MICROSEISMICITY AT ROTOKAWA GEOTHERMAL FIELD, 2008 TO 2012

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ABSTRACT

Induced microearthquake (MEQ) activity has been observed at Rotokawa Geothermal Field since deep reinjection began in 2005. Following temporary observations in 2005 and 2006, continuous MEQ recording began in 2008 and continues. A dense network and careful site selection have provided data of sufficient quality to provide constraints for reservoir modelling (detailed in a companion paper by Sewell et al., 2013) though this has required manual refinement of automatic phase picks and relocation using double-difference approaches. Since October 2008, MEQs have concentrated in a diamond-shaped region between the production zone and current reinjection zone at depths of 1.5 to 3 km, but have moved depending on where fluid has been reinjected. Before October 2008, along-strike fault-controlled permeability influenced MEQ locations, but with reinjection in the south-east of the reservoir an across-strike fault barrier to reinjected fluids is thought to be important. The rate of microseismicity has varied closely with the rate of deep fluid reinjection, especially related to extra reinjection required for the Nga Awa Purua power station. The relative importance of reinjection pressure and injectate temperature in inducing MEQs is unclear. There have been about 50 MEQs of magnitude > 2, but only three of magnitude > 3. Less than 10 events have been reported felt and all have been too small to cause public concern.

1. INTRODUCTION

Induced seismicity is a widely reported phenomena in the geothermal industry (Smith et al., 2000, Majer et al., 2007, National Academy of Sciences, 2012) and it can occur through pressure, temperature, and chemical changes associated with fluid extraction or reinjection (Majer et al., 2007, National Academy of Sciences, 2012). Worldwide there are numerous examples including: The Geysers, USA (Allis, 1982; Eberhart-Phillips and Oppenheimer, 1984; Smith et al., 2000) Larderello-Travelle, Italy (Batini et al., 1985), Puhagan, Philippines (Bromley et al., 1987). Here we summarise seismic observations at Rotokawa geothermal field, New Zealand, for the period 2008 – 2012 and show that increased microseismicity occurred due to deep fluid reinjection.

In this study, the term microearthquake (MEQ) is used to describe events of magnitude less than 3. We will use this term at Rotokawa despite a few events larger than magnitude 3.

2. ROTOKAWA GEOTHERMAL FIELD

Rotokawa is a high-temperature, liquid-dominated geothermal field in the central part of the Taupo Volcanic Zone (TVZ), New Zealand (Figure 1), approximately 15 km north-east of the town of Taupo. The reservoir is predominantly hosted in Rotokawa Andesite, approximately 1 – 2.5 km below sea level, and is underlain by greywacke basement rocks (Bowyer and Holt, 2010). Reservoir temperatures exceed 300 °C, with the highest temperatures measured in the south-southeastern part of the field (>340 °C). Discordant depths to andesite and greywacke encountered in wells are interpreted as a north-east to south-west trending graben structure that is believed to provide the main permeability in the reservoir (Bowyer and Holt, 2010, Figure 1).

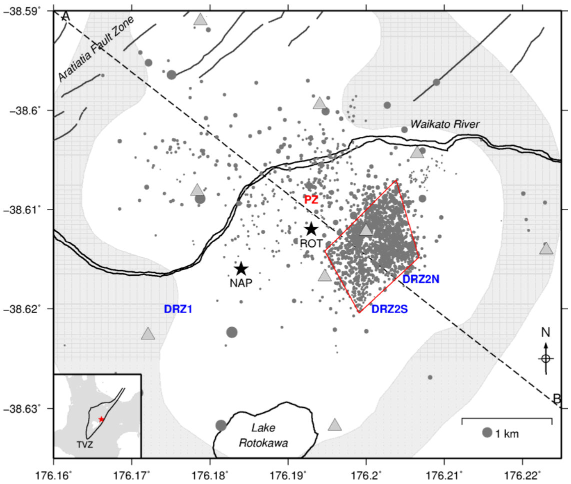

Figure 1: Rotokawa and microseismicity. The field resistivity boundary is shaded grey (Risk, 2000). Surface traces of active faults (GNS Active Fault Database) are black lines. PZ, DRZ1 and DRZ2 are the production zone and deep reinjection zones, respectively. ROT and NAP are Rotokawa and Nga Awa Purua power stations. Seismographs, at December 2012, are grey triangles. MEQ epicentres are grey circles, scaled by magnitude. The red diamond-shaped area is the most active zone. A-B marks the cross-section in Figure 2.

There are two power stations at Rotokawa, Rotokawa (ROT, Figure 1) currently producing 34 MWe (Bowyer and Holt, 2010, Quinao et al., 2013) and Nga Awa Purua (NAP, Figure 1) that produces 140 MWe (Quinao et al., 2013). Both ROT and NAP are operated by Rotokawa Joint

Venture (RJV), a partnership between the Tauhara North No. 2 Trust and Mighty River Power.

Initially almost all steam condensate and brine was reinjected into a shallow aquifer (depth < 1000 m) in the centre of the reservoir, but in 2005 this was diverted to a deep reinjection zone (DRZ1, Figure 2) in the south-west of the reservoir to limit a buildup in shallow aquifer pressure. Tracer tests showed a good connection between the deep reinjection at DRZ1 and the main production area (Quinao et al., 2013), so in October 2008, deep reinjection was transferred to a new reinjection zone in the south-east of the reservoir (DRZ2N, Figure 1).

In February 2010, total extraction and reinjection flow rates increased for testing prior to commissioning of NAP, and subsequently stabilised at c. 48,000 tonnes/day (550 L/s), four times the pre-NAP rate. Reinjection began in the southern part of the south-east reinjection zone (DRZ2S, Figure 1).

In late-2010 about 60% of the total field reinjection was transferred from the southern part of the south-east reinjection zone (DRZ2S, Figure 1) to the northern part of the same zone (DRZ2N, Figure 1).

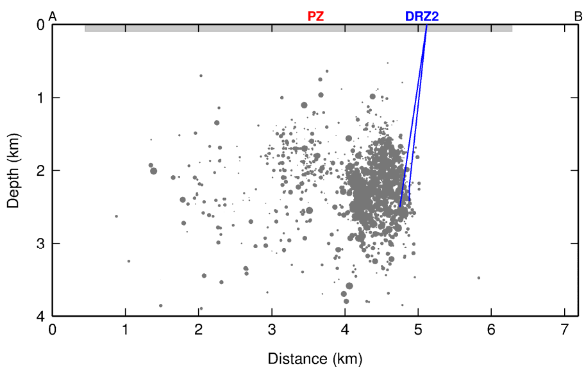

Figure 2: Cross-section for MEQs within 1 km of A-B in Figure 1. Production and reinjection zones, and representative reinjection wells are shown. The grey band is the position of the geothermal field.

2.1 Seismic Measurements

In 2005, just after the start of deep reinjection in DRZ1 (Figure 1), a single seismograph was deployed at Rotokawa. In 8 weeks it recorded more than 350 MEQs within c. 2.5 km of the well. The largest two had magnitudes of 2.0 and 2.3. The cause of the MEQs could not be determined, but given later observations a trigger caused by the start of deep reinjection seems likely.

In 2006, a 10 station microseismic network operated for 4 months with deep reinjection predominantly in DRZ1 (Figure 1). Almost 200 MEQs, the largest of magnitude 1.7, were located east and north-east of the reinjection zone (DRZ1, Figure 1). No definite conclusion about whether the MEQs were induced was drawn (Bannister et al., 2008), though again, later observations point to deep reinjection as a likely source.

In July 2008, a seismic network was again installed at Rotokawa, and continues to operate. The network initially had 8 instruments, but in October 2008 this was increased to 10 (Figure 1).

2.2 Instrumentation and Data

The microseismic network collects continuous data at 200 samples per second from 4.5 Hz 3-component geophones buried 0.5 to 1 m deep in soil. Data are written to memory cards on the seismographs which are collected periodically. Timing is by GPS synchronised clock within the digitisers and is accurate to better than 0.05 ms.

Instrument locations were selected to obtain the best overall network geometry, while avoiding high noise sites close to power stations, thermal areas with hot ground, and some land access restrictions.

Initial processing was required to be as automatic as possible. MEQs were detected automatically from the continuous data and clustered to form events. P-phases and S-phases were picked automatically and microseismic events located with a velocity model appropriate to the TVZ (Maunder, 2001).

Automatic locations are sufficiently accurate to identify the active part of the field and the approximate depth of activity, but are not precise enough to be incorporated into reservoir modelling work, largely due to inaccuracies in the automatic phase picks. We therefore carried out manual repicking and subsequent relocation using the TomoDD code (Zhang and Thurber, 2003) using a preliminary 3-D velocity model derived from local tomography. Estimated location uncertainties for absolute locations are less than 50 m in position and depth, but uncertainties in the shallow velocity structure mean that depth uncertainties of more than 100 m are probably more realistic.

Microearthquake magnitudes were determined from the peak amplitude recorded by seismographs and calibrated against larger earthquakes at Rotokawa recorded by a regional network.

3. MICROSEISMICITY

From July to September 2008, while reinjection was in the south-west of the reservoir (DRZ1, Figure 1), MEQs mostly occurred in production zone PZ (Figure 1) close to the ROT power station and north-east of the reinjection zone.

Within a few days of reinjection commencing in a new south-east reinjection zone (DRZ2, Figure 1) in October 2008, microseismicity began nearby and has subsequently formed a dense diamond-shaped region between reinjection and production zones at depths of 1.5 to 3 km (Figure 2), broadly similar to permeable zone depths in reinjection wells in that area.

While the production reservoir has some microseismicity and there are a few events north of the Waikato River, and the southern part of the high temperature reservoir, south of NAP, has been almost aseismic (Figure 1).

3.1 Changes in Microseismicity Rate

For 2008 – 2012 the microseismic catalogue is believed to contain all events at Rotokawa of magnitude ≥ 0.8 and only some of the smaller events. In examining changes in the rate of microseismicity (Figure 3) we use only events of magnitude ≥ 0.8, to ensure that network configuration and changes in detection threshold do not substantially affect our results.

From July 2008 to December 2008 MEQs occurred at a mean rate of 23 events per month, starting higher than this and gradually decreasing with time. From December 2008 the rate dropped by more than a third to a mean of 7 events per month and this continued until February 2010. The mean rate from February 2010 until December 2012 was 26 events per month, and increase over the previous period of 3.7 times.

We do not discuss the microseismic moment release or changes in the rate of larger events here, other than to note that all three MEQs larger than magnitude 3 occurred in 2012.

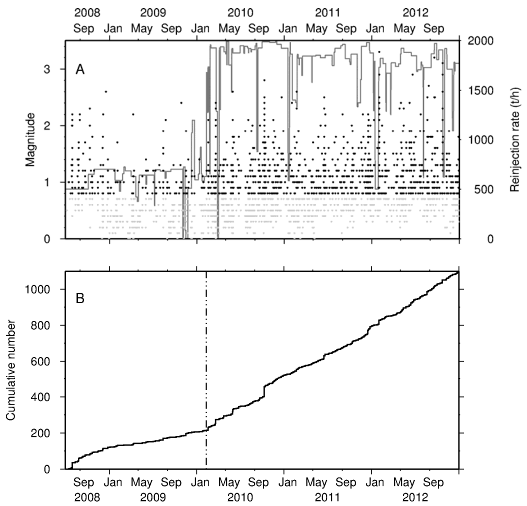

Figure 3: MEQ rate changes. A: MEQ magnitudes, darker symbols above magnitude 0.8, and total rate of deep reinjection. B: Cumulative number of MEQs. Dashed line shows a change associated with the NAP power station.

4. DISCUSSION

We consider that most MEQ activity at Rotokawa since 2005 has been induced by the effects of deep reinjection of condensate and brine, and this is evidenced by changes in both the location and rate of activity that have occurred following three major changes to reinjection at Rotokawa:

- When reinjection moved to the south-east of the reservoir in October 2008, MEQs began close to the reinjection wells within a few days and subsequently persisted in this area.
- In early-2010 the rate of MEQ activity increased by 3.7 times in the reinjection zone, when total production and reinjection rates rose 4 times.
- In late-2010 c. 60% of the total field reinjection was transferred from the southern part of the reinjection zone to the northern part, and this was accompanied by a decrease in MEQ rate in the southern zone that has persisted.

Throughout this period there have been no corresponding changes in the rate of microseismicity in the production zone (PZ, Figure 1).

4.1 Factors Influencing the Microseismicity Distribution

During 2006, MEQs occurred between reinjection and production zones consistent with reinjected fluid moving towards the production reservoir where pressures declined 9 – 10 bar (0.9 – 1 MPa) between 1997 and 2010 (Quinao et al., 2013), and through an area that tracer returns suggested had along-strike fault-controlled permeability (Bowyer and Holt, 2010). This influence appears to have continued from July to September 2008.

Since October 2008, microseismicity has been concentrated between the production zone (PZ, Figure 1) and south-east reinjection zone (DRZ2N and DRZ2S, Figure 1). The general area of microseismicity is consistent with reinjected fluid moving towards a lower pressure part of the reservoir. However, the sharp north-west boundary to the activity (Figure 1) parallels inferred faults in the field, and probably marks a fault forming a barrier to fluid moving into the production zone. A similar observation of sharply bounded microseismicity has been seen at Awibengkok, Indonesia (Stimac et al., 2008).

In some situations, faults at Rotokawa seem to provide an easy path for along-strike movement of reinjected fluid and precise MEQs hypocentres can track that movement. In other cases faults appear to form a barrier to across-strike fluid movement and precise MEQs hypocentres can identify those faults by highlighting areas of dense MEQ activity with sharp boundaries.

4.2 Relationship Between Rates of Reinjection and Microseismicity

Shapiro et al. (2007) and Shapiro and Dinske (2009) found that for a constant or increasing pore-pressure perturbation the number of MEQs induced by fluid injection increased approximately proportionally to injection volume and a similar pattern has been seen in some seismically active fields such as The Geysers in the 1970s and 1980s (Majer et al., 2007).

The increase in total reinjection volume at Rotokawa in 2010 was 4 times and microseismicity increased 3.7 times. This suggests that we can directly ascribe the increase in microseismicity at that time to the additional reinjection required for the NAP power station. In effect, additional power production resulted in more MEQs.

4.3 Mechanism of Induced Microseismicity

In Enhanced Geothermal Systems (EGS) the effect of fluid pressure and its subsequent diffusion is widely accepted as the dominant mechanism for induced seismicity (Shapiro et al., 2005, Majer et al., 2007, Shapiro and Dinske, 2009). A reduction in the effective normal stress due to an increase in fluid pressure on appropriately oriented faults allows those close to failure to slip under existing shear stresses (Rutledge et al., 2004). In Conventional Geothermal Systems (CGS), such as Rotokawa, other mechanisms including a decrease in reservoir temperature caused by cool reinjected fluids have also been proposed (Majer et al., 2007). The cooling effect would tend to contract pre-fractured rock, resulting in a slight opening of those fractures allowing fracture slip and/or propagation in a similar manner to the effect of increasing pore pressure.

Reinjection pressures at Rotokawa are typically 5 – 10 bar (0.5 – 1 MPa), at least an order of magnitude smaller than at EGS, so if pressure is the main driver of induced microseismicity the Rotokawa reservoir will have to be highly fractured with many appropriately oriented fractures naturally close to failure. The temperature of reinjected fluid at Rotokawa is ~200 °C cooler than the pre-exploitation reservoir temperature so realistically this must contribute in some way to induced seismicity at Rotokawa.

To determine the relative importance of pressure and temperature in induceding microseismicity will probably require detailed MEQ observations during controlled changes in injection pressure and temperature, and this may be a difficult proposition in an established, operating field. An alternative approach may be coupled reservoir-geomechanical modelling, provided that thermal stresses were included. At the nearby Ngatamariki field which began power production in 2013, there are preliminary microseismic data that point to the importance of injectate temperature in inducing MEQs.

4.4 Hazard Implications

Between July 2008 to December 2012 there were 50 MEQs with a magnitude > 2, and three with a magnitude > 3. The total seismic moment release is equivalent to a single event of magnitude 3.9.

For a magnitude 3.3 event in February 2012 over 100 felt reports were received at distances up to 25 km, with a maximum reported intensity near the source of MM5 (generally felt outside and by almost everyone indoors, GeoNet Project). However all MEQs have been too small to cause public concern.

From a hazard perspective the MEQ activity at Rotokawa can therefore reasonably be referred to as nuisance seismicity.

5. CONCLUSIONS

Rotokawa has experienced induced microseismicity since deep reinjection began in 2005, although it is not clear if perturbations to reservoir pressure or temperature are the main driver. The location and rate of microseismicity has been largely determined by the location and rate of reinjection. The currently active seismic zone is interpreted as being bounded by a major NE-SW oriented fault. Although three events of magnitude ≥ 3 have occurred, the microseismicity has had no impact on local residents.

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