Shallow Geophysical tools to Investigate the Potential Extent of Subsidence Anomalies Associated with Hydrothermally Altered and Compressible Clays

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ABSTRACT

Identifying the potential extent of future subsidence associated with deeply buried compressible clay-rich materials of hydrothermal origin, is a useful objective for planning and hazard assessment purposes. Geotechnical assessments of foundation conditions are often undertaken in advance of construction and infrastructure projects, but these typically focus on detailed shallow investigations using tools such as cone penetrometers and shallow core drilling. Geophysical methods, however, can offer a more cost-effective means of covering larger areas and penetrating to greater depths where subsidence and ground deformation effects might become an issue, especially for buildings, in the future. This study reviews the application of a variety of shallow geophysical tools to help map the extent and depth of buried hydrothermally altered clay-rich materials that might compact when subjected to pore pressure decline (e.g. a drop in groundwater level) or an increase in surface loading. Methods include ground penetrating radar (GPR), electro-magnetic soundings (TEM), resistivity mapping, electro-kinetic soundings (EKS), seismic refraction and reflection, and seismic attenuation. The results are presented of trial GPR, TEM, and EKS surveys at Crown Park, Taupō, across an area of known subsidence anomalies. Previous measurements here revealed changes in subsidence rates over time, and nearby core-drilling has revealed the anomalous physical properties of some highly compressible clay-rich materials.

1. INTRODUCTION

1.1 Subsidence associated with Wairakei-Tauhara geothermal system

Subsidence was observed at Wairakei (New Zealand) shortly after production began, with reservoir pressure declines observed from the early 1960's (Brockbank et. al. 2011) due to geothermal fluids being extracted from the reservoir without replacement via reinjection. A levelling network was set up to monitor this subsidence, starting with ~100 survey points in 1960 and progressively expanding since then. The most recent full survey, undertaken by Energy Surveys for Contact Energy Ltd (Appendix 1 in Bromley et al., 2021), included 3845 survey points across the Wairakei and Tauhara geothermal fields. Six subsidence anomalies (or "bowls") have been identified: Wairakei, Spa, Rakaunui, Tauhara golf course (Broadlands Road Thermal Reserve), Digger McEwen, and Crown Park (see Figure 1). All bowls (excluding Rakaunui) are located close to sites of historical geothermal fluid discharge at the surface. The Wairakei bowl has recorded the most accumulated subsidence, sinking 16 m from 1955-2021, with a peak subsidence rate in the mid-1970's of almost 500 mm/yr. Subsidence at the other bowls is lower, with a total subsidence of about 1-3 m recorded since their identification.

The cause of subsidence at these bowls has been identified as compaction of hydrothermally altered clay-rich deposits at shallow depths (geological and geotechnical details are found in Bromley et al., 2013). This, in turn, is a result of pressure decline from cooling shallow steam zones, and declining groundwater levels (Bromley et al., 2009). Numerical modelling has successfully managed to reproduce many of the features of these subsidence bowls, such as their shape and magnitude (Bromley et al., 2009, Koros et al., 2016). Projecting these models forward based on likely ground pressure scenarios shows that subsidence rates are expected to taper off as shallow steam zones are saturated and deep reservoir pressures are restored with ongoing reinjection at Wairakei (Appendix 2 in Bromley et al., 2021).

The timing of changes in subsidence rates seems to be controlled by the compressible clay-rich deposits passing a critical yielding stress threshold (Brockbank et al., 2011), so identifying clay-rich deposits that are still prone to compaction is key to understanding the future evolution of subsidence at these sites.

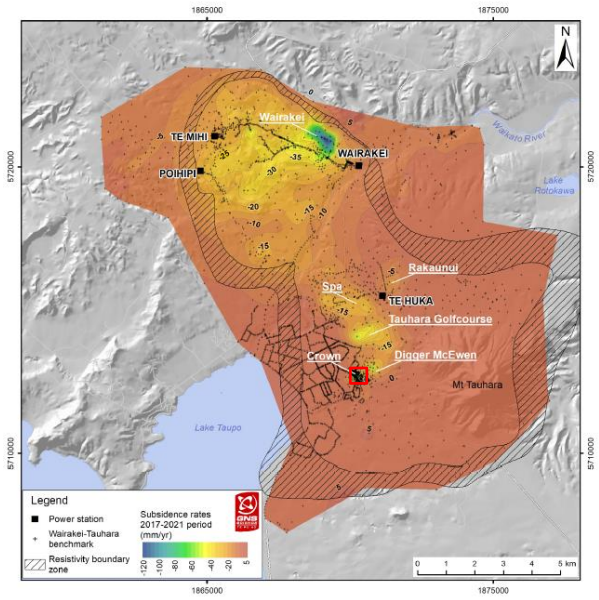

Figure 1: Map of the Wairakei-Tauhara geothermal system, showing the six subsidence bowls, with the Crown bowl highlighted by the red box. Subsidence rates are contoured every 5 mm/yr, with the data from the 2017-2021 survey period. From Bromley et al., 2021.

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1.2 Crown Park subsidence bowl

For this paper we will focus on the Crown Park subsidence bowl, the subsidence anomaly in closest proximity to residential and industrial properties and urban infrastructure. It is shown as a SW-NE conceptual cross-section in Figure 2. This subsidence bowl is located near the junction of Crown and Invergarry roads in Taupō, and has a lateral extent of about 400-500 m, centred above a buried hydrothermal eruption crater. A total of 1.8 m of subsidence at the centre of the bowl (benchmark RM59) has been recorded since the levelling surveys began, with most of this occurring since 2000. Subsidence rates increased notably from their earlier rates of ~5 mm/yr, with two bursts of activity being responsible for most of the accumulated subsidence. The first acceleration occurred during 2003-2008, when peak subsidence rates increased to ~70 mm/yr before reducing again. The second occurred between 2016-2018, when subsidence rates increased to a maximum of 330 mm/yr for a short period (Bromley et al., 2019). Subsidence rates have since declined to 76 mm/yr during the latest survey period from 2019-2021.

Subsidence here is theorised to be due to the compaction of hydrothermally altered clay-rich materials buried within an extinct hydrothermal eruption crater (Bromley et al., 2013). Bromley et al. (2009) modelled the observed subsidence by using a simple 2D Geertsma model (Geertsma, 1973), along Crown Road, showing that the subsidence observed at the surface could be successfully reproduced by a compacting 85 m radius vertical cylinder buried below about 34-42 m depth. Comparing these depths to well logs from THM16 and nearby THM21 places the top of the compaction somewhere between the base of the Taupo Pumice and the upper units of the Crown Breccia hydrothermal eruption deposits (see Figure 2). If the compacting materials are restricted to the former eruption crater (with maximum depth of about 200m, from the THM16 core log, and maximum lateral extent at its rim of about 100m to 150m, coinciding approximately with the 30 mm/yr brown contour on Figure 3), then subsidence should remain confined to its current area. However, if additional compressible clay-rich layers pass through their critical yielding stress, either inside or just outside this crater, further episodes of higher subsidence rates are possible. Identifying shallow clay-rich layers here, or elsewhere, may therefore provide valuable insight into the future evolution of the Crown bowl and similar subsidence anomalies.

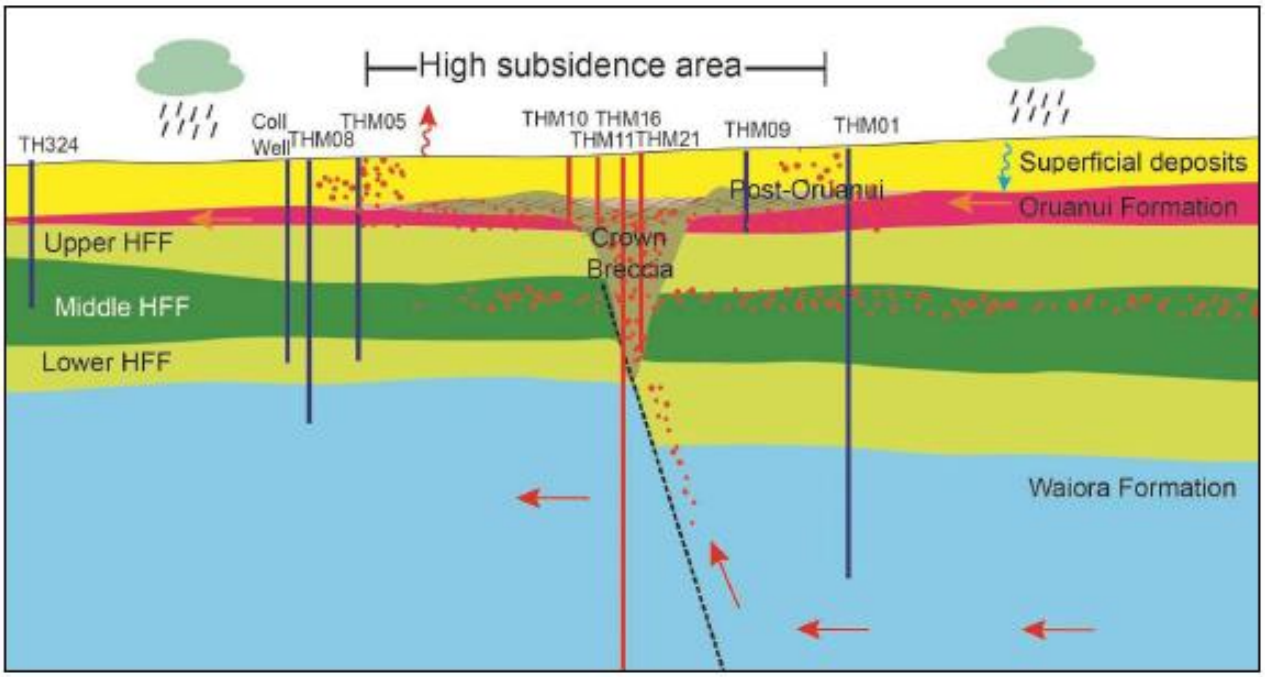

Figure 2: Conceptual model of the Crown bowl subsidence anomaly drawn as a SW to NE cross section. Geological units are the Taupo Pumice, Post-Oruanui Sequence, Oruanui formation, the Huka Falls formation (HFF), the Crown Breccia, and Waiora formation. Steam zones, and fluid pathways highlighted by the red dots and arrows respectively. (Figure from Appendix 2, by John O'Sullivan and his colleagues, in Bromley et al., 2021).

2. GEOPHYSICAL SURVEY RESULTS

The results of three geophysical surveys acquired at Crown Park are presented here: Ground penetrating radar (GPR), time-domain electro-magnetics (TEM), and electro-kinetic seismics (EKS). The former two were acquired earlier this year, and the latter is a result from 2003.

2.1 Ground Penetrating Radar (GPR)

Ground penetrating radar (GPR) is a well-established and commonly used method for imaging the shallow sub-surface, due to its high resolution, and ease of acquisition, processing, and interpretation relative to other geophysical methods (Davis and Annan, 1989). It involves recording signal returns from the transmission of high frequency electromagnetic energy (10-10,000 MHz) down into the ground, where it is

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transmitted/reflected from buried objects or layers of soil and sediments to varying degrees based on their dielectric permittivity (a measure of the degree of polarization a material experiences in the presence of an external electric field). The depth that can be reliably imaged depends on the medium and the signal frequency, but is typically on the order of 1-10 m.

We trialled this method across the subsidence bowl at Crown Park on the 14th of June 2022 using a PulseEKKO GPR system from Sensors & Software with a 250 MHz transducer. A number of GPR datasets were acquired, including a 15 x 50 m 3D grid at 1 m line spacing, nine 2D lines ranging from 5 to 163 m in length, and two Common Mid Point (CMP) lines to estimate the electromagnetic velocity (see Figure 3).

The data was acquired the day after some heavy rain, and we had some light showers on the day, so there were some concerns that the data quality and penetration depth would be degraded due to water saturation in the shallow soils. Soils around Taupō have a high pumice content and drain freely, so the data quality proved to be very good, with strong reflections down to ~3 m recorded in most places.

The first CMP line was acquired 10 m west of the intersection of lines 1 and 2 (see Figure 3), and the second 50 m to the south. CMP analysis for the first line suggested a consistent electromagnetic velocity profile with depth, with values in the range 0.08-0.1 m/ns, while further south at the second line a velocity in the range 0.1-0.12 m/ns provided a better fit. A velocity of 0.1 m/ns was therefore adopted for the whole dataset.

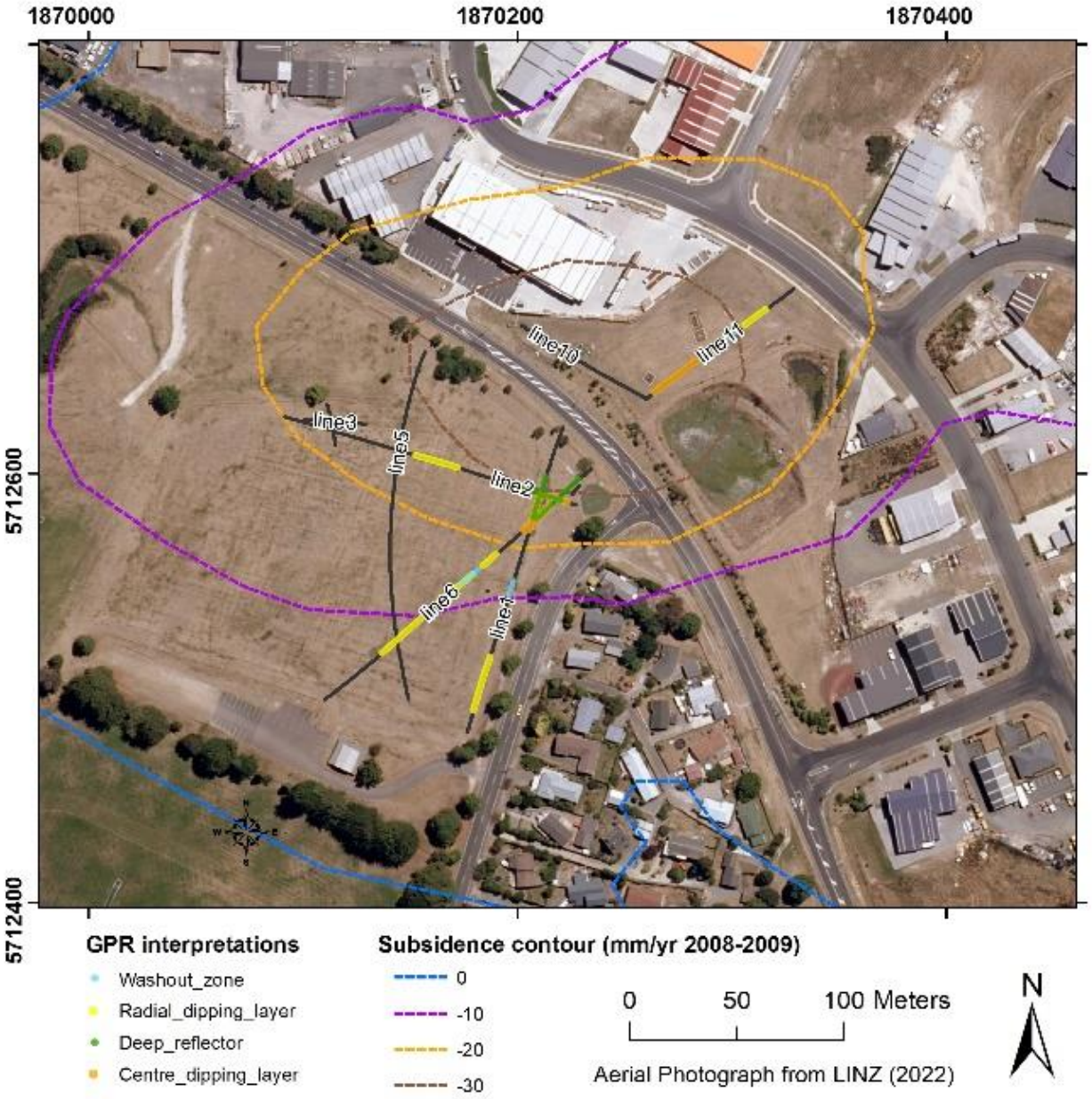

Figure 3: Map of 2D GPR line locations, with subsidence contours from the 2008-2009 levelling survey overlain. The surface locations of interpreted layers are highlighted as coloured points.

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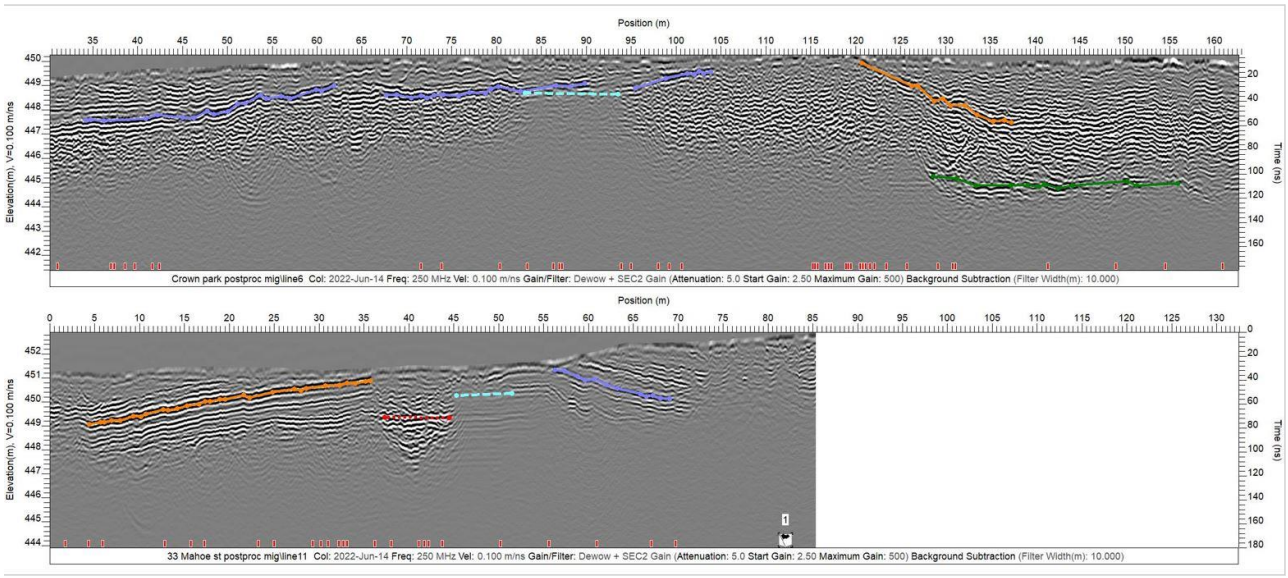

Figure 4: GPR lines 6 and 11, plotted with a consistent aspect ratio and topographic corrections. The interpreted centre dipping layer is plotted in orange, the radial dipping layer in purple, the "washout zone" in light blue, the well interference zone in red, and the former gully in green.

While the 3D grid provided a great visualisation of the shallow structure, the 2D lines offered the more interesting insight into the shallow structure of the subsidence bowl due to their greater spatial extent. Lines running radially from the centre of the bowl showed laterally coherent reflections dipping towards the centre of the bowl, and other coherent reflectors dipping radially, in all surveyed directions, out towards the outer edges of the bowl (i.e. beyond the inferred buried crater rim). A 10 m wide "washout zone", where the GPR signal attenuates rapidly and only very shallow reflections are observed, occurs near the bowl "shoulder", and disrupts deeper reflections from the radial-dipping layers (see Figure 4). The south-western "washout zone" lines up with an observed fracture across Invergarry road (noted in Bromley et al., 2019), at the location of maximum extensile stress on the ground surface. The north-eastern high attenuation zone (at 45-50m on line 11) lies just beyond well THM16 (at 40m) where multiple deeper reflectors are assumed to be caused by lateral inductive interference from the well infra-structure (i.e. steel casings).

The centre dipping layers on either side of the bowl centre are separated by ~120 m at their top, and ~70 m at their observed base. The vertical displacement from the top to bottom of both the centre and radially dipping layers is roughly equivalent, with a value of about 2.5 m on the SW lines, and 1.9 m on the NE lines. The horizontal dimensions are roughly similar to the inferred width of the compaction column (Bromley et al., 2009). The Taupō Pumice deposits are therefore seemingly draped over the former hydrothermal eruption crater, in which the compaction is inferred to be confined. This infers a pre-Taupō eruption topography that was significantly different from the surface topography today.

Deep (~5 m) flat lying reflectors were also observed on several lines towards the northern end of Crown Park, near the intersection of Invergarry and Crown roads (Figure 4). These correspond with an eastward extension of a gully that was visible in aerial photos from 1961, that was subsequently filled in when establishing the park and building roads for urban housing (Bromley et al., 2004).

2.2 Time-domain Electro-Magnetics (TEM)

Time-domain Electro-Magnetics (TEM or TDEM) is a resistivity sounding technique that is suited to resolving lateral (by comparing 1D models along profiles) and vertical resistivity structures within the earth. The method involves measuring the decay of the vertical magnetic field over time from an electrical pulse applied through a wire loop (Nabighian and Macnae, 1991). Measurements can be made either inside or outside the loop, with results depending on the amount of current used, the size of the loop, and the resistivity structure of the earth. Reeves et al. (2011), describe the in-loop TEM method as used to investigate shallow resistivity anomalies at the nearby Spa Park (Otumuheke Spring) thermal area of Taupō.

Ten in-loop TEM soundings were collected using an ABEM WalkTEM 2 system at Crown Park on 27 May 2022. Data were collected along approximate west-east and north-south lines, starting from the north-east corner of the park (Figure 5). A 40 m transmitter (Tx) loop with both high and low moment receiver coils was used to acquire six soundings along the lines. A coincident north-south series of soundings was also acquired using a 20 m Tx loop with a low moment receiver coil. The smaller loop size results in a shallower penetration depth (~60 m) compared to the larger loop (~170 m), but is faster to acquire, and allows the consistency of the results in the near surface to be tested. The centre of each site was recorded (to $\pm$ 4 m) using a handheld GPS, but the recorded elevations were less accurate, so an elevation of 445 m, based on a nearby benchmark, was used for all measurement sites.

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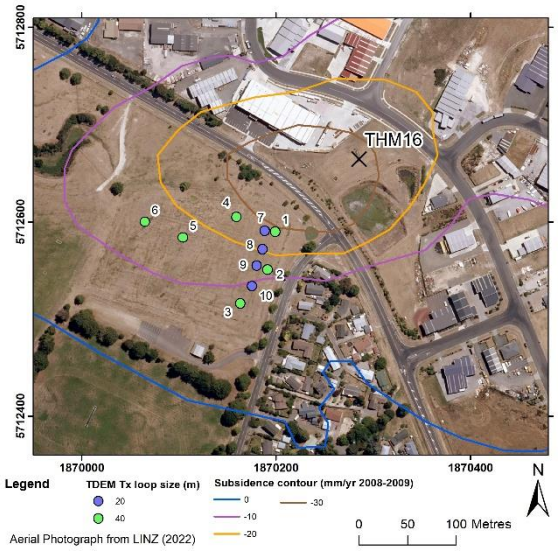

Figure 5: Map of TEM sounding locations, with subsidence contours from the 2008-2009 levelling survey overlain. The stratigraphy shown in Figure 6, is from the well THM16, marked by an X.

The data were then imported into the SPIA software package for quality control, and 1D smooth and layered resistivity models were generated. Data from all 10 soundings and the 1D models were then imported into the Workbench software package, where a spatially controlled inversion (SCI) resistivity model (Viezzoli et al., 2009) was generated. The SCI inversion uses data from neighbouring sites to help constrain the modelling. Data residuals at each site can act as an indicator to how well the resistivity models fit the data. The fit was generally found to be good (e.g. Figure 6), with residuals less than 1, except at sites 1 and 2, where they were between 1.5 and 1.7.

The resulting resistivity model (Figure 7) showed:

- Generally higher resistivities (>100 ohm-m) near the surface, interpreted to be due to the poorly compacted and unweathered Taupo Pumice.
- Resistivities generally decreasing with depth, interpreted to be due to increasing clay content of deposits and geothermal steam/fluid influences.
- A relatively low resistivity layer (~6 ohm-m) at around 30-35 m depth was apparent in sites along the north-south line, but not the west-east line. This is interpreted to be caused by the local presence of conductive Post-Oruanui Sequence sediments, geothermal fluids, or clay alteration at the base of the Taupo Pumice. This is a relatively thin layer and it is possible that this is an artifact of using the smooth-model approach.
- A second, relatively low, resistivity layer (< 1 ohm-m) at around 80 m depth, corresponding to the Crown Breccia unit 2 (CB2) geological layer (a moderately sorted hydrothermal eruption breccia with clasts of siltstone, sandstone, pumice and rhyolite lava) from THM16 logs, is apparent at sites 1 and 4 (the only two 40 m loop sites inside the -20 mm/yr subsidence contour, marking the approximate edge or rim of the inferred hydrothermal eruption crater). This anomalously low resistivity layer is interpreted to shallow to ~50 m depth at some southern locations, beyond the edge of the inferred hydrothermal eruption crater.

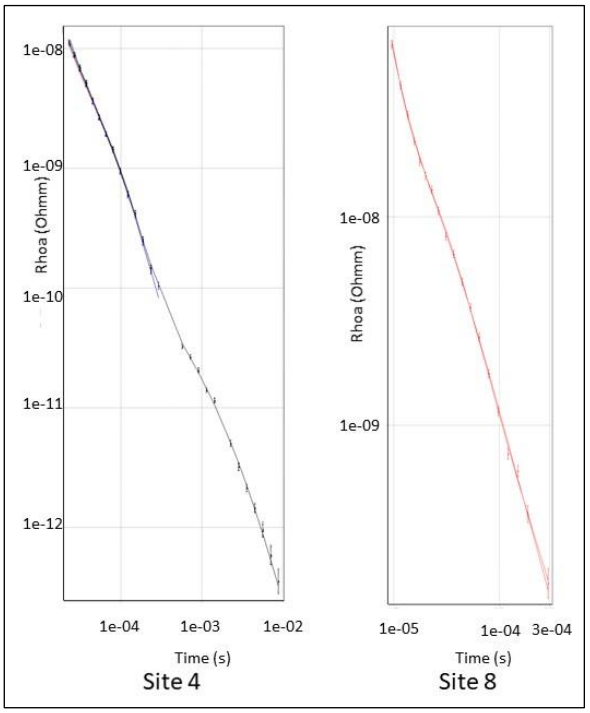

Figure 6: Example plots of the TEM data with model fits at Sites 4 and 8.

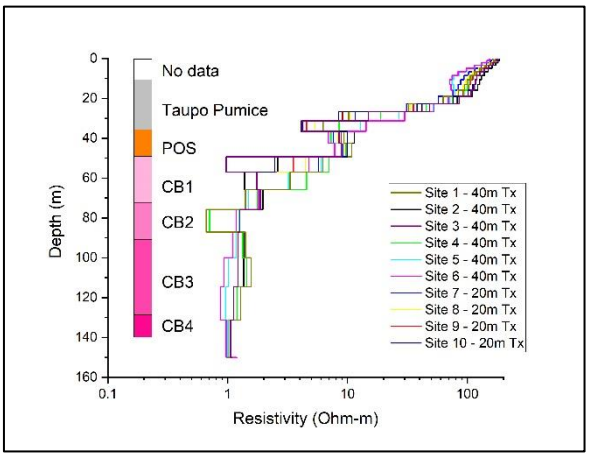

Figure 7: Layered resistivity models at each of the 10 Crown Park TEM sounding sites with simplified geology from THM 16 (See Figure 5 for location). Resistivity models generated using a spatially controlled inversion (SCI). Geological unit acronyms are: Post-Oruanui Sequence (POS), and sub-divided Crown Breccia units (CB1-4). Note that the CB units are likely to be replaced by mudstones of the Upper Huka Falls Formation outside of the inferred hydrothermal eruption crater (Sites 2, 3, 5, 6, 9, 10).

The variation in resistivity within the Crown Breccia layer provides an indication of the variation in resistivity properties across the subsidence anomaly and may provide useful information on the extent of hydrothermally altered

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clay-rich layers that may be prone to compaction. Outside the inferred crater edge, the geological formation responsible for the TEM interpreted resistivities of about 1 ohm-m is likely to be in-situ Huka Falls Formation mudstones that have been hydrothermally altered and that contain high concentrations of conductive smectite clays (as logged in nearby boreholes to the southwest, e.g. THM3, Bromley et al 2003).

2.3 Electro-Kinetic Seismics (EKS)

EKS (electro-kinetic seismics or seismo-electric soundings) is a novel method for exploring for permeable zones in groundwater aquifers, although it is perhaps fair to state that the method is controversial in that results have not always been conclusive in terms of locating aquifers of good permeability. In 2003, we trialled this method locally in four different geothermal settings, including Crown Park near Invergarry Road (Bromley et al. 2003). A seismic source (1m deep "buffalo" shotgun) generates vertical acoustic waves that vibrate water within permeable formations, generating voltages by electro-kinetic coupling (analogous to self-potential voltages induced by fluid flow). These propagate directly to the surface, where they are amplified and recorded. The rise-time of the EKS voltage signal (mV) is inversely proportional to a change in permeability. Depths of inferred changes in permeability/porosity/fluid chemistry or viscosity are determined using a layered velocity model. The method theoretically detects zones of high fluid "mobility" including fracture zones, alluvial or breccia aquifers, or regions of partial saturation (vadose or steam zone). Signal/noise enhancement is often necessary in urban settings or areas of attenuating clays (50 Hz filter; stacking). Highly mineralized fluids or clays dampen the electrical response.

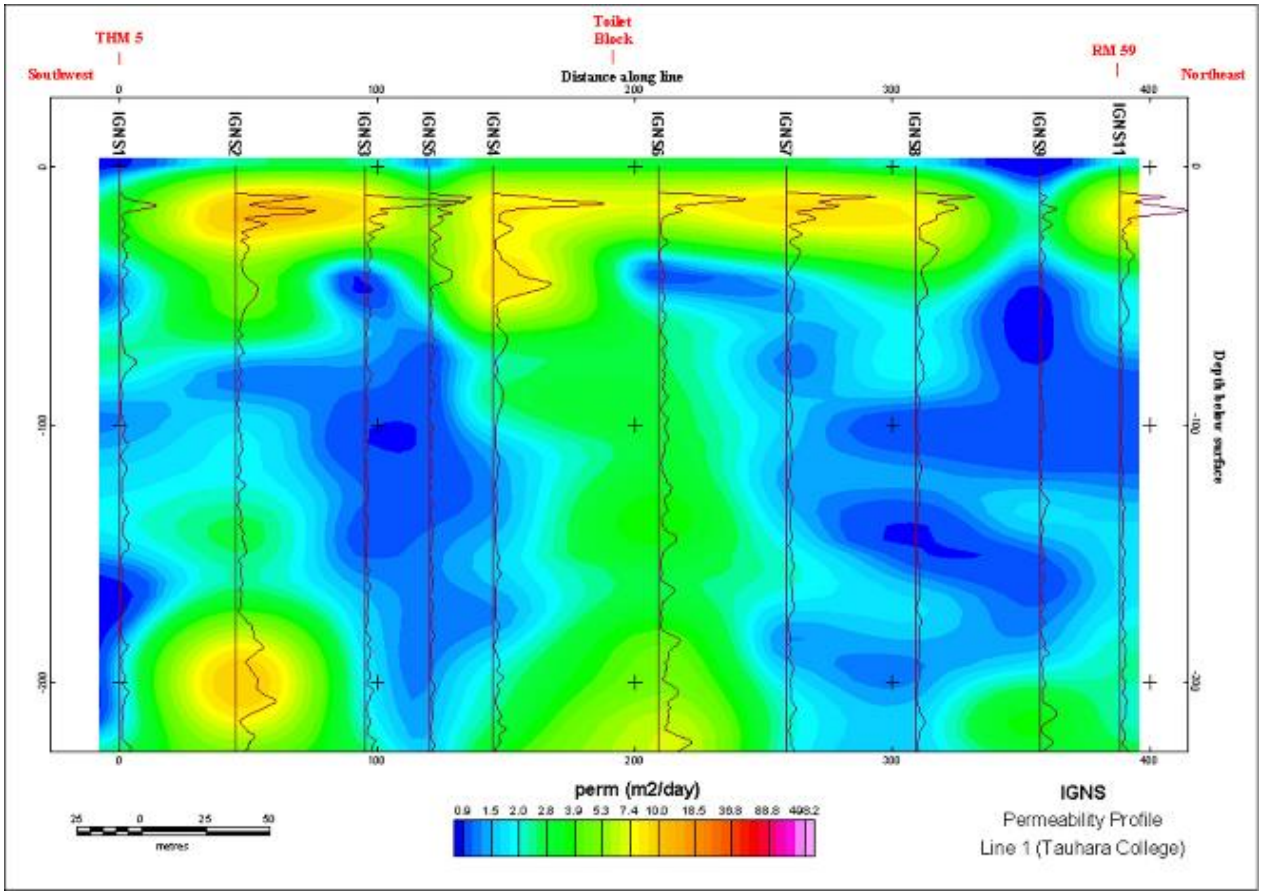

Figure 8: A 400 m SW-NE cross-section to 220 m depth of EKS soundings at Crown Park, between THM5 (Tauhara College) and RM59. Inferred transmissivity scale ranges from 1 (blue) to 10 (orange) m^2/day.

Figure 8 show the results of the SW-NE line of 10 soundings conducted between THM5 (Tauhara College) and RM59 (the centre of Crown subsidence bowl). Penetration, as plotted, is up to 220 m depth, based on an inferred velocity profile. Inferred transmissivity (permeability-thickness) ranges from 1 to 10 m^2/day (i.e. 1.1e-5 to 1.1e-4 m^2/s).

The high response at about 15 m to 45 m depth is probably related to an air-water interface as saturation increases in the groundwater aquifer hosted at the base of the Taupo pumice. The interpreted depth would be deeper if the true acoustic velocity profile in the partially-saturated, highly porous Taupo Pumice was greater than that assumed during the processing. The apparent low permeability zones (blue to green, Figure 8) at 50 to 200m depth are probably caused by strong attenuation of the electro-magnetic signal caused by high clay content in the hydrothermal eruption breccia (near RM59) or in the low permeability but high porosity Upper

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Huka Falls mudstone. Consequently, the method may have some application for identifying clay rich formations but is unlikely to successfully differentiate hydrothermal clay from clay-rich low permeability mudstone.

2.4 Horizontal to Vertical Spectral Ratio (HVSR) seismic

The horizontal to vertical spectral ratio (HVSR) passive seismic method (Scheib et. al. 2016) is a relatively new shallow exploration technique. It involves the deployment of a single three-component broadband seismometer to record low frequency ambient seismic noise (traffic, wind, swell etc.) at a site for as little as 20 minutes. The spectral signal of the recording is then extracted via a Fourier transform, and power spectrum of the horizontal components compared to the vertical component. Ambient noise reverberations in a cover layer in a simple 2-layer model tend to feature more prominently on the horizontal components than the vertical component. Plotting the ratio of horizontal to vertical spectral ratio should then yield a peak frequency (f_0), and this can be related to the depth of the layer by the following equation:

$$f_0 = \frac{V_s}{4h}$$

where V_s is shear wave velocity, and h is the thickness of the cover layer.

White et. al. (2020) tested this method on Black Terrace, Rotomahana, and imaged what they interpreted to be the bottom of the former Black Terrace Crater at about 40 m depth.

We believe this method may yield useful additional insight into the shallow structure at Crown Park and intend to test it here, and in related settings, as part of future work.

3. DISCUSSION AND CONCLUSIONS

Identifying the potential extent of future subsidence associated with buried, compressible, hydrothermal clay-rich materials is a useful objective for planning and hazard assessment purposes. The three geophysical methods tested at Crown Park all yielded useful, and complementary information on the potential presence of compressible clays in the subsurface, and the nature of the observed subsidence at Crown Park.

- The ground penetrating radar (GPR) survey was not able to "see" deep enough into the subsurface with a 250 MHz transducer to image the theorised compaction surface at 34-42 m depth. The structure it revealed in the upper 5 m did support the theory that subsidence was confined to a former hydrothermal eruption crater, with centre and radial dipping layers apparently draped over eruption deposits covering the rim of this structure. Repeating the survey with a lower frequency transducer (10-100 MHz) may allow the deeper structures to be imaged directly.
- The electro-kinetic seismics (EKS) method was able to detect shallow high-permeability water-saturated pumice interfaces at 15-45 m depth and revealed an apparent low permeability structure from 50-200 m depth near the centre of the Crown Bowl that may be related to the compacting clay-rich materials of the Crown Breccia unit. It also imaged another low permeability zone ~250 m to the southwest that was inferred to be associated with the Upper Huka Falls Formation mudstone. The method may therefore struggle to differentiate between attenuating zones of hydrothermal clay in eruption breccia, and clay-rich, low permeability mudstone.
- Modelling of the time-domain electro-magnetic (TEM) data found three anomalously low resistivity layers. The shallowest (~6 ohm-m) was observed at ~35 m depth, but only on the north-south line. The second (<1 ohm-m) was observed at ~80 m depth near the centre of the bowl, but was interpreted to shallow to ~50 m depth towards the south, beyond the rim of the inferred hydrothermal eruption crater.

The depth of the shallowest low resistivity layer in the northern TEM sites corresponds with the inferred depth of the top of the compacting cylinder in the subsidence model of Bromley et. al. (2009) (updated in Bromley et al., 2019, and illustrated in Figure 2). It is therefore likely that compacting hydrothermally altered clay-rich layers below the Taupo Pumice are responsible for both the subsidence and observed low resistivities. The deeper low resistivity layer at ~80 m depth may correspond to an additional deposit of highly compressible clays at the edge of the crater wall, as featured in the most recent models by John O'Sullivan (Appendix 2 in Bromley et al., 2021).

The three methods, as tested, have different limitations and advantages related to lateral resolution, depth penetration and imaged rock property contrasts. Other methods might be useful as well, and future work is planned to investigate several such geophysical methods. For example, in addition to the HVSR method discussed in section 2.4, closely-spaced MT or CSAMT sites that include high frequency data (up to 8 kHz) might also help identify local anomalous deposits of swelling/compressible clays, that are electrically more conductive, and within the depth range of interest. A recent Wairakei example of modified 1D inversion of existing conventional (<128 Hz) MT soundings (Ardid et al , 2021), was constrained by methylene blue indicators of the presence of swelling clay, and imaged shallow conductive layers, albeit at lower resolution.

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