REVIEW OF GEOPHYSICAL MONITORING AT WAIRAKEI-TAUHARA: WHAT HAS BEEN LEARNT

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ABSTRACT

A review of the history of geophysical monitoring at Wairakei-Tauhara has been undertaken to extract the essential knowledge about reservoir processes and environmental effects from the collection and analysis of geophysical monitoring data. The studies reviewed include changes in: ground deformation (subsidence), micro-gravity, groundwater level, heat-loss from surface thermal features, and micro-seismicity. Each of these data-sets provides a glimpse into the subsurface physical processes that accompany large scale reservoir fluid extraction and reinjection. When interpreted together with downhole data on pressures, temperatures and 2-phase saturation conditions, and modelled together as an integrated package, these geophysical monitoring datasets provide a valuable source of reservoir change information that can assist in the calibration of reservoir simulations, and improve forward projections (scenarios) of reservoir behavior under a variety of extraction-injection strategies.

1. INTRODUCTION

A comprehensive review of the history of geophysical monitoring at Wairakei-Tauhara geothermal fields (**Figure 1**) was undertaken in 2009 for a Special Issue of Geothermics Journal, marking the 50th anniversary of Wairakei production. It included a series of review papers on: subsidence (Allis et al., 2009, Bromley et al., 2009), gravity changes (Hunt & Graham, 2009), groundwater level changes (Bromley, 2009), and other geophysical investigations (Hunt et al., 2009), complemented by reviews on numerical modelling (O'Sullivan et al., 2009), reservoir physics (Bixley et al., 2009) and discharge chemistry (Glover & Mroczek, 2009). Now that Wairakei's 60th anniversary is being celebrated, it is timely, that an update be undertaken on these studies, and a summary of learnings be compiled from the joint interpretation of the observed changes.

The 60-year development history at Wairakei and Tauhara offers a unique opportunity to study the long-term physical response of a liquid-dominated reservoir to large volumes of net mass extraction. This is assisted by monitoring of key geophysical parameters that has been ongoing since the start of production. These have included: ground levelling from 1955, micro-gravity from 1961, ground-water level from 1955, seismicity from the 1950's (DSIR/Geonet regional network) augmented by a local seismic network from 2009, and heat loss assessments from the 1950's.

Pressure and temperature changes are important underlying mechanisms behind many of these geophysical responses. To illustrate this, the pressure history of various Wairakei aquifers hosted in Waiora Formation (WF) and mid-Huka Falls Formation (HFF) is shown in **Figure 2**.

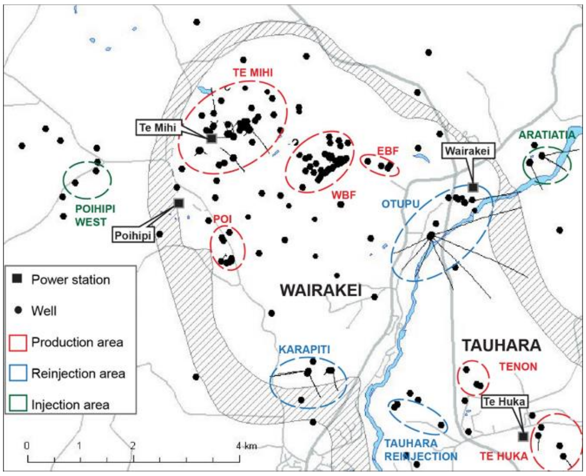

Figure 1: Location map of Wairakei-Tauhara geothermal fields: production and reinjection bore-fields, power-stations and wells (EBF, WBF, POI = Eastern, Western & Poihipi Bore-Fields).

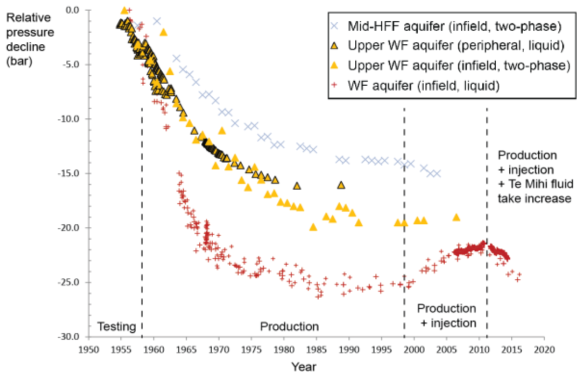

Figure 2: Pressure changes in Wairakei aquifers (from Sepulveda et al., 2017).

An integrated approach to modelling and interpretation is beneficial because of the physical links between mechanisms and dynamic processes. For example, micro-gravity surveys require good knowledge of ground levels and groundwater levels to correct for their gravity effects before interpreting the residual change as a reservoir fluid density or mass displacement effect. Also, the rock stress changes created by the thermo-mechanical effects of fluid movement (i.e. a mass change), interacting with tectonic and thermal stresses, are important triggers for micro-seismicity as well as causing observable ground deformation, particularly in areas where the rock properties are anomalous (Bromley, 2014; 2018). Insights into field boundaries and reservoir structure can also be obtained from integrating geophysics with reservoir data (e.g., at Wairakei-Tauhara; Sepulveda et al., 2014).

2. MONITORING

Since the 50th anniversary commemorative special issue of Geothermics on Wairakei (2009), updates on Wairakei and Tauhara monitoring have been presented, discussed and interpreted in several publications and reports. The following subsections give an overview of the results of these updates, in particular on : subsidence, micro-gravity, groundwater level, surface heat-loss, and micro-seismicity.

2.1 Deformation (subsidence)

Recent subsidence studies (repeat levelling history, modeling and interpretation) have been presented in Brockbank et al. (2011), Bromley et al. (2013), Koros et al. (2016) and Sepulveda et al. (2017). A representative contour map of the subsidence anomalies is shown in **Figure 3** and a plot of rate changes with time at key benchmarks near the centres of these anomalies in **Figure 4**.

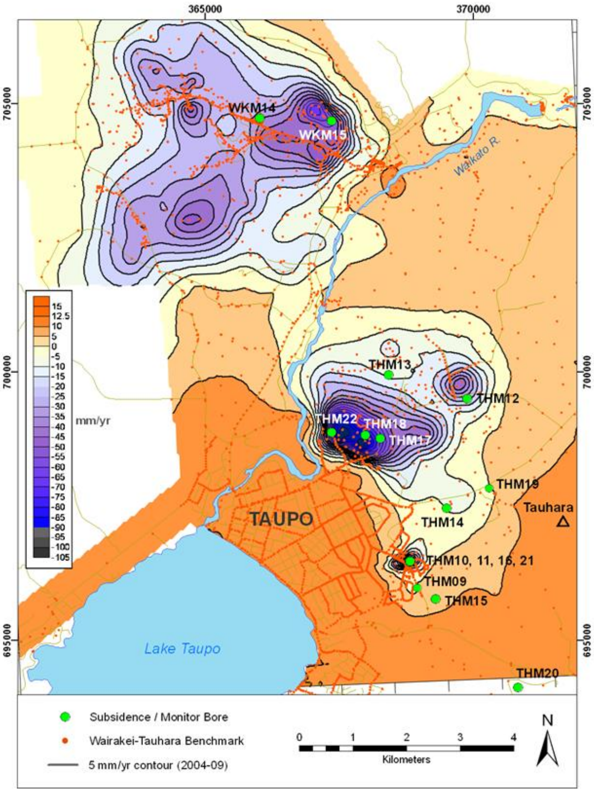

Figure 3: Subsidence rate map (2004-2009) of Wairakei-Tauhara with THM investigation/monitor bores (from Bromley et al., 2015); anomalous 'bowls' occur at Wairakei (WKM15), Spa (THM18), Rakaunui (THM12) and Crown (THM10).

Accumulated subsidence of more than 1m has occurred across a large proportion of the area of the Wairakei-Tauhara system. This is caused by the wide-spread effects of pressure drawdown in the production aquifers, which has diffused slowly up into the clay cap rock through steam zones in the Upper Waiora and Mid-HFF aquifers. This cap consists of layers of highly compressible, low permeability and hydrothermally-altered mudstones (especially Upper- and Lower-HFF). In a few specific locations, such as at the Wairakei Bowl (adjacent to Geyser Valley and NE of EBF), Spa and Rakaunui Bowls (north Tauhara) and Crown Bowl (south Tauhara), the presence of thicker and shallower layers of yielding hydrothermal clays, at depths between about 50 m and 300 m, has resulted in larger subsidence, accumulating by January 2017 up to 15.6 m, 3.1 m, 2.7 m and 1.4 m, respectively (**Figure 4**). In almost all cases the subsidence rate history follows a smooth curve. It can be simulated analytically using fitted sigmoidal (or 'Boltzmann') functions. This represents compression by an amount that is controlled by the product of pressure change, compressibility and thickness, and diffusion of the pressure change at a rate that is controlled by permeability (Bromley, 2006, Sepulveda et al., 2017). Projections out to 2020, as plotted in **Figure 4**, were originally made using fitted functions applied to data up to 2010 (Bromley et al., 2013). 1D simulations were also constructed by applying known and interpolated pressure history to measured core compressibilities and yielding parameters, averaged onto 25m thick layers across the depth range of the THM series of fully-cored investigation bores.

The observed subsidence at Crown bowl (RM59) has subsequently deviated from the simple sigmoidal projection, but it trends towards that predicted using the 1D model, which took into account likely pressure trends and timing of a non-linear transition to yielding at different depths. The Spa and Rakaunui bowl observed subsidence rates have both been slightly less than those predicted, and the Wairakei bowl subsidence rate has been slightly higher. The latter is explained and analytically simulated in Sepulveda et al. (2017) as a consequence of renewed pressure decline occuring in the Waiora aquifer (**Figure 2**) from expanded production at Te Mihi, commencing in 2011.

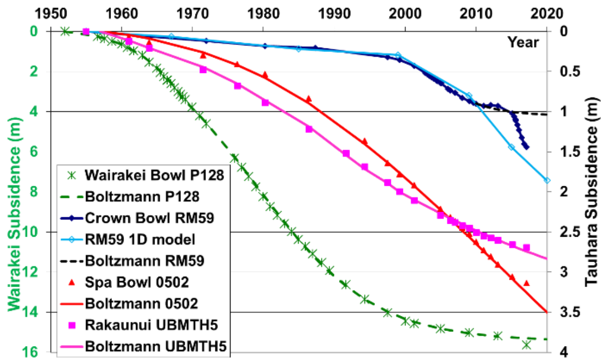

Figure 4: Subsidence level change history near centres of Wairakei, Spa, Rakaunui and Crown bowls.

Subsidence modelling efforts are on-going using coupled TOUGH2 and ABAQUS software at Auckland University. Non-linear yielding mechanisms for the weakest mudstones/clays have been successfully simulated using a 'Modified Cam Clay' approach (eg. Koros et al., 2016). The Wairakei bowl subsidence history has been matched using a 1D coupled model constrained by measured core compressibility parameters and simulated pressures.

Continuous GPS records obtained in the past decade by GNS Science and Contact Energy at several key locations around Wairakei-Tauhara (Aratiatia Dam, Taupo Airport, THM16-Crown Road, THM17-Centennial Drive, Te Huka Power Station) provide an independent and useful dataset for monitoring changes in ground levels. These data show, for example, that the Aratiatia Dam site, which is the reference station for all Wairakei-Tauhara precise levelling surveys, is not static but has been steadily subsiding over the past 8 years at an average rate of -7 mm/yr (relative to a Tasman Plate origin). This affects the determination of regional or background gravity changes (as discussed below) because of the difference between the long-term gravity reference site (Taupo Fundamental, close to Lake Taupo) and the levelling reference site.

Analysis of the continuous GPS data at THM16 (Crown bowl), in conjunction with downhole pressure and temperature, rainfall and ambient temperature, micrometer measurements of the width of a tension crack at the shoulder of the bowl (#2 Invergarry Road), and a period (in 2017) of continuous gravity monitoring, is ongoing. It is hoped that this work will illuminate the causes for the observed variations over time in subsidence rates shown in **Figure 4**.

2.2 Micro-Gravity

Repeat microgravity surveys across the Wairakei-Tauhara system have been conducted at regular intervals since the 1960's. Their purpose has been to monitor the local effects of changes in net mass caused by fluid extraction, reinjection, and recharge. These micro-gravity changes are strongly influenced by the effects of density changes in 2-phase zones, where boiling from pressure decline causes steam saturation increase, or where liquid recharge (e.g., from injected fluid, upflow, downflow or lateral inflow) causes liquid saturation increase. The results of repeat surveys of Wairakei (between 1961 and 1991), are given in Hunt (1995), while Hunt and Graham (2009) summarize the gravity change observations and interpretations (in terms of mass and density or saturation changes) from repeat surveys of Tauhara (between 1972 and 2006). Subsequent system-wide micro-gravity surveys, commissioned by Contact Energy, were conducted by GNS Science in 2009 and 2017 (**Figure 5**). The same gravity meter has been used for all the surveys; equipment age, in this case, leading to more stable measurements and better accuracy because of lower instrument drift rates.

At Wairakei, the initial response to pressure decline and boiling between 1958 and the 1970's was a large gravity decrease across all the borefield areas, indicating density decrease from steam-zone development. This was followed by gravity increases: north-eastern Geyser Valley in the 1970s, Eastern borefield (EBF) in the late 1970s, Western borefield (WBF) in the late 1980s, Te Mihi and southwest of the Western borefield in the early 1990s (Hunt, 1995). Such increases result mainly from liquid re-saturation of pores and fractures where 2-phase conditions exist, and would normally accompany a rise in deep liquid pressure. However, there was a significant delay in time between the onset of gravity increases and the onset of deep pressure increase, which only became pronounced when reinjection increased between 1999 and 2011 (**Figure 2**). This observation is consistent with the conceptual hypothesis that much of the recharge water was originating from above the steam zone (from groundwater) rather than from below (i.e. an upflow). The history of groundwater level changes (discussed below) is consistent with this hypothesis. Downflows of shallow fluid from the areas of Geyser Valley (NE of EBF in Figure 1), EBF, WBF and Alum Lakes (NW of WBF) affected local groundwater levels (Bromley and Clotworthy, 2001) and chemistry of discharge fluids (Glover and Mroczek, 2009).

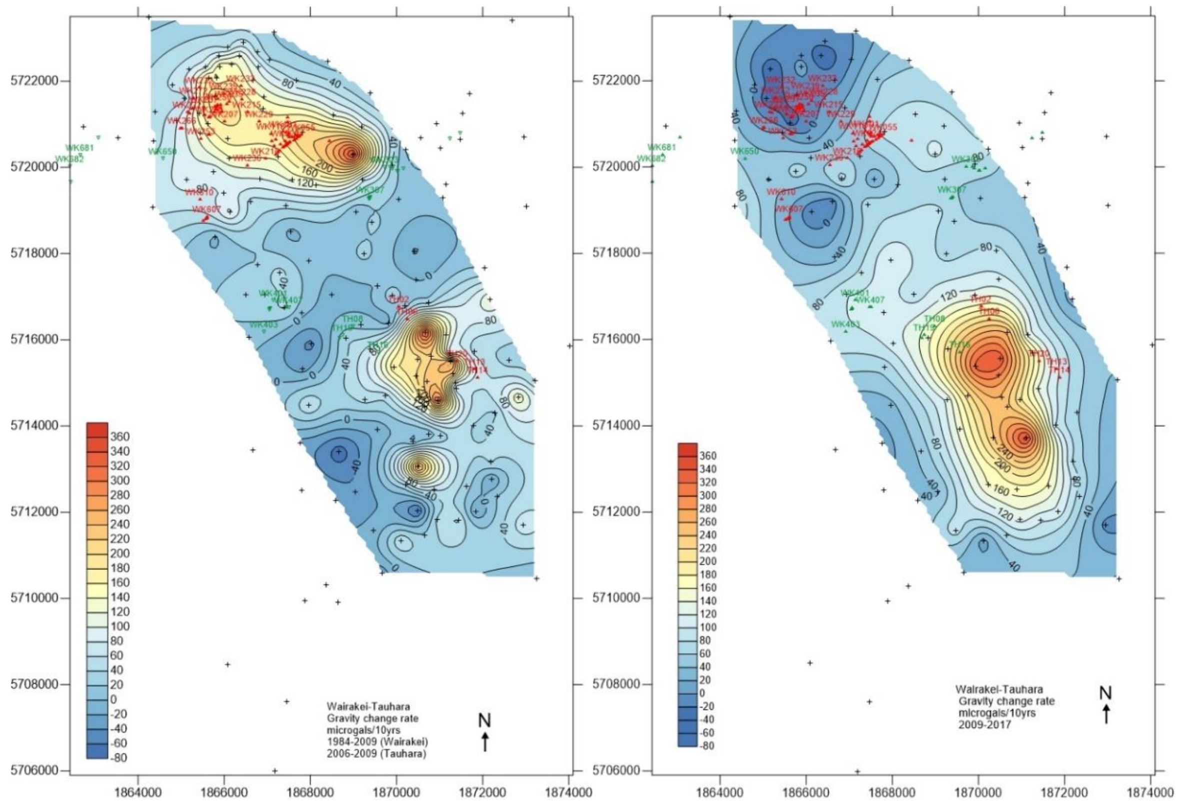

Figure 5: Wairakei-Tauhara gravity change rates (per 10 yrs) for the periods a) 1994-2009 and b) 2009-2017; red is positive, blue negative; contours masked to infield; production wells in red; re-injection wells in green; bench-marks in black.

At Tauhara, although power production (at Te Huka binary plant) didn’t commence until 2006, reservoir pressure changes originating from the Wairakei operation had already transmitted across to the Tauhara field by 1966, causing local boiling, net mass loss and gravity decline. From 1985, gravity in parts of northern Tauhara (centered at TH4, located 500m SE of TH6, **Figure 5**) also started to increase as liquid recharge began to re-saturate the steam-dominated boiling zones. A postulated explanation by Hunt and Graham (2009) was a downflow of water within TH4 from a casing break at 393 m, outflowing at 900-1000m, and raising the local pressure sufficiently to re-saturate the upper Waiora steam zone (~700m depth) causing a density increase around this well. However, given the large mass flow required (~850 t/hr), and the lack of any observed decline in groundwater levels, this seemed unlikely, so an alternative hypothesis has been suggested: after 1985 pressures in the mid-HFF aquifer fell sufficiently to allow liquid water to flow laterally into a bowl-shaped depression across the top of the lower HFF aquiclude, thereby causing ponding and local re-saturation of the steam zone at the base of the mid-HFF aquifer.

The latest micro-gravity changes, 1994-2009 (15 years) and 2009-2017 (8 years) are normalized to rates per 10 years in **Figure 5** to allow for comparison. They show that both periods were dominated by gravity increases, implying net mass increase from liquid recharge. For 1994-2009, a large positive anomaly (>160 µgal/10 yrs) was distributed across all the Wairakei borefields (Eastern, Western and Te Mihi sectors). Another positive anomaly (>100 µgal for 2006-2009) is located in northern Tauhara. Since 2009, the positive anomaly over Tauhara has intensified and broadened to the south, while the one over Wairakei has reduced to a minor negative anomaly (-20 µgal/10yrs) centered over the Te Mihi production sector. These observations are consistent with the hypothesis of an over-flow of re-saturating liquid along the base of the mid HFF at Tauhara, and increased boiling due to renewed pressure drawdown, since 2011, in the Te Mihi production sector.

Numerical integration of the gravity changes and application of Gauss’s theorem across the entire geothermal system (68 km^2 in **Figure 5**) implies net mass gain over the 2009-2017 period of 114 Mt ($\pm$ 20%). Total production was 719 Mt and injection 403 Mt, resulting in a net mass loss of -316 Mt. Therefore, induced fluid recharge is calculated to be about 430 Mt, or about 52 Mt/yr. Over the previous 1994-2009 period, the Wairakei gravity changes indicated a net mass increase of about 120 Mt ($\pm$ 20%) and, given a net mass loss from Wairakei operations of 585 Mt, an induced recharge of 705 Mt, or 47 Mt/yr, is estimated. The calculated mass increase across the Tauhara gravity change anomaly (2006-2009) was 24 Mt or 8 Mt/yr. Given the consistent gravity change rates observed at several Tauhara benchmarks between 1994 and 2006 (Hunt and Graham, 2009), the total mass recharge rate across both fields has probably remained steady since 1994 at about 52-55 Mt/yr.

2.3 Groundwater-level

Groundwater levels have been monitored throughout the Wairakei-Tauhara system. Some monitor wells have a long history dating back to 1955. An update of selected plots of water level changes is presented in **Figure 6**.

Alum lakes area (NW of WBF, **Figure 1**) experienced an anomalous period of groundwater level decline (up to 5m between 1999 and 2001) which culminated in a local hydrothermal eruption (Bromley and Clotworthy, 2001). A triggered downflow caused by dropping steam-zone pressure balancing groundwater pressure in connecting conduits, with counter-flows then controlled by relative steam/water permeability, was postulated as a mechanism at the time. Nearby monitor bores (e.g. Wk207/0 and Wk228/0 in **Figure 6**) show a continuing, but gradual, water level decline in the surrounding area, suggesting that the effect of the localized Alum Lakes downflow into the steam zone below the HFF cap has not yet stabilized.

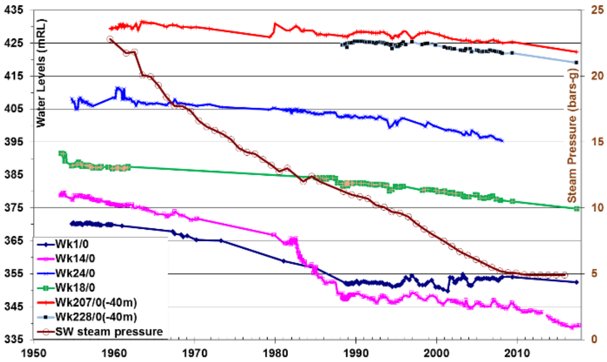

Figure 6: Wairakei groundwater level in selected monitor bores and SW steam pressure history (1954-2017).

Ground water levels near the WBF, represented here by Wk24/0 and Wk18/0, have experienced an accumulated decline of about 15 m. The decline rate accelerated between 1980 and 2005, but has since steadied. The largest water level declines occurred at the border between EBF and WBF (Wk14/0), with up to 40 m decline, at a rate that accelerated between 1982 and 1989. This is thought to have been a temporary response to local casing failures in production bores allowing increased downflows of groundwater before they were cemented up (Bixley et al., 2009). Wk1/0 and nearby E/0 in the EBF, show 18m of decline by 1989, then water level stabilized at about the same elevation as the subsidence pond in Wairakei stream (shown in **Figure 1,** east of the EBF). This is interpreted to indicate that the pond locally controls ground water levels, where shallow permeability is high, and recharging stream water now flows westwards, back towards the groundwater level depression near Wk14/0.

In the Poihipi West outfield injection area (**Figure 1**) three groundwater monitor bores reveal significant decreases in water level (up to -7.6m) between 2009 and 2017. This is interpreted to reflect a gradual return to normal water levels following the closure of the shallow Poihipi condensate injection bore (Wk680) which had previously been linked to gradually rising groundwater levels of a similar amplitude, over the period of its utilization.

At Tauhara, water levels have remained relatively stable since the previous summary (Bromley, 2009), with rainfall variations providing an explanation for <$\pm$1m changes. Importantly, there is no evidence of significant water level changes near Tauhara subsidence bowls or micro-gravity anomalies.

2.4 Surface heat-loss

Monitoring and quantifying changes in surface heat-loss is important for protecting the environment (Daysh et al., 2015) as well as for providing an input for reservoir simulation modelling (Newson et al, 2004). These efforts help improve sustainable resource management.

The last overview of Wairakei-Tauhara heat-loss, documented in Hunt et al. (2009), incorporated learnings from a series of studies undertaken at Karapiti, Wairakei ('Craters of the Moon') by Hochstein and Bromley (1999, 2001, 2005, 2007) and Bromley and Hochstein, (2000). Since then, several studies have improved the accuracy of monitored changes in surface heat-loss at Karapiti and across Tauhara (Bromley et al., 2011, 2015).

A repeat surface heat-flux survey (excluding advective discharges from visible steam vents) was undertaken of the 0.3 km^2 area of steam-heated ground at Karapiti in 2014 (Seward et al, 2018). A plot of the history of all heat loss estimations at Karapiti is given in **Figure 7**. Uncertainties are estimated at $\pm$20%. The area of thermal ground in 2014 is taken from the sum of Thermal Infra-red (TIR) pixels with surface temperature above ambient (>14 °C), whereas previous assessments were based on aerial photos.

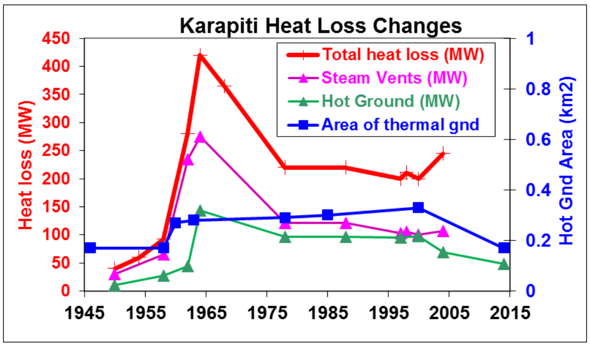

Figure 7: Karapiti surface heat loss changes over time.

In the February 2014 survey, surface heat-flux measurements were collected using a water-calorimeter, extrapolated using vegetation indicators of soil temperature and compared to inferred surface heat-flux determined from thermal imagery collected by the Landsat 8 satellite and an air-borne thermal infrared (TIR) camera (**Figure 8**). Surface heat-loss calculated using calorimetry and airborne TIR methods (described in Bromley et al, 2011) were reasonably consistent, ranging from 47 MW to 58 MW. However, the calculated radiative heat-loss from night-time satellite imagery of Karapiti was much less (2.5 MW). This is thought to be due to spatial aliasing of the low-resolution data (100 m pixel size), the contribution of non-radiative heat-loss (advective and diffusive vapour), and errors associated with corrections for atmospheric conditions (high cirrus cloud), ambient temperature and a variable wind-chill factor.

Although repeat measurements of steam-vent discharges have not been undertaken since 2004 (for safety reasons), a gradual decline is inferred in total surface heat loss from Karapiti over the past 15 years. This is inferred from the observation of reduced sizes of steam clouds at the larger fumaroles, reduced area of hot ground from the TIR surveys, increased vegetation density and height (as shallow ground temperatures cool), and reducing ground temperatures at repeat measurement sites (Mia et al., 2012). Such a decline is consistent with the observed history of a decline in the underlying SW steam zone pressure (**Figure 6**).

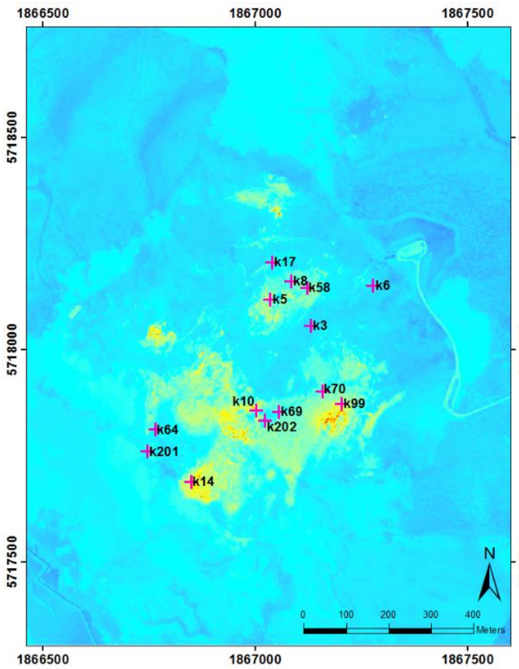

Figure 8: Karapiti Airborne Thermal Infrared image and calorimeter sites (+), February 2014. Yellows and reds indicate areas with high inferred surface temperatures (Seward et al., 2018).

2.5 Seismicity

GNS Science operates and maintains three seismic stations as part of Contact Energy's seismic hazard monitoring programme at Wairakei. These stations are part of the nation-wide GEONET network and are designed to detect relatively large seismic events (nominally M>1.5). Complementary with GNS Science seismic monitoring, Contact Energy commissioned a seismic network in 2009 (Wairakei Seismic Network, or WSN) with the purpose to monitor micro-earthquake (MEQ) activity. The WSN is currently operated by IESE Ltd and uses 13 downhole seismometers installed at depths ranging from 65 m to 1,100 m (Sepulveda et al., 2013). The downhole instrumentation has led to unprecedented sensitivity. For reference, Magnitude of Completeness (Mc) of the WSN has been estimated at Mc = 0.2 (Boese et al., 2014).

In terms of MEQ hypocentre distribution, Wairakei activity can be broadly grouped into shallow (<4 km) and deep (4-7.5 km) events. MEQ activity, with shallow MEQs occurring roughly confined to within the DC resistivity boundary and deep MEQs preferentially offset to the north-west (Sepulveda et al., 2013, 2015, 2016). The distinction between shallow and deep seismicity is illustrated in **Figure 9-B**.

Both near-injection and near-production seismic activity has been detected by the WSN (2009 to present) and this activity tends to define recurrent patterns which are described below and shown graphically in **Figure 9-A**:

1. Near-injection activity:
   a) Otupo seismicity. Some of this activity occurs centred around injection wells and another portion tends to cluster linearly (ENE-WSW strike) to the SE;
   b) Karapiti seismicity. Unlike Otupu seismicity, Karapiti seismicity tends to distribute more diffusely, clustering

preferentially to the north (also NW and NE) of existing Karapiti injection wells;

c) Te Huka seismicity. This activity tends to cluster broadly in a NW-SE direction to the NW of existing Te Huka injection wells. Note that this seismic area overlaps to some extent the east side of Karapiti.

2. Near-production activity:

Poihipi-WBF seismicity. This activity tends to distribute linearly (NE-SW strike) from Poihipi power station in the SW through to the SW end of the WBF in the NE. Overall, this constitutes the most seismically active area of the Wairakei field.

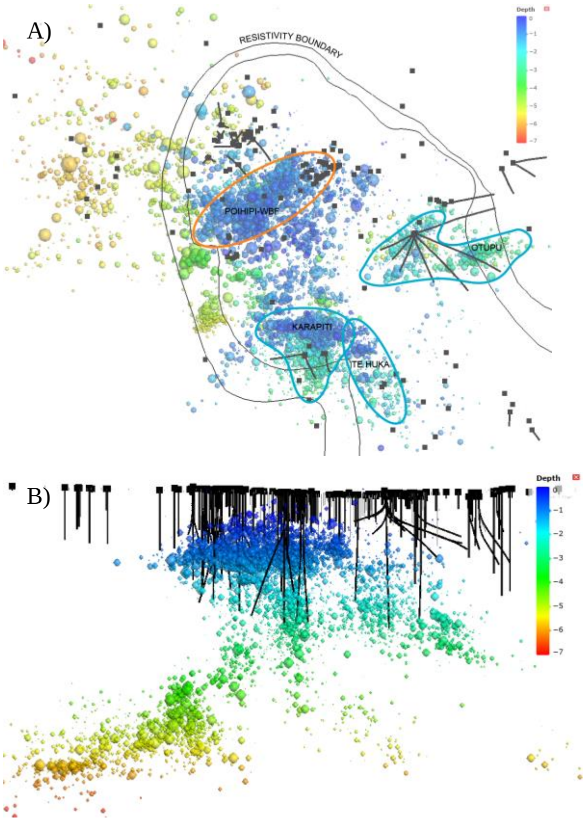

Figure 9: A) Wairakei seismicity map (period 2009-2017) showing clustered seismicity using clustering algorithm of Sepulveda et al. (2015); B) View from the south. Size of dot proportional to magnitude (relative scale) and color proportional to depth.

Regardless of the specific physical mechanism triggering induced seismicity (e.g. pressure changes, thermal stress, poro-elastic, etc.), shallow MEQs tend to cluster at some distance from wells, pointing to geological structure and fluid flow as important factors controlling the hypocentre locations.

3. PHYSICAL PROCESS MODELS

As noted by Dean et al. (2014), good reinjection management is crucial to sustainable energy extraction. Although such management is often focused on minimizing adverse effects from reinjection returns, they noted that it is also important to understand and manage 'secondary' effects, including the effects of changing pressure on boiling of up-flowing recharge fluid. As well as influencing the fluid and gas chemistry (e.g. CO_2 content), some geophysical changes may be caused by interacting fluid and rock properties (e.g. density, porosity, local stress state, strain rate, and fracture permeability). A physical process model is needed to fully interpret such changes.

4. IMPROVED RESERVOIR SIMULATIONS

Geophysical monitoring datasets provide a valuable source of reservoir change information that can assist in the calibration of reservoir simulations, and improve scenario projections of reservoir behavior under selected extraction-injection strategies. The geophysical data is interpreted together with downhole data on pressures, temperatures and 2-phase saturation conditions, and then modelled as an integrated package to achieve optimum results.

This has been particularly relevant to the recent reviews of the nature of the connectivity between the Karapiti injection and Te Huka injection. 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 is helping to improve pressure matching in the numerical model which is important when considering long term reservoir changes in response to production and injection.

5. CONCLUSIONS AND RECOMMENDATIONS

The knowledge gained from geophysical monitoring helps improve conceptual models of geothermal resources and assists development of more accurate reservoir simulations. Exploration or expansion strategies are thereby enhanced. This is clearly demonstrated by the history of monitoring for the Wairakei-Tauhara development.

Key parameters, which can vary with time, include: fracture permeability, saturation change in 2-phase reservoirs, and the flow paths of injected or recharging source fluid. Understanding the physical causes of such changes is important for constructing more robust reservoir models.

Modern micro-earthquake (MEQ) monitoring can provide a dataset suitable for tomography analysis of Vp, Vp/Vs, attenuation (1/Q), and Poisson's ratio. Such properties are strongly influenced by geothermal processes such as phase changes and hydrothermal alteration. Shear-wave analysis may also help determine anisotropic structures (fluid barriers and conduits) and reservoir phase changes (in time and space). This will be helpful for siting future make-up wells and reinjection sites. Monitoring of fluid phase changes (liquid and vapor) by combining MEQ tomography with micro-gravity change analysis also provides useful information for reservoir management, that is, for planning reinjection and production strategy. Combining MEQ with other geophysical data, such as resistivity (MT) inversions, may provide useful knowledge on the likely heat source and deep upflow locations. Deformation monitoring (subsidence) provides useful information on rock mechanical properties, which may also be useful when interpreted in conjunction with gravity change, MEQ results and hydrothermal alteration processes, such as silica dissolution or deposition. These water-rock interactions affect formation porosity, compressibility and brittleness. Finally, monitoring of surface heat-loss changes using remote-sensing methods can illuminate changes in natural and induced reservoir processes which are important to re-construct using reservoir simulators.

The improved understanding of reservoir processes from integration of geophysical monitoring information at Wairakei-Tauhara will also benefit conceptual model development of other geothermal resources, and therefore will improve projections of their long-term sustainable energy extraction capacity and recharge parameters. In general, such knowledge can be applied to exploration and expansion strategies to provide better drilling targets and improved production-reinjection strategies.

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