NOVEL APPLICATION OF CONTINUOUS GRAVITY AND GNSS TO UNDERSTAND EFFECTS OF LIQUID SATURATION CHANGES ON YIELDING DEFORMATION

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ABSTRACT

Continuous microgravity monitoring and repeated micro-gravity measurements have been trialled at the centre of a site of anomalous deformation in the Wairakei-Tauhara geothermal system. When combined with continuous data from GNSS (GPS), horizontal strain data across a monitored crack, and subsurface pressure-temperature data from shallow monitor bores, the gravity data provides additional information on possible mechanisms that may be driving changes in localized deformation rates over time.

The overall shape of the deformation anomaly remains unchanged, while rates continue to vary smoothly with time. Deformation (i.e. subsidence) mechanisms involving changing conditions in two boiling (2-phase) aquifers, at about 50-80m and 125-175m depth respectively, are postulated. An additional driving mechanism involving incremental yielding and repeated load changes (from passing trucks) is also explored.

Highly compressible hydrothermal clays are hosted within a buried hydrothermal eruption crater, which is ~200m deep near the centre of the deformation zone (based on continuous drill-core) and inferred to be ~200m wide (based on Geerstma fitted parameters to its shape). Sliding on the clay-lined crater walls may account for the shape consistency over 20 years. Significant transitions in clay yielding parameters (yield stress) and pressure decline from cooling groundwater inflow at different depths within the upper groundwater and intermediate-level boiling aquifers, can account for the observed compaction rate variations. Transient loading changes may also partly explain the ongoing deformation through incremental yielding.

1. INTRODUCTION

1.1 Crown bowl history

An anomalous zone of subsidence formed nearly 20 years ago in the Crown Road industrial area of Tauhara, Taupo. Deformation rates have been monitored regularly since 2001 using repeated precise levelling surveys and a variety of other methods (differential InSAR, [Hole et al. 2007], continuous GNSS, and ground strain across a tension crack). In 2010, Contact Energy applied for, and were granted, resource consents to expand development of Tauhara field by up to 250 MWe. The monitoring and mitigation of local subsidence that might be caused by the expansion project was a key aspect of the hearing process (Daysh et al, 2015). Anticipating the importance of understanding the physical mechanism of shallow compaction, Contact Energy Ltd (Contact) initiated a subsidence investigation program in 2009 involving continuous core-drilling, from which a catalogue of rock compressibilities and other properties was obtained. The study included drilling at the centre of the Crown bowl: THM16 to 800m depth (cased to 424m) and THM21 to 200m depth (cased to 137m). These are adjacent to shallow boreholes THM10 and THM11 (~80m depth) drilled previously (2003). Studies of the ground surface changes, the drill-hole results, the local aquifer pressure, phase and temperature changes, and interpretations of compaction mechanisms are documented in a series of papers (Bromley et al. 2003, 2004, 2009, 2010, 2013, 2015 & 2018, Manville et al. 2004 & Brockbank et al. 2011).

1.2 Wairakei subsidence history

Figure 1 is a contour map of the subsidence rates for the period of 2004-2009, illustrating the extent of Wairakei bowl (WKM15), Spa bowl (THM17, 18, 22), Rakaunui bowl (THM12) and Crown bowl (THM10, 11, 16, 21).

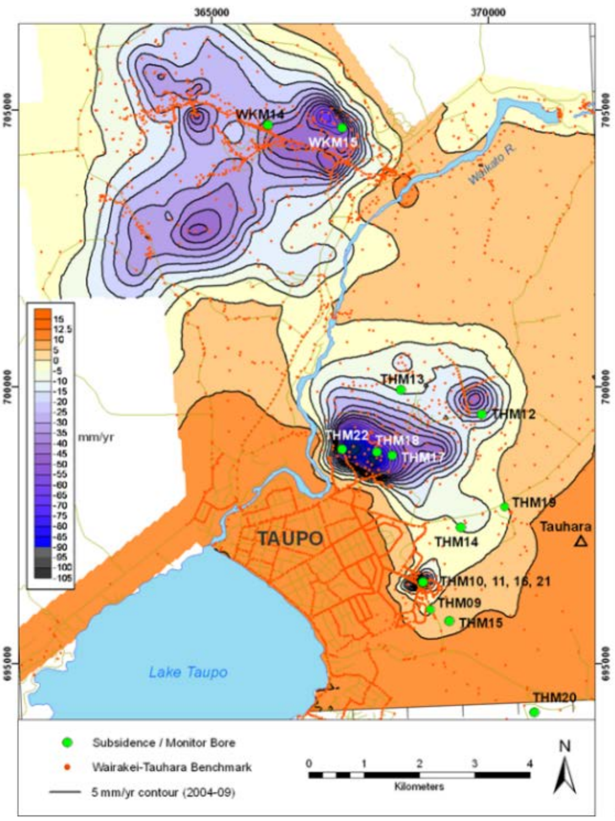

Figure 1: Wairakei-Tauhara subsidence rate anomalies (2004-2009) and investigation/monitor boreholes. Crown bowl is located at borehole THM10.

The wider picture of subsidence within the Wairakei-Tauhara system, including models or simulations of the causes or mechanisms of deformation, has been addressed in several articles over the past 10 years (Allis et al. (2009), Bromley et al. (2009), Bromley et al. (2013), Pender et al. (2013), Pogacnik et al. (2015) and Sepulveda et al. (2017)).

The Wairakei, Spa and Rakaunui subsidence bowls (Figure 1) were discovered and documented early in the history of Wairakei development (from 1958), but the Crown bowl did not become apparent until about 2000 when routine repeat surveys found one benchmark (RM59) showing an anomalous increase in subsidence rate.

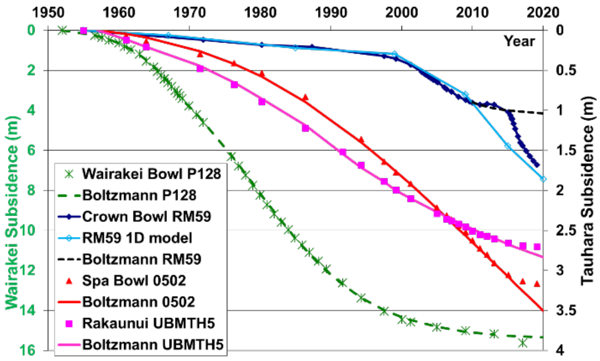

Figure 2: Wairakei-Tauhara subsidence rate history at four key locations: Crown bowl (RM 59) in blue.

Figure 2 shows the history of subsidence at benchmarks near the centres of the bowls mapped in Figure 1. Levels are extrapolated back in time using pro-rata rates from nearby benchmarks. The green curve shows maximum measured subsidence (approaching 16m) at P128, Geyser Valley, Wairakei. The red and pink curves show level changes at Spa and Rakaunui bowls (3.5m maximum), while the blue curve shows the Crown bowl level changes (at RM59). Each set of measured level data was fitted and extrapolated (in 2009) using a sigmoidal (or Boltzmann) function, as described in Bromley (2006) and Sepulveda et al (2017). Clearly, unlike the others, the behaviour of the Crown subsidence bowl has been anomalous and does not match the simple sigmoidal function fit calculated in 2009. However, the 2019 accumulated subsidence of about 2 m is similar to that predicted in 2009 (light blue) using a 1D model (Bromley et al., 2010) populated with measured drillcore compressibility properties (Pender et al., 2013). These properties included time-dependant yielding occuring beyond yield stresses that vary with depth between about 40m and 200m.

1.3 Tauhara groundwater & reservoir pressure changes

By 2009 it was apparent that groundwater levels had declined across the central part of the Tauhara field, by as much as 7m between 1995 and 2006 (Bromley, 2009). This area (Figure 4) approximately coincides with two adjacent areas of steam heated ground (Crown Rd thermal area and Broadlands Road thermal reserve) and straddles the Tauhara subsidence bowls (Figure 1). So, it was conjectured, at the time, that groundwater level decline might be a primary mechanism [#] causing the observed subsidence.

[#] Pressure decline in a porous aquifer leads to an increase in effective stress on the rock matrix. This results in formation compaction, depending on the rock compressibility. The compaction propagates to the surface as ground subsidence. The shape and amplitude of the surface anomaly depend on a spreading function (attributed to Geertsma and described by Helm, 1984) which, in turn, depends on the depth and lateral extent of the top surface of the compacting formation.

For the Crown bowl, the calculated best fit to the shape of the anomaly (particularly the south-eastern edge, see Figure 3) results in a depth to the top of the compacting formation of 34m to 42m using a Geertsma 2D modelling approach and approximating the compacting formation as a 'cylinder' (Bromley et al., 2009). This depth coincides with the base of the Taupo Ignimbrite pumice layer, and the top of an intensely altered, ca. 12000 years old, hydrothermal eruption breccia deposit. The Geertsma model results in a best fit radius for the south-eastern side of the compacting formation of 85m. The NW side is slightly broader (Figure 3), and the shape is elliptical. Hence the cause of the subsidence bowl at Crown Road is interpreted to be shallow pressure changes affecting highly compressible hydrothermal clays within a buried hydrothermal eruption crater, approximately 200m deep and 170m by 230m across (anomaly half-width). The crater was infilled, capped (and preserved) by hard sinters (probably hot spring deposits) and then covered by about 30m of Taupo pumice ignimbrite, approximately 1800 years ago.

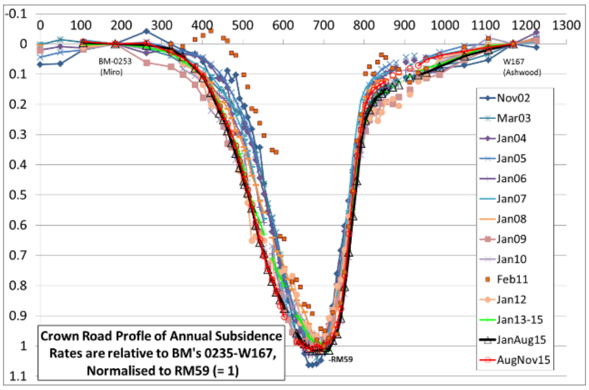

Figure 3: Crown Road annual subsidence rate profiles (NW-SE) normalised to RM59 value (=1), and outer benchmarks BM0253 and W167 (=0); 2001 to 2015.

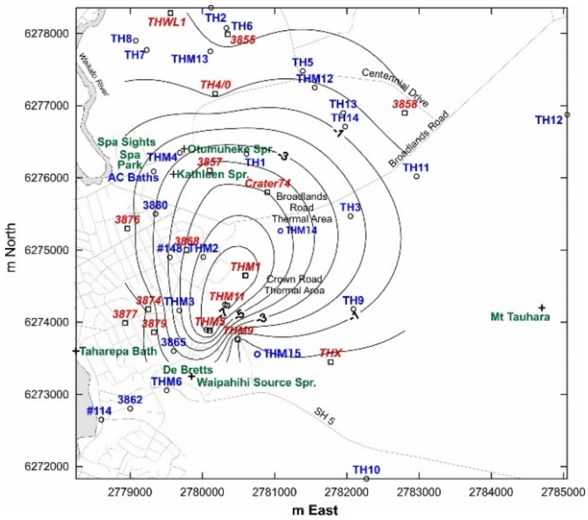

Figure 4: Contour map of uppermost groundwater level decline (up to -7m between 1995 and 2006).

The shallow pressure changes referred to above have been an important component of our subsidence studies. For the purposes of this study, fluid aquifers are classified from top to bottom into: shallow "groundwater" (< 100 m), "intermediate" or "Lake-Taupo level" aquifer (100-200 m) and "deep reservoir" (>200 m). Deep reservoir liquid pressures beneath the Crown bowl have been monitored (at ~424m depth) in THM16 since 2009. They show a steady rise in pressure, by about 3 bars, due to fluid reinjection into Karapiti and Te Huka wells close to the Waikato River. Groundwater monitoring since 2009 shows no significant change in water level across the Tauhara field. Hence, some other explanation for changing subsidence rates at Crown bowl (Figure 2) is necessary. One hypothesis, that could explain the ongoing subsidence, is pressure decline in the intermediate aquifer. Through an influx of cooling groundwater, the intermediate aquifer steam-zone is cooling and therefore pressure decline is occurring. Some evidence of this is indicated by reducing temperatures (-20 °C) in the steam-zone interval at about 130-155m depth. Also, THM21 well-head pressure (reflecting intermediate aquifer steam-zone pressure) has declined by about 4 bars since 2010. To test this hypothesis, an experiment was suggested in 2017 to install a continuous gravity meter at the THM16 well site. It was thought that this might detect changes in gravity caused by density changes as the steam zone at about 125-175m depth gradually re-saturates from cooler liquid inflows.

Hence the experiment would test the hypothesis that steam zone cooling and consequential de-pressurizing is a mechanism for ongoing subsidence at the Crown Road bowl.

2. GRAVITY MONITORING

Repeat microgravity surveys of Tauhara were conducted in 1994, 2009 and 2017 to monitor fluid mass changes in the geothermal aquifers. The largest mass changes are caused by 2-phase density changes. [Liquid reservoir pressure decline induces boiling, which forms low-density steam zones; then ingress of cooler water causes condensation and liquid re-saturation]. Contour maps of the Tauhara and Wairakei gravity changes are presented in Bromley et al (2018). From 1984 to 2009, an area of increasing gravity occurred across central Tauhara (between THM17, THM12 & THM13 in Figure 1). From 2009 to 2017 this gravity increase expanded further to the south-east to encompass THM14. Figure 5 illustrates the sequence of changes over time (corrected for elevation change using 'free-air' gravity difference) at a few northern and central Tauhara benchmarks.

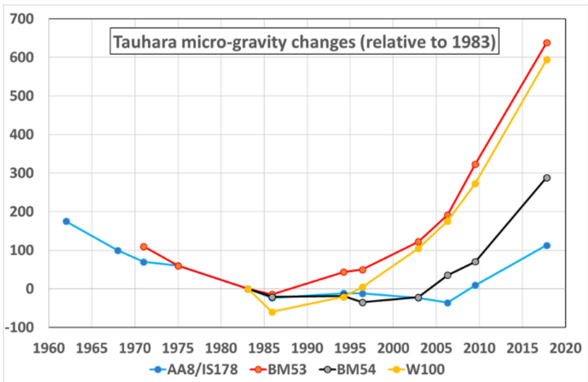

Figure 5: Repeat gravity (ugal) at several central Tauhara benchmarks (near Spa bowl) show effects of boiling and 2-phase dry-out up to 1985 then increasing rates of liquid re-saturation.

Some of these gravity measurements date back to 1960. The initial gravity decline (1960-1985) was associated with a period of 'dry-out' following liquid reservoir pressure decline (Hunt et al 2003). This was replaced by increasing gravity and greater rates of 're-saturation' as the liquid content of the steam zones increased due to cooler liquid recharge and condensation.

Continuous gravity recording at the THM10 well site (~25m from Crown Road) was initiated in June 2017 as an experiment using a GNS Science Lacoste & Romberg gravity meter (Gphone#061) that was temporarily available. (Refer to Jolly et al. (2013) for information about the setup and operation of the gravity meter.)

The gravity data were tied into the Taupo Fundamental reference site (near the Taupo Yacht Club) by undertaking several repeat measurements at nearby RM59 using the same Lacoste & Romberg gravity meter (#106) that had been used for all previous repeat surveys.

Figure 6 shows a plot of the continuous gravity monitoring records from a vault constructed at the THM10 well-site over a 3-day period (from midnight GMT time, i.e. midday local time), using a 5-minute rolling average filter of the 1-second raw data. The gravity data (in orange) show the effects of earth tides (±100 ugals) and transient spikes. These spikes correlate with the passage of heavy trucks on Crown Road. Ocean load (±5 ugals) and polar corrections (±1 ugal) are minor by comparison. Figure 7 shows a 24-hour plot from 8th July GMT (midday Saturday to Sunday). The calculated earth tide (black) closely matches the observed gravity (minus the spikes).

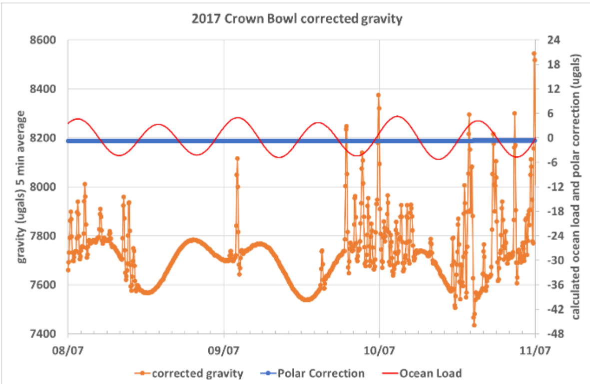

Figure 6. Gravity monitoring at THM10 and earth tides for 8th-11th July 2017 with 5-minute rolling average filter, showing earth tide, ocean load and polar correction (right axis). (Working-day truck traffic contrasts with a quiet Sunday).

Figure 8 shows 4.5 minutes from 12:07 8th July (first gravity spike of Figure 7), without filtering. Transient gravity spikes of approximately 40,000 ugal (400 g.u, or 4E-4 m/s^2) occur intermittently. They last about 10 seconds and are less prevalent on Sundays when heavy truck traffic diminishes. The velocity and position of the gravity detection beam (plotted in orange and red) swing by about ± 500 um/sec and ± 600 um respectively during each transient spike event. The long axis and short axis tilts (which are also recorded) show only minor or zero disturbance during the gravity spike, proving that change in tilt is not the predominant cause. Ground deformation surface waves caused by the weight of passing 20 to 40 tonne trucks along Crown Road are interpreted to be the dominant cause of the recorded gravity transients.

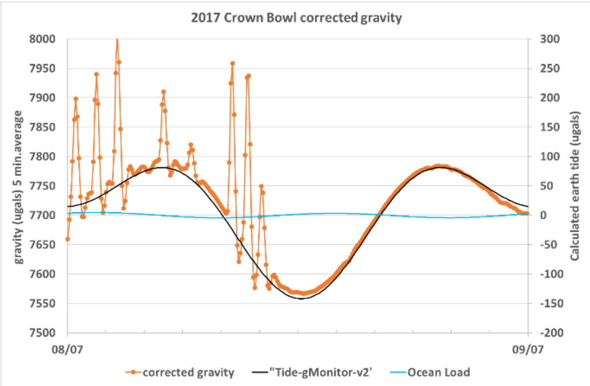

Figure 7. Gravity monitoring at THM10 and earth tides for 8th July 2017 (0:00-24:00 GMT) with 5-minute rolling average filter (midday Saturday traffic to quiet Sunday). Calculated earth tide matches observed gravity.

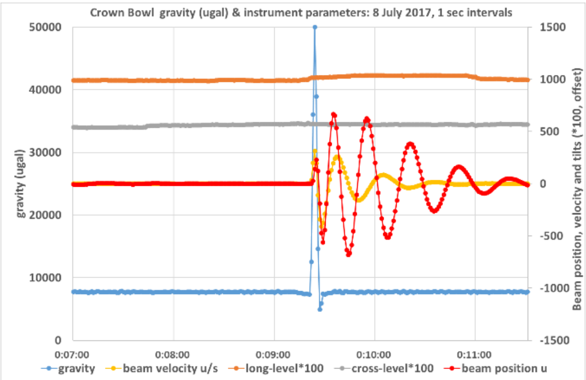

Figure 8. Gravity monitoring at THM10 for 8th July 2017 (0:07 to 0:11 GMT) 1 second data (no filter) showing a gravity spike lasting for ~10 seconds, similar to passage time of passing truck on Crown Road. Instrument beam position and velocity show resonant spring oscillations.

Repeated gravity measurements were also made at RM59 on 13 occasions over a period of 6 months in 2017, using the G106 gravity meter. Each measurement was bracketed by a loop, within the same day, from the Taupo Fundamental reference site (near Taupo Yacht Club, Lake Taupo). This helps remove linear drifts. Gravity differences are calculated relative to the reference site (which is assumed to be gravitationally stable) to determine trends with time. The gravity change at RM59 is shown in Figure 9. Free-air gravity corrections for elevation change over this 200 day period (-70 mm) amount to +21 ugals (or +38 ugal/year).

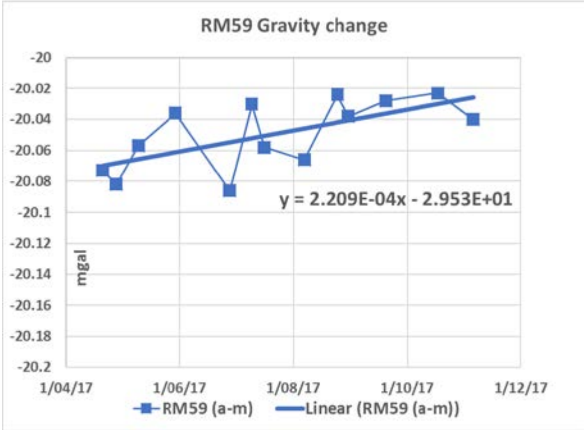

Figure 9: Trend in gravity difference (mgals) at RM59 (Crown bowl) relative to Taupo Fundamental, 200 days.

The data was processed using Gsolve gravity data reduction software (McCubbine et al., 2018). The standard error for these measurements is 12 to 15 ugals. The observed trend in Figure 9 shows an increase in gravity of 0.221ugals/day (or 80 ugals/year). Accounting for the free-air correction it reduces to 42 ugals/year. The observed scatter is about $\pm$ 20 ugals. Between 2009 and 2017, the average rate of gravity change at RM59 was +138 ugals (Bromley et al, 2018) or 17 ugals/year (elevation corrected). So, on this evidence, it appears that the gravity increase rate is accelerating at RM59, in a similar manner to the acceleration observed near Spa bowl from 2003 (Figure 5). This can be interpreted to be caused by an increasing rate of liquid recharge occurring within the steam zone at about 125-175m depth. This, in turn, is consistent with the postulated inflow of cooler water which is re-saturating the steam zone and causing the temperature and pressure to decline. The pressure decline contributes to an increase in compaction and subsidence rates, as observed after 2015.

3. LEVELLING SURVEYS

Energy Surveys have undertaken repeat levelling surveys across the Crown subsidence anomaly, for Contact Energy, at least annually since 2001. Detailed profiles are located along Crown and Invergarry Roads using 10m spaced pins inserted into the curb. Figure 10 shows a map of contours in annual subsidence rate from 2007 to 2008 when maximum rates were 65 mm/yr. Figure 11 shows the contours across the same area between October 2016 and January 2017 when rates reached a maximum of 115 mm/yr. Figure 3 shows a series of normalised (to RM59) annual subsidence rate profiles along Crown Road (north-west to south-east), illustrating overall consistency in bowl shape with time (except for 2011, when the subsidence rates had reduced significantly, Figure 2).

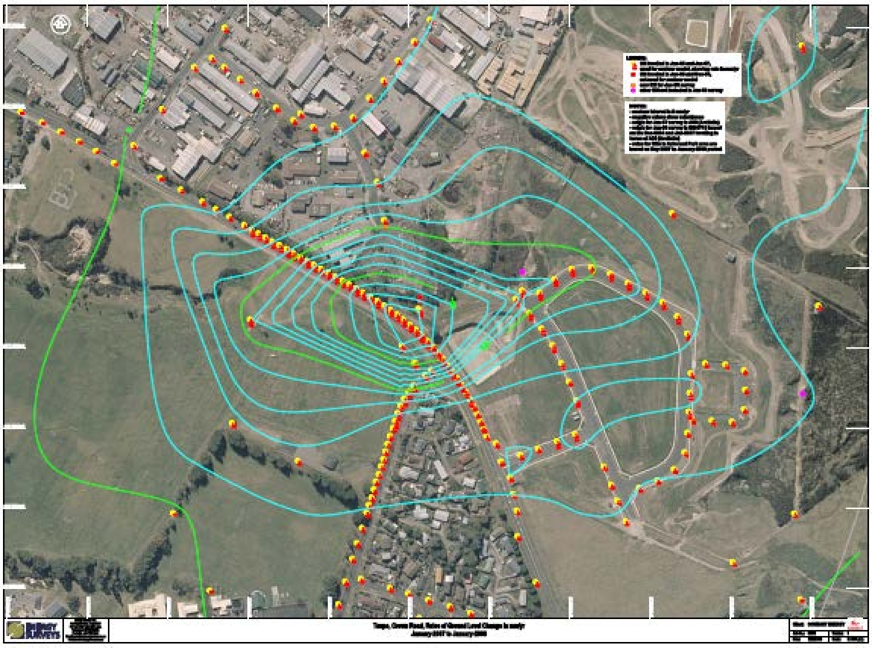

Figure 10: Crown Road anomaly, 2007-2008 rate contours (0 to -65 mm/yr, 5 mm/yr interval), Energy Surveys.

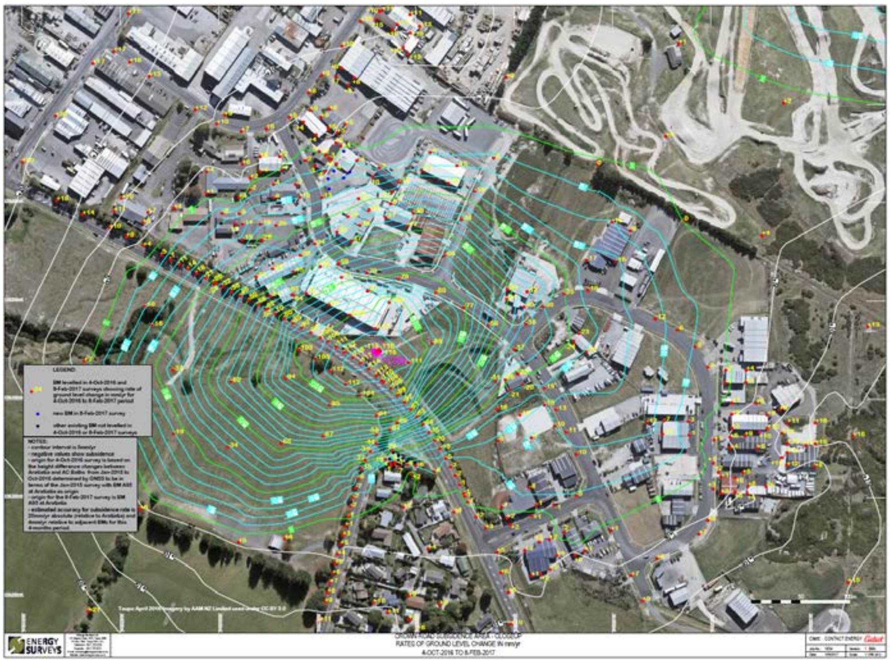

Figure 11: Crown Road anomaly, Oct.2016-Feb.2017 rate contours (+15 to -115 mm/yr, 5 mm/yr interval), Energy Surveys. More installed benchmarks allows for better resolution of the elliptical shape of the anomaly in 2017 relative to 2008.

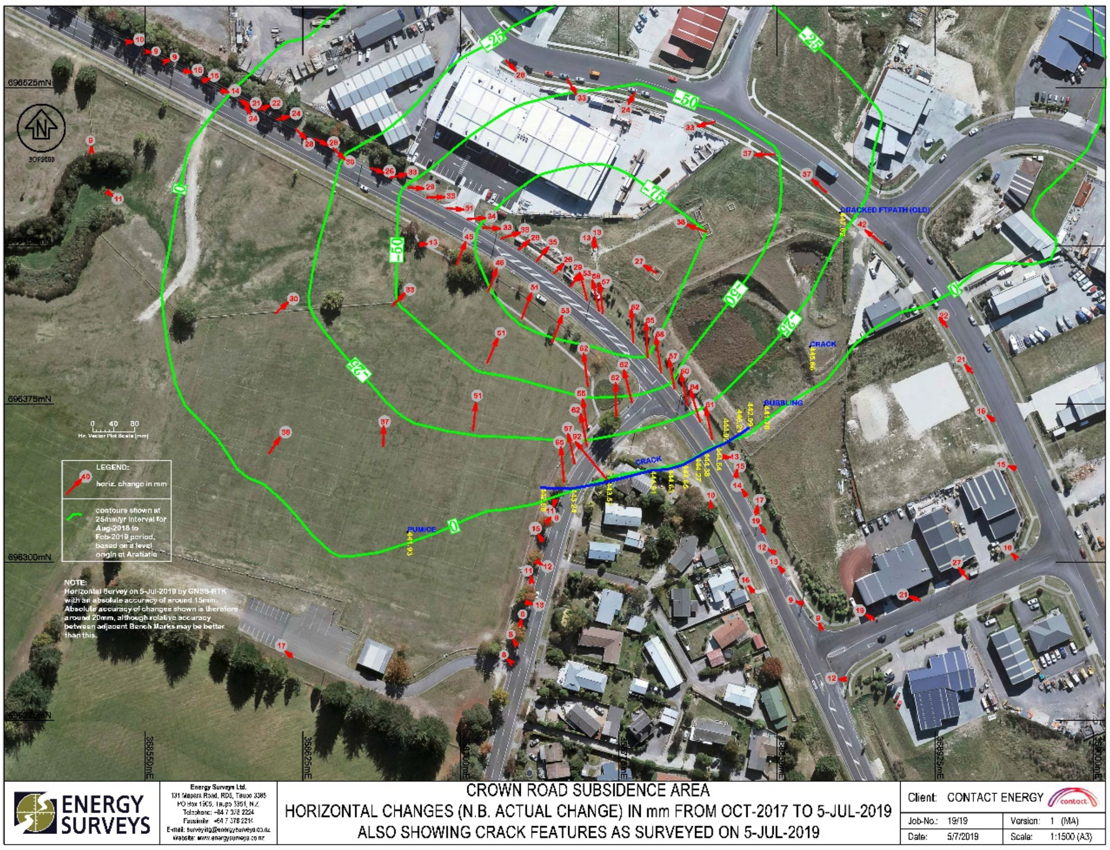

Figure 12. Crown Road anomaly: Oct.2017-July2019 (0-75 mm/yr contours (green), 25mm/yr intervals); horizontal displacement vectors (red, mm); and 4th July 2019 tensile crack (blue); from Energy Surveys.

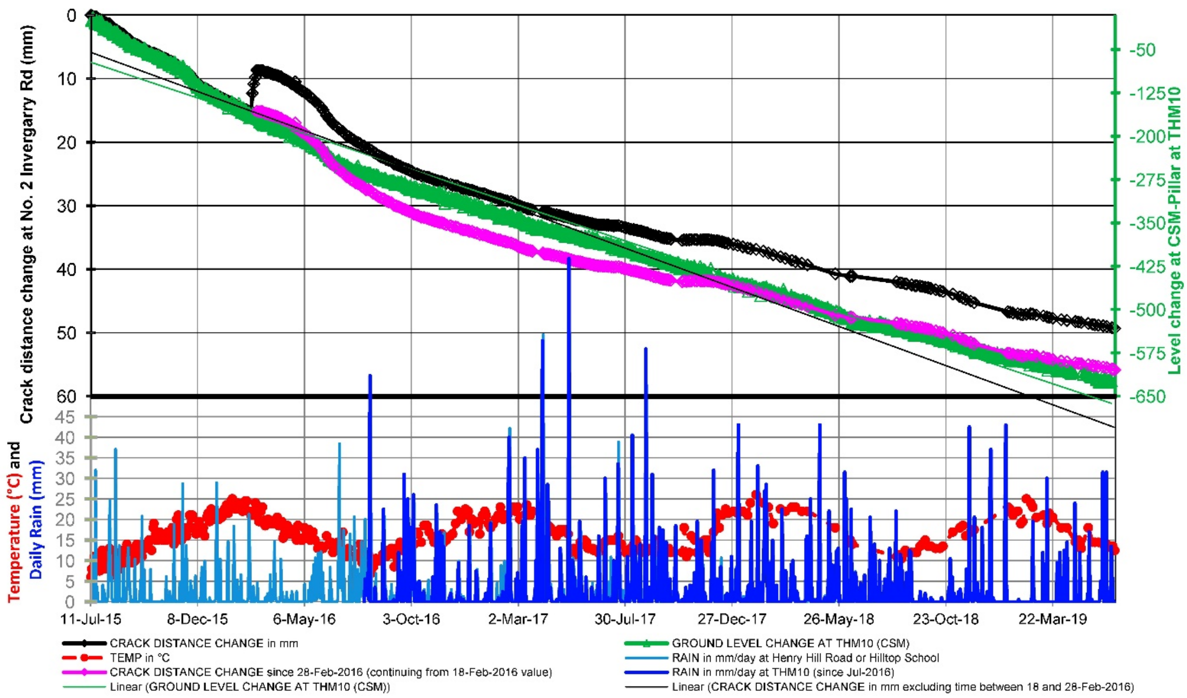

Figure 13. Crown Road anomaly: monitoring of crack width at #2 Invergarry Road (black and purple), GNSS levels (mm) at THM10 CSM pillar (green), rainfall (blue) and ambient temperature (red); July 2015 to June 2019, Energy Surveys.

A map of recently measured subsidence rate contours is shown in Figure 12 for the period August 2018 to 5th July 2019 (measured immediately after the 4th of July when a tensile crack formed along the south-east edge of the anomaly). The overall shape is unchanged, and the rates have reduced from the peak values recorded in 2016. The horizontal vectors (Oct17-July19) show the ground displacement towards the centre of the anomaly. This pattern is consistent with previous surveys.

4. CONTINUOUS GNSS

Since 2015, continuous GNSS (GPS) data has been collected at THM10 CSM ("Continuous Survey Monitoring") site near the centre of the Crown bowl, by an Energy Surveys installation as part of a network of GNSS sites around Wairakei and Tauhara for Contact (Figure 13). When the raw data is differentially corrected and processed into hourly averages the data scatter (noise level) in the vertical component (level change) is approximately $\pm$10 mm. Hence any transients caused by passing trucks with a duration of approximately 10 seconds would not be detected; they would simply be absorbed into this average noise level.

Likewise, no sudden changes were observed in the smoothed hourly GNSS data when a crack formed along the southern margin of the bowl during a heavy rainfall event on 4th of July 2019 (about 93 mm fell in 24 hours). The crack occurred along the outer, southern bowl edge (a location of maximum horizontal strain, favouring tensile failure) in the early hours of the 4th of July (Stuff, 2019). The rainfall had caused rapid accumulation of storm water from the Ashwood industrial subdivision into a purpose-built, storm-water soakage pond adjacent to Crown Road (Figure 12). This storm water accumulation found a leak through a crack in the southern wall of the pond at the outer edge of the subsidence anomaly. The crack opened by several centimetres through rapid failure along the bowl shoulder. A large over-flow of storm water then proceeded down-gradient towards Crown Park (along the blue line in Figure 12). The water flow enlarged the crack and created a 'tomo' (pumice erosion cavity) along it, passing beneath Crown Road, a house at #2 Invergarry Road and Invergarry Road. The crack severed several pipelines where it crossed the roads, and this would have contributed to the volume of water flowing through the 'tomo'. Some of this water reached the surface within the Crown Park playing fields, bringing up eroded pumice fines, and depositing them on the grass.

This July 2019 crack is located parallel to and a few meters north of an earlier crack in the garage floor of #2 Invergarry Road, that has been monitored (in terms of crack width) since it was first discovered in June 2008. The original crack width expanded by an accumulated total of about 75 mm over 11 years, increasing in rate from 2014. Changes in crack opening rate mirror changes in ground subsidence at the THM10 CSM (which is about 115m to the north), except for a brief episode in February 2016 when the crack contracted by 7 mm due to local strain changes associated with flooding from a burst water main (Figure 13). The old crack also contracted (by 43 mm) during the formation of the new parallel crack on 4th of July 2019. Although Figure 13 shows no obvious correlation between the rate of rainfall or temperature change data and the CSM subsidence rate or the crack width data, some effect on rates from accumulated rainfall is suspected based on a closer inspection of rate changes, especially during the 2015-2016 period.

5. DISCUSSION

Satisfactory subsidence mechanisms require an explanation for observed timing, amplitudes, and locations of subsidence anomalies. With respect to location and timing, subsidence at the Crown bowl, Tauhara, is interpreted to be of dominantly geothermal origin (i.e. resulting from anomalously-compressible, hydrothermally-altered clays compacting due to pressure decline). Changes in the observed subsidence rates with time can be explained in terms of a combination of: 1) the timing of pore pressure decline (due to groundwater level decline, or vapour loss, or cooling and condensation in 2-phase zones); 2) delays in deformation caused by vertical pressure diffusion through inter-layered, low-permeability formations, and 3) the effect of non-linear yield behaviour. Yielding of the more compressible hydrothermal clays involves transition to much greater rates of compaction from declining pore pressure, or load changes. This commences after a local yield stress is exceeded by the effective vertical stress.

The deformation of the softer material is mostly irrecoverable because the yielding process is largely in-elastic. The re-load compressibility is approximately 10% of the post-yield compressibility. Consequently, an increase in fluid pressure due to injection or natural recharge does not lead to a significant reversal of the subsidence process (i.e. there is negligible uplift).

At the Crown bowl, clay-rich alteration products and a hydrothermal eruption breccia were encountered in drill-core down to 200m depth. The bowl geometry (~200m diameter) and compaction depth inferred from the subsidence anomaly contours suggest a mechanism whereby the anomalous subsidence is confined to a buried eruption crater of comparable size. Petrographic examination (XRD) revealed that the breccia source rocks were hydrothermally altered before the eruption, but strong alteration also occurred after the eruption had ceased. Acidic steam from shallow boiling was able to permeate and condense in the disturbed eruption matrix more readily than it could in the surrounding country rock. In addition, clay-rich material that formed in acidic mud pools or small caverns near the base and sides of the original crater may have become entombed by fresh hydrothermal eruptions or capped and preserved by horizontal silica deposits from discharging hot springs. Hence, the primary pre-condition for the local subsidence anomaly is the presence of very weak yielding clays. However, the mechanism still requires some continuing (albeit small) pressure decline to occur within these clays.

6. CONCLUSION

Continuous monitoring and repeated micro-gravity measurements were trialled at the centre of the Crown Road site of anomalous subsidence within the Wairakei-Tauhara geothermal system. The gravity change data, including transient spikes, provide information to assist with identifying possible mechanisms for changes in localized deformation rates over time. Continuous data from GNSS, and horizontal strain data across a monitored crack at the southern edge of the anomaly are also available.

Pressure and temperature data from nearby monitor bores show that the groundwater level has not been changing significantly since 2009, and the deep liquid pressure in the Waiora formation has been rising. An alternative explanation for ongoing subsidence is therefore required. Some recent evidence of cooling in a steam zone at 125-175m depth suggests that cool water inflows may be condensing a local steam zone causing its pressure to decline and thereby contributing to local subsidence. Storm-water accumulation and focussed soakage from the expanding Ashwood park industrial subdivision (Figure 12) is probably contributing to the amount of local cool water inflow. The local compaction rate may increase as in-situ stress conditions within the compressible clays pass through the yield stress, even if the pressure decrease is relatively small. This would help to explain some of the variations in observed subsidence rates over time.

The shape of the deformation anomaly has remained essentially unchanged. Subsidence rates vary smoothly with time, but appear to consist of two separate events, one starting in the late 1990's (perhaps associated with groundwater level decline between 1995 and 2006, Figure 3) and the other in 2015. Deformation mechanisms are probably linked to changing conditions in boiling (2-phase) aquifers. The former event at about 50-80m depth (boiling groundwater) and the latter event at about 150-200m depth (boiling intermediate depth aquifer).

An additional subsidence driving mechanism is also postulated. It involves incremental yielding from repeated but transient load changes (originating from the passage of heavy trucks along Crown Road). This is based on the observation of significant gravity transients from the continuous gravity monitoring. A surface wave is an elastic response to the weight of the truck. But when the wave reaches the depth of the yielding clays it can cause an in-elastic (permanent) incremental deformation. The process is analogous to hammering a nail into wood.

Long-term changes in truck traffic are unlikely to be the sole cause of the large observed variations in subsidence rate since 2009, so other time-variable processes, such as stress-dependant yielding, and condensation of steam zones, are probably more important factors.

To summarize, highly compressible hydrothermal clays are hosted within a buried hydrothermal eruption crater, which is ~200m deep near the centre of the deformation zone (based on continuous drill-core from THM16) and inferred to be ~200m wide, based on Geertsma modelling of its shape. Sliding on the clay-lined crater walls probably accounts for the shape consistency over 18 years, despite the likelihood of changing compaction depths. These depend on both local pressure changes and the stress related timing of clay yielding. Significant transitions in clay yielding parameters (yield stress) and pressure decline from the cooling effects of groundwater inflow at different depths in the 2-phase aquifers, may account for the observed compaction rate variations over time.

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