Background Paper on Seismicity

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The New South Wales Chief Scientist and Engineer as part of the Review of coal seam gas activities in NSW

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Summary

The term "earthquake" refers to the ground shaking caused when rocks in the ground break.

Earthquakes occur naturally. Earthquakes occur when rocks rupture because of changes in the stress in the Earth or changes in the pressure of fluid in the pores of the rock. They can also be induced by human activities that affect the stress and/or fluid pressure regime in the Earth.

Mining can affect the stress regime and induce earthquakes. The withdrawal of liquids (water, oil or gas) from reservoir formations can affect the stress regime and induce earthquakes in the rocks above and below the reservoir.

Other human activities can affect the pore fluid pressure and cause hydrofracture-induced earthquakes. In this Background Paper, a distinction is made between intentional and unintentional hydrofracturing caused by human activities. Activities that intentionally or unintentionally induce earthquakes through hydrofracturing are:

- The filling of water storage dams (unintentional hydrofracture) (the filling of reservoirs can also affect the stress regime);
- Intentional hydrofracturing of gas reservoirs by the coal seam gas industry (and other parts of the oil and gas sectors); and
- Unintentional hydrofracturing in the energy industries, usually caused by the disposal of waste water (or other liquids) by injecting them into rock formations.

"Seismicity" refers to the population of earthquakes in a region. It is a term that encompasses the number of earthquakes, their magnitudes, and the time frame in which earthquakes of a particular magnitude will recur. Low seismicity means not many earthquakes and not many large ones occur, even over a long time period. High seismicity means more earthquakes, some of which could have larger magnitudes, and in a shorter time frame.

In New South Wales, the lowest natural seismicity occurs in sedimentary basins including those where coal seam gas operations are underway. Of those sedimentary basins, the seismicity in the Sydney Basin is higher than in the other basins, but it is lower than in the New England Fold Belt to the north and much lower than the seismicity in the Lachlan Fold Belt to the south.

The modes of failure in rock are tensional, shear or hybrid tensional shear failure. In tensional failure, the two sides of the rock move away from each other with no lateral displacements. In shear failure they are displaced laterally with respect to each other with no displacement away from each other. In hybrid tensional shear failure, both kinds of displacement occur.

Stress in the Earth can be resolved into three orthogonal components, of which one will be the maximum principal stress, one the minimum principal stress and the other the

intermediate principal stress. Differential stress is the difference between the maximum and minimum stresses.

Tensional failure occurs at low differential stress and high pore fluid pressure. Under the present stress regime in eastern Australia, tensional cracks will be horizontal.

Shear failure occurs at higher differential stresses and lower pore fluid pressures than tensional failure. Under the stress regime in eastern Australia, shear failure will be by reverse faulting on faults oriented at about 30° to the horizontal.

Hybrid tensional shear failure occurs at differential stresses and pore fluid pressures between those that cause tensional failure and those that cause shear failure.

Mining and the filling of water storage dams can affect both the stress regime and the pore fluid pressures. These activities are mentioned in this Background Paper for completeness but are not associated with the coal seam gas industry.

In the coal seam gas industry, intentional hydrofracturing raises the pore fluid pressure in the coal seam in order to create fractures that will act as permeability pathways. The pathways allow water in the coal seam to be pumped out to release and harvest the gas. In the coal seam gas sector, intentional hydrofracturing causes very small earthquakes, usually with magnitudes $M \leq 0$. Companies would intend to create new cracks or re-activate existing weaknesses in the coal, such as natural cleats. Case studies from overseas show that if weak, pre-existing faults exist and the hydrofractures intersect them, the faults can be reactivated at the higher fluid pressures used during the hydrofracture stimulation operations. Earthquakes caused by the reactivation of faults in this way also tend to have very small magnitudes. Both the new cracks and those from reactivating existing weaknesses and faults occur within hundreds of metres of the injection well and within days of the hydrofracture stimulation beginning. They usually stop soon after the high pressures in the well are released.

Unintentional hydrofracturing is usually associated with the injection of orders of magnitude larger volumes of water (usually waste water or other fluids) over much longer periods of time, often decades. The injected water raises the pore fluid pressure in the reservoir rocks over large areas (in some case studies up to 5 km from the injection well), and when these intersect existing weak and optimally oriented faults, the pressures induce rupture on the fault. Earthquake magnitudes can be as high as $M = 5 - 6$. When injection is stopped, the earthquakes often continue for several years because the fluid pressure front continues to spread out from the well. If suitably placed wells exist, the earthquakes can be stopped or at least their incidence decreased by pumping water, oil or gas from the reservoir and reducing the pore fluid pressure over a large area, particularly near the fault that has been reactivated.

The withdrawal of fluids (gas, oil or water) from reservoir rocks over long periods of time can also induce earthquakes. The removal of the fluids causes the reservoir rocks to contract, drawing down the land surface above the reservoir that is being depleted. This causes local stress changes above, under and on the flanks of the reservoir. Under the stress regime in eastern Australia, should earthquakes be induced in this way, reverse faults would form above and/or below the reservoir.

The mid-continent of the United States of America has experienced a 6 fold increase in seismicity (earthquakes with M > 3) since 2000. This has been associated with activities in the oil and gas industry. Increased seismicity in Arkansas and Oklahoma has been associated with the reactivation of existing faults by the long term injection of waste water. Increased seismicity has also occurred in areas of coal seam gas production although no cause has been attributed to the increase.

An analysis of coal seam wells and earthquakes in New South Wales found no unequivocal link between earthquakes recorded by the Australian National Seismograph Network (ANSN) and coal seam gas activities. No similar analysis was done for other states in Australia. The caveats that apply to these finding are (i) the readily available data on which coal seam gas wells have been hydrofractured are incomplete, and (ii) the coverage of earthquakes for the areas of interest is complete only for magnitudes above M = 3; smaller earthquakes might not have been detected. The industry here is much younger than the industry in the US, where the injection of large volumes of waste water has been underway for periods of years to decades.

Induced earthquakes differ from naturally occurring earthquakes only in that the stress or pore fluid pressure changes that induce them are from human activity rather than natural occurring. Induced earthquakes can be monitored using existing technology.

The monitoring of earthquakes caused by intentional hydrofracturing allows the rupture growth to be monitored. Monitoring rupture growth is important in deciding whether the fractures have reached the target distance, and that they have stayed within the rock formation being stimulated.

The recording systems should be kept in place for a period of time after the hydrofracture operation to check whether the fractures have reached an existing fault and it is being reactivated. The signature for a fault being reactivated would be increased seismicity in a linear band associated with the fault, and probably earthquakes with magnitudes greater than M = 0.

When an existing fault is reactivated, increased porosity would be generated in the fault. In eastern Australia, the fault would dip at 30° and therefore would initially provide a low permeability pathway for high pressure hydrofracture fluids to move into other strata. Subsequently, when water in the coal seam is pumped out to start gas production and pressures in the coal seam lowered, a reactivated fault would provide a pathway for formation waters above and below the coal seam to flow into the coal seam. This could disrupt aquifers and require additional ongoing pumping of the coal seam to continue efficient gas production.

The seismic monitoring of hydrofracture operations is a Leading Practice but not a Mandatory Practice in the NSW Code of Practice for Coal Seam Fracture Stimulation.

Earthquakes that occur during intentional hydrofracturing are best monitored using seismometers deployed down wells and placed below, above and to the sides of the area being hydrofractured. This will mean that the very high frequency signals will be recorded. They are required to determine accurately (i) their locations, and especially their depths and (ii) their magnitudes. However, for shallow hydrofracture stimulations, surface seismometers can be used.

The New South Wales Code of Practice for Coal Seam Gas Fracture Stimulation includes seismic monitoring as a Leading Practice but it is not mandatory under the code.

The analysis of earthquake data to determine the earthquake focal mechanism, and therefore whether rupture is by tensional, shear or hybrid failure, currently cannot be done rapidly (in near real time). This would inform whether hydrofracturing fluids have entered and are reactivating a fault. Turning the theory into a practical tool that can be scaled for small earthquake using high signal frequencies and sparse data is a subject for future research and development.

Any larger earthquakes that might be induced in the future by unintentional hydrofracturing can be monitored by the ANSN. However, the ANSN was not designed for and therefore cannot be relied on to detect any small ($M < 3$) earthquakes that might be pre-cursors to larger earthquakes. Local seismograph networks deployed in and around the areas of coal seam gas production could do that.

The monitoring of surface heights and well pressures would also be valuable indicators that stresses and pressures are reaching critical levels that could trigger earthquakes, especially if the monitoring results are linked with robust reservoir models that can be used to predict rupture behaviour.

Calculating the risks associated with natural earthquakes affecting coal seam gas wells and other infrastructure in a robust way is beyond the scope of this background paper and requires engineering input. However, this paper notes that coal seam gas operations are conducted in areas of low seismicity, and coal seam gas wells are designed to withstand the stresses they are likely to encounter during their life cycle. This study found no earthquakes with magnitudes $M > 4$, ie. large enough to cause even minor damage through ground shaking, close to the coal seam gas wells in NSW.

In the preparation of this report, the author identified a major asymmetry in the knowledge, skills and data available to the energy industry, government regulators and the public, with the industry the best informed and the public the least well informed. The asymmetry affected the amount and completeness of data available to the study.

This asymmetry also applies to the way people perceive the threat from earthquakes, whether natural or induced.

In the author's experience, even small earthquakes can cause concern amongst the public. The public will want to know what caused the earthquake, and especially if it will affect them. If the event poses no threat, then a "Nil Threat" bulletin issued quickly, and an explanation of why it is not a threat, can dispel the concerns. This is reflected in the number of calls that are made to emergency services before and after earthquake bulletins are made public through the media. If the earthquake has caused damage, injuries or death, then information on what is likely to have happened helps people who are not involved know that they are safe. In cases where the public holds suspicions that the earthquakes might be induced, assurances to the public would be most effective if the source of information is independent of any of the stakeholders.

1. Introduction

The New South Wales Government has commissioned the Chief Scientist and Engineer to prepare a report on coal seam gas. As inputs to that report, the Chief Scientist and Engineer has in turn commissioned a number of Background Papers on relevant topics. This report on Seismicity is one of the Background Papers. Terms of reference for the preparation of this Background Paper are in Appendix 1.

The term "seismicity" is described below. It is a term used to describe a population of earthquakes. This Background Paper identifies a number of causes of earthquakes:

- Natural earthquakes are caused by natural geological processes. They are sometimes also caused tectonic earthquakes.
- Induced earthquakes are caused by some form of human activity. This Background paper identifies a number of categories of induced earthquakes:
- Some earthquakes are induced by human activities that mainly affect the stress in the Earth. Two forms of this kind of induced earthquake are described: (i) mining induced earthquakes and (ii) earthquakes that are induced by the long term withdrawal of fluids (water, gas and oil) from reservoir rocks.
- Earthquakes are also induced when fluids injected into the ground hydrofracture rocks. This Background Paper distinguished between two kinds of hydrofractures:
    - The oil and gas industries, including the coal seam gas sector, intentionally hydrofractures reservoir rocks to create permeability that will allow the oil and gas to be extracted.
    - The industries overseas have been known to cause unintentional hydrofractures through the long term disposal of waste fluids by injecting them down wells.

This paper is in two parts. The body of the paper of the paper follows a set of questions set out in the terms of reference for the paper. This part of the paper is written so the reader can get an overview of the topic as a whole without having to delve far into any individual aspect of the topic. It refers to a number of Appendices that form the second part of the paper. The Appendices provide both background information to the content of the main body of the report, and more detail on a number of aspects.

Appendix 2 summarises the science behind hydrofracturing. Appendix 3 describes how earthquake size is measured. Appendices 4 and 5 provide overviews of seismicity in the United States of America and New South Wales, respectively. Recent seismicity in the United States was reviewed because an increase of up to 6 fold in seismicity in the US mid-continent is reported in the recent scientific literature as potentially caused by activities in the energy industries. The seismicity in New South Wales was then reviewed to examine whether similar patterns in seismicity have arisen in New South Wales (Appendix 5). Appendix 5 also examines individual earthquakes that have occurred near coal seam gas wells to assess whether a causal relationship is likely between the activities at the well and the earthquakes.

2. What are seismicity and induced seismicity?

When rocks break, some of the energy that is released is in the form of ground shaking. The ground shaking is called an earthquake (ie., the Earth "quakes"). The population of earthquakes in a region is referred to as seismicity.

Appendix 3 describes ways in which earthquake size is measured. Intensity is a measure of what people feel, observe and respond to. Intensity is measured on the 12 point Modified Mercalli Scale. Magnitude is a measure of size of the earthquake based on instrumental (seismograph) measurements. It is a proxy for the energy released by an earthquake. Magnitude scales are logarithmic and theoretically have no upper magnitude limit. Very small earthquakes can have negative magnitudes. A number of magnitude scales are in use in Australia. This paper refers to the Richter and Moment Magnitude scales, but to avoid confusion the scales are referred to interchangeably.

Gutenberg and Richter (1944) developed an empirical relationship which showed that the number of earthquakes in a region increases by around an order of magnitude for each decrease of a magnitude unit. That is, for every earthquake of magnitude M = 5, there would be around 10 earthquakes with M = 4, 100 earthquakes with M = 3, and so on. Alternatively, for every 100 earthquakes of M = 3, there is likely to be around 10 of M = 4 and probably 1 of M = 5.

The time frame for considering earthquakes in a region is also a factor in defining seismicity. In areas where few earthquakes have been monitored since seismographs were installed, a large earthquake may not have been observed because it might occur only every 10,000 or even 100,000 years. This is called the recurrence interval.

Therefore referring to the seismicity of a region includes a reference not only to the number of earthquakes, but also their size distribution and the recurrence interval.

The earthquake distribution in New South Wales can be used to illustrate this point. Figure 1 shows all earthquakes recorded in New South Wales since 1980. The base map is a satellite image (Courtesy Google earth) with the shaded areas showing the sedimentary basins.

Spatially, the earthquakes in Figure 1 fall into two categories – those in fold belts and those in sedimentary basins. Fold belts contain rocks that in general are older than those in sedimentary basins. Because they are older, they have experienced more geological processes, and are therefore, in layman's terms, harder and more brittle. The highest concentration occurs in south eastern New South Wales in a geological province called the Lachlan Fold Belt. In Figure 1, the Lachlan Fold Belt is not colour-shaded as a sedimentary basin. It has the highest seismicity of any province in New South Wales. The New England Fold Belt in the state's north east has the second highest level of seismicity in New South Wales.

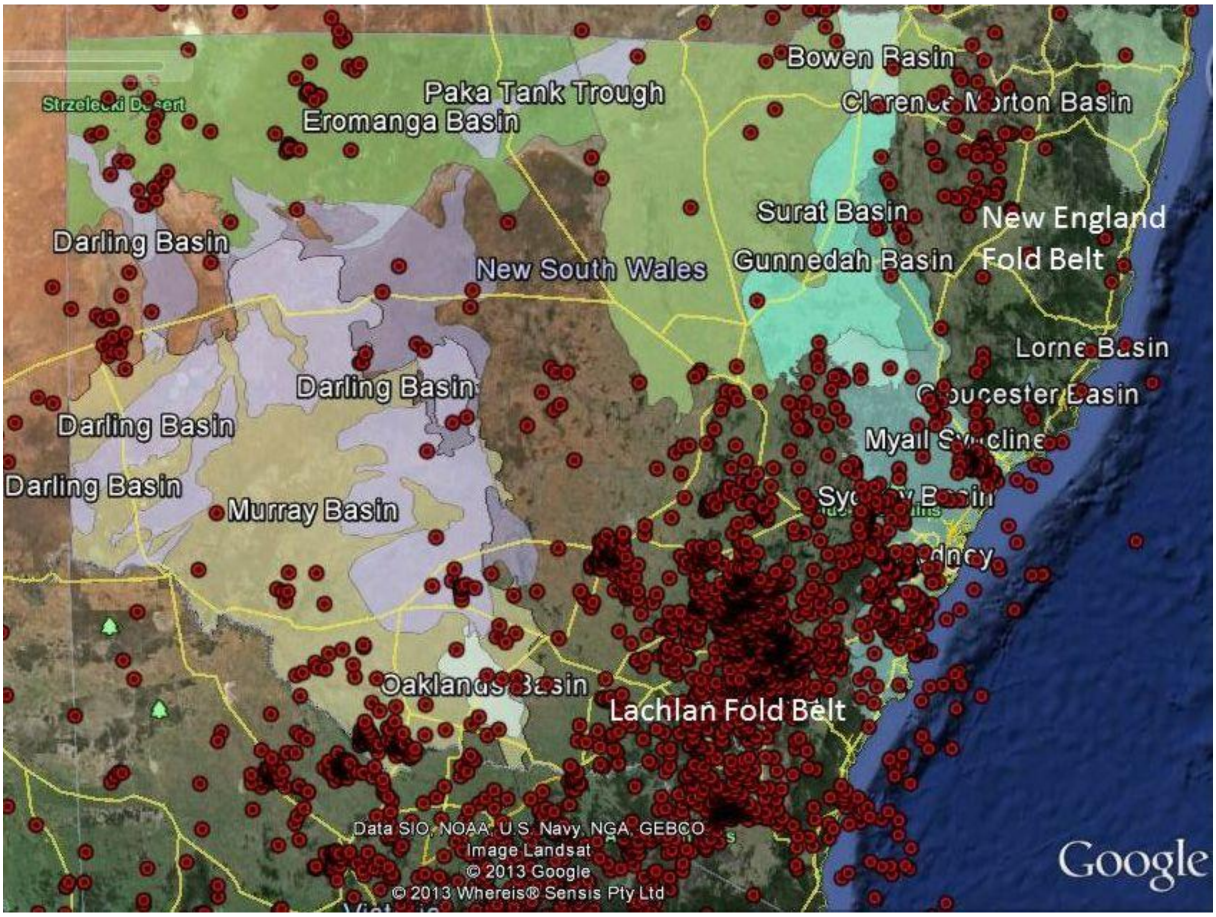

Figure 1: All earthquakes recorded in New South Wales since 1980 (red circles) superimposed on a satellite image (onshore) and a map showing the outlines of sedimentary basins (coloured polygons. Sources: Earthquakes – Geoscience Australia on line database; Sedimentary Basins – NSW Geological Survey online data warehouse; other data attributed in the image.

Coal seam gas is produced from rocks in sedimentary basins. Note that younger sedimentary basins often overlap older basins. For example, the Murray Basin in western NSW overlies a number of the remnants of the older Darling Basin. The Surat Basin in the north overlies the southern part of the older Bowen and Gunnedah Basins. Oil and gas companies tend to refer to the basin that produces their oil and gas. So, for example, where the Surat Basin overlies the Bowen Basin, the well will be referred to as in the Surat Basin if the gas is produced from the Surat Basin and the Bowen Basin if the well is extracting gas from the Bowen Basin.

Sedimentary basins have fewer earthquakes. The Sydney Basin (west of Sydney with its name partly obscured by earthquake symbols) has more earthquakes than the other basins but fewer than the Lachlan Fold Belt. Its highest seismicity is along its south western margin with the Lachlan Fold Belt, and along its north eastern margin with the New England Fold Belt, where magnitudes reach M≥5.6.

Other sedimentary basins have lower levels of seismicity.

The relative levels of seismicity between geological provinces generally hold whether earthquake size or earthquake numbers are considered.

The earthquakes in Figure 1 are natural or tectonic earthquakes[1] caused when the rocks in the Earth's crust yield to the stresses imposed on them. The stresses arise in the Earth because of external forces, most of which are imposed at the edges of the lithospheric plate on which the Australian continent is situated (Hillis et al., 2000). This phenomenon can arise at many spatial scales. For example, although the reason for the higher levels of seismicity along the boundaries of the Sydney Basin has not been absolutely determined, it is possibly caused by the buttressing of the older fold belts to the north and south against the basement rocks of the basin.

The term "induced seismicity" refers to earthquakes that are caused by some form of human activity.

Zoback et al. (2002) offered the hypothesis that the continental lithosphere in the United States (and by extrapolation in parts of other continents) is in a meta-stable equilibrium within the ambient stress field. That is, rocks that can break under the ambient stresses have broken, leaving many that are just below the yield stress threshold that will break if anything disturbs the equilibrium. The theory is supported by the continuing levels of seismicity within continents caused when conditions change as continents move across the face of the Earth and adjust to the changing stress conditions.

3. What factors can cause induced seismicity?

3.2 Factors that influence rupture in rocks

The factors that can cause otherwise intact but stressed rocks to break are an increase in the stress or an increase in the pressure of fluid in the cracks and pores in the rock. This is described more fully in Appendix 2. Only a summary is given here.

The left hand side of Figure 2 shows failure mode curves for intact[2] rock of the form introduced by Cox (2010). A failure mode diagram describes the conditions under which rocks will break. Three curves are shown, as described below. The positions of the curves are based on rock physical property values used by Cox (2010) (see also the caption to Figure A2.2 in Appendix 2) and were calculated for this report for a depth of 1,000m (1 km) which is around the maximum depth of coal seam gas wells in New South Wales.

[1] Geoscience Australia tries to distinguish between naturally occurring earthquakes and explosions caused by mining. However, in a population of earthquakes of this size, some earthquakes induced by human activity may have been included in the database at Geoscience Australia. They would be a minority of the earthquakes.
[2] The term "intact rock" was used by Cox (2010) to describe rock that does not contain any cracks, faults or other weak zones.

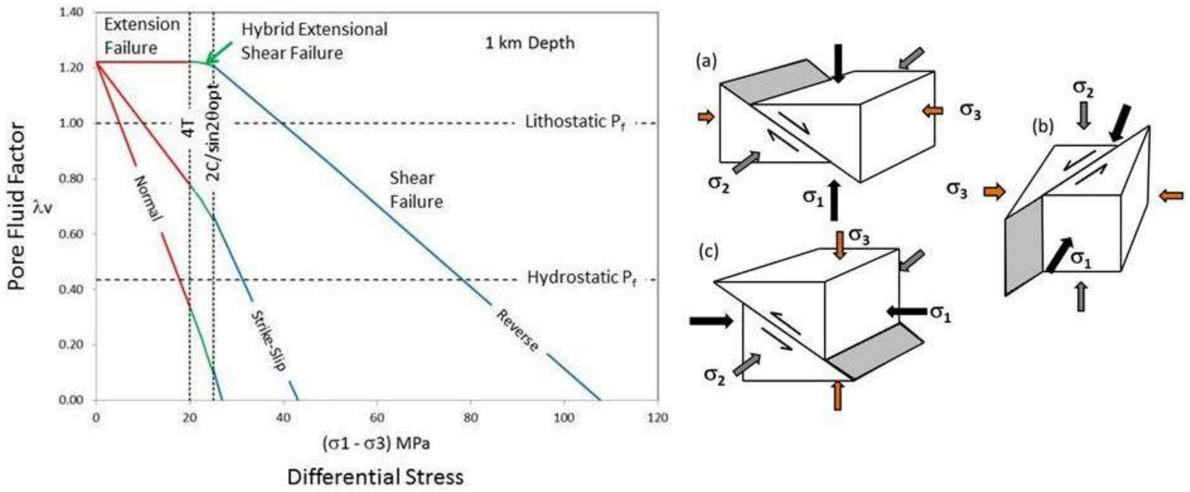

Figure 2: Left hand side: Failure mode curves for normal, strike-slip and reverse faults in intact rock. The red part of each curve is for tensional rupture; blue is for shear rupture, and green is for hybrid tensional shear rupture. Right hand side: block diagrams showing the directions rock on one side of a shear fault moves relative to the other side for (a) normal, (b) strike slip and (c) reverse faults. The coloured arrows show the directions of the principal stresses: black - σ_1, the maximum principal stress, brown - σ_3, the minimum principal stress, and grey - σ_2, the intermediate principal stress (The colour scheme in this slide is used throughout the report for consistency).

The purpose of Figure 2 is to illustrate the various forms of rock failure that can occur. It is not intended to be a model of any real situation; should fracturing in a real situation need to be modelled, physical property measurements should be made of the rocks there and the values substituted into the equations given by Cox (2010).

The vertical axis in Figure 2 (left hand side) is pore fluid factor λv, which is the ratio of the pressure of fluid in pores in the rock to the vertical stress. The vertical stress is the weight of the rocks above the depth of interest. The vertical axis does not represent a cross section through the Earth; it applies to a particular depth in the Earth. If the pressure of fluids in the pores of the rock results from the weight of water in interconnected pores and cracks through the Earth, then the pore fluid factor will be around 0.4 (shown as a dotted line labelled "Hydrostatic P_f"). If the fluid pressure in the pores of the rock is equal to the weight of rocks above the depth of interest, the pore fluid factor will be 1 (labelled "Lithostatic P_f"). Rocks in which the pore fluid factor is greater than 1 are said to be overpressured.

Within the Earth, the stresses to which rocks are exposed can be resolved into maximum, minimum and intermediate principal stresses. In Figure 2 (left hand side), the horizontal axis is differential stress (σ_1 - σ_3), where σ_1 is the maximum principal stress and σ_3 is the minimum principal stress

The three failure mode curves in Figure 1 are for three versions of the orientation of the stress field. Each curve has three parts (coloured blue, green and red, representing modes of failure in rock – shear failure, tensional failure and hybrid tensional shear. The shear and tensional failure modes are shown diagrammatically in Figure 3.

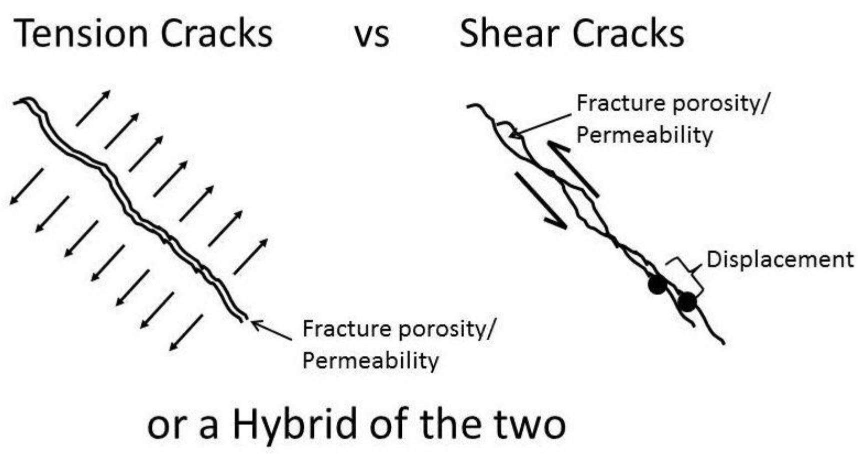

Figure 3: Diagrammatic representations of tension and shear cracks.

Tension cracks form by the rock on the two sides of the crack moving away from each other without any lateral displacement. Shear cracks form when the rocks on either side move laterally past each other. Hybrid tensional shear cracks form when both kinds of movement occur.

Whether shear, tensional or hybrid tensional shear fractures form depend on the physical properties of the rock (Tensile Strength, Cohesive Strength and Coefficient of Internal Friction – see Appendix 2) and the differential stress (Figure 2).

The orientation of the principal stresses determines what kind of shear fault occurs [See Figure 2 (right hand side) for the directions of the rock on one side of the fault moves relative to the other]:

- <u>Normal faults form when the maximum principal stress (σ_1) is vertical</u> and the minimum principal stress (σ_3) is horizontal; the intermediate principal stress (σ_2) is horizontal. Normal faults require the lowest differential stress and/or pore fluid factors.
- <u>Strike slip faults form when the intermediate principal stress (σ_2) is vertical</u>; both the maximum principal stress (σ_1) and the minimum principal stress (σ_3) are horizontal. Strike-slip faults require differential stresses and/or pore fluid factors that are higher than for normal faults but lower than for reverse faults.
- <u>Reverse faults form when the minimum principal stress (σ_3) is vertical</u> and when the maximum principal stress (σ_1) is horizontal; the intermediate principal stress (σ_2) is horizontal. Reverse faults require the highest differential stress and/or pore fluid factors.

In eastern Australia the minimum principal stress is usually vertical, which means that reverse faults form, although local exceptions occur (eg., at the Talbingo Reservoir in the Lachlan Fold Belt; Muirhead, 1981).

The failure mode curve for reverse faulting in intact rock is shown in Figure 4 (left hand side), along with the block diagram showing the displacement of the blocks either side of a shear fault (right hand side).

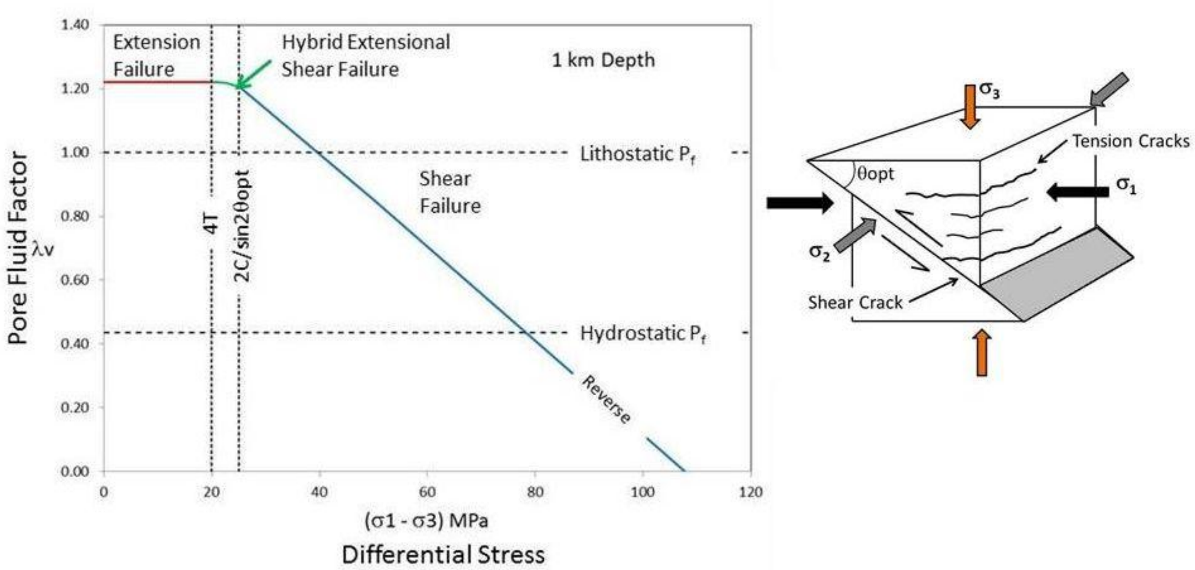

Figure 4: Right hand side: Failure mode diagram for intact rock in a stress regime in which the minimum principal stress σ_3 is vertical. Shear failure in this orientation of the stress field would result in a reverse fault. Left hand side: block diagram for a reverse fault, also showing the orientation of tensional cracks that would form instead of a reverse shear fault at low differential stresses. Only one mode of fracture can occur under a fixed stress field, depending on the differential stress (σ_1- σ_3).

Rocks are stable in the stress and pore fluid pressure regime under the failure mode curve in Figure 4. Rocks cannot sustain the pore fluid factors and differential stresses that lie above the failure mode curve.

Tension cracks form when the differential stress is less than 4 times the tensional strength (T) of the rock (Secor, 1995). They form orthogonal to the minimum principal stress σ_3. This is shown diagrammatically in Figure 4, which has the minimum principal stress vertical and the tension fractures horizontal. Shear cracks form when the differential stress is greater than (2C/sin 2θopt) (Cox, 2010). C is the cohesive strength of the rock. θopt is the angle that the shear crack will form with the maximum principal stress σ_1 (Figure 4, right hand side). For the values of rock properties used in Figure 4, θopt is 26.5° to the horizontal. Because they form at different differential stresses, tension cracks and shear faults cannot form at the same time in intact rock.

To induce a fracture and therefore an earthquake, the rock has to be moved to conditions above the failure mode curve. This means that either

- the differential stress has to be increased, which will move the rock to the right in Figure 4 towards the shear failure part of the failure mode curve, or

- the pore fluid factor has to be increased, which will move it up (ie., parallel to the vertical axis) to which ever part of the curve is relevant to the current differential stress regime, therefore triggering either tensional, shear or hybrid failure, or
- both the differential stress and pore fluid factor have to be increased, which will more the rock diagonally up to the right.

3.3 Factors that influence differential stress and pore fluid factor

Various forms of human activity can modify either the local stress regime, or the pore fluid pressure, or both.

Davies et al. (2013) listed 198 earthquakes that they or previous researchers had considered to be induced. Without exception earthquake catalogues such as those of Davies et al (2013) and The National Academies (2011) are incomplete, either

- because earthquakes that may have been induced by human activity are documented in local rather than the readily available international scientific literature (eg., the seismicity after the filling of the Thompson Dam in Victoria commenced in 1983, including an M=5.0 earthquake in 1996 (Allen et al., 2000), or
- because demonstrating an unequivocal causal link between the human activity and the earthquakes that followed can be difficult. Davies et al. (2013) acknowledged that they excluded some earthquakes from their catalogue for this reason.

One earthquake in New South Wales (a M=5.5 earthquake that occurred near the Warragamba Dam west of Sydney in 1973) illustrates the uncertainty in building catalogues of induced seismicity. It was not included in the catalogue of Davies et al. (2013) but was included in the catalogue of The National Academies (2011). Gibson et al. (1977) attributed it to the filling of the reservoir but Mills and Fitch (1977) thought that it occurred too long after the filling of the dam for the relationship to be causal.

The apparently induced earthquakes listed by Davies et al. (2013) are re-categorised in Figure 5 according to the processes that can change the pore fluid pressure, those that change the local stress through adding or removing mass, and those that can affect both the pore fluid pressure and the stress.

3.2.1 Mining

Mining contributes a large number of induced earthquakes, and their magnitudes can be significant, up to M = 5.

Mining can depress the local water table when mines are de-watered. This would reduce the pore fluid factor, moving the rock down the vertical axis away from the failure mode curve. Dewatering by itself is therefore an unlikely cause of earthquakes[3].

Mining changes the local stress regime in several ways.

- Underground mining creates a void, and the intersection of the void with the remaining rock creates a singularity in the stress field around which stresses can concentrate. Depending on the orientation of the void and the ambient regional stress field, this could increase the local differential stress (by increasing $\sigma 1$ or decreasing $\sigma 3$), thereby moving the rock to the right in the failure mode diagram and towards the shear part of the failure mode curve. This can lead to earthquakes in the immediate vicinity of the mine.
- Open cut mines create large holes from which a significant mass of rock is removed, and often placed in waste dumps to the side of the hole. The re-distribution of the rock mass can have several effects. Firstly, it reduces the vertical stress σ_v immediately under the mine more than it reduces the pore fluid pressure P_f, because rocks are denser than water. The removal of the rock therefore increases the pore fluid factor (P_f/σ_v) immediately under the mine. This will move the rock up (parallel to the vertical axis) towards the failure mode curve. Secondly, the unloading effect of large mines can cause flexure in the upper crustal rocks in the vicinity of the mine, thereby changing the local stress field. This can alter the differential stress, which, if increased, will move the rock to the right towards the shear part of the failure mode curve.
- Sudden roof collapses shake the ground, and explosions set off to break rock can also look like and feel earthquakes.

Many large underground mines have installed local seismograph networks to monitor for mining induced seismicity. If small earthquakes are detected and are interpreted as pre-cursors for larger earthquakes steps are taken to ensure the safety of miners.

Mining induced seismicity is not considered further in this report.

[3] But see the discussion below about earthquakes stimulated by the withdrawal of significant amounts of fluid from oil and gas reservoirs by affecting the local stress field.

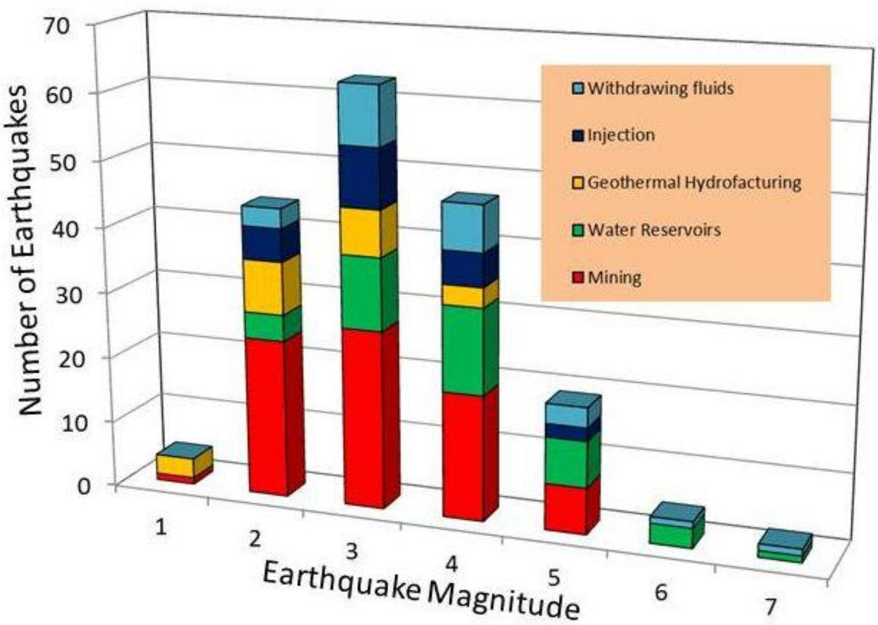

Figure 5: Histogram of earthquakes reported by Davies et al. (2013) as likely to have been induced, grouped according to human activities that would have caused a change in the stress regime, the fluid pressure regime, or both. The horizontal axis shows the magnitudes of the earthquakes in the Davies et al. (2013) catalogue; the vertical axis shows the number of earthquakes of each magnitude colour coded by category.

3.2.2 Water Reservoirs

Water reservoirs constitute the second largest category of induced earthquakes in the Davies et al., (2013) compilation, and cause some of the largest induced earthquake magnitudes (up to M = 7).

Water reservoirs induce earthquakes in several ways;

- The water in the dams constitutes an additional load on the Earth's crust, thereby modifying the local stress field. Depending on the orientation of the principal stresses and the size of the load, the differential stress could be increased, pushing the rock towards the right in the failure mode diagram and towards the shear failure mode curve[4]. Many earthquakes induced by dams appear to be on pre-existing faults (eg., at the Talbingo Reservoir in New South Wales; Muirhead, 1981), and if the faults are weak they can be reactivated at much lower differential stresses and/or pore fluid factors than those required to fracture intact rock (see Appendix 2).
- Water percolating from the dam into the country rock increases the pore fluid factor; the higher the dam, the higher the pressure driving the percolation. Increasing the

[4] The potential for taking away mass (mining) and adding weight (filling a reservoir) to both increase the differential stress would appear to be contradictory. However (i) the change in the local stress field under each activity is complex, as discussed below for the case of removing liquids from reservoirs, and (ii) the effect will also be determined by the orientation of the stress field which changes from region to region.

pore fluid factor will push the rock near the dam up (parallel to the vertical axis) in the failure mode diagram towards the failure mode curve.
Over time, the induced seismicity can migrate away from the dam as the pressure front in the percolating water moves through the rock. In the case of the Talbingo Dam the seismicity migrated about 5 km downstream (Muirhead, 1981). This is the same order of magnitude distances that induced seismicity can occur from long term injection of liquid waste into wells (see below and Appendix 4).

- Both a change in the local stress regime and a change in the pore fluid factor could apply in most cases of induced seismicity near dams, although separating the relative amounts of the two factors would require detailed modelling.

Many storage dams have local seismograph networks installed to detect and monitor reservoir-induced seismicity.

3.2.3 Geothermal Hydrofracturing

This category (hydrofracturing) is specifically called "Geothermal Hydrofracturing" because of all the applications of hydrofracturing in the energy sector, geothermal hydrofracturing seems to produce earthquakes that are large enough to be felt, including up to M = 4. Examples of large earthquakes come from both overseas and Australia; eg., Deichmann and Giardini, (2009) at Basel in Switzerland and Baisch, et al., (2006) in the Cooper Basin in South Australia.

In the hydrofracturing at Basel in Switzerland, the larger earthquakes started to occur after the hydrofracturing had been underway for 6 days using increasing flow rates and well head pressures. The injection was stopped but the earthquakes continued; magnitudes reached M = 3.4. The seismicity declined when the well was opened and hydrofracturing water allowed to flow out to relieve the reservoir pressure. However, sporadic seismicity was still occurring in the hydrofractured rock volume two years after the hydrofracturing operation. The larger earthquakes were analysed for their focal mechanism (see Appendix 3 for a discussion of focal mechanisms). Some earthquakes, including some that occurred in the hydrofractured rock volume up to several months after the well was opened, had focal mechanisms indicating a volume change at the earthquake source; ie., they were probably caused by tensional fracture. Others, including the one with the largest magnitude, had focal mechanisms indicating that they occurred on strike-slip shear faults. Deichmann and Giardini (2009) concluded these earthquakes were triggered by the increased pore pressures.

Baisch et al. (2006; 2009) analysed the earthquakes caused by several hydrofracture stimulations of a geothermal well in the Cooper Basin in South Australia. During the first hydrofracture operation in 2003, earthquake magnitudes reached M = 3.7; in the second stimulation in 2005, magnitudes were smaller, with a maximum estimated at M = 2.9. In the second stimulation, earthquakes were not detected for the first 22 hours, and they occurred on the periphery of the volume of rock hydrofractured in 2003. Baisch et al (2009) concluded that the earthquakes were the signature of shear dislocation on a sub-horizontal fracture zone, with many small movements adding to cumulative displacements that commonly reached several centimetres in the hydrofractured rock.

Hydrofracturing in other energy sectors does not tend to generate earthquakes as large as those in the geothermal sector; generally gas industry hydrofracturing produces earthquake populations with much smaller magnitudes, typically $M \leq 0$ (Maxwell et al., 2009; Shemeta and Anderson, 2010; Šilneý et al., 2009). This may be explained in part by the physical properties of the rock being hydrofractured. Granite has a shear modulus and a bulk modulus greater than those for coal and shale. Therefore for a given fault rupture area and displacement, the magnitude of the earthquake will be greater in granite than in coal and shale (see Appendix 3).

3.2.4 Injection

Injection includes the injection of liquids into wells for a number of reasons: stimulating and/or re-pressurising reservoirs for enhanced oil recovery and the disposal of waste liquids in wells.

Injection of liquids into wells where oil and/or gas production has dropped the formation pressures below pre-production levels should not pose a risk in terms of induced earthquakes if reservoir pressures everywhere are kept below pre-production levels.

However, a number of case studies have demonstrated a link between induced seismicity and injection when the injection has continued for long periods of time and reservoir pressures have been allowed to rise too high. Appendix 4 gives some examples, and examines briefly a 6 fold increase in seismicity in the US mid-continent since 2000 that correlates with activities in the coal seam gas and shale gas industries (Ellsworth et al., 2012). Increased seismicity in Arkansas and Oklahoma is attributed to the re-activation of strike-slip faults by injected fluids. In the case of Oklahoma, injection into depleted reservoirs continued for 17 years before the seismicity was triggered. A magnitude $M = 5.0$ earthquake was triggered by the increased fluid pressures. It in turn triggered a $M = 5.7$ and another $M = 5.0$ earthquake (Keranen et al., 2013).

This is induced seismicity on a previously undocumented and unprecedented scale. It is due to unintentional hydrofracturing. It was not noted in the compilation of Davies et al. (2013). Had it been included, it would have distorted their statistics on induced seismicity and severely altered the shape of the histogram in Figure 5 by increasing the number of earthquakes their magnitudes attributed to injection.

An analysis of the available earthquake and coal seam gas well data in New South Wales found no evidence for an increase in seismicity (Appendix 5). No similar analysis was made for other states in Australia.

3.2.5 Withdrawing Fluids

Segall (1989) developed a theory to explain the location and focal mechanisms for earthquakes that were spatially correlated with oil fields from which oil had been extracted for prolonged periods of time. In some of those fields, reservoir fluid pressures had dropped more than 20 MPa. Earthquake magnitudes reached M = 3.3 - 3.4. Normally, a drop in pore pressure would stabilise rather than destabilise a rock – it would move the point at which the reservoir rocks would plot in a failure mode diagram (Figure 2) downwards (parallel to the Y axis) away from the failure mode curve.

Close examination of surface faulting and the earthquake locations and focal mechanisms of the induced earthquakes showed that the earthquakes occurred in the rocks surrounding the reservoir but not in the reservoir. Depending on the orientation of the regional stress field, they tended to be caused by reverse faulting beneath and above the reservoir and normal faulting on the margins (Figure 6).

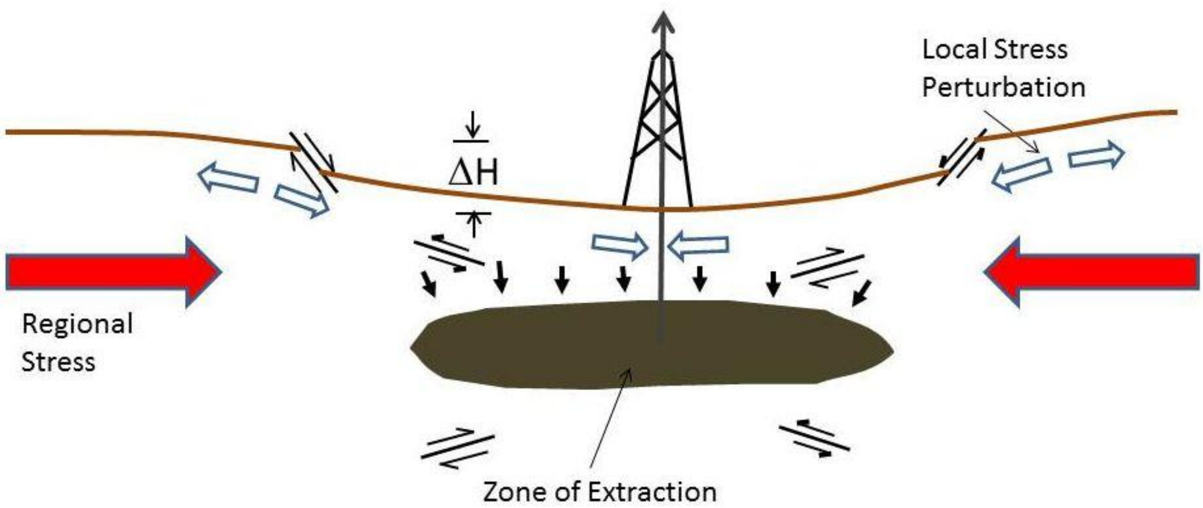

Figure 6: Perturbations in local stress (small open arrows) that are superimposed on the regional stress field (large red arrows) by the withdrawal of fluid from a reservoir, causing contraction of the reservoir and subsequent local surface subsidence. Thrust faults are induced under and above the reservoir and normal faults on the flanks. (after Segall, 1989, Figure 4).

Segall (1989) developed an analytical model to explain the stress changes caused by the withdrawal of large volumes of fluid. His model predicted stress patterns that were consistent with the observed faulting. He explained the stress pattern changes in simple terms in the following way (p945): "Fluid extraction causes the reservoir rock to contract. Contraction in the vertical direction is accommodated by subsidence of the free surface. Contraction in the horizontal direction, on the other hand, is resisted by the surrounding rocks, which are pulled toward the center of the reservoir. This causes the strata above and below the reservoir to be driven into a horizontal compression. Rock far away from the reservoir is displaced less than rock immediately above and below the reservoir, causing the flanking regions to extend."

Segall (1989) considered the case where the withdrawal of fluid was from a permeable reservoir embedded in relatively impermeable surroundings. This would be the case in coal seam gas operations where the withdrawal of formation water was via permeability induced by hydrofracturing, but where the hydrofracturing stayed within the low permeability coal seams. Segall attributed the incidence of earthquakes primarily to changes in stress in the rocks above and below the reservoir. In the failure mode diagram in Figure 2, this is equivalent to the position at which the rock plots being moved to the right towards the failure mode curve; tensional failure is unlikely. Segall observed that the earthquakes occurred on shear zones; this would be consistent with the rocks intersecting the failure mode curve on its shear (blue) segment where differential stresses are higher.

To move the position where a rock will plot in Figure 2 towards the right, the differential stress (σ_1 - σ_3) has to increase. This can be done by increasing σ_1 or decreasing σ_3. Not all areas from which Segall (1989) presented case studies would have had the stress field in the same orientation as eastern Australia (σ_3 vertical, σ_1 horizontal). Because $\sigma 1$ is the horizontal principal stress in Australia, it must be increased. This would be done where the local stress perturbations (small open arrows in Figure 6) are compressive and parallel to $\sigma 1$. Thrust faulting above or below the reservoir would result. Tensional faults on the flanks are less likely.

In the coal seam gas industry, large volumes of water are pumped from the coal seam early in the life of a well. The rates at which water is pumped from the well fall rapidly with time, but low rates continue for much of the life of the well (Figure 7). Coal seam gas wells have anticipated life times of 15 – 20 years.

Segall's (1989) estimated that the withdrawal of water from a reservoir at 1,000 m depth could cause a change of 20MPa for every metre of surface subsidence, depending on the physical properties of the rocks. The question therefore is how much surface subsidence might be expected from the withdrawal of water from a coal seam reservoir? Brown et al. (2013) estimated that surface subsidence could be of the order of decimetres at distances up to three times the radius of the draw down zone, depending on the physical properties of the rocks in and above the reservoir. This would induce stress changes of 2 – 4 MPa for a surface subsidence of 10 – 20 cm.

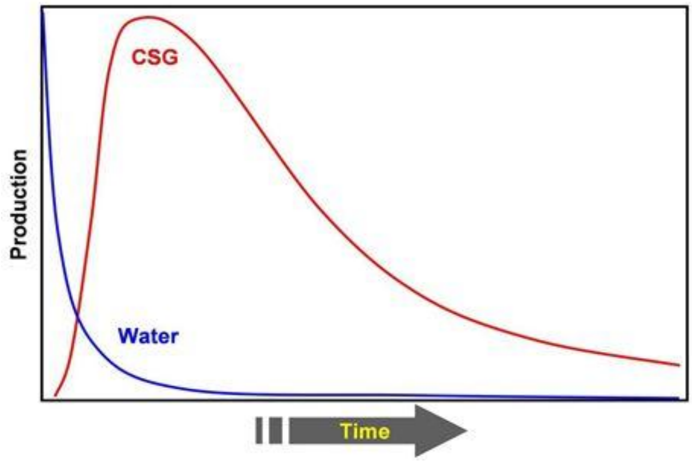

Figure 7: Withdrawal of water (blue curve) and production of gas (red curve) as a function of time for a coal seam gas well. The expected life of a coal seam gas well is 15 – 20 years. This figure:

According to data on petroleum and gas wells available from the NSW Geological Survey online data warehouse[5] the first CSG production wells in New South Wales were drilled in 2004. This would mean around 9 years of water withdrawal; production wells of that age do not have associated seismicity. One earthquake is closely spatially related to a number of production wells near Menangle Park, but the time lag between the drilling of the well and the earthquake is probably too short for a causal relationship between the earthquake and the withdrawal of water (Appendix 5).

3.3 Human Induced Seismicity Related to the Oil and Gas Sector (Summary)

Human induced seismicity related to the oil and gas industry is summarised in the following Table 1 which groups the seismicity according to whether the causes are intentional or unintentional.

Intentional hydrofracturing includes both (i) the hydrofractures close to a well and (ii) any fault reactivation in or immediately adjacent to the hydrofracture zone that happens within hours or days of the hydrofracturing stimulation taking place. These forms of hydrofracturing are discussed in Appendix 2.

Unintentional hydrofracturing is caused by fluid injection. It is also discussed in Appendix 2.

The fourth category of earthquakes in Table 1 is caused by the withdrawal of fluid from reservoirs. This is discussed above and is not due to hydrofracturing.

[5] http://dwh.minerals.nsw.gov.au/CI/warehouse

These categories are used in Appendix 5 (and Table 1 is repeated there) when reviewing whether any of the earthquakes recorded in New South Wales might have been caused by intentional or unintentional hydrofracturing or by the withdrawal of formation waters in the coal seam gas industry.

Table 1: Characteristics of seismicity induced by the injection and withdrawal of fluids

Intentional Hydrofracturing	
Number of events	1,000's for each well, and potentially for each hydrofracture treatment in each well.
Time frame	Within hours to days of start of fraccing.
Maximum Magnitudes	Usually M ≤ 0 (Maxwell et al., 2009; Shemeta and Anderson, 2010; Šilneý et al., 2009)
Where	Within a few 100's of metres of the well
Spatial Distribution	Spread radially with time

Intentional Hydrofracturing - Fault Reactivation Near a Well Being Hydrofractured	
Number of events	100's - 1,000's
Time frame	At the end of fraccing; can be after shut in
Maximum Magnitudes	Usually M ≤ 0 but can be larger (Maxwell et al., 2009; Rutledge & Phillips, 2003; Šilneý et al., 2009)
Where	Typically at the edges of the fractured volume
Spatial Distribution	Linear patterns 100's of metres long spatially related to existing faults that are usually optimally or near optimally aligned with stress field

Table 1 (Continued)

Unintentional Hydrofracturing – Injection	
Number of events	100's - 1,000's
Time frame	Time is required to raise reservoir pressure above the level required to fracture intact rock or reactivate existing fault; this can be years after the injection begins
Maximum Magnitudes	M = 5.3 (Davies et al., 2013a); M = 5.0, 5.7 (Keranen et al, 2013)
Where	At the edges of the reservoir; ; usually on faults that are optimally or near optimally aligned with stress field because they will reactivate at lower pressures than intact rock
Spatial Distribution	Linear patterns 100's to 1,000's of metres long aligned with existing faults

Unintentional - Fluid Withdrawal	
Number of events	100's
Time frame	Time is required to lower the surface of surrounding countryside; usually years after injection begins.
Maximum Magnitudes	M = 7.3 (Davies et al., 2013a); M = 4.0 (The National Academies (2011); M ≤3.4 (Segall, 1989)
Where	Reverse faults: Under or above the withdrawal zone; Normal faults: On the flanks at distances up to 3 times the width of the withdrawal zone
Spatial Distribution	Even spatial distribution under a zone of surface subsidence that extends either side of the withdrawal zone.

4. What has been the experience nationally and internationally with induced seismic events and gas? How does the NSW situation compare?

Most of the published literature on hydrofracturing and the gas industry that has been examined in the lead up to this report refers to gas wells without distinguishing between coal seam gas, shale gas and tight gas wells. The depths given for the earthquakes would imply that the studies refer to the shale gas industry. The gas industry in the US is much larger than in Australia, with shale gas now accounting for 34 % of US gas production (Medd, 2012).

Human induced seismicity is reviewed in Section 3 in this report (above) and in Appendix 4, which provides maps and comment on increased seismicity in the US mid-continent. Ellsworth et al. (2012) attributed a 6 fold increase in seismicity in the mid-continent of the

US to activities in the energy industry, including the coal seam gas sector in the Raton Basin of Colorado and New Mexico and oil and gas production in Oklahoma and Arkansas. However, they were did not assign specific causes for much of the seismicity, including the seismicity in the Raton Basin.

Large earthquakes have been induced overseas from the injection of waste waters and from the production of oil and gas (Table 1). Earthquakes in New South Wales are reviewed in Appendix 5 of this report on the basis of the parameters listed in Table 1.

Unlike the experience in the much larger gas industry in the US, (i) the sedimentary basins in New South Wales where coal seam gas operations are conducted do not have populations (clusters) of earthquakes that are spatially or temporally correlated with CSG activities; and (ii) no causal link can be demonstrated between CSG wells and individual earthquakes that were recorded on the Australian National Seismograph Network (ANSN) operated by Geoscience Australia.

However, two caveats apply to those findings:

- The data available from the NSW Geological Survey online data warehouse appear to be incomplete, particularly with respect to which wells have been hydrofractured, and
- The coverage of the ANSN is complete for eastern Australia only for earthquakes with $M \geq 3$, although smaller earthquakes are recorded in some places.

5. What is the difference between induced seismicity and other seismic events?

Hydrofracturing is a process that happens naturally. It is the mechanism that assists mineralising fluid to move from the mantle and lower crust and into the upper crust to form metallogenic ore bodies, eg., at Broken Hill, the Bathurst gold fields, the ore bodies at Cobar. It is a process that can fracture the seals over oil and gas fields and cause them to leak (eg., Davies et al., 2013b). It has occurred on Australia's North West Shelf (O'Brien et al., 2001), caused by the change in the stress field following the collision of the Australian lithospheric plate with the subduction zone south of Indonesia.

The difference between induced fractures, which can be tensional, shear or hybrid tensional shear fractures, and natural faults, which seismologists have mostly assumed to occur by shear fracture, is diminishing as researchers develop tools to study very small earthquakes. A full analysis of the stress tensor allows for tensional fracture (Julian et al,1998) as well as shear fracture. Some researchers are now discriminating between hydrofracture-induced earthquakes that have a tensional signature, those that have a shear signature and those that have both (eg., Deichmann and Giardini, 2009; Šilneý et al., 2009).

In simple terms, natural earthquakes and induced earthquakes occur when the rock that breaks experiences a change in stress or pore fluid pressure such that it crosses the failure mode curve in Figure 2. There is only one difference between induced seismicity and natural seismicity. For naturally occurring earthquakes, the cause of the change in stress or pore fluid pressure is natural; in induced seismicity it is man-made.

6. How are induced seismic events monitored and measured?

6.1 Monitoring during hydrofracture operations

Reasons for monitoring induced earthquakes during hydrofracturing stimulation include:

- To monitor fracture growth to ensure that the fractures have reached the target distance (area) to be stimulated, and
- To monitor fracture growth in order to ensure that fractures do not grow out of the formation being stimulated.

To meet these needs, the monitoring data should be analysed in real time.

The earthquakes are usually very small. Abercrombie (1995) argued that the most effective way of monitoring them is with seismometers deployed down boreholes. High frequency signals are attenuated before they reach surface seismometers (Abercrombie, 1995), and using seismometers down boreholes ensures that very high frequency seismic signals are recorded. Very high frequencies are required to (i) locate and (ii) measure magnitude accurately. Accurate depth determination is necessary for ensuring that the fractures are not extending out of the zone being hydrofractured and into the strata above and below. For accurate depth determination, the seismometers should be located above, below and to the sides of the area being stimulated. However, Fisher and Warpinski (2012) observed that arrays of surface seismometers (as distinct from individual seismometers) could be used if the hydrofractures are shallow, although seismic practice would indicate that surface arrays would not have the same depth resolution as seismometers down boreholes.

Magnitude for intentional hydrofracture earthquakes is calculated using traditional seismological methods (Shemeta and Anderson, 2010).

Seismic monitoring can be expensive. The use of borehole arrays requires extra boreholes and expensive equipment designed to operate in hostile environments down boreholes, where the risk of equipment loss through cable breakages is a concern.

The New South Wales Code of Practice for Coal Seam Gas Fracture Stimulation[6] includes seismic monitoring as a Leading Practice but it is not mandatory under the code. The code is outcome based and therefore does not specify the method to be used.

6.2 Monitoring after hydrofracture operations

In some cases earthquakes occur after the active part of the hydrofracture operation is complete. These earthquakes often form linear arrays of events that align with and probably

[6] http://www.resources.nsw.gov.au/community-information/coal-seam-gas/cop

result from the re-activation of local pre-existing faults. Figure A2.4 in Appendix 2 demonstrates that optimally oriented faults can be reactivated at much lower pore fluid factors (and therefore pressures) than those required to hydrofracture intact rock. In the days following a hydrofracture operation, particularly if the well is shut in and the fluid pressures at the well allowed to drop naturally, the pressure front from the hydrofracture will continue to move outwards from the well. If it intersects a pre-existing weak fault the fault can be reactivated.

Monitoring after the completion of the hydrofracture operations would detect the reactivation of the fault. This would be important information in managing future reservoir operations, because

- the fault could be a conduit for migration of ground water out of the reservoir into overlying strata while reservoir pressures are high from the hydrofracture stimulation, and
- into the reservoir after pressures in the reservoir have been pumped down to release the coal seam gas, This would (i) require ongoing pumping of the reservoir and (ii) water flowing into the reservoir from surrounding rock could deplete overlying aquifers.

Monitoring of the seismicity that follows the hydrofracture operations would best be done with downhole seismometers to ensure good depth resolution, as discussed above.

6.3 Regional Monitoring

Regional seismometer networks such as the ANSN would detect earthquakes with magnitudes M > 3, such as those resulting from oil and gas activities in the US, and reported in Appendix 4. At the point where such events can be detected, the problem already exists. The monitoring of seismicity induced by coal seam gas operations as a pro-active step to help mitigate the induction of the seismicity is not a role of the ANSN. Strategies for more pro-active monitoring are set out in Section 8 (below).

7. What is the potential for, and impacts of, induced seismic events associated with CSG activities?

(Include magnitude, 'worst case scenarios, risks and likelihoods of events)? Compare this to induced seismic events arising from other activities such as coal mining, shale gas, conventional gas, geothermal energy, water extraction from aquifers and dam construction.

This is the subject matter of Section 3 (above) and Appendix 4. The subject matter was introduced earlier in order to introduce the science of intentional and unintentional hydrofracturing. Maximum magnitudes for each kind of induced seismicity are given in Table 1, which summarises the data in Section 3 and Appendix 4.

The answer to this question needs to focus on two components: the magnitude of the events and the time frame over which they are likely to occur.

7.1 Seismicity Induced by Intentional Hydrofracturing

Earthquakes induced by intentional hydrofracture stimulations in the gas sector tend to be small (usually $M \leq 0$) and will not be felt, although seismometers can detect them, particularly if the seismometers are deployed down nearby boreholes. With magnitudes of $M \leq 0$ they will not be damaging to nearby infrastructure. They typically occur within hours or days of the start of hydrofracturing.

7.2 Seismicity Induced by Unintentional Hydrofracturing

Seismicity induced by waste water injection can occur close to the injection well [eg., in Oklahoma; Keranen et al. (2013)], and it can also occur kilometres (up to 5 - 8 km in some case studies) from the injection well (Healy e al., 1968; Raleigh et al., 1976). It will probably not stop when injection stops unless steps are taken to reduce the fluid pressures across the affected area of the reservoirs, eg., by pumping from a network of wells. If this is not done, earthquakes could continue to occur for several years. In some case studies, the largest earthquakes occur after injection has stopped, and they can reach magnitudes of M = 5, which can cause damage to non-engineered structures (See Figure Appendices 3 and 4).

Overseas case studies show that earthquakes caused by unintentional hydrofracturing caused by the injection of waste water are likely to occur years after the start of operations rather than soon after operations begin (Table 1; Appendix 4; Healy e al., 1968; Raleigh et al., 1976).

Data available from the NSW Geological Survey online data warehouse do not indicate which wells, if any, are used for waste water disposal in NSW. The CSG wells that are listed as production wells date from 2004. If all waste water is being re-injected down wells rather than being treated and re-used, then the elapsed time since the wells went into production is less than in some of the case studies from the US where long term injection has induced seismicity.

7.3 Seismicity Induced by the Withdrawal of Fluids

Earthquakes with M = 7 have been induced by fluid withdrawal (Figure 5). Based on case studies from the US, it could occur years and even decades after the withdrawal of fluid begins because of the time required to withdraw significant volumes of water

In areas where the maximum principal stress is horizontal, as in eastern Australia, seismicity induced by the withdrawal of fluids would occur on shallow-dipping thrust faults above and/or below the reservoir from which the fluid is being withdrawn. (If the minimum principal stress is horizontal, the induced seismicity would more likely be on shallow normal faults to the sides of the reservoir being depleted.)

No seismicity that is likely to have been induced by the withdrawal of fluids has been detected in NSW (Appendix 5). The time frame since the first recorded production well (2004) is short compared to the time frame in case studies documented by Segall (1989) from the US.

The conditions under which seismicity is likely to be induced by the withdrawal of fluids should be accompanied by a significant and measureable lowering of ground level above the zone of withdrawal (Segall, 1989). This can be monitored and if subsidence is detected early mitigations strategies such as stopping the withdrawal and even re-injecting fluid can be considered.

8. How are microseismic monitoring and other techniques used to measure geological events used in gas extraction?

8.1 Microseismic Monitoring

Under the NSW code of practice for coal seam gas hydrofracture operations, the operators of the gas leases are required to ensure that fractures remain within the target zone and do not connect with water sources. This is an outcome based code, and the process by which the outcome is achieved is not prescribed. Microseismic monitoring is a way of monitoring fracture growth, because each extension of the fracture causes a small earthquake – a micro earthquake.

When an earthquake occurs, it produces several types of seismic waves: the most commonly used are the primary, or P-waves, and shear, or S-waves. P-waves travel faster than S-waves. When recorded on seismographs, the P-waves arrive first. If the velocities of the seismic waves are known in advance, then the difference in the arrival times of the two phases can be used to calculate the distance of the seismograph from the event. Therefore an accurate velocity model must be developed for each gas field to be hydrofractured using information, for example, from seismic surveys and downhole velocity measurements made before the well is hydrofractured.

If each seismometer has three components measuring ground shaking in orthogonal directions (usually Up, North and East), the direction of the earthquake from the seismometer can be calculated by the direction of the first motion of the P-phase on the three components. Technically, the earthquake can be located by combining the distance and direction of the earthquake from one seismometer. However, this location will have an error. The error can be reduced when the locations based on the distances and directions calculated from a number of seismometers are combined.

The estimate of depth is very important for reasons given above for monitoring hydrofracture growth. Any errors in the velocity model will lead to errors in the depth estimate that are larger than the errors in the east and north estimates. The error in depth can be reduced by having seismometers at depth, particularly some below the zone being hydrofractured, and not just on the surface.

In the NSW code, microseismic monitoring is a Leading Practice but not a Mandatory Practice requirement. Under the code, whether a hydrofracture stimulation was monitored using seismic monitoring techniques is not a required parameter in reports to the NSW regulator. Companies are required to maintain records of all hydrofracture stimulation activities. These records must be made available to the regulator for inspection on request, and must be handed over once the well is plugged and abandoned.

The author is aware that at least some if not all companies provide copies of the data from the seismic monitoring of hydrofracture stimulations to the regulators but is not aware of any data sets in for which an analysis of the data is in the public domain.

8.2 Other monitoring techniques

A number of techniques can be used to monitor geological responses to fluid injection or withdrawal in the time lag between the start of CSG operations and the onset of seismicity. The time lag could be years and these techniques work most effectively over that time period. They include:

- The ANSN has the capacity to detect induced earthquakes that would be damaging but not necessarily any small pre-cursor earthquakes at the local scale. Sub-networks of seismographs deployed around the areas of CSG operations would help detect smaller earthquakes that might be indicators of stresses building up in the sub-surface, particularly if used in conjunction with data from the ANSN. Seismic monitoring is a powerful tool if a long time series of events can be developed to help identify whether any increase in the level of seismicity is significant or within the natural variability for the region – eg., see Appendix 4 for a discussion of long term changes in seismicity in the US mid-continent.
  A local network would also provide more accurate earthquake locations than the ANSN so that the spatial relationship of small events to the activities undertaken in production areas could be investigated.
- Changes in height would be an indicator of increasing stresses in the rocks above and below the zones from which water is being withdrawn. In the CSG industry this would be in production gas areas. Changes in height would therefore be an early indicator of potential induced seismicity (see Section 3.2.5).
  Continuous geodetic-standard measurements of height can detect early signs of ground subsidence from the withdrawal of water. A network of continuously recording Global Navigation Satellite Systems can measure height changes over periods of time, and interferometry using data from repeat passes of Synthetic

Aperture Radar satellites can interpolate the GNSS measurements spatially over a considerable area around the operations.
These systems require long time series (5 – 10 years) to establish a baseline before any height changes occur. They have the capacity to measure the height changes in the timescales over which induced seismicity is likely to be triggered by the withdrawal of large quantities of liquid.

- The NSW Code of Practice for hydrofracturing coal seam gas wells calls for the monitoring of water levels and pressures in bores as a means of ensuring water from the coal seams and from hydrofracture simulations do not mix with water in aquifers used for human and agricultural purposes. If undertaken for injection wells, this kind of monitoring, particularly the monitoring of pressure in the reservoir, can be used to ensure that reservoir pressures do not reach the yield threshold for the reservoir during injection.
- However, for the monitoring of reservoir pressures to have any practical benefit, a sound understanding is required of reservoir properties and how the reservoir will respond to changing stress and pore fluid pressure changes. The NSW Code of Practice for hydrofracturing coal seam gas wells requires the development of a well-attributed geological model that can be used to predict hydrofracture behaviour. The code calls for the model to be updated as new information becomes available during the hydrofracture operation. If such a model uses a reservoir engineering approach for the management of reservoir pressures, including the use of physical property values measured for the rocks in and around the reservoir, it would allow the analysis of measured stresses for predicting whether unintentional hydrofracturing is likely to occur, particularly when updated with new information provided by the active monitoring tools described in the preceding three points.

9. What are the knowledge gaps/unknowns/research questions in relation to induced seismicity, natural seismic impacts or micro seismic monitoring, in relation to CSG activities?

There are two kinds of knowledge gaps: an asymmetry in knowledge across the three sectors involved – industry, regulators and public, and areas of scientific endeavour and monitoring that could assist understanding the activities and impacts of the industry.

9.1 Asymmetry in Knowledge

Industry has the best understanding of the science and technology that is deployed in the CSG industry. It is based on decades of practice, technology developed within the industry, and scientific research developed both in the public arena and in industry research laboratories. Regulators (State Government agencies) have some knowledge; they employ trained professionals and hold confidential company reports. The Public including affected land owners have the least skills and knowledge.

The issue of asymmetry of knowledge was raised by University of Queensland researchers in their submission[7] to the process conducted by the Standing Council on Energy Resources to develop the National Harmonised Regulatory Framework for Natural Gas from Coal Seams[8]. They raised the issue raised in the context of regulators needing to have sufficient skills and expertise of what industry is doing in order to monitor the industry effectively.

The access to the kinds of data available to industry and the regulators has been a problem in the development of this report. For example information readily available in the public domain about how many wells and which wells have been hydrofractured is inconsistent – see Appendix 5 – with the result that unless there is evidence that specifically indicates that a well was probably <u>not</u> hydrofractured, the analysis in Appendix 5 has had to assume that many wells might have been hydrofractured.

That is, lack of knowledge, lack of access to knowledge, or simply being unable to find it easily, hinders analysis and requires a "worst case" assumption.

At the very least an indication that datasets are incomplete would be useful; access to complete sets of information where available would be very valuable.

9.2 Gaps in Research and Monitoring

The main gaps that have arisen in the preparation of this report are:

- No seismic monitoring systems are in place in Australia to monitor earthquakes below M = 3, and preferably down to about M = 0 in areas where CSG operations are underway. If small earthquakes are being induced, particularly by injection of waste water or withdrawal of water and gas, they are not likely to be felt. If they are being felt, then their reporting may be seen as subjective rather than objective, and they cannot be analysed to see if they are potential pre-cursors of more damaging earthquakes in the future.
  Monitoring to such low levels is not necessary everywhere – an area extending about 5 – 10 km on all sides of active gas development and production areas would be appropriate. It would be important for any information on earthquakes that are detected to be available to the companies and regulators so that action can be taken to avoid problems in the future, and to the public to keep them informed, in the spirit of the Harmonised Framework (SCER, 2013) (see the comment on this in Section 12).

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[7] http://www.scer.gov.au/files/2012/03/University-of-Queensland.pdf

[8] http://scer.govspace.gov.au/files/2013/06/National-Harmonised-Regulatory-Framework-for-Natural-Gas-from-Coal-Seams.pdf

- No rock physical property values or in-situ stress measurements are available in the public domain without having to trawl through many, large well completion reports. Companies are not required to provide all of their observations to regulators immediately, and regulators are not required to release them to the public when they are provided. Compilations of these data would be useful in developing reservoir models to monitor the behaviour of reservoirs through the development and production of gas fields. Companies would collect these data for their for own gas fields, but such compilations are not available by the research and government sectors whose research and analysis results are the most likely to placed in the public domain. The maintenance of a well-attributed rock properties database would also be useful for the broader industry sector.
- Continuous geodetic-quality height measurements across development and production areas would be valuable for detecting the first signs that induced seismicity might occur, particularly from the withdrawal of fluids. These results should be placed in the public domain.
- Near-real-time focal mechanism studies cannot be done on very small earthquakes using sparse high frequency data. Focal mechanisms would be very useful in determining whether a fracture has intersected an existing fault and the fault is being reactivated. Research and development are needed to scale existing theory to the different conditions of active hydrofracture operations.

10. Provide information on whether natural seismic events have been reported to impact CSG and other conventional hydrocarbon wells. Comment on the risks and likelihood for events in NSW.

10.1 Impact natural seismic events on CSG and other wells

No specific information on this topic is believed to be in the public domain. Insurers of infrastructure may hold confidential information.

10.2 Calculating Risk

<u>The following description of risk is provided as background information and is not definitive of the way the risk should be managed either in CSG operations or under NSW regulations. If a full risk assessment is required, it should have input from engineers and a systematic assessment of the seismic hazard.</u>

Risk is usually defined as the product of three quantities: the likelihood of hazard, what or who is exposed, and whether they are vulnerable.

10.2.1 Hazard

The hazard in the context of this question comes from a naturally occurring earthquake. Hazard is described in terms of the likelihood that an event will occur. In an earthquake risk assessment hazard is defined in terms of the likelihood that peak ground acceleration will exceed a certain amount in a defined period of time.

CSG Wells are engineered structures. Hazard is usually computed separately for each engineered structure, but in doing this for CSG wells, companies would do it in the context of the NSW Code of Practice for Coal Seam Gas Well Integrity[9] and therefore the international standards specified in the code. Although the code is outcome based, a number of the technical and engineering specifications are set out in the code.

Seismic hazard in Australia is mapped by Geoscience Australia as an input to the earthquake loading code AS1170.4 “Structural design actions: Part 4 Earthquake actions in Australia” (Burbidge, 2102) which applies to buildings that do not require their own individual assessments.

Coal seam gas wells are in sedimentary basins, which have low levels of seismicity (Section 2 and Appendix 5). Of the sedimentary basins where coal seam gas operations are underway in New South Wales, the Sydney Basin has the highest seismicity. The largest recorded earthquakes are along the basin boundaries with the Lachlan Fold Belt in the southwest (M = 5.5 near Picton on 10 March, 1995 (Sydney time)) and the New England Fold Belt in the northeast (M = 5.6 15 km south west of Newcastle on 28 December 1989 (Sydney time)). Exploration leases cover much of the Sydney Basin but current CSG development and production is not near the boundaries where seismicity is highest. Away from the boundaries of the basin levels of seismicity are low – few scattered earthquakes with magnitudes generally M < 4 and therefore not damaging to well-constructed infrastructure. Therefore the likelihood of a large earthquake occurring near the CSG operations is low – moderate; ie., the hazard in the Sydney Basin would be low - moderate.

In other sedimentary basins the hazard is low.

10.2.2 Exposure

If an earthquake does occur, what buildings and infrastructure are exposed to the ground shaking? One way to understand exposure is to consider what would happen to the exposure parameter, if the industry expands, say, by a factor of 10 and builds far more infrastructure. Clearly more infrastructure would be exposed to any ground shaking, so the parameter would be higher.

[9] http://www.resources.nsw.gov.au/community-information/coal-seam-gas/cop

Historically the larger earthquakes are on the boundaries of the Sydney Basin at some distance from the CSG infrastructure. The exposure of CSG infrastructure to high levels of ground acceleration is low to moderate.

Exposure would be lower in other basins where seismicity is lower.

10.2.3 Vulnerability

Vulnerability is defined in terms of how the buildings, wells and other infrastructure react to the ground shaking. CSG wells are engineered to withstand the stresses they might encounter during their life cycle. Therefore they should have a low vulnerability.

Other engineered and non-engineered (but well-constructed buildings and infrastructure) are designed to withstand levels of ground shaking (peak ground acceleration) commensurate with their purpose and expected life span. In this example the vulnerability is assumed to be low.

10.2.4 Application of these the three parameters – Hazard, Exposure and Vulnerability

10.2.4.1 The general case

Two examples demonstrate how the parameters of hazard, exposure and vulnerability are applied:

<u>The M = 5.5 earthquake near Picton in 1973</u>: The Warragamba dam is very close to the epicentre of this earthquake. The likelihood of this event happening during its life time was high (high levels of ground shaking); its exposure was high because the earthquake was close (close proximity); and its vulnerability was low because it is an engineered structure.

Because Risk is effectively Hazard × Exposure × Vulnerability, the risk was not high <u>for this earthquake</u> because Vulnerability was low.

<u>The M = 5.6 earthquake 15 km from Newcastle in 1989</u>: The hazard from this earthquake was high: the Geoscience Australia web site reports: "at least four other earthquakes of magnitude 5 or greater have occurred in the surrounding Hunter region since European settlement in 1804". The exposure was high because the earthquake occurred near a major population centre with many more people and buildings. Their vulnerability was high because many of the buildings were not engineered structures.

The risk was therefore high mainly because hazard, exposure and vulnerability were all high. The Geoscience Australia reports:

" One of Australia's most serious natural disasters occurred on 28 December 1989 when an earthquake shook Newcastle in New South Wales, leaving 13 people dead and more than 160 injured. The damage bill has been estimated at A$4 billion, including an insured loss of more than A$1 billion. The earthquake had a magnitude of 5.6 with an epicentre about 15km south of the Newcastle central business district at an estimated depth of 11km. Only one aftershock, magnitude 2.1, was recorded.

The effects were felt over 200 000 square kilometres with isolated reports of movement up to 800 kilometres from Newcastle. Damage to buildings and facilities was reported over an area extending 9000 square kilometres. The earthquake caused damage to more than 35 000 homes, 147 schools, and 3000 commercial and other buildings. At the height of the crisis, between 300 and 400 people were placed in temporary accommodation. In the month following the earthquake, the Disaster Welfare Recovery Centre assisted almost 14 000 people."

10.2.4.2 Specific case of CSG wells

<u>Reiterating that this is not a formal risk assessment but rather is designed to show how risk might be assessed</u>:

In the Sydney Basin, if the probability of the hazard is low - moderate, exposure is low – moderate and vulnerability is low for CSG wells, then the risk must be low or low – moderate.

Risk will be low in other sedimentary basins.

10.3 Other questions

10.3.1 Has seismicity from hydrofracturing impacted on built infrastructure?

This study has revealed no evidence of CSG activities inducing earthquakes in NSW (Appendix 5). Earthquakes magnitudes have to exceed M = 4 to cause minor damage, and higher than M = 4 to cause significant damage. Therefore this study has found no evidence to show that induced earthquakes, whether Intentional or unintentional, have impacted on built infrastructure in Australia.

10.3.2 Have natural earthquakes impacted on CSG wells

No evidence has been found of natural earthquakes impacting on CSG wells in Australia.

Segall (1989) described case studies where the reactivation of low angle shear zones induced by the withdrawal of large amounts of oil and gas "sheared off tens to hundreds of wells over several square kilometres" at depths of 470 – 520 m.

Therefore oil and gas industry activities could impact CSG wells in the future if the lessons of the past are ignored.

11. Discuss any other issues related to this topic.

The terms of reference for this Background Report ask for suggestions for further reading by the interested reader.

In preparing this report, the author found the following documents very good introductions to both the topic and to the broader literature:

- The National Harmonised Regulatory Framework for Natural Gas from Coal Seams 2013 (http://scer.govspace.gov.au/files/2013/06/National-Harmonised-Regulatory-Framework-for-Natural-Gas-from-Coal-Seams.pdf) developed by the Standing Council for Energy and Resources provides an useful overview of the coal seam gas industry in Australia at the time of its publication (May 2013).

- Comments made on the draft National Harmonised Framework also provide valuable comment as well as insights into public perceptions of both governments and the industry. (http://www.scer.gov.au/workstreams/land-access/coal-seam-gas/

- A report by the US National Academies into Induced Seismicity Potential in Energy Technologies is a well written, well rounded and objective description of the science of induced seismicity, and contains a number of very useful and interesting case studies. (http://www.nap.edu/catalog.php?record_id=13355)

- A similar study was done of hydrofracturing in the shale gas industry in the United Kingdom by The Royal Society and The Royal Academy of Engineering. Although a study of shale gas operations, it nevertheless is sufficiently generic that its findings are useful in a study of hydrofracturing in the coal seam gas industry. (http://royalsociety.org/uploadedFiles/Royal_Society_Content/policy/projects/shale-gas/2012-06-28-Shale-gas.pdf).

- The US Environmental Protection Authority (USEPA) produced a report on the impacts of hydraulic fracturing by coal bed methane industry on drinking water in 2004. Chapter 3 of that report contains a lot of useful information on hydrofracturing that is otherwise in obscure journals that are hard to access. It contains references to mine-through studies[10] of hydrofractures that are very revealing in terms of the size and geometry of hydrofractures in coal, including some references to the work of Dr Rob Jeffrey who works at CSIRO in Australia, and who has undertaken mine-through studies in Queensland and NSW. (http://water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/wells_coalbedmethanestudy.cfm.

[10] In mine-through studies, the coal seams in mines are hydrofractured before the coal is extracted. When the mining uncovers the hydrofractures, they can be measured and their behaviour documented.

12. Any other comment you believe relevant to the understanding or management of these issues.

In a previous career, the author had oversight of the operations of the Australian National Seismograph Network and the seismic monitoring part of the Australian Tsunami Warning Centre. Those two functions combined have a role in informing emergency managers when earthquakes have occurred that could impact Australians or Australian interests.

The largest part of this task was managing the public's perception of danger. The public learns of earthquakes and tsunamis from many sources; usually these events are reported quickly in the media and online social media. News of earthquakes travels fast. The author observed instances where reports were appearing on social media even before the seismic waves from the earthquake had reached seismograph stations and the location and magnitude determined (ie., within a few minutes of the earthquake). Managing public reaction and perception is often about being an independent source of accurate information, and being able to provide a simple and trusted message when they do not have to worry about an earthquake.

Most earthquakes in Australia are small, and most people are not affected by them. For those people, the notification of a "Nil threat" goes a long way to mitigate their concerns. However, some earthquakes have caused damage, and a few have injury or death. In these instances, accurate predictions of the likely impact are very valuable.

The emergency services have protocols of telling the public this kind of information.

The message should say where the earthquake happened, when it happened and how big it was. If the cause is known, that should be told as well, without any fear of repercussions. In the case of earthquakes, being able to put the earthquake into historical perspective is usually welcome, eg.:

- This is the first earthquake in this region …
- X earthquakes have happened in the area in the last 25 years …
- The earthquake had a magnitude of 4 and occurred at a depth of 10 km so it is unlikely to have caused any significant damage …
- This is the largest in the region since …

This kind of statement provides reassurance to the Public that they are being provided with up to date information. The author's experience is that once this kind of information is in the public domain there are calls to emergency services slow and even stop.

Currently this kind of information cannot be provided for many small earthquakes in areas where CSG operations are underway.

13. Acknowledgements.

People who reviewed Appendices 4 and 5 are acknowledged in the Version Control blocks in those appendices. The content but not these versions of Appendices 2 and 3 were reviewed by Dr Mark Leonard and Dr David Burbidge of Geoscience Australia. Mrs Elizabeth Fredericks of Geoscience Australia arranged permission to use Figure 7. The maps in the Appendices were produced using Google earth; sources of the imagery in those maps are acknowledged in the background images. Well locations were downloaded from the NSW Geological Survey data warehouse; earthquake information was downloaded from Geoscience Australia website. The locations of the wells and earthquakes were converted to KML format for plotting in Google earth using programs written in Python script.

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Appendix 1: Terms of reference for this Background Paper:

The following Schedule E is part of the agreement between the author and the NSW Chief Scientist and Engineer for the preparation of this Background Paper.

SCHEDULE E

TERMS OF REFERENCE FOR THE BACKGROUND PAPER ON SEISMICITY

To deliver a Background Paper to the Office of the NSW Chief Scientist and Engineer (OCSE) providing information and a discussion about induced seismicity, microseismic monitoring and natural seismic impacts, in relation to CSG activities.

1. The Background Paper should be 50 pages maximum length (excluding appendices). The Background Paper must be delivered electronically in Word format; be fully referenced and contain suggestions for further reading for those interested in gaining a more detailed understanding of the subject.

2. The purpose of the background paper is to provide an overview of induced seismicity, microseismic monitoring and natural seismic impacts, in relation to CSG activities. The paper will identify issues that may arise, their likelihood and how they are addressed.

3. The Background Paper should include discussion of the following:
a. What is seismicity and induced seismicity?

b. What factors can cause induced seismicity?

c. What has been the experience national and internationally with induced seismic events and gas? How does the NSW situation compare?

d. What is the difference between induced seismicity and other seismic events?

e. How are induced seismic events monitored and measured?

f. What is the potential for, and impacts of, induced seismic events associated with CSG activities (include magnitude, ‘worst case scenarios, risks and likelihoods of events)? Compare this to induced seismic events arising from other activities such as coal mining, shale gas, conventional gas, geothermal energy, water extraction from aquifers and dam construction.

g. How are microseismic monitoring and other techniques to measure geological events used in gas extraction?

h. What are the knowledge gaps/unknowns/research questions in relation to induced seismicity, natural seismic impacts or micro seismic monitoring, in relation to CSG activities?

i. Provide information on whether natural seismic events have been reported to impact CSG and other conventional hydrocarbon wells. Comment on the risks and likelihood for events in NSW.

j. Discuss any other issues related to this topic. k. Any other comment you believe relevant to the understanding or management of these issues.

4. The Background Paper should be developed having regard to the following:

a) Under Terms of Reference 6 of the Review (Schedule D), a series of information papers will be commissioned about the CSG industry; which are aimed at informing the Review and a wide audience, both general and technical. These information papers are likely to be publicly released and may appear on the website of the Chief Scientist and Engineer.

b) Each Review information paper will draw on multiple sources of information, including background papers which may be sourced from different experts.

c) The Review information papers are likely to include extracts from the expert background papers, including the Background Paper delivered under this contract. In some cases, a background paper may be appended to a Review information paper in part or full, and therefore may be publicly released and may appear on the website of the Chief Scientist and Engineer.

APPENDIX 2: How the Various Forms of Hydrofracturing Work

A2.1 The Purpose of this Appendix

Hydrofracturing is a process in which high fluid pressure in the presence of the ambient stress field in the Earth breaks rocks. It is a process that occurs naturally.

Hydrofracturing is also a process that is used by the energy sector to create permeability in otherwise impermeable rocks: fluids, usually water, are pumped down wells at high pressure, and the high fluid pressures fracture the rocks. In this Background Paper, this is called intentional hydrofracturing.

Other human activities can increase the fluid pressures to levels that cause rocks to break and existing faults to be re-activated. Those activities include the filling of water storage dams and the disposal of waste water down wells by the oil and gas industries. In this Background Paper, this form of hydrofracturing is called unintentional hydrofracturing.

The same theory governs both intentional and unintentional hydrofracturing. This Appendix sets out some very basic theory as an input to the discussions in the body of the Background Paper.

A2.2 Failure modes in rock

Rocks break when subjected to the stress field in the Earth. The stress required to break rocks is lower when the pores in the rock are filled with fluid under pressure.

When a rock breaks, the rock on either side of the crack that forms can be displaced in two ways, as shown in Figure A2.1.

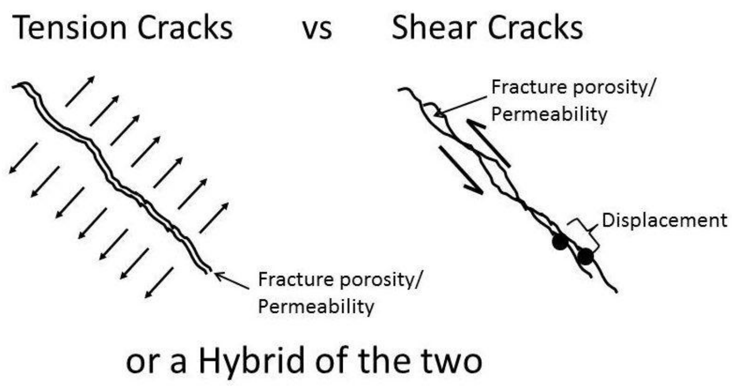

Figure A2.1: Modes of relative displacement of rocks on either side of a crack in rock.

In the crack on the left hand side of Figure A2.1, the rock is displaced orthogonally to the crack, so that one each side is not displaced laterally relative to the other. The rock breaks through tension cracking. The space formed between the rocks on either side of the tension crack is effectively new porosity in the rock, and because it is an "open" crack, it also constitutes a permeability channel through the rock.

In the crack on the right hand side of Figure A2.1, rocks on one side of the crack are displaced laterally relative to those on the other side. The rocks on either side of the crack are not displaced orthogonally relative to each other. Porosity is created between the rock either side of the crack because at some scale, which could be from grain size to regional scale, the crack will have some roughness, as shown, and this will result in open spaces in places in the crack. Any connectivity between those open spaces will constitute new permeability in the rock.

Rocks can also break by a combination of orthogonal and lateral displacement. This is called hybrid tensional shear failure.

In a hydrofracture stimulation of a well, one of these three types of failure will occur. The mode of failure cannot be pre-selected by the company undertaking the hydrofracture stimulation, because it depends not only on the pressure of the injected fluid but also on the on the stress field in the Earth.

The following discussion describes in qualitative ways how the fluid pressures and the stresses influence the type of crack that forms. Note that cracking in the context of the discussion is by Mohr-Coulomb failure (ie., in simple terms, brittle failure) and not ductile deformation. Note that the theory refers to any liquid (water, brine, oil).

Cox (2010) explored the environments in which tension and shear mode failure occurs using the form of failure mode diagram in Figure A2.2.

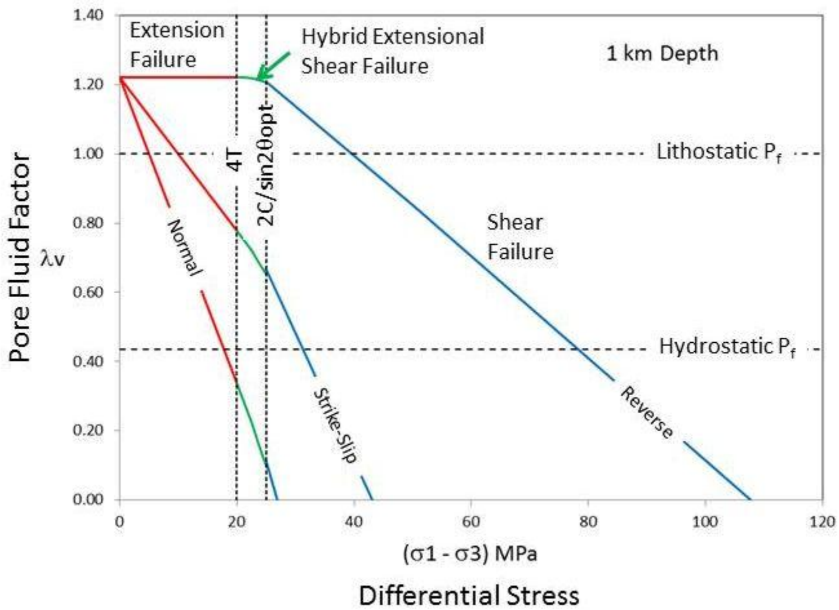

Figure A2.2: Failure mode diagrams for intact rock, modified from Cox (2010) for 1,000m depth. Whether rocks fail as reverse, strike-slip or normal faults depends on the orientation of the stress field; only one type of fault can exist in one place in a constant stress field. Rocks cannot sustain the stress and pore fluid factor regimes above the failure curve. The physical properties assumed in creating this diagram are those used by Cox (2010) for a "moderately to weakly cohesive rock"; C = Cohesive Strength= 10 MPA; T = Tensile Strength = 5 MPa; θopt = 26.5° for a Coefficient of Internal Friction = 0.75.

Most of the deliberate hydrofracturing undertaken in New South Wales occurs at depths between, say, 500m and 1,000m. The failure mode curves of Cox (2010) were therefore re-calculated for 1,000m depth for Figure A2.2 using the physical properties of rocks listed in the caption.

In Figure A2.2, the horizontal axis is differential stress, where σ_1 is the maximum principal stress and σ_3 is the minimum principal stress. The vertical axis is pore fluid factor λv ($\lambda v = P_f/\sigma_v$, where P_f is the pore fluid pressure and σ_v is the vertical stress). For the analysis of rock behaviour at a particular depth in the upper crust, pore fluid factor λv is a dimensionless quantity that needs to be calculated for that depth; ie., the vertical axis does not represent a range of depths in the crust but rather the depth of the rock of interest.

For a hydrostatic fluid pressure gradient, the pore fluid factor will be around 0.43[11] for a rock density of 2,300 kg m^{-3}, which is a commonly assumed density for calculating vertical stress (Hillis et al., 1998). For rocks in which the pore fluid pressure is greater than the lithostatic pressure, ie., the pressure in the fluids in the pores of the rock is greater than the weight of

[11] Assuming fresh water; if the water is a brine, its density will be higher than that for fresh water and the value of pore fluid factor will be slightly higher.

the overburden, the pore fluid factor will be greater than 1. Rocks in which the pore fluid factor is greater than 1 are said to be over-pressured.

For differential stresses below 4T (Secor, 1965) (T is the tensile strength of the rock), rocks break through Tensional Failure (Red part of curve). Rocks fail through shear above a differential stress of (2C/sin2θopt) (Blue part of curve). C is the cohesive strength of the rock and θopt is the optimum angle at which a shear fracture will form relative to the direction of the maximum principal stress σ_1. Between 4T and (2C/sin2θopt), hybrid tensional shear failure occurs (Green part of curve).

The implications of this failure mode diagram are:

- The stress and pore fluid factor conditions for rocks in the Earth will plot below the failure mode curve. The rocks can be fractured by increasing the pore fluid factor; ie., the pore fluid pressure – this is how hydrofracturing occurs – or by increasing the differential stress.
- In an environment where the stress field allows for tensional failure, shear failure (of intact rock) can only occur if the differential stress is increased.
- If the stress field allows shear failure, tension failure can only be induced by lowering the differential stress.
- Reverse faults require higher differential stresses than strike-slip faults, which in turn require higher differential stresses than normal faults.
- <u>The curves in Figure A2.2 are illustrative only and should should not be used to estimate rock behaviour in real situations, for which the actual physical properties should be measured and used</u>.

A2.3 Conditions for different failure modes

A2.3.1 Tension Cracks

Secor (1968) described how tension cracks form and grow in intact rock. He developed his theory for natural joints in permeable rocks with high pore fluid pressures. In the following discussion, his theory is adapted to hydrofracturing in order to explain in simple terms how hydrofracturing creates tensional cracks.

Hydrofractured cracks differ from those studied by Secor in that (i) they are formed in very low permeability rocks, whereas Secor's theory was based on fluid flowing into the crack from surrounding country rock with high permeability; and (ii) high fluid pressure in hydrofractured cracks is maintained by pumping of the hydrofracturing fluids, usually at higher pressures than those in the surrounding rock, rather than in Secor's model, in which the fluid in the surrounding rock is over-pressured and this drives fluid into the crack.

The cohesive strength of materials is often less than predicted by theory by one to two orders of magnitude. They are probably weakened by internal and surface cracks. These natural cracks provide the seed from which larger cracks can grow (Secor, 1968). In order to simply their mathematical description, Secor (1968) assumed that the cracks have an oblate ellipsoid geometry. Their number and distribution are such that some would be optimally oriented with their major axis orthogonal to σ_3 and parallel to σ_1. These cracks will develop into hydrofractures. Other internal and surface cracks that are not oriented orthogonally to σ_3 will not develop into hydrofractures. Secor then studied the behaviour of the optimally oriented cracks when subjected to high fluid pressures. He described the behaviour of cracks in three phases, as illustrated in Figure A2.3.

When the pressure of fluid in the crack is less than the minimum principal stress σ_3, the stress in the rock will force the crack to remain closed. The volume of the crack (V) will effectively be zero. This is illustrated in Figure A2.3(a).

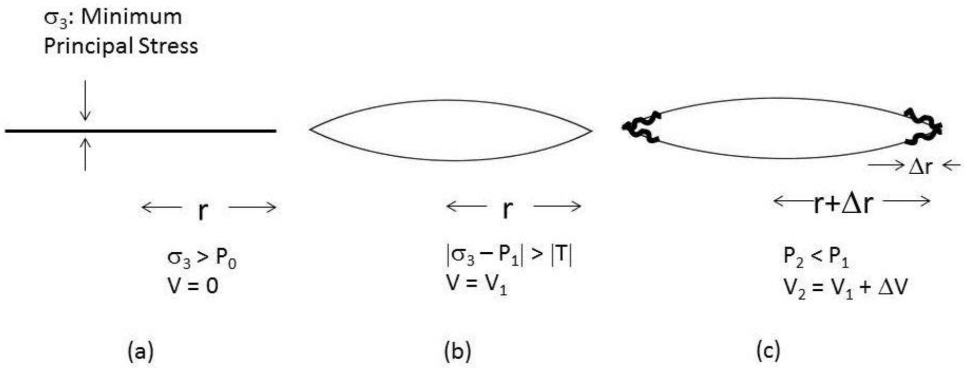

Figure A2.3: Three phases of crack development, based on Figure 1 of Secor (1968). (a) crack exists but is not filled with fluid and therefore has no finite volume; (b) crack has expanded under the influence of fluid pressure to the point where it is ready to fail at its tips; and (c) crack has failed at its at its tips and has become longer.

As pumping of high pressure fluid continues in a hydrofracture operation, fluid pressure in the crack will build and the crack will be wedged open. It will then have a finite volume [V_1 in Figure A2.3(b)]. The conditions under which a crack with internal pore pressure will fracture and grow under tension are [Figure A2.3(b), using the nomenclature of Cox (2010) where it differs from that of Secor (1968]:

$$\sigma_e = \sigma_3 - P > -T = -\sqrt{\frac{\pi E \gamma}{2r(1-\upsilon^2)}} \qquad \text{………………. Equation 1}$$

and

$$V_1 = \frac{16 r^{\frac{5}{2}}}{3}\sqrt{\frac{\pi\gamma(1-\upsilon^2)}{2E}} \qquad \text{………………. Equation 2}$$

where

σ_e = effective stress;

σ_3 = minimum principal stress;

P = fluid pressure; the subscripts 0, 1 and 2 in Figure A2.3 refer to the pressure at the three stages of crack development;

T = the tensile strength of the rock (tension considered negative);

E = Young's Modulus of the rock

υ = Poisson's Ratio

γ = the Specific Energy of the rock

V_1 = the volume of the crack just before it fails at the tips and expands; the subscripts 0 and 2 in Figure A2.3 refer to the volume before and after the crack grows; ΔV is the increment in volume when the crack grows; and

r = the half length of the cracks; ie., the radius of the major axis of the oblate ellipsoid; Δr is the increment in radius when the crack grows.

When the fluid pressure rises, the crack will open when the fluid pressure exceeds the minimum principal stress.

Once (i) the stresses have exceeded the effective stress (Equation 1; ie., the pressure in the crack exceeds the combined effects of the minimum principal stress and the tensile strength of the rock), and (ii) the volume of the crack has reached that defined in Equation 2, where the tips are under tension because the crack is wedged open by fluid pressure, the crack tips will fail and the crack will grow by brittle failure. In Figure A2.2, this would be equivalent to the pore fluid factor λ_v increasing with no change in differential stress ie., moving parallel to the vertical axis, to where it reaches the red part of the failure envelope.

Therefore the parameters that control the expansion of the crack are the physical properties of the rock, particularly its tensile strength, the effective pressure, and the volume of fluid at pressure in the crack (Equation 2).

When the crack widens, the volume of the crack increases, the fluid is decompressed and expands, and the pressure of the fluid in the crack drops (P_2 in Figure A2.3(c)). The crack will stop extending at its tips. The pressure in the crack must then be increased again by pumping, and the crack will grow in another cycle.

The rate at which a crack will grow is controlled by the supply of fluid. In the natural systems described by Secor (1968), the volume of fluid required in Equation 2 rises as the power of 5/2 of the radius of the crack, whereas the surface area of the crack through which fluids can percolate from the country rock into the crack rises as the power of 2 of the radius.

Therefore crack growth (through episodic cycles) in natural systems will slow as the crack gets larger because fluids will take longer to re-pressurise the crack.

Secor used energy balance calculations to consider how much a crack can expand in each cycle. He included the energy both outside and inside the crack: the external forces, the strain energy in the rock, the energy in the compressed fluid and the surface energy of the crack. The critical consideration is that after a cycle of crack extension, the energy must be lower than before the crack extension. The energy balance showed that the crack will expand by only a small amount relative to the existing size of the crack in each cycle.

Crack growth in natural systems should therefore be episodic with many small increments in growth.

Theoretically a crack in an ideal elastic medium can continue to propagate but two factors control how big it will become. Firstly, as the crack grows but growth rate slows, ductile creep at the crack tip will relieve the stresses that accumulate there before the volume and pressure of fluid can rise sufficiently for brittle failure to occur. Secondly, in a heterogeneous medium such as a rock with its many textural flaws and cracks, Secor believed that multiple cracks would form rather than one crack. Each would be subject to the same fluid pressures and lithospheric stresses, and another, smaller crack would then start to grow at a faster rate that the larger crack. The fluid volume budget would lead to the smaller crack growing at the expense of the larger crack. That is, the development of multiple cracks would limit the size of any one crack.

In natural systems, all cracks will cease growing when the rock is sufficiently fractured and contains enough fracture porosity for the cracks to contain all the fluids at pressures lower than that required by Equation 1.

In intentional hydrofracture stimulations, several other factors are likely to influence the rate and size of crack growth:

(i) Each time the crack grows, fluid pressures in the crack will drop. It can then be raised again by pumping, but crack growth will be episodic. This is consistent with the observation of thousands of very small earthquakes rather than fewer larger earthquakes during intentional hydrofracturing stimulations.

(ii) Fluid can only enter the crack from the end of the crack near the injection point; therefore the supply of fluid is via only a small conduit rather than through the entire surface area of the crack. This can be offset by the ability to artificially raise fluid pressures through pumping.

(iii) In hydrofracture operations where a low permeability, isotropic, homogeneous rock is hydrofractured, little or no hydrofracturing fluid should be lost to the country rock while the hydrofractures remain in the low permeability rock. If the hydrofractures stay within the low permeability rocks, eventually the volume of fluid required to fill the crack at pressures high enough to continue hydrofracturing of the crack tips will reach the limits of the pumping system. This will be a practical limit on the size of the hydrofractured zone.

(iv) However, in heterogeneous, anisotropic rocks such as those found in coal fields, fractures, whether propagating horizontally or vertically, can reach rocks with higher permeabilities. Because the hydrofracturing fluids are maintained at high pressures, fluids can then bleed off from the crack into the country rock. This loss of hydrofracturing fluids can slow and eventually stop the propagation of hydrofractures as the fluid volumes required to sustain hydrofracturing become unsustainable (Rahman & Rahman, 2012).

An important result from the above consideration of Secor's (1968) theory is that facture propagation can be slowed or stopped by reducing the pressure and volume of fluid that is pumped into the well, because this will stop the volume of fluid in the crack (V_1 in Equation 2) from reaching the required critical value for tensional failure, and will lower both σe and λ_v. <u>Therefore, if hydrofracturing operations are carefully monitored, they can be slowed or stopped if required</u>.

A2.3.2 Shear Fractures

In Section A2.2 (above), shear failure was shown to occur in higher differential stress regimes than tensional failure. This applies not only to natural systems but also to intentional hydrofracture stimulations.

The form of shear failure - normal, strike slip and reverse – depends on the orientation of the stress field. They cannot be produced in the same stress field.

Figure A2.2 refers to the creation of new cracks in intact rock. When a fault already exists in the rock, it can be reactivated rather than a new fault formed in adjacent intact rock. Whether an old fault is reactivated or a new fault forms depends on

(i) whether the old fault is partially or wholly annealed (and is therefore weak or strong), and

(ii) whether the old fault is optimally oriented or misoriented to the maximum principal stress direction.

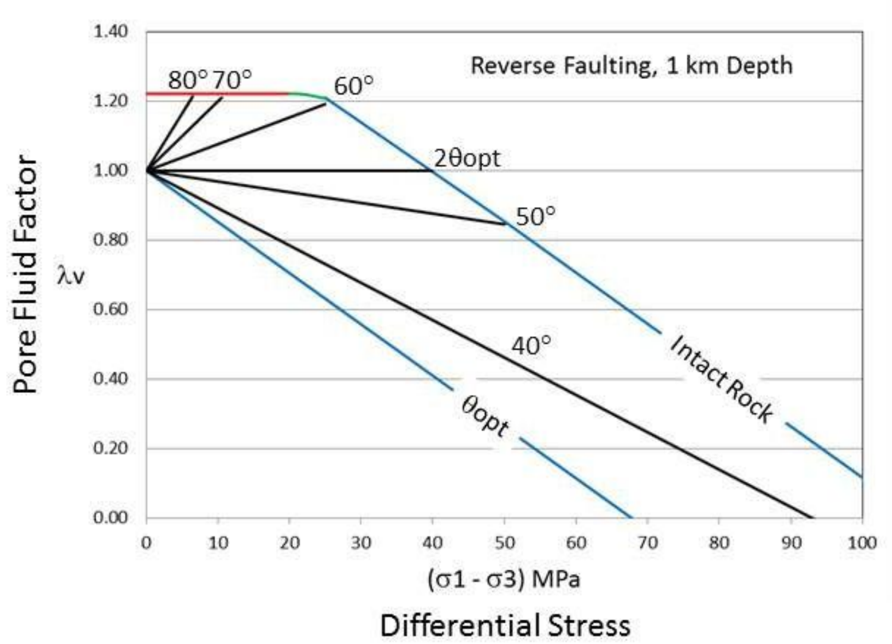

Figure A2.4: Failure mode diagrams for the reactivation of weak cohesionless faults as reverse faults compared to that for the creation of a new reverse fault in intact rock, for a number of values of misorientation of the existing faults from optimal to 80 °. Red, green and blue curves are as for Figure A2.2

Figure A2.4 reproduces the failure mode envelope for a reverse fault in intact rock. Reverse faulting is the most likely form of faulting to occur in eastern Australia where the minimum principal stress σ_3 is vertical and the maximum principal stress σ_1 is horizontal in most areas (Hillis et al., (1998, 1999, 2000).

The failure mode curve for a pre-existing cohesionless fault (ie., a "weak" fault) that is optimally oriented to the stress field is also shown (labelled θopt). It parallels and plots below that for the failure mode curve for intact rock. That is, an optimally oriented, weak pre-existing fault requires significantly lower pore fluid factors and/or differential stresses to be reactivated than those required for creating a new fault in nearby intact rock. It will be reactivated at fluid pressures that are less than lithostatic.

The slopes of the failure envelopes for the reactivation of pre-existing faults change with increasing angles of misorientation; ie., the fault is at a higher angle to the maximum principal stress than θopt. The failure envelopes for misoriented pre-existing faults are shown in black and labelled according to the angle of the fault to the maximum principal stress. Higher differential stresses and/or pore fluid factors are required to reactivate a pre-existing fault that is not optimally oriented. At all angles up to $2\theta_{opt}$ the fault will be reactivated by shear failure irrespective of whether the differential stress would require tensional or hybrid tensional shear failure in intact rock.

At increasingly greater misorientation angles beyond $2\theta_{opt}$, increasingly higher pore fluid factors are required to reactivate the fault. It is unlikely to be reactivated in shear mode because a new fault will form in nearby intact rock. Cox (2010) concluded that for severely misoriented faults, re-shear can only occur if the friction on the faults is very low.

A2.3.3 Implications for Intentional Hydrofracturing:

When a company hydrofractures coal seams to release the coal seam gas, the intention is to fracture as much coal as possible, thereby maximising the volume of coal with enhanced permeability to allow the recovery of gas. The intention may be to create fractures in intact rock or to reactivate the cleats in the coal.

Fractures would be opened incrementally through many cycles of small growth in many fractures. This approach also allows the process to be monitored closely and slowed or shut down if necessary.

An approach of slow and incremental crack growth will lead to induced earthquakes with low magnitudes. In the hydrofracture of rocks such as coal and shale, they are usually in the range M=0 to M= −2 and even M= −3[12]. (Earthquake magnitudes are discussed in Appendix 3).

If a hydrofracture spreading from the well intersects a fault, and if the fault is weak and optimally or near optimally oriented, it can be reactivated. This happens in a number of operational scenarios during hydrofracture stimulations. It can happen during the hydrofracure stimulation (eg., during a geothermal hydrofracture stimulation in Switzerland – Deichmann and Giardini, 2009).

It can also happen after the stimulation if the well is "shut in", ie., it is sealed and the fluid pressures in the rocks that have been hydrofractured are allowed to equilibrate with the surrounding rock. This usually means that they will drop in the rock adjacent to the well, but they can increase away from the well as the pressure front from the hydrofracturing spreads beyond the hydrofracture zone. Subsequently, earthquakes can happen at the edge of the hydrofracture zone because the pressure front has intersected a fault (Wessels et al., 2011), and the fault can be reactivated at pressures (pore fluid factors) lower than those required to hydrofracture fresh rock (Figure A2.4).

Case studies in the literature (eg. Maxwell et al., 2009) show that the magnitudes of the earthquakes associated with the fault reactivation are also likely to be in the M = 0 to M = -2 range. However, the seismicity from the hydrofracture of fresh rock will have relatively more earthquakes with the lowest magnitudes than the seismicity from the reactivation of the fault (Appendix 3).

[12] Higher magnitudes can occur during the hydrofracture of other kinds of rock, such as granite, which have higher shear moduli that coal and shale. See Appendix 3.

A2.3.4 Implications for Unintentional Hydrofracturing:

Earthquakes can be triggered through the unintentional hydrofracturing of rocks caused by the disposal of waste water which is re-injected into disposal wells. Earthquakes triggered this way often have a linear spatial distribution suggesting that they are due to the reactivation of existing faults (See Appendix 4).

The production of unconventional energy sources, such as coal seam gas, releases large quantities of waste water. In coal seam gas activities, the waste water includes the hydrofracturing fluids that are returned to the surface after the well has been hydrofractured. This is called flow back water. The waste water also includes formation waters; ie., water from the coal seams that is pumped out to release gas which is adsorbed onto the coal and held there by water pressure.

The disposal of waste water in deep wells is one method of disposing of the waste. Others include treatment and re-use in other hydrofracturing operations, in agriculture and pastoral activities, the re-injection into depleted water aquifers for reuse and release after treatment into rivers (SCER, 2013).

The injection of waste water down disposal wells will have the effect of raising the fluid pressure in the reservoirs in which it is to be stored. If the pressure is not monitored and kept below a critical threshold, it can cause unintentional hydrofractures. In the context of Figure A2.4, the injection of waste water increases the pore fluid factor for a given differential stress, until the failure curve for an optimally to near optimally oriented weak fault is reached, and the fault is reactivated.

The levels of seismicity in the mid-continent of the US have increased up to 6 times since 2000, attributed in large part to the activities of the coal seam and shale gas industries there (Ellsworth et al., 2012). Many of the earthquakes in Arkansas and Oklahoma occur in clusters and are attributed to the reactivation of faults. Where the disposal has been underway for some time (eg., 17 years in the Oklahoma earthquakes studied by Keranen et al., 2013), fluid pressures can build up along significant lengths of the fault, and the resulting earthquakes can be large (M=5, M=5.7). The increase in induced seismicity in the mid-continent of the US is discussed more fully in Appendix 4.

No evidence has been found of hydrofracturing operations reactivating existing faults and causing reasonably large earthquakes in New South Wales (Appendix 5).

A2.4 Summary

Fracture can occur by tensional, shear and hybrid tensional and shear failure.

Which form of failure occurs in intact rock depends on the differential stress at the depth of interest in the Earth. Only one mode of failure can occur in intact rock at any differential stress.

Tensional failure should occur by slow incremental growth. Fracture can be controlled (including slowing and stopping) by controlling the volume of injected water, the rate of injection and the fluid pressure.

When a rock fails in shear mode, the orientation of the stress field will determine whether it is a normal, strike-slip or reverse fault.

Normal faults require lower differential stresses and/or pore fluid pressures than strike-slip faults, which in turn require lower values than reverse faults.

The regional stress field in eastern Australia will most likely cause reverse faults.

Optimally to near optimally oriented weak faults can be reactivated at pressures lower than those required to form tension or shear fractures in adjacent intact rock.

Weak faults that are reactivated fracture in shear mode, irrespective of the level of differential stress.

Tensional fracture and shear faulting can co-exist near the same well, but must occur sequentially in time. This requires a low differential stress which favours tensional failure in the intact rock near the well. If the tensional hydrofractures intersect a suitably oriented weak fault, it could be reactivated. If it is reactivated, it will be in shear mode irrespective of the level of differential stress. The reactivation of the weak fault requires lower pore fluid pressures than the tensional cracking, so the tensional cracking would probably stop if the fluids are bled off into the fault and the pressures drop.

A2.5 References

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APPENDIX 3: Earthquake Size and Focal Mechanism

A3.1 Introducing basic earthquake terms

This Appendix introduces basic terminology that is used throughout the Background Paper. It is not a comprehensive treatise on seismology. It does not seek to reach specific conclusions about any aspect of the subject matter of the Background Paper.

This Appendix deliberately follows Appendix 2, which provides a scientific backdrop to various forms of hydrofracturing. It works systematically through the ways in which the size of earthquakes is assessed or measured. It then describes how the different modes of rock fracture described in Appendix 2, principally shear and tensional failure, can be recognised in the data recorded on seismographs which monitor seismicity.

The terms used to describe earthquakes were derived for large earthquakes, and refer to fracturing by faulting, and therefore fracture by shearing (ie., shearing in the context of Appendix 2). The same earthquake terms are used to describe earthquakes caused by hydrofracturing, ie., mostly small earthquakes that are caused by tensional fracture. In this Appendix, the traditional terms for describing all earthquakes will be used throughout for all earthquakes no matter which mode of cracking applies, and a section below discusses briefly what substitutions are needed in the key formulae for measuring earthquake magnitudes.

Earthquake size can be assessed in two ways: what people feel and observe, and what a seismograph registers. In this Appendix, attention is given mostly to earthquakes at the smaller end of the scale because most hydraulically induced earthquakes are small.

A3.2 Earthquake Intensity

What people feel and observe are important because they determine how people respond. Measurements made this way are called measures of the Intensity of the earthquake.

In Australia Intensity is measured on a scale called the Modified Mercalli Scale. The Modified Mercalli Scale quantifies the effects of earthquakes into 12 levels, called MM I to MM XII (ie., the Modified Mercalli Scale uses the acronym "MM" followed by a number expressed in Roman numbers). They are reproduced in the Attachment at the end of this Appendix.

MM I earthquakes are the smallest – they would not normally be felt by humans, unless they are, for example, high in a multi-storey building. Note however, that people may feel nausea and dizziness, but not recognise why because they are not conscious that an earthquake has happened.

People start to become conscious of earthquakes around MM II, and certainly MM III, provided they are close enough to the earthquake’s hypocentre (See Text Box for Earthquake Nomenclature). However, they may be aware of the earthquake more because of the effects of the earthquake on things around them, such as hanging objects swinging and houses creaking, than from feeling the ground shaking.

Damage does not start to occur until MM V is reached. By MM VI, people and animals become alarmed, and people experience difficulty standing and walking. At higher intensities, these effects are greater and damage is greater. At MM X11, an area will have experienced total damage.

The Modified Mercalli Scale is calibrated to the building code. That is, the scale values which describe damage to different types of buildings refer to building types that are described at the end of the scale.

TEXT BOX: Basic Earthquake Nomenclature:

Earthquakes occur when stresses break (rupture) rock, forming a new fault or re-activating an old fault.

Earthquakes are the signature of the release of energy stored in rocks that are under stress.

The point where the Earth starts to rupture is called the hypocentre. The hypocentre is also called the focus of the earthquake. When seismologists calculate the location of the earthquake, they calculate the position (latitude, longitude, depth) of the hypocentre because this is where the seismic energy is first released.

The epicentre is the point on the surface of the Earth directly above the hypocentre or focus.

The depth of the earthquake is the vertical distance between the hypocentre (or focus) and the epicentre.

The rupture area is small for small earthquakes and large for larger earthquakes (see later).

Larger earthquakes will normally displace the rock on either side of the rupture by larger amounts than smaller earthquakes (see later).

The Moment of an earthquake that occurs when a rock fails in shear mode is the product of the area of the fault that ruptures, the amount of lateral displacement on the fault, and the shear modulus of the rock that ruptures.

The Moment of an earthquake that occurs when a rock fails in tensional mode is a function of the area of the fault that ruptures, the displacement of one side of the fault away from the other, the shear modulus of the rock and another property of the rock called the First Lame Constant.

The Magnitude of an earthquake is related to the logarithm of the Moment by several scalar values that are derived empirically from observed data (see later).

The intensity of an earthquake is highest near its epicentre and decreases with distance from the epicentre.

In Australia intensity is mapped by subjective assessments of what people see and observe. The reported intensity may be affected by a number of factors, such as whether the observer is standing, sitting or lying down, on solid ground or on earth fill, and the time of day, which governs whether people are out and about, indoors or outdoors, in a high rise office or at home, awake or asleep.

A3.3 Earthquake Magnitude:

A3.3.1 Magnitude Scales

Whereas earthquake intensity is measured with observations that can be subjective and its value varies with distance from the hypocentre, earthquake magnitude is a single number designed to quantify the size of the earthquake. Measurements of magnitude are made with seismographs. It is not a number that depends on how far the observer or seismograph is from the earthquake; distance and attenuation of the ground shaking with distance from the earthquake, as well as the response of the seismograph, are factored into the magnitude calculation.

Geoscience Australia produces catalogues of earthquakes that occur in Australia[13]. It uses a number of magnitude scales. In a well-established earthquake monitoring centre, the various scales will have been calibrated against each other so that for all but the smallest and largest earthquakes any scale is likely to produce a magnitude that can be compared with the magnitude on any other scale. Therefore to avoid confusion, earthquakes magnitudes are given at times in this background paper without referring to which scale was used.

The Local or Richter Scale (M_L), and the Moment Magnitude Scale (Mw) are the most relevant to this paper. The Richter magnitude (symbol is M_L) is probably the most publicly known. It is used in a lot of engineering applications. However, it has several shortcomings. It was developed using earthquakes with magnitudes between M = 3 and M = 7, and does not provide accurate magnitudes for earthquakes with M > 7. It is based on measurements made with analogue seismographs that are now obsolete; approximations to the response of the old analogue instruments have to be made for measurements with modern digital instruments, which downgrade the potential of the digital data. And it was developed specifically for local earthquakes (hence the alternate name "Local" magnitude) and adjustments have to be made if it is used to provide magnitudes for more distant earthquakes.

The Moment Magnitude scale (designated Mw) was designed to address these inadequacies.

Moment Magnitude was defined by Hanks and Kanamori (1979) as

$$Mw = \frac{2}{3} log M_0 - 6.07 \quad \text{.......................... Equation 1}$$

where M_0 is the moment of the earthquake. M_0 was originally defined by

$$M_0 = \mu S d \quad \text{.......................... Equation 2}$$

where μ = the shear modulus of the rocks that are faulted,

S = the areas of the fault that ruptures, and

d = the average displacement on the fault during the rupture.

In these equations M_0 is in Nm. In their original formulation, Hanks & Kanamori used cgs units and therefore their scalar values were different.

This formulation expects that the earthquake occurred on a fault that fractured through shear failure. In earthquakes caused by tension failure, Equation 2 is replaced by a more complex formulation in which S remains the area of the fault that fails, the displacement d is the amount by which the two sides of the fault are moved apart, and the shear modulus μ is

[13] http://www.ga.gov.au/hazards/earthquakes.html

replaced by a combination of the shear modulus μ and the bulk modulus (usually denoted by the letter K) (Julian et al., 1998)[14].

The Moment Magnitude is a very useful scale to use because it relates the size of the earthquake to both the physical properties of the rock and the dimensions of the failure in the rock. The Hanks & Kanamori (1979) version of Moment Magnitude is used by a majority of geophysical contractors who undertake hydrofracturing in the US (Shemeta and Anderson, 2010), and therefore by assumption in Australia, irrespective of whether failure is by tension or shear.

A3.2.2 Negative Magnitudes

Magnitude scales represent the size of earthquakes on a logarithmic scale. Very small earthquakes can therefore have negative magnitudes.

For example, using Equations 1 and 2 above, if an earthquake has a very small Moment, eg., because the fault is weak (low shear modulus μ), or has a small rupture area (S) and /or a small displacement (d), then the magnitude can be negative.

Natural earthquakes with negative or very small positive magnitudes are common but seldom catalogued because they are not felt and not well recorded on regional seismograph networks such as the Australian National Seismograph Network (ANSN) operated by Geoscience Australia. Earthquakes with very small magnitudes are particularly common in hydraulic stimulation (hydrofracturing) of oil, gas and geothermal energy reservoirs, where the aim is to fracture rock in a controlled way, and therefore usually slowly and systematically (See Appendix 2).

Very small earthquakes are also very difficult to measure using surface seismographs. Abercrombie (1995) recorded earthquakes in a deep bore hole and demonstrated that the scaling of magnitudes of small earthquakes was affected by the attenuation of high frequency energy recorded on seismographs deployed at the Earth's surface – small earthquakes generate relatively greater amounts of high frequency energy than larger earthquakes, and high frequency energy is scattered and attenuated more than low frequency energy, particularly in the weathered rock near the surface of the Earth. Her work showed that for the accurate monitoring of the very small earthquakes (called microearthquakes or microtremours) produced during hydrofracturing operations, seismometers should be placed down deep boreholes rather than on the surface.

[14] A formulation for the Moment of a tensional fault in a form similar to that in Equation 2 is not given here. It takes the form of three equations and requires an understanding of the stress tensor. A description of the stress tensor is beyond the scope of this Background Paper.

A3.3 Intensity – Magnitude Relations:

For some earthquakes, both intensity and magnitudes can be measured. Intensity varies with distance from the hypocentre, so Greenhalgh et al. (1988) derived the relation

$$M_L = 1.2 + 0.6\, I_0 \qquad \text{………………… Equation 3}$$

for shallow earthquakes in Australia, where M_L is the Richter magnitude and I_0 is the intensity at the epicentre.

This is shown graphically in Figure A3.1. It is close to the relation for the Western United States where much of the early work on the relationship was done.

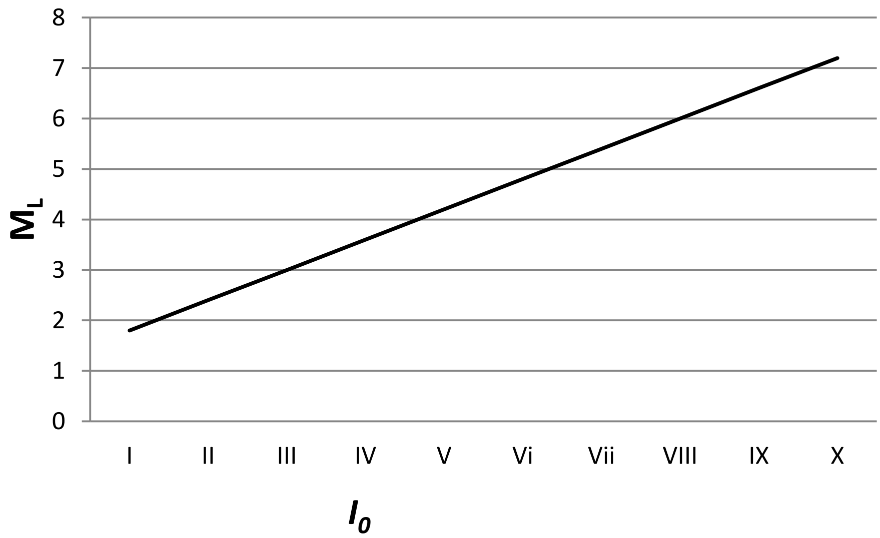

Figure A3.1: Richter magnitude vs intensity at the epicentre (for shallow earthquakes; ie, effectively near the hypocentre) for Australian earthquakes. Based on the relation in Equation 3, from Greenhalgh et al. (1988).

Note that most earthquakes caused by controlled deliberate hydrofracturing have negative magnitudes which do not have a corresponding intensity. They are therefore crowded into MM I.

Apart from exceptional circumstances, people are unlikely to feel earthquakes of Richter magnitude 2 or less (and similar magnitudes on other magnitude scales) because they correspond to MM I and MM II. They should be aware of earthquakes of M_L=3. Earthquakes up to MM IV do not cause damage, although at that level of intensity they can be unpleasant to observers who might therefore expect that the earthquake could cause damage somewhere. Mild damage starts to occur around MM V, which corresponds to M_L = 4.

3.4 Fault Rupture Parameters

In the following discussion, estimates of fault rupture area and displacement are made for earthquakes with a range of magnitudes assuming that the rupture is by shearing. The physical parameters that are used to describe rupture by tensional cracking are similar to those used for shear fracture and the dimensions of tension cracks therefore should be similar. Tensional cracks are unlikely to cause large earthquakes because incremental crack extension is by small amounts rather than by large amounts (Appendix 2). For very small earthquakes caused by tensional cracking, the increase in the size of cracks might be assumed to be of the same order of magnitude as the area of displacement for a fault cracked through shearing. Therefore the treatment of very small earthquakes in the following sections is provided in order to give an insight into estimates of crack growth through either mechanism.

Equations 1 and 2 relate rupture area and displacement to moment and magnitude. Eshleby's (1957) equation for stress drop for small earthquakes relates moment to rupture diameter for a circular rupture area:

$$\Delta\sigma = \frac{7M_0}{16r^3} \quad \text{................. Equation 4}$$

where: $\Delta\sigma$ = the stress drop during the earthquake, and

r = the source radius, assuming a circular rupture.

Equations 1, 2 and 4 allow rupture area and displacement to be calculated for an assumed shear modulus of the rock and the stress drop during an earthquake. In this analysis, Richter magnitude is assumed to be the same as Moment magnitude for small earthquakes.

The stress drop during rupture is assumed to be 5 MPa. This is consistent with estimates for many very small earthquakes studied by Abercrombie (1995), and with estimates discussed by Leonard (2010) for larger earthquakes. The area of failure is assumed to be circular (Eshelby, 1957; Leonard, 2010). Values for the shear modulus of coal and shale are set out in Table A3.1. The shear modulus for granite is also included as an example of a rock with a much higher shear modulus.

Table A3.1: Shear modulus for shale, coal and granite used to calculate the curves in Figure A3.2. Where measured values for a number of samples were available, a representative value was used.

Rock Type	Shear Modulus (GPa)	Source
Shale	1.6	Birch (1966), Table 7-15; Tieyuan Zhu, Stanford University: http://www.stanford.edu/~tyzhu/Documents/Some%20Useful%20Numbers.pdf
Coal	2.0	Greenhalgh & Emerson (1986)
Granite	24	Birch (1966), table 7-15; Tieyuan Zhu, Stanford University: http://www.stanford.edu/~tyzhu/Documents/Some%20Useful%20Numbers.pdf

Figure A3.2 shows the relationship between earthquake magnitude and (a) rupture area and (b) displacement assuming shear fracture. In (b), displacements are given for three rock types: coal, shale and granite. Shale is a rock commonly interspersed with coal; its shear modulus is the same order of magnitude as that of coal, and therefore has similar rupture dimensions in an earthquake to coal.

Granite is included in (b) (red line) to show the difference in displacement for a given earthquake magnitude if the rock is much stronger (higher shear modulus; Table 1).

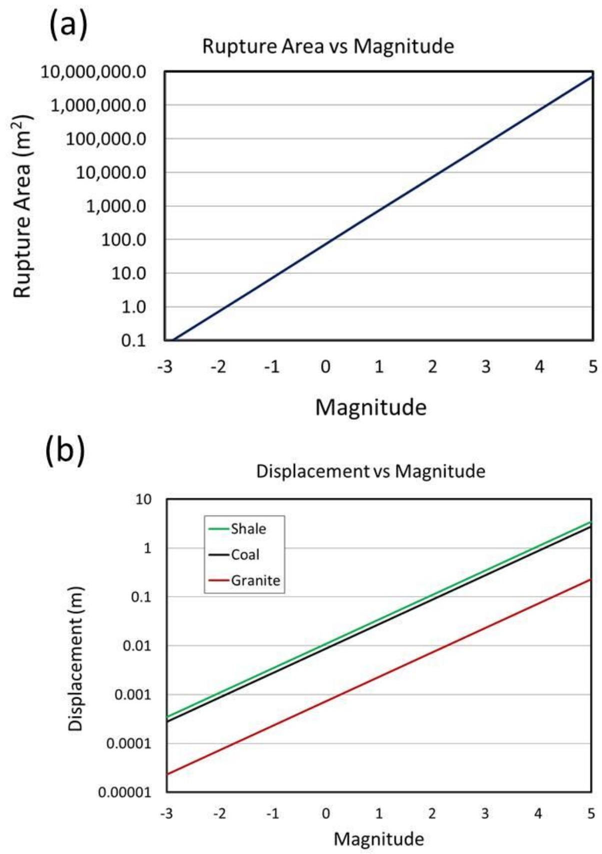

Figure A3.2: (a) Area of a circular rupture as a function of earthquake magnitude. (b) Displacement across a rupture as a function of earthquake magnitude for coal (black), shale (green) and granite (red) assuming a stress drop of 5 MPa and the shear moduli for the three rock types set out in Table A3.1.

Earthquake magnitudes larger than M=5 are not shown in Figure A3.2, firstly because the scaling relations between length and width would be different from a circle, and secondly, because earthquakes larger than that are unlikely in intentional hydrofracturing programs, although larger earthquakes have been reported from other kinds of human induced (ie., unintentional) seismicity (see Appendix 4).

The assumed stress drop used to calculate the curves in Figure A3.2 reproduces approximate rupture areas for earthquake moments of small earthquakes studied by Abercrombie (1995). The rupture areas in Figure A3.2 also agree with approximate areas of ruptures for larger earthquakes given by The National Academies (2011). The displacements in Figure A3.2(b) are higher than those listed by The National Academies (2011), for which no assumed stress drop or shear modulus were given, or for empirical values determined by Wells and

Coppersmith (1994) for larger earthquakes than those studied by Abercrombie (1995). Coal and shale have lower shear moduli than typical crustal rocks.

Table A3.2 summarises the values for fracture parameters for earthquake with magnitudes typical of those caused by hydrofracture operations. Note that both the area of the fractures and the amount of displacement are very small – of the order of metres and millimetres, respectively.

Table A3.2: Estimated rupture dimensions for earthquakes with magnitudes typical of those caused by hydrofracture operations (From Figure A3.2 and its underpinning equations). Note that the values for area (and diameter) and displacement for each magnitude were derived independently of each other using various assumptions about rock properties and may be different from the values in real earthquakes. They should be treated as order of magnitude estimates.

Magnitude	Area (m^2)	Diameter (m)	Displacement (mm)
-2	1	1	1
-1	10	4	3
0	100	11	10
1	1000	36	30

For a given earthquake magnitude, rupture displacement will be greater in rocks with low shear moduli, such as coal and shale, than in rocks more typical of deeper parts of the Earth's crust; for example, displacements in granite are more than an order of magnitude less than in coal and shale for any earthquake magnitude. Another way to consider these parameters is that the Moment of an earthquake in granite will be more than an order of magnitude greater than the Moment of an earthquake with a similar sized rupture in shale or coal, and will therefore have a magnitude nearly 1 magnitude unit greater – ie., a rupture leading to an earthquake with a magnitude of M = 1 in granite will have a magnitude of M = 0 in coal or shale.

The values in Table A3.2 are for natural shear rupture. Abercrombie (1995) and Abercrombie and Leary (1993) noted that induced earthquakes have lower reported stress drops than tectonic earthquakes. Combining Equations 2 and 4 above for a circular rupture,

$$\Delta\sigma = \frac{7\mu d\pi}{16r} \qquad \text{……………… Equation 5}$$

Therefore a smaller stress drop would imply in either a larger area (radius *r*)or smaller displacement (*d*) for the same rock type. They offered two explanations for why the differences may be apparent rather than real.

(i) The difference may be may be because small events typically do not contain high frequency seismic signals if they are recorded at or near the surface above the zone where high frequencies are preferentially attenuated, although Abercrombie (1995) had attempted to take attenuation into account.

(ii) It might also be due the scaling relationship of stress drop to earthquake rupture size represented above by Equation 4 (and therefore Equation 5) not being entirely valid because it does not take into account any change in rock volume at the earthquake focus during rupture; ie., the scaling relationship for stress drop and magnitude does not take into account whether there is any tensional rupture.

Abercrombie and Cleary therefore cautioned about using scaling relations between earthquakes with different source types. Therefore although the displacements for tensional fracture might be expected to be of the same order of magnitude as those for shear failure, this has not been demonstrated in the scientific literature that has been sighted during the preparation of this report.

A3.5 Distinguishing between tensile cracking and shearing.

A3.5.1 The distribution of earthquake size

For every large earthquake there are many smaller earthquakes. Gutenberg and Richter (1944) derive an empirical relation to describe the distribution of earthquake sizes:

$$\log N = a - b(8 - M_L) \quad \text{.................. Equation 6}$$

where N = number of earthquakes above a particular magnitude

a = a constant that describes the amount of seismicity; Gutenberg and Richter determined a value of -0.65 ± 0.09 empirically for the World's population of earthquakes;

b = a constant that relates the magnitude of the earthquake to the number of earthquakes; Gutenberg and Richter determined a value of 0.97 ± 0.15 empirically for the World's population of earthquakes; and

M_L = Richter Magnitude.

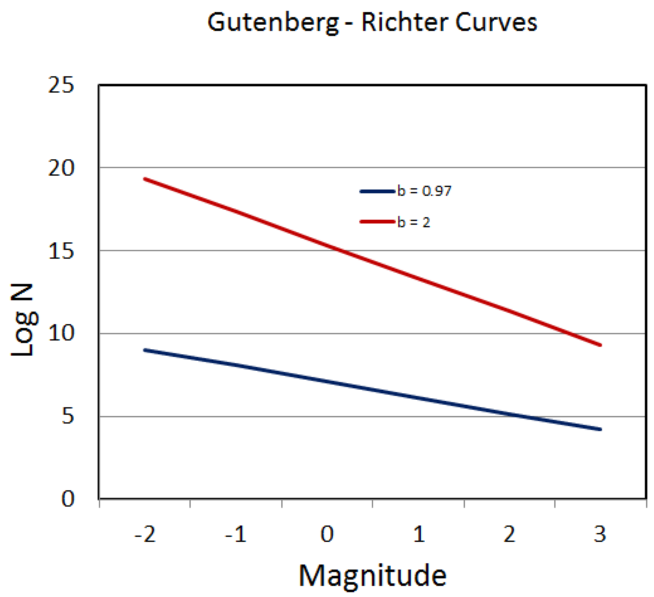

Figure A3.3: Graphical representation of the Gutenberg-Richter relation for earthquake size distribution. N is the number of earthquakes above a particular magnitude; b is the slope of the line: b=0.97 is typical of naturally occurring earthquakes; b = 2 is common in hydrofracture earthquakes.

Gutenberg and Richter's relation is shown graphically in Figure A3.3. The blue curve was calculated using their estimates of a and b. Although originally calculated for earthquakes in California, a value of b of around 1 appears to be universal. Note that the Y axis, representing the number of earthquakes, has a logarithmic scale. Gutenberg and Richter developed their relationship for earthquakes of M_L 3.5 - 4 and larger that were caused by shear failure on faults. The X-axis in Figure A3.3 (representing M_L) has been extended down to M_L -2.0 on the basis of Abercrombie (1995) being able to quantify the parameters of earthquakes of that size using a deep bore hole seismometer. In most populations of earthquakes recorded using surface seismometers, the graph would tend to flatten to the left towards smaller magnitudes, due to the difficulty of detecting extremely small earthquakes with surface seismometers and calculating accurate magnitudes.

In simple terms, the Gutenberg – Richter b value of 1 implies that for every earthquake of magnitude, say, $M_L = 5$, there will be around 10 earthquakes of size $M_L = 4$, 100 earthquakes of size $M_L = 3$, and 1000 earthquakes of size $M_L = 2$.

Another way of interpreting this relation is that if an earthquake of $M_L = 3$ were to occur, which is not uncommon in Australia, it would probably be felt by people nearby, and there would likely be several hundred aftershocks most of which would not be felt by people nearby.

Values of b for earthquakes caused by hydrofracturing often have b values significantly greater than 1. This indicates that the populations of earthquakes from hydrofracture operations have a higher number of small events compared to large events than occurs naturally. The red cure in Figure A3.3 has b value of 2, and at low magnitudes is separated and easily distinguished from the blue curve. Wessels (2011) estimated a value of ~2.2 for one set of earthquakes and ~1 for another set in a population of events from a hydrofracture stimulation of a gas well. He assigned the set with the higher b value to tensile fracturing and the one with the lower b value to the reactivation of an existing fault. Maxwell et al. (2009) made similar findings.

A measure of the b value of earthquake populations would therefore seem to be a simple, first order discriminant of the type of fracturing (tensional or shear).

A3.5.2 Determining rupture type by spatial and temporal distribution

A simple form of discrimination of rupture type caused by hydrofracture stimulation uses the spatial and temporal distribution of earthquakes. Earthquakes that are uniformly and radially spatially distributed around the well are likely to be from tensional cracking, particularly if they occur during the hydrofracturing process. Fractures that are spatially related to a known fault, or have a spatial distribution that corresponds with that of known faults (eg. in a zone with a similar strike and dip to known faults), could be on re-activated faults. Fault related earthquakes can also occur late in the hydrofracturing process, including after the initial hydrofracturing and while proppants are being pumped into the new fractures, or after the well has been shut in (eg., Maxwell et al., 2009).

A3.5.3 Focal Mechanisms

A more robust discrimination of rupture type uses focal mechanism analysis of the waveforms of the earthquake signals recorded at seismometers. The focal mechanism describes the form of faulting during the rupture. It has traditionally been applied to naturally occurring earthquakes assuming shear rupture, but the scientific literature is starting to record instances of its application to tensional rupture.

The principal behind the use of ground motion directions to determine the focal mechanism of an earthquake is illustrated in Figure A3.4.

In Figure A3.4, the directions of the ground motion at the crack or fault are shown with red and green arrows. A tensional crack is shown in a.1 (top left). In this example, the crack is assumed to be large enough that each end of the crack extends independently of the other, so that the ground motions are shown for only one end. In this type of fracture, the ground moves outwards from the crack in all directions, although the amount of motion is greatest in the direction orthogonal to the crack and least in the direction from the crack end.

Shear faults form at an angle to the maximum and minimum principal shear directions. They are often shown as one of two conjugate faults, as in a.2 (top right of Figure A3.4). Ground motion in the direction of the maximum principal stress σ_1 is towards where the conjugate faults intersect. Ground motion in the direction of the minimum principal stress σ_3 is away from where the conjugate faults intersect.

In traditional focal mechanism analyses, the locations of seismographs around the world were marked on a lower hemisphere stereographic plot. A stereographic plot is a mechanism for plotting information from a sphere (the Earth) onto a plane (a page)[15]. At each point, the directions of the first motions of the seismograms are recorded. A first motion that is up would signify motion at the epicentre like the red arrows in Figure A3.4; a motion that is down would signify motion at the epicentre that was like the green arrows. Areas with motions that are up are then coloured black (or grey as in Figure A3.4 (b.1). Areas where the motions are down are coloured white. A tension fracture should have most of the circular area coloured grey (or black). A shear fracture should have clearly defined and equal areas of white and black.

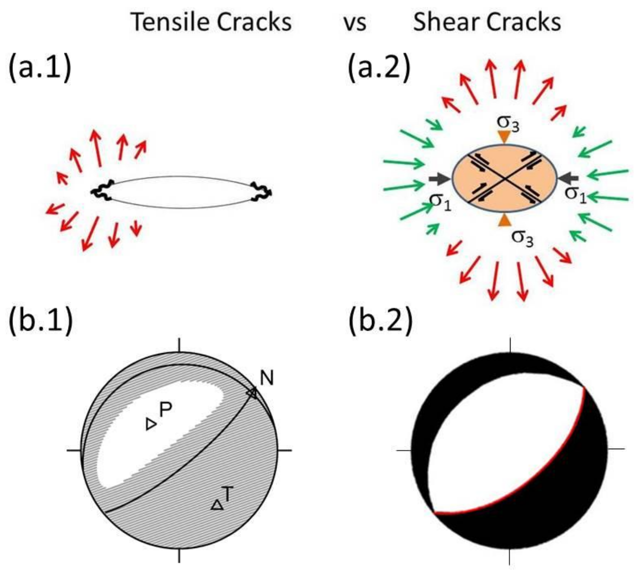

Figure A3.4: (a) a.1 Stylised tension crack expanding at its tip for which the ground motion is outwards from the crack in all directions. The amplitudes of ground motion will be smallest away from the crack tips in the direction of the long axis of the crack, and largest orthogonal to the long axis of the crack. **a.2:** shear cracks form on one of two fault planes marked with double arrows either side of the maximum compressive stress σ_1. For a shear crack ground motion is both outwards from and inwards towards the crack; amplitudes will be smallest near the fault planes where the direction changes from inwards to outwards. **(b)** when the directions of the ground motion are plotted on a lower hemisphere stereographic projection[3], they can be used to identify the type of earthquake focal mechanism. **b.1:** for tension cracks, ground motion is up almost everywhere (grey) and small or indeterminate near the point marked P (white). This is called an isotropic focal mechanism, and is typical of a tensional crack source. T denotes the direction of the minimum principal stress σ_3. P denoted the direction of the maximum principal stress σ_1. **b.2:** for shear cracks, ground motion at seismographs is both up (black zones) and down (white zones). This is indicative of a double-couple source. Double couple sources are caused by shear failure on faults. Solid lines in b.1 and boundaries between black and white (b.2) indicate positions of the nodal planes for the ambient stress field; nodal planes in focal mechanism diagrams correspond to the position of the fault planes in a.2. Red line in right hand side indicates which of the nodal planes is the fault plane. The Tension Axis T (corresponds to the direction of the minimum principal stress σ_3) is in the middle of the shaded area between the nodal planes. The examples in (b) are for a stress field in which a normal fault would form in shear mode (b2).

[15] See http://en.wikipedia.org/wiki/Stereographic_projection

The use of stereographic projections is decades old, and dates from the time when analogue seismographs were used. With modern digital data that record the full waveform of the seismograms, more robust determinations can be made by inverting the recorded waveforms to estimate the rupture mechanism. This has the advantage over using the directions of first ground motions that fewer seismic recording stations are required, provided that they have sufficient azimuthal and distance distribution from the hypocentre. That is, seismographs are deployed at a range of azimuths and distances from the earthquake so that the nature and geometry of the nodal planes can be determined (see the caption for Figure A3.4 for an explanation of nodal planes). Šilneý et al. (2009) gives examples of inversions for a number of earthquakes in which he identified those caused by tension cracking, a few formed by shearing on a fault, and some that he believed were caused by a hybrid mechanism of both types of cracking.

Focal mechanism analysis is time consuming and complex. Therefore currently it is not undertaken routinely, and particularly in real time in the field during hydrofracturing operations. However, the post stimulation analysis of seismic data to calculate focal mechanisms has provided seminal information for understanding rupture that causes hydrofracture induced earthquakes, particularly when applied within a framework for hydrofracture rupture provided by the failure mode diagrams of Cox (2010) that are used in this Appendix.

Examples of research such as those of Šilneý et al., 2009 (shale gas), Deichmann and Giardini, 2009 (geothermal) and Baisch et al., 2009 (geothermal) are from other parts of the energy sector. A study of earthquake focal mechanisms typical of coal seam gas hydrofracture stimulation would be useful for confirming that the lessons learned in the other sectors have application to hydrofracturing in the coal seam gas sector.

A3.6 Relevance of earthquake parameterisation to hydrofracturing

Earthquakes caused by hydrofracturing operations mostly have very low magnitudes; most have negative magnitudes.

Many of the relationships upon which seismology is based were derived from empirical evidence from much larger earthquakes.

In this Appendix, relationships such as those between moment, magnitude, rupture area and displacement, and the Gutenberg – Richter relation have been extrapolated to very small magnitudes. This also appears to be the practice in during hydrofracturing in the unconventional energy industry, including coal seam gas.

The very small earthquakes generated during hydrofracturing operations are unlikely to cause damage to infrastructure; most of the earthquake magnitudes correlate with intensities that are unlikely to be felt.

The difficulty in monitoring hydrofracturing using the locations of very small earthquakes increases as their size decreases, especially if surface seismometers are used; hence deep, downhole seismometers should be used.

The estimated values of any earthquake parameter, such as fault rupture area and displacement are based on relations extrapolated from higher magnitudes, and on physical properties that are not site specific for any hydrofracturing exercise. The estimated parameters should therefore be taken as indicative, order-of-magnitude values. Relative orders of magnitude between the values for shale and coal on the one hand and granite on the other are useful for comparing hydrofracturing in different regimes.

Although the earthquakes caused by hydrofracturing are unlikely to cause damage and many may not even be felt, the Modified Mercalli Scale notes that for Intensity MM I that "Dizziness or nausea may be experienced." Whether people will experience dizziness and nausea due to prolonged exposure to many extremely small earthquakes is not known.

A3.7 References

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ATTACHMENT:

Modified Mercalli Scale of Earthquake Intensity (after Eiby, 1966)

MM I Not felt by humans, except in especially favourable circumstances, but birds and animals may be disturbed. Reported mainly from the upper floors of buildings more than ten storeys high. Dizziness or nausea may be experienced. Branches of trees, chandeliers, doors, and other suspended systems of long natural period may be seen to move slowly. Water in ponds, lakes, reservoirs, etc., may be set into seiche oscillation.

MM II Felt by a few persons at rest indoors, especially by those on upper floors or otherwise favourably placed. The long-period effects listed under MMI may be more noticeable.

MM III Felt indoors, but not identified as an earthquake by everyone. Vibrations may be likened to the passing of light traffic. It may be possible to estimate the duration, but not the direction. Hanging objects may swing slightly. Standing motorcars may rock slightly.

MM IV Generally noticed indoors, but not outside. Very light sleepers may be awakened. Vibration may be likened to the passing of heavy traffic, or to the jolt of a heavy object falling or striking the building. Walls and frame of building are heard to creak. Doors and windows rattle. Glassware and crockery rattle. Liquids in open vessels may be slightly disturbed. Standing motorcars may rock, and the shock can be felt by their occupants.

MM V Generally felt outside, and by almost everyone indoors. Most sleepers awakened. A few people frightened. Direction of motion can be estimated. Small unstable objects are displaced or upset. Some glassware and crockery may be broken. Some windows crack. A few earthenware toilet fixtures crack. Hanging pictures move. Doors and shutters swing. Pendulum clocks stop, start, or change rate.

MM VI Felt by all. People and animals alarmed. Many run outside. Difficulty experienced in walking steadily. Slight damage to masonry D. Some plaster cracks or falls. Isolated cases of chimney damage. Windows and crockery broken. Objects fall from shelves, and pictures from walls. Heavy furniture moves. Unstable furniture overturns. Small school bells ring. Trees and bushes shake, or are heard to rustle. Material may be dislodged from existing slips, talus slopes, or slides.

MM VII General alarm. Difficulty experienced in standing. Noticed by drivers of motorcars. Trees and bushes strongly shaken. Large bells ring. Masonry D cracked and damaged. A few instances of damage to Masonry C. Loose brickwork and tiles dislodged. Unbraced parapets and architectural ornaments may fall. Stone walls crack. Weak chimneys break, usually at the roof-line. Domestic water tanks burst. Concrete irrigation ditches damaged. Waves seen on ponds and lakes. Water made turbid by stirred-up mud. Small slips, and caving-in of sand and gravel banks.

MM VIII Alarm may approach panic. Steering of motor cars affected. Masonry C damaged, with partial collapse. Masonry B damaged in some cases. Masonry A undamaged. Chimneys, factory stacks, monuments, towers, and elevated tanks twisted or brought down. Panel walls thrown out of frame structures. Some brick veneers damaged. Decayed wooden piles break. Frame houses not secured to the foundation may move. Cracks appear on steep slopes and in wet ground. Landslips in roadside cuttings and unsupported excavations. Some tree branches may be broken off.

MM IX General panic. Masonry D destroyed. Masonry C heavily damaged, sometimes collapsing completely. Masonry B seriously damaged. Frame structures racked and distorted. Damage to foundations general. Frame houses not secured to the foundations shift off. Brick veneers fall and expose frames. Cracking of the ground conspicuous. Minor damage to paths and roadways. Sand and mud ejected in alluviated areas, with the formation of earthquake fountains and sand craters. Underground pipes broken. Serious damage to reservoirs.

MM X Most masonry structures destroyed, together with their foundations. Some well-built wooden buildings and bridges seriously damaged. Dams, dykes, and embankments seriously damaged. Railway lines slightly bent. Cement and asphalt roads and pavements badly cracked or thrown into waves. Large landslides on river banks and steep coasts. Sand and mud on beaches and flat land moved horizontally. Large and spectacular sand and mud fountains. Water from rivers, lakes, and canals thrown up on the banks.

MM XI Wooden frame structures destroyed. Great damage to railway lines. Great damage to underground pipes.

MM XII Damage virtually total. Practically all works of construction destroyed or greatly damaged. Large rock masses displaced. Lines of slight and level distorted. Visible wave-motion of the ground surface reported. Objects thrown upwards into the air.

Categories of non-wooden construction

Masonry A Structures designed to resist lateral forces of about 0.1g, such as those satisfying the New Zealand Model Building By-law, 1955. Typical buildings of this kind are well reinforced by means of steel or ferro-concrete bands, or are wholly of ferro-concrete construction. All mortar is of good quality and the design and workmanship are good. Few buildings erected prior to 1935 can be regarded as Masonry A.

Masonry B Reinforced buildings of good workmanship and with sound mortar, but not designed in detail to resist lateral forces.

Masonry C Buildings of ordinary workmanship, with mortar of average quality. No extreme weakness, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces.

Masonry D Buildings with low standards of workmanship, poor mortar, or constructed of weak materials like mud brick and rammed earth. Weak horizontally

APPENDIX 4:

Seismicity induced by activities of the petroleum and gas industries, with particular emphasis on activities in the United States of America

A4.1 Introduction

In order to understand what to look for in a study of whether hydrofracturing can induce significant seismicity, it is useful to look at experience elsewhere, and then to compare that with what is seen in Australia. This Background Paper deals with seismicity that has been associated with activities in the unconventional energy industry, including the coal seam gas sector. Significant literature has developed around the shale gas industry in the United States of America (US), and helps to put into context much of the theory behind hydrofracture practices. This Appendix therefore attempts to identify generic issues rather than any specific to the coal seam gas industry. How those issues are reflected in the coal seam gas industry in New South Wales is addressed in the Appendix 5.

The mid-continent of the United States of America has been experiencing increased seismicity since around 2009, attributed largely to the activities in the petroleum and gas industries.

Reviews of the impact of hydrofracturing on seismicity have summarised the various types of human activities that induce earthquakes. Two recent reviews were by The National Academies (2011) and Davies et al. (2013). Each provides a comprehensive list of references to earlier work. Both reviews provide incomplete compilations of case studies. For example, they do not include all examples of earthquakes that might have been caused by the impoundment of reservoirs in Australia (eg., Muirhead, 1981; Gibson, 1997; Allen et al., 2000).

Reviews such as these would be incomplete for several reasons. Firstly, combined spatial and temporal relationships between a human activity, such as the filling of a reservoir and a nearby earthquake, do not unambiguously imply a causal relationship. Secondly, the publication of case histories in Australia by Gibson (1997) and Allen et al., (2000) in local rather than international journals is unlikely to be visible to overseas scientists; similarly examples published in local overseas journals are difficult for Australian scientists to access unless the case studies are subsequently re-published in more accessible main stream journals. Such is the case of the initial publications of a seminal case study at the Rocky Mountains Arsenal in the United States, which will be discussed briefly below.

However, all reviews agree on the list of likely human activities that induce earthquakes. Figure A4.1 attributes the case studies to activities, showing the numbers both globally and within the US (The National Academies, 2011.

Note that the number of case studies does not reflect the number of earthquakes. Some case studies report many earthquakes. Nor does the number of case studies reflect the size of the earthquakes that were induced. The figures shown are for case studies where earthquakes with magnitudes M>0 were recorded. An earthquake with M<3 is unlikely to be felt, although it can be recorded by seismographs.

Of particular interest in this report are the numbers of earthquakes caused by hydraulic fracturing, waste water injection and the withdrawal of fluids. The figures indicate no case studies from the deliberate hydrofracturing of coal seams to release coal seam gas (CSG), at least in which earthquake magnitudes were greater than M>0. They list a significant but small number of case studies for earthquakes caused by waste water injection, most of which are in the United States. These earthquakes would have been caused by unintentional hydrofracturing. The case studies indicate a significant number of case studies in which the earthquakes were caused by oil and gas extraction.

Davies et al. (2013) found that the categories with the largest numbers of case studies were mining activities and reservoir impoundment. Hydrofracturing comprises a very small percentage of the case studies, and earthquake magnitudes do not exceed M=4.

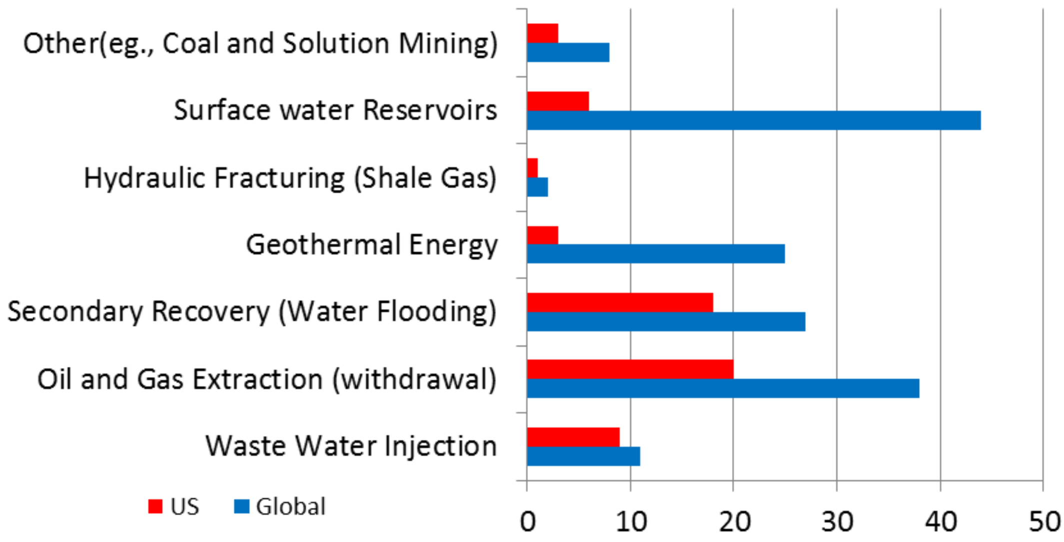

Figure A4.1: Seven human activities that cause earthquakes and the number of case studies identified by The National Academies (2011). Blue bars indicate the number of case studies globally (which include those in the United States), and red bars those within the United States.

Davies et al. (2013) separated waste water injection into two categories: flowback water[16] injection and waste water injection. Both are listed as minor categories. The figures in The National Academies (2011) also suggested that the injection of waste water is not a major cause of induced seismicity.

However, several recent studies of earthquakes in the US would suggest otherwise; ie., the number of earthquakes caused by the gas industries which re-inject significant amounts of waste water is growing. This is discussed below.

[16] Flowback water is fluid that was originally injected into a well to induce hydrofractures which later flows back out of the well after the hydrofracturing process is completed.

A4.2 Numbers of Earthquakes Caused by Energy Related Activities in the United States

Ellsworth et al. (2012) reported that the number of earthquakes occurring in the mid-continent of the United States has increased 6 fold over 20th century levels since 2000.

Figure A4.2 shows the number of earthquake with M>3 for each year between 1973 and 2013 (to 30 July, 2013)[17] for the area studied by Ellsworth et al. (2012) (85°W - 108°W, 25°N - 50°N). Ellsworth et al. (2012) separated the data into three time periods:

- between 1973 and 2000 (highlighted with a dotted line labelled A-A' in Figure A4.2),
- from 2001 – 2008 (B – B'), and
- from 2009 – 2013 (C – C').

Figures A4.3 shows maps of the earthquakes.

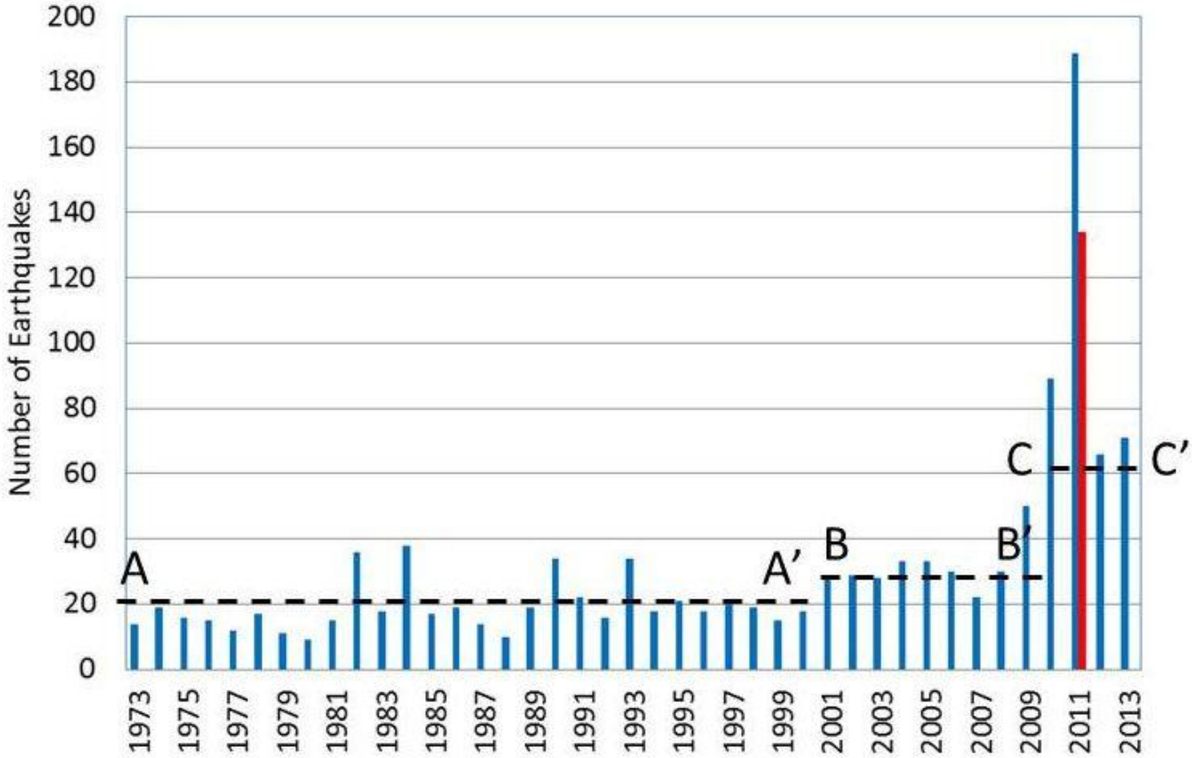

Figure A4.2: Number of earthquakes each year from 1973 – 2013 (year to date) in the US mid-continent based on a catalogue of earthquakes downloaded from the USGS online earthquake database[2]. Dotted horizontal lines show the three periods identified by Ellsworth et al. (2012) as indicative of previous seismicity levels (A – A'), an increase due largely to CSG production (B – B') and an increase due to CSG and other energy-related activities (C – C'). In 2011, several M≥5 earthquakes occurred in Oklahoma. The two bars for 2011 show the total number of events in the USGS database (in blue) and the number after Ellsworth et al. (2012) had removed the aftershocks of the Oklahoma earthquakes.

Prior to 2000, the US mid-continent experienced around 20 earthquakes a year. They were distributed (i) largely through Wyoming, Colorado and New Mexico in the west of the area

[17] Downloaded from http://earthquake.usgs.gov/earthquakes/eqarchives/epic/ on 30 July 2013

under consideration [Ellipse (i) in Figure A4.3(a)], (ii) in a belt extending from Indiana south west through Illinois and Missouri and western Tennessee into Arkansas [Ellipse (ii)], and (iii) a relatively low level of seismicity distributed throughout the rest of the.

Between 2001 and 2009, the average number of earthquakes each year rose to around 29; ie., an increase of nearly 50%. This is illustrated in Figure A4.2 by the dashed line B – B'. However, although earthquakes occurred across the region in the three zones described above for pre-2000 earthquakes, they were particularly concentrated in the Raton Basin on the border of Colorado and New Mexico [Figure A4.3(b)].

The increased level of seismicity in the Raton Basin continued between 2009 and 2013 (year to date). It also increased significantly in the shale gas basins in Oklahoma and Arkansas [Figure A4.3(c)].

Figure A4.6 shows the distribution of the earthquakes in the three areas (Raton Basin, Arkansas and Oklahoma) in more detail.

A4.3 Causes of the induced seismicity in the United States

Ellsworth et al. (2012) attributed the increased seismic activity in the Raton Basin to CSG production in the basin, but did not indicate whether it was from deliberate hydrofracturing, water withdrawal or water injection. The distributed nature of the earthquakes would suggest causes that are distributed, but not what the causes would be.

During deliberate hydrofracturing, occasionally large (possibly up to M=3+) earthquakes can occur late in the hydrofracturing stimulation. They appear to be of an induced tectonic (shear) nature rather than part of the initial smaller tension group of hydrofracture earthquakes. Whereas the deliberate hydrofracture earthquakes spread outwards from the well that is being hydrofractured, the later tectonic earthquakes tend to be on the periphery of the hydrofractured area (eg., Maxwell, et al., 2009). The tectonic earthquakes are probably caused by the hydrofracturing fluids entering and reactivating a weak, pre-existing fault at the local scale (See Section 3.3 and Table 1 in the main part of the Background Paper).

Whether this is the cause of the Raton Basin earthquakes is speculation. The earthquakes in the Raton Basin have no clear spatial pattern (Figure A4.4 (a)) reflecting the reactivation of a structure over a more regional scale, as discussed for some of the other earthquakes below.

In contrast, almost all of the increased seismicity in Arkansas lies on a linear northeast to southwest trend, shown with small black circles in Figure A4.4 (b). The induced earthquakes are in a region with traditionally low levels of seismicity, except for a small cluster shown as yellow circles to the east of the linear belt of earthquakes and occasional earthquakes at greater distances.

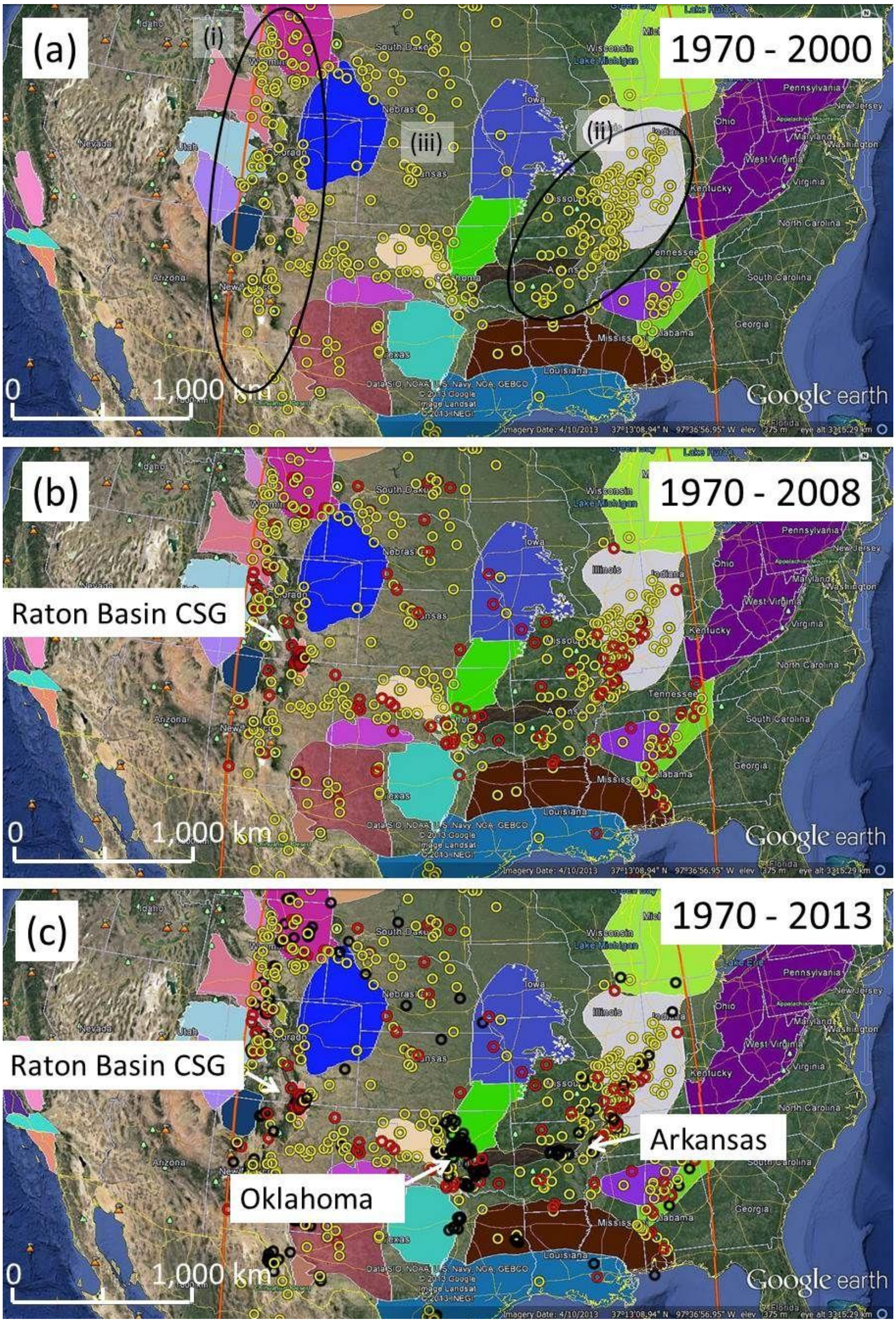

Figure A4.3: (a) Earthquakes with M>3.0 that occurred between 1973 and 2000, from the USGS online database (yellow circles). Solid orange lines show the eastern and western extent of the area studied by Ellsworth et al. (2012). Colour shaded areas are the outlines of sedimentary basins containing shale gas (larger areas), and areas of various shale plays within those basins (from US Energy Information Administration website[18]). Black ellipses and numbers in brackets refer to portions of the earthquake population described in the text. (b) Earthquakes from 1970 – 2000 (yellow circles) and 2001 – 2008 (red circles). (c) Earthquakes from 1970 – 2000 (yellow circles), 2001 – 2008 (red circles) and 2009 – July 30 2013 (black circles).

[18] http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/maps/maps.htm#geoscripts

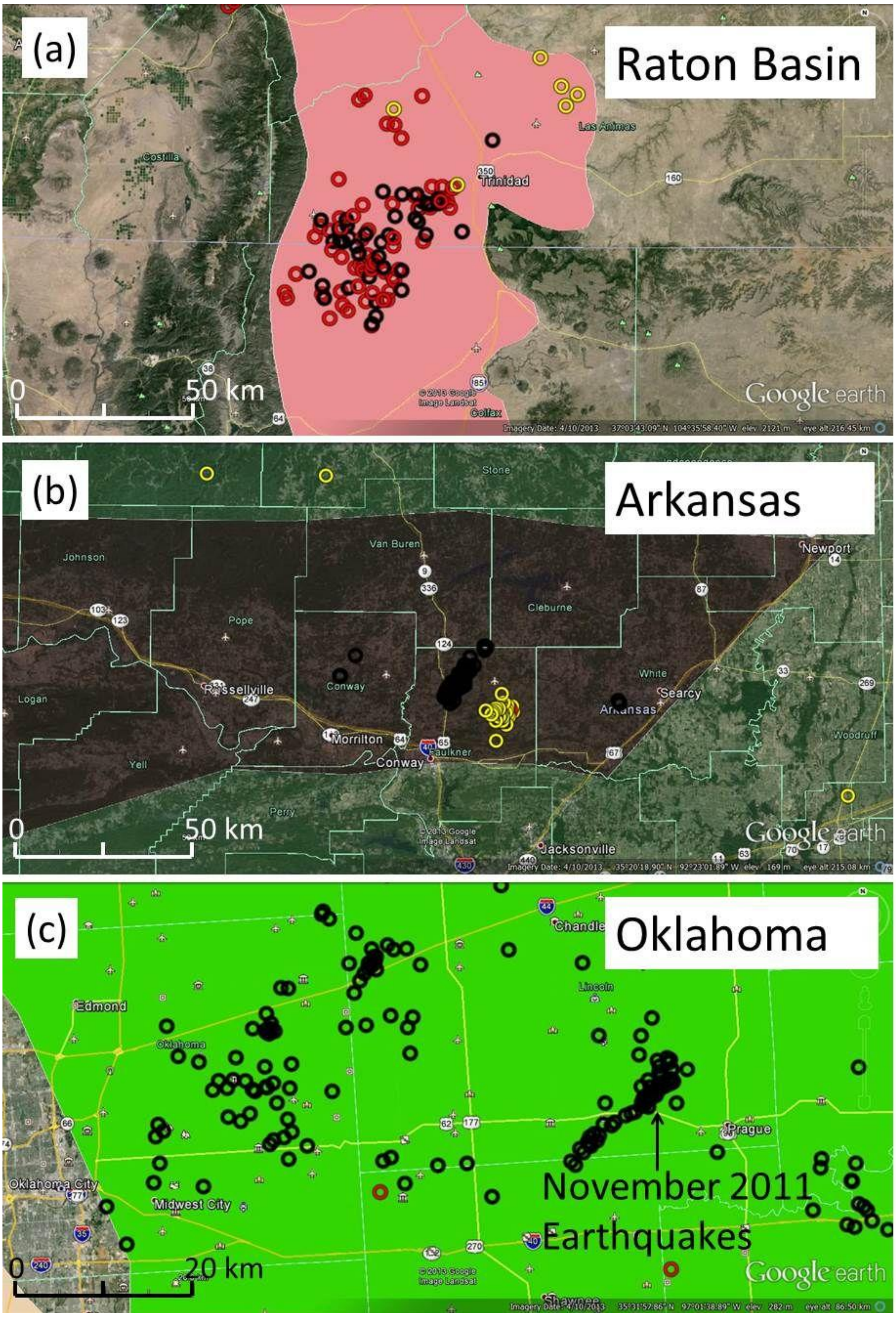

Figure A4.4: Distribution of earthquakes in three zones that experienced increased seismicity between 2001 and 2013. Bright red circles show earthquakes between 1973 and 2013. Very dark red circles are for earthquakes from 2001 to 2008. Black circles are for earthquakes between 2009 and 2013. (a) Raton Basin, (b) Arkoma Basin in Arkansas, (c) Cherokee Platform in Oklahoma.

The reasons for the increased seismicity in Arkansas were not canvassed in detail by Ellsworth et al. (2012). They stated: "Horton, et al. (2012) provided strong evidence linking the Guy, AR activity to deep waste water injection wells." (but they did not give a reference for the Horton paper and therefore it cannot be checked and fully cited).

When the injection of waste water into deep rocks induces earthquakes, the earthquakes often result from the reactivation of existing faults and therefore lie in linear belts. One of the earliest occurrences of waste fluid injection triggering earthquakes along a linear trend was at the Rocky Mountains Arsenal in Nevada, where the injection of 638 megalitres of chemical waste into basement rocks under sedimentary cover induced earthquakes up to 5 km from the well. The injection took place over a number of years. When the link was made between the fluid injection and the earthquakes, injection was ceased but earthquakes continued to occur for some time while the pressures of fluid in the storage rocks fell to a new regional equilibrium below the critical level that triggered the earthquakes (Healy et al., 1968; Hsieh and Bredehoeft, 1981).

The experience at the Rocky Mountains Arsenal led the United States Geological Survey to develop theories on the processes by which increased fluid pressure contributes to the fracturing of rock. They tested these theories at the Rangely gas field in Colorado in an experiment undertaken with the cooperation of the company operating the gas field. An increase in earthquake occurrence had been noted at the Rangely field, where fluid injection had been undertaken for 10 years to stimulate enhanced oil and gas recovery. The earthquakes occurred in a linear belt 4 – 5 km long and 1 – 2 km wide along strike from a fault mapped in the basin. The earthquakes had focal mechanisms indicating that the fault was reactivated by strike slip movement consistent with the regional stress field.

Raleigh et al. (1976) were able to predict the critical fluid pressure above which earthquakes would be triggered by the ambient stress field. When the operating company increased the pressure above that level, earthquakes occurred. When the pressures were dropped below the critical level, either by pumping water from wells or by oil and gas production without further water being injected, the incidence of earthquakes dropped.

The increased numbers of earthquakes in Oklahoma between 2009 and 2013 lie in the Cherokee Platform (shaded area in Figure A4.4(c), which is a shale gas province. They fall into two spatial groups:

- A northeast to southwest trending linear belt of earthquakes and aftershocks that occurred following a M=4.1 earthquake in the Wilzetta oil field in 2010, and three M≥5 earthquakes in the field in November 2011 [Figure A4.4 (c)]. The linear belt is approximately 15 km long and 1 – 2 km wide.
- Other increased seismicity was observed across a broad region east of Oklahoma City. Earthquakes in this category do not seem to lie in linear belts, although there is a hint of some linear trends in a few of the earthquakes.

The November 2011 sequence of earthquakes was studied by Keranen et al. (2013). They concluded that waste water injection into deep wells drilled into fault bounded compartments triggered several earthquakes which in turn caused two more large earthquakes, one of M5.6, and their aftershocks. Waste water injection had been underway in the gas field for 17 years before the first earthquakes were triggered.

A4.4 Lessons Learned from Experience in the United States of America

If the experience in the US is a guide to what to look for in Australia, the following observations are relevant:

- The regional increase in seismicity in all three provinces shown in Figure A4.4 is sufficiently high that it is unlikely to be explained as a natural variation within the statistics of normal background seismicity.
- The increased seismicity follows increased activity by the gas industry, both temporally and spatially from CSG operations in the Raton Basin and shale gas operations in the Arkoma and Cherokee Basins.
- It includes both an increase in seismicity above naturally occurring levels over broad areas (especially in the Raton Basin and in the Cherokee Platform east of Oklahoma City), and in linear belts in the Arkoma Basin in Arkansas and the Cherokee Platform in Oklahoma.
- The increase in seismicity over broad areas has not been explained.
- Linear belts of increased seismicity in the Arkoma Basin in Arkansas and the Cherokee Shelf in Oklahoma have been attributed to waste water injection, although the source of the finding for the Arkoma Basin cannot be found in the literature.
- However, in the case of the Oklahoma earthquakes, waste water injection had been underway for some years before the trend of increased earthquakes between 2009 and 2013 occurred. Therefore if underground storage is to be used for waste water, increased seismicity may not occur for many years after injection begins.
- These findings are consistent with documented case studies of earthquakes induced by the injection of waste fluids, including not only those summarised above but also others referred to in the publications about those case studies, and in The National Academies (2011) for both the US and some other countries.
- If injection of waste water is stopped, the level of induced seismicity will not drop until the fluid pressures in the rocks drop below the critical levels above which earthquakes are triggered. US experience indicates that this could take some years unless pressures are reduced by fluid removal.

A4.5 References

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APPENDIX 5:

Is there evidence for increased seismicity in New South Wales from Coal Seam Gas Activities?

A5.1 Introduction:

This Background Paper distinguishes between earthquakes resulting from a number of causes.

Natural earthquakes are the result of changes in (i) the stress in the Earth and/or (ii) the pressure of fluids in the pore spaces in rocks that are caused by natural phenomena.

Induced earthquakes result from changes in the stress in the Earth or the pressure of fluids caused by some kind of human activity. Four types of induced seismicity (1a, 1b, 2 and 3 below) are identified in the body of this Background Paper. They are summarised in this Appendix (with references) in Table 5.1, which is copied from the Background Paper.

1. Small earthquakes occur when rocks are hydrofractured by the oil and gas industries to enhance permeability in the oil and gas reservoirs. In this Background Paper, this hydrofracturing is called intentional hydrofracturing. It has two parts, each of which causes small earthquakes:
    - 1a. The hydrofracture stimulation of a gas well causes cracks in the rock to grow outwards from the well that is being stimulated. Each time the crack grows by a small increment, energy is released. Some of the energy is in the form of a small earthquake.
    - 1b. Sometimes the hydrofracture cracks intersect an existing weak fault. When the fluids enter the fault it can be re-activated. This often occurs near the periphery of the hydrofractured zone a few hundred metres from the well, and usually during or just after the hydrofracture stimulation period. Earthquakes induced in this way are usually small.

    The intentional hydrofracturing process in the coal seam gas industry can be monitored and controlled by managing the pressures, volumes and rates of injection of the hydrofracuring fluids (Appendix 2). The earthquake magnitudes are typically very small, mostly M<0. Earthquakes with such small magnitudes would not be felt at the surface by people. Earthquakes with magnitudes M>2 and even M>3 should not result from carefully controlled deliberate hydrofracturing of coals and other sedimentary rocks by the CSG industry.

2. When large volumes of waste water are injected into disposal wells, particularly over periods of years and decades, pore fluid pressures can grow in the reservoir into which the waste is being injected, and existing weak faults can be reactivated. Because this kind of earthquake is stimulated by increases pore-fluid pressure, this Background Paper refers to the re-activation of the faults as unintentional hydrofracturing. International experience shows that the resulting earthquakes can be quite large [eg., M = 5.6, Kernanen et al (2012)]. They can either occur soon after injection of waste water begins, or based on the results in some case studies in the United States they can happen much later, sometimes after more than a decade of

injection (see Appendix 4). They can occur several kilometres from the injection well and when the do they do not always stop immediately when injection is stopped.

3. Some sectors of the oil and gas industry extract large volumes of fluid from reservoirs – oil, gas, formation waters. Experience overseas shows that this can cause a re-distribution of the stresses in the rocks surrounding the reservoir that are sufficient to trigger earthquakes. In the ambient stress field in Australia, the earthquakes would most likely be on shallowly dipping thrust faults in the rocks above and below the reservoir. This kind of faulting is stress-driven and not pore-fluid pressure driven, and is therefore not hydrofracturing.

Earthquakes caused by unintentional hydrofracturing can have much larger magnitudes than those caused by intentional hydrofracturing. Earthquakes caused by fluid withdrawal can also be larger than those caused by intentional hydrofracturing. Therefor earthquakes resulting from unintentional hydrofracturing or fluid withdrawal are more likely to be felt and reported by people who are nearby than those caused by intentional hydrofracturing.

Demonstrating a causal relationship between the processes (fluid injection or fluid withdrawal) and earthquakes can be difficult. A number of approaches can be taken.

Firstly, Ellsworth et al. (2012) found a spatial and temporal correlation between activities in the energy industries in the United States and increases by up to 6 fold in seismicity (but he did not attribute the increase in seismicity to any specific activity). This approach looks at the population of earthquakes in a region, rather than specific earthquakes, and was outlined in Appendix 4:

- The regional increase in seismicity is unlikely to be explained as a natural variation within the statistics of normal background seismicity.

- The increase in regional seismicity occurs both (i) over broad areas and (ii) in linear belts probably associated with the reactivation of faults by waste water injection.

Secondly, Davis and Frohlich (1993) erected a set of questions to use in making objective assessments of whether earthquakes are induced by the energy industries or were from natural causes. The questions are more closely related to specific wells and nearby earthquakes rather than regional populations. For example, they might be applied to each of the earthquakes that are in the first category from the work of Ellsworth et al. (2012); ie., individual earthquakes scattered across a broad region, provided that the locations of wells and the dates they were drilled are known. The questions are:

1. Are these events the first known earthquakes of this character in the region?
2. Is there a clear correlation between injection and seismicity?
3. Are epicentres near wells (within 5 km)?
4. Do some earthquakes occur at or near injection depths?
5. If not, are there known geologic structures that may channel flow to sites of earthquakes?

6. Are changes in fluid pressures at the bottoms of the wells sufficient to encourage seismicity?
7. Are changes in fluid pressures at hypocentral distances sufficient to encourage seismicity?

This approach has the disadvantage of mixing up the various causes of induced seismicity:

- Intentional hydrofractures start within hours of the hydrofracture stimulation beginning but unintentional hydrofractures could occur decades after waste injection begins (Question 2).
- Intentional hydrofractures would be within hundreds of metres of a well but a fault could be reactivated kilometres from a well that is used for waste injection Question 3)

Another approach would be to consider the likelihood that earthquakes were likely to have been induced by any of the four causes listed above, using the descriptions of the earthquake populations in Table 5.1 as discriminators.

This Appendix uses aspects of all approaches to determine whether New South Wales has experienced an increase in seismicity caused by the CSG industry?

Data from the online data warehouse operated by the New South Wales Geological Survey can be downloaded as comma-separated-variable (CSV) files. The data contain information on 557 wells that are described in the column called "Bus_Purpose" as Coal Seam Methane wells. The positions of 556 are shown in Figure A5.2; one well has no latitude and longitude information and cannot be mapped.

Whether the wells have been hydrofractured is contained in the column "Hole_Tests" in text strings such as "Well has been fracced"; the "Hole Tests" field also includes text strings that describe other tests done on the well. One hundred and three (103) wells were identified as having been hydrofractured. They are classified in the data as either Exploration or Pilot wells. The data show 84 wells as Production wells. The data do not show any of the Production wells as having been hydrofractured.

The "Hole_Tests" field does not have entries for all wells. Coupled with the nature of the entry as a text string rather than a mandatory field this means that all wells that have been hydrofractured may not have been identified.

A5.2 Do the New South Wales seismicity data show correlations with CSG activities?

A5.2.1 Data for New South Wales and Data Limitations

CSG operations in New South Wales began in the Sydney Basin in 1980 and have now been conducted in the Sydney, Gunnedah, Surat, Bowen, Clarence Moreton Basin and Murray Basins. The sedimentary basins in New South Wales are shown in Figure A5.1.

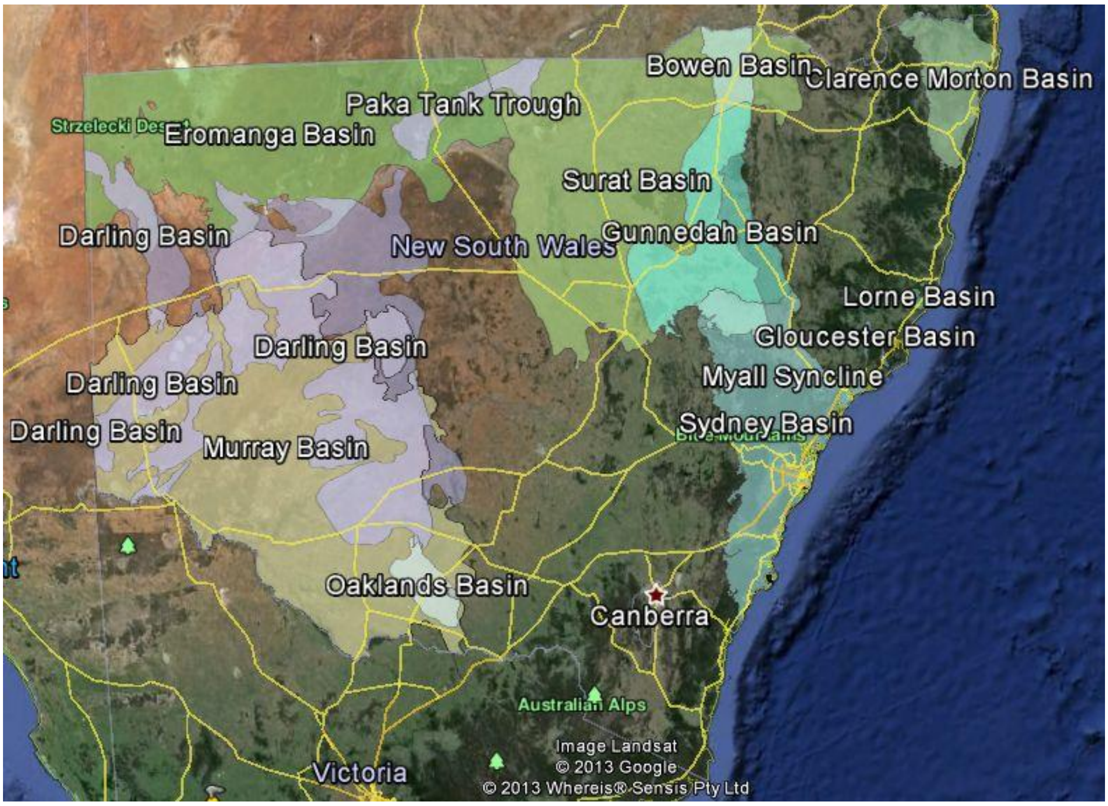

Figure A5.1: Locations of sedimentary basins in New South Wales. Source: Basins - NSW Geological Survey website: http://dwh.minerals.nsw.gov.au/CI/warehouse; Base map – Google earth.

Evidence of this is given in the report of a review into the coal seam gas industry by the NSW Legislative Council (NSW Legislative Council, 2012). The report notes [Clause 5.5] that 131 out of 205 wells in the Camden Gas Project have been hydrofractured; this number alone is greater than all the wells listed in the data from the NSW data warehouse as having been hydrofractured. Furthermore, the Legislative Council Report noted [Clause 5.7] that in "New South Wales the Government estimates approximately 160 wells have been fracced since 1980 but due to differing reporting arrangements cannot 'guarantee the completeness of this information.'" (NSW Legislative Council, 2012).

The locations of earthquakes from 1980 until the present are shown as red circles in Figure A5.2. These earthquakes were detected by the Australian National Seismograph Network. All earthquakes with $M \geq 3$ since 1980 in the areas where coal seam gas activities have been undertaken should have been detected and their locations determined (Burbidge, 2012). Earthquakes with smaller magnitudes may also have been detected; for example, the earthquakes mapped in Figure A5.2 have magnitudes as low as M=1.9. However, if insufficient seismograph stations detected the small earthquakes then their locations and magnitudes could not have been calculated and they will not be included in the data set. Therefore the data set will probably be incomplete for earthquakes with magnitudes $M \leq 3$.

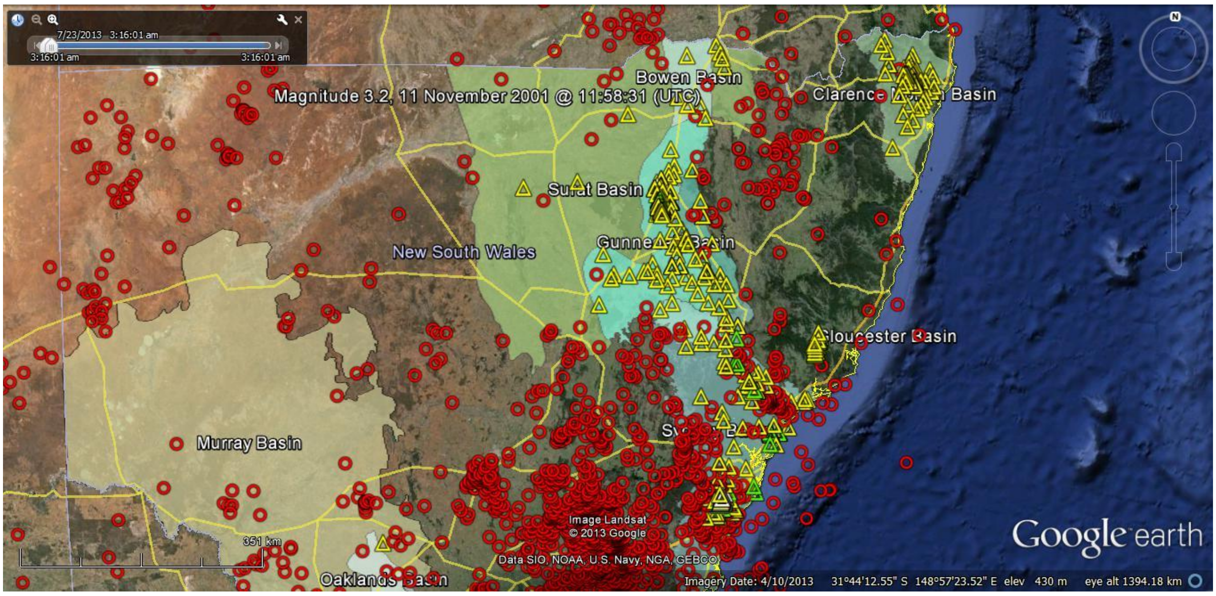

Figure A5.2: Locations of 556 CSG wells in New South Wales (Triangles: Green – Hydrofractured; White – Production; Yellow – all other wells). The locations of earthquakes in the national earthquake database maintained by Geoscience Australia are shown as red circles.

A5.2.2 Data Analysis

A5.2.2.1 Increase in Regional Seismicity in the Area of CSG Operations

The data in Figure A5.2 are shown in more detail for individual basins in Figure A5.3.

The CSG wells in the Clarence Moreton Basin are shown in Figure A5.3(a). None of these wells were described in the data from the NSW Geological Survey data warehouse as having been hydrofractured. Only one earthquake occurred in this basin and that was before the wells were drilled – there is no increase in recorded seismicity following the drilling of the wells.

Figure A5.3(b) shows wells and earthquakes in the southern Surat and Bowen Basins and the northern Gunnedah Basin. As with the Clarence Moreton Basin, the number of earthquakes is small and not spatially correlated with the wells.

The southern Gunnedah Basin [Figure A5.3(c)] has low levels of recorded seismicity that do not correlate spatially or temporally with the CSG wells drilled in the basin, with the exception of one earthquake that occurred near a well; this earthquake is discussed further below. Nor is there recorded seismicity in the Gloucester Basin that correlates spatially or temporally with CSG wells.

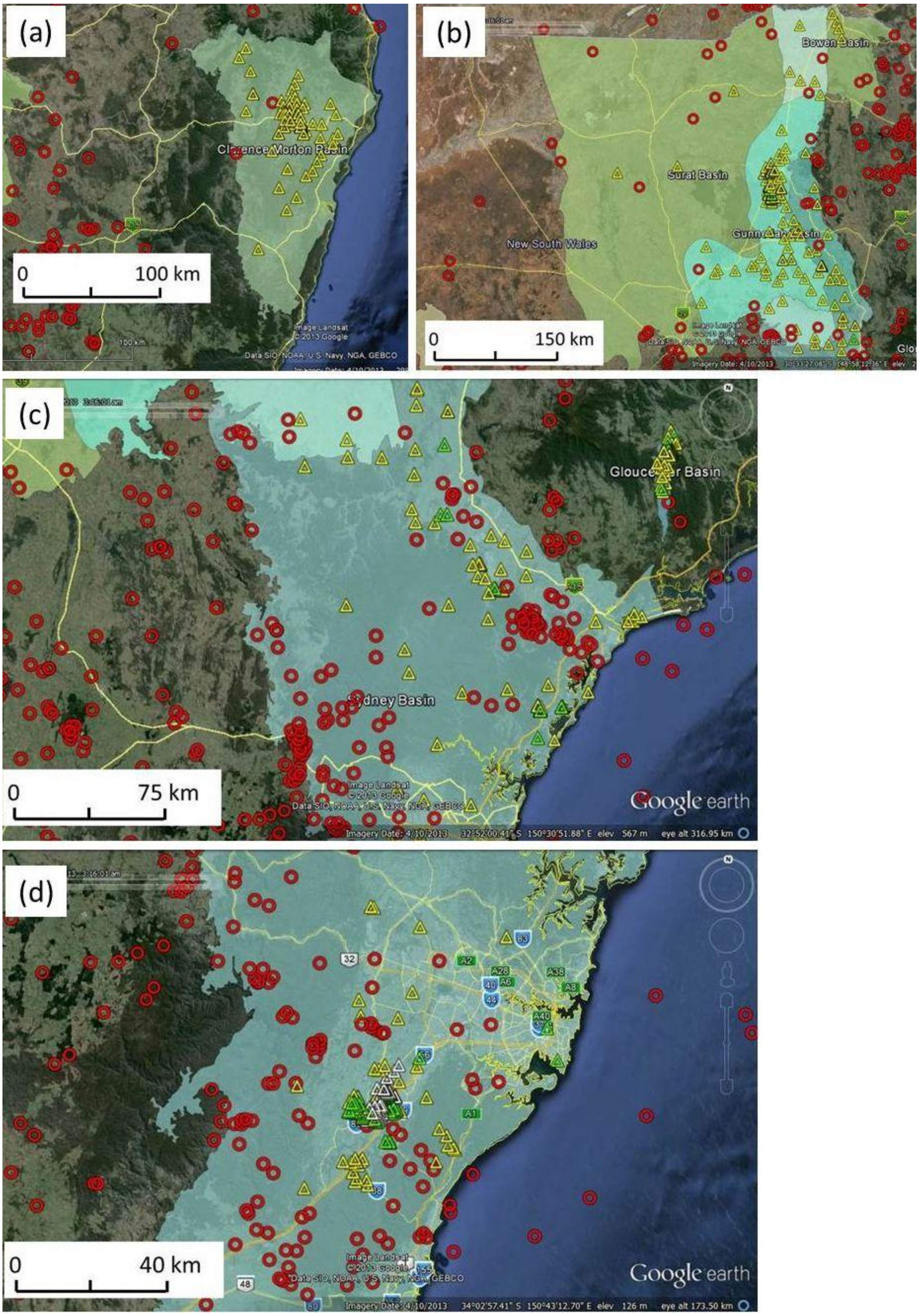

Figure A5.3: CSG wells and earthquakes in (a) Clarence Moreton Basin, (b) Southern Surat and Bowen basins and the northern Gunnedah Basins, (c) Southern Gunnedah and northern Sydney Basins and Gloucester Basin, and (d) Southern Sydney Basin. Wells are shown as triangles (Green – Hydrofractured; White – Production; Yellow – All other wells). Red circles are earthquakes; Diameter of circle reflects earthquake magnitude.

The Sydney Basin has a level of seismicity that is historically higher than the other sedimentary basins shown in Figure A5.3. It tends to be highest along the margins of the basin, eg., in clusters to the west of Newcastle in the north and west of Sydney (lower left corner of Figure A5.3(d). The clusters along the margins of the basin are not spatially correlated with CSG wells and are part of the on-going levels of seismicity in the basin. Low levels of seismicity also occur throughout the basin away from these clusters [Figure A5.3 (c) and (d)]. The earthquakes are scattered across the basin and most do not occur near CSG wells; those that do occurred before the wells were drilled, with 4 exceptions that are examined further below.

This section has considered the approach of Ellsworth et al. (2012) who argued that a six-fold increase in the level of seismicity in the mid-continent of the US could not be explained by natural variations in seismicity (Appendix 4). That is, they looked at the population of earthquakes as a whole, rather than individual earthquakes. An examination of the recorded earthquakes in the sedimentary basins in New South Wales where CSG exploration and production are occurring therefore reveals no compelling evidence of an increase in regional seismicity that is spatially and temporally correlated with CSG activities of the form reported from unconventional energy activities in the United States.

A5.2.2.2 Correlation of wells with nearby earthquakes

The five earthquakes that occurred near CSG wells reported in the previous section were considered further using the approach of Davis and Frohlich (1993) and the analysis of induced seismicity outlined in Table 5.1 of the Background Paper.

Questions 5 – 7 from Davis and Frohlich (1993), set out above, can only be answered using site specific information that is not publicly available. Question 4 is difficult to answer because of the lack of precision in estimates of earthquake depth that are based on regional seismograph network data.

Questions 1 – 3 can be considered using information in the public domain, especially the temporal correlation of the earthquakes and the drilling of the wells, and partially with respect to their spatial correlation.

Each of the earthquakes would have an uncertainty in its reported location because the process of calculating the location involved a least squares fit to the reported arrival times at the seismograph stations that detected the earthquake. The uncertainties are not given in Geoscience Australia's on-line earthquake database. The uncertainties are on average between 5 and 15km, depending on the azimuths from the earthquakes to the seismograph stations used to detect and analyse the earthquakes (Hugh Glanville, Geoscience Australia, personal communication, August 2013).

The earthquake and well data in Figure A5.3 were examined to find earthquakes that occurred within ~15 km of a well; ie., the earthquake could have occurred at or near the well after location uncertainties are considered. The data were then time sliced to check whether the earthquakes occurred before or after the wells were drilled. All data entries for wells include the year in which the well was drilled. Some have start and completion dates. Where the start and completion dates of the wells are provided, they were used to exclude earthquakes that occurred in the same year that the well was drilled but before the well was drilled. This process identified 5 well-earthquake pairs in which the earthquakes occurred or may have occurred after the wells were drilled. They are shown in Figure A5.4 and listed in Table A5.2. The numbers beside each earthquake and well pair (Circle and Triangle) in Figure A5.4 correspond to the well-earthquake pairs in Table A5.2.

Four of the wells are in the Sydney Basin and one is in the southern Gunnedah Basin. One is a production well and the others were exploration wells. One of the wells was flagged in the data from the New South Wales data warehouse as having been hydrofractured.

The attributes of each of the induced earthquake populations identified in the Background Paper were then used to analyse each of the earthquake – well pairs.

<u>Well-Earthquake Pair 1</u>: The well Hunter Llanillo 1 is an exploration well that has been hydrofractured. The earthquake's reported location is 12.4 km from the well. Unless the earthquake's location error is at the maximum bounds of the location uncertainty, it probably did not coincide spatially with the well.

Intentional Hydrofracturing: Earthquakes with M=3.2 should not be caused by intentional hydrofracturing. This predicted by the theory of hydrofracturing and consistent with observations in reported case studies, although case studies in the gas industry mostly come from the shale gas sector.

Intentional Hydrofracturing – Fault Reactivation: Earthquakes of this magnitude can occur in hydrofracture stimulation of wells in granite, which has a higher shear modulus than coal. However, an earthquake of magnitude M = 3.2 in coal would require an area of fault of around 100,000m^2 to rupture (Appendix 3, Figure A3.2), which would be have a width of 360 m. This is of the order of the maximum extent of hydrofractures in coal. Therefore a single rupture on a pre-existing fault would use a large portion of the fluid budget for the hydrofracture stimulation of this well, which was conducted in multiple stages and not one stage. Furthermore, when faults are reactivated during hydrofracture stimulations, multiple earthquakes usually occur in linear belts whereas only one earthquake was recorded in this instance.

The time lag between the end of injection, reported in the Well Completion Report for this well (WCR 244 available from the NSW Geological Survey on-line DIGS Database) is 47 days. After injection, the well went through a cycle of "Production" which would have reduced the formation pressures after the hydrofracture stimulation, therefore making late unintentional hydrofractures highly unlikely.

Unintentional Hydrofracturing - Fluid Injection and withdrawal:

The well was not used for production ("Production" in the Well CompletionReport refers to production testing, not the long term commercial production of gas). Therefore it should not have had large quantities of gas and water withdrawn; equally, it should not have have had large quantities of waste injected over a long period of time.

The earthquake is therefore unlikely to have been caused by unintentional hydrofracturing.

The magnitude of this earthquake and the occurrence of only one earthquake indicate that a causal relationship between activities at the well and the earthquake is highly unlikely.

The remaining four well-earthquake pairs contain wells that are not listed as hydrofractured. However, because not all fields in the data from the NSW data warehouse are complete, these wells are considered below. If they weren't hydrofractured then there can be no causal link between the hydrofracturing of the well and the nearby earthquakes. The data downloaded from the NSW Geological Survey data warehouse do not indicate what wells, if any, were or are used for the disposal of waste water.

<u>Well-Earthquake Pair 2</u>: The well Hunter Corehole 6 was an exploration well that is now "Plugged and Abandoned". The earthquake occurred more than 8 months after the well was completed at a distance that might be outside the location uncertainty for the earthquake.

This is a very long time lapse for an earthquake to have been induced by the hydrofracture stimulation of a well, either through intentional hydrofracturing or the reactivation of an existing fault.

Earthquakes can be caused this long after a well is first used for waste water disposal, but the data contain no evidence that this well was used for that purpose.

Earthquakes can also be caused by long term fluid withdrawal from a well, but this well is plugged and abandoned and therefore unlikely to have had large quantities of fluid withdrawn.

On the basis of the available data a causal link between this hole and the nearby earthquake is highly unlikely.

<u>Well-Earthquake Pair 3</u>: The time lag between the drilling of the well Turnermans 1 and the nearby earthquake is unknown because the start and end dates for drilling the well are not provided. However, the earthquake occurred early in the year and may have pre-dated the drilling.

The magnitude of the earthquake (M=3.6) is large compared to earthquakes induced by well managed hydrofracturing operations and by the reactivation of an existing fault, and the well is not reported as having been hydrofractured.

Table A5.1: Characteristics of seismicity induced by injection and withdrawal of fluids (From Section 3 of the Background Paper)

Intentional Hydrofracturing	
Number of events	1,000's for each well, and potentially for each hydrofracture treatment in each well.
Time frame	Within hours to days of start of fraccing.
Maximum Magnitudes	Usually M ≤ 0 (Maxwell et al., 2009; Shemeta and Anderson, 2010; Šilneý et al., 2009)
Where	Within a few 100's of metres of the well
Spatial Distribution	Spread radially with time

Intentional Hydrofracturing - Fault Reactivation Near a Well Being Hydrofractured	
Number of events	100's - 1,000's
Time frame	At the end of fraccing; can be after shut in
Maximum Magnitudes	Usually M ≤ 0 but can be larger (Maxwell et al., 2009; Rutledge & Phillips, 2003; Šilneý et al., 2009)
Where	Typically at the edges of the fractured volume
Spatial Distribution	Linear patterns 100's of metres long aligned with existing faults that are usually optimally or near optimally aligned with stress field

Table À5.1
(Continued)

Unintentional Hydrofracturing – Injection	
Number of events	100's - 1,000's
Time frame	Time is required to raise reservoir pressure above the level required to fracture intact rock or reactivate existing fault; this can be years after the injection beginss
Maximum Magnitudes	M = 5.3 (Davies et al., 2013a); M = 5.0, 5.7 (Keranen et al, 2013)
Where	At the edges of the reservoir; ; usually on faults that are optimally or near optimally aligned with stress field because they will reactivate at lower pressures than intact rock
Spatial Distribution	Linear patterns 100's to 1,000's of metres long aligned with existing faults

Unintentional - Fluid Withdrawal	
Number of events	100's
Time frame	Time is required to lower the surface of surrounding countryside; usually years after injection begins.
Maximum Magnitudes	M = 7.3 (Davies et al., 2013a); M = 4.0 (The National Academies (2011); M $\leq$3.4 (Segall, 1989)
Where	Reverse faults: Under or above the withdrawal zone; Normal faults: On the flanks at distances up to 3 times the width of the withdrawal zone
Spatial Distribution	Even spatial distribution under a zone of surface subsidence that extends either side of the withdrawal zone.

Table A5.2: Pairs of wells and earthquakes for which the earthquake occurred after the well was drilled. The "Distance" field shows the distance between the well and earthquake location given in the Geoscience Australia on-line database. "Time lag" in the Comments field is the time between the drilling and the earthquake.

	Well & Magnitude	Well Commenced & Event Date	Well Completed & Event Time (UTC)	Well Purpose	Fracced	Latitude	Longitude	Distance	Comment
1	Hunter Llanillo 1 M3.2	18/01/1991 17/07/1991	24/06/1991 2:34:11	Exploration	Yes	-32.44 -32.54	150.84 150.90	12.4 km	Last injection 31/05 (WCR 244); time lag 47 days
2	Hunter Corehole 6 M3.1	26/03/2008 5/09/2008	22/05/2008 5:39:20	Exploration	No	-32.83 -32.85	150.87 150.78	8.7 km	Time lag 8+ months
3	Turnermans 1 M3.6	Drilled 2009; no specific dates given 11/03/2009	 13:25:40	Exploration	No	-32.48 -32.56	150.68 150.69	8.9 km	Time lag unknown
4	Menangle Park 23 M1.9	Drilled 2009; no specific dates given 25/03/2010	 17:37:42	Production	No	-34.10 -34.16	150.76 150.77	6.7 km	Time lag unknown
5	Turill 1 M2.5	Drilled 2009; no specific dates given 16/04/2010	 19:26:21	Exploration	No	-32.06 -32.07	150.06 149.99	6.7 km	Time lag unknown

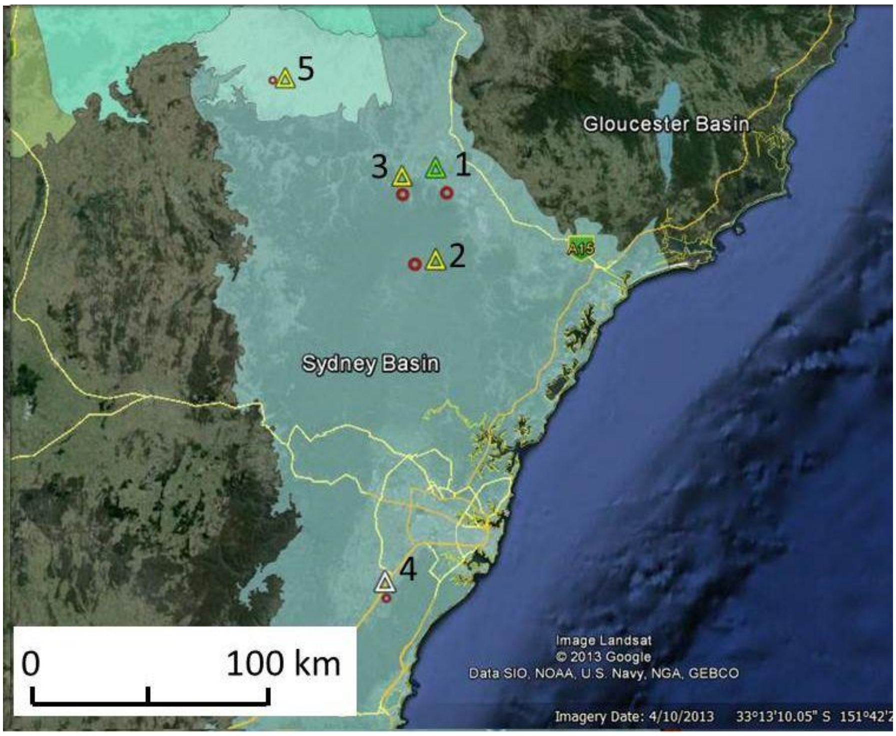

Figure A5.4: Five CSG wells (triangles) near which earthquakes (red circles) occurred during or shortly after the wells were drilled. Numbers beside the triangles refer to the well-earthquake pairs in Table A5.2 (above). Green triangles – hydrofractured; White – production; Yellow – all other wells.

Well-Earthquake Pair 3 (Continued): The data show no evidence that large quantities of fluid were injected into the well for waste disposal. Even if the well was used for that purpose, and if the earthquake did occur after the well was drilled, insufficient time would have passed for the earthquake to have been stimulated by fluid injection. Furthermore, only one earthquake occurred rather than a linear belt of them.

The data also show no evidence that long term production of fluids has occurred from the well, therefore the earthquake was unlikely to have been induced by fluid withdrawal.

On the basis of the available data a causal link between this well and the nearby earthquake is highly unlikely.

Well-Earthquake Pair 4: No start and end dates are available for the drilling of this well. The earthquake occurred early in the year and may have pre-dated the well.

Menangle Park 23 is a production well that is reported as not having been hydrofractured. The operator for this well has adopted a practice of drilling holes that are deviated from the vertical to penetrate the coal seam as horizontal wells, thereby avoiding the need to hydrofracture the well (NSW Legislative Council, 2012). The data for this well from the NSW Geological Survey data warehouse show it to be a deviated well, so it is unlikely to have been hydrofractured. Therefore the earthquake is unlikely to have been induced by deliberate hydrofracturing or the reactivation of an existing fault.

Coal seam gas production wells produce significant volumes of water early in their operational life. The time lag between drilling and the earthquake must have been only days or weeks. This is insufficient time for the earthquake to have been caused by fluid withdrawal.

Production wells are not used for injection of waste water so the earthquake would not have been caused by the unintentional hydrofracturing of a pre-existing fault.

All of the available evidence would therefore suggest no causal relationship between the well and earthquake.

Well-Earthquake Pair 5: Turill 1 was drilled in the southern Gunnedah Basin as an exploration well in 2010. Its status is not defined in the data from the NSW Geological Survey data warehouse; nor is the time of year in which it was drilled. The earthquake occurred in April and may have predated the well.

The earthquake is consistent with the low level of ongoing seismicity in the area.

The magnitude of the earthquake is quite high for an intentional hydrofracture earthquake. No other earthquakes have occurred to form a linear belt of earthquakes, and the magnitude is high for an earthquake on a reactivated fault. The available data give no indication that the well is used for production or waste disposal by fluid injection, so a fluid injection or by fluid withdrawal cause can be ruled out.

On the basis of the available data a causal link between this well and the nearby earthquake is unlikely.

A5.2.3 One more well

One well not considered in the above analysis (Noonameena 1) was drilled in the Murray Basin in 2003 (Figure A5.2). The nearest earthquakes that occurred after the well was drilled are too far from the well for a causal relationship to exist.

A5.3 Summary

The available data on coal seam gas wells and earthquakes in New South Wales indicate no unequivocal causal link between the recorded seismicity and coal seam gas well operations. However, this result must be qualified:

1. Any seismograph network cannot detect every earthquake; networks are designed with a purpose (or several purposes) in mind, and the Australian National Seismograph Network operated by Geoscience Australia was designed with a detection threshold for earthquakes of magnitude M3 – 3.5, ie., the magnitude threshold above which earthquakes can be damaging. Although some earthquakes with smaller magnitudes can be detected, as demonstrated by the earthquakes

discussed in this document (eg., Table A5.2), the catalogue of earthquakes below M=3 is probably not complete for the areas considered in this study.

2. Location uncertainties are not available for the earthquakes considered in this study (Table A5.2) and estimates have to be used. Nevertheless the estimates are probably sufficiently robust to be applicable.
3. A major uncertainty in the analysis arises because of the incompleteness of the information about the CSG wells. The inconsistencies between the number of hydrofractured wells listed in the NSW Geological Survey data warehouse and the figures quoted in the NSW Legislative Council (2012) report are significant. As a consequence, whether a well is reported to have been hydrofractured, or might be used for waste disposal, are two of the factors considered in the discussion above in assessing causality between wells and nearby earthquakes.
4. A lack of information in the public domain about the magnitudes of earthquakes caused by intentional hydrofracturing operations in New South Wales is a major inadequacy in the available data; companies that monitor hydrofracturing operations using seismographs should have these data. Therefore earthquakes that are caused by deliberate hydrofracturing have been assumed to be very small, consistent with case studies in the scientific literature (eg., mostly M<0)..

A5.4 Acknowledgements

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