite inspections as appropriate to ensure that wells are constructed according to the agreed design. • Operators should ensure that well integrity tests are carried out as appropriate, such as pressure tests and cement bond logs." p6 & p27 "The results of well tests and the reports of well examinations should be submitted to the Department of Energy and Climate Change (DECC)." p6 & p27
W.3	Migration along casing between rock layers	Not assessed	
W.4	Migration along decommissioned/ abandoned wells	Unlikely	"Risks should be assessed across the entire lifecycle of shale gas extraction, including risks associated with the disposal of wastes and abandonment of wells." p5 "Recommendation to detect groundwater contamination: Arrangements for monitoring abandoned wells need to be developed. Funding of this monitoring and any remediation work needs further consideration." p6
W.5	Loss of well control	Not assessed	

2.5 Qualitative review of the findings from: Drilling for Oil and Gas in New Zealand: Environmental Oversight and Regulation; (Wright, 2014)

Background and scope

Analysing the system of laws, agencies, and processes that oversee and control onshore oil and gas extraction. At the end of the report, recommendations on addressing weaknesses in the system are made

Study area

New Zealand

Authors

Jan Wright

Key findings

The impacts of an individual well are generally small – it is the cumulative effect of many wells on the landscape, on the risk to groundwater, and so on, that matters most.

The biggest issue is not a local environmental effect, but the global effect of climate change.

While there were specific concerns about the impacts of fracking itself, most of the concern was about what fracking enables – that is, the expansion of the onshore oil and gas industry within and beyond Taranaki, and all that might come with this.

Qualitative review of the report findings for each impact mode

A qualitative review of the findings from Wright (2014) has been undertaken though analysis of key excerpts from the text. The qualitative review (based on the likelihood descriptions in Table 4 and Table 5) provides a likelihood score for each impact mode. The likelihood score for each impact mode with related supporting excerpts are shown below in Table 10.

Table 10 Excerpts from Wright (2014) related to each impact mode

	Causal Pathway	Likelihood score	Key excerpts from: Drilling for Oil and Gas in New Zealand: Environmental Oversight and Regulation; (Wright, 2014)
Hydraulic fracture growth			
F.1	Hydraulic fracture growth into aquifer	Not assessed	
F.2	Hydraulic fracture growth into well	Not assessed	
F.3	Hydraulic fracture growth into fault	Not assessed	
Compromised well integrity			

W.1	Well rupture or failure across barriers	Rare	"A well leaking into the Heretaunga aquifer or groundwater in the Poverty Flats could be very damaging, although it is unlikely." p7
W.2	Migration along casing from reservoir	Rare	"Ensuring the wells have what the industry calls 'integrity' is vital for protecting the health and safety of the workers at the well site, as well as protecting the environment. The updated Petroleum Exploration and Extraction Regulations put into effect last year are a great improvement in this area, but there is a need to ensure that the well is cased adequately when it passes through freshwater layers." p7
W.3	Migration along casing between rock layers	Not assessed	
W.4	Migration along decommissioned / abandoned wells	Unlikely	"In particular, it is not enough to abandon wells and assume they will never leak. In Canada, well operators pay a levy into a fund that is then available for cleaning up any contamination in the future. Such a fund can also be used to pay for monitoring the environment – necessary for detecting contamination. Monitoring is a recurring theme in the report, with New Zealand clearly out of step with international 'best practice'." p7
W.5	Loss of well control	Not assessed	

2.6 Qualitative review of the findings from: *Environmental impacts of shale gas extraction in Canada* (Council of Canadian Academies, 2014)

Background and scope

The Council of Canadian Academies was asked by the federal Minister of Environment to assemble an expert panel to assess the state of knowledge about the impacts of shale gas exploration, extraction, and development in Canada.

In response, the Council recruited a multidisciplinary panel of experts from Canada and the United States to conduct an evidence-based and authoritative assessment supported by relevant and credible peer reviewed research. As with all Council panels, members were selected for their experience and knowledge, not to represent any particular stakeholder group.

The report does not include recommendations, since policy prescription falls outside the Council's mandate.

Study area

Canada

Authors

John Cherry, FRSC (Chair), Michael Ben-Eli, Lalita Bharadwaj, Richard Chalaturnyk, Maurice B. Dusseault, Bernard Goldstein, Jean-Paul Lacoursière, Ralph Matthews, Bernhard Mayer, John Molson, Kelly Munkittrick, Naomi Oreskes, Beth Parker and Paul Young.

Key findings

The rapid expansion of shale gas development in Canada over the past decade has occurred without a corresponding investment in monitoring and research addressing the impacts on the environment, public health, and communities.

Regional differences are essential to understanding these environmental impacts of shale gas development.

Assessment of environmental impacts is hampered by a lack of information about many key issues, particularly the problem of fluids escaping from incompletely sealed wells.

Because groundwater flow is slow, it can take decades or longer for contamination by recalcitrant chemicals to become a recognised problem.

However, the mere existence of a conduit is not enough to contaminate potable groundwater as there also needs to be sufficient and sustained pressure to push the contaminating fluid to a height where it could overcome the hydraulic head of the freshwater zone. Gas rather than brine and flowback water is the more likely cause of contamination of the Fresh Groundwater Zone

(FGWZ) from below. Because they are buoyant and an upward gradient in fluid pressure is present, gases will behave differently here than saline water or hydraulic fracturing fluids.

Even if baseline data did exist, it would not be possible to clearly differentiate contamination through natural pathways from that caused by previous or current drilling activities, leaky well casings, or from active fracturing. Without good baseline data, the task is immensely more difficult.

There is reason to believe that shale gas development poses a risk to water resources, but the extent of that risk, and whether substantial damage has already occurred, cannot be assessed because of a lack of scientific data and understanding.

The main potential cause of groundwater contamination is expected to be from upward gas migration along well casings or in combination with natural fractures causing entry of gas over extended time into freshwater aquifers or into the atmosphere.

Qualitative review of the report findings for each impact mode

A qualitative review of the findings from Council of Canadian Academies (2014) has been undertaken though analysis of key excerpts from the text. The qualitative review (based on the likelihood descriptions in Table 4 and Table 5) provides a likelihood score for each impact mode. The likelihood score for each impact mode with related supporting excerpts are shown below in Table 11.

Table 11 Excerpts from Council of Canadian Academies (2014) related to each impact mode

	Impact Mode	Likelihood score	Key excerpts from: *Environmental impacts of shale gas extraction in Canada* (Council of Canadian Academies, 2014)
Hydraulic fracture growth			
F.1	Hydraulic fracture growth into aquifer	Rare	“No comprehensive study in Canada has defined the depth of the bottom of the FGWZ [Fresh Groundwater Zone], which varies from region to region. A general estimate is between 100 and 300 metres below land surface, although it may be as deep as 500 to 600 metres.” p62 “Non-peer reviewed literature commonly states that no impacts have been proven or verified. For example, the American Water Works Association’s White Paper on Water and Hydraulic Fracturing states: “At this time, AWWA is aware of no proven cases of groundwater contamination directly attributable to hydraulic fracturing” [cited as AWWA, 2013 in Council of Canadian Academies, (2014)].” p66 “Jackson et al., (2013) provide a much more nuanced statement of this generalization: ‘There is no evidence that fracture propagation out-of-zone to shallow groundwater has occurred from deep (>1,000 metre) shale gas reservoirs, although no scientifically robust groundwater monitoring to detect gas migration has been attempted to our knowledge.’” p67 “Vidic et al. (2013) summarize this controversy as follows: ‘Since the advent of hydraulic fracturing, more than 1 million hydraulic fracturing treatments have been conducted, with perhaps only one documented case of direct groundwater pollution resulting from injection of hydraulic fracturing chemicals used for shale gas extraction. Impacts from casing leakage, well blowouts and spills of

> contaminated fluids are more prevalent but have generally been quickly mitigated. However, confidentiality requirements dictated by legal investigations, combined with the expedited rate of development and the limited funding for research, are substantial impediments to peer-reviewed research into environmental impacts.'" p67

"[three issues where]… private well owners who have claimed that shale gas or other oil and gas industry affected their wells have had their claims settled, their water supply replaced, and their losses compensated (Dutzik et al., 2012; Vidic et al., 2013)…

(i) sufficient data to evaluate the claims (for and against) of contamination related to hydraulic fracturing have not been collected;

(ii) sufficient data to understand the various possible pathways of contamination that may occur in the future have not been collected; and

(iii) the time frame to judge potential long-term, cumulative impacts has been inadequate." p67

"Hydraulic fracturing and other shale gas extraction activities may create or enhance preferential pathways for gas and saline waters to move upward more actively through the Intermediate Zone into the FGWZ." p73

"…the movement of the more buoyant natural gas through fractured sedimentary rock following its release by hydraulic fracturing has not yet been rigorously analyzed or assessed." p74

"…large volume of liquids used in a single shale gas well during fracturing (as much as 80,000,000L)… raises the concern that any induced fractures could breach the overlying geological strata and interact directly with shallow aquifers via existing faults and fracture zones (Myers, 2012; Gassiat et al., 2013)." p78

"Industry has maintained that the risk of hydraulic fracturing creating vertical conduits that would communicate with, and therefore contaminate, shallow groundwaters is extremely small for deep wells (i.e., those greater than about 1.0 kilometre)." p79

"According to Fisher and Warpinski, (2012):

> 'Under normal circumstances, where hydraulic fractures are conducted at depth, there is no method by which a fracture is going to propagate through the various rock layers and reach the surface. This fact is observed in all of the mapping data and is expected based on the application of basic rock-mechanics principles deduced from mineback, core, lab, and modelling studies.'" p79

"Generally, the Panel accepts the above statement as likely, provided that the qualifier, **great depth**, is included. However, the Panel notes that this is a largely empirical belief based on microseismic measurements and geomechanical considerations, rather than on more definitive types of measurement. The literature does not specify the minimal depth at which hydraulic fracturing is too risky to undertake. Nor does it specify what data and analysis are needed to determine if conditions are too risky to proceed." p79

F.2	Hydraulic fracture growth into well	Unlikely	“According to the B.C. Oil and Gas Commission (2010a), 18 known fracture communications have occurred in British Columbia alone, and the AER has records of about 20 such cases in Alberta [cited as Eynon, (2012) in Council of Canadian Academies, (2014)] taking place before the Innisfail event in 2012 [Energy Resources Conservation Board, 2012a]. That event was caused by an operator drilling a horizontal well too close (about 130 metre) to a producing well. The hydraulic fracture stimulation in the horizontal well caused fluids to discharge at the surface around the pump jack of the producing well [Energy Resources Conservation Board, 2012a]. This type of communication can lead to the unintended discharge of water, gas, mud, or sands into FGWZ and Intermediate Zone aquifers and onto the surface.” p82
F.3	Hydraulic fracture growth into fault	Unlikely	“Thus it is necessary to increase understanding of natural brine migration so as to evaluate brine mobilization and redistribution in areas of shale development.” p69 “Whereas the contaminative potential of the Intermediate Zone is likely much greater than that of the shale gas zone, the extent of fractures connecting to natural pathways or boreholes or seals has not been rigorously confirmed with field performance assessments and it likely varies by region.” p69 “It is now understood that the volume of the rock mass that is affected by a fracturing operation can be far larger than the volume of rock reached by the proppant itself. This effect arises because the volumetric strains in the region close to the fracturing point cause stresses in the rock mass, and the high injection pressure reduces the frictional strength along natural joints. These processes lead to wedging open of more distant fractures and shear displacement across natural fractures. Because a natural fracture is a rough surface, if it is displaced by as little as millimetres, it will no longer fit together snugly when the active fracturing pressure dissipates during the flowback period. This shear dilation leads to enhanced flow capacity (i.e., transmissivity) of the naturally fractured reservoir, opening up minute flow paths far from the proppant zone but still within the shale reservoir (Dusseault and Jackson, 2014).” p78
Compromised well integrity			
W.1	Well rupture or failure across barriers	Rare	“Only one documented case exists of a shallow aquifer becoming contaminated with hydraulic fracturing fluids, most likely as result of human error (Energy Resources Conservation Board, 2012b). This event took place during a stimulation of a shale gas reservoir in Alberta and was due to the accidental injection of hydraulic fracturing fluids directly into sandstone at a depth of 136 metres when the operators believed they were fracturing at about 1.5 kilometres.” p82
W.2	Migration along casing from reservoir	Unlikely	“Leaky wells due to improperly placed cement seals, damage from repeated fracturing treatments, or cement deterioration over time, have the potential to create pathways for contamination of groundwater resources and to increase GHG emissions.” pES-xiii “Several factors make the long-term impact related to leakage greater for shale gas development than for conventional oil and gas development. These are the larger number of wells needed for shale gas extraction; the diverse chemicals used in hydraulic fracturing operations; the potential development of shale gas resources in rural and suburban areas that rely on groundwater resources; and possibly the repetitive fracturing process itself.” pES-xiii “The greatest threat to groundwater is gas leakage from wells for which even existing best practices cannot assure long-term prevention. The degree to

			which natural assimilation capacity can limit the impacts of well leakage is site specific due to variability in the magnitude of natural gas fluxes (or loadings) and aquifer hydro-geochemical compositions. These potential impacts are not being systematically monitored, predications remain unreliable, and approaches for effective and consistent monitoring need to be developed." pES-xiv "Consequently, the most likely pathway for gas to seep from the Deep Zone and/or the Intermediate Zone to the FGWZ is via this annular pathway." p80 "Even if impermeable caprocks did exist above a shale gas reservoir, seepage via leaky well seals and abandoned wells and fluid flow along faults could bypass otherwise low permeability rock strata or displace fluids in the Intermediate Zone. The risks of such events are both variable and poorly quantified. They need to be carefully considered, particularly near wetlands, in populated areas served by domestic wells, and in near-urban areas that may have abandoned wells." p97
W.3	Migration along casing between rock layers	Unlikely	"If wells can be sealed, the risk to groundwater is expected to be minimal, although little is known about the mobility and fate of hydraulic fracturing chemicals and wastewater in the subsurface. The pertinent questions are difficult to answer objectively and scientifically, either because the relevant data have not been obtained; because some relevant data are not publicly available; or because existing data are of variable quality, allow for divergent interpretations, or span a wide range of values with different implications." pES-xiii "…one of the most probable pathways for leakage is from the Intermediate Zone along the annulus between the cement seal and the rock into the FGWZ." p70 "Existing cases of groundwater contamination due to upstream oil and gas activities have typically been caused by gas on account of its buoyancy and in situ pressure gradient. Brine or saline water are dense and not prone to migrating upwards along a well column or through fractured rock except from rare, over-pressurized zones." p70 "…in Bainbridge Township, Ohio, [a well integrity failure was observed] following hydraulic fracture stimulation of the Clinton sandstone [cited as Bair et al. (2010) in Council of Canadian Academies, (2014)]. Because of poor cement completion and the possible effect of the stimulation on the cement sheath, shutting in of the annular space between the production casing and rock led to over-pressurization of this space and the vertical migration of natural gas up the well. The gas escaped into the Berea sandstone aquifer and contaminated local water wells." p81 "Behind-the-casing pathways of gas leakage are often difficult to detect using standard geophysical logging tools (e.g., cement bond logs). Although improved logging tools are becoming available, they are fairly expensive to use (at least $30,000 per well) and may not be required by regulations." p84
W.4	Migration along decommissioned / abandoned wells	Unlikely	"A risk to potable groundwater exists from the upward migration of natural gas and saline waters from leaky well casings, and possibly also natural fractures in the rock, old abandoned wells, and permeable faults." pES-xiii "Information concerning the impacts of leakage of natural gas from poor cement seals on fresh groundwater resources is insufficient. The nature and rate of cement deterioration are poorly understood and there is only minimal

			or misleading information available in the public domain. Research is also lacking on methods for detecting and measuring leakage of GHGs to the atmosphere." pES-xvi "Because intense development in most shale gas plays has been taking place for less than 20 years, questions about the longer-term cumulative effects cannot yet be answered." p68 "Schlumberger states: "public data suggests that there are +18,000 leaking wells in Alberta" [cited as Bexte et al., (2008) in Council of Canadian Academies, (2014)]." p80 "Gas leakage pathways may result because of difficulties in positioning the cement or because the cement deteriorates over time. In many cases, there is no requirement to cement off thin gassy formations in the Intermediate Zone." p84
W.5	Loss of well control	Not assessed	

References contained within Table 11 Excerpts from Council of Canadian Academies (2014) related to each impact mode

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2.7 Qualitative review of the findings from: *Report of the Nova Scotia Independent Panel On Hydraulic Fracturing* (Atherton et al., 2014)

Background and scope

The mandate for the review was to: create a panel of technical experts based on input from the public and hire technical consultant(s) to facilitate the work of the panel; hire a part-time project administrator; conduct public consultations on the process of hydraulic fracturing with online tools and face-to-face meetings with stakeholders; and conduct a literature review on the health and socio-economic impacts of hydraulic fracturing. These activities would result in a final report to the Government of Nova Scotia with recommendations on the potential of hydraulic fracturing to develop unconventional gas and oil resources in the Province.

Study area

Nova Scotia, Canada

Authors

Frank Atherton, Michael Bradfield, Kevin Christmas, Shawn Dalton, Maurice Dusseault, Graham Gagnon, Brad Hayes, Constance MacIntosh, Ian Mauro, Ray Ritcey, David Wheeler (Chair)

Key findings

The mandate was to conduct public consultations on the process of hydraulic fracturing with online tools and face-to-face meetings with stakeholders; and conduct a literature review on the health and socio-economic impacts of hydraulic fracturing.

The study concluded that it is a relatively straightforward task to establish good well integrity regulatory practices (guidelines and enforcement), quality control, and monitoring to ensure that potential sites are geologically understood, that wells are properly installed, and that well abandonment is done according to regulatory requirements. However, this is not a risk-free activity and hence the establishment of an appropriate monitoring and regulatory system would clearly be needed if large-scale unconventional oil and gas resource development were ever to take place.

Unconventional gas and oil development, using modern cementing and completion techniques, usually leads to good wellbore integrity.

In the case of hydraulic fracturing and its associated activities and technologies, we can safely say that proper application of a precautionary approach means that the burden of proof on avoiding public harm rests with developers and those governments (i.e. federal, provincial, municipal and Aboriginal governments) that may wish to pursue the possible application of the technology in the future.

Water quality and quantity concerns are regularly cited as the top issues for the public in considering the potential impacts of hydraulic fracturing.

Risk management plans need to consider the safety of the industrial process itself and the development of water safety plans for the protection of neighbouring groundwater and surface water systems. The latter water safety plans would ensure that chemicals used by the industry are publicly declared and appropriate monitoring programs and risk mitigation programs are designed and available for public scrutiny.

The best guarantee against future leaky well problems is a high-quality initial well installation (primary cementation); so, attention should be paid to well casing and cementing. Although well cementing does not have to take place under direct supervision of a professional engineer, it is important to verify that the appropriate materials and procedures are used and that the installed well meets mandated performance criteria (pressure tests, bond log quality). In this way, future issues relating to well integrity and risks of interaction with shallow aquifers are reduced.

Nevertheless, as in any complex industrial activity, there will always be some cases where sealing of all leakage pathways for the entire life of the well, including the post-decommissioning period, is not achieved.

There is a great deal of indirect evidence suggesting that gas leaking into groundwater wells is not a major public health issue. Much of this indirect evidence is a general lack of morbid effects noted despite many hundreds of thousands of known cases of naturally occurring methane seepage into water wells around North America.

An example of a recent survey of wells above an American oilfield (Wattenburg, CO) that has been active since 1970 and has more than 19,000 producing wells and more than 7,500 decommissioned wells was published in early 2014 (Li and Carlson, 2014) The study found that in a sample of 223 groundwater wells, a number of which were resampled over a period of five years, 78% had dissolved methane. The occurrence of methane did not correlate with proximity to energy wellbores, and the methane was found to be more than 98% of biogenic (shallow) origin, therefore, not from thermogenic sources (deep, from the intermediate or the producing zone). Even for the few cases where the gas was of thermogenic origin, the specific pathway (natural or man-induced) could not be deduced.

In contrast, some work has shown that methane found in groundwater wells in certain areas in Pennsylvania is somewhat correlated to the distance from recent energy wells drilled in the five- to six-year period before the study was done (R. B. Jackson et al., 2013). Specifically, methane occurrences in groundwater wells were found to be statistically more common nearer to energy wells in this region, although the authors did not prove that the methane actually came from the proximal energy wells.

The results are reminders that vigilance is needed, baseline data must be established (it is too late in many oil and gas areas to collect true baseline data), and careful scientific analysis performed before wide-sweeping conclusions about well integrity, groundwater contamination, and gas migration pathways can be drawn.

Good quality data on the composition and geochemical nature of the gases is collected through what is referred to as "mud-gas logging," which is the collection of samples of gas released from the rocks during drilling (Rowe and Muehlenbachs, 1999). Energy companies regard this information as strategic, of economic interest, and, therefore, confidential. Means can easily be established within a regulatory framework to store this data and make it available under controlled conditions when claims are made related to fugitive gas emissions.

Three known significant consequences exist: contamination of groundwater, turning it unpalatable; escape of natural gas to the atmosphere, where it has a greenhouse gas effect; and direct safety risk associated with potential explosion of an accumulation of gas in a confined space. Although not desirable, groundwater souring is not a serious public health issue because methane itself is not toxic.

The science regarding contamination of well water from hydraulic fracturing is controversial and inconclusive. Two US studies indicate homes within one kilometre of unconventional gas production may be six times more likely than homes further away to be contaminated with stray gases such as methane, methane, and propane (R. B. Jackson et al., 2013; Vengosh et al., 2013). Contrasting studies suggest stray gases are naturally occurring in aquifers and cannot be definitively linked with unconventional gas activities (Molofsky et al., 2013; Baldassare, McCaffrey and Harper, 2014).

Qualitative review of the report findings for each impact mode

A qualitative review of the findings from Atherton et al. (2014) has been undertaken though analysis of key excerpts from the text. The qualitative review (based on the likelihood descriptions in Table 4 and Table 5) provides a likelihood score for each impact mode. The likelihood score for each impact mode with related supporting excerpts are shown below in Table 12.

Table 12 Excerpts from Atherton et al. (2014) related to each impact mode

	Impact Mode	Likelihood score	Key excerpts from: *Report of the Nova Scotia Independent Panel On Hydraulic Fracturing* (Atherton et al., 2014)
Hydraulic fracture growth			
F.1	Hydraulic fracture growth into aquifer	Rare	"In Nova Scotia, drinking water aquifers are usually less than 150 m below the surface [cited as 'J. Drage, personal communication February 04, 2014' in Atherton et al. (2014)]. The target zone for unconventional gas and oil exploration in the Horton formation, a bedrock formation within the sedimentary grouping where the hydraulic fracturing could occur, is between 900 and 1,500 m below the surface [cited as Ryder Scott (2008) in Atherton et al. (2014)]." p178 "Due to the compressive stress of the weight of the soil and rock (or lithostatic stress) that exists at the depth of these geological formations (such as the Horton formation), the fractures generated by hydraulic fracturing typically extend approximately 100 m vertically and approximately 200 - 300 metres laterally (King, 2012)." p179 "Therefore, the fractures could be hundreds of metres away from the underside of the aquifer. Flewelling and Sharma, (2014), conducted a numerical analysis and literature review and found that where upward flow occurs within the fracture, both permeability and flow rates are low

			and therefore, timescales for transport are long. The authors estimated the travel time would be on the order of 105 to 108 years to travel across a 100 metres thick layer (Flewelling and Sharma, 2014). In contrast to this study, others (e.g., Myers 2012) have suggested shorter time scales for vertical flow, based on modeling under case specific conditions." p178 "…based on current knowledge and documented evidence, it is anticipated that flow through the fractures would not likely extend from the shale to the aquifer and thus direct contamination from hydraulic fracturing fluids would appear less likely than other pathways (e.g., accidental spills; well bore stability)." p178 "Once gas production begins, pressure drops and gas and fracturing fluids tend to migrate towards the wellbore, rather than to the surface by some undefined pathway (Council of Canadian Academies, 2014)." p178 "…it is recognized that the risk to water quality from unconventional gas and oil operations is more related to operational practices (e.g. chemical handling or waste management), rather than the fracturing and extraction process." p178 "…has triggered much concern among stakeholders (see Chapter 8). However, there is apparently no known case of fracturing liquids or gas migration from the target horizon directly up through the rock mass to the surface or into shallow aquifers during or after well stimulation (Council of Canadian Academies, 2014). A typical induced fracture height may range from tens of metres to perhaps several hundred metres, whereas the well interval fractured is 1.5 to 4 kilometres deep. Monitoring of the active fracturing process for hydraulic fracture rise shows that induced fracturing terminates in the zone just above the target formation and induced fractures do not rise a thousand metres or more to the surface (Fisher and Warpinski, 2012). There are many reasons why this should be the case, but perhaps the most important one is that to double the height of an induced hydraulic fracture, one must pump in about eight times the liquid,9 and this is not done because there is no economic incentive to propagate fractures into the non-productive strata above the target formation. Thus, Pathway 1 remains speculative and extremely unlikely, compared to other pathways. It can reasonably be judged to be of far less interest than other pathways in the context of possible onshore Nova Scotia oil and gas development." p208
F.2	Hydraulic fracture growth into well	Unlikely	"…fluid migration up an offset well during hydraulic fracturing, has happened at least once in practice in Canada. In 2012, injected fluids rose to the surface in an offset legacy well producing from the same formation during active fracturing of a horizontal well north of Calgary, AB. This incident caused the Alberta Energy Regulator (AER) to initiate and publish a detailed study of the event (Energy Resources Conservation Board, 2012) and also led to the issuance of new guidelines to reduce the probability of such an incident in the future (AER, 2013)." p208-209 "…the presence of nearby active or legacy wells must be considered during planning for drilling and well stimulation in order to preserve the integrity of the offset wells." p209 "Fluid migration is not the same as a detectable pressure pulse. High pressure fracturing operations can create a pressure response some

			distance away, certainly hundreds of meters in some cases, but because water is relatively incompressible, a pressure response can be detected at great distance and is not proof that a breaching of a barrier has taken place by direct flow of significant volumes of fluid." p217
F.3	Hydraulic fracture growth into fault	Not assessed	
Compromised well integrity			
W.1	Well rupture or failure across barriers	Very rare	"…regulations tend to stipulate performance goals, as determined by measurements, such as a measurement of casing string pressure integrity before it is cemented into place [cited as (British Columbia Oil and Gas Commission, 2014) in Atherton et al. (2014)]. A properly assembled casing string has adequate pressure integrity for its entire length, and this integrity is tested to meet regulatory standards before well assembly is complete" p200 "The high alkalinity of the cement also protects the steel casing from deterioration if there are acidic gases in the formation such as carbon dioxide (CO_2) or hydrogen sulphide (H_2S) dissolved in the water." p201
W.2	Migration along casing from reservoir	Rare	"Osborn et al., (2011) while studying methane occurrence in shallow Pennsylvania groundwater wells, ruled out migration through the shale formation as a possible explanation for methane occurrence in groundwater wells. The authors cited leaky well casings and naturally occurring methane as more likely scenarios for methane occurrence (Osborn et al., 2011)." p178 "…improper well construction, which allows hydraulic connection of deeper strata and the shallower drinking water aquifer that drilling operations pass through, is an important consideration" p179 "…unconventional gas and oil development, using modern cementing and completion techniques, usually leads to good wellbore integrity." p194 "However, as in any industrial activity, there will never be 100 per cent success in sealing all wellbores against all possibilities of any future leakage." p194 "Generally, the intermediate casing string is cemented all the way to surface in modern practice." p201 "The goal is to achieve a continuous, effective seal between the casing and the rock mass or between the current casing and the previous casing, so that the steel-cased wellbore has full pressure integrity along its entire length for the period of time it will be operational and for the range of conditions it will experience (Dusseault, Jackson and MacDonald, 2014)." p202 "Use of additives is typically not mandated or controlled by the regulatory agency; it is the responsibility of the owner of the well to ensure that appropriate cement formulations and additives are used in the conditions encountered so that the energy well is properly sealed, ready for service, and resistant to impairment." p204 "Because a reservoir is depleted by production, the fluid pressure in the target horizon is reduced over time to much lower values than in the fluids above the reservoir. This inhibits gas migration and acts against

			development behind the casing of a continuous buoyant gas column having its origin in the producing formation.... would be of limited concern in Nova Scotia, providing that good quality assurance of the primary cementing operation is maintained." p209
W.3	Migration along casing between rock layers	Rare	"One of the major wellbore integrity issues in the unconventional gas and oil industry is related to gas migration (or 'stray gas') outside of the production casing, up around the surface casing shoe, and interacting with shallow groundwater or venting to the surface (Dusseault, Gray and Nawrocki, 2000; Watson and Bachu, 2009)." p206 "SCVF[1] data must be registered with the regulatory agency; for example, the AER keeps records of all occurrences; therefore, there are excellent statistics available in this area, in contrast to gas migration behind casing, where there are data or observed incidents, but data based on surface observations only are insufficient to draw strong quantitative conclusions about the overall rate of well leakage." p206 "...the buoyancy of the gas leads to slow seepage, perhaps into shallow aquifers or to the surface where methane enters the atmosphere." P209 "In Nova Scotia, because there are probably none or few intermediate-depth gas-bearing zones, except in the coalbeds of the northern part of the province, these two pathways might be expected to be far less frequent and problematic compared to some other jurisdictions, such as eastern Alberta and western Saskatchewan, where there may be a half-dozen thin gas sands at depths of 200 to 1000 m, i.e., below the surface casing shoe but above the producing zone (Erno and Schmitz, 1996)." p209 "...there is good evidence that a significant percentage (from a few to as many as 10 per cent – Bexte et al., 2012[2]) of oil and gas wellbores in some areas in Canada experience gas migration (Dusseault and Jackson, 2014; Dusseault, Jackson and MacDonald, 2014)." p210 "Once a gas migration event has been identified during operations or at a later date (by the company or a plaintiff), sampling and analysis help reveal the source and give clues about the pathway. It is a standard regulatory requirement that the operator report gas migration events. Once the source is located, perf-and-squeeze operations (see above) can be used to shut the pathway above the source and greatly reduce the chances of further gas seepage." p210 "Although an undesirable event from a greenhouse gas and aesthetic perspective, the impact of methane entering potable water sources is not a serious health issue, in comparison to many other chemical contaminants (Goldstein et al., 2014)." p210 "Gas entering shallow groundwater wells may be a nuisance and can, exceptionally, be an explosion hazard if gas accumulates in poorly ventilated spaces. However, other than making groundwater unpalatable in some cases, no severe health impacts appear to have been recognized at this time..." p210

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[1] Surface Casing Vent Flow

[2] Cited as Bexte et al., (2012) in Atherton et al. (2014) but believed to be Bexte et al., (2008)

W.4	Migration along decommissioned / abandoned wells	Likely	“The most common, long-term well integrity issue after decommissioning is slow gas seepage around the external casing. Such leaks appear not to lead to a major public health threat because methane is not a toxic substance, the number of wells that display high-rate leaks is low, and the overall average leakage rates appear to be low.” p194 “However, the long-term behaviour of cemented wellbores remains of interest because the rates and consequences of gradual steel and cement deterioration at depth remain ill-defined.” p194 “The long-term integrity of wells at a time scale of many decades after decommissioning remains poorly understood; this is an area where further measurements, experiments, and monitoring efforts are needed to evaluate risk and establish means of addressing these risks if they are found to be significant.” p202 “If there is any detectable SCVF, which occurs in perhaps 10-15 per cent of wellbores, or evidence of seepage or loss of pressure integrity between the intermediate string and the production string, remediation must be implemented to reduce such flows to negligible values before the well is sealed.” p211 “Cement bond logs, temperature logs, and noise logs may be used to identify the source of the gas migration to guide the location of the perforating action, and the well will have to be monitored again for SCVF before decommissioning. Several perf-and-squeeze episodes may be required to reduce seepage rates to mandated levels.” p211 “…more publicly available data on the efficacy of practices such as cement squeezing over time are needed.” p211 “Gas migration issues must be fixed when noted, but based on many years of history in Alberta and elsewhere, there is no evidence of major environmental problems arising from the existence of these decommissioned wells at this time.” p212 “There is evidence that the development of slow gas migration can take place years after decommissioning if a buoyant gas column gradually develops behind the casing.” p212 “Liquid seepage is far less probable because liquids are not buoyant.” p213 “…if gas migration is detectable at the surface, there is a high probability, almost a certainty, that some gas is also entering into shallow sandy aquifers behind the surface casing.” p212 “Modern well cementation practices are barely 60 years old, and the lifespan of steel in the ground, perhaps subjected to electro-chemical corrosion (the steel is a good electrode), is not known, nor is it known if gas migration pathways could develop once the casing has corroded and is breached in many places. The products of steel corrosion and cement degradation are solid materials, so energy well deterioration over many decades or centuries will not lead to wide open channels to the surface, but there is a possibility, perhaps small, that additional pathways for slow gas seepage could develop.” p213

			"The most important integrity problem, after wellbore decommissioning, appears to be gas seepage along the outside of casing." p213 "Probably from 1 to 10 per cent of energy wells may be slowly leaking natural gas, most likely sourced from intermediate depth uncommercial gas zones, and such leaks are difficult to detect if they have little or no surface expression." p214 "Suppose that 10% (a high estimate) of the approximately 175,000 decommissioned and suspended energy wells in Alberta are slowly seeping methane at a mean rate of 500 kg/yr (this is a very high estimate); this gives about 9,000 tCH_4/yr, similar to the cattle herd emissions in Nova Scotia and about a third of the CH_4 equivalent of the Lingan plant." p214
W.5	Loss of well control	Rare	"…standard well designs and safety measures would be sufficient to address the small risk of a blowout if overpressures are absent." p199

References contained within Table 12 Excerpts from Atherton et al. (2014) related to each impact mode

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2.8 Qualitative review of the findings from: *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018)

Background and scope

Inquire into the impacts and risks associated with hydraulic fracturing in the NT

To assess and determine:

- the nature and extent of the risks associated with hydraulic fracturing of onshore unconventional shale gas reservoirs and its associated activities on the environmental (aquatic, terrestrial and atmospheric), social, cultural and economic conditions of the NT;
- whether these risks can be mitigated to an acceptable level;
- if they can, by what methodology or methodologies can these risks be mitigated; and
- whether the existing regulatory framework is sufficient to implement these methodologies, and if not, what changes need to be made.

Study area

NT, Australia

Authors

Justice Rachel Pepper, Alan Andersen, Peta Ashworth, Vaughan Beck, Barry Hart, David Jones, Brian Priestly, David Ritchie, Ross Smith

Key findings

It is the Panel's opinion that, provided that all of the recommendations made in this report are adopted and implemented in their entirety, not only should the risks associated with an onshore shale gas industry be minimised to an acceptable level, in some instances, they can be avoided altogether.

Qualitative review of the report findings for each impact mode

A qualitative review of the findings from Pepper et al. (2018) has been undertaken though analysis of key excerpts from the text. The qualitative review (based on the likelihood descriptions in Table 4 and Table 5) provides a likelihood score for each impact mode. The likelihood score for each impact mode with related supporting excerpts are shown below in Table 13.

Table 13 Excerpts from Pepper et al. (2018) related to each impact mode

	Impact Mode	Likelihood score	Key excerpts from: *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018)
Hydraulic fracture growth			
F.1	Hydraulic fracture growth into aquifer	Rare	"…likelihood of fractures growing out of the shale rock region for distances of 1,000 to 3,000 m is extremely low.280 For example, the majority of fractures in the Marcellus shale basin were found to have heights of less than 100 m, although fracture lengths up to approximately 600 m have been recorded." p159 "… the Panel finds that based on the available evidence, the likelihood of contamination of NT groundwaters by the upward migration of contaminated fluids as a result of hydraulic fracturing is 'very low'" p149
F.2	Hydraulic fracture growth into well	Not assessed	"… fractures intersecting with other wells (including active and abandoned wells), are not likely given that there are currently very few deep wells drilled in the NT. However, this is very unlikely to be an issue in the NT given the very low number of deep wells that have been drilled, and moreover, because those that exist are well documented." p159
F.3	Hydraulic fracture growth into fault	Rare	"The only hydraulically plausible opportunity for limited fluid migration along faults is during the intense pressurisation of the actual hydraulic fracturing. However, it is considered that with close monitoring and management of the pressurisation to ensure that only the desired interval is fractured, this scenario can be prevented. Accordingly, there is a low likelihood of aquifer contamination as the result of groundwater flow through faults as the result of, or exacerbated by, hydraulic fracturing." p159 "The Panel has therefore assessed this risk as 'low', given the vertical distance between the fractured rocks and surface aquifers, and the hydraulic potential for flow between fractured rocks and surface aquifers, provided that fracturing operations avoid proximity to faults" p159 "… the occurrence of large faults that can allow vertical connection with the near surface is a risk factor that must be avoided as part of the well design phase." p69
Compromised well integrity			

	Impact Mode	Likelihood score	Key excerpts from: *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018)
W.1	Well rupture or failure across barriers	Rare	"Overall, the Panel concludes that provided a well is constructed to the high standard required for the particular local geology, and provided that it has passed all of the relevant integrity tests prior to, during, and after hydraulic fracturing, there is a 'low' likelihood of integrity issues. There does, however, need to be a program of regular integrity testing during the decades-long operational life of the well to ensure that if problems do develop, they are detected early and remediated quickly (as specified in Recommendation 5.4). In particular, the well must pass a rigorous set of integrity tests prior to being decommissioned because once a well has been abandoned, it is difficult to re-enter it." p81 "The likelihood of a well integrity failure (that is, where all barriers fail), which is required for an actual release of fluids to the environment, is very low, typically less than 0.1%." p64 "The greatest potential for contamination of freshwater aquifers from a leaky well is if the leak occurs in the section of the well where it goes through the aquifer. This can occur as a result of casing failure that occurs when the system is under maximum pressure during the hydraulic fracturing operation. It is this type of failure that has the greatest potential to quickly release large volumes of contaminants directly into the aquifer. The evidence presented in Chapter 5 has shown that the likelihood of this occurring is 'low'." p147
W.2	Migration along casing from reservoir	Rare	"CSIRO found overall that the rate of well integrity failures that have the potential to cause environmental contamination is approximately 0.1%, with several studies finding no well integrity failures." P81 "It is clear that wells are now being increasingly completed to higher standards and are performing much better than those completed to lower standards. In this context, the Panel notes that the Amungee well was a Category 9 well with cement casing along the full length of the well casing to the surface." p147 "There has been considerable effort over the past decade by both the gas industry and regulators in Australia, the US and elsewhere, to improve the design, construction and operation of onshore shale gas wells. … the incidence of these issues has markedly declined as more modern methods of design, construction and regulation are implemented and is now relatively low" p147

	Impact Mode	Likelihood score	Key excerpts from: *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018)
W.3	Migration along casing between rock layers	Unlikely	"The rate for a single well barrier failure, however, was much higher: approximately 1–10%. However, there were very few single barrier failures observed for wells constructed to Category 9 or above, and no well integrity failures for wells built to those categories. The Amungee NW-1H well that was constructed by Origin in the Beetaloo Sub-basin was of Category 9 standard, with casing cemented to surface along the entire length of the well." p81 "A key distinction must also be made between the detection of methane at the surface and/or in groundwater, and the potential for that groundwater to be contaminated by chemicals from the formation water or fracturing fluids, which would cause it to become unsuitable for use for drinking or stock watering, or for general environmental use." p147 "Methane has been detected in groundwater adjacent to shale gas bores in the Denver-Julesburg basin of north-eastern Colorado with a frequency that suggests a low to medium likelihood of occurrence. The most recently published work on this subject concluded that most of this methane was microbially generated and likely to have come from shallow coal seams that occur in the basin, and not from the deep shale gas formations. Only 0.06% of sampled bores contained methane at depth. The reason that methane was able to migrate upwards was because these shallow coal seams had not been effectively sealed off as part of the well construction process, thereby indicating the need for much closer attention to be paid to the identification of and planning for isolation of such sources during the well design phase of operations." p147 "…there was no evidence of contamination of the shallow drinking water wells near active drilling sites from deep brines and/or fracturing fluids, with the concentrations of salts measured in these wells being consistent with the baseline historical water quality data. This conclusion is consistent with other published work." p148 "In summary, therefore, the Panel finds that based on the available evidence … the likelihood of contamination by methane is 'low' to 'medium'. The consequence to water quality (specifically the impact on groundwater used for drinking or stock watering) from the occurrence of methane is rated as 'low' because methane in water is non-toxic. However, the presence of methane above a threshold value (10-28 mg/L) could result in an explosion risk under certain, albeit unlikely, circumstances." p149

	Impact Mode	Likelihood score	Key excerpts from: *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018)
W.4	Migration along decommissioned / abandoned wells	Unlikely	"The Panel has found that there is a paucity of information available on the performance of decommissioned and/or abandoned onshore shale wells (refer also to Section 9.8). Indeed, it appears to be only recently that specific attention has been paid to this issue by regulators." p54 "the evidence on methane emissions from decommissioned and abandoned gas wells is mixed. It is clear, however, that properly decommissioned wells (wells that have been cut-off, sealed (plugged) and then buried under soil) have generally lower methane emissions than wells that have been not been properly (or at all) decommissioned and have been abandoned with well head infrastructure left above the surface;" p234 "fugitive methane emissions from any onshore shale gas industry in the NT (for the case of 1,000 decommissioned wells) is estimated to represent 0.7% of Australia's inventory fugitive methane emissions and 0.005% of the global anthropogenic methane emissions from fossil fuels;" p234 "the assessed risk of fugitive methane emissions from decommissioned wells resulting from any new shale gas industry in the NT, without any further mitigation, is 'medium'." p234 "CSIRO also found that for shale gas wells decommissioned using current practices, if any of the potential leakage pathways were to develop, it was highly unlikely that they would allow large fluid flow rates along the wellbore" p81 "The assessment of post-decommissioning or abandonment performance is an aspect that requires greater attention by both the regulator and the gas industry and is the subject of specific recommendations by the Panel" p81
W.5	Loss of well control	Not assessed	

2.9 Qualitative review of the findings from: Independent Scientific Panel Inquiry into Hydraulic Fracture Stimulation in Western Australia (Hatton et al., 2018)

Background and scope

In 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 WA, 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 WA, 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 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.

The 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.

Study area

Onshore environment of WA

Authors

Tom Hatton, Philip Commander, Fiona McKenzie, Jackie Wright, and Ben Clennell,

Focus

Potential risks arising from the implementation of hydraulic fracture stimulation on the onshore environment of WA and recommendations that may be employed to mitigate these risks.

Key findings

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.

Fluid spills at the well site are the most serious threat to groundwater quality.

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.

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.

The risk to water resources through below-ground pathways for contaminants is generally low …[however the] most consistently raised concern in all public meetings and submissions was the impact of hydraulic fracture stimulation and its associated activities on water.

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 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’.

Qualitative review of the report findings for each impact mode

A qualitative review of the findings from Hatton et al. (2018) has been undertaken though analysis of key excerpts from the text. The qualitative review (based on the likelihood descriptions in Table 4 and Table 5) provides a likelihood score for each impact mode. The likelihood score for each impact mode with related supporting excerpts are shown below in Table 14.

Table 14 Excerpts from Hatton et al. (2018) related to each impact mode

	Impact Mode	Likelihood score	Key excerpts from: Independent Scientific Panel Inquiry into Hydraulic Fracture Stimulation in Western Australia (Hatton et al., 2018)
Hydraulic fracture growth			
F.1	Hydraulic fracture growth into aquifer	Rare	"…hydraulic fracture growth and limits to fracture extent are complex topics that depend on the geology and stress state." p143 "… [The] 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))… [however] practical solutions usually involve many simplifications ((Lecampion et al., 2018))." p143 "Adequate models are based on fundamental physical principles, validated in controlled laboratory experiments and verified in-situ conditions… 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." p144 "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." p144 "… a good regulatory environment should encourage data collection, dating sharing and the development and uptake of new technologies to further reduce risks." p144 "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." P162 "Davies et al. (2012) reported that the longest stimulated fracture … was around 600 metres. … 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." P163 "Flewelling et al., (2013) reported … modelling constrained by data from 12,000 hydraulic fracture stimulations that the maximum observed vertical fracture length was about 600 metres." p163 "Flewelling et al., (2013) 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." p163

			"Scenarios [modelled for the case of the Bowland Shale in Lancashire in the United Kingdom by Wilson et al. (2017) showed] 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." p194 "Westwood, Toon and Cassidy (2017) [Westwood et al., 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." p194 "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 1,000 m or more. This is generally the case in the Perth Basin." p342 "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." p343
F.2	Hydraulic fracture growth into well	Rare	"The Report makes a number of recommendations … [including] a minimum separation distance of 2,000 metres between stimulated oil and gas wells and bores used for public drinking water sources." p49 "A 'frac hit', according to King et al. (King, Rainbolt and Swanson, 2017) 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, 2017b, 2017a). 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 and Swanson, 2017; Rainbolt and Esco, 2018)." p164 "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." p164

			"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." p349
F.3	Hydraulic fracture growth into fault	Unlikely	"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." p164 "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)." p164 "Therefore, the reactivation of faults is perceived as a geological risk for fluid leakage (O'Brien et al., 1999; Langhi et al., 2012) 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 and Hawkes, 2009), which may cause seismicity or relatively slow slip (undetectable from the surface)." P165 "The risk assessment should commence with an analysis of the formation pressures (Ruth et al., 2013) and 3D stress state (Reynolds et al., 2006; Nelson et al., 2007), 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 et al., 2016)." p192 "…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 prerequisite 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." p194

			“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.” p253 “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.” p262 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. [When monitoring for fault movement during hydraulic fracturing]“… micro-seismic monitoring can only detect brittle rupture episodes and not slower ductile deformation that may accompany renewed faulting and fracturing in softer shales.” p345 “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.” p346
Compromised well integrity			
			“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 (Taoutaou et al., 2010; Huddlestone-Holmes et al., 2017).” p153 “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).” p155

			"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 and Wang, 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." p156 "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." p156 "Poor well construction techniques are considered the most significant cause of well integrity failure by a number of the reviewed reports (Sinclair Knight Merz Pty Ltd, 2014; New York State Department of Environmental Conservation, 2015; Gosine et al., 2016)." p157 "High fluid overpressures in a rock layer penetrated by a well is a significant contributor to well integrity. … overpressured formations are not common in the rock formations overlying unconventional oil and gas resources…" p171 "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." p171 "Patel, Webster and 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." p173 "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." p174
W.1	Well rupture or failure across barriers	Rare	"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 44-20SWH well in North Dakota (US EPA, 2015)." p171 "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." p171

			"The documented well integrity failure rates from these [depths and in geological conditions comparable to those likely to be encountered in Western Australia] 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." p173
W.2	Migration along casing from reservoir	Not assessed	"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." p171
W.3	Migration along casing between rock layers	Rare	"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." p321 "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." p352
W.4	Migration along decommissioned / abandoned wells	Unlikely	"Inquiry finding: 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." p51, p352 & p526 "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." p168 "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." p168 "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." p168 "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 … [studies focused on relatively harsh (acidic) geochemical environments]… are much more corrosive than found in a shale gas basin, with methane under pressure less corrosive than carbon dioxide (Popoola et al., 2013).” p168 “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.” p267 “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.” p381
W.5	Loss of well control	Not assessed	

References contained within Table 14 Excerpts from Hatton et al. (2018) related to each impact mode

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Cooper addendum

Hydraulic fracturing impact mode review for the Cooper GBA region

The first hydraulic fracturing for stimulation in Australia was carried out in the Cooper Basin of SA in 1969 in a tight gas reservoir (McGowen et al., 2007) and hydraulic fracturing has been used to stimulate conventional oil, conventional gas and unconventional gas reservoirs in the Cooper GBA region over the past 50 years. There are significant differences in the extraction techniques for the different forms of unconventional gas:

- Shale gas: Extraction of gas from shale always requires hydraulic fracturing. Only a portion of the water that is used in the hydraulic fracturing process is returned to the surface. Horizontal drilling is most common.
- Tight gas: Porosity and permeabilities are so low that hydraulic fracturing is necessary to allow the trapped gas to be produced at economic rates, but unlike coal seam gas, it does not need to remove large quantities of existing groundwater for gas to be produced. On the contrary, large amounts of water are required for hydraulic fracturing fluids. Only a portion of the water that is used in the hydraulic fracturing process is returned to the surface. Vertical wells are most common for tight gas extraction.
- Deep coals: Deep coals require hydraulic fracturing to extract gas from the generally dry porous coals, oversaturated with gas. If layers have a mixed lithology it can result in complex hydraulic fracture geometry.

From 1969, over 815 petroleum wells have been stimulated with hydraulic fracturing in the Cooper GBA region (South Australian Department for Energy and Mining (2018) and State of Queensland (2018)) as shown in Figure 1. Approximately 720 of these hydraulically fractured wells were gas wells in the Cooper GBA region and were completed primarily in the Nappamerri and Patchawarra troughs.

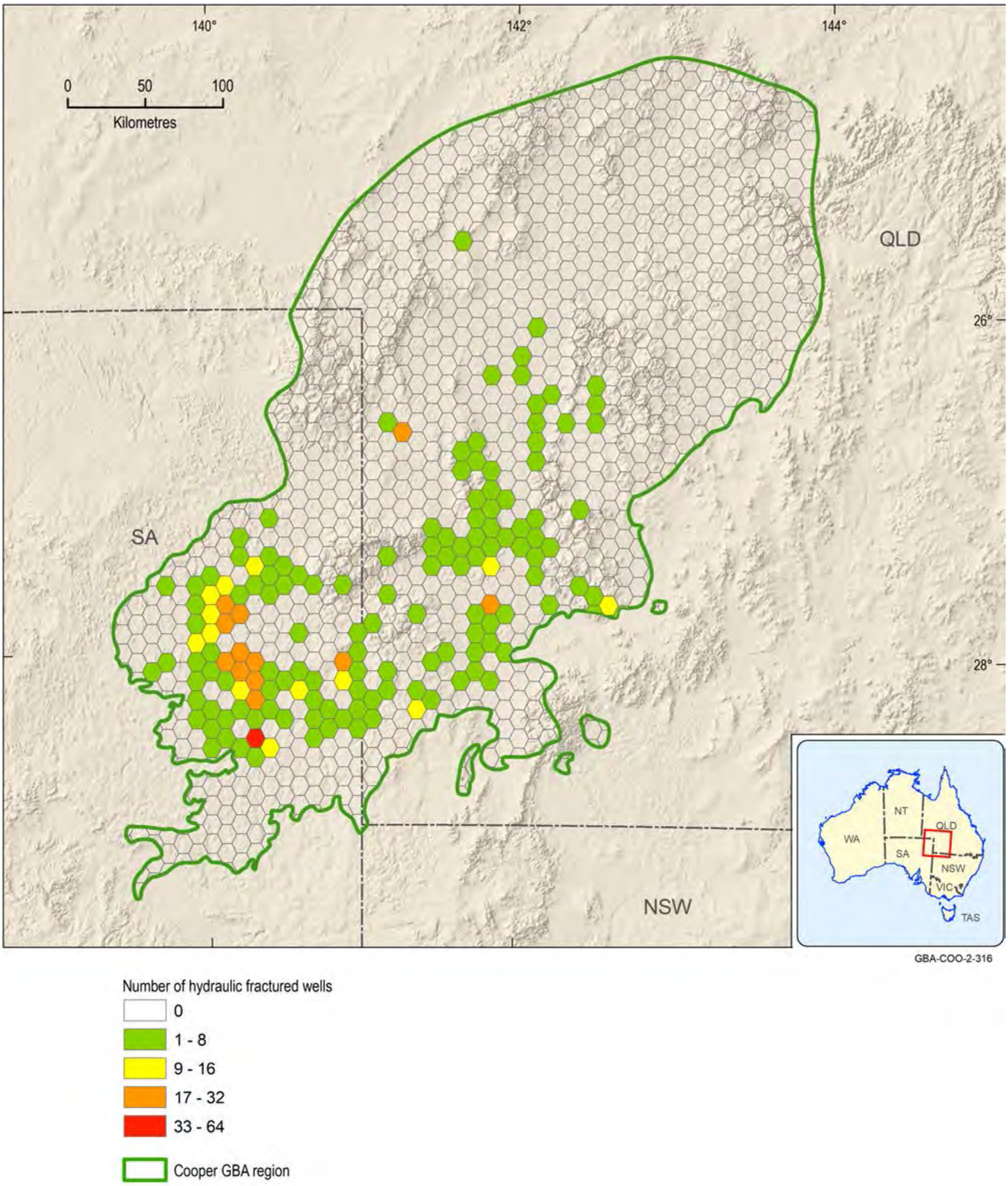

Figure 1 Map of 817 hydraulically fractured petroleum wells in the Cooper GBA region

Data: South Australian Department for Energy and Mining (2018) and State of Queensland (2018)
Element: GBA-COO-2-316

Since 1995 in the South Australia section of the Cooper GBA region, the volume of hydraulic fracturing fluid used per successful hydraulic fracturing stage has averaged ~212,000 L and ~57,000 L for gas and oil wells respectively. It is anticipated that future developments in the Cooper GBA region will use higher volumes of hydraulic fracture fluid in order to target new unconventional hydrocarbon-bearing formations. It is expected that most unconventional and tight gas stimulation will require between 0.4 and 1.2 ML per fracture stage for an approximate total of 5.7 ML required per unconventional well stimulation, 1.6 ML per conventional gas well stimulation and 0.5 ML per conventional oil well stimulation (Santos, 2015). This reflects both the greater stimulated reservoir volumes needed for economic gas flow in unconventional gas resources and the design of horizontal wells where larger scale lateral propagation of fractures is desired.

Each hydraulic fracturing stage comprises of injecting fluid into one or more perforated intervals isolated from the rest of the well by equipment such as packers or bridge plugs. Vertical wells (if installed) in the Cooper are expected to be hydraulically fractured in 3-5 stages while horizontal wells (the most likely scenario) are likely to be hydraulic fractured in ten or more stages over a 500-3000 m horizontal length. As drilling technology evolves, the typical length of the horizontal well sections is expected to increase. Hydraulic fracture stimulation of these longer horizontal well sections will likely involve a larger number of fractured stages. Gilbert and Greenstreet (2005) found that treating perforated intervals individually in the Cooper GBA region yielded better results than treating multiple perforated intervals at once. This technique is sometimes referred to as pinpoint hydraulic fracturing or PPX. PPX fracturing has used an average of 175,000 L of hydraulic fracturing fluid across 271 completed successful stages in the Cooper GBA region.

Monitoring of hydraulic fracture growth is possible by installing an array of geophones which record the noise emitted by the surrounding rock as the hydraulic fracture grows. This microseismic monitoring is not always conducted however in the Cooper and Eromanga basins, a dataset of microseismic monitoring of 34 wells is available (summarised in Figure 2 below). The data show the hydraulic fractures to grow to a maximum 290 m height above and 240 m below the perforation midpoint (depth of hydraulic fracture fluid injection). The average extent for hydraulic fracture height growth was 150 m above and 90 m below the perforation midpoint. The total maximum height growth from the shallowest measurement to the deepest point was 541 m.

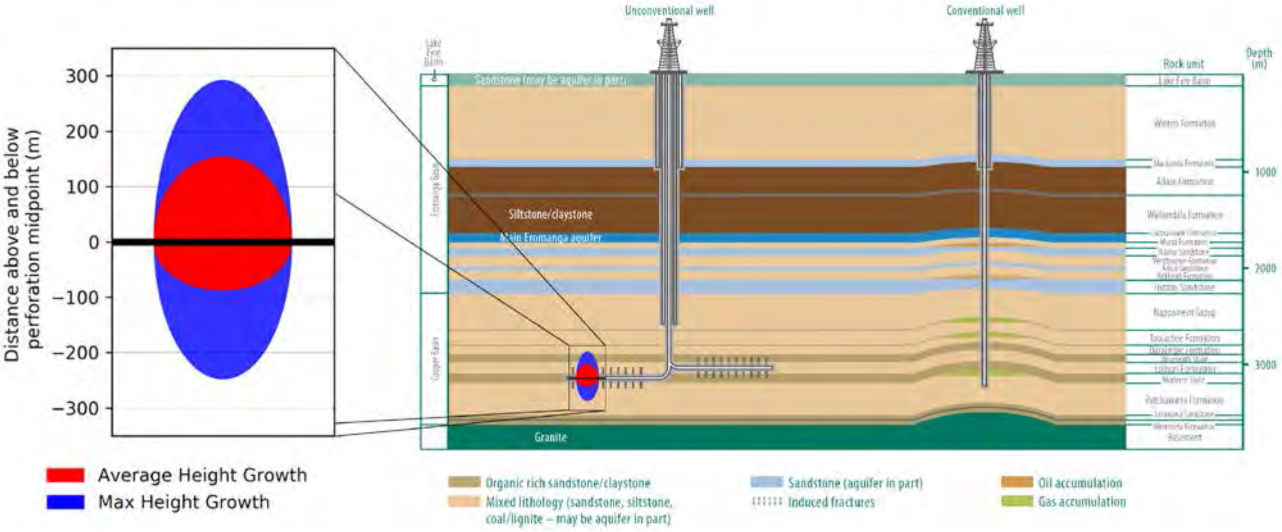

Figure 2 Sketch of the hydraulic fracture stimulation height data based on microseismic measurement results from the Cooper GBA region

Note: The measured hydraulic fractures were conducted in both horizontal and vertical wells primarily in the Nappamerri and Patchawarra troughs. While the vertical height is sketched to scale, the stratigraphy should be taken as generally representative of the Cooper GBA region rather than specific to the locations of the hydraulically fractured wells.

Source: Hydraulic fracture height data from Department for Energy and Mining (2018). Stratigraphy image from Cook et al. (2013)
Element: GBA-COO-2-338

This measured order of magnitude of growth is similar to large datasets of hydraulic fractures monitored in international basins. Data from 10,000 fractures in the Marcellus and Eagle Ford shale in USA were measured with an interpreted maximum fracture height of 588 m, but also showed hydraulic fracture growth in shallower target zones led to an increase in the horizontal component and a decrease in the fracture height (Fisher and Warpinski, 2012). Vertical hydraulic fracture height growth is desirable when stimulating thick or dispersed target intervals in order to maximise the production from the well. However hydraulic fracture treatments will be designed to ideally limit the vertical extent of the fracture growth to the intended target interval(s).

Line of evidence 1 qualitative assessment for Cooper GBA region hydraulic fracturing impact modes

F.1 Hydraulic fracture growth into aquifer

The maximum recorded extent of hydraulic fracture height growth in the Cooper GBA region was calculated as being 290 m above the injection location. Across the Cooper GBA region, the vertical separation between the deeper GAB aquifers and the shale, tight and deep coal gas is typically between 600 and 2000 m (Evans et al., 2020; Owens et al., 2020). However, in some parts of the Cooper GBA region, this vertical separation can be smaller such as the 300 – 800 m presented in Hawke (2014) based on an interpretation of the geology by Cook et al. (2013).

Due to the relative proximity of the deeper GAB aquifers in some parts of the Cooper GBA region, there is a slightly higher potential likelihood (Unlikely vs. Rare) of a hydraulic fracture extending into an aquifer unit than in other international shale gas developments where there is a consistently significant (>1,000 m) distance between the target interval and the closest aquifer.

Modelling and spatial analysis will be undertaken in Stage 3 to clarify locations in the Cooper Basin where vertical height growth could conceivably intersect the base of the deeper GAB aquifers (inform likelihood understanding) and estimate the potential hydraulic conductivity of such a fracture (inform consequence understanding).

F.2 Hydraulic fracture growth into well

Although significant conventional development has occurred in the Cooper GBA region, the spacing of wells is still large therefore the current likelihood of a hydraulic fracture treatment intersecting an offset borehole is very remote.

However, this likelihood will increase if large-scale shale gas development occurs with multiple vertically and horizontally stacked horizontal wells being drilled and hydraulically fractured from the same pad. Propagation of fractures between wells from the same pad completed in the same formation are common and pose a low risk as the wells would be designed and constructed to withstand the imposed fluid pressure from the intersecting hydraulic fracture.

Therefore, a qualitative analysis of the Cooper GBA region indicates the potential likelihood of a hydraulic fracture intersecting and propagating along or damaging another well is similar to other international shale gas developments (Unlikely).

F.3 Hydraulic fracture growth into fault

Evidence from hydraulic fracturing activities to date in the Cooper GBA region has not indicated that excessive vertical hydraulic fracture growth has occurred though intersection with transmissive vertically oriented faults. Seismic mapping of key faults and avoidance of those areas is anticipated as development continues in the Cooper GBA region.

Therefore, a qualitative analysis of the Cooper GBA region indicates the potential likelihood of a significant vertical hydraulic fracture growth following intersection of a fault is similar to other international shale gas developments (Rare).

Summary of line of evidence 1 qualitative assessment

The results of the Stage 2 qualitative assessment of three hydraulic fracturing impact modes against historical data for the Cooper GBA region are summarised below in Table 15. These results are combined with line of evidence 2: Findings from relevant reviews and inquiries (Table 4) to form the qualitative assessment presented in (Holland *et al.*, 2020).

Table 15 Qualitative assessment of likelihood of hydraulic fracturing impact modes from historical Cooper GBA region data

Impact mode	Line of evidence 1 Summary for hydraulic fracturing impact modes in the Cooper GBA region
F1 – Hydraulic fracture growth into aquifer	Between 1969 and 2017 over 900 wells were stimulated with hydraulic fracturing in the SA Cooper and Eromanga Basins. Of the hydraulic fracture treatments monitored with microseismic, the maximum recorded extent of hydraulic fracture height growth in the Cooper GBA region was calculated as being 290 m above the injection location. The deeper GAB aquifers are vertically separated by 300-2000 m from the unconventional gas target formations (Evans et al., 2020; Owens et al., 2020; Hawke, 2014). F1 impact mode likelihood summary for the Cooper GBA region: **Unlikely**
F2 – Hydraulic fracture growth into well	Although significant conventional development has occurred in the Cooper Basin, as the spacing of wells is still large the current likelihood of a hydraulic fracture treatment intersecting an offset borehole is very remote. However, this likelihood will increase if large-scale shale gas development occurs with multiple vertically and horizontally stacked horizontal wells being drilled and hydraulically fractured from the same pad. Propagation of fractures between wells from the same pad completed in the same formation are common and pose a low risk as the wells would be designed and constructed to withstand the imposed fluid pressure from the intersecting hydraulic fracture. F2 impact mode likelihood summary for the Cooper GBA region: **Unlikely**
F3 – Hydraulic fracture growth into fault	Evidence from hydraulic fracturing activities to date in the Cooper GBA region has not indicated that excessive vertical hydraulic fracture growth has occurred though intersection with transmissive vertically oriented faults. Seismic mapping of key faults and avoidance of those areas in the Cooper GBA region is anticipated. F3 impact mode likelihood summary for the Cooper GBA region: **Rare**

Well integrity impact mode review for the Cooper GBA region

Well integrity data in the Cooper GBA region is scarce. Product 2.3 for the Cooper subregion from the Lake Eyre Basin Bioregional Assessment (Smith et al., 2016) cites a personal communication from 2015 from the SA Department of State Development where four recorded instances of petroleum well failure were reportedly observed out of 2288 petroleum wells drilled into the Patchawarra and Nappamerri troughs as of 2015. These wells targeted conventional reservoirs which, in some cases, can pose additional challenges which are not experienced when developing shale or coal resources. In this context 'failure' was defined as an event in a well that caused either:

- fluid crossflow between two formations or,
- fluid flow from a formation to the surface (not including wellhead leaks).

One instance of well integrity failure leading to uncontrolled migration of fluids to surface was identified in Smith et al. (2016):

- Tirrawarra-3 (2019 m total depth; low-rate uncontrolled flow of fluid to surface), drilled in 1971 (leak detected and remediated in 2009).

One instance of Migration along casing between rock layers was identified in in Smith et al. (2016):

- Della-20 (3018 m total depth; crossflow between formations behind casing), drilled in 2000.

This recorded failure occurred on a well drilled more recently than the other failures. However, this causal pathway is not always visible at the surface or easy to detect with downhole tools. It is possible that there have been other instances of fluid migration between rock layers which have not been recorded.

Two instances of loss of well control (blowout) in historical Cooper GBA region petroleum operations were identified in Smith et al. (2016):

- Big Lake-2 (2500 m total depth; blowout), drilled in 1963
- Della-1 (2179 m total depth; blowout), drilled in 1970.

As of 2016 these two instances corresponded to an approximate rate of 0.1% of all petroleum wells. However, both events occurred approximately 50 years ago when targeting conventional resources and it is accepted that due to tightened regulatory requirements and technological and operational improvements in the oil and gas industry the likelihood of well blowouts is decreasing over time (Bannerman et al., 2005; Ground Water Protection Council, 2011). Therefore, the actual likelihood is considered to be lower than 0.1%.

Line of evidence 1 qualitative assessment for Cooper GBA region well integrity impact modes

W1 - Well rupture or failure across barriers

None of the four cases of well integrity failure recorded in the Cooper GBA region appear to be related to rupture of the well and no evidence of well rupture or total well integrity failure in historical Cooper GBA region operations identified to date.

Therefore, a qualitative analysis of the Cooper GBA region would suggest the potential likelihood of 'W1 - Well rupture or failure across barriers' is in line with other international shale gas developments (Rare).

W2 - Migration along casing from reservoir to surface

One instance of migration of fluids to surface in the Cooper GBA region (assumed to be along casing annulus) was identified in Smith et al. (2016). The leaking well was Tirrawarra-3 (2019 m depth) drilled in 1971. The leak was described as a low-rate flow to surface and the failure occurred over 45 years ago.

Given the current controls and significant depth of the target layers the qualitative potential of this impact mode is considered very unlikely.

W3 - Migration along casing between rock layers

One event of crossflow between formations behind casing recorded in the Cooper GBA region however the causal pathway may be difficult to detect from surface or downhole measurements.

Given the current controls and significant depth of the target layers the qualitative potential of this impact mode is considered unlikely.

W4 - Migration along decommissioned / abandoned wells

No evidence of fluid migration along decommissioned / abandoned wells in historical Cooper GBA region operations identified to date. There was insufficient data for an initial qualitative assessment of impact mode 'W4 - Migration along decommissioned / abandoned wells'.

W5 - Loss of well control (blowout)

Two instances of loss of well control (blowout) in historical Cooper GBA region petroleum operations were identified in Smith et al. (2016). As of 2016 this corresponds to an approximate rate of 0.1% however both events occurred greater than 50 years ago. Due to technological and operational improvements in the oil and gas industry the actual likelihood is likely to be lower than 0.1%.

Given the historical data, current controls and significant depth of the target layers the qualitative potential of this impact mode is considered very unlikely.

Summary of line of evidence 1 qualitative assessment

The results of the Stage 2 qualitative assessment of five compromised well integrity impact modes against historical data for the Cooper GBA region are summarised below in Table 16. These results are combined with line of evidence 2: Findings from relevant reviews and inquiries (Table 5) to form the qualitative assessment presented in (Holland *et al.*, 2020).

Table 16 Qualitative assessment of likelihood of well integrity impact modes from historical Cooper GBA region data

Impact mode	Line of evidence 1 Summary for well integrity impact modes in the Cooper GBA region
W1 - Well rupture or failure across barriers	None of the four cases of well integrity failure recorded in the Cooper GBA region appear to be related to rupture of the well. Therefore there is no evidence of well rupture or total well integrity failure in historical Cooper GBA region operations identified to date. W1 impact mode likelihood summary for the Cooper GBA region: **Rare**
W2 - Migration along casing from reservoir to surface	One instance of migration of fluids to surface in the Cooper GBA region (assumed to be along casing annulus) was identified in (Smith et al., 2016). The leaking well was Tirrawarra-3 (2019 m depth) drilled in 1971 targeting an overpressured geological layer. The leak was described as a low-rate flow to surface and the failure occurred over 45 years ago. Given the current controls and significant depth of the target layers the potential of this mode of failure is considered very unlikely. W2 impact mode likelihood summary for the Cooper GBA region: **Very unlikely**
W3 - Migration along casing between rock layers	One event of crossflow between formations behind casing was recorded in the Cooper GBA region however the causal pathway may be difficult to detect from surface or downhole measurements. Given the current controls the potential of this mode of failure is considered unlikely. W3 impact mode likelihood summary for the Cooper GBA region: **Unlikely**
W4 - Migration along decommissioned / abandoned wells	No evidence of fluid migration along decommissioned / abandoned wells in historical Cooper GBA region operations identified to date. W4 impact mode likelihood summary for the Cooper GBA region: **Not assessed**
W5 - Loss of well control (blowout)	Two instances of loss of well control (blowout) in historical Cooper GBA region petroleum operations were identified in Smith et al. (2016). As of 2016 this corresponds to an approximate rate of 0.1% however both events occurred greater than 50 years ago. Due to technological and operational improvements in the oil and gas industry the actual likelihood is likely to be lower than 0.1%. W5 impact mode likelihood summary for the Cooper GBA region: **Very unlikely**

Isa addendum

Hydraulic fracturing impact mode review for the Isa GBA region

The Isa GBA region is in north-west Queensland and extends approximately 50 km south and 200 km west of Burketown (see Figure 3). Petroleum industry activity in the Isa GBA region has been minimal to date with the Egilabria 2 exploration well, which was hydraulically fractured over the Lawn Supersequence in 2013, the only hydraulic fracturing production stimulation in the region to date. The location of the Isa GBA region and the Egilabria 2 exploration well are shown in Figure 3 below.

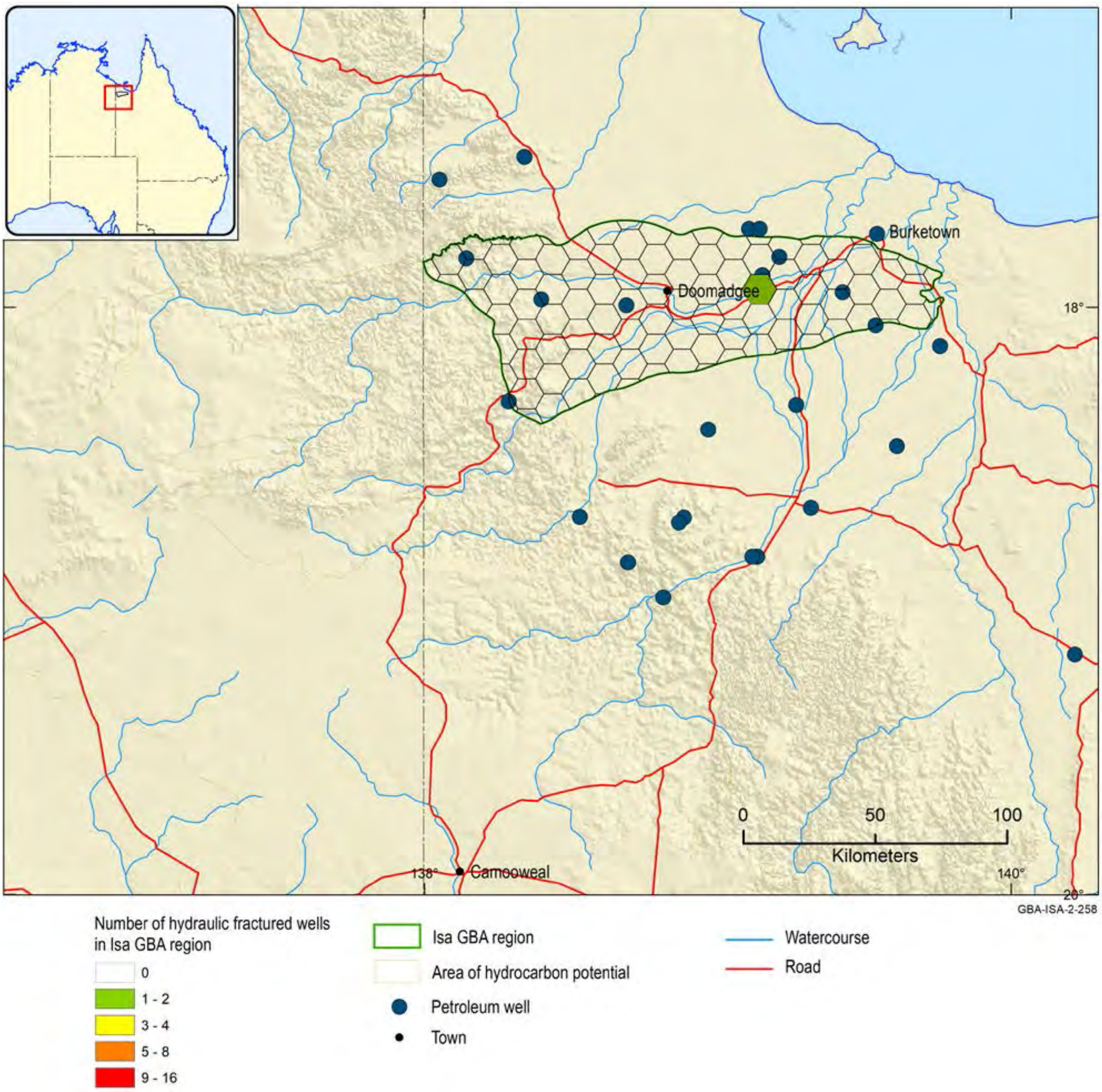

Figure 3 Map of oil and gas wells in the Isa GBA region and surrounding area (with the location of the 2013 hydraulic fracture stimulation in the Egilabria 2 exploration well shown in green)

Data: State of Queensland (2018)
Element: GBA-ISA-2-258

In the 2013 hydraulic fracture stimulation of the Lawn Supersequence in the Egilabria 2 well, a total 1.8 ML of hydraulic fracturing fluid was injected over eight fracture stages. However not all the hydraulic fracturing stages in the Egilabria 2 well were successful from a production perspective (Johnson and Titus, 2014). Depending on the stimulation design, future unconventional reservoir hydraulic fracturing stimulations are estimated to require 0.4 to 1.2 ML of water for each hydraulic fracturing stage (Santos, 2015).

Figure 4 Hydraulic fracturing operation at the Egilabria-2 well pad in the Isa GBA region

Credit: Armour Energy 2012
Element: GBA-ISA-2-252

Line of evidence 1 qualitative assessment for Isa GBA region hydraulic fracturing impact modes

F.1 Hydraulic fracture growth into aquifer

Due to the stress variations in the Isa GBA region, hydraulic fractures placed in the Lawn and River supersequences are expected to be contained locally in the respective intervals (Bailey *et al.*, 2020). This would suggest a minimal likelihood of hydraulic fracture impact mode ‘F1 – Hydraulic fracture growth into aquifer’, however, the underlying Lady Loretta aquifer unit is in relatively close proximity to the base of the River Supersequence.

There are also places within the Isa GBA region where both the Lawn and River supersequences are in direct stratigraphic connection with the overlying basal GAB aquifer of the Gilbert River Formation.

Therefore, a qualitative analysis of the Isa GBA region indicates that in and near the zones of close aquifer proximity there is a slightly higher potential likelihood (Unlikely vs. Rare) of a hydraulic fracture extending into an aquifer unit than in other international shale gas developments where there is significant (>1000 m) distance between the target interval and the closest aquifer.

F.2 Hydraulic fracture growth into well

The density of wells in the Isa GBA region is very low and therefore the current likelihood of a hydraulic fracture treatment intersecting an offset well is very remote.

However, this likelihood will increase if large-scale shale gas development occurs with multiple vertically and horizontally stacked horizontal wells being drilled and hydraulically fractured from the same pad. Propagation of fractures between wells from the same pad completed in the same formation are common and pose a low risk as the wells would be designed and constructed to withstand the imposed fluid pressure from the intersecting hydraulic fracture.

F.3 Hydraulic fracture growth into fault

Detailed analysis of the likelihood of excessive hydraulic fracture growth though vertical faults is not currently possible as potentially conductive vertically oriented faults are not mapped or characterised at the resolution required across the Isa GBA region.

Although natural fractures are prevalent in some intervals in the Isa GBA region, the natural fractures and faults are not expected to cause significant vertical hydraulic fracture growth.

Prior to exploration or production activity, seismic mapping of key faults and avoidance of major vertical faults in the Isa GBA region is anticipated.

Summary of line of evidence 1 qualitative assessment

The results of the Stage 2 qualitative assessment of three hydraulic fracturing impact modes against historical data for the Isa GBA region are summarised below in Table 17. These results are combined with line of evidence 2: Findings from relevant reviews and inquiries (Table 4) to form the qualitative assessment presented in (Lewis *et al.*, 2020).

Table 17 Qualitative assessment of likelihood of hydraulic fracturing impact modes from historical Isa GBA region data

Impact mode	Line of evidence 1 Summary for hydraulic fracturing impact modes in the Isa GBA region
F1 – Hydraulic fracture growth into aquifer	As only one well in the Isa GBA region has been hydraulically fractured to date there is limited evidence to review for this impact mode. Across the Isa GBA region there are places where the Lawn Supersequence is likely to be in direct stratigraphic connection with the overlying Gilbert River formation aquifer (especially in the east of the region). However, the distance between the units varies and in the central and western parts of the Isa GBA region there is likely to be significant separation between the Lawn Supersequence and the Gilbert River formation aquifer. See Buchanan et al. (2020) for more detail and geological cross-sections of the Isa GBA region. The Egilabria-2 hydraulic fracture stimulation was placed in the Lawn Supersequence. At the location of the Egilabria-2 well, there is significant vertical distance above the Lawn Supersequence to the nearest overlying aquifer. Another shale gas target reservoir / aquifer interaction exists between the River Supersequence and the underlying aquifer of the Loretta Supersequence. Although both the Egilabria 4 and Desert Creek 1 penetrated to the River Supersequence neither was hydraulically fractured for production analysis in that formation. Therefore, very little evidence exists in line of evidence 1 on the likelihood of hydraulic fracture growth from the River Supersequence into the underlying Loretta Supersequence. The variation in the proximity of the potential target intervals and aquifer units means this impact mode cannot be ruled out for the Isa GBA region via line of evidence 1. Tier 1 conceptual impact analysis will be undertaken in Stage 3 to clarify conceptual prioritisation and identify additional characterisation required to undertake future impact analysis work in the Isa GBA region. F1 impact mode likelihood summary for the Isa GBA region: **Unlikely**
F2 – Hydraulic fracture growth into well	As the Isa GBA region is not currently under active development for shale gas, the spacing of wells is very large and the current likelihood of a hydraulic fracture treatment intersecting an offset well is very remote. However, this likelihood will increase if large-scale shale gas development occurs with multiple vertically and horizontally stacked horizontal wells being drilled and hydraulically fractured from the same pad. Propagation of fractures between wells from the same pad completed in the same formation are common and pose a low risk as the wells would be designed and constructed to withstand the imposed fluid pressure from the intersecting hydraulic fracture. F2 impact mode likelihood summary for the Isa GBA region: **Rare**
F3 – Hydraulic fracture growth into fault	Although natural fractures are prevalent some in intervals in the Isa GBA region, the natural fractures and faults are not expected to cause significant vertical hydraulic fracture growth. Seismic mapping of key faults and avoidance of major vertical faults in the Isa GBA region is anticipated. F3 impact mode likelihood summary for the Isa GBA region: **Rare**

Well integrity impact mode review for the Isa GBA region

Petroleum industry activity in the Isa GBA region has been minimal to date and as such there is limited data on well integrity in the region (see Figure 5). Two aspects of the Isa GBA region could potentially affect the likelihoods of the five well integrity impact modes:

Firstly, the Isa GBA region is not expected to contain a significant overpressure region (Bailey *et al.*, 2020) however overpressure intervals and difficulty cementing were noted in (Johnson and Titus, 2014). A difference in fluid pressure between intervals is required to drive subsurface fluid flow. In the absence of significant overpressured intervals there is no driving force to create subsurface flow.

Secondly, as detailed in Johnson and Titus (2014) the Egilabria 2 well experienced difficulty in maintaining well stability in the Lawn hill formation. Therefore a two-stage cement job was required and areas of poor cement bonding were noted. If wells drilled in the Isa GBA region experience difficulty in achieving a good seal between the cement and the rock/casing outside of the target intervals this may increase the potential for subsurface fluid flow along the well. However as more wells are drilled, operators will become more adept at managing the conditions in the Isa GBA region.

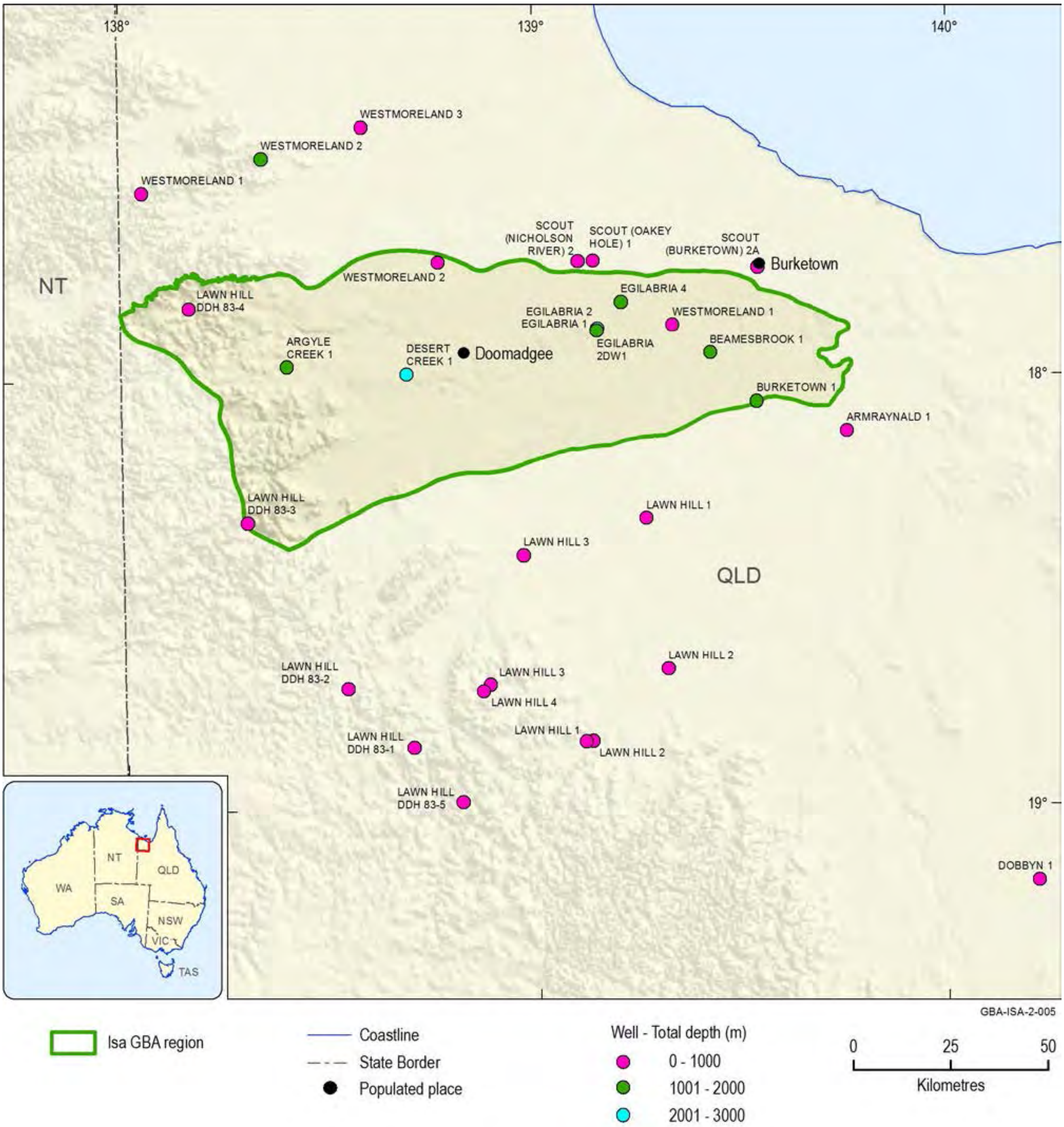

Figure 5 Location of petroleum exploration wells in and near the Isa GBA region

Source: State of Queensland (2018)
Element: GBA-ISA-2-005

Line of evidence 1 qualitative assessment for Isa GBA region well integrity impact modes

W1 - Well rupture or failure across barriers

Any analysis of potential well rupture or failure across multiple well barriers would be strongly influenced by local in-situ geological conditions and individual well design and construction.

There has been no evidence of well rupture or total well integrity failure in historical Isa GBA region operations identified to date.

W2 - Migration along casing from reservoir to surface

There was no evidence of well rupture or total well integrity failure in historical Isa GBA region operations identified to date.

In order for liquids to migrate along a well in the event of a failed well annulus they must be driven from an interval with overpressured pore fluids (Huddlestone-Holmes et al., 2018). While intervals of overpressured pore fluids were noted when drilling the Egilabria 2 well (Johnson and Titus, 2014), overpressured intervals are not expected to commonly feature in the Isa GBA region (Bailey *et al.*, 2020). An assessment of the likelihood of this impact mode would rely on data for both well integrity and pore fluid pressure in the rock layers. However, there have been no studies of formation pressure within the Isa Superbasin (Bailey *et al.*, 2020) and well integrity data in the Isa GBA region appear to be scarce.

W3 - Migration along casing between rock layers

It is not always possible to detect fluid flow in the well annulus between different formations either from surface measurements or with downhole tools. In the Isa GBA region, Johnson et al. (2014) noted that horizontal drilling instabilities in Egilabria 2 led to a two-stage cement job with areas of poor cement bonding. These apparently difficult geological conditions in the Lawn Supersequence could require operators to develop appropriate engineering techniques to achieve competent cement jobs to reduce the likelihood of well annulus integrity problems. However, it is important to note that any drilling instabilities in the horizontal section of the well would not facilitate vertical flow between formations.

W4 - Migration along decommissioned / abandoned wells

No evidence of failure of well integrity in decommissioned wells in the Isa GBA region has been identified to date. However, the data are scarce, and the reviewed inquiries considered that either some decommissioned wells are likely to leak methane and some level of monitoring is required, or that methane leakage from decommissioned wells is certain. If monitoring data were gathered for existing and future decommissioned wells, then further analysis could be undertaken to achieve a more specific likelihood of occurrence for the Isa GBA region.

W5 - Loss of well control (blowout)

Instances of loss of well control (blowouts) are most commonly associated with conventional reservoirs where the production interval is overpressured and permeability is sufficient to support significant pressure and flow at surface. Shale gas wells are intrinsically less prone to significant loss of well control due to the lower initial permeability of the target interval (i.e. the well could not support significant flow to surface until after the well has been completed and hydraulically fractured) (Huddlestone-Holmes et al., 2018). However, there have been examples of blowouts in shale gas wells, for example in Pennsylvania and West Virginia in the USA (Zoback et al., 2010; USEPA, 2016).

In the Isa GBA region there has been no evidence of loss of well control and while overpressured intervals have been noted they are not expected to be common in the region.

Summary of line of evidence 1 qualitative assessment

The results of the Stage 2 qualitative assessment of five compromised well integrity impact modes against historical data for the Isa GBA region are summarised below in Table 18. These results are combined with line of evidence 2: Findings from relevant reviews and inquiries (Table 5) to form the qualitative assessment presented in (Lewis *et al.*, 2020).

Table 18 Line of evidence 1 qualitative assessment for Isa GBA region well integrity impact modes

Impact mode	Line of evidence 1 Summary for well integrity impact modes in the Isa GBA region
W1 - Well rupture or failure across barriers	No evidence of well rupture or total well integrity failure in historical Isa GBA region operations identified to date. W1 impact mode likelihood summary for the Isa GBA region: **Rare**
W2 - Migration along casing from reservoir to surface	No evidence of well rupture or total well integrity failure in historical Isa GBA region operations identified to date. W2 impact mode likelihood summary for the Isa GBA region: **Rare**
W3 - Migration along casing between rock layers	Johnson et al. (2014) noted that horizontal drilling instabilities in Egilabria 2 led to a two-stage cement job with areas of poor cement bonding, however cementing issues in the horizontal section of a well would not lead to vertical migration of fluids. W3 impact mode likelihood summary for the Isa GBA region: **Unlikely**
W4 - Migration along decommissioned / abandoned wells	No evidence of fluid migration along decommissioned / abandoned wells in historical Isa GBA region operations identified to date. Minimal numbers of abandoned wells in the Isa GBA region from which to gather data. Companies could be approached for monitoring data on decommissioned / abandoned Isa GBA region wells or data could be generated from fieldwork for potential Stage 3 analysis. W4 impact mode likelihood summary for the Isa GBA region: **Not assessed**
W5 - Loss of well control (blowout)	No evidence of loss of well control or blowout has been identified in the Isa GBA region to date. Overpressured intervals have been noted but are not expected to be common in the Isa GBA region. W5 impact mode likelihood summary for the Isa GBA region: **Rare**

Beetaloo addendum

Hydraulic fracturing impact mode review for the Beetaloo GBA region

The Beetaloo basin is in the early stages of a resurgence of exploration and appraisal including hydraulic fracture stimulation activities. Two hydraulic fracture stimulations have been conducted in the Beetaloo GBA region to date (see Figure 6). The first hydraulic fracture stimulation of a petroleum well in the Beetaloo GBA region was in 2011 in the Shenandoah 1A exploration well in the Velkerri Formation. The Velkerri Formation was targeted by a second exploration well in the Beetaloo GBA region, Amungee NW-H1, which was hydraulic fractured in August 2016. The hydraulic fracture stimulation of the Amungee NW-H1 well was completed in accordance with industry standards and best practices issued by the American Petroleum Institute (Origin Energy, 2016) and as documented in Close et al., (2017) was the stimulation was completed successfully with no environmental incidents.

The operator, Origin Energy, has submitted an Environmental Management Plan (EP117 N2) to the NT Department of Natural Resources proposing the construction of another exploration petroleum well (Kyala 117 N2-1) in the Beetaloo GBA region. This new exploration well would target the Kyalla formation. As noted in Origin Energy, (2017), both the Kyalla and Velkerri formations are potential target formations for development in the Beetaloo GBA region.

Approximately 1 ML of hydraulic fracturing fluid was pumped in each of 11 stages in the hydraulic fracturing stimulation of the Amungee NW-H1 exploration well (Close et al., 2017). The recent Environmental Management Plan submission, proposes approximately 1.3 ML of hydraulic fracture fluid will be pumped in each stage of the hydraulic fracture stimulation of the Kyalla 117 N2-1/1H exploration well (Origin Energy, 2019).

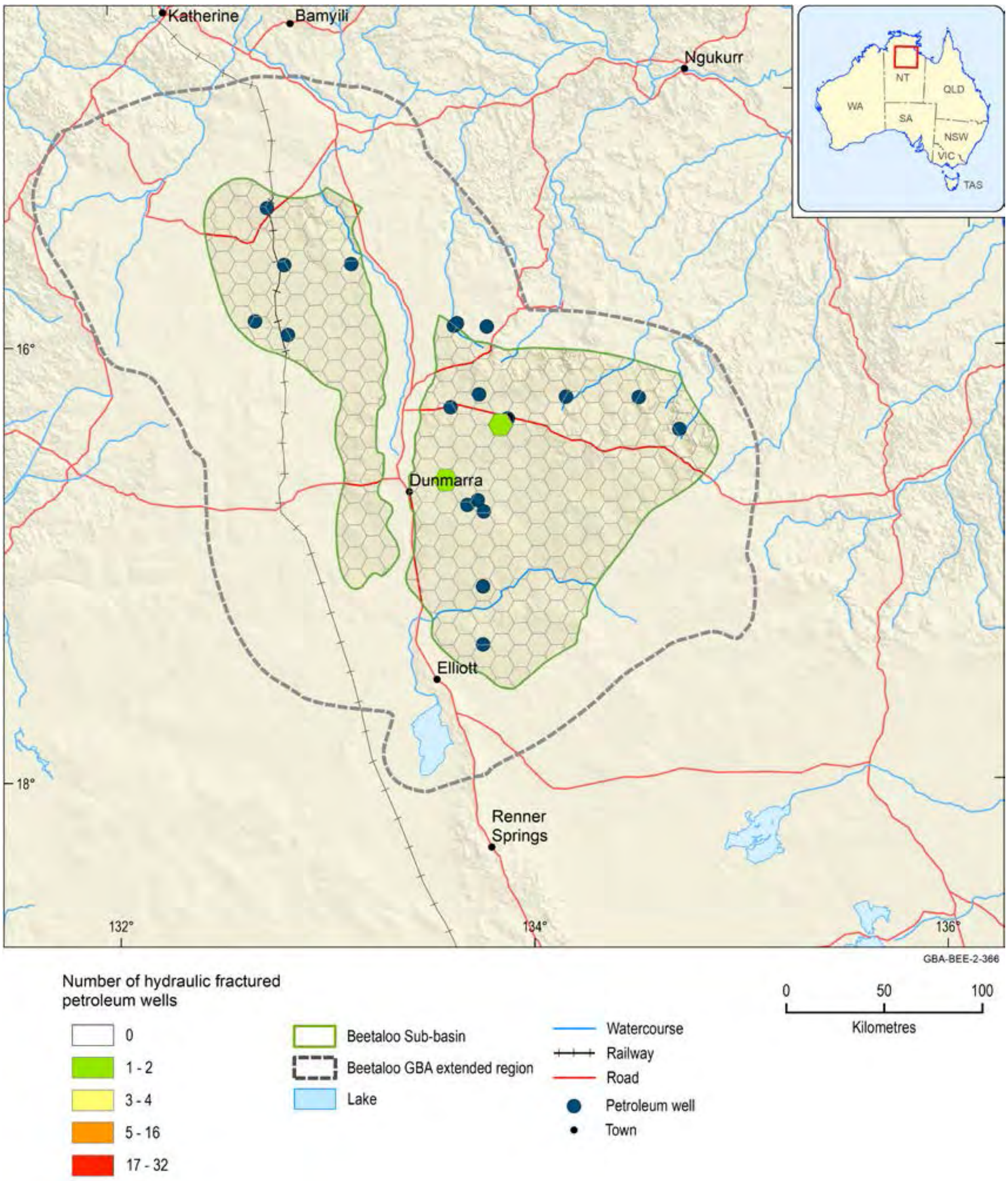

Figure 6 Map of petroleum wells in the Beetaloo GBA region and surrounding area (with the location of the hydraulic fracture stimulations in the Shenandoah 1A and Amungee NW-H1 exploration wells shown in green)

Data: Hydraulically fractured locations from Origin Energy (2016) and Close et al. (2017).
Element: GBA-BEE-2-366

Data for Origin's broader Beetaloo exploration area indicates there are very few major faults present (Origin Energy, 2019). Current industry practice is to analyse geological data prior to hydraulic fracture stimulation to determine the presence of minor and major faults which may impact the growth of hydraulic fractures. (Origin Energy, 2019) A number intersected of faults were identified in the Amungee NW-H1 and the hydraulic fracturing stimulation design was adapted to avoid these areas through conservative buffer zones (Close et al., 2017). No excessive vertical hydraulic fracture growth was observed though intersection with transmissive vertically oriented faults.

Line of evidence 1 qualitative assessment for Beetaloo GBA region hydraulic fracturing impact modes

F.1 Hydraulic fracture growth into aquifer

As hydraulic fracture stimulation has only been applied to two wells in the Beetaloo GBA region, there is limited there is limited evidence to review for this impact mode, however, there is substantial physical separation between the Kyalla and Velkerri formations and the closest overlying aquifers.

Therefore, a qualitative analysis of the Beetaloo GBA region indicates the potential likelihood of a hydraulic fracture extending into an aquifer unit is similar to other international shale gas developments (Rare) where there is significant (>1,000 m) distance between the target interval and the closest aquifer. This also reflects the findings of the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018).

F.2 Hydraulic fracture growth into well

The density of wells in the Beetaloo GBA region is very low and therefore the current likelihood of a hydraulic fracture treatment intersecting an offset well is very remote.

However, this likelihood will increase if large-scale shale gas development occurs with multiple vertically and horizontally stacked horizontal wells being drilled and hydraulically fractured from the same pad. Propagation of fractures between wells from the same pad completed in the same formation are relatively common but pose a low risk as the wells would be designed and constructed to withstand the imposed fluid pressure from the intersecting hydraulic fracture.

Therefore, a qualitative analysis of the Beetaloo GBA region indicates the potential likelihood of a hydraulic fracture intersecting and propagating along or damaging another well is similar to other international shale gas developments (Rare).

F.3 Hydraulic fracture growth into fault

Evidence from hydraulic fracturing activities to date in the Beetaloo GBA region has not indicated that excessive vertical hydraulic fracture growth has occurred though intersection with transmissive vertically oriented faults.

Current industry practice of adapting hydraulic fracture stimulation designs to avoid fault zones reduced the likelihood of this impact mode.

Prior to exploration or production activity, seismic mapping of key faults and avoidance of those areas in the Beetaloo GBA region is anticipated.

Therefore, a qualitative analysis of the Beetaloo GBA region indicates the potential likelihood of a significant vertical hydraulic fracture growth following intersection of a fault is similar to other international shale gas developments (Rare). This qualitative likelihood of 'Rare' also reflects the findings of the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018).

Summary of line of evidence 1 qualitative assessment

The results of the Stage 2 qualitative assessment of three hydraulic fracturing impact modes against historical data for the Beetaloo GBA region are summarised below in Table 19. These results are combined with line of evidence 2: Findings from relevant reviews and inquiries (Table 4) to form the qualitative assessment presented in (Frery *et al.*, 2020).

Table 19 Qualitative assessment of likelihood of hydraulic fracturing impact modes from historical Beetaloo GBA region data

Impact mode	Line of evidence 1 Summary for hydraulic fracturing impact modes in the Beetaloo GBA region
F1 – Hydraulic fracture growth into aquifer	As hydraulic fracture stimulation has only been applied to two wells in the Beetaloo GBA region, there is limited there is limited evidence to review for this impact mode, however, there is substantial physical separation between the Kyalla and Velkerri formations and the closest overlying aquifers. F1 impact mode likelihood summary for the Beetaloo GBA region: **Rare**
F2 – Hydraulic fracture growth into well	As the Beetaloo GBA region is not currently under active development for shale gas, the spacing of wells is very large and the current likelihood of a hydraulic fracture treatment intersecting an offset well is very remote. F2 impact mode likelihood summary for the Beetaloo GBA region: **Rare**
F3 – Hydraulic fracture growth into fault	Evidence from hydraulic fracturing activities to date in the Beetaloo GBA region has not indicated that excessive vertical hydraulic fracture growth has occurred though intersection with transmissive vertically oriented faults. F3 impact mode likelihood summary for the Beetaloo GBA region: **Rare**

Well integrity impact mode review for the Beetaloo GBA region

Representative well integrity data in the Beetaloo GBA region is scarce due to the early stage of petroleum industry operations however the inquiry 'Scientific inquiry into hydraulic fracturing in the Northern Territory' undertaken in 2018 provides a reference for the qualitative review. The STRIKE database (strike.nt.gov.au) shows 23 petroleum wells drilled to date in the Beetaloo GBA region with additional detail of the industry activity to date provided in the petroleum prospectivity technical appendix (Hall et al., 2020).

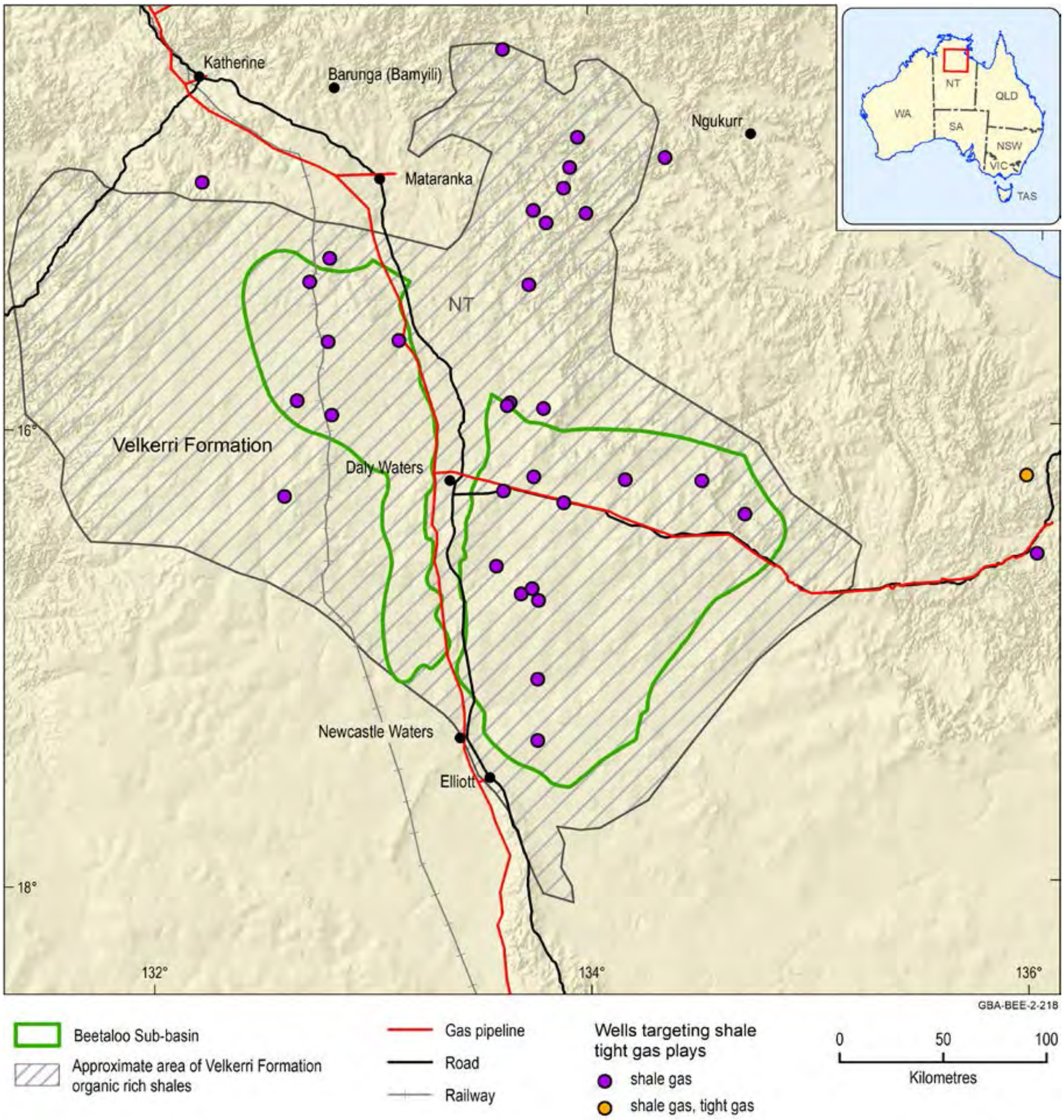

Figure 7 Map of petroleum wells in the Beetaloo GBA region and surrounding area from (Frery et al., 2020).

Source: adapted from Pepper et al, (2018)
Data: Australian Topographic Base Map (Web Mercator) Web Map Server (WMS) (Geoscience Australia, 2017a). Oil and gas pipelines from the National Oil and Gas Infrastructure WMS (Geoscience Australia, 2017b). Beetaloo GBA region based on the NT DPIR Beetaloo Sub-basin definition (Department of Primary Industry and Resources (NT), 2017). Approximate extent of the organic-rich Velkerri and Barney Creek formations is based on the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018)
Element: GBA-BEE-2-218

The proposed industry well integrity controls for upcoming exploration wells include: cementing to surface of all annuli, pressure testing of production casing (but not annuli), routine inspection and validation of all well integrity barriers and monitoring of offset aquifer bores for Kyalla112 N2-1/1H. (Origin Energy, 2019). Additionally, all wells drilled in the NT require a cement bond log to verify the quality of the well construction (Northern Territory Government, 2019).

The Beetaloo GBA region does not have enough well integrity data for a quantitative assessment but qualitatively the likelihoods of well integrity impact modes appear to be similar to shale gas developments in other international jurisdictions with similar industry practices and regulation. The qualitative assessments of each impact from the Beetaloo GBA region reflect the findings of the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018).

Line of evidence 1 qualitative assessment for Beetaloo GBA region well integrity impact modes

W1 - Well rupture or failure across barriers

There has been no evidence of well rupture or total well integrity failure in historical Beetaloo GBA region operations identified to date. Any analysis of potential well rupture or failure across multiple well barriers would be strongly influenced by local in-situ geological conditions and individual well design and construction.

The qualitative likelihood of 'Rare' for impact mode 'W1 - Well rupture or failure across barriers' for the Beetaloo GBA region reflects the findings of the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018).

W2 - Migration along casing from reservoir to surface

Well integrity data in the Beetaloo GBA region appear to be scarce. In order for liquids to migrate to the surface along a well in the event of a failed well annulus, there must be an interval with overpressured pore fluids (Huddlestone-Holmes et al., 2018). As described in the GBA Stage 2 Beetaloo petroleum prospectivity appendix (Hall et al., 2020) overpressured intervals have been reported in the Velkerri and Kyalla formations and the Moroak Sandstone in the Beetaloo GBA region. Overpressure intervals are commonly targeted in petroleum wells and it is anticipated that operators will develop appropriate engineering techniques to achieve competent cement jobs to minimise the likelihood of well annulus integrity problems in the Beetaloo GBA region.

The qualitative likelihood of 'Rare' for impact mode 'W2 - Migration along casing from reservoir to surface' for the Beetaloo GBA region reflects the findings of the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018).

W3 - Migration along casing between rock layers

It is not always possible to detect fluid flow in the well annulus between different formations either from surface measurements or with downhole tools. No evidence of fluid migration between subsurface layers in historical Beetaloo GBA operations identified to date however as with 'W2 - Migration along casing from reservoir to surface', the presence of overpressure intervals in the Beetaloo GBA could provide a pressure differential to drive fluids if a conductive pathway existed along the well casing.

The qualitative likelihood of 'Unlikely' for impact mode 'W3 - Migration along casing between rock layers' for the Beetaloo GBA region reflects the findings of the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018).

W4 - Migration along decommissioned / abandoned wells

No evidence of failure of well integrity in decommissioned wells in the Beetaloo GBA region has been identified to date. However, the data are scarce, and the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018) considered that some decommissioned wells were likely to leak methane albeit at low levels and some level of monitoring is required.

The qualitative likelihood of 'Unlikely' for impact mode 'W4 - Migration along decommissioned / abandoned wells' for the Beetaloo GBA region reflects the findings of the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018).

W5 - Loss of well control (blowout)

Shale gas wells such as those which would target the Beetaloo GBA region are intrinsically less prone to significant loss of well control incidents due to the lower initial permeability of the target interval (i.e. they could not support significant flow to surface until after the well has been completed and hydraulically fractured) (Huddlestone-Holmes et al., 2018). The qualitative likelihood was not assessed for impact mode 'W5 - Loss of well control (blowout)' for the Beetaloo GBA region reflecting the early stages of the industry operations as outlined in the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018).

Summary of line of evidence 1 qualitative assessment

The results of the Stage 2 qualitative assessment of five compromised well integrity impact modes against historical data for the Beetaloo GBA region are summarised below in Table 20. These results are combined with line of evidence 2: Findings from relevant reviews and inquiries (Table 4) to form the qualitative assessment presented in (Frery *et al.*, 2020).

Table 20 Qualitative assessment of likelihood of well integrity impact modes from historical Beetaloo GBA region data

Impact mode	Line of evidence 1 Summary for well integrity impact modes in the Beetaloo GBA region
W1 - Well rupture or failure across barriers	No evidence of well rupture or total well integrity failure in historical Beetaloo GBA region operations identified to date. Given the controls outlined in Table 2, the likelihood of this impact mode reflects the findings of the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018). W1 impact mode likelihood summary for the Beetaloo GBA region: **Rare**
W2 - Migration along casing from reservoir to surface	No evidence of fluid migration to surface in historical Beetaloo GBA operations identified to date. Given the controls outlined in Table 2, the likelihood of this impact mode reflects the findings of the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018). W2 impact mode likelihood summary for the Beetaloo GBA region: **Rare**
W3 - Migration along casing between rock layers	No evidence of fluid migration between subsurface layers in historical Beetaloo GBA operations identified to date. Given the controls outlined in Table 2, the likelihood of this impact mode reflects the findings of the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018). W3 impact mode likelihood summary for the Beetaloo GBA region: **Unlikely**
W4 - Migration along decommissioned / abandoned wells	No evidence of fluid migration along decommissioned / abandoned wells in historical Beetaloo GBA region operations identified to date. Given the controls outlined in Table 2, the likelihood of this impact mode reflects the findings of the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018). W4 impact mode likelihood summary for the Beetaloo GBA region: **Unlikely**
W5 - Loss of well control (blowout)	No evidence of Loss of well control or blowout has been identified in the Beetaloo GBA region to date. The likelihood of this impact mode marked as ‘not assessed; reflects the findings of the *Final report of the scientific inquiry into hydraulic fracturing in the Northern Territory* (Pepper et al., 2018). W3 impact mode likelihood summary for the Beetaloo GBA region: **Not assessed**

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Glossary

The register of terms and definitions used in the Geological and Bioregional Assessment Program is available online at https://w3id.org/gba/glossary (note that terms and definitions are respectively listed under the 'Name' and 'Description' columns in this register). This register is a list of terms, which are the preferred descriptors for concepts. Other properties are included for each term, including licence information, source of definition and date of approval. Semantic relationships (such as hierarchical relationships) are formalised for some terms, as well as linkages to other terms in related vocabularies. Many of the definitions for these terms have been sourced from external glossaries – several from international sources; spelling variations have been preserved to maintain authenticity of the source.

abandonment: a process which involves shutting down the well and rehabilitating the site. It includes decommissioning the well.

accumulation: in petroleum geosciences, an 'accumulation' is referred to as an individual body of moveable petroleum

activity: for the purposes of Impact Modes and Effects Analysis (IMEA), a planned event associated with unconventional gas resource development. For example, activities during the exploration life-cycle stage include drilling and coring, ground-based geophysics and surface core testing. Activities are grouped into ten major activities, which can occur at different life-cycle stages.

anticline: an arch-shaped fold in rock in which rock layers are upwardly convex. The oldest rock layers form the core of the fold and, outward from the core, progressively younger rocks occur.

aquifer: rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit quantities of water to bores and springs

aquitard: a saturated geological unit that is less permeable than an aquifer, and incapable of transmitting useful quantities of water. Aquitards commonly form a confining layer over an artesian aquifer.

asset: an entity that has value to the community and, for the purposes of geological and bioregional assessments, is associated with a GBA region. An asset is a store of value and may be managed and/or used to maintain and/or produce further value. An asset may have many values associated with it that can be measured from a range of perspectives; for example, the values of a wetland can be measured from ecological, sociocultural and economic perspectives.

bed: in geosciences, the term 'bed' refers to a layer of sediment or sedimentary rock, or stratum. A bed is the smallest stratigraphic unit, generally a centimetre or more in thickness. To be labeled a bed, the stratum must be distinguishable from adjacent beds.

biogenic gas: hydrocarbon gases (which are overwhelmingly (greater than or equal to 99%) methane) produced as a direct consequence of bacterial activity

bore: a narrow, artificially constructed hole or cavity used to intercept, collect or store water from an aquifer, or to passively observe or collect groundwater information. Also known as a borehole or piezometer.

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

casing string: steel pipe used to line a well and support the rock. The casing extends to the surface and is sealed by a cement sheath between the casing and the rock. Often, multiple casings are used to provide additional barriers between the formation and well.

causal pathway: for the purposes of geological and bioregional assessments, the logical chain of events – either planned or unplanned – that link unconventional gas resource development and potential impacts on water and the environment

cement bond log: a key method for testing the integrity of cement used in the construction of the well, especially whether the cement is adhering effectively to both sides of the annulus between casings or between the outer casing and the rock sides

cementing: the application of a liquid slurry of cement and water to various points inside and outside the casing

charge: in petroleum geoscience, a 'charge' refers to the volume of expelled petroleum available for entrapment

Christmas tree: control valves, pressure gauges and chokes assembled at the top of a well to control the flow of gas after the well has been drilled and completed

cleat: the vertical cleavage of coal seams. The main set of joints along which coal breaks when mined.

coal: a rock containing greater than 50 wt.% organic matter

coal seam gas: coal seam gas (CSG) is a form of natural gas (generally 95% to 97% pure methane, CH_4) extracted from coal seams, typically at depths of 300 to 1000 m. Also called coal seam methane (CSM) or coalbed methane (CBM).

compression: lateral force or stress (e.g. tectonic) that tends to decrease the volume of, or shorten, a substance

conceptual model: an abstraction or simplification of reality that describes the most important components and processes of natural and/or anthropogenic systems, and their response to interactions with extrinsic activities or stressors. They provide a transparent and general representation of how complex systems work, and identify gaps or differences in understanding. They are often used as the basis for further modelling, form an important backdrop for assessment and evaluation, and typically have a key role in communication. Conceptual models may take many forms, including descriptive, influence diagrams and pictorial representations.

confined aquifer: an aquifer saturated with confining layers of low-permeability rock or sediment both above and below it. It is under pressure so that when the aquifer is penetrated by a bore, the water will rise above the top of the aquifer.

consequence: synonym of impact

context: the circumstances that form the setting for an event, statement or idea conventional gas: conventional gas is obtained from reservoirs that largely consist of porous sandstone formations capped by impermeable rock, with the gas trapped by buoyancy. The gas can often move to the surface through the gas wells without the need to pump.

Cooper Basin: the Cooper Basin geological province is an Upper Carboniferous – Middle Triassic geological sedimentary basin that is up to 2500 m thick and occurs at depths between 1000 and 4400 m. It is overlain completely by the Eromanga and Lake Eyre basins. Most of the Cooper Basin is in south-west Queensland and north-east SA, and includes a small area of NSW at Cameron Corner. It occupies a total area of approximately 130,000 km^2, including 95,740 km^2 in Queensland, 34,310 km^2 in SA and 8 km^2 in NSW.

crude oil: the portion of petroleum that exists in the liquid phase in natural underground reservoirs and remains liquid at atmospheric conditions of pressure and temperature. Crude oil may include small amounts of non-hydrocarbons produced with the liquids.

crust: the outer part of the Earth, from the surface to the Mohorovicic discontinuity (Moho)

cumulative impact: for the purposes of geological and bioregional assessments, the total environmental change resulting from the development of selected unconventional hydrocarbon resources when all past, present and reasonably foreseeable actions are considered

current controls: the methods or actions currently planned, or in place, to detect hazards when they occur or to reduce the likelihood and/or consequences of these hazards should they occur

dataset: a collection of data in files, in databases or delivered by services that comprise a related set of information. Datasets may be spatial (e.g. a shape file or geodatabase or a Web Feature Service) or aspatial (e.g. an Access database, a list of people or a model configuration file).

deep coal gas: gas in coal beds at depths usually below 2000 m are often described as ‘deep coal gas’. Due to the loss of cleat connectivity and fracture permeability with depth, hydraulic fracturing is used to release the free gas held within the organic porosity and fracture system of the coal seam. As dewatering is not needed, this makes deep coal gas exploration and development similar to shale gas reservoirs.

deformation: folding, faulting, shearing, compression or extension of rocks due to the Earth’s forces

development: a phase in which newly discovered oil or gas fields are put into production by drilling and completing production wells

discovered: the term applied to a petroleum accumulation/reservoir whose existence has been determined by its actual penetration by a well, which has also clearly demonstrated the existence of moveable petroleum by flow to the surface or at least some recovery of a sample of petroleum. Log and/or core data may suffice for proof of existence of moveable petroleum if an analogous reservoir is available for comparison.

dome: a type of anticline where rocks are folded into the shape of an inverted bowl. Strata in a dome dip outward and downward in all directions from a central area.

ecosystem: a dynamic complex of plant, animal, and micro-organism communities and their non-living environment interacting as a functional unit. Note: ecosystems include those that are human-influenced such as rural and urban ecosystems.

effect: for the purposes of Impact Modes and Effects Analysis (IMEA), a change to water or the environment, such as changes to the quantity and/or quality of surface water or groundwater, or to the availability of suitable habitat. An effect is a specific type of an impact (any change resulting from prior events).

Eromanga Basin: an extensive geologic sedimentary basin formed from the Early Jurassic to the Late Cretaceous that can be over 2500 m thick. It overlies several older geological provinces including the Cooper Basin, and is in part overlain by the younger Cenozoic province, the Lake Eyre Basin. The Eromanga Basin is found across much of Queensland, northern SA, southern NT, as well as north-western NSW. The Eromanga Basin encompasses a significant portion of the Great Artesian Basin.

exploration: the search for new hydrocarbon resources by improving geological and prospectivity understanding of an area and/or play through data acquisition, data analysis and interpretation. Exploration may include desktop studies, field mapping, seismic or other geophysical surveys, and drilling.

extraction: the removal of water for use from waterways or aquifers (including storages) by pumping or gravity channels. In the oil and gas industry, extraction refers to the removal of oil and gas from its reservoir rock.

fault: a fracture or zone of fractures in the Earth's crust along which rocks on one side were displaced relative to those on the other side

field: in petroleum geoscience, a 'field' refers to an accumulation, pool, or group of pools of hydrocarbons or other mineral resources in the subsurface. A hydrocarbon field consists of a reservoir with trapped hydrocarbons covered by an impermeable sealing rock, or trapped by hydrostatic pressure.

flowback: the process of allowing fluids and entrained solids to flow from a well following a treatment, either in preparation for a subsequent phase of treatment or in preparation for cleanup and returning the well to production. The flowback period begins when material introduced into the well during the treatment returns to the surface following hydraulic fracturing or refracturing. The flowback period ends when either the well is shut in and permanently disconnected from the flowback equipment or at the startup of production.

flowback water: the fluids and entrained solids that emerge from a well during flowback

fold: a curve or bend of a formerly planar structure, such as rock strata or bedding planes, that generally results from deformation

formation: rock layers that have common physical characteristics (lithology) deposited during a specific period of geological time formation fluid: any fluid within the pores of the rock. It may be water, oil, gas or a mixture. Formation water in shallow aquifers can be fresh. Formation water in deeper layers of rock is typically saline.

formation water: water that occurs naturally in sedimentary rocks

fracking: see hydraulic fracturing

fracture: a crack or surface of breakage within rock not related to foliation or cleavage in metamorphic rock along which there has been no movement. A fracture along which there has been displacement is a fault. When walls of a fracture have moved only normal to each other, the fracture is called a joint. Fractures can enhance permeability of rocks greatly by connecting pores together, and for that reason, fractures are induced mechanically in some reservoirs in order to boost hydrocarbon flow. Fractures may also be referred to as natural fractures to distinguish them from fractures induced as part of a reservoir stimulation or drilling operation. In some shale reservoirs, natural fractures improve production by enhancing effective permeability. In other cases, natural fractures can complicate reservoir stimulation.

free gas: the gaseous phase present in a reservoir or other contained area. Gas may be found either dissolved in reservoir fluids or as free gas that tends to form a gas cap beneath the top seal on the reservoir trap. Both free gas and dissolved gas play important roles in the reservoir-drive mechanism.

geological formation: stratigraphic unit with distinct rock types, which is able to mapped at surface or in the subsurface, and which formed at a specific period of geological time

groundwater: water occurring naturally below ground level (whether stored in or flowing through aquifers or within low-permeability aquitards), or water occurring at a place below ground that has been pumped, diverted or released to that place for storage there. This does not include water held in underground tanks, pipes or other works.

groundwater system: see water system

hazard: an event, or chain of events, that might result in an effect (change in the quality and/or quantity of surface water or groundwater)

horizontal drilling: drilling of a well in a horizontal or near-horizontal plane, usually within the target hydrocarbon-bearing formation. Requires the use of directional drilling techniques that allow the deviation of the well on to a desired trajectory.

hydraulic fracturing: also known as ‘fracking’, ‘fraccing’ or ‘fracture simulation’. This is a process by which geological formations bearing hydrocarbons (oil and gas) are ‘stimulated’ to increase the flow of hydrocarbons and other fluids towards the well. In most cases, hydraulic fracturing is undertaken where the permeability of the formation is initially insufficient to support sustained flow of gas. The process involves the injection of fluids, proppant and additives under high pressure into a geological formation to create a conductive fracture. The fracture extends from the well into the production interval, creating a pathway through which oil or gas is transported to the well.

hydraulic fracturing fluid: the fluid injected into a well for hydraulic fracturing. Consists of a primary carrier fluid (usually water or a gel), a proppant such as sand and chemicals to modify the fluid properties.

hydraulic fracturing stage: hydraulic fracture stimulation conducted at a defined interval along a well. Hydraulic fracture stimulation of horizontal wells will often involve multiple hydraulic fracture stages so as to create hydraulic fractures at multiple locations along the length of the well.

hydrocarbons: various organic compounds composed of hydrogen and carbon atoms that can exist as solids, liquids or gases. Sometimes this term is used loosely to refer to petroleum.

hydrogeology: the study of groundwater, including flow in aquifers, groundwater resource evaluation, and the chemistry of interactions between water and rock

hydrostatic pressure: equal pressure in all direction, equivalent to the pressure which is exerted on a portion of a column of water as a result of the weight of the fluid above it

impact: the difference between what could happen as a result of activities and processes associated with extractive industries, such as shale, tight and deep coal gas development, and what would happen without them. Impacts may be changes that occur to the natural environment, community or economy. Impacts can be a direct or indirect result of activities, or a cumulative result of multiple activities or processes.

impact cause: an activity (or aspect of an activity) that initiates a hazardous chain of events

impact mode: the manner in which a hazardous chain of events (initiated by an impact cause) could result in an effect (change in the quality and/or quantity of surface water or groundwater). There might be multiple impact modes for each activity or chain of events.

Impact Modes and Effects Analysis: a systematic hazard identification and prioritisation technique based on Failure Modes and Effects Analysis

injection: the forcing or pumping of substances into a porous and permeable subsurface rock formation. Examples of injected substances can include either gases or liquids.

Lake Eyre Basin: a geologic province containing Cenozoic terrestrial sedimentary rocks within the Lake Eyre surface water catchment. It covers parts of northern and eastern SA, south-eastern NT, western Queensland and north-western NSW. In the Cooper GBA region, the basin sedimentary package is less than 300 m thick.

life-cycle stage: one of five stages of operations in unconventional gas resource development considered as part of the Impact Modes and Effects Analysis (IMEA). These are exploration, appraisal, development, production, and rehabilitation. Each life-cycle stage is further divided into major activities, which are further divided into activities.

likelihood: probability that something might happen likelihood score: for the purposes of Impact Modes and Effects Analysis (IMEA), the annual probability of a hazard occurring, which is scored so that a one-unit increase (or decrease) in score indicates a ten-fold increase (or decrease) in the probability of occurrence

lithology: the description of rocks, especially in hand specimen and in outcrop, on the basis of characteristics such as colour, mineralogic composition and grain size

major activity: for the purposes of Impact Modes and Effects Analysis (IMEA), a group of activities associated with a common part of the shale, tight or deep coal gas resource development process. There are ten major activities used in geological and bioregional assessments ranging from 'construction' through to 'well abandonment and rehabilitation'. Major activities may occur across different life cycles, though often with differing levels of intensity; for example, drilling may occur in the exploration, appraisal, development and production life cycles but is at its peak during development.

material: pertinent or relevant

mature: a hydrocarbon source rock that has started generating hydrocarbons

metamorphic rock : a rock formed from pre-existing rock due to high temperature and pressure in the Earth's crust, but without complete melting

methane: a colourless, odourless gas, the simplest parafin hydrocarbon, formula CH4. It is the principal constituent of natural gas and is also found associated with crude oil. Methane is a greenhouse gas in the atmosphere because it absorbs long-wavelength radiation from the Earth's surface.

migration: the process whereby fluids and gases move through rocks. In petroleum geoscience, 'migration' refers to when petroleum moves from source rocks toward reservoirs or seep sites. Primary migration consists of movement of petroleum to exit the source rock. Secondary migration occurs when oil and gas move along a carrier bed from the source to the reservoir or seep. Tertiary migration is where oil and gas move from one trap to another or to a seep.

natural gas: the portion of petroleum that exists either in the gaseous phase or is in solution in crude oil in natural underground reservoirs, and which is gaseous at atmospheric conditions of pressure and temperature. Natural gas may include amounts of non-hydrocarbons.

oil: a mixture of liquid hydrocarbons and other compounds of different molecular weights. Gas is often found in association with oil. Also see petroleum.

operator: the company or individual responsible for managing an exploration, development or production operation

organic matter: biogenic, carbonaceous materials. Organic matter preserved in rocks includes kerogen, bitumen, oil and gas. Different types of organic matter can have different oil-generative potential.

outcrop: a body of rock exposed at the surface of the Earth overpressure: occurs when the pore pressure is higher than the hydrostatic pressure, caused by an increase in the amount of fluid or gas in the rock, or changes to the rock that reduce the amount of pore space. If the fluid cannot escape, the result is an increase in pore pressure. Overpressure can only occur where there are impermeable layers preventing the vertical flow of water, otherwise the water would flow upwards to equalise back to hydrostatic pressure.

P10: in terms of petroleum resource classification, P10 indicates a 10% probability that this volume of oil or gas will be found or exceeded

pay: a reservoir or portion of a reservoir that contains economically producible hydrocarbons. The term derives from the fact that it is capable of 'paying' an income. Pay is also called pay sand or pay zone. The overall interval in which pay sections occur is the gross pay; the smaller portions of the gross pay that meet local criteria for pay (such as minimum porosity, permeability and hydrocarbon saturation) are net pay.

pay zone: see pay

perforation: a channel created through the casing and cement in a well to allow fluid to flow between the well and the reservoir (hydraulic fracturing fluids into the reservoir, or gas and oil into the well). The most common method uses perforating guns equipped with shaped explosive charges that produce a jet.

permeability: the measure of the ability of a rock, soil or sediment to yield or transmit a fluid. The magnitude of permeability depends largely on the porosity and the interconnectivity of pores and spaces in the ground.

petroleum: a naturally occurring mixture consisting predominantly of hydrocarbons in the gaseous, liquid or solid phase

petroleum system: the genetic relationship between a pod of source rock that is actively producing hydrocarbon, and the resulting oil and gas accumulations. It includes all the essential elements and processes needed for oil and gas accumulations to exist. These include the source, reservoir, seal, and overburden rocks, the trap formation, and the hydrocarbon generation, migration and accumulation processes. All essential elements and processes must occur in the appropriate time and space in order for petroleum to accumulate.

play: a conceptual model for a style of hydrocarbon accumulation used during exploration to develop prospects in a basin, region or trend and used by development personnel to continue exploiting a given trend. A play (or group of interrelated plays) generally occurs in a single petroleum system.

plug: a mechanical device or material (such as cement) placed within a well to prevent vertical movement of fluids

porosity: the proportion of the volume of rock consisting of pores, usually expressed as a percentage of the total rock or soil mass potential effect: specific types of impacts or changes to water or the environment, such as changes to the quantity and/or quality of surface water or groundwater, or to the availability of suitable habitat

produced water: a term used in the oil industry to describe water that is produced as a by-product along with the oil and gas. Oil and gas reservoirs often have water as well as hydrocarbons, sometimes in a zone that lies under the hydrocarbons, and sometimes in the same zone with the oil and gas. The terms 'co-produced water' and 'produced water' are sometimes used interchangeably by government and industry. However, in the geological and bioregional assessments, 'produced water' is used to describe water produced as a by-product of shale and tight gas resource development, whereas 'co-produced water' refers to the large amounts of water produced as a by-product of coal seam gas development.

producing: a well or rock formation from which oil, gas or water is produced

production: in petroleum resource assessments, 'production' refers to the cumulative quantity of oil and natural gas that has been recovered already (by a specified date). This is primarily output from operations that has already been produced.

production activity: any physical activity associated with drilling and hydraulic fracturing (which may include clearing and/or well construction) pursuant to the granting of production approvals for onshore shale gas on a production licence

production approvals: all operational approvals granted under the Schedule and all environmental approvals granted under the Petroleum Environment Regulations on a production licence for a production activity

production casing: a casing string that is set across the reservoir interval and within which the primary completion components are installed

production well: a well used to remove oil or gas from a reservoir

production zone: hydrocarbon producing zone of the shale formation

proppant: a component of the hydraulic fracturing fluid system comprising sand, ceramics or other granular material that 'prop' open fractures to prevent them from closing when the injection is stopped

reservoir: a subsurface body of rock having sufficient porosity and permeability to store and transmit fluids and gases. Sedimentary rocks are the most common reservoir rocks because they have more porosity than most igneous and metamorphic rocks and form under temperature conditions at which hydrocarbons can be preserved. A reservoir is a critical component of a complete petroleum system.

reservoir rock: any porous and permeable rock that contains liquids or gases (e.g. petroleum, water, CO_2), such as porous sandstone, vuggy carbonate and fractured shale

ridge: a narrow, linear geological feature that forms a continuous elevated crest for some distance (e.g. a chain of hills or mountains or a watershed) risk: the effect of uncertainty on objectives (ASNZ ISO 3100). This involves assessing the potential consequences and likelihood of impacts to environmental and human values that may stem from an action, under the uncertainty caused by variability and incomplete knowledge of the system of interest.

sandstone: a sedimentary rock composed of sand-sized particles (measuring 0.05–2.0 mm in diameter), typically quartz

seal: a relatively impermeable rock, commonly shale, anhydrite or salt, that forms a barrier or cap above and around reservoir rock such that fluids cannot migrate beyond the reservoir. A seal is a critical component of a complete petroleum system.

sediment: various materials deposited by water, wind or glacial ice, or by precipitation from water by chemical or biological action (e.g. clay, sand, carbonate)

sedimentary rock: a rock formed by lithification of sediment transported or precipitated at the Earth's surface and accumulated in layers. These rocks can contain fragments of older rock transported and deposited by water, air or ice, chemical rocks formed by precipitation from solution, and remains of plants and animals.

seismic survey: a method for imaging the subsurface using controlled seismic energy sources and receivers at the surface. Measures the reflection and refraction of seismic energy as it travels through rock.

sensitivity: the degree to which the output of a model (numerical or otherwise) responds to uncertainty in a model input

severity: magnitude of an impact

shale: a fine-grained sedimentary rock formed by lithification of mud that is fissile or fractures easily along bedding planes and is dominated by clay-sized particles

shale gas: generally extracted from a clay-rich sedimentary rock, which has naturally low permeability. The gas it contains is either adsorbed or in a free state in the pores of the rock.

shear: a frictional force that tends to cause contiguous parts of a body to slide relative to each other in a direction parallel to their plane of contact

source rock: a rock rich in organic matter which, if heated sufficiently, will generate oil or gas. Typical source rocks, usually shales or limestones, contain about 1% organic matter and at least 0.5% total organic carbon (TOC), although a rich source rock might have as much as 10% organic matter. Rocks of marine origin tend to be oil-prone, whereas terrestrial source rocks (such as coal) tend to be gas-prone. Preservation of organic matter without degradation is critical to creating a good source rock, and necessary for a complete petroleum system. Under the right conditions, source rocks may also be reservoir rocks, as in the case of shale gas reservoirs.

spring: a naturally occurring discharge of groundwater flowing out of the ground, often forming a small stream or pool of water. Typically, it represents the point at which the watertable intersects ground level.

stratigraphy: the study of the history, composition, relative ages and distribution of stratified rock strata, and its interpretation to reveal Earth's history. However, it has gained broader usage to refer to the sequential order and description of rocks in a region.

stress: the force applied to a body that can result in deformation, or strain, usually described in terms of magnitude per unit of area, or intensity

stressor: chemical or biological agent, environmental condition or external stimulus that might contribute to an impact mode

structure: a geological feature produced by deformation of the Earth's crust, such as a fold or a fault; a feature within a rock, such as a fracture or bedding surface; or, more generally, the spatial arrangement of rocks

surface casing vent flow: flow of gas from a vent in the annulus between surface casing and other casing strings in a well

surface water: water that flows over land and in watercourses or artificial channels and can be captured, stored and supplemented from dams and reservoirs

sustained casing pressure: sustained pressure in the annulus between casing strings

thermogenic gas: hydrocarbon gases generated by the thermal breakdown of organic matter. These usually occur at depths exceeding 1000 m below the land surface or seabed

tight gas: tight gas is trapped in reservoirs characterised by very low porosity and permeability. The rock pores that contain the gas are minuscule, and the interconnections between them are so limited that the gas can only migrate through it with great difficulty.

trap: a geologic feature that permits an accumulation of liquid or gas (e.g. natural gas, water, oil, injected CO_2) and prevents its escape. Traps may be structural (e.g. domes, anticlines), stratigraphic (pinchouts, permeability changes) or combinations of both.

unconventional gas: unconventional gas is generally produced from complex geological systems that prevent or significantly limit the migration of gas and require innovative technological solutions for extraction. There are numerous types of unconventional gas such as coal seam gas, deep coal gas, shale gas and tight gas.

water system: a system that is hydrologically connected and described at the level desired for management purposes (e.g. subcatchment, catchment, basin or drainage division, or groundwater management unit, subaquifer, aquifer, groundwater basin)

watertable: the upper surface of a body of groundwater occurring in an unconfined aquifer. At the watertable, pore water pressure equals atmospheric pressure.

well: typically a narrow diameter hole drilled into the earth for the purposes of exploring, evaluating, injecting or recovering various natural resources, such as hydrocarbons (oil and gas), water or carbon dioxide. Wells are sometimes known as a 'wellbore'.

well barrier: envelope of one or several dependent barrier elements (including casing, cement, and any other downhole or surface sealing components) that prevent fluids from flowing unintentionally between a bore or a well and geological formations, between geological formations or to the surface.

well barrier failure: when a single, specific barrier fails to contain fluids (remaining barriers maintaining containment)

well integrity: maintaining full control of fluids (or gases) within a well at all times by employing and maintaining one or more well barriers to prevent unintended fluid (gas or liquid) movement between formations with different pressure regimes, or loss of containment to the environment

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

well pad: the area of land on which the surface infrastructure for drilling and hydraulic fracturing operations are placed. The size of a well pad depends on the type of operation (for example, well pads are larger during the initial drilling and hydraulic fracturing than at production).

zonal isolation: exclusion of fluids such as water or gas in one zone from mixing with fluids in another zone

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