OBSERVATIONS OF DEEP AND SHALLOW SEISMICITY WITHIN THE WAIRAKEI-TAUHARA GEOTHERMAL SYSTEM

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ABSTRACT

Over the lifetime of the Wairakei Seismic Network (2009 to present), deep microseismicity (> 4 km depth) has been consistently detected near the north-western part of the Wairakei field including outfield areas. Episodes of deep microseismicity often correlate temporarily with shallow (< 4 km depth) microseismicity detected near production and injection areas of Wairakei and northern Tauhara. In order to better understand the meaning of this deep microseismicity – in terms of its connection with the Wairakei-Tauhara geothermal system, selected swarms of deep microseismicity detected over the period Jan 2013-March 2015 were studied against field operating history. The temporal correlation between deep and shallow microseismicity is discussed in the light of evidence presented here.

1. INTRODUCTION

1.1 The Wairakei Geothermal Field

The Wairakei Geothermal Field has an installed capacity of nearly ~ 353 MWe, with a contribution of 132 MWe from the Wairakei Power Station (commissioned in 1958) and associated binary plant (commissioned in 2005), 55 MWe from the Poihipi Power Station (commissioned in 1996), and 166 MWe from the Te Mihi Power Station (commissioned in 2014). However, resource consent constraints on mass extraction limit the average generation from the Wairakei Geothermal Field to around 330 MWe. A further 28 MWe is generated from the northern sector of the Tauhara Geothermal Field by the Te Huka Power Station commissioned in 2010 (Figure 1). The capacity added since 2010 at Wairakei-Tauhara has been accompanied by overall increase in mass extraction and therefore injection volumes and a geographic diversification of injection areas. In order to assist this study, injection areas active during the period 2013-2014 are classified in terms of location, depth and operating history as shown in Table 1.

Following the first decade of production (ca. 1958-1970), Wairakei reservoir pressures dropped by 23-25 bar (Bixley et al., 2009). This pressure drop is confined to within the resistivity boundary (e.g. Milloy and Lim, 2012). Reservoir pressures subsequently stabilized and even increased with the commencement of large scale injection at Otupu in 1998. A plot of mass take, injection volumes and relative reservoir pressures for the period 2013-2014 (Figures 2 and 3) is a good approximation of the current behaviour of the Wairakei system in terms of transient pressures. In detail, these figures illustrate:

a) The correlation between increasing mass extraction and decreasing reservoir pressure near production areas (Figure 2; location of wells WK121 and WK218 shown in Figure 1);
b) The correlation between increasing reservoir pressure near Karapiti injection area with increasing Karapiti injection load (Figure 3; location of well WK402 shown in Figure 1);
c) The correlation of increasing mass extraction with increasing injection load.

As discussed in Milloy and Lim (2012), Karapiti pressures are closely related to Tauhara pressures. In terms of episodes of variations of mass take at Wairakei, based on Figures 2 and 3, episodes of increased mass take can be expected to induce a pressure drop in the productive reservoir and a pressure increase in injection areas (due to associated increased injection volumes).

1.2 Overview of seismic monitoring with WSN

The Wairakei Seismic Network (WSN) was installed in 2009 with the aim to:

1) Provide improved understanding of the permeability structure of the geothermal system
2) Monitor seismic activity throughout the geothermal field

The WSN is unique in the context of the Taupo Volcanic Zone in that it operates with downhole seismometers providing unprecedented spatial resolution (e.g. Boese et al., 2014). For details on the WSN array configuration and sensitivity, readers can refer to Sepulveda et al (2013) and Boese et al (2014), respectively.

As discussed in Sepulveda et al. (2013, 2014, 2015), seismic data collected by the WSN has revealed a heterogeneous spatial distribution of seismicity, with the bulk of seismicity migrating to the west with depth. The consistent occurrence of deep microseismicity (> 4 km depth) near the western edge of Wairakei cannot be attributed to artefacts of network array geometry or sensitivity, as M>0.2 seismic events are detected as far as ~10 km from the field (both laterally and vertically) and M>1 seismic events are commonly recorded at tens of kilometres from the field boundary.

2. OBJECTIVES

The probability of a seismic event to be induced by changes in mass take or injection volumes decreases with increasing distance from production or injection wells. The deepest production well at Wairakei is less than 2.8 km depth. Figure 4 summarises injection depths for Wairakei-Tauhara (injection areas as in Figure 1). The bulk of injection occurs at depth ranging from 200 m to ~3 km (i.e. depth below casing depth), although the effective depth range of injection is best constrained by permeability distribution (feed zone depth range in Figure 4). A number of wells inject at depth less than 1.5 km (e.g. Poihipi, Poihipi West, and Tauhara – except for TH19). On this basis, deep microseismicity – defined as microseismicity occurring at depths greater than 4 km – is generally thought of as likely tectonic in origin. At shallower depths, the proportion of induced seismicity can be expected to increase, although a conclusive assessment of physical triggers can be challenging in the context of Taupo Volcanic Zone (i.e. tectonically active region), due to potentially overlapping effects of pore fluid pressure, thermal stress, tectonic stress and mechanical rock properties. The aim of this paper is to test the assumption of deep microseismicity being mainly tectonic, by investigating 2013-2015 episodes of deep microseismicity in more detail against field operations (mass take and reinjection volumes).

3. METHODS

In the case of multiple seismic events occurring closely related in time and space – events collectively referred to as "seismic cluster", additional knowledge gained from spatial characteristics of the cluster (e.g. linear versus diffuse distribution) can give some insight into the physical trigger of microseismicity. By applying the clustering algorithm of Sepulveda et al (2015) to the WSN earthquake catalogue, deep (> 4 km) clusters of ten or more events were identified and used to define periods of interest (shown in Table 1). Figure 5 shows location of deep clusters and shallow seismicity detected within ± 7 days of the start date of deep seismicity.

As shown in Figure 1, production areas at Wairakei are within relative close proximity of each other (making distinction harder in terms of reservoir response to mass take) and, conversely, injection areas are relatively distant of each other (making distinction easier in terms of reservoir response to injection). Because total mass take and reinjection volume variations are proportional (as illustrated in Figures 2 and 3), we use injection volumes to track large-scale operational changes across the Wairakei and Tauhara fields (Figure 6). Well WK407 (Karapiti area) has been singled out in Figure 1 and Figure 4 due to its relatively large injection capacity and its frequent use for disposal of condensate and cooled separated geothermal brine, which is colder than separated geothermal brine. Other wells singled out in Figure 1 and/or Figure 4 include TH19, WK650, WK321 and WK317.

4. RESULTS

Table 1 below presents a summary of observations applicable to each of the periods of interest. Some general observations from Figures 5 and 6, and from further in-house histogram analysis of seismic frequency (not detailed here) include:

1) Episodes of deep microseismicity at Wairakei are often accompanied by shallow (< 4 km depth) microseismicity near production and/or Karapiti/Otupu/Tauhara injection areas.
2) There is no general rule as to the time sequence of shallow and deep microseismicity, with instances of deep microseismicity occurring both prior and after shallow microseismicity.
3) The time between the actual reservoir change (i.e. measurable change in reinjection volume as in Figure 5) and the associated seismic response appears to vary from hours to weeks.
4) Outfield injection and Tauhara injection represent proportionally a minor component of the overall injection strategy of Wairakei-Tauhara and episodes of deep microseismicity do not appear to occur linked to changes in these areas. As an example, Poihipi West injection is shallow (Figure 4) and comparatively minor in terms of injection volumes (Figure 5),

Start date of deep microseismic activity	**Shallow seismic activity within ± 7 days (yes/no/ location)?**	**Main operational highlights**
15/10/2013 5/11/2013	Yes (Otupu, Karapiti, Te Huka) Yes (Otupu, Karapiti, Poihipi, Te Huka)	WK407 variable flow and Karapiti increase WK407 variable flow and Karapiti increase
3/03/2014 18/06/2014 through 2/07/2014 to 21/07/2014 14/09/2014	Yes (Otupu, Karapiti, Te Huka, WBF) Yes (Otupu, Karapiti, Te Huka, EBF) Yes (Karapiti, Poihipi, Te Mihi South, WBF)	WK407 reduced load Otupu injection load decreased (early June) and increased (mid-late July) Karapiti and Otupu injection load dropped to near zero
5/01/2015	Yes (Otupu and Karapiti)	Otupu reinjection decreased during 3 last weeks of Dec14
1/04/2015	Yes (Otupu, Karapiti, Te Huka)	Otupu and Karapiti injection loads increased

Table 1: Operational highlights for selected periods of increased deep microseismicity based on data presented in Figure 6.

5. DISCUSSION

Earthquakes induced by injection are thought to be the result of increased pore pressures that decrease normal stresses, and allow critically stressed faults to slip. Other processes may include thermal stresses induced by injection of cold fluid into hot rock. In production areas, where pressures are expected to decrease as a result of fluid extraction, the physical trigger of induced seismicity is less clear. Yet, the evidence of microseismicity near production areas is compelling and observed in both geothermal (e.g. Wairakei; Sepulveda et al., 2015 and this study) and oil fields (e.g. Segall, 1989).

At any one time, pressure trends from production and injection areas of Wairakei follow opposite directions (Figures 2 and 3). This is to say, while mass take induces a pressure drop in production areas, reinjection loads induce a pressure increase in injection areas. Extrapolation of pressure effects is not straightforward, particularly for regions that are transitional between production and injection areas, or deep areas of the geothermal system. At Wairakei, episodes of deep microseismicity seem to correlate with both increased injection – hence, increased mass extraction – and decreased injection – hence, decreased mass extraction (Table 2). An example of the latter is the seismic event of Sept 2014 (Table 2; Figure 4), located in a "transitional area".

6. CONCLUSION AND REMARKS

In this paper, we show that deep microseismicity rarely occurs in isolation at Wairakei-Tauhara, but in close temporal correlation with shallow microseismicity. Based on this correlation and the common observation of changes in field operations during episodes of combined shallow and deep microseismicity, we postulate that physical and mechanical changes in the reservoir due to variations of mass take and injection volumes can be far reaching. The nature of the physical trigger causing deep microseismicity is not well understood. This is work in progress and future complementary work is envisaged to improve our understanding of microseismicity. The observations of this study could be used to test various numeric modelling scenarios with a range of tectonic, thermal, hydrological, and geomechanical input conditions.

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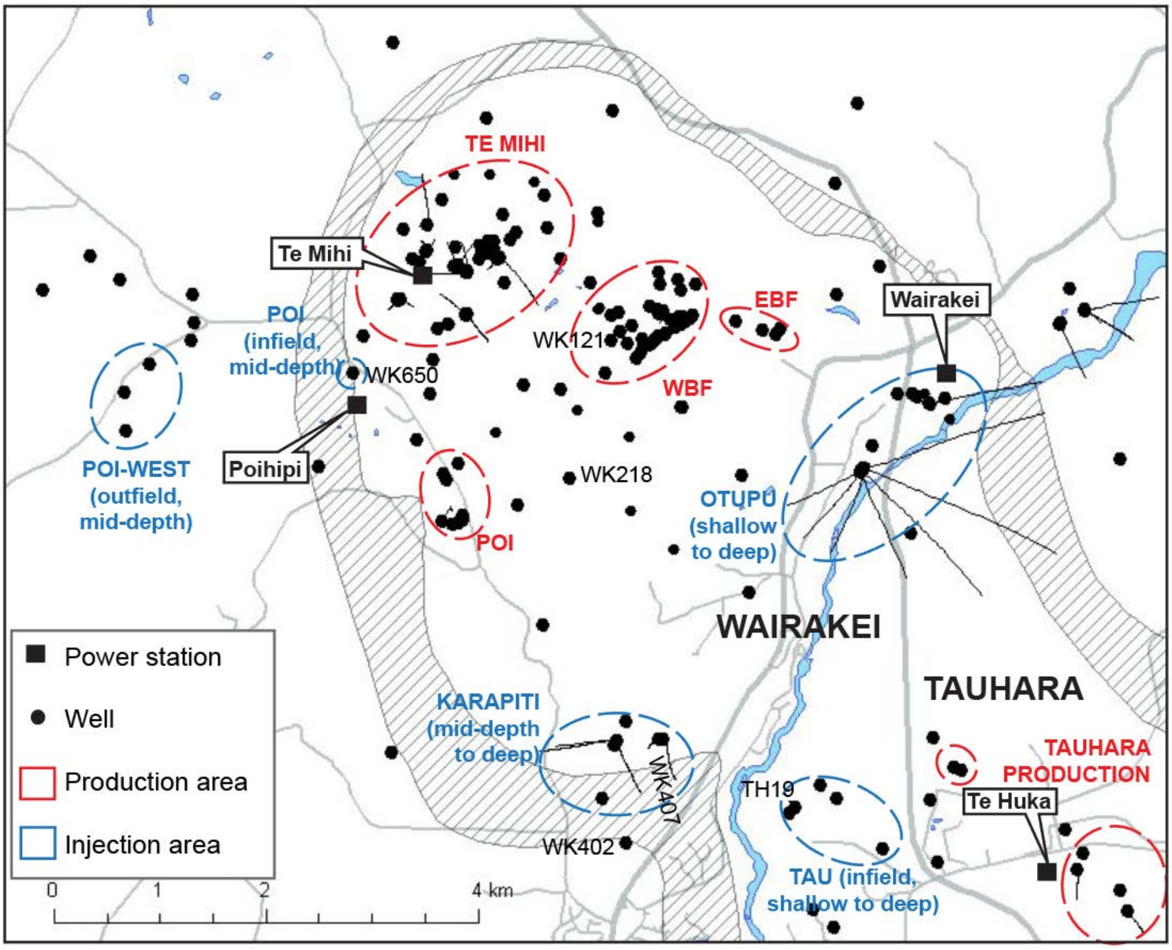

Figure 1: Production and injection areas of the Wairakei geothermal field active during the period 2013-2015. Injection areas are described in more detail in Table 1.

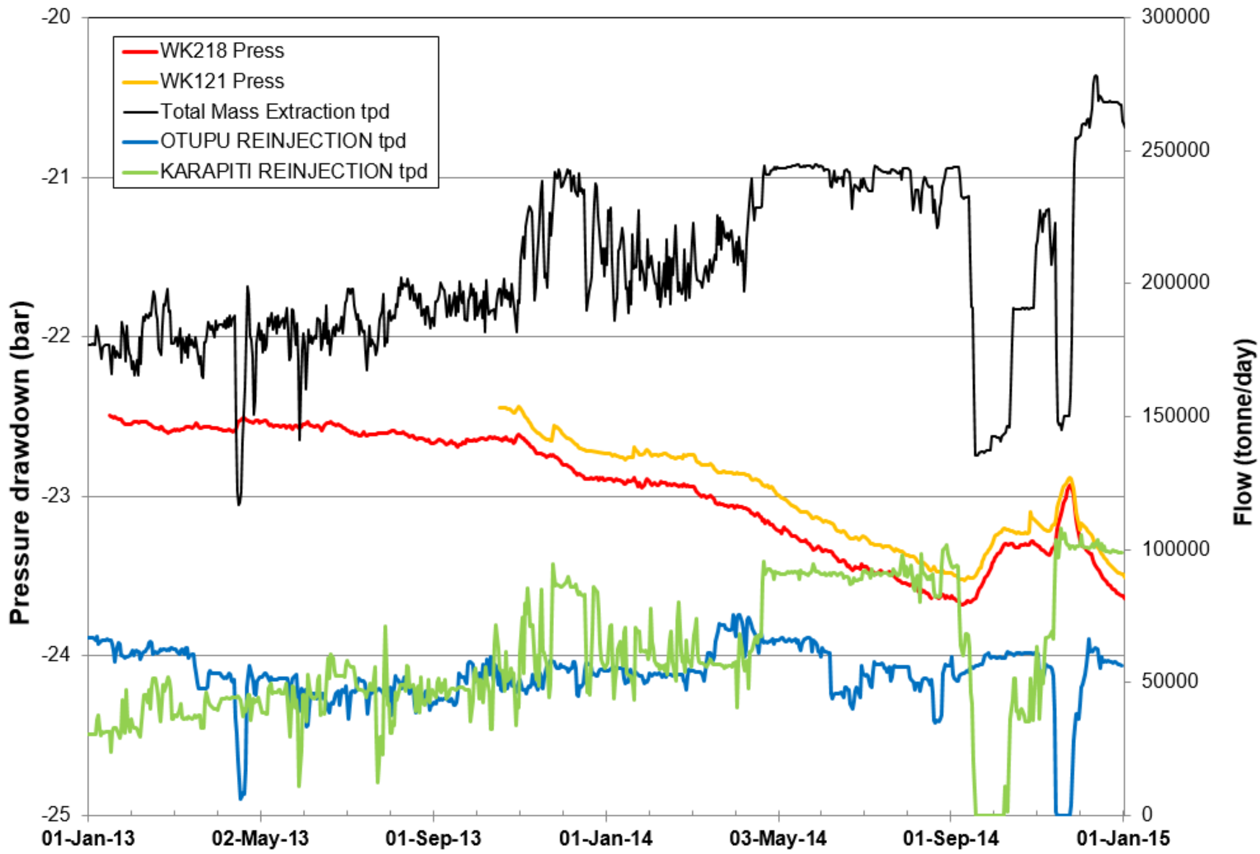

Figure 2: Plot of near-production reservoir pressure, mass take and injection volumes (2013-2014).

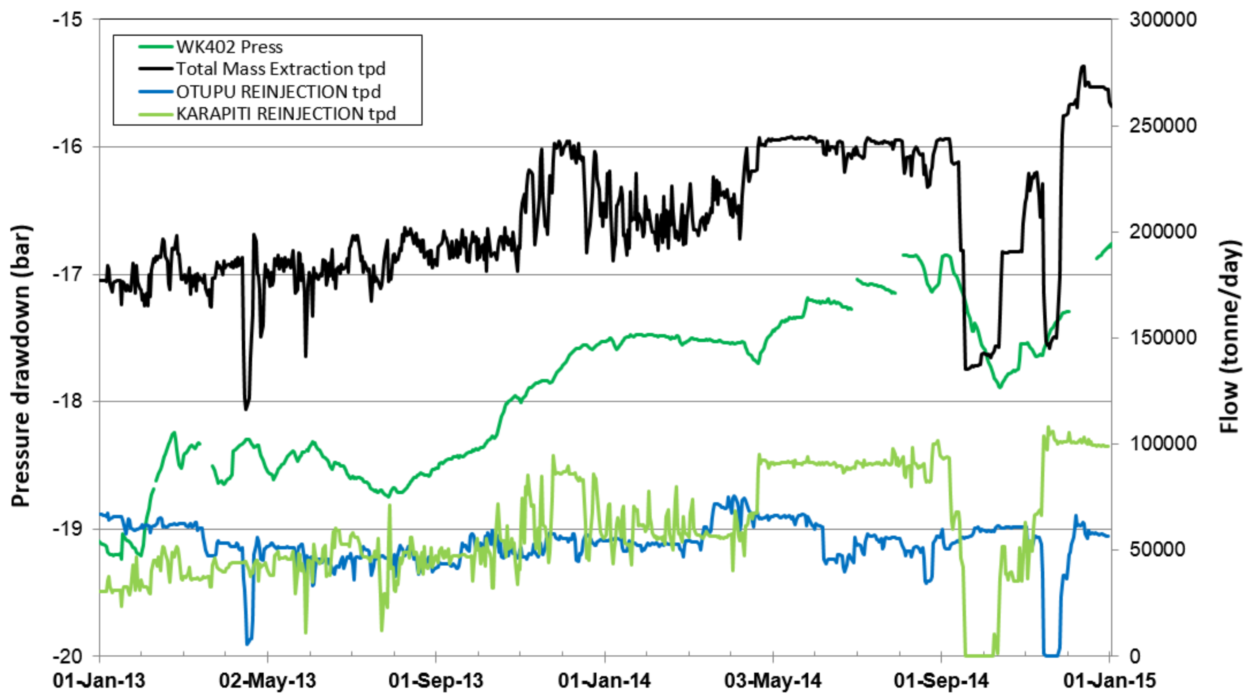

Figure 3: Plot of near-Karapiti injection volumes, and WK402 pressure drawdown (period 2013-2014).

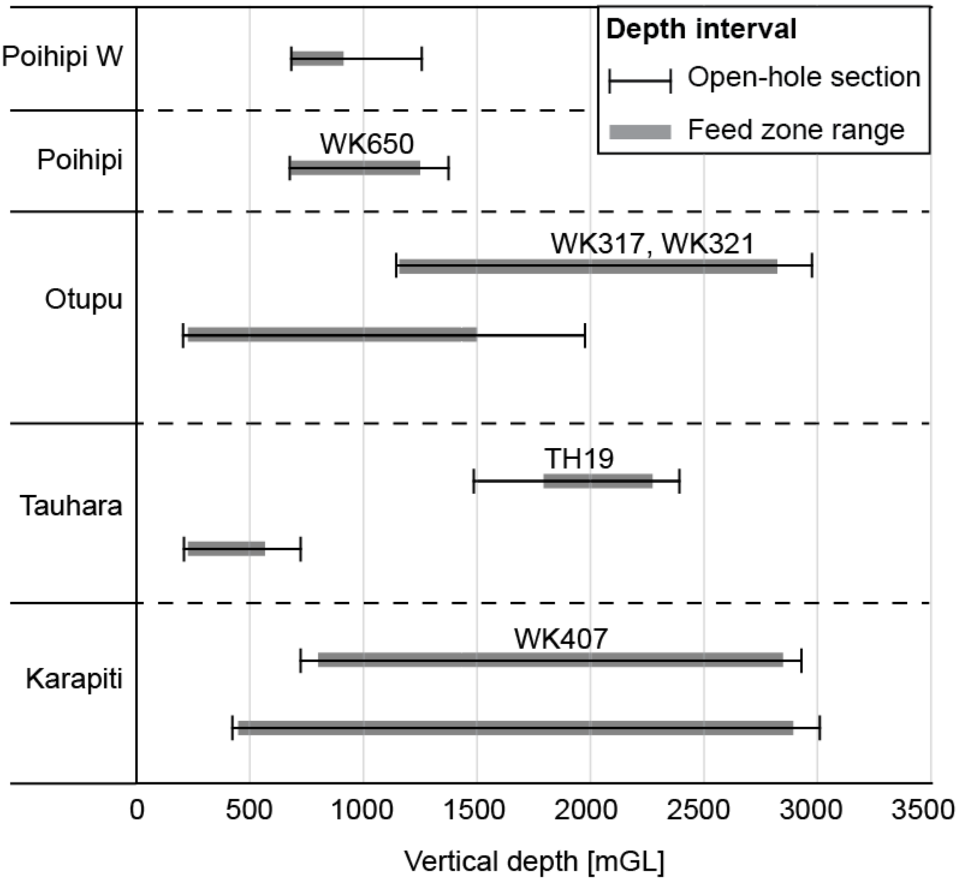

Figure 4: Injection depths for the different injection areas shown in Figure 1.

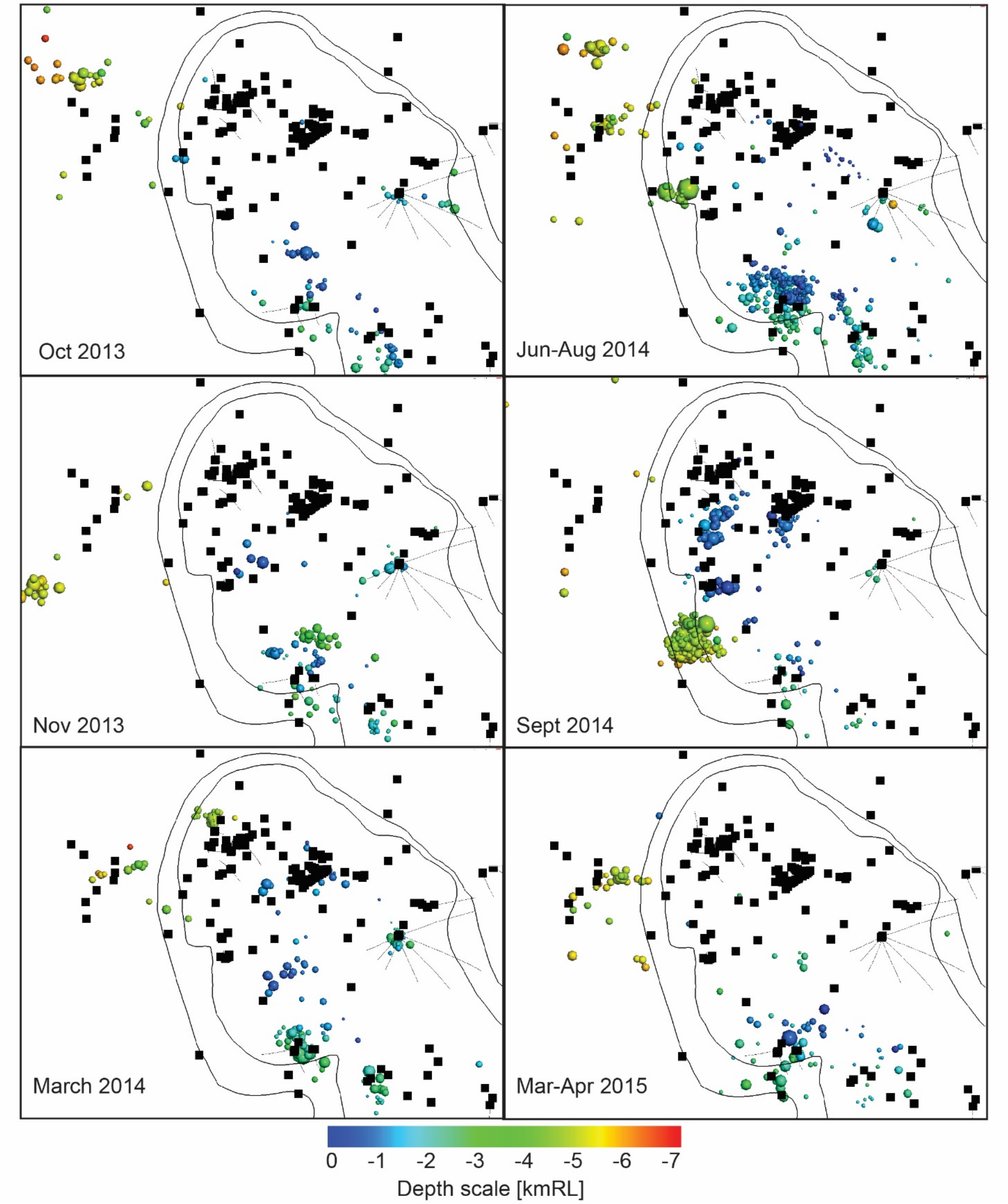

Figure 5: Maps of selected episodes of deep clustered microseismicity for the period January 2013 to March 2015 (see dates in Table 1), showing all seismicity within ± 7 days of the start of deep microseismicity. Depths given in kilometres below sea level (kmRL). Size of seismic event given by relative magnitude scale (Mw range -1.0 to 3.7).

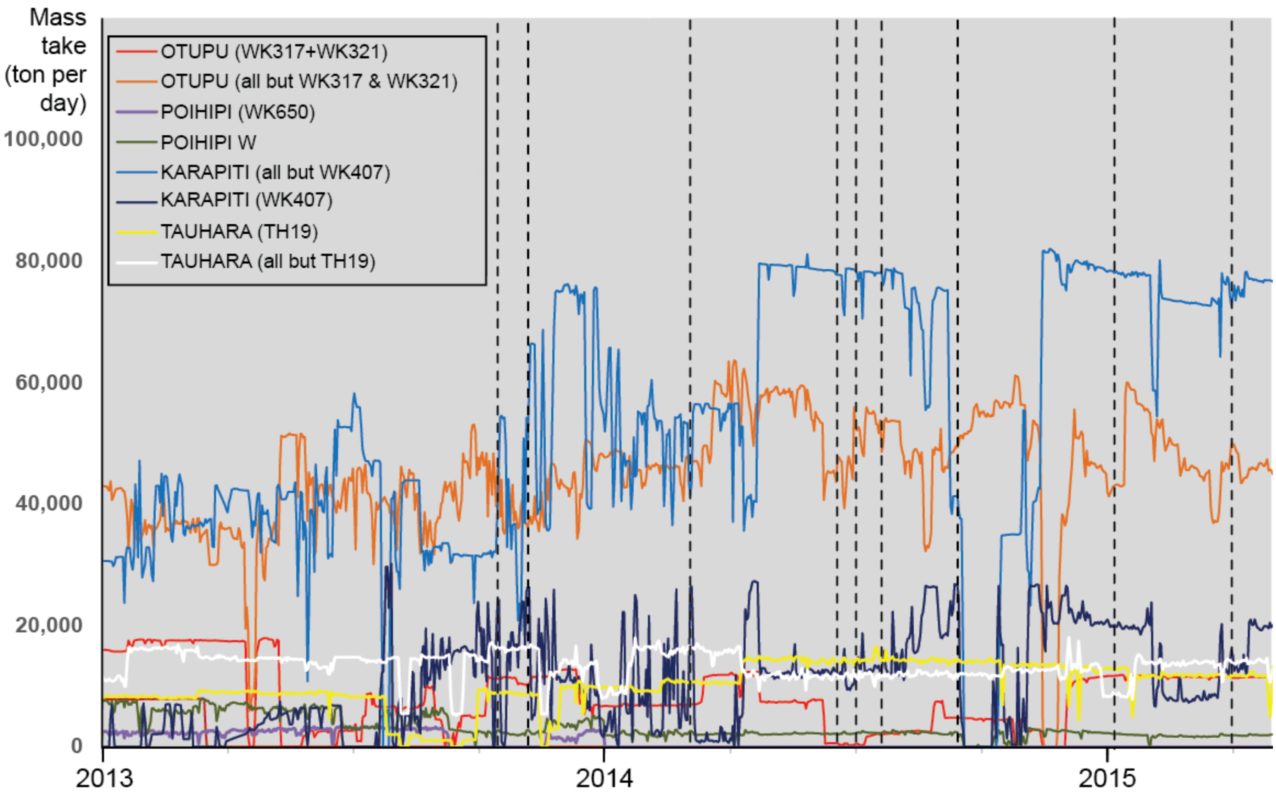

Figure 6: Plots of daily average injection volumes (tons per day) highlighting start date of episodes of deep microseismicity shown in Figure 4 (vertical dashed lines).