

## Subsidence: an Update on New Zealand Geothermal Deformation Observations and Mechanisms

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### ABSTRACT

Subsidence, and its effects, from conventional geothermal operations in New Zealand have been well documented and closely studied for many decades. Examples are presented here of local subsidence anomalies that show associations with relatively-shallow, anomalously-compressible, porous formations, weakened by hydrothermal alteration from boiling fluids that passed through shallow outflow structures. Pressure decline, originating from deep production, but diffusing slowly into shallow aquifers and aquiclude, has previously been attributed as the principal cause. Anomalous deformation is found to be the product of subsurface changes in effective stress (either pressure or temperature in origin), acting on a thick sequence of clays, or fractured rocks, which exhibit anomalous geo-mechanical properties. Consideration of the transition between brittle failure and ductile behaviour across a range of temperatures and rock types is also needed. Settlement can increase over time due to non-linear stress-strain relationships such as clay yielding.

This paper reviews New Zealand geothermal case studies from Wairakei, Tauhara, Ohaaki and Kawerau, where applications were recently granted for resource consent renewal or development expansion. These efforts have stimulated additional studies of observed changes in subsidence rates, corresponding horizontal deformation, inferred deformation mechanisms, model predictions and possible mitigation options. Mechanisms involving subsurface temperature change and chemical alteration, as well as transient pressures, are sometimes implicated. Transient tectonic creep, 'shake-induced' subsidence and groundwater level fluctuations acting on buried deposits of unconsolidated alluvium, are also plausible mechanisms for fluctuating deformation rates of natural origin in some settings (for example, Kawerau).

To properly simulate the deformation processes, fully inter-coupled Thermal-Hydraulic-Mechanical-Chemical modelling would be preferred, but history matching suffers from a plethora of variables and a shortage of good subsurface data. Fundamental rock properties used in traditional reservoir simulation, such as permeability, porosity and stress state, which are usually treated as constant parameters in history matching and subsequent scenario predictions, turn out to be significant variables in deformation modelling. Alternative and more pragmatic modelling approaches that simplify the geothermal subsidence process have proven to be reasonably successful where rate changes are smoothly varying, but predictions retain significant uncertainty, particularly where non-geothermal mechanisms are important, and where the hydro-geological properties of shallow layers are poorly represented in the simple models. However, adaptive mitigation options for adverse effects of subsidence, using comprehensive monitoring, are generally accepted. These are usually expressed in terms of targeted injection management to control pressure and temperature.

### 1. INTRODUCTION

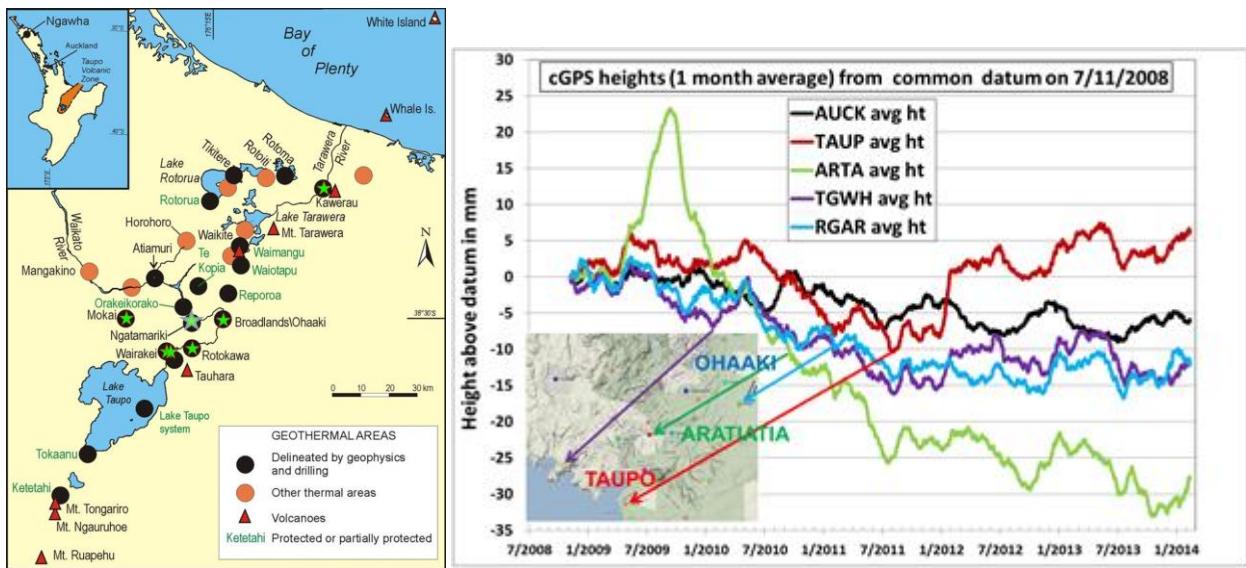
Rates of tectonic deformation across New Zealand's geothermal systems hosted in the Taupo Volcanic Zone (TVZ), a volcano-tectonic rift setting (Figure 1(a)), are relatively high. Consequently, rates of anomalous ground surface deformation and natural seismicity can also be relatively high, both inside and outside geothermal systems (Bromley, 2014). There are also a variety of other causes for observed anomalous ground deformation occurring within the reservoir boundaries of New Zealand's geothermal systems, including reservoir pressure or temperature change, ground vibration and groundwater level changes. The key factor that appears to control the location of most local subsidence anomalies is the presence of buried anomalously-weak material.

The tectonic rifting process stresses the ~12 km thick brittle crust, which generally deforms seismically, that is, by brittle failure. The underlying wedge of mantle material (from ~12 km to ~150 km depth) is hot enough to deform a-seismically (that is, by plastic or ductile deformation). The deeper subducting Pacific Plate (>150 km depth) is cooler and more rigid, and therefore again hosts earthquakes, although the effects of these, at the surface, are attenuated by the hot ductile layer. Within the TVZ crust, pockets of partial melt ('magma chambers') are inferred to exhibit ductile deformation including periods of inflation and contraction during and after episodes of magmatic fluid injection. They also exhibit anomalous seismic velocity, density and thermal properties.

The rifting process also causes horizontal stretching of the ground surface (or extension) by about 5 to 15 mm/yr and regional subsidence averaging 3 mm/yr. The variability in time and space of such rates over recent years is illustrated by data from continuous GPS stations (GeoNet.org.nz) and differential InSAR images (Samsanov et al., 2011, and Hole et al., 2007). An example is given in Figure 1(b) of the history of relative changes in height observed at several cGPS sites at central TVZ sites surrounding (but not within) the geothermal fields near Taupo (referenced to the Tasman Plate). Consistent regional variations in deformation (~7 mm) across this central TVZ area are presumed to be transient tectonic 'creep' events, of several months duration.

At Aratiatia, between Wairakei and Rotokawa, an out-field injection-induced elastic response to a brief pressure increase occurred in 2009. After 2011, long term trends at Aratiatia (which is used as an external base station for Wairakei, Tauhara and Rotokawa levelling surveys) suggest that it is subsiding (relative to the Tasman Plate) at about 5 mm/yr. Conversely, a brief inflation event recorded in early 2012 at Taupo Airport and nearby Kinloch Bay is thought to have been caused by a deep-seated magma intrusion event beneath Lake Taupo volcano.

Graben structures associated with the TVZ spreading rift are in-filled (to about 1-3 km depth) with young erupted volcanic rock and sedimentary material. This is generally of lower density, higher porosity and weaker strength than the basement. The shallower deposits in particular are generally poorly consolidated. The basement is mapped or inferred using gravity surveys and borehole geology, and consists mostly of greywacke, with some cooled intrusives and buried lavas (e.g. andesite). Such formations are relatively strong. If the temperatures are below about 370-400 °C, the basement rocks deform under tectonic stress by fracturing, generating micro-earthquakes and thereby creating or maintaining permeable faults and associated structures. These sustain natural fluid flow over the life-time of geothermal systems by counteracting the natural process of fracture sealing through hydrothermal mineral deposition and clay alteration. If the temperatures of the basement are much higher, then the deformation is likely to be ductile or plastic, that is, aseismic.



**Figure 1: a) Locations of geothermal fields in the TVZ; \* marks producing systems with regular subsidence levelling surveys; b) cGPS heights from GEONET sites near Wairakei, Tauhara, Rotokawa and Ohaaki geothermal systems.**

Part of the TVZ infill consists of a sedimentary sequence of mudstones, siltstones and sandstones, for example, the Huka Falls Formation at Wairakei and Ohaaki or the older Tahuna Formation at Kawerau (Figure 1a). These formations are found beneath many central and northern TVZ geothermal fields at intermediate depths of up to 600m. The siltstone and mudstone components usually act as capping layers or aquitards to fluid flow. They are generally more porous (30% to 60%) and up to two orders of magnitude more compressible than the basement rocks (typically 5-10% porosity). These sediments are therefore much more susceptible to compaction following pressure decline. The low vertical permeability of the aquitard provides a delaying mechanism whereby pressure and temperature changes diffuse relatively slowly, postponing the subsidence effect.

Subsidence has been an environmental issue at several New Zealand geothermal fields. Consequently, it has been comprehensively dealt with through submissions to geothermal resource consent hearings, subsequent operational consent conditions and long-term monitoring programs. For predicting future effects, however, there is a need, in all cases, to consider carefully all potential deformation mechanisms, particularly when building detailed Thermal-Hydraulic-Mechanical-Chemical (THMC) models.

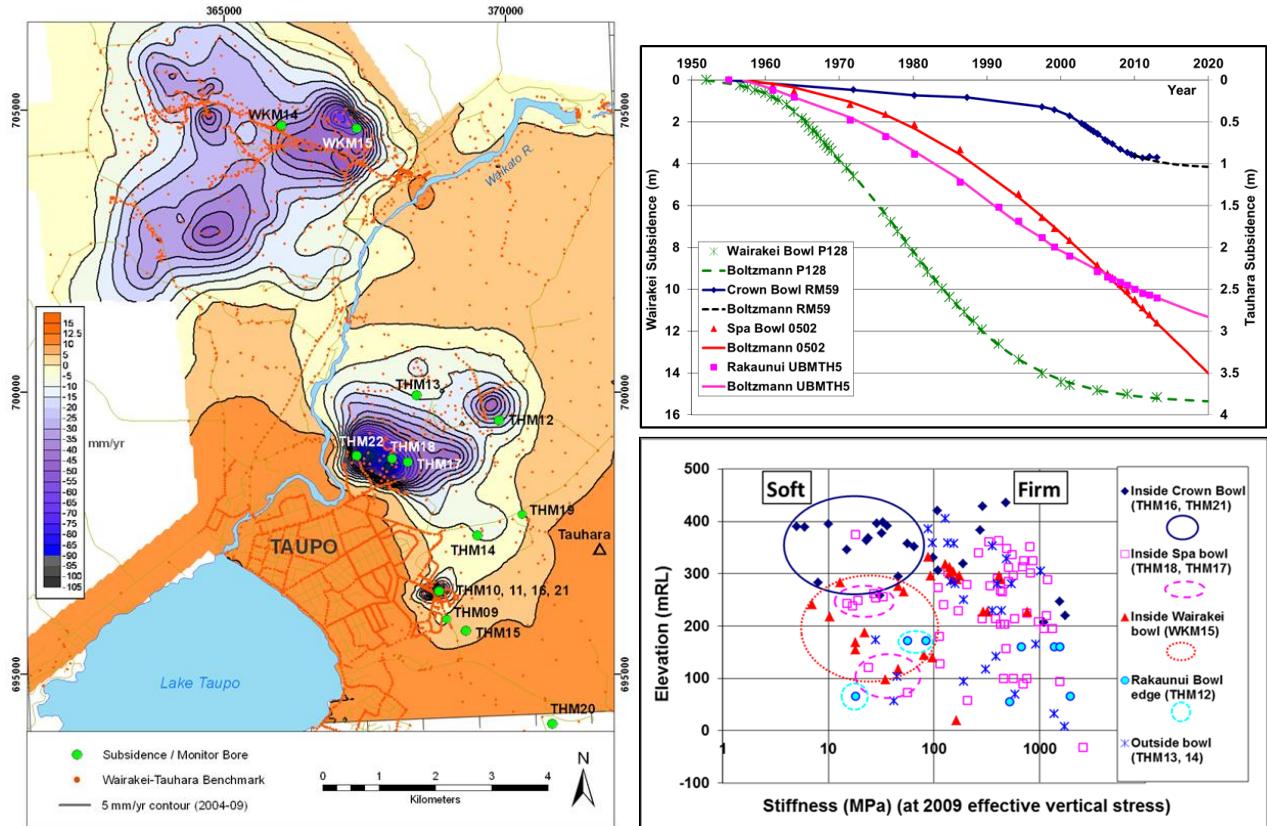
## 2. SUBSIDENCE SURVEYS

Subsidence levelling surveys have been conducted routinely across all the New Zealand producing geothermal fields, and the results from Wairakei, Tauhara, Ohaaki, Kawerau, Mokai and Rotokawa have been described in numerous publications, reports and public submissions in connection with resource consent applications. The history of levelling survey techniques and instrumentation used was described by Currie (2001). As a resource consent condition, regular reports on repeat levelling surveys are prepared by survey companies (Central Surveys for Ohaaki and Energy Surveys for the others) and submitted to the appropriate Regional Council (Bay of Plenty for Kawerau, Northland for Ngawha and Waikato for the others) for review by the appropriate independent Peer Review Panel. In some parts of Wairakei, Tauhara, and Ohaaki, accumulated maximum subsidence of more than 3m (or rates greater than 100 mm/yr) were measured historically within several 'bowls' or anomalies. These have been discussed and modelled in, for example, Allis *et al.* (2009), Bromley *et al.* (2013), and Bromley and Reeves (2013). Table 1 is a summary of the maximum accumulated subsidence and subsidence rates within each of the main 'bowls' in geothermal fields with long term monitoring records.

### 2.1 Wairakei -Tauhara

Levelling surveys at Wairakei date back to the commencement of production testing in the 1950s (Currie, 2001). Measurements on samples from relatively shallow deposits of mudstone, pyroclastics, hydrothermal eruption debris, or hydrothermally-altered

breccia, show locally anomalous properties, i.e., relatively high porosity and clay content, and compressibility that can be about ten times greater than that of surrounding or deeper formations. Samples from such deposits sometimes reveal ‘yielding’, whereby the compressibility increases a further 5- to 10-fold when subjected to an effective vertical stress change exceeding the yield stress. This yield stress can be within the range of in-situ vertical stress (that is, overburden weight minus pore pressure) experienced by these deposits over the duration of production-induced pressure decline. Weak, yielding formations have been found to be responsible for the main subsidence bowl (15m of accumulated subsidence) within Wairakei, (Bromley *et al.*, 2013). These very weak formations consist of hydrothermally altered Huka Falls Formation and hydrothermal eruption breccia, at ~100m to 300m depth. Porosities range up to 65% and compressibility ranges from  $2 \text{ E}^{-3} \text{ MPa}^{-1}$  to  $130 \text{ E}^{-3} \text{ MPa}^{-1}$ . The driving mechanism is pressure change which diffuses slowly through aquitards into shallower aquifers (Brockbank *et al.*, 2011).



**Figure 2:** a) Wairakei-Tauhara geothermal system subsidence rate anomalies and investigation/monitor boreholes. Aratiatia Dam, the reference site, is located in the top right corner; b) Subsidence history (with some backwards projections from nearby BMs) and fitted analytical models at BMs near the centres of the 4 main bowls: Wairakei-WKM15, Spa-THM18, Rakaunui-THM12, Crown-THM10; c) K0 compressibility test results.

**Table 1: Summary of subsidence bowls in New Zealand geothermal fields**

NZ Geothermal subsidence summary				
Field & bowl	Total	Max rate	Year max	Current rate
	m	mm/yr	yr	mm/yr
Wairakei Valley	15	500	1974	50
Ohaaki West	6	400	1994	170
Tauhara- Spa Valley	3	110	2005	110
Tauhara- Crown Rd	1	60	2004	20
Kawerau	0.75	50	2012	50
Mokai (injection)	0.2	30	2009	10
Rotokawa (injection)	0.2	50	2007	10
Ngawha	0.03	3	2012	3

**Table 2: Fitted analytical model parameters (Boltzmann functions)**

Boltzmann :	S=P(T)HC*(1-1/(1+exp((T-Tm)/Td)))			
Bowl (BM)	P(min)HC (m)	T(Pmin)	Tm(yrs)	Td(yrs)
Wairakei (P128)	15.45	1968.8	1979.1	8.2
Spa (BM0502)	4	2020	1989	18
Rakaunui (TH5)	3.5	1994	1994	18
Crown (RM59)	0.73	1980	2004.6	3.1
Ohaaki (SP1)	7.2	2001	2001	6.5

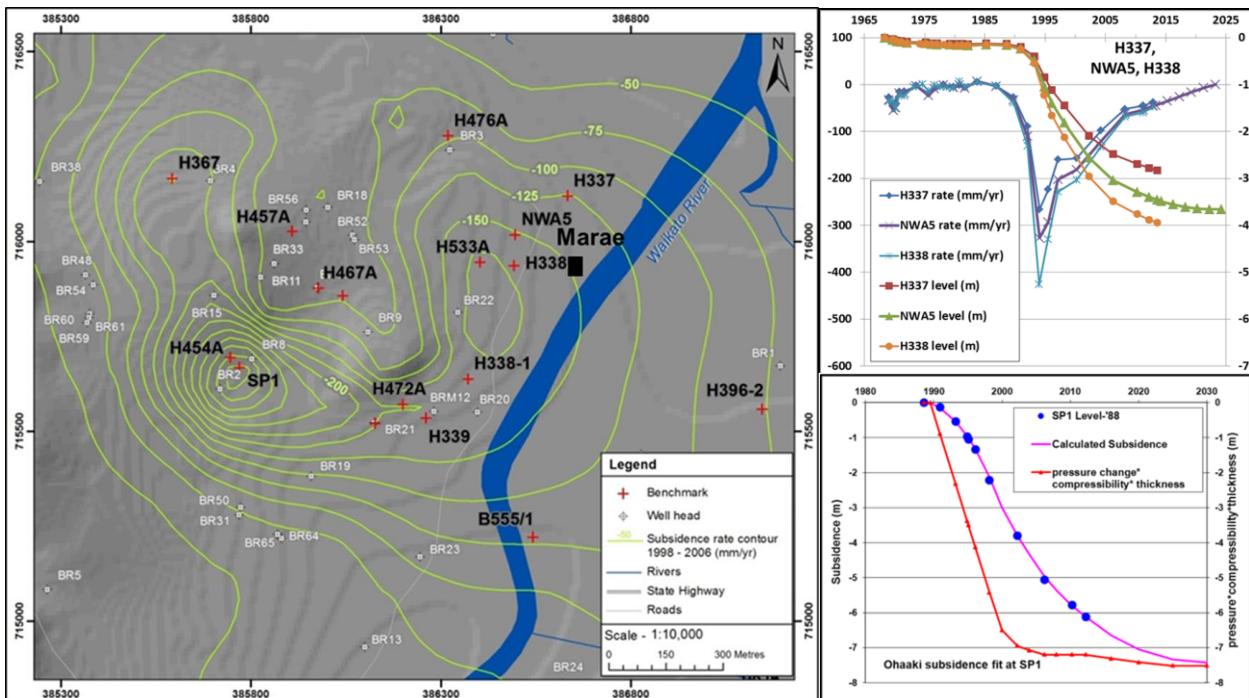
Analytical modelling using a fitted Boltzmann function was first described in Bromley (2006). The method represents diffusion through low permeability cap rock of a driving parameter consisting of the product of pressure change, thickness and compressibility. It was applied to the Wairakei, Tauhara and Ohaaki subsidence anomalies to assist with subsidence projections. The results are illustrated in Figure 2b, and the fitted parameters are listed in Table 2. The diffusion time is  $T_d$ ; the year when the subsidence event reaches its peak rate is  $T_m$ ; the year the driving force (the pressure decline) reaches its minimum is  $T(P_{min})$ ; and the final subsidence ( $m$ ) is the integrated product of the pressure change  $P_{(min)}$ , layer thickness ( $H$ ), and compressibility ( $C$ ).

The local subsidence anomaly at Crown Road is relatively small in area ( $<1 \text{ km}^2$ ) but controversial because of its proximity to urban areas, and late commencement (1999, Figure 2b). Its cause was initially attributed to the effects of shallow groundwater level decline, acting on a deposit of hydrothermally-altered material (Bromley *et al.*, 2009). After further investigation drilling, a 30m to 200m deep hydrothermal eruption breccia deposit was found. It in-filled a buried 11 ka crater (Bromley *et al.*, 2013). The results of  $K_0$  compressibility testing of core from within the Wairakei and Tauhara subsidence bowls (Pender *et al.*, 2013) showed the effects of anomalous clay yielding at effective yield stresses within the range of in-situ vertical stresses. The anomalous deformation process is largely inelastic and permanent.

## 2.2 Ohaaki

Subsidence monitoring at Ohaaki dates from the earliest period of reservoir testing in the 1960s. As a consequence, some local subsidence was expected when full-scale production for a 105 MW power station commenced in 1988, so the levelling survey network was intensified and monitoring continued at a minimum of 4 yearly intervals (Central Surveys, 2012). The shape of the anomaly thereby revealed has changed over time. It started off as a simple bowl centred in the western borefield (at Benchmark H467A in Figure 3a), but, in the 1990s it expanded into a subsidence ‘moat’ incorporating a local anomaly (centred on SP1), as revealed by the subsidence rate contours for the period 1998 to 2006 (Figure 3a). The proposed geological explanation for this shape change is that the subsidence has largely resulted from consolidation (through pressure decline in a shallow aquifer) of anomalously compressible portions of Huka Falls Formation sediments where they have draped over a buried rhyolite dome (Ohaaki Rhyolite). The top of the dome around H467A was affected first, then its flanks (Allis *et al.*, 1997). The timing of changes in rate was affected by significant permeability variations (both vertical and horizontal) within the draped sequence of hydrothermally-altered sands, mudstone and breccia. The shape of the anomaly is also influenced by lateral variations in average compressibility of the material. Hence the SP1 anomaly is attributed to a difference in rock properties rather than a local difference in pressure changes.

Figure 3b illustrates the changes in level and rate over time at benchmarks near the Waikato River and the Ohaaki Marae, a group of buildings and cultural features that are vulnerable to accumulated subsidence because of the risk of inundation during flood events. The changes can be divided into three events: a) the initial changes during the 1960s test period, b) a short duration high amplitude event in 1994 during the period of greatest pressure decline, and c) a broader event peaking in 2000 that is now slowly dissipating. At SP1 the rates were dominated by the long-duration event which peaked in rates in 2000. Figure 3c illustrates how this has been used to: a) establish an analytical model to represent the subsidence process; b) optimize a fit to the observed data; and c) provide predictions for future subsidence. The process involves use of the ‘Boltzmann’ function, as at Wairakei and Tauhara (Table 2). The subsidence driver is the product of pressure change\*layer thickness\* compressibility, while the Boltzmann function simulates diffusion through low permeability cap rocks.

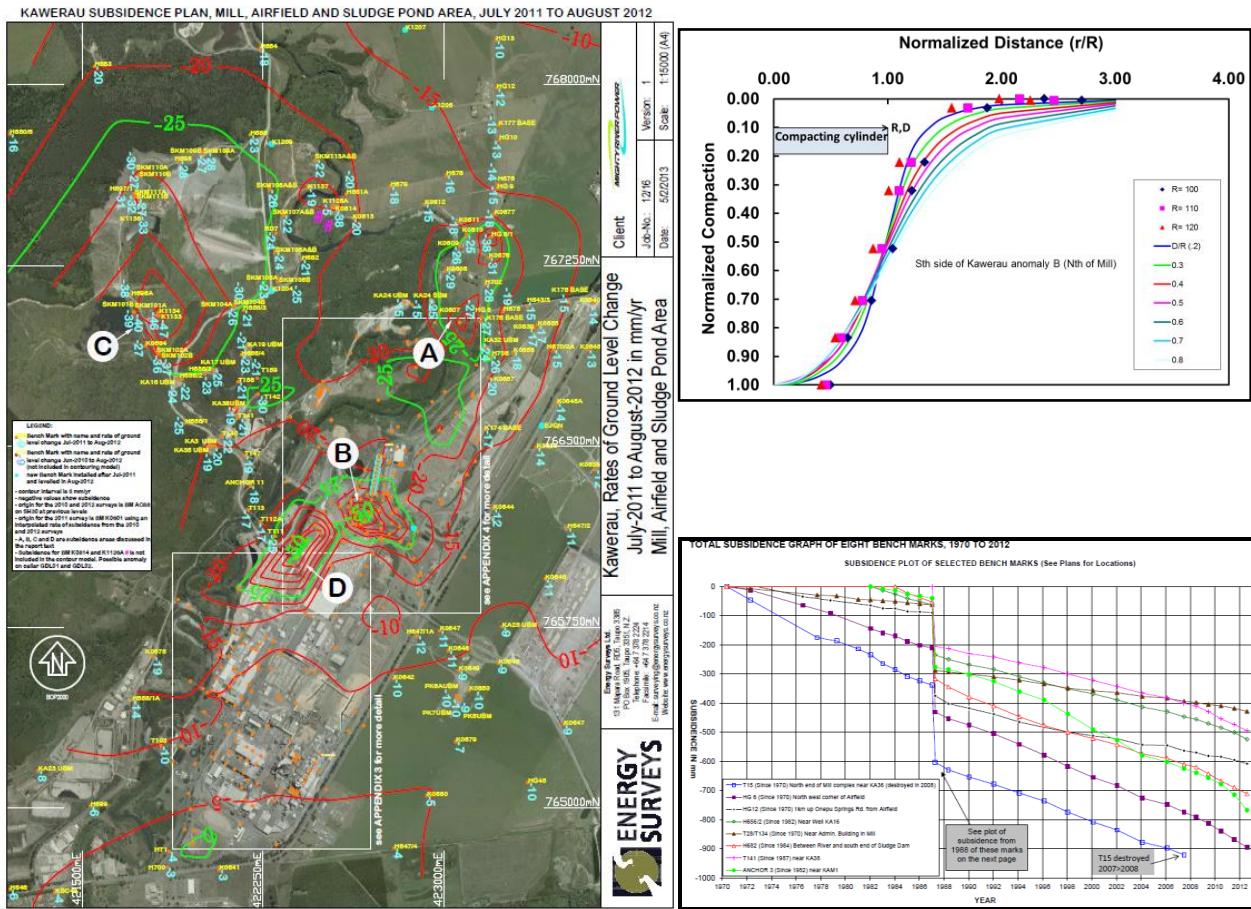


**Figure 3: Ohaaki : a) contour map of average subsidence rates 1998 to 2006; b) history of level and rate changes since 1967 near Ohaaki Marae; c) analytical model fit (Boltzmann) and projection of levels at SP1 from 1989 to 2030.**

In the future scenario illustrated, the driving factor is anticipated to decline slightly based on predicted shallow pressure changes from the current reservoir simulator, for the recently-consented extraction and injection volumes (40,000 t/d).

### 2.3 Kawerau

Kawerau Geothermal Field commenced production for industrial direct use in 1957, and subsidence level monitoring across the field commenced in 1970. Total mass discharge subsequently grew from 6 Mt/yr (190 kg/s) in 1972, to 12 Mt/yr by 1988. It remained approximately the same until 2008, then increased to 36 Mt/yr (1140 kg/s) when MRP's 100 MW Kawerau Power Station was commissioned. Shallow reinjection amounted to about 2-4 Mt/yr from 1992, and deep reinjection has been about 16 Mt/yr since 2008. Hence, the net mass extraction from the reservoir went through two significant increases: 1972 to 1988, and from 2008 onwards (~17 Mt/yr). Average subsidence rates, calculated on an annual basis, have been quite erratic. However, when smoothed out across intervals of 2-4 years, there is a weak correlation ( $R^2=0.4$ ) between net mass extraction and average subsidence rate at 16 indicative benchmarks, indicating that for every additional 1Mt/yr of net mass discharge there has been an additional average subsidence of about 1 mm/yr at the indicative benchmarks. The origin of this subsidence is attributed to reservoir pressure and temperature decline. Bruno (2013) modelled the geothermal component of this subsidence using the deformation of modelled pressure and temperature changes, by integrating their surface effect across the gridded block model of the reservoir, and by using fitted values for rock compressibility and thermal expansion coefficients for each lithology. This accounted for a broad anomaly across the entire geothermal field, with a central maximum rate of about 10 mm/yr. What was not modelled was an inferred "non-geothermal" component which consists of several local anomalies. These are labelled A to D in Figure 4a, the 2011-2012 contour map of rates in mm/yr across the central part of Kawerau field. Level changes at selected benchmarks, including those nearest the centres of these local anomalies (A to D), are illustrated in Figure 4c. Figure 4b illustrates a model for the likely origin depth of these local anomalies. A simple analytical approach, based on a formulation by Geerstma (1973) allows calculation of the likely depth of the top surface of a compacting cylinder which would recreate the approximate shape of the southern edge of anomaly B. The best fit model has a cylinder radius of 110 m and a depth of 33m. The same method has been used at the other fields.



**Figure 4: Kawerau (from Bromley, 2013a) : a) Subsidence rate contour map for 2011-2012 (Energy Surveys, 2012); b) normalized subsidence profile through south side of anomaly B with fitted compaction depth/radius parameters using compacting cylinder model; c) Subsidence level changes over time of selected benchmarks. The step change in 1987 resulted from the nearby Edgecumbe earthquake (see section 3.1).**

At shallow levels (up to 100m depth) deposits of weak, unconsolidated alluvium can vary significantly in thickness across relatively short horizontal distances, particularly where they have formed in buried topographic depressions such as paleo-river channels. They may be responsible for some elongated local subsidence anomalies, such as observed at Kawerau Geothermal Field. Several of these elongated anomalies located adjacent to the Tarawera River (Figure 4a) have relatively steep edges, implying a shallow origin, and appear to be connected, implying a source related to a buried channel. Based on borehole geology, this inferred channel appears to have been eroded into the underlying Matahina ignimbrite at about 30-100m depth. A deep paleo-river channel could have been the result of a period of rapid fluvial erosion after the volcanic ignimbrite episode. Over time, this and subsequent

erosional channels, may have been refilled by flood deposits, peats, reworked volcanic ash, and other sediments accumulated by a meandering river. Such alluvial deposits could include sequences of unconsolidated sands, clays and organic material, which are potentially highly compressible and subject to significant consolidation or settlement by a variety of mechanisms. Examples of mechanisms include vibration from earthquakes or heavy vehicles, oxidation and drying of organic material (peat), or compaction through declining ground water pressure. Locally, the Tarawera river bed has been steadily declining through erosion (at about 40 mm/yr), and the resulting average river level decline has transmitted to the surrounding groundwater, causing a similar long term decline, and providing a plausible natural mechanism for long-term subsidence.

Potential subsidence mechanisms at Kawerau, particularly those of relatively shallow origin, were also addressed in a thesis by Mackenzie (2012). Modelling of the historic and predicted subsidence contribution from deep geothermal operations, and the issue of subsidence mechanisms and effects has been an on-going subject at four recent public resource-consent hearings (for Bay of Plenty Regional Council) to consider planned incremental increases in geothermal fluid extraction and reinjection. At Kawerau, subsidence mechanisms can be grouped into three main types: a) deep tectonic movement (major earthquakes plus rifting of about 3 mm/yr); b) geothermal reservoir changes (pressure and temperature decline) amounting to about 10 mm/yr; and c) local compaction of buried shallow sediments by up to 50 mm/yr. In 1987, the M 6.3 Edgecumbe earthquake, which was located at 8 km depth and about 20 km NE of Kawerau, caused significant co-seismic subsidence within the geothermal field of about 250 ( $\pm$  120) mm. Some of the earthquake-induced subsidence can be attributed to local fault movement (that is, deep tectonic adjustment to stress changes), but some can also be attributed to differential settlement of sediments during the seismic shaking of the main-shock and aftershocks. This is based on the observed differences of up to 50 mm in subsidence between adjacent benchmarks, suggesting control by local variations in subsoil consolidation properties.

## 2.4 Rotokawa and Mokai

Subsidence levelling surveys have been undertaken using networks of benchmarks established prior to the first stages of production at both Rotokawa (1997, ~35 MW) and Mokai (2000, ~58 MW). Repeats have been undertaken at intervals of 2 to 4 years (Energy Surveys, 2011, Energy Surveys, 2013). In both cases, binary power plants were installed with ~100% reinjection into shallow 2-phase aquifers (at ~400m depth). The injected fluid was about 100 °C cooler than the receiving formation, so subsidence can be attributed, in part, to cooling contraction around the injection wells, as the transient cooling front radiates slowly outwards. This was initially observed near the shallow injection area at Mokai (MK4). Once the local 2-phase conditions become fully saturated, then liquid pressures begin to rise in the injection aquifer. This causes a zone of tumescence or ground inflation to form, which counteracts the effect of the cooling. At Rotokawa, the tumescence effect dominated the cooling effect for the first 7 years (up to +7 mm/yr), but then cooling, centred near the shallow RK12 reinjection area, became the dominant effect from 2004 to 2007. At Mokai, the tumescence formed an anomaly (also up to +7 mm/yr) to the north of the injection sector, furthest away from the drawdown production sector.

Production increased at both fields, to 174 MW at Rotokawa, from 2010, and to 115MW at Mokai, from 2007. In preparation for this, in 2005 and 2008 respectively, reinjection strategies changed in both fields from predominantly shallow to predominantly deep peripheral injection wells. As a consequence, flowrates and pressures in the shallow injection aquifers declined, and the transient tumescence and cooling effects diminished. Superimposed on these injection effects, there have also been small amounts of subsidence originating from pressure drawdown in the deep production aquifers (ground level changes of up to -12 mm/yr). The overall effect, however, has been that maximum rates of ground level change in Rotokawa (Energy Surveys, 2013) reached -47 mm/yr near RK12 (2004-2007), then reduced to about -10 mm/yr (2011-2013). In Mokai (Energy Surveys, 2011), the peak rate was -28 mm/yr at MK4 (2001-2003), declining to -12 mm/yr in the production sector (2009-2011). These rates of ground level change are distributed across quite wide areas and have not caused, to date, any adverse differential subsidence effects on infrastructure or buildings.

An interpretation of observed long-term (pre-production) subsidence rates at Rotokawa by Powell et al. (2011), suggests that natural-state subsidence of 2 mm/yr occurred inside the boundaries of the geothermal system prior to production start-up (pre-1997). This was observed at benchmarks distributed along the Waikato River, which bisects the field. The natural subsidence may have been caused by gradual mass removal from the reservoir through hydrothermal alteration. The main natural alteration process is depletion in silica, creating an increase in porosity. The silica is re-deposited in veins or discharged from hot springs. When accompanied by weakening of the surrounding rock matrix, this process leads to collapse of some (but not all) of the newly created pore space. The resulting formation consolidation causes surface subsidence. This is in addition to natural deformation of tectonic origin, as discussed in the introduction (Figure 1).

## 3. DEFORMATION MECHANISMS

### 3.1 Subsidence from Earthquakes and ‘Creep’

Large earthquakes have been reported to cause co-seismic deformation, in the form of subsidence, within geothermal areas. An example is the 2010, M 8.8, Maule earthquake off the coast of Chile which caused subsidence of 50-150 mm across five remote geothermal systems in the nearby Andes volcanic chain (Pritchard *et al.*, 2013). Another example is the 1987 Edgecumbe earthquake, which caused about 250 mm of subsidence at Kawerau (Figure 4c). This subsidence is largely caused by co-seismic shaking and consolidation of weak sub-soils, including hydrothermal clay alteration.

Intermittent strain release along faults in geothermal areas can also be regulated by visco-elastic processes or ‘creep’. An example is documented by Glowacka *et al.* (2000) at the Imperial Fault near Cerro Prieto geothermal field in Mexico. Continuous monitoring of deformation across the fault revealed relative vertical movement that was not constant but concentrated during ‘creep events’ lasting several days and separated by months of quiescence. The timing of these events did not coincide with production or injection changes, nor with local micro-seismicity, but the principal subsidence driving mechanism was still inferred to be deformation associated with geothermal fluid pressure drawdown within the borefield 8 km away. ‘Slow-slip-event’ earthquakes of a similar visco-elastic nature have been well documented along the eastern margin of the TVZ, where the subducting Pacific Plate

is sliding in a stick-slip fashion beneath the Tasman Plate. Continuous GPS records from central TVZ sites (Figure 1b) suggest that such processes, on a more local scale, are also occurring within the high temperature (ductile) regions and geothermal settings of the overlying TVZ crust.

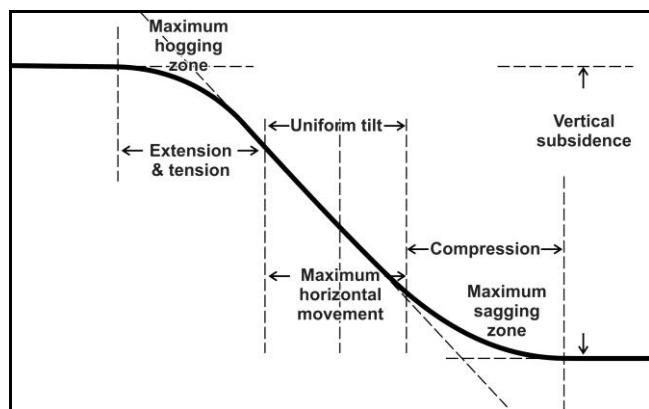
### 3.2 Compressibility and Phase Changes in Steam Zones

An important consideration in conceptual models of the underlying mechanisms behind deformation processes within high temperature geothermal systems is the effect of fluid phase changes. Intuitively, it would seem that boiling linked to pressure decline, or re-saturation of a steam-zone caused by reinjection or natural liquid recharge, should cause a change in the compressibility of the fluid in the pore space, and therefore a change in the effective compressibility for the host formation. In reality, however, it doesn't. A change in pore fluid compressibility does not directly change the associated formation strength; what can change is the pore fluid pressure and temperature, which will, in turn, affect the deformation process through a change in effective stress or vertical load. These fluid property changes are accounted for in a multi-phase reservoir simulator such as TOUGH2. There is no need, therefore, to incorporate, in a simulation model, time-dependent changes in strength parameters when such phase changes occur. However, indirect effects that accompany phase changes may cause rock strengthening or weakening over time. These include acid-condensate hydrothermal alteration into weak clay, or boiling deposition of a stronger mineral such as quartz. Hence, there is probably a need for fully-coupled THMC modelling to simulate the full subsidence story.

At The Geysers Geothermal Field, California, Mossop (2001) identified poro-elastic stressing, due to steam pressure decline, and associated thermal contraction, due to cooling, as mechanisms for shear reactivation on fractures, leading to both micro-seismicity and subsidence. Conversely, however, in 1997 and 2003, subsidence rates slowed within a 1-2 km radius of injection wells in response to increasing cold water injection at 1-2 km depth, while the micro-seismic event rate increased. The dominant mechanism, in The Geysers' case, is thought to be increasing steam pressure from boiling of injected fluid. If however, cooler injected fluid enters the liquid zone directly beneath a parasitic steam zone, then the situation changes. Liquid pressures will rise, and this may halt any subsidence originating from compressible layers at that depth, but the cooler water will also suppress boiling and this will initially reduce the recharge of steam to the overlying layer. This could have the effect of causing a *reduction* in the parasitic steam zone pressure. Accordingly any subsidence sourced from compressible material at the depth of the steam zone would increase. Such a mechanism is postulated to be an explanation for the continued high rate of subsidence at Spa Bowl, Tauhara, despite rising liquid pressures from local reinjection (Figure 2b). By contrast, rates at the adjacent Rakaunui bowl are now showing some evidence of rate reduction, and this is because the local parasitic steam zone has already been fully quenched.

### 4.0 DEFORMATION EFFECTS

Surface manifestations of subsidence include: vertical settlement, uniform tilt, differential tilt, curvature (hogging and sagging), horizontal tension and compression. These are illustrated graphically in Figure 5 (Bromley, 2013b).



**Figure 5: Cross-section of the edge of a subsidence anomaly to illustrate the effects of deformation on rigid structures.**

Simple vertical settlement from subsidence has little direct effect on structures because it is uniform and slow (relative to seismic movements, for example). However, when adjacent to water bodies, inundation can become an issue. An example of the observed effect of settlement is increased flooding of land adjacent to the banks of the Waikato River at Ohaaki Marae, particularly during periods of high river flow-rate.

Tilt typically reaches a maximum near the mid-point of the edges of the subsidence anomaly. Maximum tilt coincides with the location of maximum horizontal movement. These horizontal movement vectors are directed towards the centre of the anomaly, and perpendicular to the contours of subsidence rate. When the source of the compaction is relatively deep, tilt is uniform over a broad zone. This can be seen in Figures 2a, 3a, and 4a, where the contours of subsidence rate are evenly spaced apart. Uniform tilt can adversely affect the performance of surface water, sewerage and storm-water drainage infrastructure, but is seldom, in itself, a cause of serious damage to structures. An obvious example of tilt is the original 25m swimming pool at Wairakei Resort Hotel, still in use today despite an accumulated 1:100 tilt, obliquely aligned to its principal axis.

Differential tilt (sometimes referred to simply as differential settlement) occurs where two parts of a rigid structure (such as a building or pipeline) tilt by different amounts, resulting in hogging or sagging effects. The ground surface, in this setting, deforms into a curve which can be characterized mathematically as the second derivative of the subsidence with respect to horizontal distance. This effect occurs along the inner and outer 'shoulders' of the anomaly, shown as zones of maximum curvature on Figure 5, and typically where the contour spacing changes on a subsidence rate map.

A consequence of anomalous curvature or ground bending is deformation associated with horizontal strain. Compression and tension effects are manifest as buckling and stretching, sometimes forming cracks through rigid structures such as buildings, pipeline foundations, and across hard surfaces. These effects have been seen at several locations around the edges of the Wairakei Tauhara and Ohaaki anomalies, for example, cracks across concrete roadside kerbs.

Despite the apparent severity of the subsidence anomalies shown in Figures 2b and 3c, engineering solutions have been found for the structural effects observed to date. In the case of the risk of flood inundation of the Ohaaki Marae, projections of future subsidence rates (Figure 3b) and 1:100 flood events were used to arrive at a long term solution acceptable by all parties that did not require removal of the buildings but instead the construction of a flood protection bund (Bromley, 2013b).

## 5. DISCUSSION AND CONCLUSIONS

Survey technology is steadily improving. For example, during 2013-2014, continuous subsidence monitoring has been successfully deployed in the Spa anomaly area of Tauhara, by Energy Surveys for Contact Energy, using several short-baseline permanent Global Navigation Satellite System (GNSS) instruments, that is, GPS technology with weekly data solutions accurate to 2mm in 3D. The observed subsidence rates are consistent with those determined from conventional annual levelling surveys. Rapid Real-Time Kinematic (RTK) GPS surveys, now accurate to 15-20mm, can also provide valuable horizontal strain data in areas of significant subsidence, especially if the interval between surveys is 2-4 years. In addition, Lidar survey data in conjunction with photogrammetric mapping, in areas of large subsidence (>1m), can provide a more detailed total subsidence map than is possible from a discrete benchmark levelling survey.

Geothermal subsidence mechanisms can involve a variety of processes. A transition between brittle and ductile deformation may occur at high temperatures. Non-linear stress-strain relationships such as yielding might be important. Settlement can also originate from shaking of seismic origin or vibration from a variety of local sources. Attempts at explaining and modelling subsidence for predictive purposes should take all these possibilities into account.

Advances in joint geophysical imaging, joint deformation interpretation, and advanced data analysis (e.g. THMC modelling) could prove invaluable as a field management tool to optimize make-up and step-out drilling, as well as to better predict the effects of changes in injection strategy on ground deformation.

Injection management is the preferred adaptive tool for mitigating adverse effects from anomalous deformation (subsidence or tumescence effects). The objective is to control or limit induced stress and strain changes without losing the long-term benefits of reservoir development for sustainable energy extraction.

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