Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

New Zealand Geothermal Induced Seismicity: an overview

Steven Sherburn[1], Chris Bromley[1], Stephen Bannister[1], Steven Sewell[2], Sandra Bourguignon[1]

[1] GNS Science, Wairakei Research Centre, Bag 2000, Taupo 3352, New Zealand

[2] Mighty River Power Limited, 283 Vaughan Road, Rotorua 3010

s.sherburn@gns.cri.nz, c.bromley@gns.cri.nz

Keywords: induced seismicity, triggered micro-earthquakes, reinjection management, permeability enhancement

ABSTRACT

New Zealand's geothermal systems are mostly located in high-temperature, volcano-tectonic settings, but background levels of local natural microseismicity (micro-earthquakes) are quite variable. Triggered or induced seismicity effects from geothermal operations have also been very mixed. Understanding the reasons for these differences leads to better comprehension of the potential seismic risks and rewards (or opportunities) of different development options.

Large-scale NZ geothermal projects started in the late 1950's, but reinjection, the most commonly attributed cause of induced seismicity, only commenced in the mid 1980's (at Wairakei). Here, initial injection trials were relatively shallow (~1.3 km) and triggered some local low-magnitude microseismicity, at high effective stimulation pressure (~5 MPa). Other, low-pressure, reinjection projects soon followed, with subsequent changes in injection strategy (depth, location, in-situ temperature, pressure and flow-rate). They included: Ohaaki (1988, deep to shallow), Kawerau (1992, shallow to deep), Rotokawa (1997, shallow to deep), Ngawha (1998, deep), Mokai (2000, shallow to deep), and Ngatamariki (2013, deep). A wide range of induced seismicity responses has accompanied these injection strategies and this paper provides an overview of these experiences. The overall objective of much of this research is to illuminate probable mechanisms, identify zones of potential fracture permeability enhancement from microseismic locations, thereby provide information on probable reservoir boundary conditions for simulation models, and help provide possible mitigation options, if (and when) induced seismicity magnitudes and felt event rates exceed acceptable values.

At Ohaaki and Ngawha, natural seismicity rates are relatively low, and local induced seismicity (M>2) has not been detected, despite Ngawha's 100% peripheral injection to ~1 km depth and Ohaaki's 70% peripheral injection (<1km depth). At Kawerau, natural rates of seismicity are high (average 2 felt events/month), but there have been no obvious triggered events associated with production or injection changes, including an expansion and transition in 2008 from shallow (0.4 km) infield to mostly deep (2 km) peripheral injection. At Wairakei, Rotokawa, Ngatamariki and Mokai (adjacent systems), natural seismicity is moderate, but locally variable. Deep reinjection (increasing since 2006) has, in places, triggered moderate levels of microseismicity within inferred fault zones between injection and production sectors. The maximum magnitude recorded has been M_L 3.5 (local network magnitude 3.1), but most are well below M_L 2.5, and felt seismicity effects have not been an issue with the local rural inhabitants, who are familiar with similar-sized natural events. There is some evidence of cooling contraction increasing permeability with time, and microseismicity constrained by fault-controlled flow barriers.

Our conclusion is that, in New Zealand, where examples of induced seismicity have occurred, the favoured mechanism is associated with the indirect effects of increased fluid-flow on pre-stressed, pre-existing, fracture networks. This flow induces stresses from cooling contraction, and is driven by pressure gradients through the fracture network, but triggers seismic failure only on favourably-oriented fractures, through thermal, chemical, or pressure transients, or by associated micro-stress perturbations, locally unlocking asperities on pre-stressed fractures. We propose several conditions that increase the likelihood that an operating geothermal field will experience reinjection-driven induced seismicity.

1. INTRODUCTION

Induced seismicity in connection with utilization of geo-resources has become a popular subject in the international media in recent years, largely as a result of a notable increase in the rate of magnitude ≥ 3 events in the central USA over the past decade (Ellsworth, 2013). There is growing evidence that much of this seismicity may have been induced by disposal of waste fluid, particularly from oil and gas industries. While in New Zealand induced seismicity attributed to oil and gas industries has not been observed, including any associated with hydraulic fracturing (Sherburn and Quinn, 2012), public concern led the Parliamentary Commissioner of the Environment to produce a report on the subject (Parliamentary Commissioner, 2012).

Within the geothermal industry, induced seismicity associated with both conventional operations and with high pressure permeability stimulation operations (EGS) has been recognized for over 30 years; a brief summary, with examples, is found in Bromley and Mongillo (2008). Collaborative international research work has been undertaken recently under the auspices of working groups within the IPGT (International Partnership on Geothermal Technology) and IEA-GIA (Geothermal Implementing Agreement). Figure 1a from a recent IPGT (2014) white paper on induced seismicity illustrates the global extent and maximum magnitudes of documented examples from a variety of industrial activities, based on published data from 1930 to the present. Protocols to assist geothermal regulators to manage the issue of induced seismicity have also been developed through IEA-GIA collaboration (Majer et al, 2008) and a special issue focusing on the topic of EGS induced seismicity was published in 2014 by the journal *Geothermics.*

Different local communities view the issue of induced seismic hazard and potential nuisance effects in quite different ways. The potential risks and rewards, and the significance of perceived risk, are discussed, for example, in Bromley and Majer (2012). In order to keep the discussion of the potential effects of induced seismicity in geothermal systems at an objective and scientific level, rather than an emotional level, there is a continuing need, in our view, to document examples of operating geothermal systems, both with and without associated induced seismicity.

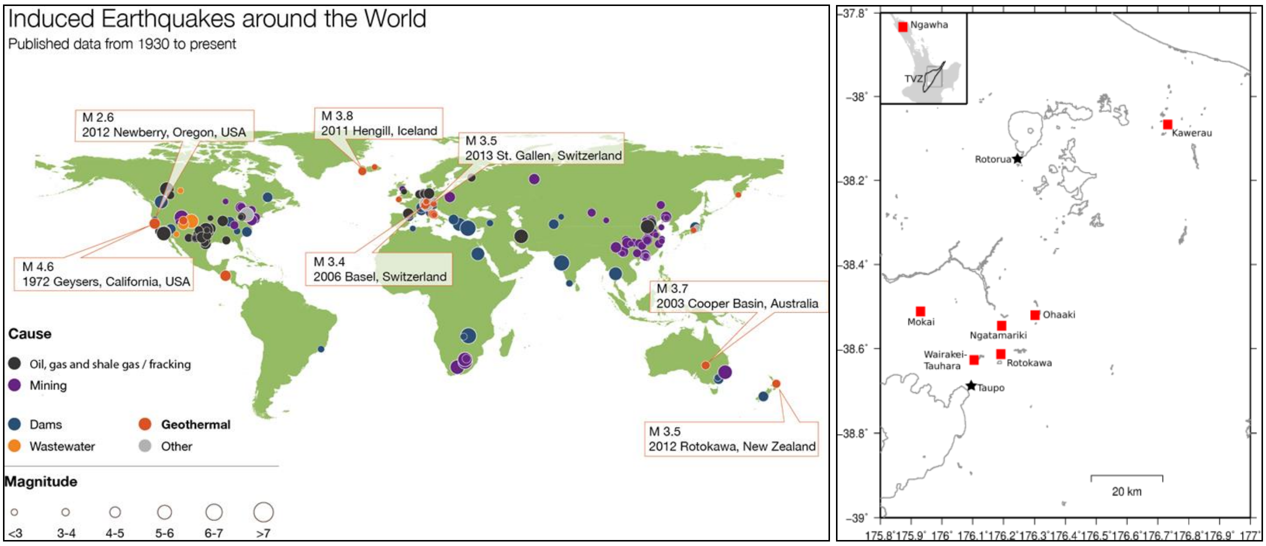

Figure 1: a) Global induced seismicity published cases – maximum sized events from various activities (from IPGT, 2014) b) Locations of developed geothermal fields in New Zealand discussed in this paper.

New Zealand's geothermal systems are mostly located in the high-temperature, volcano-tectonic setting of the Taupo Volcanic Zone (TVZ, Figure 1b). Ngawha, in Northland, is the only producing system outside the TVZ. While New Zealand, as a whole, is seismically very active, background levels of natural microseismicity (micro-earthquakes, or MEQ) at exploited geothermal systems are quite variable. Induced seismicity attributable to geothermal operations has been observed, or is inferred to have occurred, at some systems, but not at others, with a wide range of responses to production and reinjection strategies. Understanding the reasons for these differences leads to better comprehension of the potential seismic risks, and the benefits or opportunities of adopting different development options.

This paper represents the first attempt at a comprehensive overview of geothermal induced seismicity in New Zealand. Within New Zealand, the objective of geothermal microseismic research is largely to illuminate probable mechanisms, identify zones of potential fracture permeability enhancement from microseismic locations, and to help provide possible mitigation options, if (and when) induced seismicity magnitudes and felt event rates exceed acceptable values.

2. REINJECTION MANAGEMENT

The most commonly attributed cause of geothermal induced seismicity is reinjection (Bromley and Majer, 2012). Although large-scale New Zealand geothermal projects started in the late 1950's, reinjection did not commence until the mid-1980's, at Wairakei (Sherburn, 1984, Allis et al., 1985). For environmental reasons, reinjection is now mandatory at all fields, as a means of disposing of condensate and brine. It also provides potential improvement in long-term sustainable resource utilisation by sustaining pressures through fluid recharge, particularly where natural recharge is low. Consequently, most fields have at least some potential for induced seismicity related to injection management.

During their production history, the reinjection strategy used at most New Zealand fields has changed in: depths, locations, in-situ and injection temperatures, pressures and flow-rates. More recently-developed fields have benefited from earlier experiences. Injection at relatively shallow depth (~500m) was common as a starting strategy to minimize rapid reinjection fluid returns to deeper production aquifers (~1-3km depth). This was particularly successful where suitable aquifers could be found for injection that were of intermediate temperature and depth, and isolated by a low permeability aquitard from production depth aquifers. In some cases however, this starting strategy eventually lead to rising pressures at intermediate levels that started to have an impact on near surface aquifers causing increasing discharge from surface features. Most fields now adopt an adaptive injection strategy that relies mostly on deep reinjection, that is, at or below the depth from which production fluids are extracted. Fields where the reinjection depth has changed from shallow to deep include: Kawerau (1992 shallow to 2008 deep), Rotokawa (1997 shallow to 2006 deep), and Mokai (2000 shallow to 2008 deep). At Ohaaki reinjection changed from deep (1988) to shallow (1993) for reasons explained later. At Ngawha (from 1998) and Ngatamariki (from 2013), injection has thus far been deep.

3. MICROSEISMIC DATA AVAILABILITY

Microseismic networks are operated at five New Zealand geothermal fields: Wairakei-Tauhara, 10 sites from 2009, 13 since 2013 (Contact Energy); Kawerau, 5 sites from 2008, 10 since 2012 (Mighty River Power (MRP)); Rotokawa, 10 sites since 2008 (MRP); Ngatamariki, 10-12 sites since 2012 (MRP); and Mokai, 10 sites since 2013 (MRP). Analyses of data from these networks have been published for Wairakei-Tauhara (Sepulveda et al., 2013) and Rotokawa (Sewell et al., 2013, Sherburn et al., 2013). Data from the local networks at the other three fields are currently not public. For those fields, (Kawerau, Ngatamariki, and Mokai), the only publically available data are those acquired by a regional seismic network operated by the government-funded GeoNet project (www.geonet.org.nz). That network currently provides a capability to locate most microseismicity above about magnitude 2 at all fields except Ngawha (where it is higher [~2.4] because of local limits to the network coverage). Some smaller events are also located, depending on their depth and location relative to local seismographs, but this varies between fields. Based on analysis at Rotokawa, event locations determined by GeoNet are currently within ~1 km of those derived by local microseismic networks, although a lower level of accuracy applies before 2005, prior to upgrading the TVZ portion of the GeoNet regional network.

4. INDUCED SEISMICITY IN NEW ZEALAND FROM GEOTHERMAL FIELDS UNDER PRODUCTION

4.1 Ngawha

In 1998, a 10 MWe Ngawha binary power plant commenced operation, along with full reinjection. In 2008, it was expanded by a further 15 MW (~ 290 kg/s fluid production). Full reinjection of available fluid is undertaken at similar depths to production wells, ~0.7-1.5 km (Koorey, 2008). Despite full reinjection, a small amount of net mass loss (~2% non-condensable gas vented to the atmosphere), has resulted in a small pressure decline of a few bars over the first 6 years of operation. From 2008, supplementary injection of cold surface water into a deep well (NG2) was undertaken in order to make up for the small net mass loss, and thereby sustain pressures within the reservoir, in particular, beneath some culturally significant surface geothermal features, the Ngawha Springs. Reservoir temperatures are generally 230-250 ^{o}C although a maximum downhole temperature of 300 ^{o}C at greater depth (~2.2 km) has also been recorded (Koorey, 2008). The permeable reservoir is hosted in fractured greywacke basement. It is capped by an impermeable sequence of sediments, and may be underlain by a low-density silicic intrusive, potentially both a heat source and a mechanism for permeability enhancement during its emplacement. Steeply dipping NE-SW faults, with offsets of less than 100m, probably also transect the reservoir, but they are not considered to be active (Mongillo, 1985).

Natural seismicity rates are very low in the Ngawha area, and throughout the whole of the Northland Peninsula; the lowest of anywhere in New Zealand. The nearest seismograph is ~30 km away from the Ngawha field, and local seismicity (M>2) has not been detected. This is despite Ngawha's 100% in-field injection to ~1km depth, 14 years of fluid circulation through a fractured reservoir, and the thermal stresses inferred from 6 years of cold water injection into NG2. It is concluded, from this, that the natural state of stress at Ngawha is apparently insufficient to create the conditions necessary for induced seismicity. Small pressure, flow or temperature perturbations from field operation have failed to trigger failure on critically stressed fractures, and thereby produce seismicity of large enough magnitude to be detected by the GeoNet network.

4.2 Ohaaki

Ohaaki power plant (105 MWe of condensing turbines) was commissioned in 1988 with ~ 50 kt/d (578 kg/s) production, and reinjection of available brine and surplus condensate (~70% of the mass withdrawn; the rest vents through a cooling tower). Pressure drawdown has amounted to ~20 bars at ~0.5-1 km depth; an additional ~40 bars drawdown at ~1.5-3 km depth occurred after 2008 (Carey et al, 2012). The initial reinjection strategy was to use mostly edge-field deep injection but this changed within 5 years to mostly shallow outfield injection because of rapid returns of the deeply-reinjected fluids into production wells. This had caused adverse effects such as enthalpy decline. Production at Ohaaki has declined, and over the past 15 years it has varied between ~ 25 and 40 kt/d. In 2013, re-consenting allowed continued operation at a reduced maximum take of 40 kt/d (462 kg/s) for a further 35 years. The intermediate depth aquifer has cooled by an average of 10 degrees due to shallow groundwater incursion, creating some differential thermal stresses. After 2008, deeper production wells (up to 3 km depth) were drilled into a high-temperature permeable aquifer in the northwest sector of the field. This aquifer is partially isolated from the cooler intermediate aquifer, causing the observed further decline in deep pressures, and another potential source of differential stress.

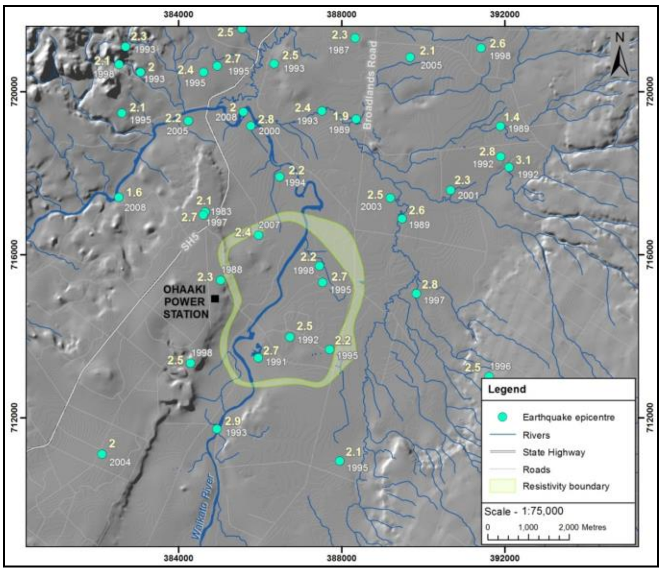

Figure 2: Ohaaki: all earthquakes located by GeoNet in the Ohaaki area between 1980 and 2011. The labels show the magnitude of the event and the year it occurred. Natural seismicity is low, and there is no evidence of induced events.

Natural seismicity rates in the vicinity of Ohaaki (Figure 2) are relatively low (Bryan et al, 1999). Four local seismic stations were operated at Ohaaki between July 1987 and November 1992, through the large pressure transients of pre-commissioning and early operation. Although some nearby seismicity was recorded, no detectable induced seismicity (M>2) was observed (Sherburn et al.

1993). There has been no increase in seismicity in or near the geothermal field throughout its history of development. Again, in the case of Ohaaki, it is concluded that the local state of stress in the bore-field area is insufficient to allow for triggered failure on faults by pressure, flow or temperature perturbations. We speculate that, in this case, the pressure drawdown at Ohaaki may actually have helped strengthen the fractures passing through the reservoir. Alternatively, this part of the TVZ crust may be accommodating tectonic stress build-up through ductile or creep deformation (Bromley, 2014).

4.3 Kawerau

Geothermal fluid production at Kawerau, for direct industrial use, commenced in 1957. By 2000, steam output had built-up steadily to about 320 t/h, or 45 MWe equivalent (Bloomer, 2011). In 2008, a 100 MWe power plant was installed by MRP. Partial infield reinjection started at shallow depth in 1992, but for the 2008 development a deep and peripheral (northeast) reinjection strategy was adopted (Siega et al, 2011). Natural state temperatures at ~2km depth ranged from 240 ^{o}C in the north to 320 ^{o}C in the south. Temperatures have cooled around the deep peripheral injection sector and at intermediate depth near a location of inferred local groundwater downflow. Production zone pressures initially declined by ~4 bars between 1957 and 1990 then further declined by ~4 bars between 2008 and 2013. Consequently, the Kawerau field may have experienced sufficient reservoir pressure and temperature changes over time to have generated stress perturbations and triggered seismicity on critically stressed fractures.

Natural rates of seismicity at Kawerau are relatively high compared to surrounding parts of the TVZ, with an average of two events felt per month. GeoNet data show a cloud of microseismicity about the field (Figure 3a). There are no obviously induced events, either in terms of locations with respect to wells, or temporal changes in rates of microseismicity associated with production or injection changes, including the expansion and transition in 2008 from shallow (0.4 km) infield to mostly deep (2 km) peripheral injection (Figure 3b). Natural swarm-style seismic activity is common, with a few events exceeding magnitude 3. A transect from northeast to southwest through the field shows events outside the field up to 12 km deep with those inside no deeper than 3 - 5 km. This may be due to shallow hot ductile conditions beneath the field. The b-slope for events since 1993 is also relatively high (b=1.5 for 1000 events of magnitude 2.2-3.2) compared, for example, to b=1 for 2000 events of magnitude 2-5, along a parallel zone of deeper seismicity located 15 km northwest of Kawerau. We speculate that the relatively high b-slope and shallow depths of the geothermal events are inter-related in that large contiguous fault planes (and therefore larger magnitude events) are under-represented in this setting. Also, the lack of clear identifying signatures for induced events may simply be a consequence of masking by the high level of natural seismicity.

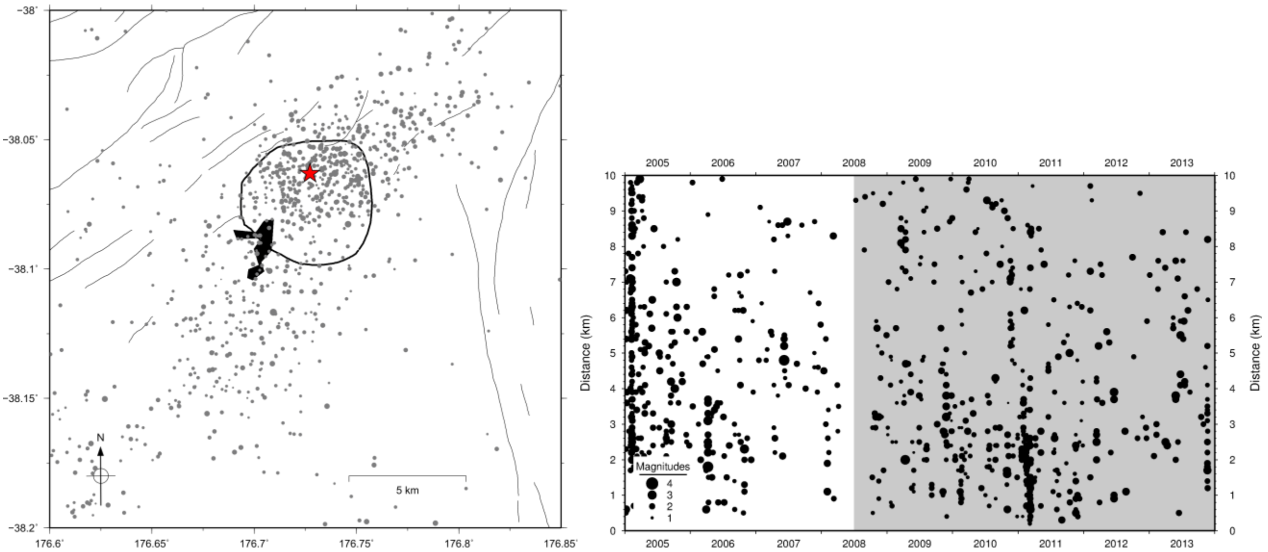

Figure 3: Kawerau: a) Epicentres (depth < 20 km) located by GeoNet (2005-13); scaled by magnitude. The black contour is the field boundary (Allis 1997); red star is the MRP power station; black shaded area is Kawerau township; b) timeline of events within 10 km radius of field centre; grey indicates MRP power station operation.

4.4 Wairakei-Tauhara

Wairakei field has been under large-scale production (c. 200 MWe) since 1958. With no reinjection, reservoir pressures across both Wairakei and the interconnected Tauhara fields dropped by 25 bars over the first 20 years and then stabilized. Cold water injection trials in 1984 into a permeable zone at ~1300 m initially triggered some local, low-magnitude microseismicity, though this was at high effective stimulation pressures of ~5 MPa (Sherburn 1984, Allis et al. 1985). This is probably the first case of geothermal induced seismicity in New Zealand. A subsequent, low-pressure, reinjection project followed at Wairakei in 1988-89 in which 5.2 Mt of water at 130 ^{o}C was injected into well WK62 at about 450 m depth in the Eastern Borefield (Hunt et al. 1990; Hunt et al. 2009). The well accepted the fluid under gravity, and therefore downhole pressure increases were minor. At the end of the test the fluid had accumulated around the well forming a temporary 50 m high cone of pressure increase in the deep liquid zone. Four seismic monitoring stations were operated during the test to supplement a single existing instrument. It is estimated that this network was able to locate all events of magnitude 1 or larger, within 5 km of the centre of the network. Induced seismicity, if any occurred, was not distinguishable from the background seismicity, which at Wairakei is at a relatively high level compared to Tauhara (Sherburn et al. 1990). Subsequent to the nil-result from reinjection testing in 1988-89, further limited seismic deployments accompanied later, short-term reinjection tests. This included the start of the first long-term reinjection in the 1990s in the Otupu area, and pressurized (25 bar, 90 °C) outfield injection tests during 2005 in the Aratiatia area, close to the Wairakei power station. None of these subsequent seismic studies showed any observable (M≥1.5) induced seismicity.

Over time, additional Wairakei-Tauhara power plants have been built: Poihipi (1997, 55 MWe, west Wairakei), Centennial Drive (2010, 22 MWe, central Tauhara) and Te Mihi (2013, 166 MWe, north-west Wairakei) and the total mass flowrate from the reservoir has increased to 245,000 t/d (2835 kg/s), of which ~50% is reinjected. Pressures in the liquid zone (below 700m depth) have been stable or slowly rising since 2005, throughout the southern Wairakei and Tauhara interconnected reservoir, as a result of increasing reinjection rates.

In 2009, a permanent seismic network began to be installed, and was completed in 2013 with 13 downhole instruments, including one at a depth of almost 1400 m (Sepulveda et al. 2013). In 2011, reinjection began in the South Karapiti area (Figure 4a), as well as the Owen-Delany Park area in the adjacent Tauhara field, close to Taupo. The results from the Wairakei network show a microseismic cloud that corresponds with the drawn-down Wairakei reservoir extent, as defined by the field hydrological boundary, along with significant numbers of events outside the boundary especially to the north-west and east. Relatively few events were recorded in the Tauhara field to the southeast despite similar pressure and temperature transients (Sepulveda et al., 2013). A WNW-ESE cross-section of located 2009-2012 Wairakei seismicity, using the dedicated local network, is reproduced in Figure 4b (from Sepulveda et al, 2013). Two features that stand out are the concentrations of events at shallow depths (1-2 km) within the main bore-field area, and a dipping trend at 4-6 km depth (‘Fault A’) that the authors interpreted as an expression of the ‘Te Mihi-Poihipi’ Fault, underlying a high-temperature fluid upflow zone at Te Mihi (north-west Wairakei). Significant numbers of events can also be seen at about 2.5 km depth beneath the deviated injection wells of the Otupu sector, near the original Wairakei Power Station, at the ESE end of the profile.

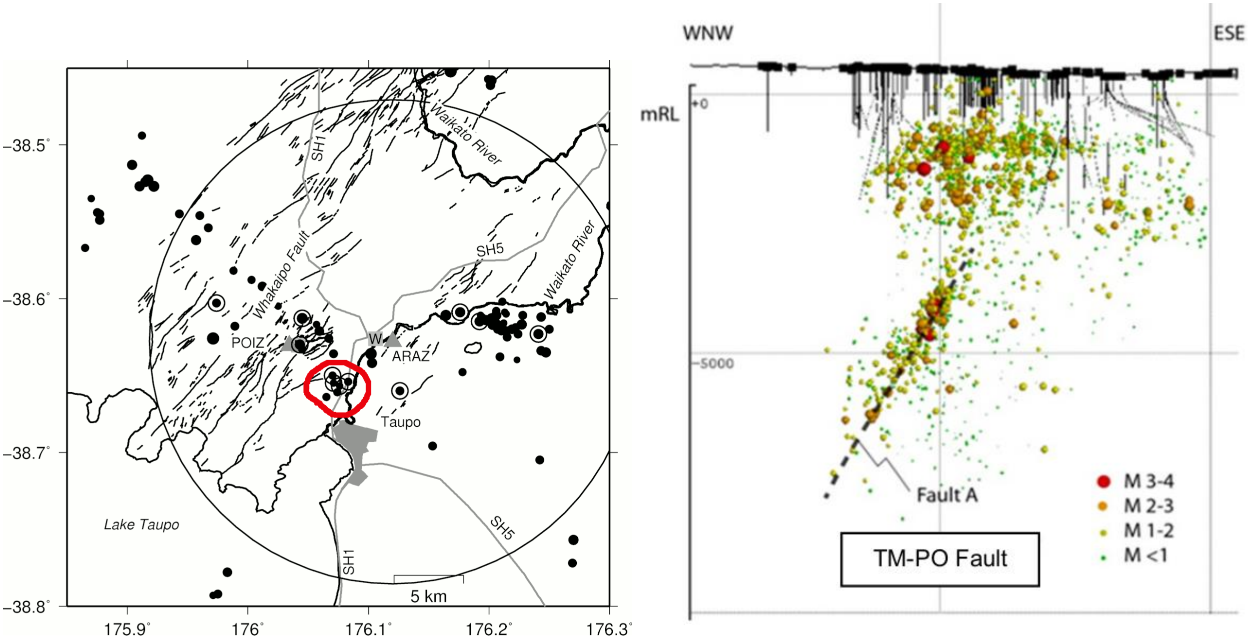

Figure 4: Wairakei-Tauhara: a) Microseismicity located by GeoNet in the Wairakei-Tauhara area in 2011. Events with an outer ring were felt. Triangles mark the Wairakei (ARAZ) and Poihipi (POIZ) monitoring sites. Active faults from the GNS database are also shown. Events near Karapiti South injection area are circled in red; b) Depth cross-section of located 2009-2012 Wairakei seismicity using dedicated local network (from Sepulveda et al, 2013).

Data from the public GeoNet network show a small cluster of microseismicity in August-September 2011, when reinjection in the Karapiti area started, and also in the same area in January-February 2012. A total of 12 events were located with magnitudes between 1.2 and 2.5. Several of the events were reported as felt. Assessing the seismic response of different production and reinjection strategies at Wairakei-Tauhara is made more difficult because the natural level of microseismicity at Wairakei-Tauhara before 1958 is unknown. However, there does appear to be a significant difference between Wairakei seismicity to the northwest, and Tauhara seismicity to the southeast, despite similar pressure histories, and this again is attributed to different natural stress conditions across the connected fields.

4.5 Ngatamariki

Power production at Ngatamariki began in 2013, with an 82 MWe binary plant and 100% reinjection (Clearwater et al, 2012). An assessment of local microseismicity made using GeoNet data in 2009 showed very few events within 5 km of the field over the preceding 9 years. The GeoNet network was not adequate to locate microseismicity at Ngatamariki accurately enough to comment on local activity before about 2000.

Subsequent to the start of power production, in April 2013, GeoNet had located a small cluster, less than 15 events, close to the southern boundary of the field where reinjection occurs (Figure 5). The largest event in this cluster had a magnitude of 2.7. Only four events have been located in the north of the field, the other reinjection area, the largest with a magnitude 1.8.

The small southern cluster lies close to several strands of the active Aratiatia Fault (GNS Science 2014). This microseismicity could conceivably represent natural activity associated with that fault zone, as there is some in the nearby Rotokawa field, but may also represent induced seismicity, possibly as a result of injected fluid entering the fault zone.

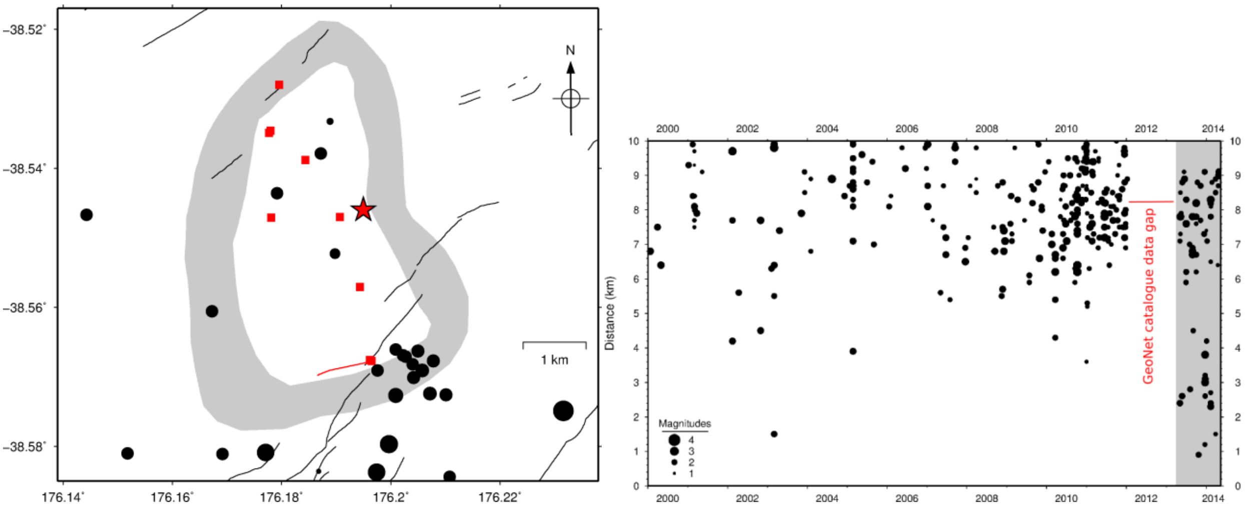

Figure 5: Ngatamariki: a) Epicentres (depth < 20 km) located by GeoNet (2000-14); scaled by magnitude. The grey zone is the field boundary (Boseley et al., 2010); red star is the power station; red squares are wells; red line a deviated reinjection well; black lines are active faults from the GNS database; b) timeline of events within 10 km radius of field centre; grey indicates production (>2013); possible induced events occurred near southern deep injection bore NM10 along active fault belt.

4.6 Mokai

Power production at Mokai began in 2000 and doubled in 2007 to 115 MW. Reinjection was initially shallow, to the northwest, while production was to the south. Following an increase in fluid flow to the surface affecting nearby natural features (O'Brien et al, 2013), deep reinjection to the north began in 2008. Pre-production natural seismicity was low, but substantial nearby swarms of activity (within 10 km) had occurred on several occasions.

Following the start of deep reinjection the GeoNet network began to locate persistent, but low level microseismicity at Mokai. These events were mostly in the central part of the field (between production and injection sectors), and the first persistent activity within that area for more than 10 years. The largest was magnitude 3.2, with eight events of magnitude ≥ 2.7. Several north-east trending faults, parallel to nearby active fault traces (Figure 6a) have been inferred from drilling results (Ramirez et al., 2009), although there is no clear evidence that these provide a strong control on fluid flow (Bignall et al., 2010). The presence of faults within the field means that post-2008 microseismicity might be of natural origin, but the timing of the start of the activity, coincident with the start of deep reinjection, suggests the events are more likely to be induced in some way by fluid flow between the injection and production sectors.

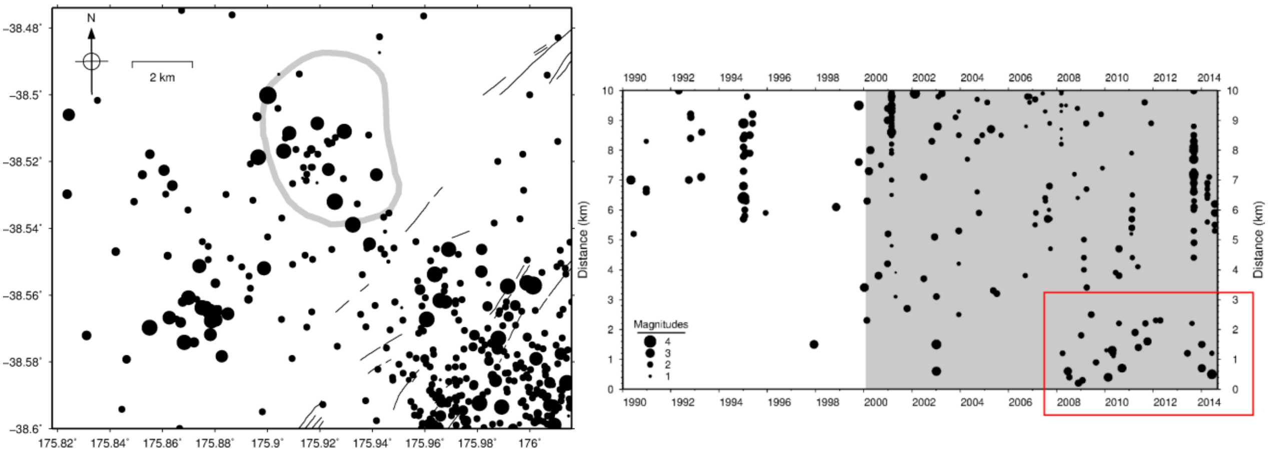

Figure 6: Mokai: a) Epicentres and relative magnitudes of GeoNet located events (depth < 20km, 2008-2014). Grey outline is field boundary (Bibby et al. 1984); lines show active faults; b) timeline of events within 10 km radius of field centre; grey indicates production (>2000); possible induced events in red box occurred after deep injection commenced (to the north) in 2008.

4.7 Rotokawa

Power production at Rotokawa began in 1997 at ~ 35 MWe ('ROT' in Figure 7a), and then increased significantly in 2010 by an additional 140 MWe ('NAP'). Pre-production natural seismicity did occur in the area, but only at a low to moderate level.

Reinjection was initially at shallow depth above the production reservoir. Since deep reinjection of condensate and brine began in 2005, Rotokawa has experienced persistent microseismicity (Bannister *et al*, 2008, Sewell *et al*., 2013, Sherburn *et al*., 2013).

Between mid-2008 and end-2012, more than 1000 events of magnitude ≥ 0.8, 50 of magnitude ≥ 2, and 2 of magnitude ≥ 3 (largest M3.1) were located in the field using data from a network operated by Mighty River Power. Over 70% of the microseismicity occurred in a sharply-bounded zone approximately 1 km^2 in area and 1.5 to 3 km deep located between reinjection and production zones (Figure 7a). A substantial increase in microseismicity rate was observed starting in early-2010 when NAP was commissioned (Figure 7c).

Microseismicity is thought to be induced mostly by stress triggers caused by cooling-driven reservoir contraction as the temperature of reinjected fluid is c. 200 ^oC lower than the reservoir temperature, and injection area pressure changes have been very small. The boundary of the main microseismicity zone closest to the production reservoir is controlled by a fault (Central Field Fault shown in Figure 7b) which acts as a partial barrier to lateral flow towards the pressure sink of the production zone. Larger events at Rotokawa can be felt in nearby Taupo, 15 km away, but have never caused any public concern.

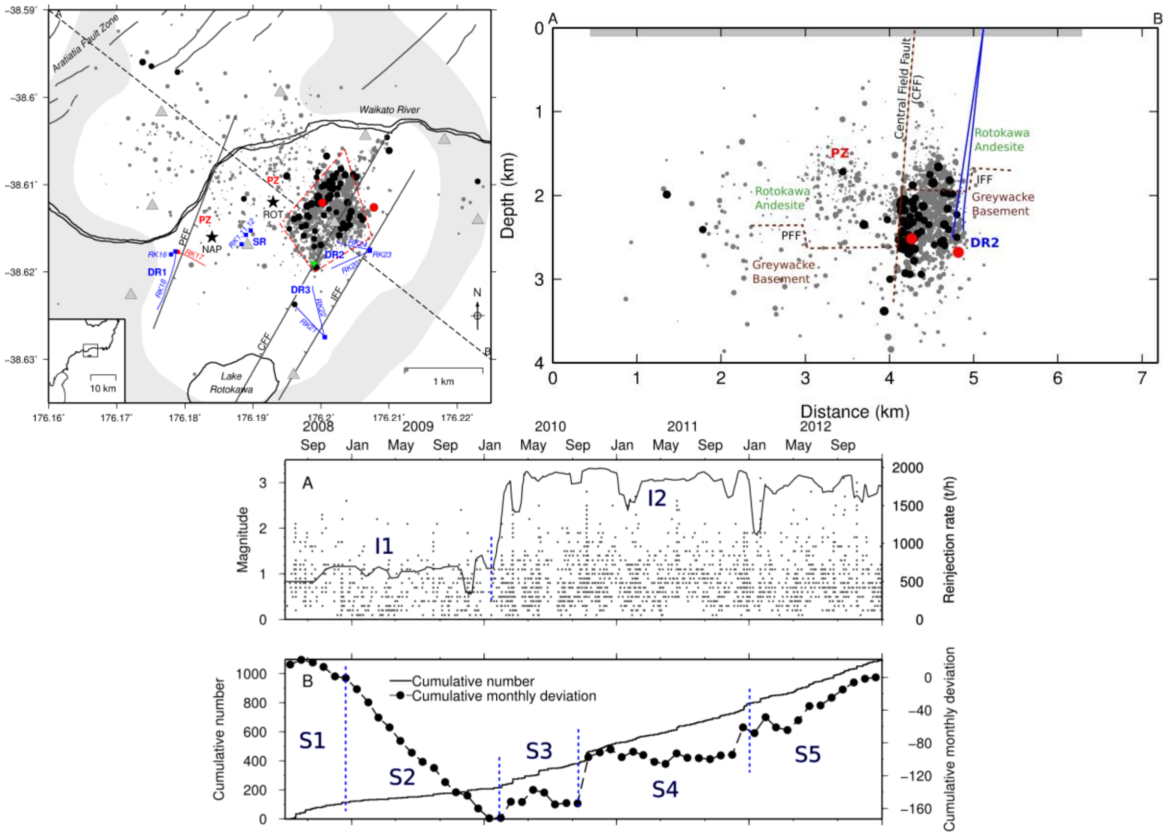

Figure 7: Rotokawa: a) Epicentres (black=M>2, red=M>3) from local network for July 2008 to December 2012, showing: active faults; resistivity boundary (grey, Risk, 2000); pz=production; SR=shallow reinjection, DR1-3= deep reinjection; blue lines=reinjection wells; ROT & NAP=power stations; grey triangles=seismographs; b) Cross-section A-B (marked on map) of geology and MEQ; c) Time-line from 2008 of MEQ and 30 day smoothed total injection rate (I2 marks period of different average injection rate after startup of NAP); d) cumulative event count and deviation from mean rate; S1 to S5 mark different periods of MEQ event rate.

4. DISCUSSION AND CONCLUSION

In New Zealand there are examples of producing geothermal fields both with and without induced seismicity. Our conclusion is that, where induced seismicity has occurred, the favoured mechanism is associated with the indirect effects of increased fluid-flow on pre-stressed, pre-existing, fracture networks. This flow is driven by pressure gradients through the fracture network and induces stresses from cooling contraction. The fluid flow triggers seismic failure only on favourably-oriented fractures, through thermal, chemical, or pressure transients, or by associated micro-stress perturbations. These transients locally unlock asperities on pre-stressed fractures. In several geothermal fields where levels of natural seismicity have been relatively low, and induced seismicity has not been observed, despite prolonged periods of pressure and temperature change, the most plausible explanation is that in-situ reservoir stress conditions at these locations are not close enough to critical. Reservoir fractures are not, therefore, actively poised for failure in the event of stress perturbations.

Sewell *et al.*, (2013) and Sepulveda *et al*., (2013) comment on the practical applications of the detailed microseismic information, from the point of view of a field operator, for Rotokawa and Wairakei, respectively. In general, the hypocenter locations have assisted in constraining the reservoir simulation models, in terms of : a) the probable locations of permeable upflows beneath the production aquifers, b) the probable depth of the brittle-ductile transition zone where permeability reduces due to high-temperature plastic deformation, and c) the probable locations of major faults that act to compartmentalize reservoirs, restricting cross-flow but assisting parallel flow.

Experience shows that automated routine location of micro-earthquakes in these fields is usually inadequate to extract the maximum information present in the data. At a minimum, subsequent relocation techniques that are capable of resolving the "fine structure" of hypocentre distributions, such as lineations associated with faults, is necessary. Bannister *et al.*, (2013) stress the usefulness of double-difference tomography for this purpose, particularly if sufficient data from a large network of closely spaced instruments is available.

With this small sample of six operating geothermal fields, we don't expect to be able to identify a unique set of conditions that will guarantee whether or not a field will experience reinjection-driven induced seismicity. However, based on our observations, we can note some qualitative conditions. Several of these are similar to those proposed by Davis and Frohlich (1993) for general reinjection-driven induced seismicity, but others are specific to geothermal systems.

Conditions likely to increase the probability of induced seismicity include:

1. Deep reinjection, below ~1.5 km.

2. Reinjection of fluids substantially cooler than the natural reservoir temperature (>100 ^{o}C temperature difference).

3. Reinjection at sufficient pressures or flowrates to increase pore fluid pressures over a large reservoir volume (>1 km^3)

4. Reinjection into a critically stressed area that has high levels of natural seismicity.

5. The presence of active faults and associated fractures that might readily slip with perturbations in the stress field or with changes in rock cohesive strength.

In conclusion, geothermal microseismic research in New Zealand is ongoing, and many questions remain. The objective of the research is largely to illuminate probable mechanisms and to identify zones of potential fracture permeability enhancement. Although levels and magnitudes of induced seismicity to date have not caused concern within local communities, ultimately, the objective would be to help provide avoidance and mitigation options, if, and when, felt event rates ever do exceed acceptable values.

REFERENCES

Allis, R.G., Currie, S.A., Leaver, J.D., and Sherburn, S.: Results of injection testing at Wairakei geothermal field, New Zealand. Geothermal Resources Council International Symposium on Geothermal Energy: International Volume, (1985), 289-294.

Allis, R.G.: The natural state and response to development of the Kawerau geothermal field, New Zealand. Geothermal Resource Council Transactions, 21, (1997), 3-10.

Bannister, S.C., Sherburn, S., Powell, T., and Bowyer, D.: Micro-earthquakes at the Rotokawa geothermal field, New Zealand. *Transactions* Geothermal Resources Council **32**, (2008), 259 – 263.

Bannister, S.C., Bourguignon, S., Sherburn, S., Bertrand, E.: Seismic imaging of the Central Taupo Volcanic Zone using double-difference tomography, *Proceeding*s, 35th New Zealand Geothermal Workshop, University of Auckland (2013), 6p.

Bibby, H.M., Dawson, G.B., Rayner, H.H., Stagpoole, V.M. and Graham, D.J., The structure of the Mokai geothermal field based on geophysical observations. J. Volcanol. Geotherm. Res., 20: (1984).1-20.

Bignall, G., Rae, A., and Rosenberg, M.: Rationale for targeting fault versus formation-hosted permeability in high-temperature geothermal systems of the Taupo Volcanic Zone, New Zealand. *Proceedings,* World Geothermal Congress (2010).

Bloomer, A.: Kawerau direct heat use: historical patterns and recent developments. *Proceeding*s, 33rd New Zealand Geothermal Workshop, University of Auckland (2011), 6p.

Boseley, C., Cumming, W., Urzúa-Monsalve, L., Powell, T., and Grant, M. : A Resource Conceptual Model for the Ngatamariki Geothermal Field Based on Recent Exploration Well Drilling and 3D MT Resistivity Imaging. *Proceedings,* World Geothermal Congress (2010).

Bromley, C.J. and Mongillo, M.A.: Geothermal energy from fractured reservoirs: dealing with induced seismicity. OPEN energy technology bulletin, **48**, Accessed: 15/5/14 from http://www.iea.org/impagr/cip/pdf/Issue48Geothermal.pdf (2008), 7p.

Bromley, C.J.; Majer, E.L.: Geothermal induced seismicity: risks and rewards. *Proceeding*s, 34th New Zealand Geothermal Workshop, University of Auckland (2012), 7p.

Bromley, C.J.: "Seismicity and Subsidence: Examples of Observed Geothermal Deformation Synergies from New Zealand", *Proceedings,* 38th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, Ca, (2014), 7p.

Bryan, C.J., Sherburn, S., Bibby, H.M., Bannister, S.C., and Hurst, A.W.: Shallow seismicity of the central Taupo Volcanic Zone, New Zealand: its distribution and nature. New Zealand Journal of Geology and Geophysics, 42(4), (1999), 533-542.

Carey, B., Rae, A., Alcaraz, S., Lewis, B., Soengkono, S., Reeves, R., Mroczek, E., Bromley, C., Bixley, P. : Ohaaki Geoscientific and Reservoir Engineering Review, GNS Science Consultancy Report 2011/273. (2012).

Clearwater, J., Burnell, J., Azwar, L. : Modeling the Ngatamariki Geothermal System. Proceedings, 37th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, Ca, (2012), 7p

Davis, S.D.; Frohlich, C. : Did (or will) fluid injection cause earthquakes? - criteria for a rational assessment. Seismological Research Letters 64, (1993), 207-224

Ellsworth, W. L.: Injection-Induced Earthquakes. Science (New York, N.Y.), 341, 142–149. doi:10.1785/gssrl.83.2.250 (2013).

GNS Science: http://www.gns.cri.nz/Home/Products/Databases/Active-Faults-Database-of-New-Zealand. Accessed 15/5/14 (2014).

Hunt, T.M., Bixley, P.F., Carey, B.S., McCabe, W.M., and Young, R.M.: Results of a 13-month reinjection test at Wairakei geothermal field, New Zealand. *Transactions*, Geothermal Resources Council, 14(2), (1990), 1193-1200.

Hunt, T.M., Bromley, C.J., Risk, G.F., Sherburn, S., and Soengkono, S.: Geophysical investigations of the Wairakei field. *Geothermics*, **38(1)**, (2009), 85-97.

IPGT: International Partnership for Geothermal Technology, Induced Seismicity: Recommendations for Research and Development : White Paper, draft under review, http://www.internationalgeothermal.org/, (2014).

Koorey, K.: Ngawha Geothermal Field expansion project, geothermal fluid conveyance system. *Proceedings* 30th New Zealand Geothermal Workshop, University of Auckland, (2008), 208-213.

Majer, E., Baria, R. and Stark, M.: Protocol for induced seismicity associated with enhanced geothermal systems. Report produced in Task D Annex I (9 April 2008), International Energy Agency - Geothermal Implementing Agreement. Accessed on 16/5/14 at: http://iea-gia.org/category/publications/annex-xi-publications/, (2008).

Mongillo, M. (ed.): The Ngawha Geothermal Field: New and updated scientific investigations, DSIR Report 8, (1985).

O'Brien, J., Le Brun, M., Addison, S. : Mokai Annual Report: April 2012 – March 2013, Mighty River Power annual report to Tuaropaki Power Company and Waikato Regional Council., (2013).

Parliamentary Commissioner of the Environment: Evaluating the environmental impacts of fracking in New Zealand: An interim report. Accessed, on 16/5/14, at http://www.pce.parliament.nz/assets/Uploads/Fracking-interim-web.pdf, (2012).

Ramirez, L.E., Rae, A.J., Bardsley, C., Bignall: Spatial variation of high temperature hydrothermal activity at Mokai geothermal field, Taupo Volcanic Zone, New Zealand. *GRC Transactions*, **33**, (2009), 855-857.

Risk, G.F., Electrical resistivity surveys of the Rotokawa Geothermal Field, New Zealand. *Proceedings,* 22nd New Zealand Geothermal Workshop, (2000). 121-126.

Sepulveda, F., Andrews, J., Alvarez, M., Montague, T., and Mannington, W.: Overview of deep structure using microseismicity at Wairakei. *Proceedings,* 35th New Zealand Geothermal Workshop, University of Auckland (2013).

Sewell, S.M., Cumming, W., Bardsley, C.J., Winick, J., Quinao, J., Wallis, I.C., Sherburn, S., Bourguignon, S. and Bannister, S.: Interpretation of micro-earthquakes at the Rotokawa geothermal Field, 2008-2012. *Proceedings,* 35th New Zealand Geothermal Workshop, University of Auckland, (2013), 8p.

Sherburn, S.: Seismic monitoring during a cold water injection experiment, Wairakei geothermal field. *Proceedings,* 6th New Zealand Geothermal Workshop, University of Auckland (1984), 129-133.

Sherburn, S., Allis, R., and Clotworthy, A.: Microseismic activity at Wairakei and Ohaaki Geothermal Fields. *Proceedings,* 12th New Zealand Geothermal Workshop, University of Auckland (1990), 51-55.

Sherburn, S., Clotworthy, A., and Hunt, T.M.: No induced seismic activity at Ohaaki Geothermal Field. *Proceedings,* 15th New Zealand Geothermal Workshop, University of Auckland (1993), 201-206.

Sherburn, S. and Quinn, R.: An assessment of the effects of hydraulic fracturing on seismicity in Taranaki. GNS Science Consultancy Report 2012/50. (2012), 28p.

Sherburn, S., Bourguignon, S., Bannister, S., Sewell, S., Cumming, W., Bardsley, C., Quinao, J., and Wallis, I.C.: Microseismicity at Rotokawa geothermal Field, 2008 to 2012. *Proceedings,* 35th New Zealand Geothermal Workshop, University of Auckland, (2013), 5p.

Siega, C., Siega, F., Pezaro, B., and Wallis, I.C., 2011, Kawerau Geothermal Limited (KGL) Annual Report: 2010 Calendar Year, Mighty River Power.