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An Assessment of the Effects of Hydraulic Fracturing on Seismicity in the Taranaki Region

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Seismic monitoring in Taranaki is carried out by GNS Science through the GeoNet project. Felt events are posted on the GeoNet web page. Non-felt earthquakes are also located and are archived in a publicly available National Earthquake Information Database. GeoNet operates seismic monitoring sites (seismographs) throughout New Zealand at an average spacing of about 100 km. There are additional seismographs at a closer spacing in Taranaki. The Taranaki network was originally designed to provide specific monitoring for volcanic activity at Mt Taranaki, but has been extended and upgraded more recently to provide data on seismic activity throughout the region, as well as to increase its sensitivity. This network has been used to monitor seismic activity since 1994. Data are reported annually to the Taranaki CDEM Group, and this report is available to the public on the Taranaki Regional Council's web site.

There are a few cases overseas where hydraulic fracturing or the deep well re-injection of petroleum waste fluids have been found to be associated with seismic events, and hydraulic fracturing has become a matter of recent public concern in New Zealand. Taranaki Regional Council asked GNS Science to query the New Zealand earthquake database to determine if there is any evidence for hydraulic fracturing triggering seismic activity in Taranaki, how that is assessed, and what the effects on people and structures could be if hydraulic fracturing were to trigger earthquakes in Taranaki.

Taranaki is an area of considerable seismic activity, although not as much as some other parts of New Zealand. The region typically accounts for 1-2% (or about 300 annually) of all located earthquakes nation-wide.

The strength of earthquakes is measured in two ways. There is the magnitude (M) of the earthquake itself. This is a measure of the energy released at the point of origin. The magnitude scale is logarithmic, that is, each change of one unit in magnitude represents approximately a 10-fold increase in seismic shaking, and a 30-fold increase in total energy release. An earthquake of M3 is approximately 30 times as energetic as one of M2; M4 is approximately 30 times as energetic as one of M3 and approximately 900 times as energetic as one of M2. There are also the felt effects. These are measured by the Modified Mercalli Intensity scale (MM).

MM 1: Imperceptible Barely sensed only by a very few people.

MM 2: Scarcely felt Felt only by a few people at rest in houses or on upper floors.

MM 3: Weak Felt indoors as a light vibration. Hanging objects may swing slightly.

MM 4: Largely observed Generally noticed indoors, but not outside, as a moderate vibration or jolt. Light sleepers may be awakened. Walls may creak, and glassware, crockery, doors or windows rattle.

MM 5: Strong Generally felt outside and by almost everyone indoors. Most sleepers are awakened and a few people alarmed. Small objects are shifted or overturned, and pictures knock against the wall. Some glassware and crockery may break, and loosely secured doors may swing open and shut.

A very shallow earthquake (5 km deep or less) of magnitude M2 might produce a maximum intensity for the closest people of up to MM4. This would be equivalent in its effect to that of someone sitting in a house when a large truck drove past on a road outside. There would be an intensity of MM3 within the adjacent area. The minimum magnitude for an earthquake to possibly be damaging is M4-5, which is 1,000 to 30,000 times more energetic than one of M2.

The effectiveness of the GeoNet system at detecting and then determining a point of origin for any seismic event is affected by how small, how far from any detector, how shallow the event is, and the extent of interfering ‘noise’ at the time. For example, the system’s sensitivity means that heavy surf conditions on Taranaki’s beaches interfere with its low-frequency sensitivity. In relation to hydrocarbon exploration and development, the siting of the GeoNet seismographs is well suited for the McKee and Kaimiro fields around and north-east of Inglewood, but less so for fields around Stratford (Cheal, Waihapa, Kapuni) and south to Hawera-Manutahi (Rimu, Kauri/Manutahi). In the on-shore area of gas and oil exploration in Taranaki (east of Mt Taranaki), the GeoNet system in Taranaki can detect some earthquakes of magnitude down to about M1.5, but cannot pinpoint (depth and horizontal location) all events of this magnitude. The GeoNet system is considered to be able to detect and locate all earthquakes in Taranaki above about M2.0 or a little higher.

This report examines seismic data for any evidence of seismic activity associated with hydraulic fracturing or deep well re-injection operations in Taranaki, over the period 2001-2011.

Hydraulic fracturing is a procedure used to enhance the flow-rate of fluids into or out of a well. The technique is applicable to oil and gas production. A pressurised mixture of water, sand and other chemicals (known as the fracking fluid) is pumped underground to open fissures or fractures in the hydrocarbon reservoir by a process known as tensile failure.

Tensile failure: high pressure injected fluid essentially splits the rock apart by exceeding the ability of the rock to ‘stretch’ as liquid is forced into it. The rock failure ceases when the gap increases and the fluid pressure drops, so it is no longer high enough to crack the rock further apart. Tensile failure produces relatively high frequency signals as the seismic source is small at the crack tip only, which can usually only be detected by specialised downhole instruments and unlikelyever to be felt on the surface. The magnitude for these seismic signals is typically M<0. The effects of tensile failure fracturing is unlikely to ever be felt on the surface, as the intensities are thousands of time too small to cause effects detectable by humans even with shallow fracturing.

Shear failure can also occur as a result of hydraulic fracturing, though it is a secondary effect which does not physically open fractures, but can improve permeability. .

Shear failure: elevated pressure spreads through the reservoir rocks, and to the extent that pre-existing favourably oriented cracks and fractures under existing high shear stress and already close to failure (release) exist, can cause slip (and produce an earthquake). The size of any seismic event triggered in this way depends entirely on the area of the fracture that slips and on how much it slips. The possibility of an event being induced artificially (e.g. through fracturing) depends on the existing shear stress within any formation, and the need for high injection pressures. These in turn depend on the geology and depth of the rock. Shear failure will generate earthquakes larger than those generated by tensile failure, and in some cases large enough to be felt nearby. In recent cases attributing earthquakes to hydraulic fracturing (in Lancashire, UK and Oklahoma, USA) the largest earthquakes of M2.3 and M2.8, respectively, were triggered by shear failure not tensile failure.

Almost all damaging earthquakes start at least 5 – 10 km underground and require a fault to slip over a length of several kilometres as a minimum, with lateral formation movement of tens of centimetres or more, resulting in a magnitude of at least M4-5 (at least 1,000 to 30,000 times more energetic than occurs with hydraulic fracturing). Hydraulic fracturing typically involves fault slip over a length of a few metres to perhaps one hundred metres long, with actual lateral movement of a few millimetres. The pore pressure effects that could be generated by hydraulic fracturing will dissipate as the pressure front spreads, and before they can reach the depth that is generally understood to be necessary to trigger damaging earthquakes. Based on overseas examples, the maximum seismic event that could be credibly envisaged in Taranaki due to hydraulic fracturing is an event of about M2. Such an event would be very shallow and non-damaging, but would be felt nearby.

Deep well re-injection: this is a process of injecting wastes (typically produced water, which is highly saline with traces of hydrocarbons) back into depleted oil or gas reservoirs (which are the source of the produced water in the first place), or more typically, into saline formations far below the fresh water-saline water interface. Injection pressures have to be high enough to overcome the natural pressures within the formation, but they are still significantly lower than the pressures needed to cause fracturing. Because deep well injection is a continuing process over the long term, if it triggered detectable earthquakes we might expect to see a long-term cluster of earthquakes close to (say within 10 km) any re-injection well at which earthquakes were triggered. This is not seen in Taranaki.

Key findings and conclusions:

Within the limitations of the seismic monitoring system to detect and locate seismic activity, there is no evidence that hydraulic fracturing activities in Taranaki between 2000 and mid-2011 have triggered, or have had any observable effect on, natural earthquake activity.

There is no evidence that long-term deep injection activities, typically associated with waste water disposal at oil and gas operations in Taranaki, have had any observable effect on natural earthquake activity.

Given the location of hydraulic fracturing and deep injection operations there is no evidence of any effect on volcanic activity at Mt Taranaki.

It is unlikely that any earthquakes that may be induced by hydraulic fracturing operations in the Taranaki Region would have a significant effect.

Observations do not support any suggestion that hydraulic fracturing or deep well re-injection activities could trigger in Taranaki a large earthquake, a sequence of moderate-sized earthquakes, or a widespread zone of earthquakes.

1.0 INTRODUCTION

1.1 CONTEXT

In early November 2011, local news media picked up on a report published in the United Kingdom that stated it was highly probable that hydraulic fracturing related to gas production in Lancashire, had triggered two nearby earthquakes of magnitude 2.3 and 1.5 (de Pater and Baisch, 2011). Articles were published that expressed concern about whether earthquakes could be caused in New Zealand in a similar way. Consequently, Taranaki Regional Council (TRC) asked GNS Science to determine if there is any evidence for hydraulic fracturing triggering seismic activity in Taranaki, how that is assessed, and what the effects on people and structures could be if hydraulic fracturing were to trigger earthquakes in Taranaki.

Taranaki Regional Council (2011) published a hydrogeological risk assessment of hydraulic fracturing in the Taranaki Region. In this report they summarised hydraulic fracturing operations in Taranaki from 2000 to mid-2011 using data provided by oil and gas companies. The full suite of data included times, locations and depths of hydraulic fracturing operations, together with more detailed information including fracture fluid pressures for two specific examples. We have used these data in our assessment of the effects of hydraulic fracturing on natural seismicity in Taranaki.

1.2 HYDRAULIC FRACTURING

Hydraulic fracturing is a procedure used to enhance the flow-rate of fluids into or out of a well. The technique is applicable to oil and gas production, as well as geothermal power generation. A pressurized mixture of water, sand and other chemicals (known as the fracking fluid) is pumped underground to open fissures in the hydrocarbon (or geothermal) reservoir. As the purpose of hydraulic fracturing is to create additional permeability in the reservoir (in the form of fractures), the pressure has to be high enough to crack the rock in a controlled fashion. Taranaki Regional Council (2011) noted that during hydraulic fracturing operations, surface pumping pressures of up to 25 MPa (255 bars) were used at wells in the Cheal Field in 2010, and up to 19 MPa (189 bars) at wells in the Manutahi Field in 2005 (Figure 1). Once the cracks have been created and held open by the injected sand, the fracking fluid is flowed back up the well, and is removed from the site for disposal at approved facilities.

Hydraulic fracturing locations in Taranaki for 2000 to mid-2011 are all east of Mt Taranaki and west of the Taranaki Fault (Figure 1). Most hydraulic fracturing operations in Taranaki have occurred at depths of between 3 and 5 km (Taranaki Regional Council, 2011). Hydraulic fracturing commonly occurs for short periods of time, commonly less than a day, and is more common in reservoirs with low natural permeability[1].

1 Permeability is a measure of the ability of reservoir material to allow fluids to pass through it. The unit of permeability is the millidarcy (mD). One mD is 10^{-12} m^2.

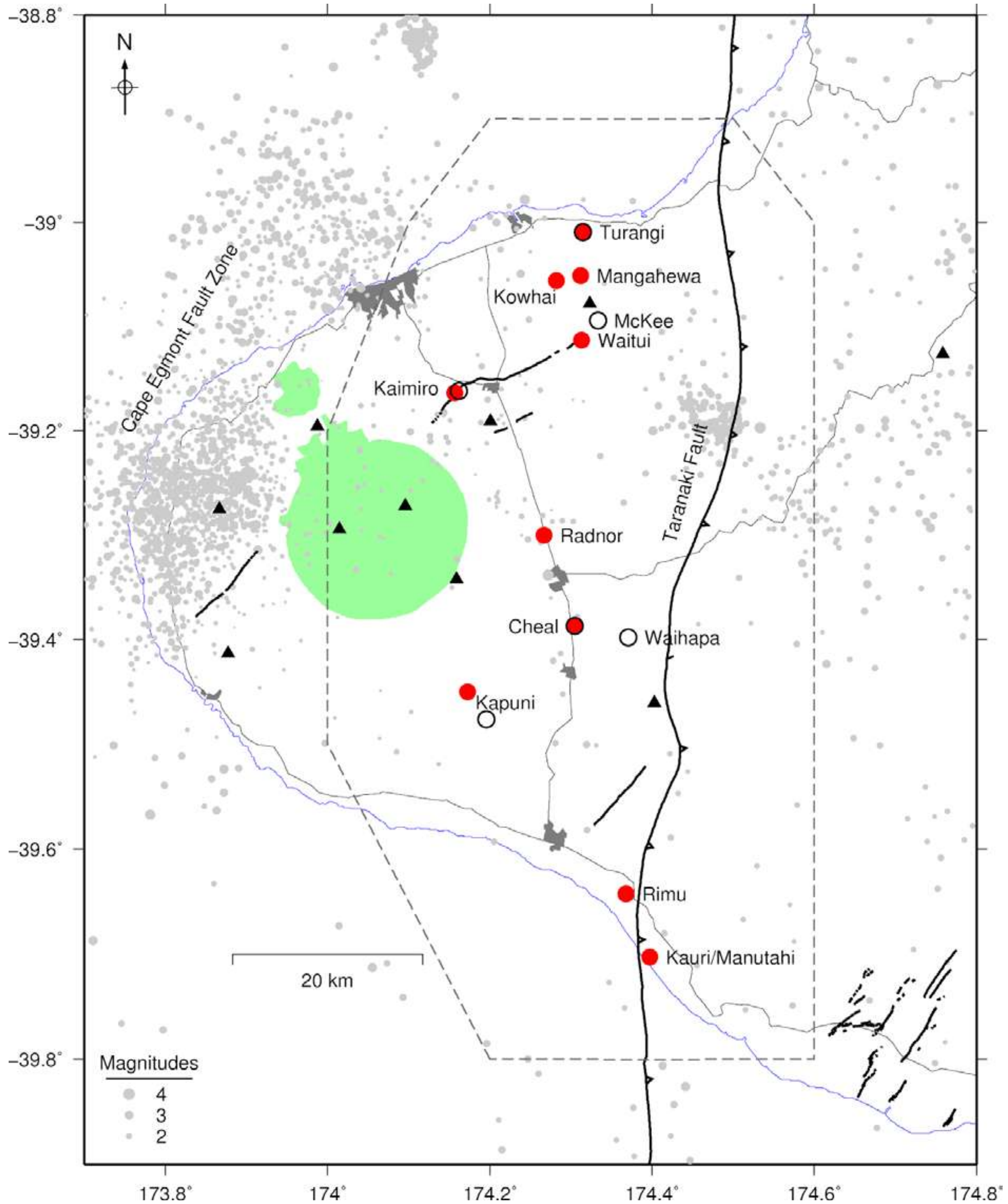

Figure 1 Hydraulic fracturing (red circles) and deep injection (open circles) sites in Taranaki for 2000 – mid-2011. Seismographs (at 2011) are shown as triangles and earthquake epicentres (depth < 20 km) as grey circles. Active faults (from the GNS Science active faults database) are thick black lines, and the Taranaki fault, not classified as active, is also shown. The dashed grey region is where Mc was determined (refer to Appendix 1 for more details). Population centres, roads, and Egmont National Park are also shown.

1.3 DEEP INJECTION

Oil and gas operations can produce 'waste fluids' as part of their normal operations and these fluids (typically produced water, which is highly saline with traces of hydrocarbons) are often disposed of by injecting them back into the oil and gas reservoirs, or into saline formations far below the fresh water-saline water interface, in a process referred to as 'deep injection'.

Deep injection occurs in several oil and gas reservoirs in Taranaki, including some at which hydraulic fracturing has also been performed (Figure 1). Distinct from hydraulic fracturing, deep injection is a long-term operation that can continue for years. Reports to TRC from petroleum companies contain information on the volumes of fluids disposed of in deep injection operations and the injection pressures used (Cheal Petroleum Limited, 2009; Greymouth Petroleum, 2009; Origin Energy Resources New Zealand, 2009; Shell Todd Oil Services Limited, 2009). The injection pressures used in long-term deep injection are significantly lower than those used for hydraulic fracturing: the maximum pressure for deep injection operations in Taranaki from 2006 to 2009 was 15 MPa (155 bars), but average values at reservoirs are typically only 10-30% of the maximum values.

2.0 SEISMICITY IN TARANAKI REGION

2.1 SEISMIC MONITORING

Seismic monitoring in Taranaki is carried out by GNS Science through the GeoNet project[2]. GeoNet operates seismic monitoring sites (seismographs) throughout New Zealand at an average spacing of about 100 km. There are additional seismographs at a closer spacing in Taranaki to provide specific monitoring for volcanic activity at Mt Taranaki, which last erupted as recently as about 1800 AD. No seismic monitoring occurs in Taranaki specifically for hydraulic fracturing operations or any other operations associated with oil or gas exploration or production.

Earthquakes in Taranaki, like those elsewhere in New Zealand, are located by the GeoNet project and felt events are posted on the GeoNet web page. Non-felt earthquakes are also located and are archived in a publicly available National Earthquake Information Database[3]. Felt earthquakes are usually located within a few minutes of their occurrence, preliminary locations are available for many non-felt earthquakes within a day, and final locations for all earthquakes are available from the database within two or three weeks of their occurrence.

Shallow seismicity in Taranaki (depth < 20 km) for 2000 – late-2011 is shown in Figure 1. Information on uncertainties for the locations, depths, and magnitudes of these earthquakes are given in Appendix 1. The most active area is associated with the Cape Egmont Fault Zone (CEFZ) north and west of Mt Taranaki and largely offshore (Sherburn & White, 2005). The number of located earthquakes east of Mt Taranaki, where hydraulic fracturing and deep injection operations have taken place is significantly lower than that associated with the CEFZ (Figure 1). There are also significant differences in the depth of earthquakes across Taranaki: west of Mt Taranaki earthquakes occur at depths of 5 – 20 km, beneath and for about 25 km east of the summit of Mt Taranaki they are less than 10 km deep, and further east they are confined to depths between 25 and 35 km (Sherburn & White, 2005). Most

2 www.geonetorg.nz
3 http://www.gns.cri.nz/Home/Products/Databases/National-Earthquake-Information-Database

earthquakes occur within the basement rocks beneath the sedimentary basin, though a few (< 5%, Sherburn & White, 2005) have been located within top 5 km or so, within the sediments where Taranaki Basin oil and gas operations take place.

For volcano monitoring purposes GNS Science reports on seismicity in Taranaki to TRC annually (e.g. Sherburn et al., 2011). The distribution of earthquakes and their depths have changed little since monitoring began in the mid-1990s.

2.2 LIMITATIONS OF SEISMICITY DATA

To examine any effects on natural seismicity in Taranaki from hydraulic fracturing or deep injection we need to compare locations and times of these operations with the corresponding data from the earthquake database. There are uncertainties in the position, depth, origin time, and magnitude of all earthquakes in the database. A more detailed explanation of the uncertainties in the seismicity data is given in Appendix 1.

For shallow seismicity in Taranaki (depth < 20 km) from 2000 to late-2011 we estimate an uncertainty in position and depth of 4 km (at a 95% confidence interval). In other words, we consider that the calculated location of an earthquake in Taranaki is within 4 km, in position and depth, of the actual origin of the earthquake. The uncertainty in earthquakes located offshore, outside the seismic monitoring network, will be greater.

The geometry involved in the earthquake location problem means that it is usually not possible to obtain a reasonable estimate of depth if the nearest seismograph recording the earthquake is further than twice the depth of the earthquake. To possibly be associated with hydraulic fracturing or deep injection, we need to be able to show that earthquakes occur at a similar depth to those operations. This is possible at most hydraulic fracturing or deep injection sites, but not at the Rimu and Kauri/Manutahi reservoirs were earthquakes are likely to have their depth fixed (Figure A2), most likely at 5 or 12 km.

Uncertainty in location and other factors mean that magnitudes for earthquakes in New Zealand are considered to have an uncertainty of about 0.3 magnitude units (Kevin Fenaughty pers. comm. 2011).

Some earthquakes will always occur that are too small to be located. The 'magnitude of completeness', Mc, which is the magnitude above which it is thought the database contains all earthquakes is, for that part of Taranaki in which hydraulic fracturing and deep injection have occurred (dashed region in Figure 1), about magnitude 2.0. The database will always contain some earthquakes smaller than Mc, but not all of them. Ongoing research (Matt Gerstenberger pers. comm. 2012) suggests a higher Mc for Taranaki, and if that is the case then the seismic monitoring system may struggle to locate most earthquakes triggered by hydraulic fracturing.

Our conclusions about any triggering of earthquakes by hydraulic fracturing can only be supported for earthquakes of magnitude Mc and larger.

3.0 MECHANISMS FOR TRIGGERING EARTHQUAKES

3.1 TENSILE FAILURE

Hydraulic fracturing attempts to create, and then prop open, new fractures in reservoirs by injecting water or other fluid at high pressure. Fracturing takes place when the fluid injection pressure exceeds the rock fracture gradient and tensile failure occurs, creating a “driven” fracture. Rock failure should cease when the pressure is no longer above the fracture gradient (Majer et al., 2007). Tensile failure produces relatively high frequency signals as the seismic source is small, at the crack tip only, which can usually only be detected by specialised downhole instruments and unlikelyever to be felt on the surface. The magnitude for these seismic signals is typically M<0 (e.g. de Pater and Baisch 2011).

3.2 SHEAR FAILURE

Shear failure of pre-existing fractures, the more usual process generating earthquakes, is also observed in association with hydraulic fracturing operations. In this case the mechanism is widely accepted to be the diffusion of elevated pressure through the reservoir rocks. This causes pore pressure to increase on favourably oriented cracks and fractures that are already close to failure. The increase in pore pressure results in a decrease in the effective normal stress, usually acting in compression on the fracture plane, and allows the fracture to slip under existing shear stresses (Shapiro et al., 2005). This mechanism is also considered responsible for induced seismicity due to fluid injection in geothermal systems, especially enhanced geothermal systems (Majer et al., 2007), and as a result of dam impoundment (Talwani & Acree, 1984).

In the simplest case, if τ and σ_n are the shear and normal stresses resolved on a fracture plane, ρ is the pore fluid pressure, and μ is the coefficient of friction on the fracture surface, then shear failure will occur if:

$$\frac{\tau}{\sigma_n - \rho} > \mu$$

Earthquakes produced by shear failure triggered by increased pore pressure are typically larger than those due to tensile fracturing. The size of the earthquakes capable of being triggered by elevated pore fluid pressure depends on the area of the fracture that slips and how much it slips. The slip area is in part determined by the location of asperities or lock points on the fracture plane. These factors are dependent on the geological conditions in an area before commencement of hydraulic fracturing or deep injection operations. Where the hydraulic fracturing or deep injection can have a direct effect is in the magnitude of ρ, which is controlled by the fluid pressure applied at the surface to pump fluid into the well. The higher ρ, the greater the likelihood of shear failure when injection pressure is increasing or constant (Shapiro et al. 2010). Empirical data published by Shapiro et al. (2007) shows a clear correlation between injection rate, pumped fluid pressure, and induced seismic activity.

Shapiro et al. (2003, 2005) and others have used a parameter called the 'hydraulic diffusivity' to quantify the movement of a pressure front which, spreading out from an injection well, triggers earthquakes (Figure 2). Here we use the same concept to derive an estimate of the possible distance from an injection well of any earthquakes triggered by hydraulic fracturing or deep injection operations, and the time window when those earthquakes might occur.

The rate that pore fluid pressure moves away from an injection well depends on the permeability and porosity[4] of the reservoir rocks; in Taranaki oil and gas reservoirs these are highly variable and range from a few mD to more than a 1000 mD, and 10 to 30%, respectively (New Zealand Petroleum and Minerals, 2011). To estimate the distance and the time window for earthquakes we should ideally use actual permeability and porosity values

4 Porosity is a measure of void space in a rock; it is usually expressed as a percentage.

for the part of the reservoir into which injection is taking place, but that information may not be available when a possible link between earthquakes and oil and gas operations are being assessed, especially if hydraulic fracturing takes place soon after drilling. We therefore use a range of permeabilities and porosities to estimate likely values of the hydraulic diffusivity (D). If κ is permeability (10 mD, 100 mD, and 1000 mD), μ is the viscosity of water (0.3×10^{-3} Pa.s at $100^{o}C$), ϕ is porosity (10, 20, and 30%), and β_F is the compressibility of water (5×10^{-10}/Pa) we can calculate a range of representative values for hydraulic diffusivity using (Talwani & Acree, 1984):

$$D = \frac{\kappa}{\mu\varphi\beta_F}$$

D ranges over two orders of magnitude, from 0.67 m^2/s to 67 m^2/s, because of the corresponding range of observed permeability values. Based on comparison with hydraulic diffusivities estimated from other hydraulic fracturing operations (Figure 2, Shapiro et al., 2005) hydraulic fracturing is likely to be required only if permeability is at the lower end of this range; it is not needed if natural permeability is higher. For a hydraulic diffusivity of 0.67 m^2/s we observe that within the first few days of a hydraulic fracturing or deep injection operation any earthquakes are likely to be confined to within 1-2 km horizontal distance of a well, within three weeks they could occur as far as 3-4 km from a well, and so on (Figure 3). These distances represent likely maxima, and as examples from other hydraulic fracturing operations show (Figure 2), earthquakes may still occur closer to the well than these distances. As the elevated fluid pressures propagate outward the pressures will lessen and at some point the likelihood of shear failure on existing stressed fractures will be no greater than normal.

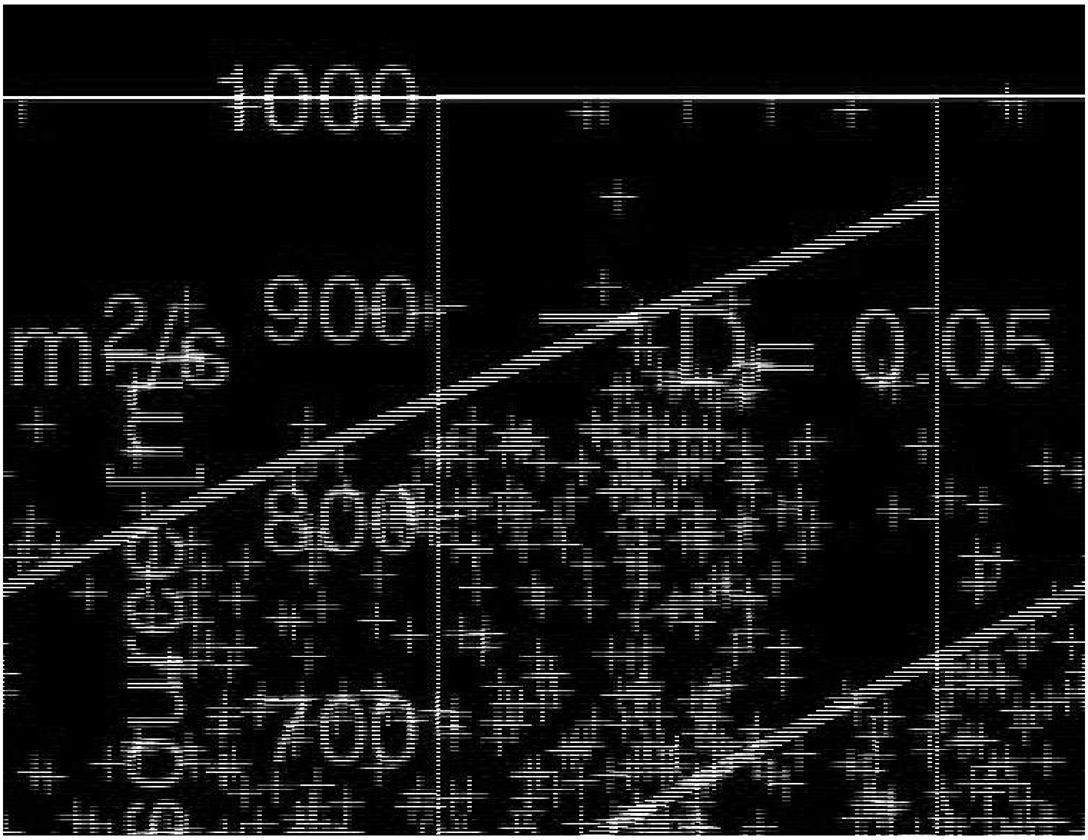

Figure 2 Distances of earthquakes from an injection well at Soultz-sous-Forêts, France in 1993. Earthquakes are marked by dots and a curve, representing a hydraulic diffusivity of 0.05 m^2/s is shown bounding the earthquakes furthest from the well. From Shapiro et al. (2003).

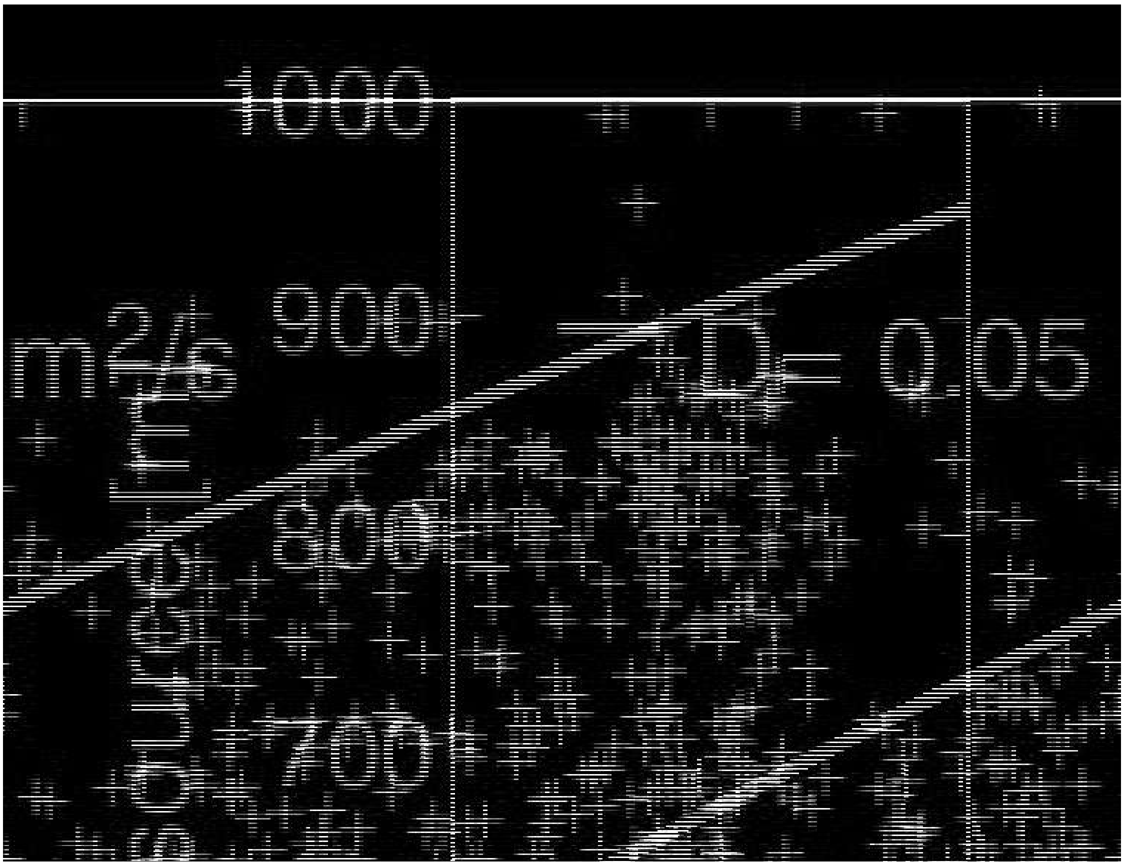

Figure 3 Distances of earthquakes from an injection well at Soultz-sous-Forêts, France in 1993. Earthquakes are marked by dots and a curve, representing a hydraulic diffusivity of 0.05 m^2/s is shown bounding the earthquakes furthest from the well. From Shapiro et al. (2003).

3.3 CHARACTERISTIC EVENTS AS AN AID TO IDENTIFICATION

The waveforms produced by earthquakes that might be due to shear failure resulting from hydraulic fracturing will have waveforms no different from those that occur completely naturally. This is because the earthquake mechanism, slip on a pre-stressed fracture, is the same in both cases. The addition of pore fluid pressure by pumping merely reduces the stress on opposing sides of the fracture required to cause it to slip. Examination of waveforms therefore does not offer any help in distinguishing natural from induced earthquakes.

4.0 POTENTIAL MAGNITUDE OF SEISMICITY INDUCED BY HYDRAULIC FRACTURING

All reports and articles seen by the authors indicate that the magnitude of earthquakes that may be induced by hydraulic fracturing is small. There are strong indications that the M2.3 event associated with the Preese Hall hydraulic fracturing operations in Lancashire, UK can be considered a “worst case scenario” since the well is very close to a large scale, critically stressed fault (de Peter and Baisch 2011). This is consistent with data published by Holland (2011) that discusses a swarm of nearly 50 earthquakes that were detected in the range of M1.0 to M2.8 (Figure 4), associated with hydraulic fracturing operations in the Eola Field, Oklahoma, USA. In this case too, the majority of the earthquakes were located along nearby faults.

Fluid injection into rocks to create enhanced geothermal systems (EGS) can sometimes produce significant seismic events (e.g. Majer et al. 2007) but this is rarely seen in the case of hydraulic fracturing of hydrocarbon reservoirs (Shapiro et al. 2010). The largest earthquakes triggered during a hydraulic fracture operation were in Basel, Switzerland (magnitude 3.4) and in the Cooper Basin, Australia (magnitude 3.7) (Majer et al., 2007); both of which were related to stimulation for proposed geothermal energy generation rather than hydrocarbon production.

Longer-term injection that continues for many days, months or years has generated larger magnitude earthquakes. Examples are well documented by authors such as Nicholson and Wesson (1990, 1992) and Suckale (2009, 2010), and in references therein. It should be noted that the majority of occurrences have been related to injection of fluids for disposal purposes and not for hydrocarbon production.

Shapiro et al. (2010) propose a “seismogenic index” (Σ) as a way of assessing the likelihood of an injection or fracturing operation being of seismic significance in an area. Shapiro et al’s Σ is independent of injection time or pressure and is completely defined by the seismic and tectonic features of a location. The larger the index, the larger the chance of a significant seismic event occurring.

Shapiro et al (2010) analysed published data for injection at the Ogachi (Japan), Cooper Basin (Australia) and Basel (Germany) geothermal sites; and compared them to data from saline injection in the Paradox Valley (Colorado, USA) and hydraulic fracturing for gas production from the Cotton Valley Sands and Barnett Shale in Texas, USA. They generalised their results to state that the seismogenic index for the geothermal locations is significantly higher than for the locations where hydraulic fracturing for hydrocarbon production was carried out[5]. This corroborates the statement made by de Pater and Baisch (2011) in their report into the Preese Hall seismic events in Lancashire, UK that the M2.3 event was a “worst case scenario”.

Damaging earthquakes, usually considered to be M>4 or 5, require a fault to slip over a length of several kilometres (Raleigh et al. 1976; Bommer et al 2001 for example). According to Bune & Thatcher (2002) almost all damaging earthquakes start at least 5 – 10 km underground. From the numerical exercise above, we can show that the pore pressure effects that could be generated by hydraulic fracturing dissipate before they reach the depth that is generally understood to be necessary to trigger damaging earthquakes.

5 This may partly be due to transient stresses due to large differences in temperature between geothermal reservoirs and cold injected fluid that is not such a significant factor in injection into hydrocarbon reservoirs.

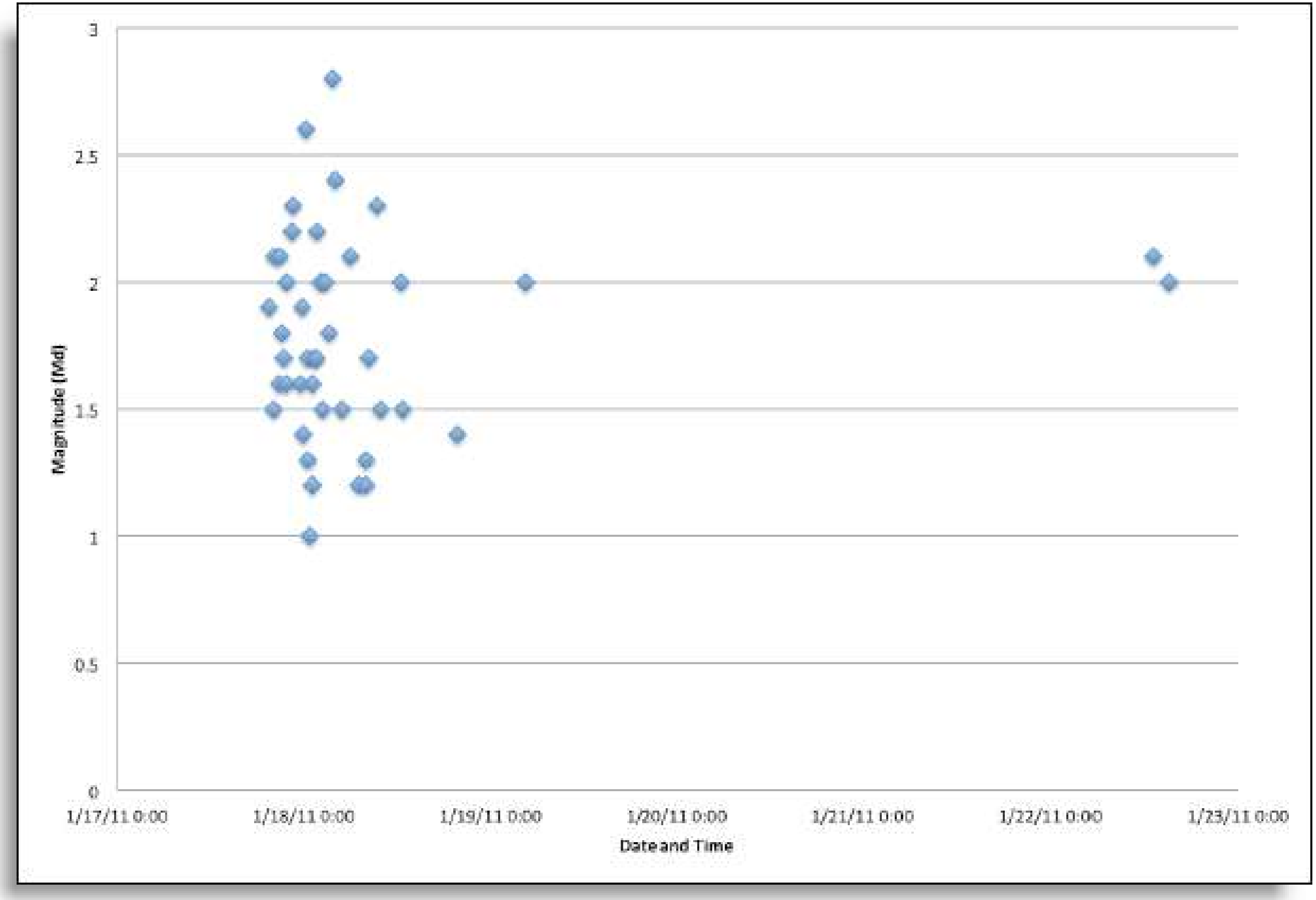

Figure 4 Time versus magnitude plot of Eola Field earthquakes following the start of hydraulic fracturing operations at around 12:00 on 17 January 2011

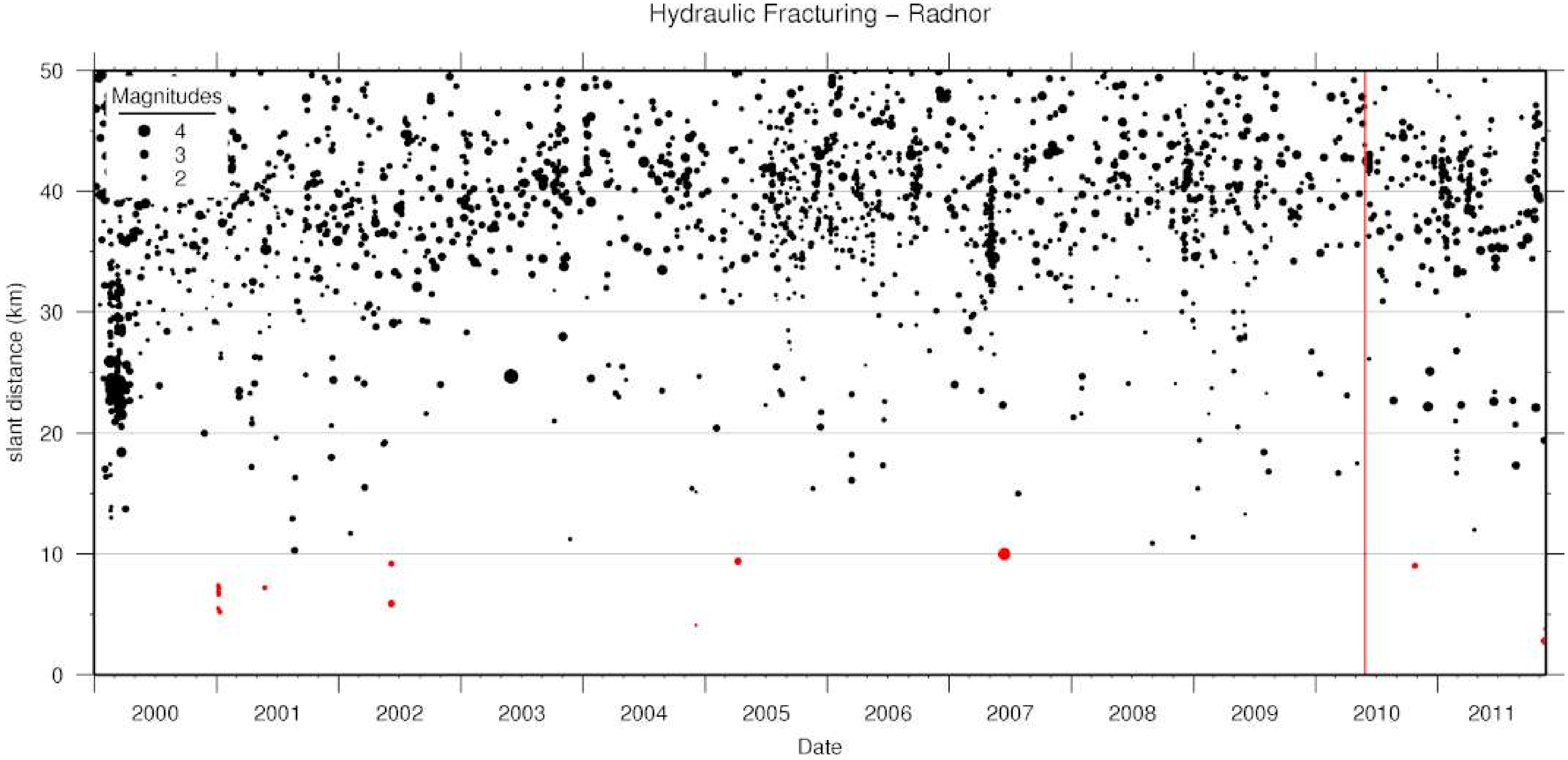

Figure 5 The distance of earthquakes from the Radnor reservoir. Earthquakes closer than a slant distance of 10 km are shown in red. The vertical red linein May 2010 represents the only hydraulic fracturing operation at Radnor. Symbol size is proportional to earthquake magnitude.

4.1 DESCRIBING EARTHQUAKE EFFECTS

Earthquake magnitude (M) is a measure of energy released at the source of the earthquake. It is a logarithmic scale, so that the ground shaking amplitude from a M2 earthquake is 10 times that from a M1, from a M3 is 10 times that from a M 2, and so on. The increment in seismic energy between one magnitude and the next is a factor of 30, so a M3 earthquake releases about 1000 times the energy of a M1. The magnitude scale does not necessarily give a good indication of the felt effects of a seismic event. The Modified Mercalli Intensity scale (MM) relates to how an earthquake was experienced by people or objects[6]:

- **MM 1: Imperceptible**
  Barely sensed only by a very few people.
- **MM 2: Scarcely felt**
  Felt only by a few people at rest in houses or on upper floors.
- **MM 3: Weak**
  Felt indoors as a light vibration. Hanging objects may swing slightly.
- **MM 4: Largely observed**
  Generally noticed indoors, but not outside, as a moderate vibration or jolt. Light sleepers may be awakened. Walls may creak, and glassware, crockery, doors or windows rattle.
- **MM 5: Strong**
  Generally felt outside and by almost everyone indoors. Most sleepers are awakened and a few people alarmed. Small objects are shifted or overturned, and pictures knock against the wall. Some glassware and crockery may break, and loosely secured doors may swing open and shut.
- **MM 6: Slightly damaging**
  Felt by all. People and animals are alarmed, and many run outside. Walking steadily is difficult. Furniture and appliances may move on smooth surfaces, and objects fall from walls and shelves. Glassware and crockery break. Slight non-structural damage to buildings may occur.
- **MM 7: Damaging**
  General alarm. People experience difficulty standing. Furniture and appliances are shifted. Substantial damage to fragile or unsecured objects. A few weak buildings are damaged.
- **MM 8: Heavily damaging**
  Alarm may approach panic. A few buildings are damaged and some weak buildings are destroyed.
- **MM 9: Destructive**
  Some buildings are damaged and many weak buildings are destroyed.
- **MM 10: Very destructive**
  Many buildings are damaged and most weak buildings are destroyed.
- **MM 11: Devastating**
  Most buildings are damaged and many buildings are destroyed.
- **MM 12: Completely devastating**
  All buildings are damaged and most buildings are destroyed.

6 http://www.geonet.org.nz/earthquake/geonet-modified-mercalli-intensity-scale.html

The magnitude 2.3 and 1.7 events that were associated with the Preese Hall hydraulic fracturing in Lancashire, UK probably fall within the MM band 3, which indicates that they would be felt by a very few people, probably only those indoors. This agrees with the reports that were received by the British Geological Survey (BGS) at the time of the events in April 2011. Even the larger events associated with geothermal fluid injection that are felt close to the source only rarely result in shaking of more than MM4, which would mean that they are typically no more noticeable than a large truck passing nearby (a few metres to tens of metres away).

Using a formula in Dowrick & Rhoades (1999) we can estimate the felt intensity (MM scale) for specific earthquake magnitudes at specific depths. If we apply this to an earthquake of magnitude 2.0, a possible maximum for seismic activity directly induced by hydraulic fracturing, at a depth of 3 km, typical of hydraulic fracturing in Taranaki the maximum estimated intensity would be MM4, with MM3 more widespread. When placed in this context, it is unlikely that any earthquakes that may be induced by hydraulic fracturing operations in the Taranaki Region would have a significant felt effect.

5.0 DISCRIMINATING BETWEEN INDUCED AND NATURAL SEISMICITY

If an earthquake occurs close to a hydraulic fracturing or deep injection operation, what is the likelihood that it is related to those operations, or that it is just a coincidence? Davis and Frohlich (1993) proposed seven yes/no questions to help assess whether particular earthquakes can be attributed to fluid injection (Table 1). The questions are phrased so that a 'yes' answer supports injection as the cause of earthquakes.

Davis and Frohlich (1993) answered the questions for 20 earthquake sequences thought possibly related to fluid injection and concluded that in every case where there were five or more questions with a 'yes' answer, professional seismologists would conclude injection triggered the earthquake sequence.

We propose to use these same questions, with some minor modifications to account for earthquake location uncertainties in Taranaki, to assess the relationship between hydraulic fracturing and deep injection and seismicity (Table 1).

Table 1 Questions designed to help assess if earthquakes can be attributed to fluid injection. Modified from Davis and Frolich (1993).

Question	Explanation	Taranaki Situation
Background seismicity		
1. Are these events the first known earthquakes of this character in the region?	If earthquakes occur regularly near the injection well, the occurrence of seismicity is not strong evidence for a trigger, unless the character of the earthquakes is somehow unusual.	Natural seismicity is common in Taranaki. Earthquakes often occur near some reservoirs (such as Radnor), and are uncommon near others (such as Kapuni[7]).
Temporal Correlation		
2. Is there a clear correlation between injection and seismicity?	Even if we lacked a clear understanding of the processes	Times of hydraulic fracturing and deep injection have to be compared

7 On 5 January 2012 a M4.1 earthquake was located 30 km deep within 5 km of Kapuni. The depth of this earthquake means it is unlikely to be associated in any way with the Kapuni field.

Question	Explanation	Taranaki Situation
	causing the earthquakes, most would be convinced of a causal relationship if seismicity 'turned on' when injection started and 'turned off' when it stopped.	with the earthquake database.
Spatial Correlation		
3a. Are epicentres near wells (within 5 km)?	It is more plausible that earthquakes are triggered if injection would cause fluid pressure increases where earthquakes occur.	Taking into account estimated uncertainties in earthquake positions of ~4 km (at 95 % confidence level) 'within 10 km' is a more appropriate distance.
3b. Do some earthquakes occur at or near injection depths?	Triggered earthquakes would likely occur at depths similar to injection if the injectate flows along approximately horizontal strata.	Taking into account estimated uncertainties in earthquake depths, 'at or near injection depths' should be within 5 km of injection depths.
3c. If not, are there known geological structures that may channel flow to sites of earthquakes?	Fluid pressures might affect seismic activity at considerably greater distances if faults or fractures exist that can channel flows towards the hypocentral region.	Tikorangi formation that hosts Wiahapa-Ngaere, Toko, Piakau, Kupara and Rimi reservoirs has fracture controlled permeability. Kaimiro and Waitui reservoirs lie at opposite ends of the active Inglewood fault. In these reservoirs it is therefore potentially more likely that fluid pressures could be channelled to a point of potential seismic activity.
Question	**Explanation**	**Taranaki Situation**
Injection practices		
4a. Are changes in fluid pressures at well bottoms sufficient to encourage seismicity?	The largest pressure increase will be close to the well bottom, if these pressures are insufficient to induce seismicity it is unlikely to be triggered further away.	As the intention is to hydraulically fracture rock injection pressures are always sufficient. Injection depth is more appropriate than 'well bottoms'.The answer is always 'yes' for hydraulic fracturing, maybe for injection.
4b. Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?	This is often difficult to ascertain without hydrologic modelling and detailed permeability information.	Given the very high injection pressures (>20 MPa) used in some hydraulic fracturing the answer is probably always 'yes'. Pressures for deep injection are lower so 'yes' may not be a guaranteed answer.
4b. Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?	This is often difficult to ascertain without hydrologic modelling and detailed permeability information.	Given the very high injection pressures (>20 MPa) used in some hydraulic fracturing the answer is probably always 'yes'. Pressures for deep injection are lower so 'yes' may not be a guaranteed answer.

6.0 DATA FROM TARANAKI REGION

We calculated the slant distance[8] from wells that have been used for hydraulic fracturing or deep injection to earthquakes in Taranaki that were < 20 km deep. Figure 5 is an example of the data for the Radnor well near Midhurst; others for hydraulic fracturing are shown in Appendix 2, and for deep injection in Appendix 3.

Table 2 is an assessment of the likelihood of hydraulic fracturing having triggered seismicity in Taranaki. Based on criteria in Table 1 we consider any earthquakes within 10 km of a well to potentially be triggered. It must be remembered that not all earthquakes smaller than magnitude 2 will be in the earthquake database.

Table 2 Summary of earthquakes near hydraulic fracturing locations, and comments regarding the likelihood of induced seismicity due to hydraulic fracturing.

Reservoir	Seismicity within 10 km (2000 - 2011)[9]	Comments (hf = hydraulic fracturing)	Likelihood triggered seismicity has occurred
Cheal	3 events	no events since hf in 2010	unlikely
Kapuni	3 events	one event ~6 months after hf in 2005	unlikely
Kaimiro	10+ events	1 event ~3 months after hf in 2011	possible, but unlikely
Kauri and Manutahi	1 event	4 years after hf	unlikely
Kowhai	6 events	no events since hf in 2009	unlikely
Mangahewa	7 events	no events since hf in 2010	unlikely
Radnor	10+ events	1 event ~5 months after hf in 2010	unlikely
Rimu	no events	no events since hf in 2010	unlikely
Turangi	5 events	no events since hf in 2006 and 2008	unlikely
Waitui	7 events	no events since hf in 2011	unlikely

Earthquakes have occurred within 10 km of Kaimiro and Radnor in the months following hydraulic fracturing:

- Kaimiro is an interesting case as the wells are located within 1 km of the trace of the active Inglewood fault, which last moved significantly 3300 to 3500 year ago (Hull 1994). If elevated fluid pressures were to occur in the fault, they might have the potential to trigger seismicity. Some seismicity is to be expected on the fault, and this is observed at the south-west end (Figure 1); it would be difficult to distinguish natural seismicity from that triggered by hydraulic fracturing or deep injection here.
- If we answer the questions in Table 1 for Kaimiro we get 5 'yes' answers, one 'no', answers, and one unknown answer. This suggests that it is possible that hydraulic

8 Slant distance takes into account both horizontal distance and earthquake depth. A representative depth of 3 km was assumed for all hydraulic fracturing and deep injection operations.
9 Using all earthquakes in the database.

fracturing in June 2011 triggered seismicity, but with only one earthquake in the database the evidence for a temporal correlation is slim.

- For the Radnor well we get 4 'yes' answers, two 'no', answers, and one unknown answer. This suggests that hydraulic fracturing is unlikely to have triggered seismicity.
- The Radnor well is an interesting case of 'by chance' seismicity. There is an average of about one earthquake per year in the database near the well. If seismicity occurs naturally close to a well-used for hydraulic fracturing or deep injection it will be more difficult to attribute any seismicity as being due to anything other than 'by chance'.

As deep injection is a long-term process we might expect to see a long-term cluster of earthquakes close to (within ~10 km) any well that triggers seismicity. This is not seen (Appendix 2).

7.0 EFFECT ON MT TARANAKI VOLCANO

If hydraulic fracturing and deep injection can potentially trigger earthquakes in Taranaki then it is logical to ask if they can affect volcanic activity at Mt Taranaki. All hydraulic fracturing and deep injection operations have occurred at least 10-15 km east of the summit of Mt Taranaki and Davis and Frohlich (1993) suggest 5 km as a practical limit for the effect of injection fluid over-pressure on earthquakes. This suggests Mt Taranaki is too far from hydraulic fracturing and deep injection operations, and earthquakes beneath the summit are unlikely to be triggered by those operations.

While we understand the mechanism by which fluid over pressure can trigger earthquakes, it is not clear how it might trigger or modify volcanic activity. However, it is a reasonable initial assumption that the stress perturbation caused by fluid over pressure would be relatively small compared to natural stresses at depths beneath a volcano, so that fluid over pressure might only have an effect if a volcano were already close to eruption.

In Taranaki there is no evidence that recent hydraulic fracturing and deep injection operations have had any effect on volcanism at Mt Taranaki.

8.0 CONCLUSIONS

We have found no evidence for either hydraulic fracturing or long-term deep injection activities in Taranaki between 2000 and mid-2011 having any observable effect on natural earthquakes of magnitude 2 or larger, the magnitude threshold of the earthquake catalogue.

In terms of any seismic activity that might be associated directly with hydraulic fracturing, an earthquake of about magnitude 2 would be a relatively large event. At a depth of 2-4 km such an earthquake is likely to produce (for those in the near vicinity) ground shaking similar to that caused by a nearby passing truck, but no more.

A series of questions with yes/no answers will help assess if any seismic activity could be due to hydraulic fracturing operations. It will be difficult to distinguish earthquakes due to hydraulic fracturing or deep injection from natural seismic activity if natural earthquakes are common close to those sites.

Given the location of hydraulic fracturing and deep injection operations there is no evidence of any effect on volcanic activity at Mt Taranaki.

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APPENDIX 1: LIMITATIONS OF SEISMICITY DATA

In assessing any relationship between hydraulic fracturing or deep injection and seismicity in Taranaki we have to consider the uncertainties in the seismic locations in the database. For a technical article on the uncertainty in earthquake locations refer to Husen and Hardebeck (2010).

Position and Depth

Earthquake locations are estimates of the source of an earthquake using observations that have uncertainty together with models and calculations that often contain simplifying assumptions. In other words, locations of earthquakes do not represent the exact earthquake source, but are an estimate of that source.

Seismologists determine the location of an earthquake using P and S seismic wave times at seismographs. The measurements of these arrival times have uncertainties. In addition, the location process uses a model for the speed of seismic waves in the Earth that is a simplification of what actually exists which adds its own uncertainty to the location estimate.

In its simplest form an earthquake source can be represented by four parameters: an origin time, a position, a depth, and a size (or magnitude). Our estimates of these parameters have uncertainties, but because as we never know exactly when and where an earthquake originated even the uncertainties have to be estimated.

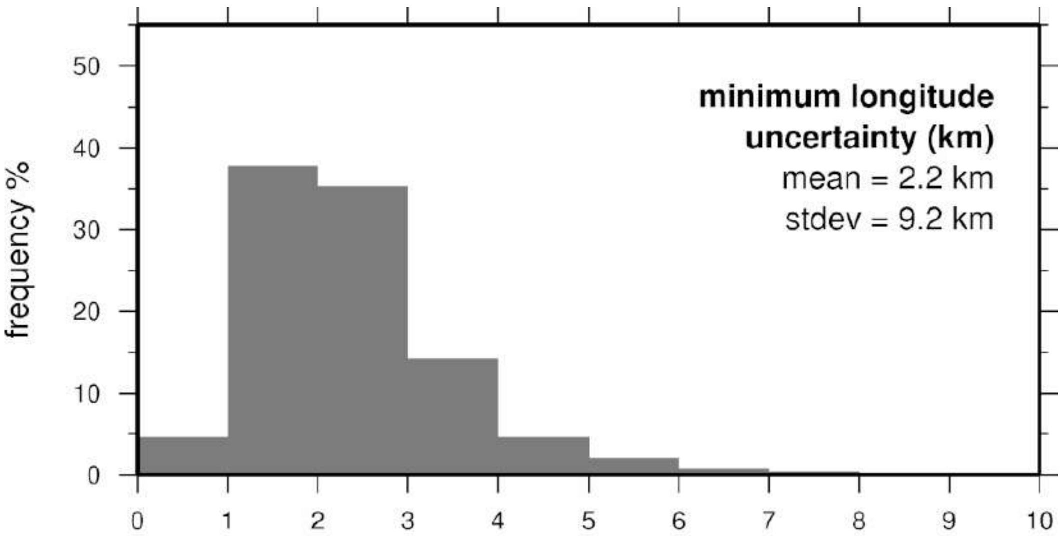
In locating an earthquake we can derive an estimate of the uncertainty in the origin time, position, and depth by how well the arrival times of seismic waves matches the best location estimate. Those estimates are considered to be smaller than the actual uncertainties, possibly by a factor of two or more. For shallow seismicity in Taranaki (depth < 20 km) from 2000 to late-2011 the minimum uncertainties in position and depth are 1 – 2 km (Figure A1). Given that these do not consider simplifications due to the model of the speed of seismic waves we will use a value that encompasses 95% of all events. For position this is 4 km and for depth 3.5 km; we adopt a value of 4 km for both. In other words, we consider that the calculated location of an earthquake in Taranaki is within 4 km, in position and depth, of the actual origin of the earthquake.

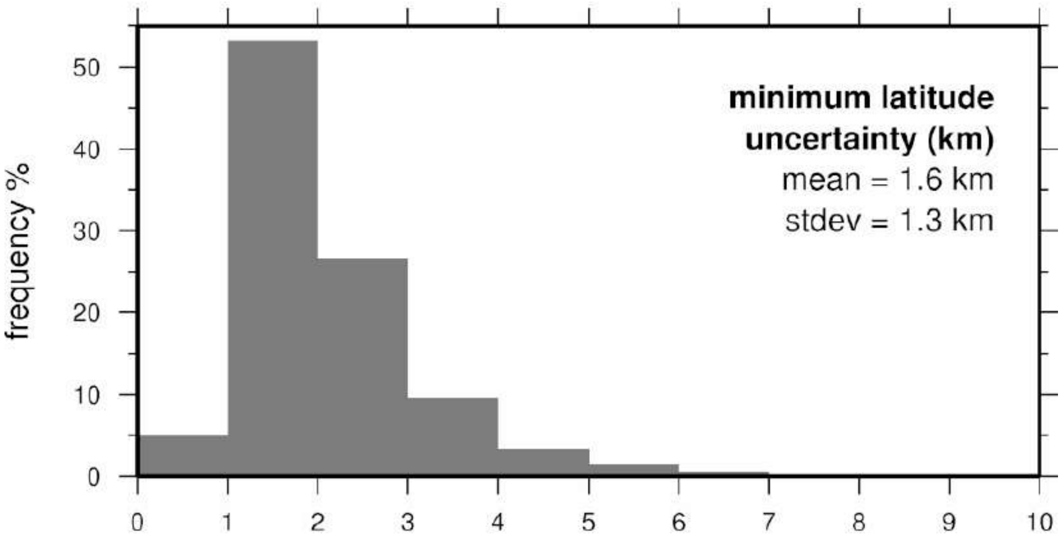
Minimum Depth Estimation

The geometry involved in the earthquake location problem means that it is usually not possible to obtain a reasonable estimate of depth if the nearest seismograph recording the earthquake is too far from the earthquake epicentre[10]. In this case the depth is often fixed to a value considered appropriate and only a position and origin time calculated. A 'rule of thumb' is that to be able to calculate a depth the nearest seismograph must be no further than a distance equivalent to about twice the depth of the earthquake. Figure A2 shows the minimum depth able to be determined throughout Taranaki using this rule of thumb.

Hydraulic fracturing and deep injection occur at 3 – 5 km depth. To demonstrate that hydraulic fracturing or deep injection induces earthquakes, we need to be able to show that they occur at a similar depth to those operations. This is possible at most sites, but not at the Rimu and Kauri/Manutahi reservoirs were earthquakes are likely to have their depth fixed. However, even in these reservoirs we should be able to say if an earthquake occurred in the shallow crust rather than the mid- or lower-crust (depth > about 15 km).

10 The epicentre is the position on the surface directly above the earthquake.





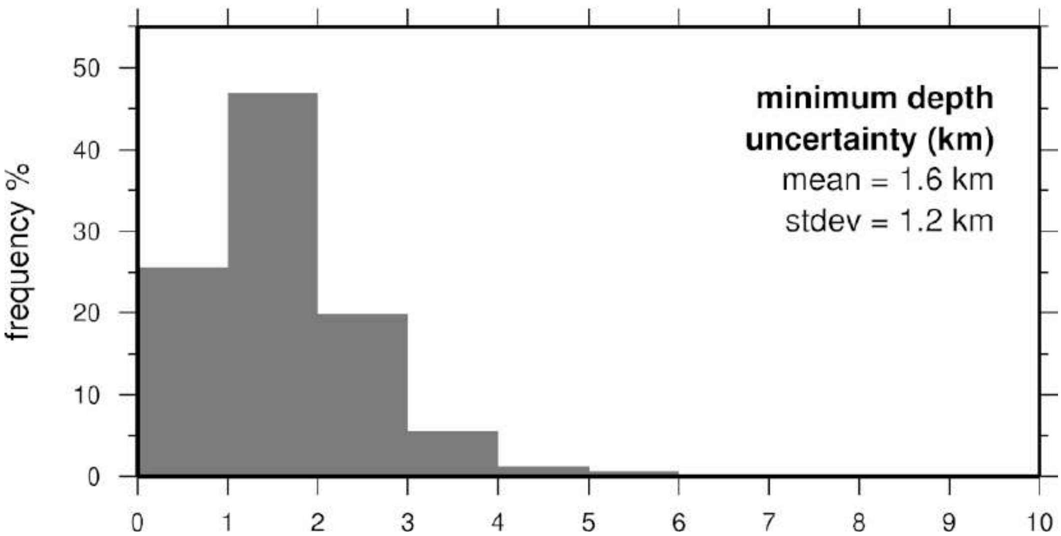


Figure A1 Earthquake location uncertainties estimated from how well the arrival times at seismographs fit the calculated earthquake location. These uncertainties are considered minima and a more conservative measure is the uncertainty which includes 95% of all values, about 4 km in both position and depth.

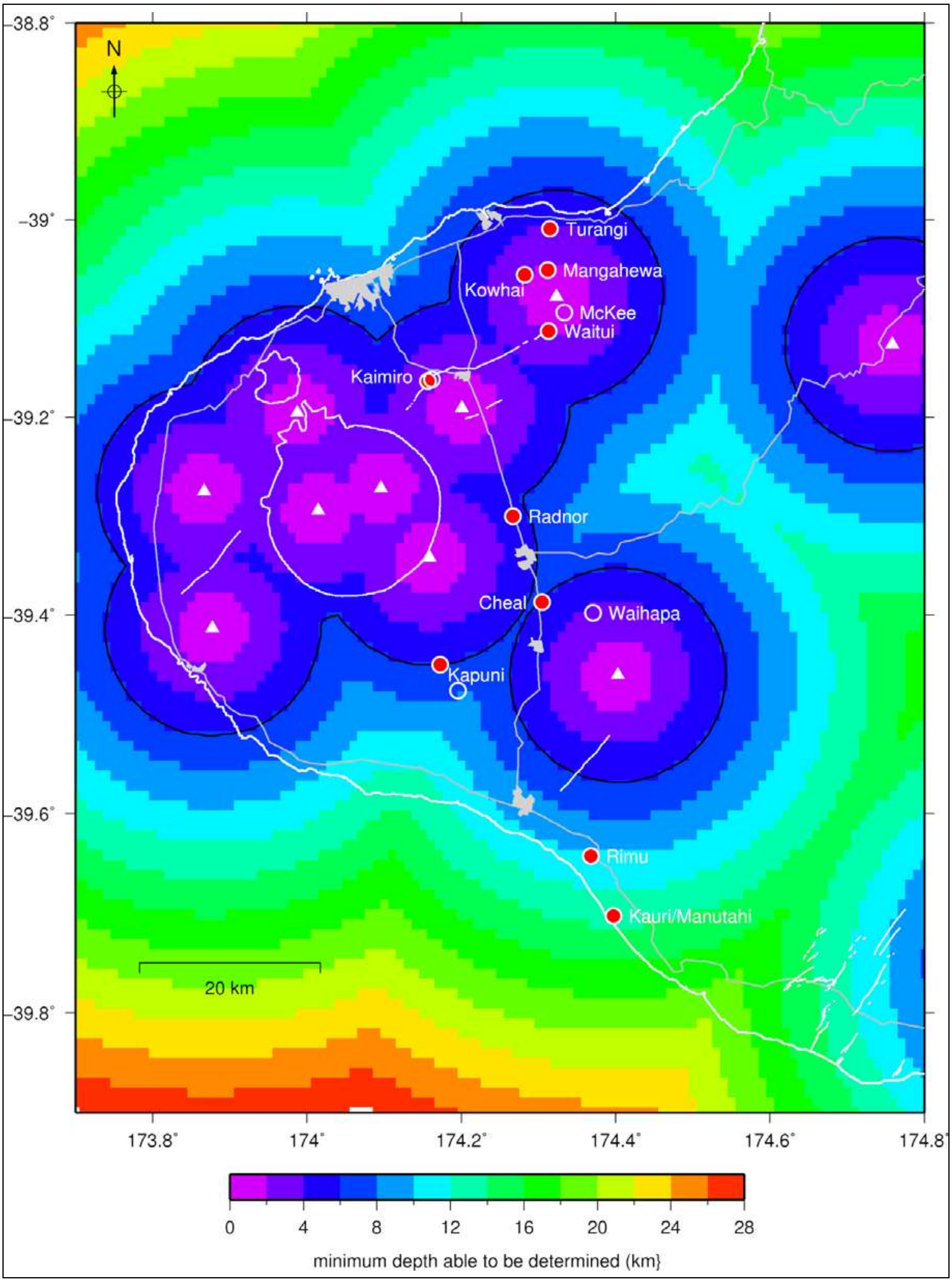


Figure A2 An estimate of the minimum measurable earthquake depth in Taranaki based on the spacing between seismographs. Refer to Appendix 1 for more explanation.

Origin Time

The uncertainty in an earthquake origin time estimated from a location in Taranaki is always much less than 1 second, and can be ignored when comparing earthquakes with hydraulic fracturing or deep injection.

Magnitude

Magnitude is a measure of earthquake size[11]. There are several measures of magnitude that use different parts of the information recorded by a seismograph. GeoNet uses a magnitude calculated from the maximum amplitude of the ground shaking recorded at a seismograph, corrected for the distance from the seismograph to the earthquake. Uncertainty in a location and other factors mean that magnitudes for earthquakes in New Zealand are considered to have an uncertainty of about 0.3 magnitude units (Kevin Fenaughty pers. comm. 2011).

Magnitude of Completeness

Some earthquakes will always occur that are too small to be recorded by individual seismographs or located by groups of seismographs. This occurs as there is always a certain level of 'background noise' at a seismograph, caused by things such as wind noise, wave noise if near the sea, traffic, and animals or people walking nearby[12], and an earthquake signal may be smaller than the background noise.

In terms of an earthquake database there is a concept called the 'magnitude of completeness', Mc, which is the magnitude above which it is thought the database contains all earthquakes. A database will always contain some earthquakes smaller than Mc, but not all of them. Mc usually varies with position and time and is likely to be lower where there are many seismographs than where there are only a few. Lowering Mc results in an increase in the number of earthquakes located.

For that part of Taranaki where hydraulic fracturing and deep injection have occurred (dashed region in Figure 1) Mc is estimated to be about 2.0. This means that if earthquakes triggered by hydraulic fracturing or deep injection have a magnitude smaller than about 2, then some or all of those earthquakes may not be in the earthquake database.

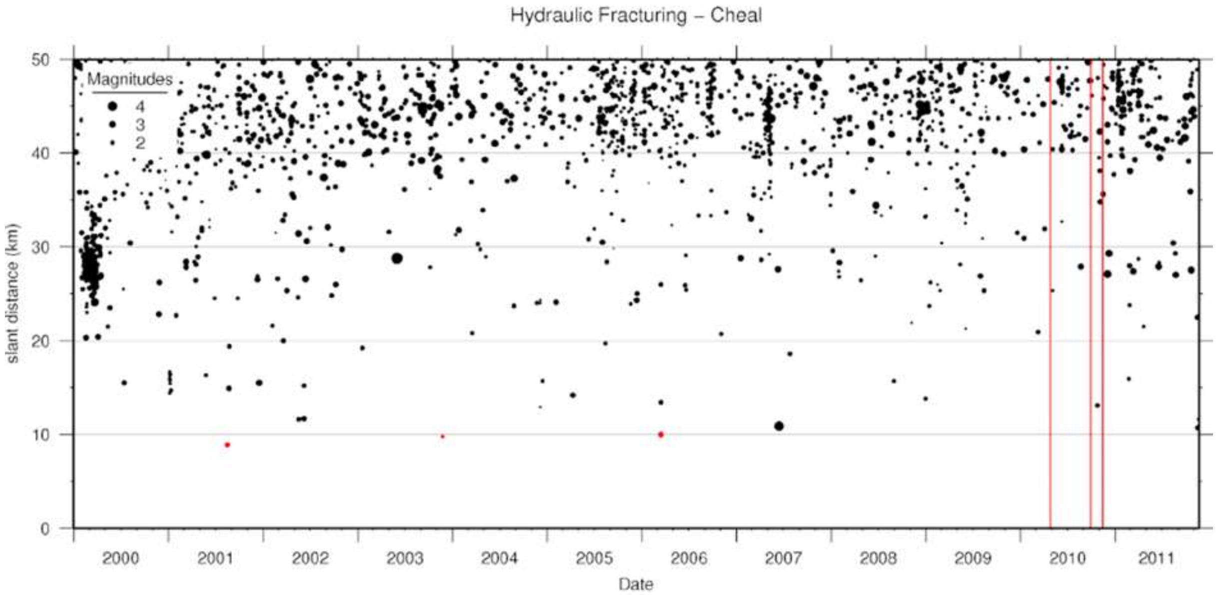
Ongoing research (Matt Gerstenberger pers. comm. 2012) suggests a higher Mc for Taranaki, and if that is the case then the seismic monitoring system will struggle to locate even the largest of any earthquakes triggered by hydraulic fracturing.

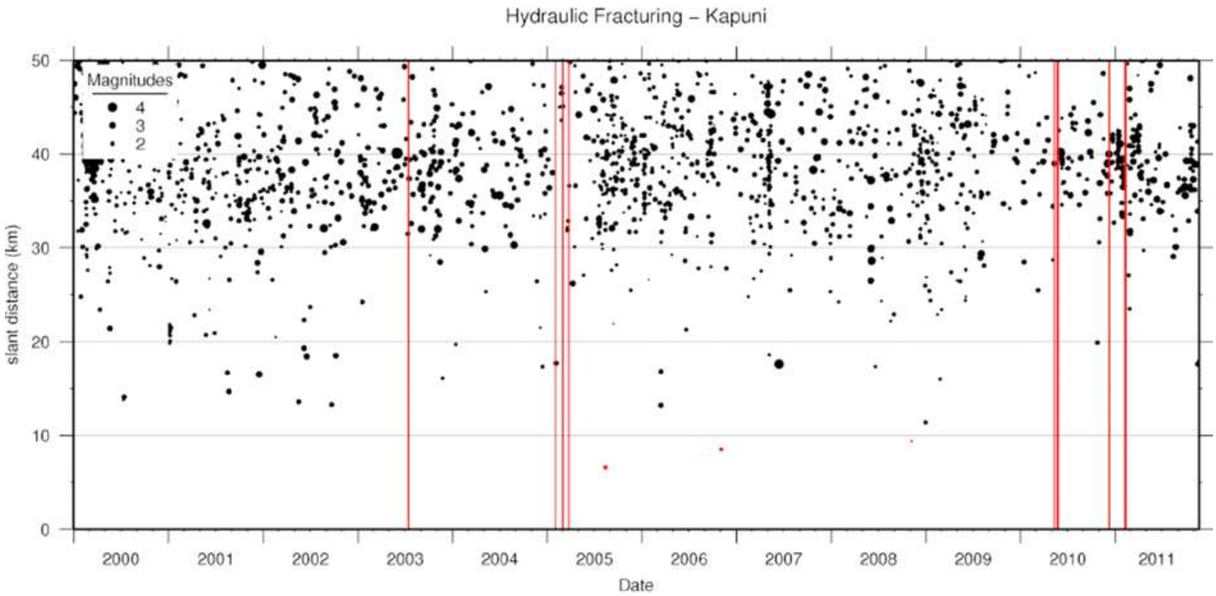
11 Magnitude is a logarithmic scale, in other words, the ground shaking amplitude from a magnitude 2 earthquake is 10 times that from a magnitude 1, from a magnitude 3 is 10 times that from a magnitude 2, and so on. The increment in seismic energy between one magnitude and the next is a factor of 30.

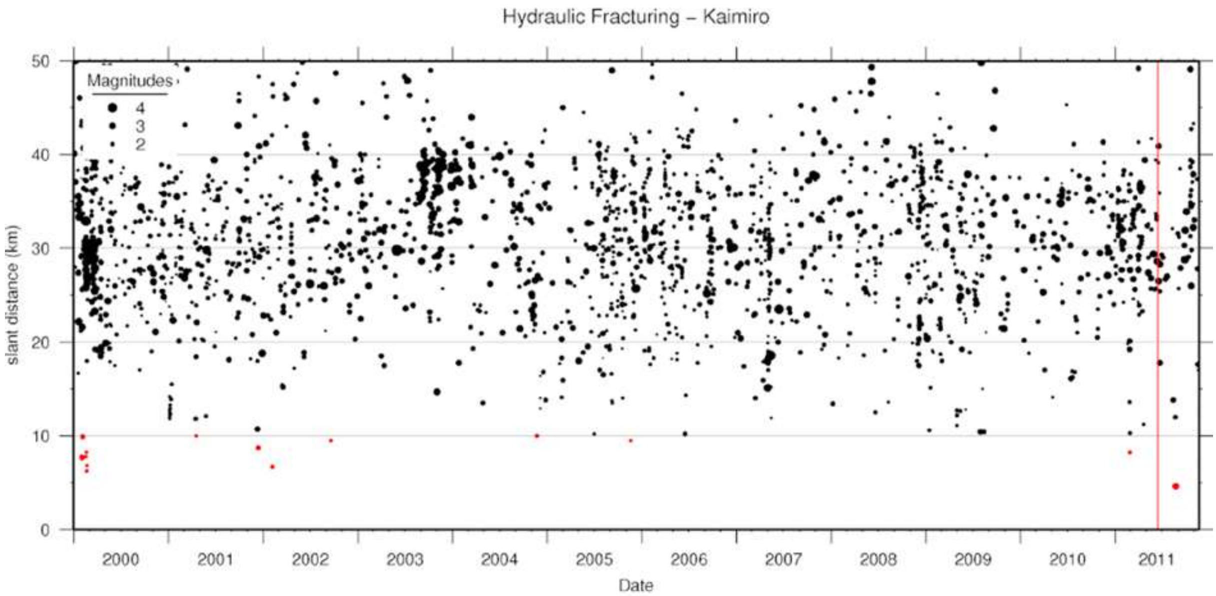
12 Seismographs are very sensitive instruments and can sense ground movements much smaller than people can feel.

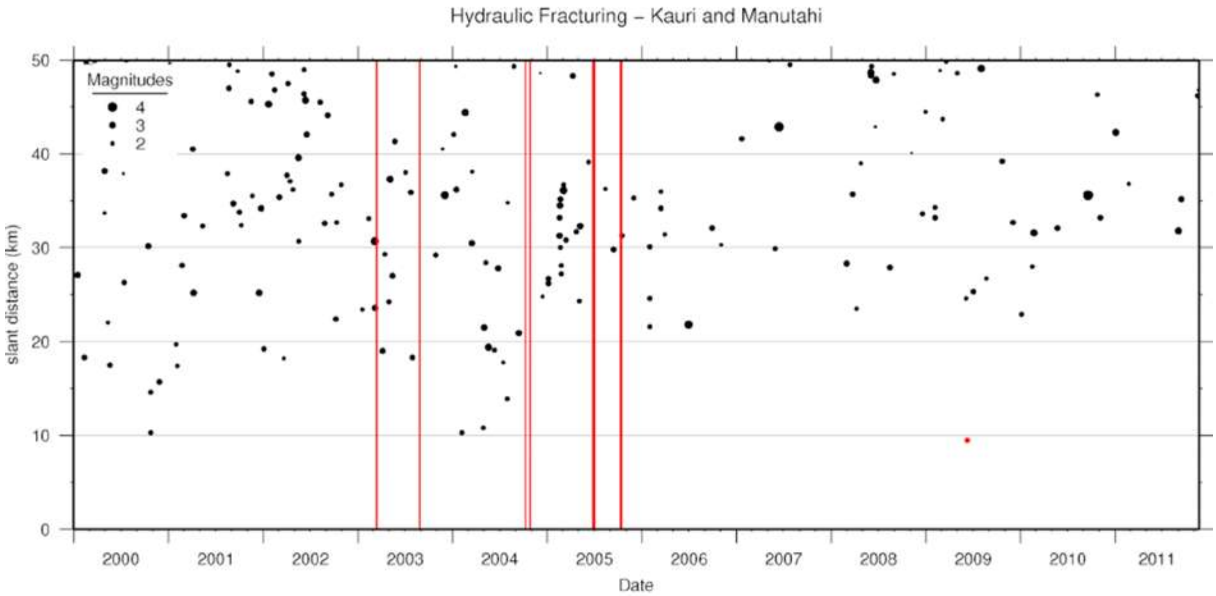
APPENDIX 2: COMPARISON BETWEEN HYDRAULIC FRACTURING AND SEISMICITY

Plots show the distance of earthquakes from each of the reservoirs in which hydraulic fracturing has taken place. Earthquakes closer than a slant distance of 10 km are shown in red. Vertical red lines represent hydraulic fracturing operations. The size of the symbol is proportional to earthquake magnitude.






Hydraulic Fracturing – Kaimiro
Magnitudes
4
3
2
slant distance (km)
0
10
20
30
40
50
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Date


Hydraulic Fracturing – Kauri and Manutahi
Magnitudes
4
3
2
slant distance (km)
0
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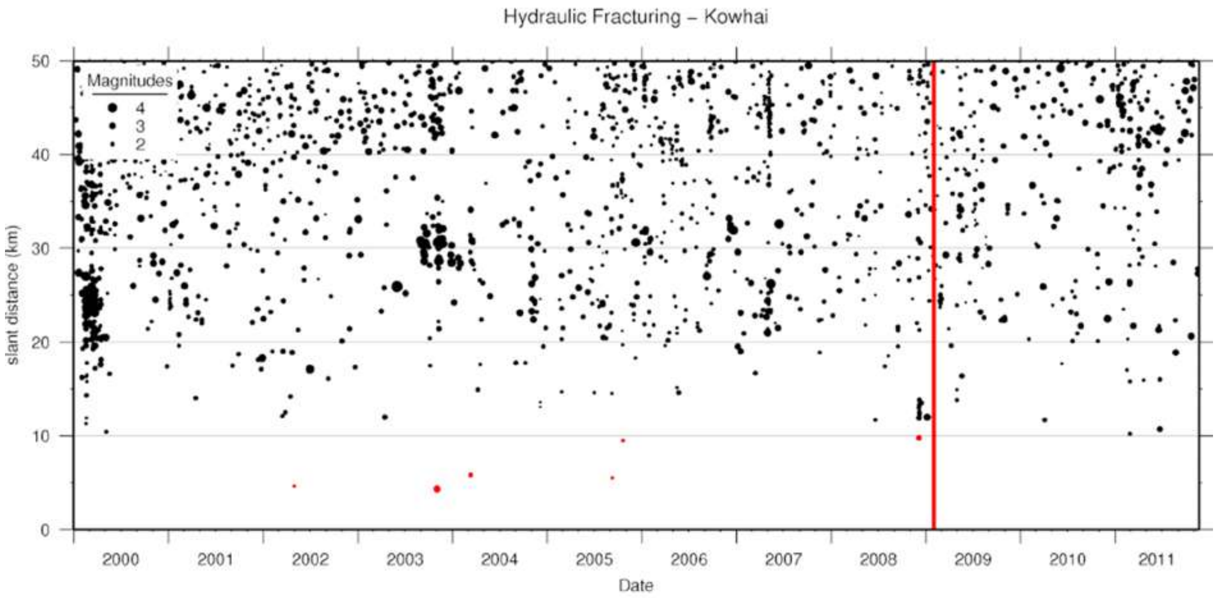
Hydraulic Fracturing – Kowhai
Magnitudes
4
3
2
slant distance (km)
50
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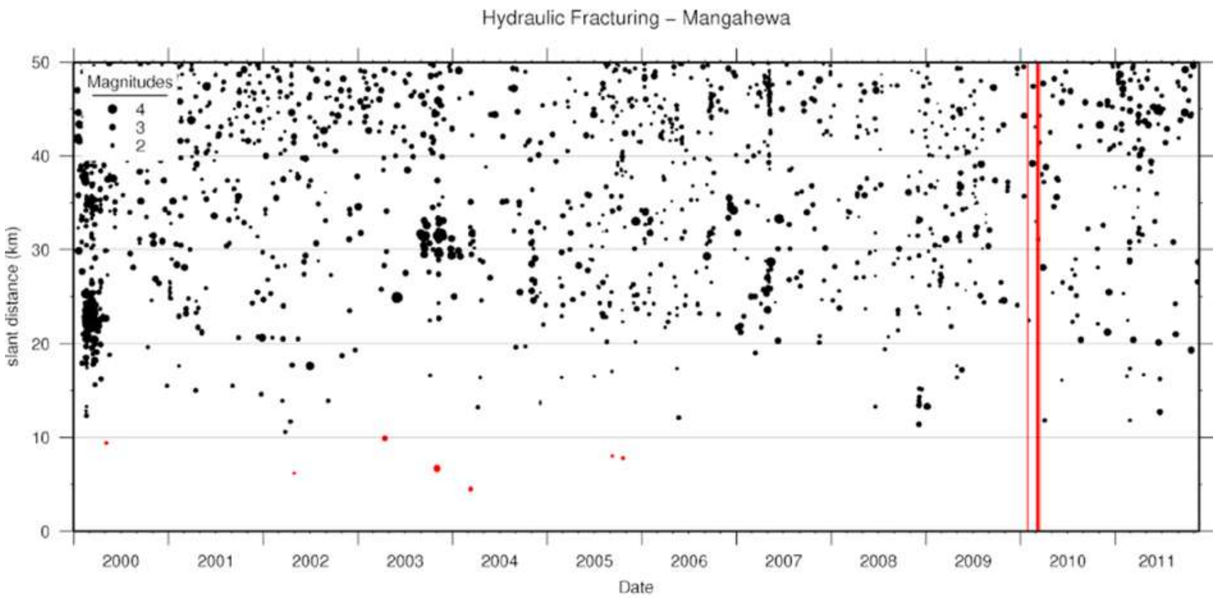
Date


Hydraulic Fracturing – Mangahewa
Magnitudes
4
3
2
slant distance (km)
50
40
30
20
10
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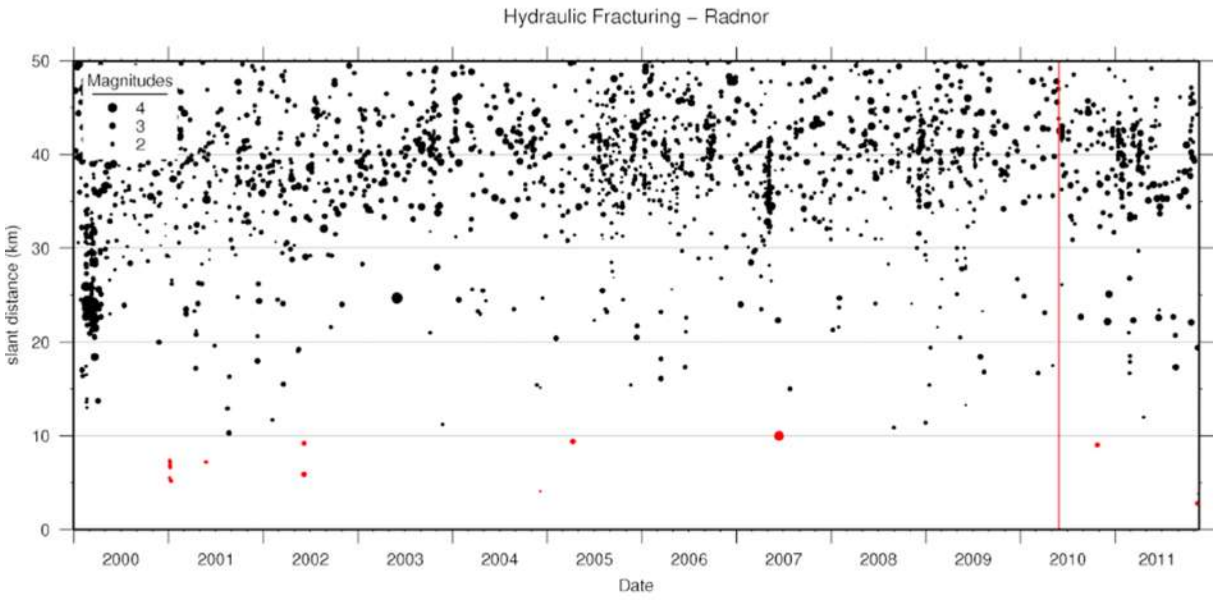
Date


Hydraulic Fracturing – Radnor
Magnitudes
4
3
2
slant distance (km)
0
10
20
30
40
50
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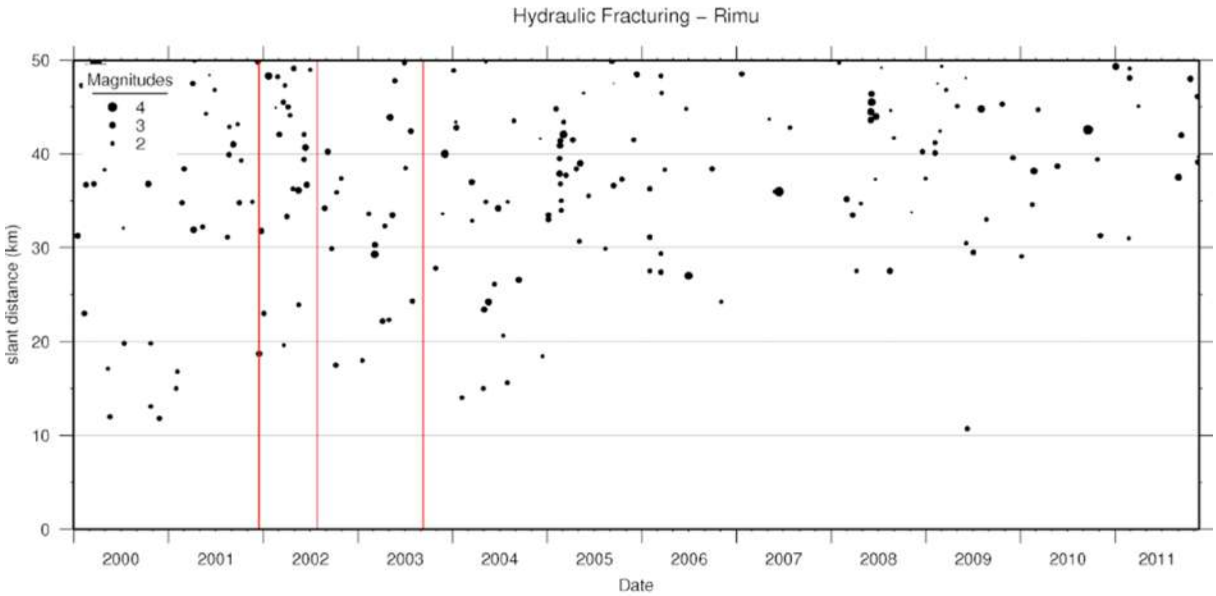
Date


Hydraulic Fracturing – Rimu
Magnitudes
4
3
2
slant distance (km)
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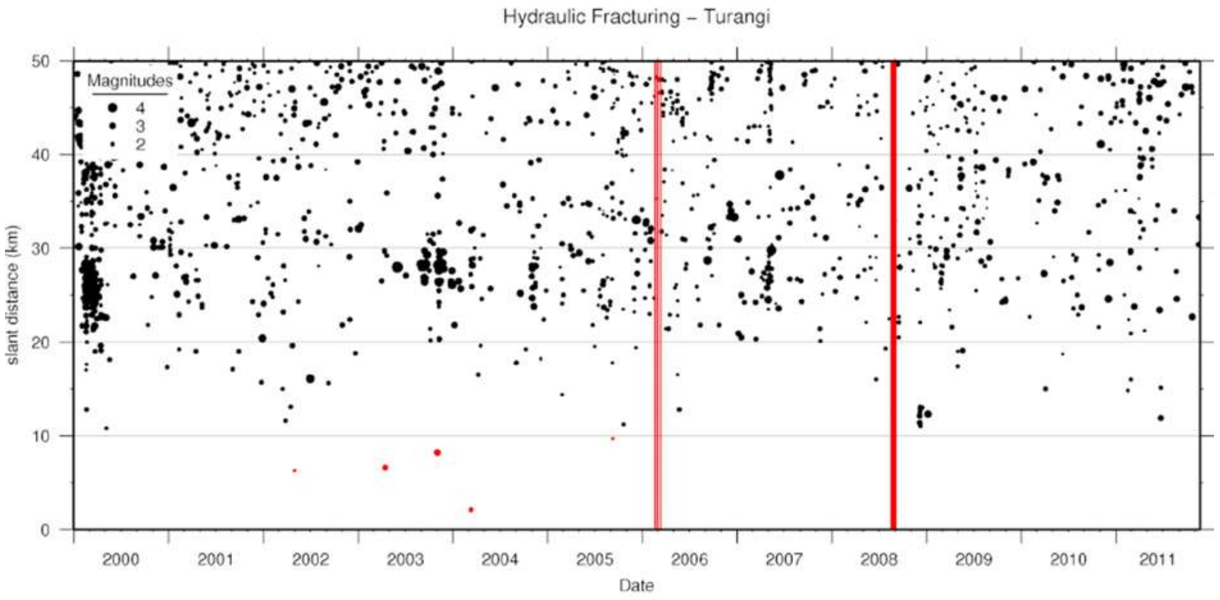
Date


Hydraulic Fracturing – Turangi
Magnitudes
4
3
2
slant distance (km)
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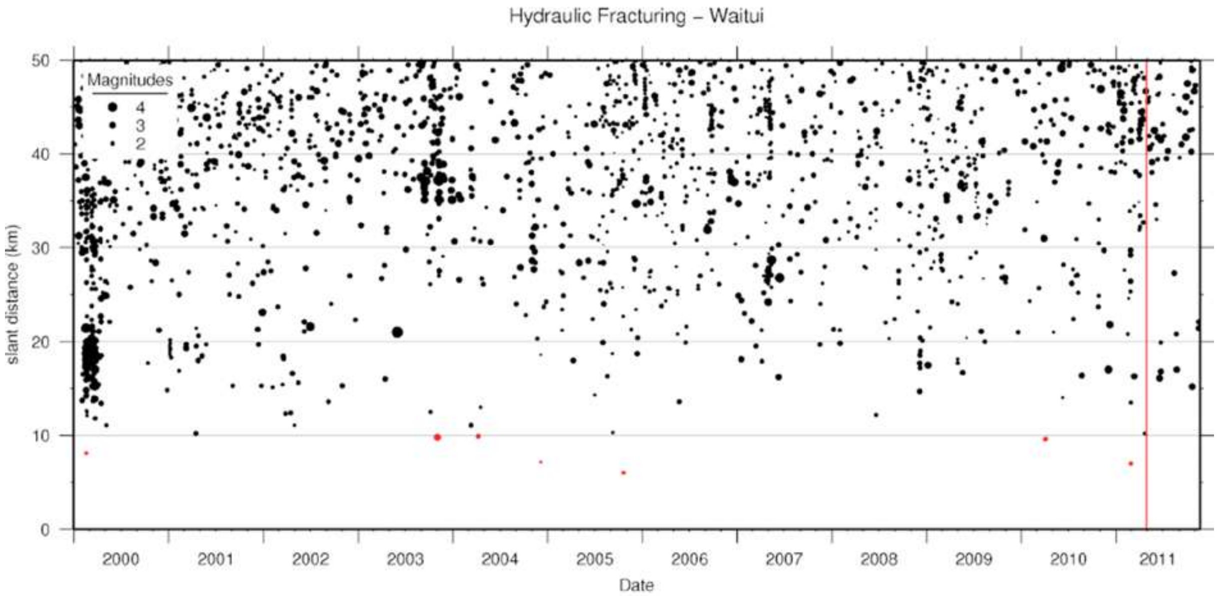
Hydraulic Fracturing – Waitui
Magnitudes
4
3
2
slant distance (km)
0
10
20
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2000
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2003
2004
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2006
2007
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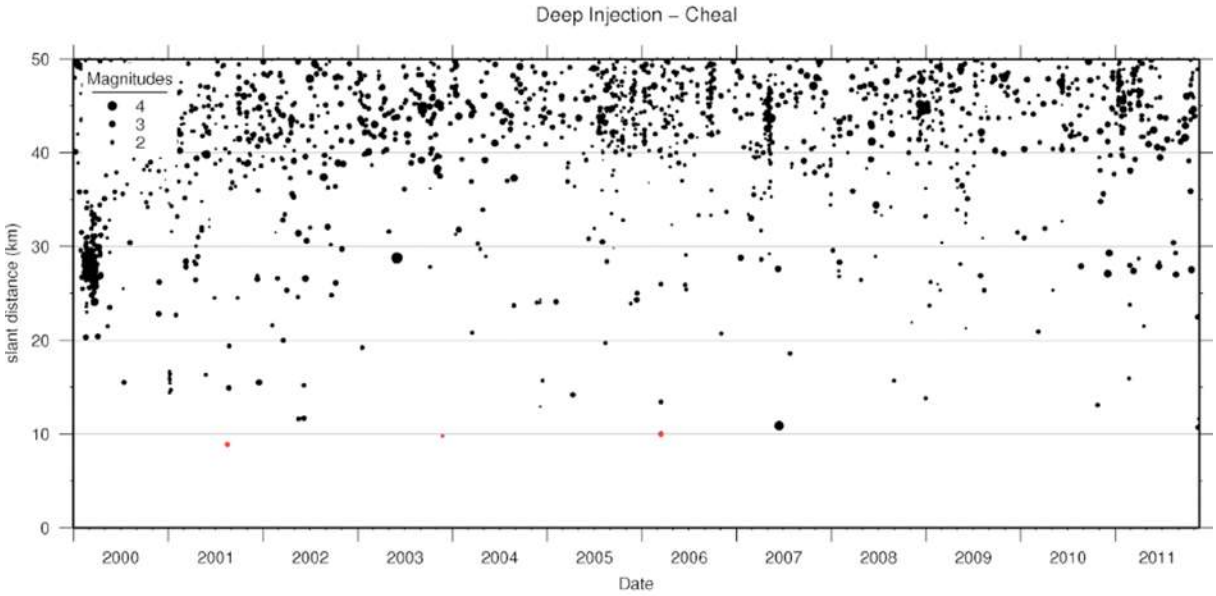
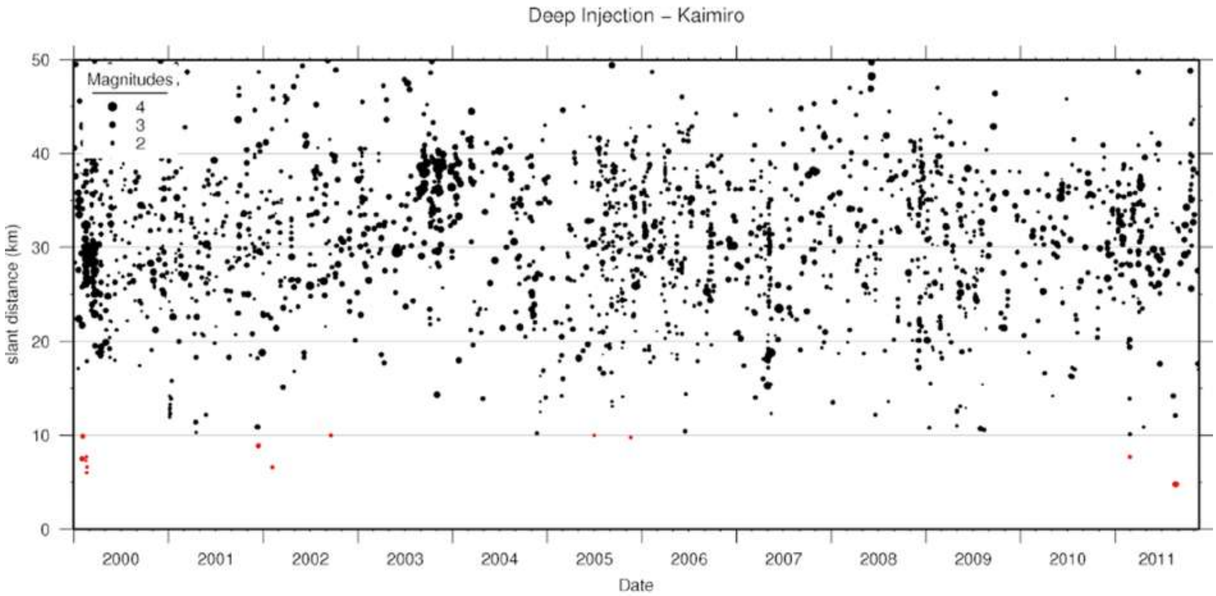
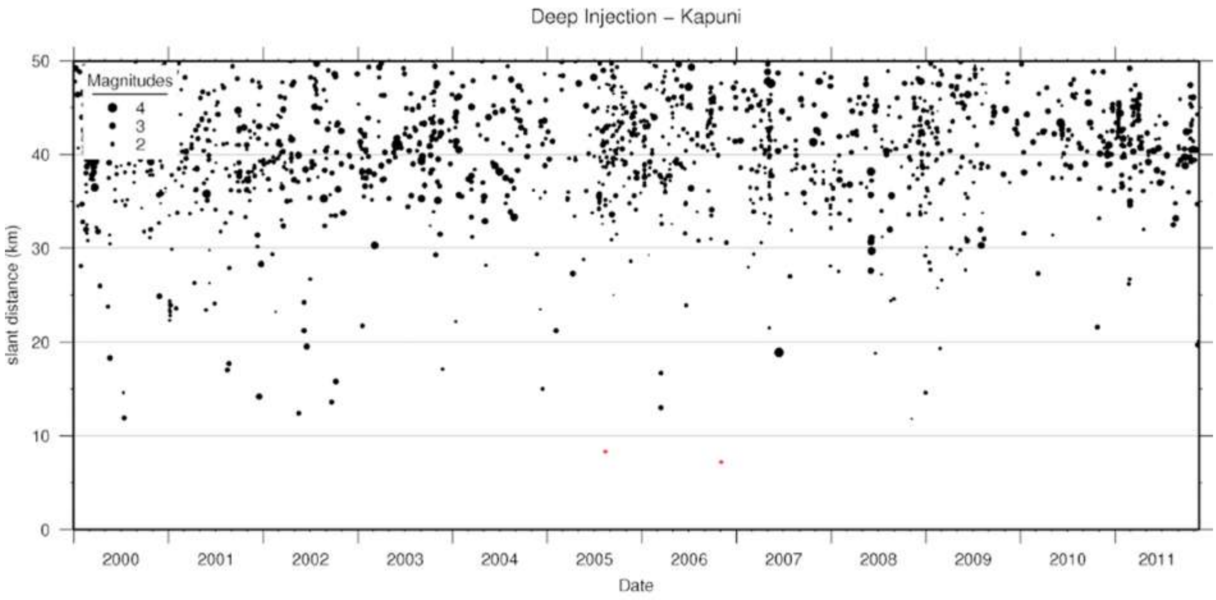
2009
2010
2011
Date

APPENDIX 3: COMPARISON BETWEEN DEEP INJECTION AND SEISMICITY

The distance of earthquakes from each of the reservoirs in which deep injection has taken place has been calculated. Earthquakes closer than a slant distance of 10 km are shown in red. The size of the symbol is proportional to earthquake magnitude.






Deep Injection – Kapuni
Magnitudes
4
3
2
slant distance (km)
50
40
30
20
10
0
2000
2001
2002
2003
2004
2005
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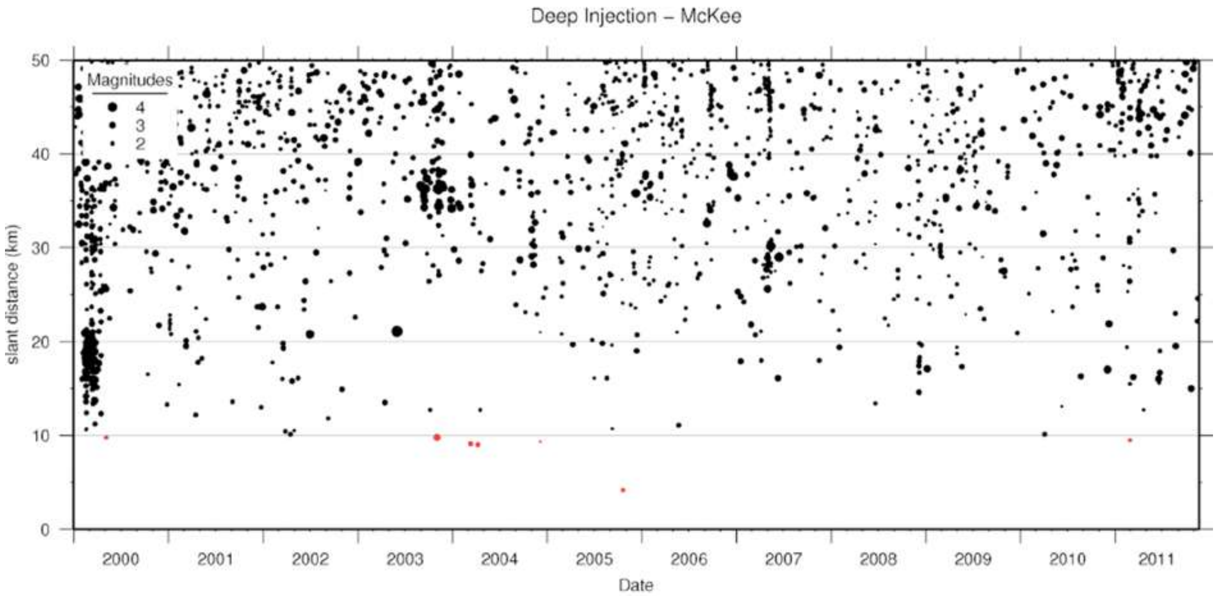
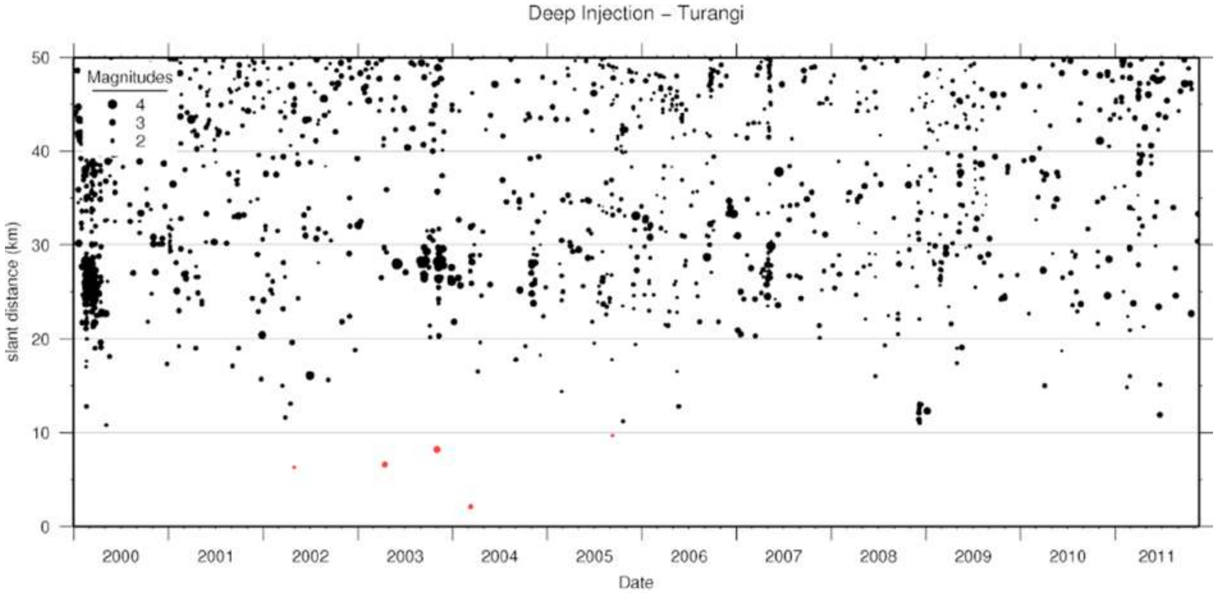
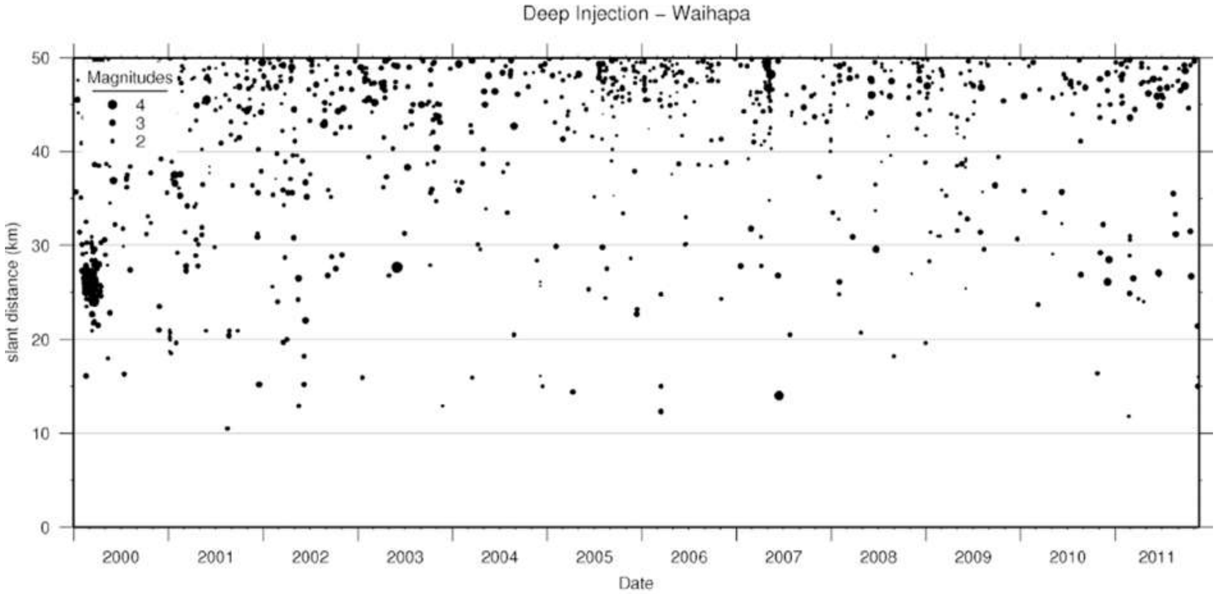
2007
2008
2009
2010
2011
Date


Deep Injection – McKee
Magnitudes
4
3
2
slant distance (km)
50
40
30
20
10
0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Date



Deep Injection – Turangi
Magnitudes
4
3
2
slant distance (km)
0
10
20
30
40
50
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Date



Deep Injection – Waihapa
Magnitudes
4
3
2
slant distance (km)
0
10
20
30
40
50
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Date