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Induced Seismicity - a Perspective on Monitoring, Mechanisms and Public Acceptability for Hydrothermal Systems

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ABSTRACT

Induced seismicity risk is a topic that has been addressed on numerous occasions since 2004 by collaborating countries within the IEA (International Energy Agency) Geothermal Technology Collaboration Programme (TCP) Working Groups (most recently under WG13, Task D). It remains an issue for geothermal projects, worldwide, particularly those involving deep EGS fracture stimulations, and those located near fragile buildings or in densely-populated regions where people are not used to natural earthquakes. The initial induced seismicity Working Group focus was on developing a protocol to assist developers and regulators, as well as providing a forum for research collaboration and information exchange. Efforts also focussed on establishing consistent data protocols, understanding mechanisms, and improving advanced forecasting methods. Such methods may use a modified traffic-light approach for adaptive response to observed levels of seismicity, by modifying injection and stimulation parameters. A further objective was to better understand, through collaborative modelling and data sharing, the key mechanisms behind induced seismicity that can sometimes accompany long term injection.

In conventional operating geothermal fields, typically hosted in fractured hydrothermal systems and in tectonically stressed regions, monitoring of micro-seismicity provides geothermal reservoir modelers and resource managers with improved information on geothermal reservoir behaviour and extent. This information complements other geophysical monitoring tools, enabling production and reinjection strategies to be fine-tuned to improve utilization sustainability. The knowledge gained can also help develop better strategies for resource expansion and for choosing targets for make-up drilling.

In the spirit of IEA-Geothermal collaboration, this paper shares examples of such reservoir management benefits from seismically active volcanic zones, including the Taupo Volcanic Zone of New Zealand. Numerous induced events have been documented, typically several per year in the magnitude range of 3 to 4. So far, there have been no cases of significant damage, and perhaps consequently, no public opposition to ongoing geothermal development. In New Zealand, all felt event information (above magnitude 2), whether induced or natural, are almost immediately available online (www.geonet.co.nz). This openness appears to provide the public with a sense of reassurance.

1. INTRODUCTION

Collaborative research through the International Energy Agency Geothermal Technology Collaboration Programme, IEA-Geothermal, into the topic of induced seismicity started in 2004 as a task in Annex 1, then switched to Annex 11, and in 2015 transferred to Task D under WG 13 (Weber et al, 2019). Participating countries with a strong interest in this topic are: Germany, France, Switzerland, Iceland, Japan, USA and New Zealand. The main topics of interest to collaborating researchers have been: seismicity observations, network design, processing improvements, triggers, mechanisms, models, seismic tomography, risk governance, policy and social impacts. The initial focus was on developing a protocol (Majer et al., 2007, 2012) to assist EGS developers and regulators, as well as providing a forum for research collaboration and information exchange. Through collaboration with IPGT (https://ipgtgeothermal.org/), efforts also concentrated on establishing consistent data protocols, understanding mechanisms, and improving advanced forecasting methods for EGS projects using a modified 'traffic-light' approach for adaptive response to observed levels of seismicity based on modifying injection and stimulation parameters (Trutnevyte & Wiemer, 2017). Further advances were described in a Geothermics Special Issue on the topic of Induced Seismicity published in 2014 (Zang, Majer & Bruhn, 2014). Aspects of the traffic light approach are ongoing (Mignan et al, 2017). Case studies have recently included: Pohang (Korea), The Geysers, Fenton Hill & Utah Frontier (USA), Espoo (Finland), Basel & St Gallen (Switzerland), Taupo Volcanic Zone (New Zealand), and Hellisheidi (Iceland). Although seismicity induced by EGS high-pressure stimulations has been the focus of most of the work during the past 15 years, a new research focus is emerging. The objective is to better understand, through collaborative modelling and data sharing, the key mechanisms behind induced seismicity that accompanies some long-term geothermal production-injection operations. This paper will focus mainly on the topic of induced seismicity from these conventional hydrothermal system operations.

Micro-seismic (MEQ) monitoring of operating geothermal fields has benefits other than hazard assessment. It complements other geophysical monitoring tools, such as micro-gravity, ground deformation, and repeat downhole surveys. Bromley (2018) discusses how together they provide geothermal reservoir modelers and resource managers with improved information on geothermal reservoir behavior. Operational scenarios (production and reinjection strategies) can then be fine-tuned to improve utilization sustainability. The knowledge gained can also help develop better strategies for resource expansion and help choose targets for make-up drilling.

The results of MEQ monitoring have helped improve simulation models of the behavior of geothermal reservoirs when fluids are extracted and injected. Physical changes to fluid and rock properties are induced by fluid pressure, temperature and flowrate changes. These can, in principle, be detected using methods such as MEQ velocity tomography and amplitude attenuation. Improved use of these geophysical tools assists understanding of the dynamic response of reservoirs to various levels of energy extraction, and various

production/injection strategies. This knowledge can be applied to exploration, expansion and make-up drilling strategies as well. The overall objective is to reduce the cost of drilling required to expand or sustain energy extraction, and thereby to improve the economics of future geothermal development. These benefits need to be weighed up against the risks of adverse effects of induced seismicity, such as damage to infrastructure, and potential loss of public acceptance. Bromley & Majer (2012) addressed the risks and rewards of geothermal induced seismicity. They argued for a balanced view of the risk of damage to surface infrastructure from larger induced events, versus the long-term benefits to a sustainable operation of the continuous stimulation of interconnected fractures, which enhances and expands reservoir permeability.

2. INDUCED SEISMICITY BENEFITS- 'WELCOME RELIEF AFTER ENJOYING A CRACKING GOOD STORY'

This review of MEQ benefits draws on examples selected from New Zealand, the Philippines, Indonesia, USA and Kenya. Table 1 provides a listing of some key parameters from selected producing geothermal reservoirs in these countries (modified from Bromley, 2018). The data are obtained from literature and approximated or extrapolated where necessary. Together, these examples represent approximately 30% of the worldwide installed capacity. This list illustrates the similarities and differences in the MEQ responses of a wide range of producing geothermal fields, each with its own unique development management plan in terms of the history of net mass extraction, production targets and reinjection strategies.

In the seismically active Taupo Volcanic Zone of New Zealand, there are five operating geothermal fields with a history of more than 10 years of micro-seismic monitoring using local network arrays (Table 1). Many induced events have been documented, with several per year in the magnitude range of 3 to 4, but there have been no cases of significant damage. There has been no consequential public opposition to ongoing geothermal development. Information on all felt events (above magnitude 2), whether induced or natural, is immediately accessible through a website (www.geonet.org.nz). Such openness appears to engender public reassurance. New Zealand case studies are discussed in more detail in section 4.

Table 1. Operational parameters and micro-seismic (MEQ) data from selected geothermal fields (approximations extrapolated from literature). MWe installed + heat supplied PJ/yr; *= binary plant; typical MEQ/month above a threshold magnitude; maximum magnitude, and maximum depth range across sectors; accumulated net mass loss of fluid in Mtonnes (production-injection); and **accumulated maximum pressure change (-ve decline or +ve increase) in reservoir sectors, at various stages in development history.

Geothermal Field	MWe (+PJ/yr)	Operation yrs	MEQ /month	MEQ max mag.	MEQ max depth km	Massloss ~Mt net	Pressure change ~MPa **
Wairakei	390+1.5PJ	61	~20	3.2	3 - 7	2500	-2 -2.5 +.3
Rotokawa	175	22	~100	4.1	3 - 5	50	-4
Mokai *	115+0.3PJ	19	~50	3.3	3	0.4	-1.5 -3.5
Kawerau	170 +6PJ	61	~20	3.2	5	500	-1
Ngatamariki *	82	6	~180	3.2	2.5 - 3	0.1	0.2
Ngawha *	25	21	0	NA	NA	0.2	-0.2
Ohaaki	58+0.1PJ	30	0	NA	NA	200	-2.5 -3.5 +1
MacBan	400	37	~75	2.9	3 - 5	750	-4.5 -5.5
Tiwi	200	40	~80	2.9	4	900	-5.5 -6.2 +1.5
Palinpinon	200	36	~400	2	3 - 5	270	-6
Olkaria	670	38	~200	2.5	3.5 - 6.5	200	-1.2
Salak	375	25	~80	3.6	4.5	500	-6.8
Darajat	260	25	~10	3.4	3.5 - 5	200	-1.6

The pressure changes in these geothermal reservoirs resulting from accumulated net mass loss of several hundred mega-tonnes are within the range of -1 to -7 MPa. Pressure increases in injection sectors are much less, sometimes up to + 1.5 MPa. Therefore, excessive pore pressure (a recognized mechanism for MEQ triggering during EGS fracture stimulation) is not a significant mechanism for induced seismicity in these operating fields. Large numbers of seismic events are triggered over decades of operational history, but the maximum magnitude is typically constrained to the range of 2 to 4, and the maximum depth extent (within the geothermal field) is typically in the 3-5 km range, with some examples extending up to 7 km.

An example from Olkaria (Kenya), by Simiyu (2000), provides early evidence of the application of MEQ monitoring data and interpreted seismic velocity structure to characterize the large Olkaria geothermal reservoir, which has multiple fluid upflows. Stress along the floor of the Kenyan rift zone is associated with MEQ activity in geothermal areas, while larger earthquakes occur along the rift boundary faults. Within the Greater Olkaria region (central rift), cross-sections of hypocenters show localized clustering and several up-doming regions of ductile (aseismic) rock which are correlated with high-temperature at depth. The brittle-ductile transition in these regions ranges from about 3.8 km to 6.5 km depth, and the anomalies are inferred to be related to magmatic (intrusive) heat sources from about 6 km depth beneath the known Olkaria reservoirs. Anisotropy in the stress and heat source orientation is inferred from Poisson's ratio distribution versus azimuth and depth. Low Vp/Vs anomalies in several production zones are interpreted to be due to exploitation-induced phase changes caused by: a) pressure drop and boiling, b) high steam saturation, c) high crack density, d) high CO_2 gas or e) very high temperature (or some combination of these).

A study from the Darajat field in Indonesia (Nelson et al, 2018) provided further evidence of how the use of MEQ induced by fluid injection has helped with reservoir characterization and ongoing reservoir management. Improvements in permeability of injection and production wells has helped keep the overall costs down, reduced the need for make-up wells, and reduced the number of wells

required per unit of electricity production. Keeping track of changes in fluid flow through the reservoir is also important because of the potential for fast-tracking of injected fluid under induced horizontal pressure gradients back to production wells, causing cooling and premature enthalpy decline. If the network of inter-connected fractures is enhanced over time by widely distributed MEQ, rather than a single fault plane, then resource sustainability is improved because of the larger water-rock, heat-exchanger interface.

3. TOMOGRAPHY

Locating permeable fracture zones or faults that are seismically active is an important objective for geothermal exploration and assists in selecting well targets. Imaging of seismic properties (velocities and attenuation) can provide information on the physical properties of rocks and fluids within and adjacent to geothermal reservoirs. Micro-seismic (MEQ) monitoring has long been undertaken, particularly for environmental reasons, at geothermal development sites. Initially, hypocenter distribution maps were used as preliminary indicators of fault-related permeability, especially in resources that are associated with regions of anomalous tectonic or volcanic stress (e.g. above young intrusions, or within extensional basins). Early on it was recognized, however, that not all geothermal resources host natural seismicity, so the passive MEQ monitoring method went out of favor as an exploration method. Subsequently, however, with better-quality 3-component digital data, the ability to invert such data to produce seismic velocity (Vp, Vs, Vp/Vs,), and amplitude attenuation (Qp, Qs) tomography, as well as indications of stress direction, and fracture anisotropy (from fault-plane solutions or moment tensors) has rejuvenated interest (e.g. Bannister et al, 2015, Tezel et al, 2016). Seismic reflection imaging using MEQ as a source has also been proposed (Asanuma et al, 2011). Temporal variations in Vp/Vs ratio correlating with injection volume at The Geysers were described by Gritto & Jarpe (2014). [Vp/Vs increases are caused by water saturation increases]. Some studies (eg. Fang et al, 2018) link induced seismicity to changes in reservoir permeability by assuming simple shear dilation. Complications (not yet adequately modelled) include the probable occurrence of clay gouge causing permeability to decrease on faults, also long-term shear-slip and aseismic deformation induced by thermal contraction as cooler fluids pass through the fractures.

At the Geysers field in California (USA) many reservoir studies using seismic monitoring techniques have been published using well-located events (approximately 1000 events per year of M 1.5 to 4.6). Several studies have linked rates of induced seismicity to rates of steam extraction and water injection. Tezel et al (2016) discusses the use of seismic tomography images as a monitoring tool through time (4D). Lin & Wu (2018) present a comprehensive study of seismic velocity structure at The Geysers which shows that Vp is mainly influenced by rock composition, while Vp/Vs anomalies are correlated with fluid content; low Vp/Vs values map the extent of the vapour-dominated geothermal reservoir. A change in the mix of focal mechanisms (more reverse type, relative to the common normal and strike-slip types) between 2008 and 2012 was tentatively linked to a period of deep injection stimulation in Northwest Geysers, causing local cooling and volumetric contraction.

In a similar study, Mhana et al (2018) describe seismic tomography (TOMO4D) as a tool to track reservoir changes at Coso Geothermal Field (USA). Warren et al (2018) also discuss the use of passive seismic tomography constrained by active seismic and resistivity data to map permeability. Although modellers generally agree that seismic tomography can be a useful tool, we are reminded by Tezel et al (2016) that an assessment of uncertainties caused by imperfect ray-path geometries should always be done when undertaking a joint inversion for locations and seismic velocities; convergence to best-fit models from different starting models does not always lead to consistent patterns of velocity anomalies.

4. MECHANISMS

Understanding of the triggering mechanisms (cause and effect) of induced seismicity in hydrothermal systems has been the subject of much research effort for many years (e.g. Allis, 1982, Martínez-Garzón et al., 2017). The key mechanisms proposed initially by Allis (1982) and summarized in Bromley & Majer (2012) remain as follows: a) increased pore pressure that decreases normal stress on existing fracture surfaces, allowing critically stressed faults to slip; b) redistribution of thermal stress induced by injection of cooler water into hot rock; and c) redistribution of volumetric contraction stress induced by pressure decline. Hence any pressure transient, small or large, and any change in temperature from injection flow-rate changes, has the potential to be a seismic trigger. The natural state condition in the reservoir of numerous critically-stressed fractures, oriented across a wide range of angles with respect to the variable stress transients, allows for the stimulation of persistent ‘clusters’ or ‘swarms’ of earthquakes through dispersion of these stress transients. The first triggered seismic event can sometimes be correlated with operational changes in well flowrate, but diffusion effects of both pressure and temperature changes can create significant delays. Cause and effect are not then so obvious. Sepulveda et al. (2016) observes that deep (> 4km) and shallow (~2 km) seismicity at Wairakei occur together in coincident time-clusters, implying that ‘self-triggering’ acts across large volumes of rock. In most cases, stress redistribution following one event will trigger others, rather than a specific production-induced or injection-induced pressure/temperature transient.

Simulation models of the transient, seismic-triggering processes have been attempted. Rinaldi & Nespoli (2017) discussed a modelling approach that linked reservoir simulation (TOUGH2) with a mechanical and stochastic approach to model injection-induced seismicity. Rivera & Dempsey (2017) also coupled TOUGH2 to an earthquake simulator to model the evolution of fracture permeability in geothermal reservoirs over time. Newman and Petrov (2018) discuss seismic source mechanism estimation assuming an elastic 3D media. De Simone et al (2017) address the mechanisms for post-injection seismicity (events triggered after stopping injection). They superpose the thermal effects due to cooling and stress redistribution due to fault slip, with the direct hydraulic pressure effect of injection stimulation. The resulting combination of anisotropic and heterogeneous stress tensor variations tend to stabilize some fracture orientations but destabilize others. As fluid pressures decay following injection shut-off, the combination of these stress rotations, and the difference in timing of hydraulic and thermic effects, allows some previously stable fracture planes to become destabilized and therefore to slip.

In 2-phase reservoirs, the effects of thermal stress transients are further complicated by the dual mechanisms of advective cooling from injected fluid (in a liquid state) and thermo-elastic stress from evaporative cooling of boiling pore fluid (in a 2-phase state). Furthermore, some pressure triggers (i.e. a tremor source, analogous to water-hammer) might be instigated by 2-phase slug flow occurring along parts of the permeable fractures linking injection and production sectors.

Models have also been developed and applied to make better use of the passive seismic data by inverting for seismic rock properties. Mhana et al. (2018) demonstrated some of the benefits of using TOMO4D by describing the effects upon Vp, Vs and Vp/Vs of processes that occur in geothermal areas. The dominant effect on Vp is an increase from greater water saturation (or decrease from more steam saturation, i.e. boiling). The dominant effects on Vs are an increase from decreasing temperature or pore pressure and dehydration of minerals; a decease occurs from increasing pressure and more fracturing. Finally, the dominant effects on Vp/Vs are as follows: a decrease from mineral dehydration, pore pressure decrease, temperature decrease, and boiling (higher steam saturation); an increase from water saturation, pressure increase and fracturing. The combined effect of these various processes can be quite difficult to untangle.

5. NEW ZEALAND CASE STUDIES

A description of the induced and natural seismicity that occurs within and adjacent to many of the operating geothermal fields in New Zealand is provided in Sherburn et al (2015). Seismic tomography and hypocenter distribution from the numerous events recorded at Rotokawa, Ngatamariki, Wairakei, Mokai and Kawerau fields have been used to draw conclusions regarding the permeability structure of these fields (Sepulveda et al, 2016, Sewell et al, 2017, Bromley et al, 2018, Hopp et al, 2019). Figure 1 shows these geothermal fields alongside a google-earth image of 385 earthquake locations, 1999-2019, of magnitude M > 3, depth <12 km.

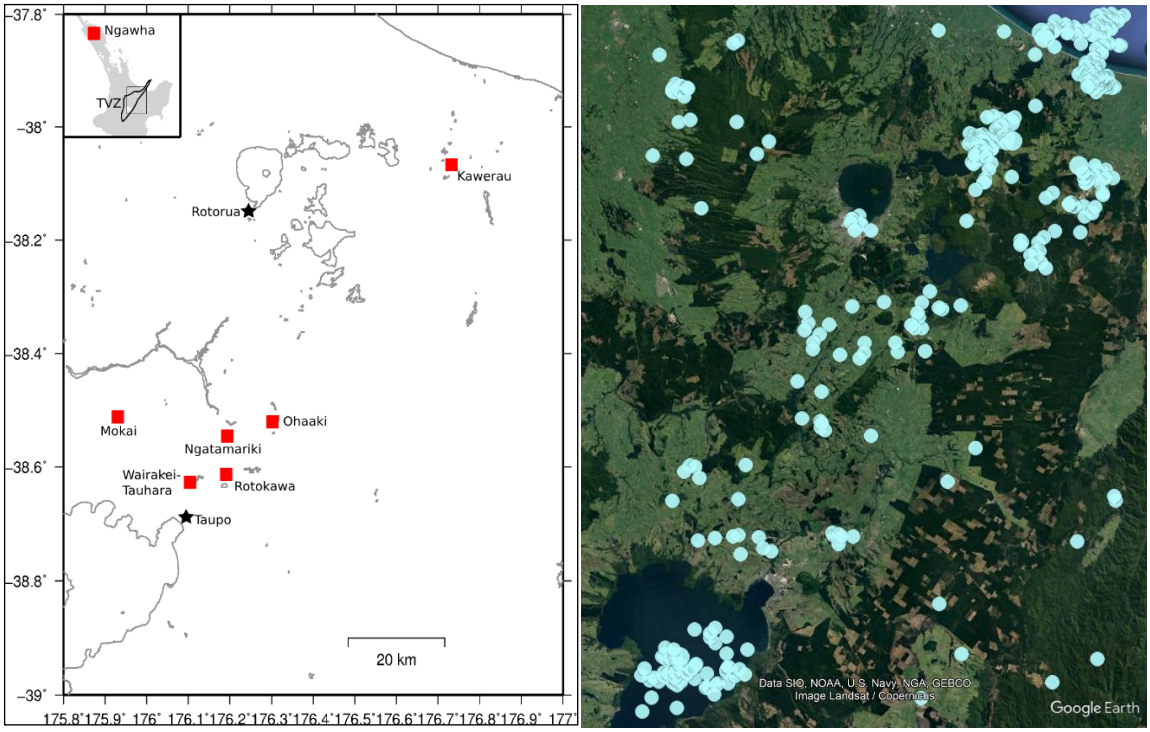

Figure 1. (a) Locations of developed TVZ (New Zealand) geothermal fields discussed in this paper. (b) Same area, 385 earthquake locations (1999-2019) of M>3 and depth <12 km, downloaded July 2019 from www.geonet.org.nz.

Figure 1 (b) shows that clustered natural seismicity of tectonic origin is prolific in the Taupo Volcanic Zone (TVZ), but an observation from the New Zealand examples listed in Table 1 is that most producing geothermal fields also exhibit some induced seismicity. There are, however, two exceptions: Ohaaki and Ngawha. In the case of Ngawha, a suggested explanation for the absence of seismic events (M>1.5) is that the natural state of stress is relatively low (i.e. the field is located outside the tectonically active region, with negligible natural seismicity), and the net mass loss and pressure drop has also been very low (i.e. a relatively small binary plant operation with full infield reinjection at ~1km depth). In the case of Ohaaki (located within the tectonically active TVZ), the explanation is not so clear. Possibly, the natural stress state is locally sub-critical (deformation may be locally accommodated through ductile or creep processes) and the pressure and temperature transients from production have been insufficient to trigger induced seismicity. Reinjection is partial (~50%) and mostly outfield and shallow (~0.4 km depth) to minimize the adverse cooling effects of reinjection returns. Note, also, that Ohaaki is the only New Zealand field where well productivity has not been sufficient to sustain the initial (1989) installed turbine capacity of 114 MWe (current running capacity has been reduced by about 60%). Despite significant reservoir pressure decline, deep hot fluid recharge is limited, and this may be related to poor recharge permeability indicated by the local absence of natural or induced seismicity.

Most other producing TVZ fields exhibit ongoing induced seismicity. However, in the case of Kawerau geothermal field (Sherburn et al, 2015, Bromley, 2014), the presence of significant natural seismicity throughout the local surrounding area (averaging 2 felt events per month, Figure 1 (b)), and the absence of correlations in timing or location between operational changes (injection and production wells) and recorded seismicity within the field boundaries, makes it difficult to identify causes, and equally difficult to differentiate induced from natural events. Consequently, the operators (Mercury) decided to remove their local geothermal seismic station network in 2016. Larger local events (M>1.5) are still documented by the nation-wide Geonet network and made publicly accessible. It was noted by Clark et al (2009) that earthquakes located within the Kawerau geothermal field are aligned along northeast trending lineaments consistent with the predominant alignment of surface-mapped faults.

Typically, the remaining New Zealand operating fields (Wairakei, Mokai, Rotokawa, Ngatamariki) contain induced seismic events that cluster in both time and space. Event clusters are associated with both production and reinjection sectors, and the flow channels linking them. That is, they are apparently triggered by both positive and negative pressure transients and injection cooling, as well as the redistributed stress transients from shear failure or aseismic slip. The dominant mechanisms appear to be linked to fluid flow through fracture networks. Maximum magnitudes are typically in the range of 2 to 4 (i.e. felt, but not damaging, earthquakes). The depth range is typically 3 to 5 km, with one example (Wairakei) reaching depths of about 7 km. The maximum depth is inferred to indicate a transition to ductile deformation, and probable supercritical temperatures (>400 ºC) (Bromley et al, 2020). The permeability is assumed to be constrained because of the absence of brittle failure. This information is sometimes used to establish the bottom boundary in reservoir simulation models. Hence it is an important parameter for estimating sustainable reservoir capacity.

5.1 Wairakei Geothermal Field example

Over 50 years of seismicity has been observed at and near Wairakei. Three local seismic stations are part of the nation-wide GEONET network that is designed to detect relatively large seismic events (nominally M>1.5). Operators, Contact Energy, commissioned a local seismic network in 2009 (WSN). The WSN uses 13 downhole seismometers installed at depths ranging from 65 m to 1,100 m (Sepulveda et al, 2016). The downhole instrumentation has led to improved sensitivity. Magnitude of Completeness (Mc) of the WSN has been estimated at Mc = 0.2 (Bromley et al, 2018).

Both near-injection and near-production seismic activity has been detected by the WSN and this activity tends to define patterns which are described below and shown in Figure 2. MEQ hypocenter distribution at Wairakei can be broadly grouped into shallow (<4 km) and deep (4-7.5 km) events. Shallow MEQs are confined to within the shallow resistivity boundary and deep MEQs are preferentially offset to the north-west (Sepulveda et al, 2016). The distinction between shallow and deep seismicity is illustrated in Figure 3.

Near-injection activity: a) Otupo seismicity sometimes occurs around injection wells and sometimes in linear clusters (ENE-WSW strike); b) Karapiti seismicity tends to distribute more diffusely, clustering preferentially E-W along the fluid flow-path north of Karapiti injection wells; c) Te Huka seismicity tends to cluster broadly in a NW-SE direction to the NW of Te Huka injection wells. Note that this seismic area overlaps to some extent the eastern side of Karapiti, and reservoir modelers have recently used this information to modify the local permeability structure. This improved the history match to measured pressure and temperature changes. Specifically, Karapiti injection is helping to raise the pressures in the Te Huka sector.

Near-production activity: Poihipi-WBF seismicity. This activity tends to distribute linearly (NE-SW strike) between Western Bore-Field (WBF) in the NE and Poihipi power station in the SW. Overall, this constitutes the most seismically active area of Wairakei.

Regardless of the specific physical mechanism triggering the induced seismicity (pressure changes, thermal stress, etc.), shallow MEQs tend to cluster at some distance from wells, pointing to geological structure and fluid flow as important factors controlling their locations. This has been relevant to a review of the connectivity between Karapiti and Te Huka injection sectors. The seismic activity at depth in this part of the field suggested greater permeable connection in the numerical model than previously captured. The adjustment of deep permeability in this area of the model has helped to improve pressure matching in the numerical model which is important when considering long term reservoir changes in response to production and injection.

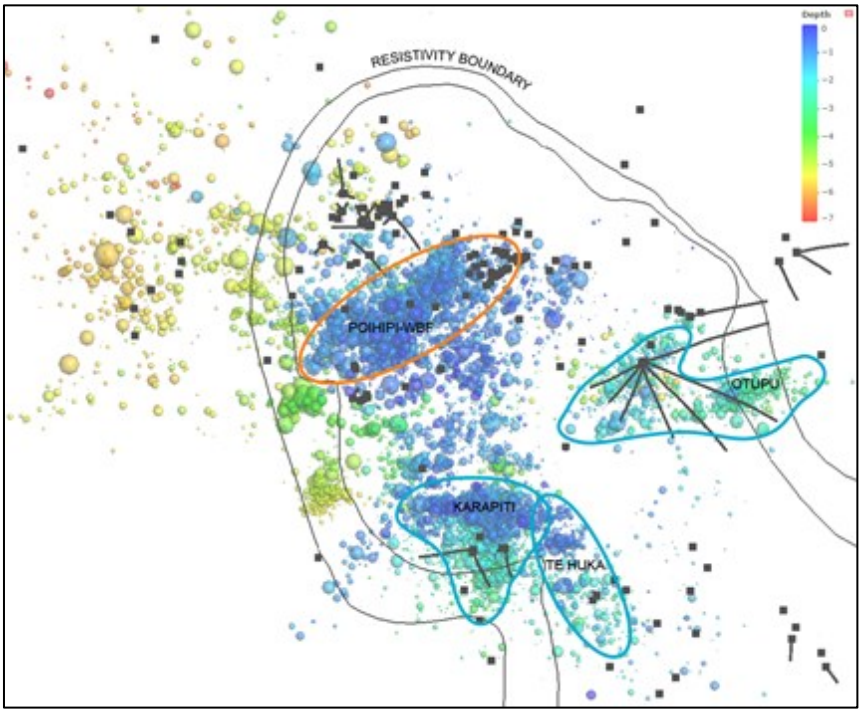

Figure 2. Wairakei seismicity map (period 2009-2017, Bromley et al, 2018) showing clustered seismicity using clustering algorithm of Sepulveda et al (2016). Size of dot is proportional to magnitude; color is proportional to depth; black dots are wells and black lines are deviated well tracks. Map extent is 9 km by 11 km.

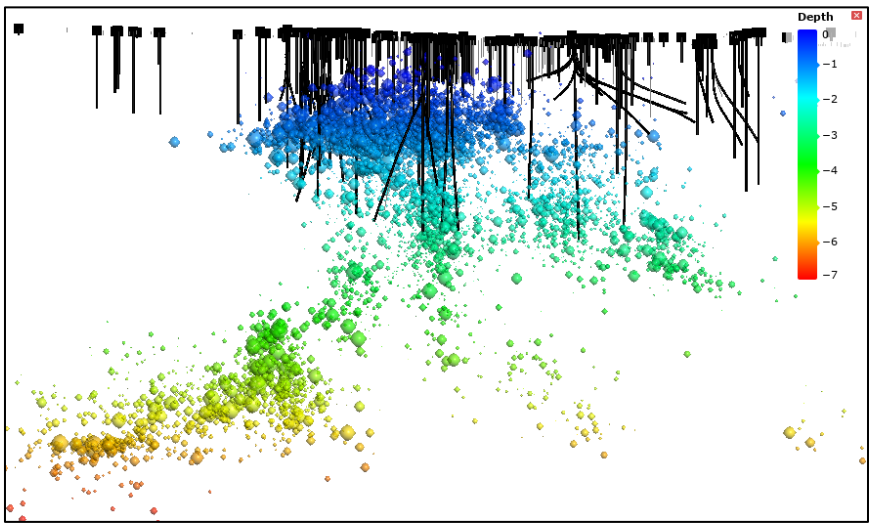

Figure 3. West to east cross-section view of Wairakei seismicity (2009-2017), viewed from the south. Size of dot is proportional to magnitude; color is proportional to depth; color scale is labelled 0 to 7 km (Bromley et al, 2018).

5.2 Rotokawa and Ngatamariki Geothermal Field examples

The history of induced seismicity at Rotokawa has been well documented. Since deep injection trials started in 2005, for the 140 MWe NAP turbine (commissioned in 2010), induced seismicity studies have been reported by: Bannister et al, (2008), Sherburn et al, (2013), Sewell et al, (2013), Sherburn et al, (2015), Sewell et al, (2017), and Sewell et al, (2020). Induced seismicity was initially found to accompany trial injection into deep wells (RK16-18) located ~1.5 km to the southwest of the production sector (Figure 4). Trends in the located events, along with other evidence (tracer tests), suggested a strong connection along a permeable fault zone linking these trial injectors directly with production wells. Fearing premature cooling, the long-term injection strategy was radically modified, and new wells were drilled to the southeast (RK20-24). Subsequent seismic monitoring showed that the induced seismicity then switched to this new deep injection sector. The results of monitoring using a dedicated local network at Rotokawa, from 2008 to 2012 (Sherburn et al, 2013), revealed more than 1000 events of M>0.8 and 50 of M>2, located within the field. Of these ~70% were located within a sharply bounded volume of about 1.5 km^3 between southeast reinjection wells (RK20-24) and northwest production sectors (RK5, Figure 4). A northeast trending central bounding structure, the 'Central Field Fault', appeared to have limited the cross-strike flow of injected fluids driven by the pressure gradient between these sectors, whilst allowing fluids to disperse along-strike, within fault-controlled permeable fractures, and presumably throughout the volume of increased induced seismicity. The bulk of this seismicity appeared to be related to changes in flowrate into one of the injection wells (RK20). Injection depth was about 2-2.5 km, and the base of the zone of induced seismicity and stimulated permeability was initially thought to be at about 3.5 to 4 km depth. This was interpreted, at the time, to indicate the probable limit of natural fracture permeability within the reservoir, where conductive heat-flow predominates, temperatures climb rapidly, and high-temperature ductile conditions are inferred to commence. The maximum measured downhole temperature reached 337 ºC at 2.7 km depth in RK22, so it seemed reasonable that temperatures exceeding the critical point (373 ºC) could exist at the relatively shallow depth of 4 km.

The original temperature difference between the injected fluids and the receiving formation at 2-2.5 km depth was ~200 ºC, so most of the induced MEQ near the injection wells are thought to have been triggered by thermal stress transients related to cooling of fracture surfaces. Some evidence of cooling contraction and widening of fracture apertures is revealed by an observed improvement in injectivity over time (t^n dependence, where n=0.4 to 0.7), as discussed in Grant et al (2013). Permeability is sufficient that pumped injection is not required, so the pressure increase in the injection sector is relatively low (~1 bar). Never-the-less, injection-induced pressure transients that propagate through the interlinked fracture network may be responsible for triggering of seismicity at greater radial distances, particularly if the reservoir rock (predominantly andesite and basement greywacke) is critically stressed and favorably-oriented fractures are close to failure.

By 2017, a revised best-fitting 1D velocity model had been developed for automatic hypocenter calculations of data from a combined Rotokawa-Ngatamariki seismic network. This was reported by Sewell et al (2017). The new model indicated a layer of higher velocity below ~3km depth. The revised hypocenter depths of recorded events were therefore interpreted to extend to deeper levels than initially thought (i.e. to about 5 km depth, Figure 4). This has implications for the assumed base of the permeable reservoir in the model and the assumptions regarding the depth of super-critical temperature and brittle-ductile transition conditions. Also, the locations of the events have dispersed further northwards from the injection sector, beyond the Central Field Fault, and towards the production sector at about 3-5 km depth (Figure 4). Tracer tests have confirmed that some reheated reinjected fluid is slowly reaching the production sector and therefore supporting pressures and hot fluid recharge. The seismicity pattern supports the conceptual model of enhanced permeability facilitating deep advection of the injectate through very high temperature formations.

Production and injection into the Ngatamariki reservoir (north of Rotokawa, Figure 1) commenced with commissioning of an 82 MWe binary power station in 2012-2013. The reservoir temperature is ~280 ºC at 1.5-2.5 km depth. Full mass injection (<100 ºC) is undertaken (minus ~2% gas which is vented), and the net effect is relatively minor pressure drawdown (-0.2 MPa) across the field. Seismicity is significant, with many thousands of events being located every year. Hopp et al (2019) have studied the seismic response to three separate injection tests at Ngatamariki between 2012 and 2015, in some detail, and conclude that aseismic opening or slip,

rather than seismic shear, is the active process driving well stimulation in this (and probably many other) hydrothermal settings. Observed increases in injectivity index (which is a measure of near-well permeability from flowrate/well head pressure) are poorly correlated with seismicity, and the locations of the MEQ are not coincident with the zone of injection stimulation. Injectivity is correlated instead with injection temperature, which directly affects near wellbore fracture aperture (Grant et al, 2013). Aseismic slip on fractures can occur because of increasing apertures from cooling. This, in turn, can act as a trigger for induced seismicity on other, favorably-oriented, but widely distributed, fractures, through stress transfer mechanisms. Some of these triggered events could occur on remote hydraulically-isolated fractures, and these, in turn could trigger other events leading to expanding event clusters in time and space. The seismicity enhances overall reservoir permeability but is not necessarily limited to fractures that are hydraulically well connected.

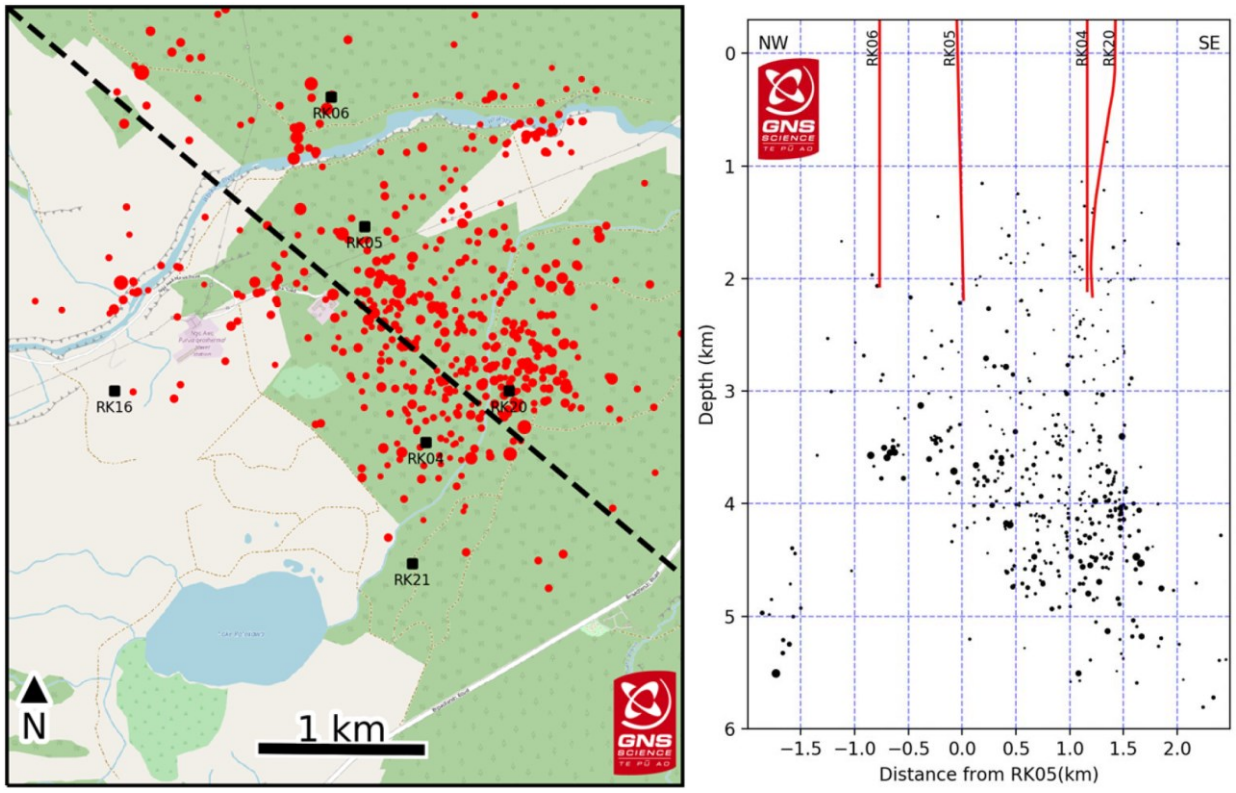

Figure 4. Rotokawa seismicity for July 2017-2018 showing selected wells - reinjection (RK20) and production (RK5) : a) Map of event locations; symbol size scaled according to magnitude (up to 3.2); b) NW-SE cross-section (from Pogacnik et al, 2018).

6. PUBLIC ACCEPTABILITY

Felt earthquakes have the potential to be large enough to increase public anxiety, and to cause minor damage to infrastructure and buildings. Protocols to deal with this issue, especially in terms of information collection and public dissemination, have been developed and published (Majer et al, 2007, 2012) and these have benefitted from international collaboration (Bromley & Majer 2012). On the positive side, the primary benefit of induced seismicity is an associated increase in permeability (productivity or injectivity), and thereby the extraction rate of heat-energy. On the negative side, there is a risk is earthquake damage and loss of public support. In terms of reducing the risk of induced seismicity damage from larger earthquakes, while enabling the benefits, controllable factors available to an operator are generally limited to: site-selection, well-selection, injection pressure, injection temperature, fluid volume, and pumping rates. In practice, uncertainties and variable geological settings and rock stress states, make it difficult to establish reliable correlations between the level or magnitudes of seismicity and any of these controllable factors. Accordingly, it is not realistically feasible, at present, to apply consistent guidelines for injection operation to eliminate large earthquakes in new geothermal settings. Efforts are ongoing, however, to attempt to rectify this situation, especially for EGS stimulation projects (e.g. the European DESTRESS project which advocates 'soft' stimulation methods, http://www.destress-h2020.eu/en/home/, Hofmann et al, 2019).

The main conclusions of the protocol development, in terms of dealing with public acceptability issues, are as follows:

- Induced seismicity need pose no threat to future development of geothermal resources, so long as sites are selected judiciously, community issues are handled effectively, and operators and licensing authorities understand the potential mechanisms.
- Provided the risks are appropriately managed, and the local inhabitants are well informed, induced seismicity is generally beneficial for monitoring the effectiveness of permeability enhancement, for providing information on reservoir fluid-flow processes, and for locally re-distributing accumulated rock stresses.
- The protocol notes that vibration hazards or nuisance effects from geothermal induced seismicity are similar in principle to other underground activities such as mining, hydrocarbon production and brine disposal, or CO_2 injection, where a possibility exists of triggering seismic stress release if a load changes. In common with these other industries, criteria used

for assessing the relative magnitude of induced seismicity, from the perspective of potential effects, should be peak ground velocity and frequency content (rather than peak amplitude which is often used to obtain a local magnitude). Geothermal induced seismicity frequencies, of peak strength at locations close to the hypocenter, are typically in the range of 100-300 Hz, although some larger events (M3-4) can generate vibrations at around 40 Hz. These are generally too high to cause significant structural damage (requiring frequencies <10 Hz), but a case-by-case assessment of vibration hazard is prudent.

- When undertaking a hazard assessment and while considering new geothermal development sites, especially urban locations, it is prudent to consult geological and seismological information to gauge suitability in relation to background natural seismicity, the state of stress, the existence of superficial deposits (e.g. alluvium) with potential for exaggerated ground shaking, and the capability of existing buildings and services to withstand predicted seismic shaking.

Induced seismicity is a community issue, that also involves a perception of risk. Communities in tectonically active areas are usually quite familiar with feeling the effects of small, natural earthquakes, and are familiar with stricter building codes to withstand earthquake shaking. In such areas, it is therefore rare to see constraints on conventional geothermal developments imposed by publicly-perceived seismic risks. In some instances, however, felt induced seismic events do generate public concern. This is location dependent, but may result from the notion that larger, potentially damaging events could result from future geothermal activities. Because naturally occurring earthquakes are less common in some EGS settings, often in quieter geological settings far from tectonic plate boundaries, public perception of the risk of large induced seismic events can be a much bigger issue. The perceived risk does become a real risk, however, if the presence of un-strengthened historic buildings, or simply complacency or ignorance, has led to low seismic tolerance of buildings and infrastructure to earthquake shaking.

Public perception, whether reasonable or not, is still important and should be dealt with correctly at the start. Expectations and fears should be taken seriously. Prior communication about the advantages and potential adverse effects of reservoir fracturing helps. An explanation of mechanisms is also important, to alleviate miss-placed concerns. For example, it may help to explain that, in most situations, the underlying cause of geothermal induced seismicity is accumulated stress in the ground caused by slow natural processes such as tectonic plate motion. The resulting rock stress reaches a near critical state (close to failure). This stress may be partly released, or re-distributed, through seismic failure, and this can be triggered by a relatively small perturbation in fluid pressure, thermal stress or mechanical stress. Hence induced seismicity tends to occur in clusters both in time and space.

In the Taupo Volcanic Zone of New Zealand, which is a typical seismically-active, volcano-tectonic setting, numerous induced geothermal events have been documented. Several per year occur in the magnitude range of 3 to 4. So far, there have been no cases of significant damage. As noted in section 2, there has been negligible public opposition to ongoing geothermal development. All felt event information (M>2), whether induced or natural, are immediately available through a website where the public can record their own impression of the felt intensity. This is collated, mapped and presented with other felt reports in near-real time. The provision of a felt feedback process, and open information from a trusted source, appears to provide the public with some sense of reassurance.

7. CONCLUSIONS

In many geothermal reservoirs, modern MEQ monitoring generates large datasets of micro-seismic events located within and around the reservoir. Consequently, refined hypocenter location algorithms, along with tomography based on Vp, Vp/Vs, attenuation (1/Q), Poisson's ratio, and shear-wave analysis from these datasets, can all provide useful tools for determining anisotropic structures (fluid barriers and conduits) and reservoir phase changes (in time and space). This information is helpful for siting of make-up wells, or exploration (expansion) targets and choosing reinjection sites. Monitoring of fluid phase changes (liquid and vapor) by combining MEQ with other geophysics datasets such as micro-gravity results also provides useful information for reservoir management. Planning of reinjection and production strategies is thereby better informed. Combining MEQ with resistivity (MT) inversions can provide useful knowledge on the likely locations of heat sources and deep fluid up-flows. Ultimately this improves understanding of reservoir processes. The integration of MEQ and other geophysical monitoring information improves conceptual models of under-utilized geothermal resources. Reservoir property changes are tracked over production time-frames, and therefore better projections are made of long-term sustainable energy extraction capacity and recharge parameters. Such knowledge can also be applied to exploration and expansion strategies to provide better drilling targets and improved production-reinjection strategies for mature geothermal developments.

As was discussed in section 4, supported by examples in section 5, injection of drilling fluid, separated brine or condensate (at ~100 ^{o}C) into high temperature geothermal reservoirs induces seismicity and stimulates fracture permeability through a variety of mechanisms: pore fluid pressure increases, reservoir volume changes (due to injection or extraction), reservoir temperature decreases and chemical changes to fracture surfaces. Thermal effects of cool water injection cause tensile stress (fracture opening) and volumetric stress (thermal contraction) around the injection point, but also along the flow-path between injection and production wells. Redistribution of these thermal stresses can activate or trigger seismicity on other critically-stressed and favorably-oriented fractures that may or may not be hydraulically connected to the fracture containing the injected fluid (Jeanne et al, 2017). Hence, thermally triggered seismicity can occur outside the reservoir. In general, however, if the reservoir has good permeability to start with, then the chances of an induced fracturing event occurring on an interconnected fracture are high, and the resulting long-term consequence is an increase in reservoir permeability.

Further efforts to strengthen international collaboration on geothermal induced seismicity will continue. Lessons learnt will be compiled into documents to assist developers, policy makers and, most importantly the public, to make informed opinions about the risks involved. Outcomes of this work of the IEA-Geothermal TCP, Working Group 13, Task D, are expected to result in: better informed decisions, improved protocols, and optimized monitoring schemes for new or expanded geothermal projects.

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