Seismicity & induced earthquakes

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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.

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Summary

This report aims to describe the characteristics of triggered earthquakes, and to develop a path towards quantification of the earthquake hazards and induced seismicity effects associated with coal seam gas (CSG) production.

It consists of five parts, as follows:

1. This starts with a brief introduction to the basics of earthquake seismology. Several of these topics are particularly relevant for earthquake triggering, including earthquake depths, magnitudes, and clustering.
2. The characteristics of Australian earthquakes are described, with emphasis on how they differ from earthquakes in more active regions as well as regional patterns in seismicity.
3. The third section considers triggered and induced (human triggered) earthquakes in more detail. Worst-case scenarios for CSG activities in Australia are discussed in more detail.
4. The fourth section covers microseismicity, including the physics of rupture, and the typical monitoring systems required to fully quantify the rupture process.
5. The final concluding section summarises the main knowledge gaps and issues that need to be considered in future research.

Much work has been done on investigating triggered earthquakes under large water reservoirs and in underground mines. An increasing amount of work is being done on earthquake-triggered earthquakes, and also on triggering by fluid injection/extraction (induced seismicity).

A critical issue in seismology is to understand the relationship between earthquakes on various scales, giving the similarities and differences between the large earthquakes that occur on plate boundaries through to the very small shallow events associated with mining.

It is important to emphasise that CSG extraction occurs at shallow depths usually less than 1 km, compared with shale gas extraction at depths to 3 km, and EGS (enhanced geothermal system) production at depths of 3 to 5 km. Shallow rocks and especially shallow sedimentary rocks, tend to be weaker than those at greater depth, and can support a lower stress (strain energy density), limiting the magnitudes of earthquakes that can occur within them, and limiting the chance of inducing a larger earthquake at depth.

The risk of significant induced earthquakes caused directly from hydraulic fracturing will be less than that from the separate process of wastewater disposal, especially if disposal is at greater depths where tectonic strain energy density is higher.

Earthquakes

Earthquake Basics

Earthquakes are the motion produced when stress within the earth exceeds the strength of rocks at its weakest points. For moderate to large earthquakes this motion always occurs on pre-existing faults, resulting in relative slip across the fault. The rupture causes radiation of seismic waves that dissipate about 1 to 10% of the total elastic energy released. Energy is also expended in heating rocks in the fault zone and creating new fractures.

The radiated seismic waves include three-dimensional body waves that travel through the earth with both longitudinal P waves (sound waves) and slower but larger transverse S waves. In addition, surface waves propagate across the earth's surface, including Love waves (shaking the surface horizontally in a transverse direction), and Rayleigh waves (shaking the surface vertically and horizontally in a radial direction with retrograde elliptical motion). Recorded motion at the surface is the sum of these, together with motion that has passed through a variety of reflected, refracted and diffracted wave paths.

An earthquake origin time is the instant when the earthquake rupture begins, usually measured to a fraction of a second in Universal Co-ordinated Time (UTC). Seismometers measure the arrival times of seismic waves at stations located on or below the earth's surface. The interval between the earthquake origin time and the seismic wave arrival time is the wave travel-time[1].

To locate an earthquake, seismometers surrounding the epicentre measure wave arrival times. A preliminary earthquake location is selected (e.g. at some depth under the nearest seismometer), and a travel-time model[2] is then used to estimate the origin-time for the earthquake. The errors (or residuals between measured and calculated arrival-times) are then used to adjust the location of the earthquake to give a better fit. This is repeated iteratively until the residuals cannot be reduced further, and the earthquake is then assumed to have originated at this epicentre and depth.

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[1] There are two main ways of representing the seismic wave velocities within the earth, either of which may be used to determine the time interval between the origin time of an earthquake and the arrival of the wave at a point on the earth's surface. A table of travel times has distances from the epicentre on one axis and the depth of the earthquake hypocentre on the other axis. Given an earthquake distance and depth, interpolation between point values will give the travel time. Alternatively, a model showing the variation in seismic wave velocities is developed. The model may be one-dimensional, where velocities only vary with depth, the simplest model being a series of horizontal layer, each with constant velocities (P and S). More complex models may include velocities that vary (usually increasing with depth), or have variations in two- or three-dimensions.

[2] In practice, horizontally layered velocity models are normally used for nearby earthquakes, and tabular travel times are used for distant earthquakes.

An earthquake occurs when rocks break and move as a result of stresses caused by plate motions which, in turn, result from heat loss from within the earth. The energy input occurs at a near constant rate, and is a result of slow continuous deformation. Depending on the local tectonics, deformation ranges between shortening, extension and horizontal shear. For low to moderate levels, the stress within the rocks is approximately proportional to the deformation (strain). Faults are usually strongest under compression, leading to higher stress changes under these conditions than in situations with either shear or tension[3].

Stress within the earth is variable over space and time, depending on the time interval since the last moderate earthquake at each point, when the last large earthquake occurred within the surrounding region, and possibly when the last very large earthquake occurred at a nearby plate boundary. Tectonic stress magnitudes cycle as earthquakes occur in and around each location, with the pattern strongly affected by the pre-existing fault distribution and the regional stress orientation.

Tectonic plate boundaries, can accommodate relative plate motions of 50 millimetres per year or more, so it takes as little as few tens to hundreds of years to strain the boundary to failure sufficient to release up to 10 metres of relative motion[4]. The rate of accumulation of stress within continental interiors in intraplate settings, such as Australia, occurs at a very much lower rate than at plate boundaries, by several orders of magnitude. The relatively thin seismogenic layer within continents tends to restrict earthquakes to the upper crust. This depth limitation together with a typical maximum credible fault rupture length of 100 to 150 km limits the maximum earthquake magnitude that can occur to about magnitude 7.5. The slow deformation rate and magnitude limit combine to give infrequent large earthquakes, such as a magnitude 6.0 or larger in all of Australia about every eight years, and a magnitude of 7.0 or larger about every eighty years.

The distribution of small to moderate earthquakes depends on the local geological structures, and there is usually a distinct pattern in earthquake activity across a continent. For example, in eastern and central Australia, where the tectonic plate movement gives rise to a compressional stress state, most earthquakes occur under mountainous or uplifted regions (Eastern Highlands, Flinders Ranges). Large flat-lying sedimentary basins remain in those regions experiencing relatively few earthquakes. The higher level of activity in the more active regions leads to weaker faults, and a higher proportion of small to large earthquakes than in more stable regions (a higher seismicity b-value, as discussed later).

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[3] Strictly, all natural stresses within the Earth are compressional, with an extensional stress field referring to a stress regime with the magnitude of vertical stress component in excess of the maximum horizontal component ($\sigma_v > \sigma_{SHmax}$).

[4] An example, the 27 February 2010 earthquake along the coast of Chile produced a rupture with length about 550 kilometres north-south, dipping to the east under Chile with a rupture width of almost 150 kilometres.

Fluids in the Earth's crust, such as water, are thought to play a critical role in crustal seismicity (e.g. Simpson et. al., 1988). Large faults are likely to be fluid-lubricated, mainly by groundwater. Evidence includes the lack of heat flow anomaly in the San Andreas Fault Zone through which it is inferred that the effective friction is significantly lower than for dry rock. Co-seismic groundwater changes have also been observed for large earthquakes, and the injection of fluid into the crust often results in induced seismicity. These phenomena are interpreted as resulting from pressure changes in pre-existing fault networks.

Earthquake Sizes

Earthquake magnitude is a measure of the "size" of an earthquake on an arbitrary scale, usually determined from a measure of ground motion as recorded by a seismometers (such as the maximum displacement) then corrected for distance. The original Richter scale, ML, used the logarithm to base ten of the maximum horizontal ground displacement with an empirically determined correction that varied with distance from 0 to 600 km.

Because magnitude is a logarithmic scale, one magnitude unit increase corresponds to an increase in displacement by a factor of 10, and two units give a factor of 100. An earthquake of magnitude 0.0 gives ground displacement at a given distance of ten times of that given by a magnitude -1.0 at that distance.

Because the duration of motion also increases with magnitude the energy release corresponding to one magnitude unit is about a factor of 32, and two units give about 1000 times more energy. For more information on magnitudes, see Bormann et.al. (2013), especially section 3.2 and 3.2.7.

There is a huge range in earthquake sizes from the smallest events recorded in mines with magnitude -3.0 to the largest known earthquake in Chile during 1960 of magnitude 9.5.

Earthquakes smaller than magnitude 3.0 are often called microearthquakes, and the associated seismicity called microseismicity. Normal tectonic earthquakes in this range may be felt or heard, but rarely cause any damage, and never produce serious structural damage. However, because of the short distances involved, induced earthquakes in mines with magnitudes from less than 1.0 may cause local safety problems, and magnitudes larger than 2.0 may cause serious damage.

Several different magnitude scales are used, using different seismic waves (P, S or surface waves) and motion of different frequencies. The original Richter Local magnitude, ML, is suitable for smaller earthquakes within 600 km of the seismometer and is best up to ML 5.0. Two newer scales are moment magnitude, Mw, which is based on low frequency spectral displacement (best from Mw 6.0 to Mw 9.0), and energy magnitude, Me, which depends more on high frequency motion. All magnitude scales were originally defined to be consistent with the original ML scale as applied in California, but because they are based on different measures of ground motion, their values are not consistent outside of the ideal size range.

The attenuation of ground motion with distance depends on local properties of the rocks in the earth. Unconsolidated, hot or young rocks attenuate seismic wave motion more quickly with distance than hard, cold or old rocks because more energy is lost per cycle due to non-elastic behaviour. This variation is most significant for high frequency motion, so most magnitude scales are based on displacement, which emphasises low frequency motion.

Earthquake Numbers

While the relative number of small to large earthquakes does vary from point to point, on average there are about ten times as many magnitude M events as magnitude M+1.0 events. This is known as the Gutenberg-Richter relationship. When plotted logarithmically this gives a straight line with gradient b = $-\log_{10}$ (ratio of number of M events to M+1 events). The b-value is typically about 1.0 (a ratio of 10 times), but varies from about 0.7 (ratio of 5) to about 1.4 (ratio of 25). The absolute number of earthquakes is always dependent on the number/quality of local and regional seismometers. The number of earthquakes must always be read in context, i.e. “an increase in M > 3 events”, otherwise it may simply reflect changes in the observational limit.

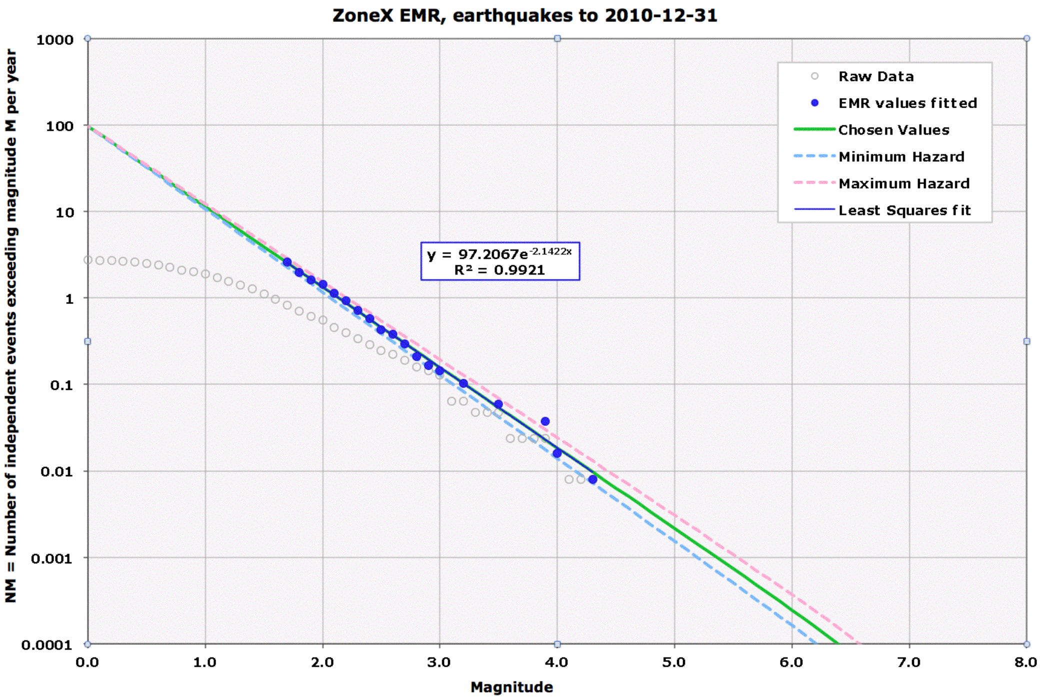

Figure 1: Sample Earthquake Magnitude Recurrence (EMR) plot Source - unpublished work of the authors.

In Figure 1, the intercept on the vertical axis gives the number of earthquakes in the zone per year exceeding magnitude 0. In this zone there are 97 earthquakes of magnitude 0.0 or larger per year, and the earthquake that occurs on average every 1000 years (i.e. 0.001 events per year) has magnitude about 5.3.

The gradient of the exponential least squares fit (β, 2.14 in this case) is used to determine the b-value by the equation:

$b = \beta/\ln(10) = 2.14/2.30 = 0.93$

The b-value is an indicator of prevailing stress levels, with low b-values in high stress regions (in stable continents, infrequent earthquakes, and strong faults), and high b-values in low stress regions (at active plate boundaries, with frequent earthquakes, and weak faults). Because of this relationship with stress, the b-value varies with space and time and can be used to understand the temporal sequence of foreshock and aftershock sequences. A well-defined but low b-value, indicating high stress, is sometimes considered to be a precursor to a large event.

The maximum earthquake magnitude that can occur on a fault or in a region depends on the dimensions of the fault, or on the dimensions of the faults within the region. A large simple tectonic plate boundary (Chile, Alaska, Indonesia) can provide a rupture longer than 1000 kilometres, corresponding to an earthquake of magnitude above Mw 9.0 to a maximum of about 9.5. A more complex tectonic plate boundary (such as around Papua New Guinea) can provide a rupture of up to a few hundred kilometres, corresponding to earthquakes up to a little over Mw 8.0, so tectonic energy is released in a larger number of relatively smaller earthquakes than experienced on more simply structured plate boundaries.

Intraplate fault ruptures rarely exceed 100 km length, corresponding to a maximum of about Mw 7.5. Such limits apply for smaller earthquakes, with a magnitude 4.0 corresponding to a rupture length of about a one kilometre.

The change in earthquake energy corresponding to one magnitude unit is about 32 times, so that, for instance, a magnitude 5.0 releases about 1000 times as much energy as a magnitude 3.0 (i.e. ~ 32 times 32). Empirically, the Gutenberg-Richter relationship shows that the number of earthquakes reduces by a factor of 10 for a unit magnitude increase. As a consequence, in any given earthquake cluster, or any given region, the great proportion of total energy release is from the largest, or few largest, events.

Earthquake Depths

An earthquake source is best represented by the fault rupture. This is a surface over which there has been relative movement between fault blocks. Depending on the earthquake magnitude, in Australia this may extend horizontally and vertically over tens of metres (for magnitude 1.0) to tens of kilometres (for magnitude 7.0). Reverse faults dip under the upthrust block usually at about 35° but varying by 20° or more, normal faults dip under the downthrust block at about 70°, and strike-slip faults which give horizontal relative movement at the surface are usually near vertical. Many faults have combinations of reverse or normal and strike-slip motion.

The displacement varies over the rupture, decreasing to zero at buried edges of the rupture, and giving the observed surface displacement if it reaches the surface. The fault rupture contains regions of low or high displacement depending on geological structure and the tectonic stress field.

The rupture extends over a depth range from metres to more than ten kilometres for earthquakes larger than magnitude 6.0.

The earthquake depth that is often quoted is not the depth of the rupture (which covers a range of depths), but is the depth of the point on the fault where the rupture started. This is the earthquake hypocentre or focus, and is not necessarily the point on the fault that gives the maximum displacement or energy release. For example, the hypocentre of the 26 December 2004 Sumatra Mw 9.0 earthquake was more than 300 kilometres from the maximum displacement and energy release.

Another point on the rupture is the centroid, which approximates the centre of energy release. The hypocentre is easily determined from seismograph data, but the centroid is much more difficult to determine. An earthquake of magnitude ML 4.0 gives a rupture are of about 1 km^2, so on a global scale it may be considered as a point source, but on the scale of microearthquakes being located to a precision of 100 metres or less it is an extended source.

Characteristics of earthquake activity include the rate of activity (either number of earthquakes or energy release per year), the stress drop associated with individual earthquakes, the relative number of small to large earthquakes (b-value), and the maximum credible magnitude.

These characteristics can vary significantly from place to place over the surface of the earth. They also vary with time on scales of years to thousands of years, with periods of high activity and long periods of quiescence.

Most significantly, they vary with depth, from the earth's surface to the base of the seismogenic zone. For example, the earthquakes that originate at shallow depths (within a few kilometres of the surface), have a higher ratio of small to large earthquakes, and a lower maximum magnitude than those that originate deeper. Almost all earthquake surface ruptures are from large earthquakes that originate beneath the zone of shallow earthquakes, and then rupture through it using energy released from more highly stressed deeper rocks.

Convergent plate boundaries are zones where cold lithosphere is recycled into the mantle. If one or both of the plates is an oceanic plate (relatively thin, basaltic), it may subduct under the other plate and descend into the earth's mantle at an angle that ranges from a dip of about 25° to beyond vertical in some extreme cases. Most earthquakes associated with subduction range in depth from the surface to over 3000 kilometres, followed by a depth range with little activity to about 500 km, then a range of low to moderate activity to about 700 km. Dip angles and depth ranges vary between different subduction zones.

In continental regions most earthquakes occur within the upper crust, typically to a depth of about half the crustal thickness (15 to 20 km), but varying with location depending mainly on crustal temperatures.

In general, near surface rocks do not permit storage of high strain energy density (stress). Large earthquakes may rupture through the surface sediments to give a surface rupture, but the energy released originates from deeper levels, and the near-surface layers tend to absorb energy, rather than provide energy, because of their greater non-linear inelastic behaviour. This means that an earthquake originating near to the surface is much less likely to produce a higher magnitude.

The maximum depth of earthquakes in a region occurs at the brittle-ductile boundary level, which depends on the temperature profile and composition of the crust. Rocks below this level store little strain energy as stresses are relaxed by ductile flow. Hence the maximum strain energy density will be somewhere near the mid-range depths of the seismogenic zone.

A phenomenon that is common in Australia, probably due to its high compressive stress levels, is the shallow swarm, where tens or hundreds of small events occur close to the surface over a period of weeks to months, with the largest being only of magnitude 3 to about 5.

In places without a dense seismometer network, it is not easy to determine earthquake depths, so studies of depth variations are not possible. While shallow swarms only produce small earthquakes, they do show that relatively high stress levels are attained at shallow levels in some parts of the Australia crust. This is consistent with some underground mine observations in Western Australia. Shallow swarms unrelated to mining are common in Western Australia, and occur in Eastern Australia every year or two.

Earthquake Faults

Natural tectonic earthquakes tend to occur on pre-existing faults, because pre-existing faults are much weaker than intact, unfaulted rock masses. As more earthquakes occur on a fault, the rupture area (length and width) and total displacement across the fault increase. The larger the available rupture area, the larger the earthquake that can occur on a fault.

Stress at any point within the earth can be resolved into three orthogonal components, the maximum, medium and minimum principal stresses (σ_1, σ_2 and σ_3 respectively). Earthquakes occur when shear resulting from the difference between σ_1 and σ_3 exceeds the strength of the rock, usually along pre-existing fault planes.

Because the earth's surface is a free surface, one of the principal stresses is usually near vertical. If maximum principal stress, σ_1, is near vertical then normal faulting occurs resulting in crustal extension and crustal thinning. If σ_2 is near vertical, then strike-slip faulting occurs with a near vertical fault and the block on one side moving horizontally relative to the other, with little change in crustal thickness. If minimum principal stress, σ_3, is near vertical, then σ_1 will be near horizontal, resulting in reverse faulting with a compressive failure and crustal thickening.

A fault is most susceptible to failure if the fault plane intersects the normal to the σ_1 - σ_3 plane and at about 35° from σ_1 and 55° from σ_3.

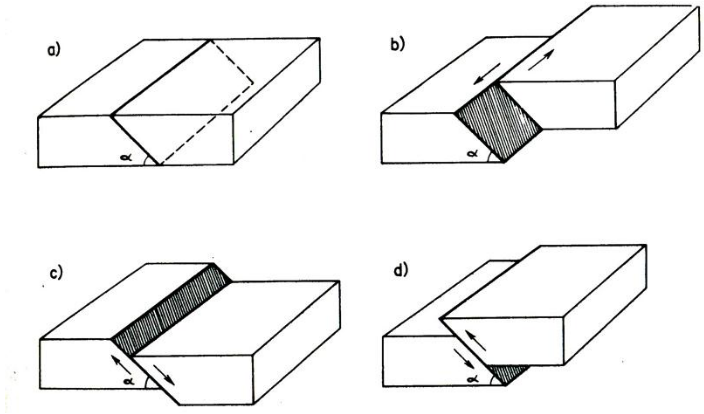

Figure 2: Types of faulting. a) shows a pre-existing fault dipping at angle α
b) is a strike-slip fault with blocks moving horizontally, α *is normally about 90°, c) normal faulting,* σ_1 *near vertical,* σ_3 *left-right, extensional, crustal thinning,* α *about 70°, d) reverse faulting,* σ_3 *near vertical,* σ_1 *left-right compression, crustal thickens,* α *about 35°. Source - from Bott (1959).*

Magnitude can be approximately related to rupture size and duration of each earthquake, as given in Table 1. High stress continental earthquakes rupture smaller areas than given by this simplification, while low stress drop plate boundary earthquakes rupture larger areas.

The values in Table 1 are approximate, but measured values of rupture area are usually within a factor of 2 (from half to double). The aspect ratio (length/width of the rupture) of some faults, especially larger faults, can exceed ten.

Moment Magnitude (Mw)	Rupture Area (km^2)	Rupture Length x Width (km, km)	Fault Slip (m) ~ Length /20,000	Rupture Duration (s) ~Length/3	Global numbers (per year)
1	0.001	0.03 x 0.03	0.0015	0.01	
2	0.01	0.1 x 0.1	0.005	0.03	
3	0.1	0.3 x 0.3	0.015	0.1	>> 20,000
4	1	1 x 1	0.05	0.3	20,000
5	10	3 x 3	0.15	1.0	2,000
6	100	10 x 10	0.50	3.0	200
7	1000	30 x 30	1.5	10	20
8	10,000	200 x 50	(5 – 10)	60	1
9	100,000	670 x 150	(10 - 25)	200	0.05

Table 1: Approximate earthquake rupture parameters. Source - unpublished work of the authors.

Earthquake Clusters

Large earthquakes are often preceded by foreshocks, and almost always trigger aftershocks. These events are clustered in time and space. The mainshock is defined as being the largest event in a cluster, or the first to occur in the rare case of two or more events in a cluster having the same magnitude. The mainshock usually but not always causes the majority of the damage produced by a cluster.

The events in a cluster are temporally clustered about the mainshock, with foreshocks occurring minutes to days before the mainshock, and aftershocks occurring seconds to years after the mainshock. The total duration increases with the magnitude of the mainshock, ranging from days for clusters with a mainshock of magnitude less than about 5.0, to years for some very large earthquakes.

The size of the spatial distribution of a cluster also increases with magnitude, ranging from kilometres for magnitudes less than about 5.0, to hundreds of kilometres for magnitudes greater than 8.0, corresponding to a volume a little larger than that required to enclose the mainshock rupture.

The number of events in a cluster varies widely, from a minimum of two with only one dependent event.

A large cluster has many thousands of events, usually ill defined because locations of smaller events are limited by the sensitivity of the local seismometer coverage.

The Gutenberg-Richter relationship applies to earthquake clusters. The frequency-magnitude distribution of events in a cluster gives b-values a little higher than normal (corresponding to low stress), but still about $b = 1.0$ where there are ten times as many events of magnitude 3 than 4, and ten times as many magnitude 2 than 3.

Earthquake hazard studies that use probabilistic methods must deal with independent events, and both foreshocks and aftershocks are dependent on the independent mainshock. If the many smaller foreshocks and aftershocks were incorporated into a normal probabilistic hazard analysis, they would significantly increase the estimated relative number of small to large events (the Gutenberg-Richter b-value), and if, as is normally the case, the analysis is extrapolated to a return period interval longer than the duration of data collection, then the recurrence rate of larger earthquakes is under-estimated. For this reason, most probabilistic hazard studies consider the recurrence of clusters rather than individual earthquakes, and use a declustered earthquake catalogue excluding foreshocks and aftershocks.

Triggered and Induced Earthquakes

The following is intended as a brief overview to triggered earthquakes. See Section 3, "Induced Seismicity", for greater detail. Earthquakes are commonly "triggered" in an entirely natural way. The term "induced" is used to indicate possible anthropogenic impact on the event. A very small number of earthquakes seem to have been triggered by large distant earthquakes, a phenomenon known as dynamic triggering. Small earthquakes are sometimes seen in recorded seismic waves from the large earthquakes only while these waves pass through the region about the seismometer. These are at distances far beyond normal aftershocks, which result from stress changes within a distance of a few rupture lengths (a few hundred kilometres for large earthquakes). Such "static" stress changes can trigger small earthquakes in the surrounding region during an extended period after the triggering earthquake. Static triggering is the cause of most aftershocks, with observed temporal delay patterns being due to the evolution of friction in response to the change in stress.

From experience it is possible to say that, if they trigger any earthquakes at all, most water reservoirs trigger only small earthquakes, a few have triggered magnitudes exceeding 5.0 and a couple of large reservoirs have triggered magnitudes larger than 6.0. Most reservoir triggered earthquakes are located under or near large reservoirs, with water depths exceeding 60 metres, and reservoir volumes exceeding 1.0 km^3. Examples are given in the following section on induced seismicity. Gupta and Rastogi (1976) described many examples of reservoir-induced earthquakes

A relatively high proportion of underground mines trigger earthquakes compared with the proportion of water reservoirs that trigger earthquakes. Mining earthquakes tend to give many events, mainly small. Mines that trigger events of magnitude 4.0 or above are usually large mines (open-cut or underground) and maximum magnitudes experienced are about 5.5.

It is possible to say that a high proportion of cases where fluids are injected into well-consolidated rock will trigger earthquakes, especially if the rock is fractured or jointed. All known examples of this give shallow earthquakes in the immediate vicinity of the fluid injection. The total volume of fluid injected into rocks seems to be a key determinant for increasing the size of an induced earthquake. Hydraulic fracturing, in which flow rates are high but durations are short, have only induced seismicity up to about M 3.0. Long-duration underground storage, on the other hand, is capable of triggering earthquakes up to about M 6.0 (Keranen et. al., 2013). Wastewater reinjection may be applied in Australian CSG projects due to concerns about surface storage.

Effects of Earthquakes

The effects of earthquake shaking depend on the amplitude of the motion, the frequency content, and the duration. Amplitude is determined by magnitude and distance (epicentral distance and earthquake depth). Frequency content is determined by the earthquake magnitude and stress change, with small earthquakes giving dominantly high frequency motion, and increasing magnitudes give an increasing proportion of energy at decreasing frequencies (longer periods). Duration of earthquake motion is determined by the earthquake magnitude, and is comparable with the rupture duration (less than 1 second for magnitudes less than 5.0 and greater than 10 seconds for magnitudes larger than 7.0).

An earthquake of magnitude Mw 5.0 will cause ground motion that will damage structures within a few kilometres. This means that it will need to be relatively shallow to cause much damage, within 5 km for major damage.

An earthquake of magnitude Mw 6.0 will cause major damage within about 10 kilometres, and damage to some tens of kilometres. The devastating Christchurch earthquake of magnitude Mw 6.1 on 21 February 2011 at 2351 UTC was an extreme example. The hypocentre was about 6 km southeast of the city centre at a depth of about 6 km, but the rupture did not reach the surface.

Earthquake of magnitude Mw 7.0 to 8.0 have rupture lengths from about 30 km to 200 kilometres, causing damage within an elongated region.

Proximity to the fault rupture is a major factor in the level of destruction, and proximity to an active fault is a major factor in estimating earthquake risk.

Earthquake effects on structures and people are minimised by building to an earthquake code. In practice, this means buildings that will not collapse, even if they are badly damaged by the earthquake. In the future, more emphasis will be given to minimising economic losses. Building codes use risk criteria, which usually specify the average return period of earthquake ground motion that should not interrupt the operation of the structure, and the longer period that should not cause collapse of the structure.

Many earthquake building codes, such as the Australian Earthquake Loading Code AS1170.4, adopt the 500-year earthquake as the criterion. This means that a building designed to last 100 years will have a 20% chance that its design motion will be exceeded during its lifetime. This does not matter very much in active areas on tectonic plate boundaries where the 500-year earthquake is almost as large as the largest credible earthquake. However, in relatively stable continental regions such as Australia, the 500-year earthquake is quite small, and will give much lower level of motion than an earthquake with a magnitude that will recur at intervals of thousands of years.

1. Australian Earthquakes

Characteristics of Australia Earthquakes

Australian earthquakes occur in a “stable” continental region, so are infrequent compared to those in plate boundary settings. In a typical region an event is only felt on average each 5 to 10 years. The whole continent experiences about 600 recorded events each year, with 2 events of M > 5 (Leonard, 2008). Moderate magnitudes occur within 25 km every few thousand years. Large magnitudes occur within 50 km each 20,000 to million years. However, historical and recorded seismicity shows Australia is one of the most active intraplate areas.

The record of seismicity in continental Australia is quite heterogeneous. A number of distinct zones of seismicity have been defined across the Australian continent. Figure 3 shows that one of these, known as the South Eastern Seismic zone, corresponds broadly with the southern part of the Eastern Highlands. Compared to other areas of Australia, seismicity in this region has been quite steady for the past 10 years, and seems to be controlled by the arrangement of dense, highly interlinked fault networks with typically short fault lengths. For many other parts of the Australian continent, an episodic seismicity model is consistent with the seismological, palaeoseismic, and strain rate data. Areas will typically experience brief (1 -10 years) periods of activity before quiescence sets in for many thousands or many tens of thousands of years.

Earthquakes in all regions of Australia are distributed over many faults, but with few longer than 100 km. It follows that there is relatively low maximum magnitude, probably Mw 7.2 to 7.5, limited by the thickness of the seismogenic zone and the length of active faults. This also means hazard is widely distributed compared with plate boundary regions, but still varies by a factor of 1000:1 at different places across the country.

Almost all Australian earthquakes are in the upper crust, from the surface to a depth of about 20 km. Moderate magnitudes can cause damage, such as Newcastle, 1989, ML 5.6, which caused about A$3 billion damage. Events above Mw 6.5 usually give surface rupture. While the orientation of the stress field in Australia is well constrained, variations in its magnitude are not as well understood. Stress is almost always horizontal compression, and reverse faults therefore predominate. Ruptures tend to have high stress drop, giving high frequency, high acceleration and short duration motion.

Year	Location	State	Magnitude	Effects/notes
1892	Flinders Island	TAS	~ 6.9	Offshore sequence, felt widely across SE Australia.
1897	Beachport	SA	~6.5	Felt widely. Significant damage in vicinity.
1906	Newcastle	NSW	na	Mining induced “creep”; buildings rocked, walls cracked, gas mains burst.
1929	Broome	WA	~6.6	Felt in Perth.
1941	Meeberrie	WA	~7.1	Australia’s largest onshore earthquake. Felt over much of WA including Port Hedland and Albany.
1959	Jindabyne	NSW	5.0	Induced by Eucumbene Reservoir filling
1968	Meckering	WA	6.8	Significant building and infrastructure damage (millions of dollars)
1970	Lake Mackay	WA	6.7	Significant subsequent aftershocks
1973	Warragamba	NSW	5.5	Induced by Warragamba Reservoir filling
1989	Newcastle	NSW	5.6	12 deaths; very significant building and infrastructure damage (billions of dollars)
1996	Thomson Dam	VIC	5.0	Induced by Thomson Reservoir filling

Table 2: Some significant Australian earthquakes including notable “induced” earthquakes. Source Leonard (2008), McCue (1990), Gibson (1997), McCue (2012).

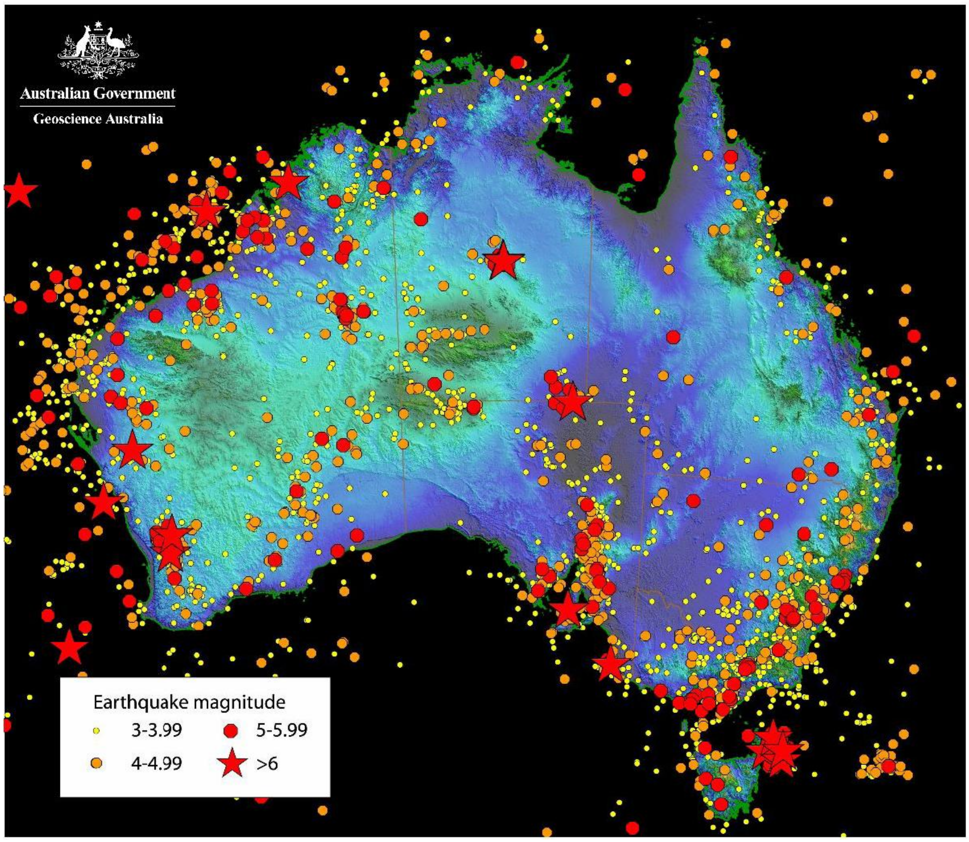

Figure 3. Historical Earthquakes M > 3. Source Lieba (1993).

2. Induced Seismicity

Overview of Induced Seismicity

Earthquakes can be triggered by human activities, including filling of large water reservoirs, mining, and activities involving pumping fluids into and out of the crust, such as required in hydrocarbon, geothermal energy and some water resource activities. These types of earthquakes are called induced.

There are two broad mechanisms for triggered earthquake activity. The first involves changing the stress within the crust, the second involves reducing the strength of faults. Since most earthquakes occur at depths from at least a couple of kilometres to about 20 kilometres (or much deeper in regions with subducting plates), it is usually not possible to determine either the stress, or the strength of the faults at their weakest points.

It is not easy to significantly affect the horizontal stress in the crust, but vertical stress can be increased by loading (for example a large dam and water reservoir with a total mass of perhaps 1,000 million tonnes) or by unloading (for example a very large open-cut mine such as the Kalgoorlie Super Pit, or by releasing a large volume of water from a reservoir). The most common way to trigger earthquakes is to increase the ground water pore pressure, decreasing the stress at which failure will occur on faults.

Apart from the microseismicity associated with hydro fracturing (where a large part of the energy comes from the well-bore pressurisation) triggered earthquakes represent the premature release of tectonic stress. It follows that the relationship between "anthropogenic" stress disturbances and the resulting earthquake magnitude will always be somewhat unpredictable, insofar as it is partly associated with "background" event probabilities. Nevertheless, the factors that could influence the maximum size of induced earthquakes are of great interest. In the case of fluid injection, some candidate parameters are the total volume of fluid, the injection rate, the time since injection commenced, the temperature conditions and injection depth.

There is general agreement that the increase in M > 3 earthquakes since 2001 in mid-continental US are manmade (Jones, 2013), mainly due to wastewater reinjection. This increase is observed in the context of a "complete" earthquake catalogue of about 30 years for M > 3.

Reservoir Triggered Earthquakes

Worldwide, about 2% of large reservoirs are known to have triggered earthquakes, although many do not have local seismometer coverage and if events were of small magnitude such activity may not have been detected (Gupta & Rastogi, 1976; Simpson et.al., 1988). Magnitudes of this type of seismicity range from less than 1.0 to 7.9, although the larger case relates to the 2008 Wenchuan Earthquake, where triggering is debated. The largest confirmed reservoir triggered earthquakes were of magnitude 6.3 near the Hsinfengkiang Dam in China in 1962 and the Koyna Dam in India in 1967. In Australia, five of the seven deepest water reservoirs have triggered earthquakes (Thomson, Talbingo, Warragamba, Gordon and Eucumbene – Dartmouth, the deepest, did not), and the three largest reservoirs all triggered earthquakes (Gordon, Argyle, and Eucumbene).

Ground water pore pressure is increased by compression under the weight of the reservoir, which will increase as the reservoir fills, and can trigger earthquakes almost immediately. Decrease in seismic activity has also been reported at certain reservoir sites, as would be expected for compressive stress regimes including (counter to observations) Australia's. This problem is resolved by an alternative triggering mechanism where pore fluid pressure increases as a result of diffusion of water under a reservoir. It has been found that this mechanism can trigger earthquakes at surprisingly large depths of 10 km to perhaps 20 km (Gupta, 2002). The earthquakes triggered by this mechanism are delayed after reservoir filling because of the low permeability. Thomson and Warragamba Dams both experienced earthquakes exceeding magnitude 5.0 more than ten years from commencement of filling. The volume of upper crust where ground water pore pressure has been affected by a large reservoir is significant, perhaps 2,000 to 20,000 km^3 or more. In comparison, a magnitude 5.0 earthquake involves a source volume of something like 30 km^3, and a magnitude 6.0 about 1000 km^3.

The relative number of small to large reservoir triggered earthquakes, the Gutenberg-Richter b-value, is often comparable with background seismicity in the region. Reservoir triggered earthquakes often come in clusters of a few to tens of events. In most cases the rate of reservoir-triggered activity reduces after about 20 years, and the probability of earthquake activity reverts to the levels that existed prior. Both total reservoir volume and maximum water depth are observed to have a correlation with the presence of reservoir triggered seismicity.

Mining Triggered Earthquakes

Large open-cut mines in hard rock reduce the vertical principal stress under the mine, and so tend to trigger earthquakes in reverse faulting environments. The most significant example of this in Australia was the shallow magnitude ML 5.0 event a couple of kilometres southwest and under the Kalgoorlie Super Pit open-cut mine on 20 April 2010.

Underground hard-rock mining triggered earthquakes are mainly caused by changes in the stress field due to mining. They are often affected by blasting in mines, and many earthquakes occur seconds or minutes after large blasts. The mining causes many small-scale changes that produce large numbers of very small micro-earthquakes. Magnitudes from -3 up to 0 are common[5], events up to

[5] Note that as the magnitude scale is logarithmic negative magnitude events are allowable.

magnitude 2 are not unusual in some mines, and larger events are sometimes triggered, with magnitudes to 4 or more.

Large open-cut coal mines are located in relatively unconsolidated sediments which do not store significant strain energy. Deformation is by large-scale creep movement within soft surface sediments over a prolonged period of months to years, rather than a sudden release of energy, so open-cut coal mines rarely triggers earthquakes.

Underground coal mines often have rockbursts or mine collapses that have similarities with induced earthquakes, but the energy released is often just gravitational potential energy rather than tectonic strain energy. A possible exception was the magnitude 5.1 earthquake near Ellalong, NSW, on 6 August 1994, which was in the immediate vicinity of an active coal mine.

Even the largest known mining triggered earthquakes have volumes less than the total volume affected by mining at the particular mine. That is, the maximum magnitude appears to be limited by the affected volume. Because the activity is at shallow depth, where strain energy density is low, they are normally not in a position to rupture a large fault. It appears that large faults usually rupture from a relatively weak point at depth, but where there is sufficient strain energy available to maintain the rupture. The size of the largest Mining Triggered Earthquakes depends on the volume and the spatial and temporal extent of rock extraction (Mendecki, 2011).

Fluid Injection Triggered Earthquakes

One of the most reliable ways of triggering small earthquakes is to inject fluids or gas into highly stressed rock. Injecting fluid into the crust is primarily done to increase hydrocarbon extraction, develop porosity through hydraulic fracturing and for the long-term storage of waste fluids and gas.

Hydraulic fracturing involves pumping liquid into a geological formation under pressures high enough to cause cracks to open (Shapiro et. al., 2009, Majer, 2006). Fluid pressure at the injection point usually exceeds the minimum principal stress, facilitating the opening of fractures perpendicular to minimum principal stress direction. This dominantly dilatational character of hydraulic fractures contrasts the shear character of most natural earthquakes. In technical terms hydraulic fractures typical have a non-double couple source mechanism (Siliny et al., 2009). However, the injected fluid used for hydraulic fracturing may enter pre-existing faults and, on rare occasions, trigger slip-events that mimic natural earthquakes in the sense of having double-couple mechanisms (Siliny et al., 2009).

In Australia, where reverse faulting dominates, the minimum principal stress is usually near vertical (Coblentz et al., 1995), and hydraulic fracturing occurs on near horizontal surfaces. Pre-existing faults that may trigger earthquakes are reverse, with a strike direction approximately perpendicular to the maximum principal stress. Even if the stress directions vary from pure reverse faulting, the focal mechanisms of hydraulic fractures and triggered earthquakes will vary.

Expensive underground monitoring would be needed to determine the mechanisms of very small events, but the focal mechanisms of triggered events could be determined using high resolution surface monitoring.

Hydraulic fracturing associated with Enhanced Geothermal Systems (EGS) in the Cooper Basin has been conducted at peak flow rates on the order of 10^5 m^3/month (Hunt and Morelli, 2006, page 30), with a total injected volume of 20,000 m^3. The resulting earthquakes tend to be small, usually less than magnitude 3.0, with the vast majority much smaller. The proportion of small to large events is high, giving a high Gutenberg-Richter b-value, reflecting the relatively low stress levels at shallow depths. The b-values tend to increase after fluid injection has stopped.

Fluid injection into geological basins is used in solution mining, EGS, hydrocarbon recovery, and storage of gases, contaminants and waste fluids. The latter case may be widely applicable to CSG operations in Australia, consistent with the principles outlined in the National Water Commission Coal Seam Gas and water position statement[6] which states "potential options to minimise the cumulative impacts of extraction on the water balance should be pursued as a first priority. These options include aquifer reinjection, where water quality impacts are acceptable, and groundwater trading or direct substitution for other water use." Flow rates for wastewater injection associated with triggered earthquakes are usually low, e.g. $\sim 10^3$ m^3/month for the earthquake sequence near Prague, Oklahoma, USA, which included an Mw 5.7 earthquake in November 2011(Keranen et al., 2013). However, in the Oklahoma case the injection was maintained for over a decade, with a total volume of around 200,000 m^3. Figure 4 shows that total injected fluid volume is correlated with the maximum size of induced earthquakes, see also Dinske (2013).

Seismicity triggered by fluid injection tends to be distributed throughout a small volume with fairly well defined limits. The Habanero activity triggered by enhanced geothermal operations in the Cooper Basin (Hunt and Morelli, 2006, page 41) is a good example of this, with many thousands of small events contained within a volume of less than 3 km^3. A rupture that includes this entire volume would have a magnitude of a little over M 4.0. It is highly unlikely that this volume will contain what is, or could become, the weakest point on a fault large enough to produce a large earthquake. At this stage we know of no examples where this has occurred, but it is possible that an existing fault may rupture for some distance beyond the volume affected by the fluid injection. There is evidence that typical wastewater reinjection depths will contain sections of faults capable of contributing to a moderate sized earthquake of M 4.0 – 6.0 (Keranen et al., 2013).

The pattern of activity through a sequence of induced earthquakes gives an indication on the origin of the earthquakes between the two end members: creation of new (small) fractures, and reactivation of geologic faults. In hydraulic fracturing, the seismicity rate and b-value are variable and related to fluid

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[6] http://nwc.gov.au/nwi/position-statements/coal-seam-gas. See also footnote 8.

injection rates (at least at the microseismic level). Increases in the magnitude of earthquakes sometime after the onset of pumping are consistent with fault reactivation.

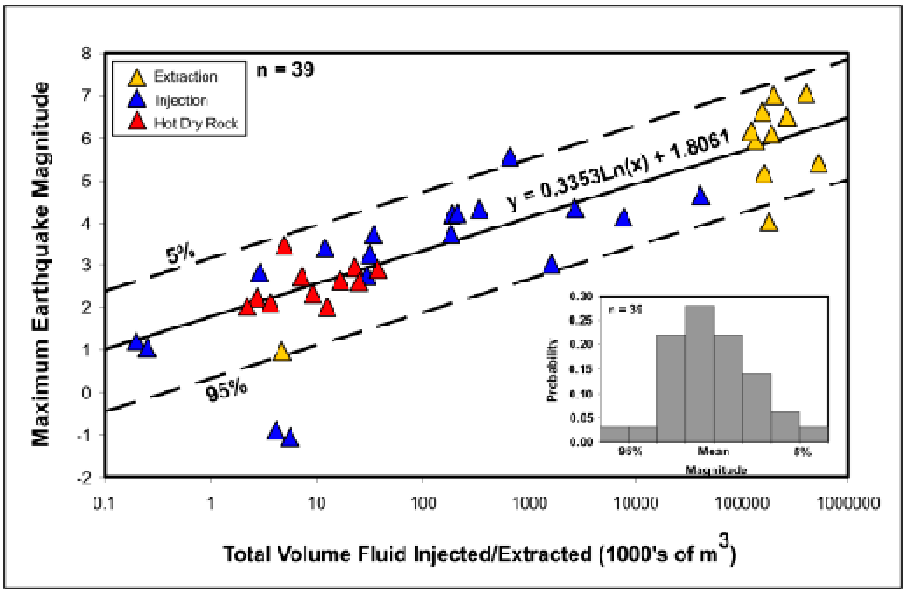

Figure 4: Maximum induced earthquake in relation to fluid injection volume. Source Nicol (2011).

Fluid Depletion Triggered Earthquakes

Subsidence occurs over regions of hydrocarbon or production primarily as a result of extraction of material (fluids/gas) and a reduction in pore pressure. Significant seismicity can be related with this process, which is likely to be part of the subsidence and associated local stress changes. In general, however, fluid depletion should suppress shear failure by increasing the effective normal stress on pre-existing structures. Nevertheless, it is likely that moderate events have been caused by depletion, the Lacq gas field in France witnessing many thousands of events up to a magnitude of 4.2 (NAP, 2012, p45).

Characteristics of Induced Seismicity

Induced earthquakes differ from normal earthquakes in that they have occurred prematurely due to an external trigger. Except for much of the microseismicity, the energy in a fluid injection triggered earthquake is normal tectonic strain energy that would have been released eventually. The type of faulting (reverse, strike-slip, or normal) of an induced earthquake is not different from a normal earthquake at this location. As with normal tectonic earthquakes, the magnitude of the induced earthquake depends on the stress levels about the fault. If the stress is high over a long segment of the fault, the magnitude may be large. The frequency-size distribution of induced earthquakes has the general form of the Gutenberg-Richter relationship, that is, a power-law or log-linear relationship.

Since induced events usually occur at shallow depths, they tend to have small magnitudes similar to those in normal shallow earthquake swarms, with a maximum magnitude between ML 1.0 and ML 4.0. An exception is for reservoir-induced earthquakes under large water reservoirs (usually at least 60 metres deep and at least 1.0 km^3 of water). In that case the increased ground water pore pressure affects a much larger volume to a much greater depth than shallow fluid injection, and has resulted in induced earthquakes exceeding magnitude 6.0.

Worst Case Scenarios

A site that is susceptible to induced earthquakes generally has a pre-existing susceptibility to natural earthquakes. This means that the worst-case scenario for a site is the same maximum credible magnitude earthquake that would have occurred eventually without any artificial trigger mechanism (without being induced).

Most of the larger earthquakes experienced as a result of fluid injection are from depths from about 3 to 5 kilometres, where less weathering and fracturing allows higher strain energy density. The largest event associated with wastewater reinjection occurred near Prague, Oklahoma, USA at 2011-11-06 03:53 UTC, with a magnitude Mw 5.7 (Keranen et al., 2013), as described above. The largest confirmed reservoir triggered earthquakes were of magnitude 6.3 about the Hsinfengkiang Dam in China in 1962 and the Koyna Dam in India in 1967. The epicentre of the Wenchuan, Sichuan, China earthquake of Mw 7.9 in May 2008 was near to a large new dam, and it possibly acted as a trigger. However the fault rupture in this event was almost 250 km long, with a large proportion of energy being released far from the influence of the reservoir pore-pressure changes.

Typically, CSG extraction occurs at depths of less than one kilometre. Depending on the setting, CSG may or may not require hydraulic fracturing and the extraction of large amount of ground water. Shallow rocks and especially shallow sedimentary rocks tend to be weaker than those at greater depth limiting the magnitudes of earthquakes that can occur. Worst-case scenarios with CSG activities are likely to be involved with wastewater injection, rather than hydraulic fracturing and water and gas extraction. Australia Pacific LNG has undertaken injection trials in various aquifers in SE QLD. Meanwhile, Queensland Gas Company (QGC) has injection trial approval. QGC claims that reinjection into the active coal seams is not possible, and have indicated they will be targeting deeper sandstone aquifers (1-2 km deep).

Induced seismicity under large reservoirs can be delayed for up to several years after reservoir filling due to slow increase in pore pressure as groundwater slowly permeates to greater depths. The activity can then continue for many years, typically 10 to 30 years, before a new equilibrium is established and seismicity returns to normal levels. The induced seismicity resulting from fluid injection is more like that due to stress change, and occurs soon after injection starts, and ends within days or weeks of the end of injection. However, if wastewater reinjection is employed at a large scale, the hazard associated with induced seismicity will remain for many years.

3. Microearthquake Monitoring

Monitoring of Earthquakes

Earthquake monitoring is conducted over a wide range of scales, including global, regional, local, and microearthquake using surface instruments or widely spaced borehole instruments. The seismometer arrays concerned cover thousands, hundreds, and tens of kilometres, down to kilometres for microearthquake monitoring. In each case, the normal practice is to surround the study area by a sufficient number of instruments to allow accurate event locations and determination of focal mechanisms (usually from 8 to 20 instruments). Events outside the array can be recorded, but with much lower accuracies in the analysis.

Monitoring of Induced Earthquakes

Monitoring of induced earthquakes is always done on a much smaller scale (network diameter to tens of kilometres), and usually at a much higher resolution than earthquake monitoring on normal local (to 100 km), regional (usually to 1000 km) and global scales.

The relative cost reduces dramatically with increasing scale, with deep borehole monitoring being very expensive, shallow boreholes being expensive, and surface monitoring being relatively inexpensive. Such costs explain why just 3 % of hydraulic fracturing operations have been monitored for microseismicity in the US (Zoback, 2010, page 8)

The monitoring of induced earthquakes can be further divided according to size, location and rupture mechanics:

Monitoring the progress of hydraulic fracturing

Events are in the true microseismic range, from magnitude 0.0 to less than magnitude -2.0. Earthquake locations are usually sought to an accuracy of metres. This precision requires borehole seismometers or accelerometers located at depth in three dimensions about the site. Very high sample rates are required, usually from 2000 to 20,000 samples per second. Continuous recording at this rate would lead to huge data volumes, so systems usually use triggered recording, with a pre-event buffer and duration of recording ranging from seconds to over a minute for larger events. Recording may be on a central system, but the sample timing must be very accurate and consistent on all digitisers (usually varying less than tens of microseconds). The number of detectors depends on the accuracy required, but is typically 8 to 20. Monitoring is only relevant during fracturing operations.

Monitoring the larger events associated with hydraulic fracturing

This requires the location of events from magnitude 0.0 to higher than magnitude 2.0, usually to an accuracy of better than tens of metres. This precision usually can be achieved using a very high-density surface network of seismometers and/or accelerometers about the site, especially if used together with some data from borehole instruments. High sample rates are required, usually 500 to 2000 samples per second, and timing accuracy should be within 100 microseconds. It is feasible to use central recording, or individual recorders using GPS for precision timing. These events are in a crossover range from those produced primarily by pressurised fracture generation to those associated with "natural" stress. These types of ruptures are often targeted in hydraulic fracturing.

Monitoring of triggered earthquakes

This requires the location of events from magnitude 1.0 to higher than magnitude 5.0, usually to an accuracy of better than hundreds of metres, and at high sample rates of at least 500 per second on each channel. This is usually done with a surface network of seismometers and/or accelerometers with a diameter of 10 to 40 kilometres. Sample rates are preferably in the range 500 to 2000 per second, with individual digitisers using continuous and/or triggered recording.

As scale increases, the monitoring period required increases. For hydraulic fracturing or mining activity, the induced events usually cease within days of the fracturing, blasting or mining activity. For large water reservoirs, triggered earthquakes can occur from up to more than three years after filling commences, and may last for more than 20 years after the first filling of the reservoir.

Microseismic and triggered rupture mechanisms

Triggered earthquakes may be the same as typical tectonic earthquakes, involving slip on a pre-existing fault oriented appropriately for the existing stress field. This orientation determines the type of faulting, such as reverse, normal or strike-slip (see Figure 2, page 11). This type of earthquake mechanism is known as a double-couple mechanism, and involves negligible volume change of the rock mass.

Like hydraulic fracturing, some triggered earthquakes do involve a volume change, such as fissures opening in an extensional stress field. For example, a series of reservoir triggered earthquakes about Katse Dam in Lesotho led to opening of a set of surface rupturing fissures with gaps up to about 50 mm[7]. Some tens of events with magnitudes up to ML 1.5 each produced fissures typically about 30 metres long, with the zone of fissuring extending for more than a kilometre. One fissure propagated through an unreinforced masonry building caused a wall to collapse into the building. This non-double-couple movement was comparable to that produced by hydraulic fracturing, although

[7] Kaste DAM seismicity is documented in Brandt, M.M.B.C., 2000, A Review of the Reservoir Induced Seismicity at the Katse Dam, Kingdom of Lesotho, November1995 to March 1999, Masters thesis, **University of Bergen**. Images are available at http://www.internationalrivers.org/resources/earthquakes-triggered-by-africa-s-katse-dam-force-families-to-abandon-damaged-village-3860

the underlying mechanism was likely due to enhancement of tensional stress rather than an increase in pore pressure.

In hydraulic fracturing (or stimulation), three types of sources are generally present. The first results from the perforation of the well casing, the second are induced fracturing in the reservoir rock which may have double-couple (shear), volumetric (opening/closing), or a combined mechanism. The third are the larger “triggered” earthquakes on reactivated faults, which usually show double couple mechanisms. Microseismicity is predominantly associated with the first two sources, although since natural fractures exist at a range of scales, the size of triggered earthquakes overlaps with those from fracture generation events.

4. Knowledge Gaps, Unknowns and Research Questions

Incomplete Datasets

There are abundant examples of triggered earthquakes (reservoir, mining, fluid/gas extraction, hydraulic fracturing), and we have a reasonable understanding of their different magnitude, spatial distribution and depth ranges (although much mining earthquake data is confidential). In the case of large-scale fluid injection where increased ground water pore pressure will induce earthquakes, for example, carbon dioxide sequestration and water disposal, there are fewer examples limiting our understanding of the processes involved.

Improved Models of Induced Seismicity

Comparison of triggered earthquakes under a variety of natural and manmade conditions are needed to allow more certainty than simple qualitative statements of the ilk "it is likely that small earthquakes will be triggered and unlikely that moderate or large earthquakes will be triggered". Recent studies around waste-water injection emphasise correlations between total injected fluid volume and maximum event size (Dinske et al., 2013). The role of factors like injection rate remains less clear. Improving our understanding triggered earthquakes will inform risk mitigation strategies.

Long-Term Effects of Fluid Injection

Large-scale, long-term waste-water injection into sub-surface reservoirs is known to have potential to induce significant earthquakes long after injection commenced (e.g., Keranen et al., 2013). The mechanism is analogous to large water reservoir-triggered earthquakes, in that failure on already loaded persisting, compliant fault planes is induced by an increase in pore pressure along the fault plane. As such, such earthquakes release tectonic stress, and once activated would seem unlikely to do so again until tectonic processes rebuild the stress. When a significant volume of waste-water is generated by activities such as CSG[8], and is disposed of by reinjection, understanding the long-term seismic potential in such reinjection is crucial.

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[8] For example, in its position statement on coal seam gas the National Water Commission notes "Current projections indicate the Australian CSG industry could extract in the order of 7,500 gigalitres of co-produced water from groundwater systems over the next 25 years, equivalent to ~300 gigalitres per year. In comparison, the current total extraction from the Great Artesian Basin is approximately 540 gigalitres per year." In order to deal with this issue the commission argues "Potential options to minimize the cumulative impacts of extraction on the water balance should be pursued as a first priority. These options include aquifer reinjection, where water quality impacts are acceptable, and groundwater trading or direct substitution for other water use." See - http://nwc.gov.au/__data/assets/pdf_file/0003/9723/Coal_Seam_Gas.pdf

Advanced Microseismic Source Models and Monitoring

Microseismic monitoring is routinely used to locate induced fracture events and map fracture networks. There is, however, some disagreement as to whether hydraulic fracturing causes predominantly shear-slip ruptures, or tensile (opening) ruptures (Taleghan et al., 2011). Earlier studies concluded that shear failure on pre-existing fractures were the typical event. The interpretation was that fluid percolation resulted in a reduction in effective normal stress, allowing shear stress to relax. More recently, a number of studies have indicated that tensile opening perpendicular to the hydraulic fracture is the predominant microseimic signature. Understanding this problem is connected to wider questions of stress state, fluid migration and evolution of fracture networks in the crust, which have bearing on seismic hazard in CSG and other subsurface activities.

5. Conclusions

Seismicity induced associated with fluid injection, infiltration and extraction is a commonly observed phenomenon. While these earthquakes are generally small, they can exceed magnitudes of Mw 6. At these scales, they have the potential to impact on the containment, infrastructure and public perceptions of such activities.

It is important to emphasise that coal seam gas extraction occurs at shallow depths, usually less than one kilometre, compared with shale gas extraction at depths to 3 km, and proposed enhanced geothermal production typically at depths of 3 to 5 km. Shallow rocks and especially shallow sedimentary rocks, tend to be weaker than those at greater depth, and can support a lower strain energy density, limiting the magnitudes of earthquakes that can occur within them, and limiting the chance of inducing larger earthquake.

For all applications of hydraulic fracturing, the possibility of induced earthquakes may be greater in the related process of wastewater disposal reinjection, especially when this is done at greater depths than for production. There is evidence that typical wastewater disposal depths will contain sections of faults that are capable of contributing to a moderate sized earthquake (Keranen et al., 2013), and that such earthquakes may occur many years after reinjection commences.

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7. Appendix 1. Terms of Reference

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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 is microseismic monitoring 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.