Geophysical techniques for shallow hot water exploration: lessons from some New Zealand case studies

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GEOPHYSICAL TECHNIQUES FOR SHALLOW HOT WATER EXPLORATION: LESSONS FROM SOME NEW ZEALAND CASE STUDIES

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SUMMARY - In New Zealand, the search for hot water resources at shallow depths for the purposes of direct heating applications has a long history. Geophysical methods, particularly resistivity, are frequently called upon to provide a robust exploration target for drill hole siting (often in conjunction with less scientifically robust methods such as water divining). We have compared the results of recent resistivity trials, conducted in a variety of settings, and using a variety of DC and electromagnetic (EM) methods, with the more traditional methods used in the past. These trials have been conducted at Whitford and Naike in the Auckland region; Miranda and Pipiroa in the Hauraki Plains, Hot-water beach at Coromandel; Awakeri, Mokoia, and Horohoro in the Taupo Volcanic Zone (TVZ); Ohakune to the SW of TVZ; and at Hanmer Springs in the South Island.

The results of these trials show that temperature measurements at shallow depth (≤6m) may, in some places, help detect shallow hot water resources. Detailed gravity measurements can be useful, but are usually ineffective at directly detecting fracture zones that channel upflows of hot water into shallow aquifers. Electrical resistivity investigations using the electromagnetic (EM) methods (particularly CSAMT) have some advantages in terms of efficiency of data collection and improved resolution of subsurface resistivity structure to about 300m depth, but are highly susceptible to cultural electrical noise sources. DC resistivity methods (especially tensor-gradient and Schlumberger array) have some advantages in such environments, but they are usually less efficient at resolving narrow target structures. All the resistivity methods suffer from distortions caused by earthed metal structures, and from penetration depth limitations in regions containing highly conductive clays. Interpretation of resistivity anomalies is site specific. In some settings a narrow resistive structure may signal a fault-controlled zone of silicification within an otherwise impermeable clay-rich layer. In other settings, a permeable fault zone may contain conductive clays and mineralized hot fluids within an otherwise resistive host rock. Where structure is complicated (3-D) a full tensor approach may be advisable, despite the added cost, because of the risk that distorted scalar resistivity results may be misinterpreted.

1. INTRODUCTION

Shallow hot water resources associated with low enthalpy geothermal systems are usually difficult to explore with geophysical techniques, mainly because the hot water creates insufficient physical changes to the host rocks to be detectable. Some low enthalpy geothermal systems in New Zealand are associated with deeply penetrating fractures which allow hot water from depth to ascend, and mix with shallow groundwater or discharge as surface thermal springs. Although such fracture zones may have significant contrasting physical properties with respect to the surrounding host rocks, their limited width often makes detection of the fault zone with surface geophysical measurements very difficult, particularly when basement fractures are buried beneath thick overburden layers.

This paper presents New Zealand case studies of a variety of geophysical techniques which have been used to explore shallow hot water resources at ten localities shown in Figure 1.

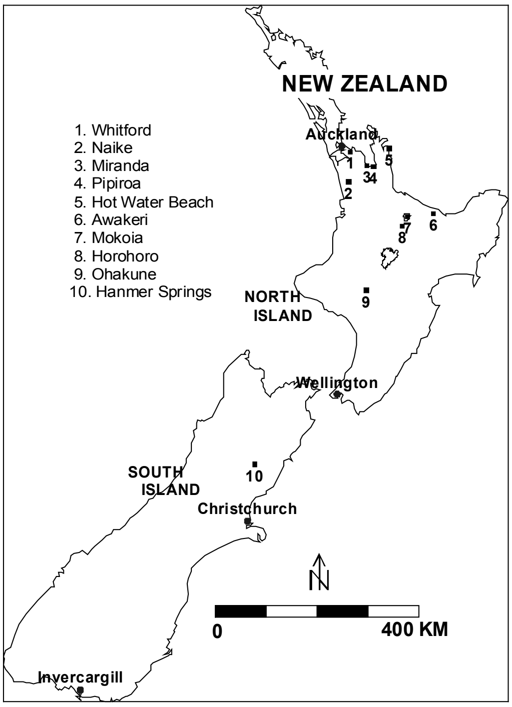

Figure 1. Location map of the study areas.

2. AUCKLAND REGION

2. 1 Whitford Warm Water Prospect

The occurrence of thermal water near Whitford at South Auckland (Fig. 2) was revealed during the drilling of a few wells for a farm water supply. The wells intersected a warm water reservoir (maximum temperature 55°C) at about 80-100m depth near the contact between a fractured greywacke basement and the overlying Tertiary rocks which are almost impermeable.

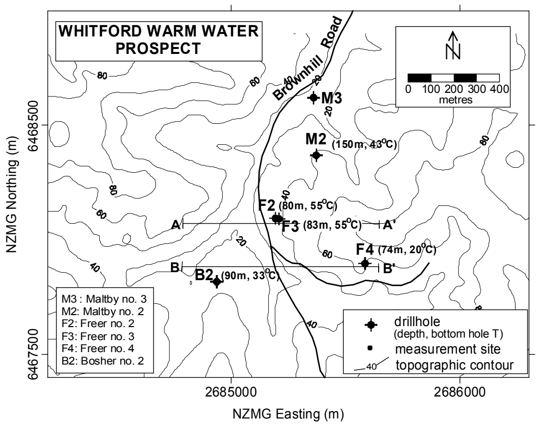

Figure 2. Map of Whitford warm water prospect showing drill hole localities and temperatures.

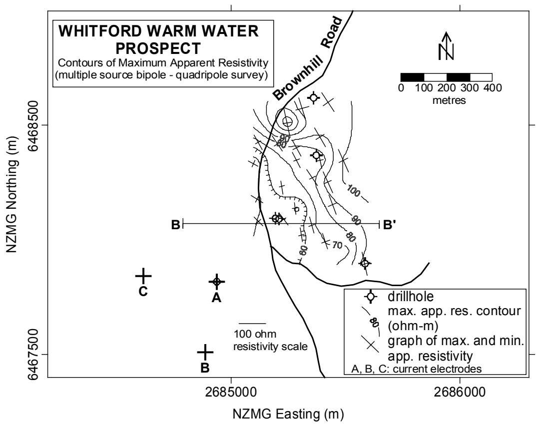

Figure 3. Results from multiple source bipole – quadripole survey, Whitford warm water prospect (data from Yang, 1989).

Between 1987 and 1990, a number of geophysical investigations were carried out at Whitford by students and staff of the Geothermal Institute, University of Auckland, which included repeated temperature measurements in a series of 6m depth holes (Boedihardi and Hochstein, 1990), DC resistivity surveys (Mohamed, 1988; Yang, 1989; Yang and Hochstein, 1989; El-Shariff, 1990), and gravity measurement (Chen, 1990).

Apparent resistivity tensor measurements (see Fig. 3) together with ground temperature survey and borehole temperature data (Boedihardi and Hochstein, 1990) suggest the presence of a zone of NNW oriented basement fractures associated with the warm water at Whitford. The existence of such a fracture zone is also supported by a circular electrical sounding (CES) using the Schlumberger array carried out near drill hole F3. These showed a NW-SE maximum apparent resistivity for AB/2 = 159m and 200m (Yang, 1989). (Note that current channeling creates an apparent resistivity high along the strike of an elongated low resistivity body).

There also appears to be a resistivity decrease in the Tertiary rocks above the fracture zone, as indicated by apparent resistivity gradients computed from Schlumberger traversing data (El-Shariff, 1990), and layered interpretation of Schlumberger vertical electrical soundings (VES), (Mohamed, 1988), (Fig. 4).

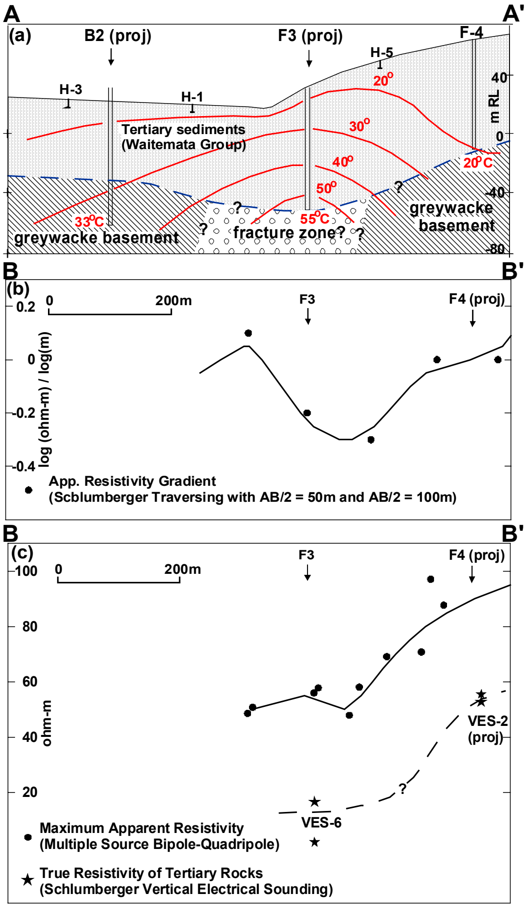

Figure 4. (a) Geological and temperature profile along section A-A' (Boedihardi and Hochstein, 1990), (b) & (c) resistivity profiles along section B-B' computed from data presented by Yang (1989) and El-Shariff (1990), and 1-D VES interpretation by Mohamed (1988).

Detailed gravity measurement over the Whitford warm water prospect (Chen, 1990) did not show any obvious relationship with the inferred fracture zone shown in Fig. 4 (a).

2. 2 Naike Hot Springs

The Naike Hot Springs is a low enthalpy geothermal system located near Naike Village, about 100km south of Auckland (Fig. 1). Two thermal springs (maximum temperatures ranging from 65 to 93°C) and numerous seepages occur along a small river (Te Maire Stream), close to a contact between outcropping Early Jurassic "greywacke basement" (Fig. 5) and the overlying Tertiary rocks consisting of claystones, limestones and sandstones (Siswojo et al., 1985). It has been postulated that the hot water ascends along deeply penetrating basement fractures after deriving heat from either deep magmatic sources or anomalous terrestrial heatflux associated with hot upper mantle rocks (Hochstein, 1978).

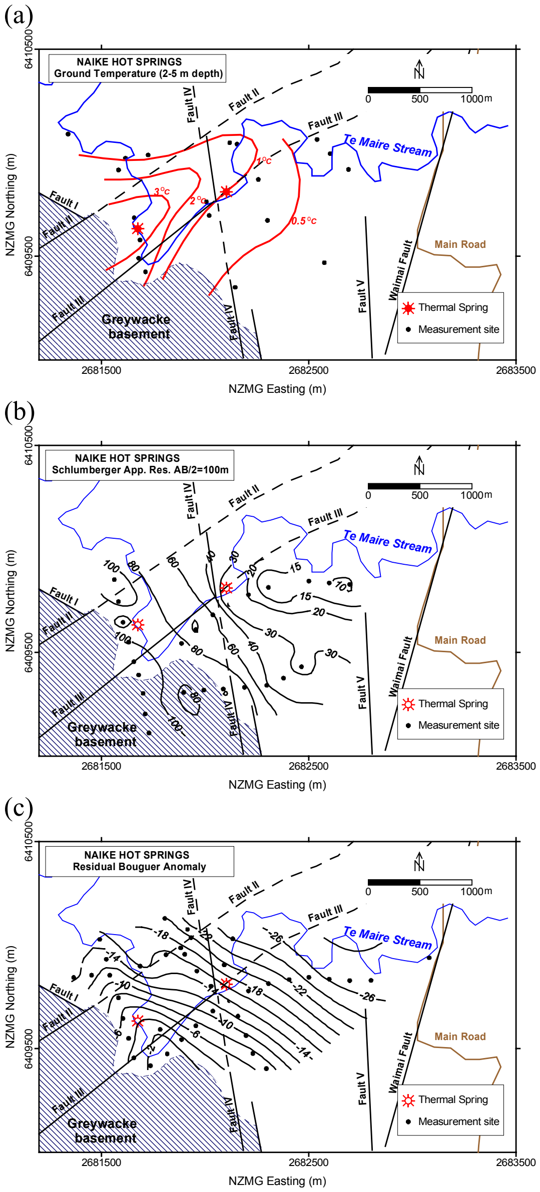

Figure 5. Ground temperatures (a), Schlumberger app. resistivity (b) and residual Bouguer anomaly (c) of the Naike hot springs (from Simandjuntak, 1983; Kasonta, 1984; Siswojo et. al , 1989).

This low enthalpy system was studied and used as a field laboratory by students and staff of the Geothermal Institute between 1983 and 2002. Geophysical techniques that have been applied to explore the system included measurements of ground temperatures and DC resistivity by diploma students (1983-2002) (eg. Simandjuntak, 1983), gravity and self potential (SP) techniques (Kasonta, 1984).

Some of the results are shown in Fig. 5 (a, b, c). Fig. 5(a) suggests a relationship between the ground temperature and Faults II and III which were mapped by Siswojo et. al. (1989) from an examination of aerial photographs. However, this relationship is inconclusive because of the limited number of ground temperature sites. Schlumberger DC apparent resistivity (Fig. 5(b)) and residual gravity data (Fig. 5(c)) appear to indicate the deepening of greywacke basement under the overlying Tertiary rocks, but show no obvious correlation with the thermal springs. SP measurements reported by Kasonta (1984) showed only random anomalies, interpreted as geological noise. A correlation between residual gravity anomaly and faults II and III seems to occur close to the greywacke basement outcrop (see Fig. 5(c)), but this is questionable because of the limited number of measurement sites.

3. HAURAKI PLAINS

3. 1 Miranda Hot Springs

A number of warm and hot springs (33-57°) occur around a large public swimming pool at Miranda, near the western coast of the Firth of Thames, about 70 km SE of Auckland. These springs are believed to be associated with the inferred Firth of Thames fault (Fig. 6) which bounds the western edge of the Hauraki Depression (Hochstein, 1978; Hochstein and Nixon, 1979).

DC resistivity measurements using Schlumberger traversing with AB/2 = 150m and 300m and some vertical electrical soundings (VES) to a maximum AB/2 of 420m were carried out across the Miranda hot springs by Sudarman (1982). Fig. 6 shows that the group of hot springs at Miranda is associated with a small area (~0.3 km^2) of low apparent resistivity (AB/2=300m). The further decrease of apparent resistivity to the east may indicate the influence of seawater.

2-D interpretation of the Schlumberger traversing data, combined with 1-D interpretation of the vertical electrical soundings (VES), suggest a deepening of a resistive sub-stratum towards the north and east. An E-W oriented displacement of the resistive sub-stratum (see Fig. 6) was interpreted by Sudarman (1982) as a possible deep structural scarp that may be associated with the Miranda hot springs.

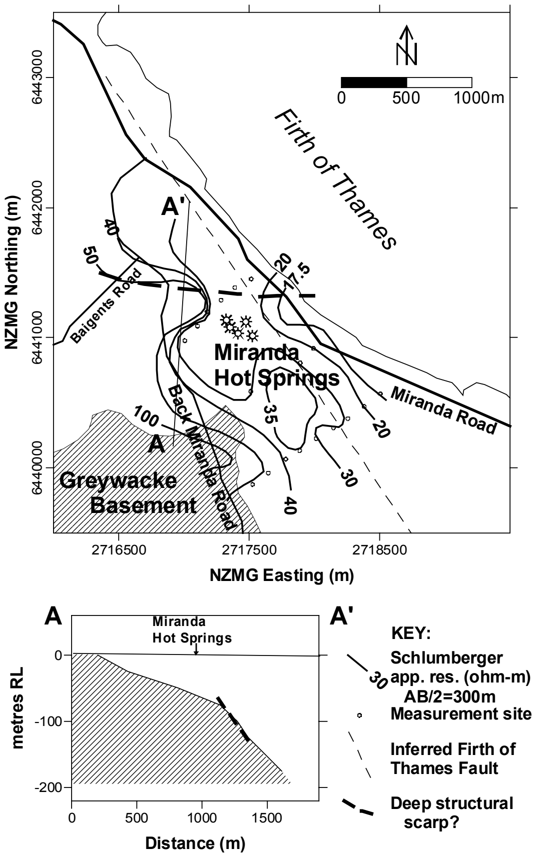

Figure 6. Results of DC resistivity survey over the Miranda hot springs (from Sudarman, 1982).

Additional resistivity measurements were later made near Miranda hot springs using the magneto-telluric (MT) method and the gradient array/VES method (Bennie and Graham, 2001a). The MT soundings were interpreted to support a northern outflow of thermal fluid, and a marked contrast in resistivity across a structural scarp north of the springs. Resistive (300-500 ohm-m) greywacke basement was modeled at depths of 100 to 200m, deepening to the north. The resistivity of the overlying Waitemata sediments is 20-40 ohm-m. Shallow resistivities of about 10 ohm-m indicate areas where clay-rich sediments are saturated with thermal fluids, particularly in the immediate vicinity of the hot springs. Because of the proximity of the coast, seawater and marine clays produce strong distortions to the deeper and wider penetrating low-frequency MT resistivities. Gradient array resistivity measurements made around the hot spring area, using a single straddling SW-NE current dipole of 530 m length, reveal a pattern of apparent lateral resistivity changes (between 11 and 38 ohm-m). However, these can be explained by the effects of the strongly layered resistivity structure, and the varying penetration depths, causing higher apparent resistivities at sites further away from the current electrodes.

3. 2 Pipiroa

At Pipiroa (between Miranda and Thames, Fig.1), GNS undertook a TEM resistivity sounding and 30 temperature gradient measurements (0.2 and 1m deep) during September 2005 in the vicinity of a capsicum producing greenhouse to search for evidence of a hot water resource. Use of hot water could have helped reduce the cost of greenhouse heating in winter. Anecdotal and historical evidence had suggested the presence of warm waters and surface gas discharges in the past, particularly along the inferred trace of the nearby Kerepehi fault, and at Ngatea, about 8km to the south.

The temperature gradient survey included a 1 km east-west profile, at 50m intervals, west of the Piako River, across the inferred northern extension of the Kerepehi Fault. Temperatures (at 1m depth) did not vary by more than 0.5 °C from 15 °C reflecting normal ambient temperatures. Slightly warmer temperatures (up to 19°C) were measured beneath several nearby drains where warmer surface waters (22 to 26 °C) or gas discharges had been noted.

The results of the TEM resistivity sounding showed that resistivity would probably be ineffective at targeting hot water in this area because of the pervasive deposits of puggy blue/grey marine clays, which have very low resistivities. Apparent resistivities dropped from about 10 ohm-m at the surface to about 1 ohm-m in the marine clay deposit, and then increased to 4 ohm-m between 100 and 200m depth (Figure 7). Such low values are difficult to distinguish from those caused by geothermal fluids.

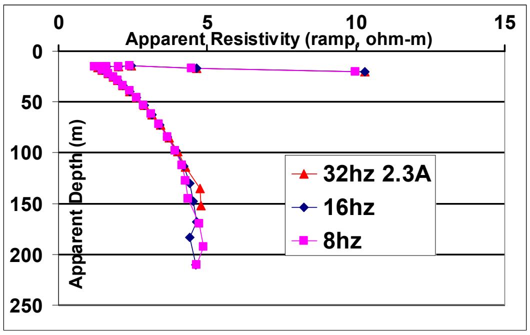

Figure 7. Pipiroa TEM apparent resistivity sounding, 100m loop sides, 10000 m^2 coil receiver, repeat frequencies of 8, 16 and 32 hz.

4. COROMANDEL

4. 1 Hot Water Beach

Thermal seeps of neutral pH Na-Cl water at Hot Water Beach on the eastern coast of Coromandel Peninsular are a well known bathing attraction. Hot fluid outflows are thought to originate from an inferred NNE trending fracture zone, and fed by deep circulation of mineralized water to depths of 1.5 - 2 km. The hydrological setting is described in Hochstein et al (1996) along with the results of local resistivity surveys consisting of Schlumberger array traversing (AB/2=500m) and an MT sounding. Low apparent resistivity values of 5-19 ohm-m (relative to background values of 50-60 ohm-m) revealed the local extent of hydrothermally altered rock. The lowest values were recorded along the fracture zone and closest to the hot springs. The sounding suggested a vertical extent of about 500m for the thermal alteration anomaly.

Subsequently, a resistivity gradient array survey was also conducted by GNS on a profile across the inferred fracture zone to see if it could be resolved. Resistivities increase steeply across the fracture zone (from NW to SE in the vicinity of the Taiwawe Stream road-bridge). This could be the result of a sub-vertical interface between conductive clays and more resistive material SE of the inferred fracture zone.

5. TAUPO VOLCANIC ZONE (TVZ)

5. 1 Awakeri

The results of a detailed geophysical investigation of the Awakeri hot spring site, near Whakatane (Fig.1), using gradient resistivity and gravity, were published by Bromley et al (2003). The hot Na-HCO$_3$ waters (50-70^{o}C) are weakly mineralized and probably derive from deep fluid circulation along a major NE-trending, graben-bounding fault in greywacke. Above the basement, (at about 50-100m depth) hot fluids enter horizontal aquifers in Matahina ignimbrite and alluvial sediments, and rise to the surface on a separate fault that penetrates the ignimbrite.

The gravity data were useful because they showed evidence of displacement of formations of different density along a cross fault that appeared to intersect the main graben-bounding fault at Awakeri. Tensor resistivity gradient data, using an adaptation of the multiple-source tensor bipole-dipole method, with effective probing depths of 50-150 m, revealed anomalously low resistivities (about 15 ohm-m) in the vicinity of the spring and the productive bores, compared to background values (about 60 ohm-m). Another characteristic of the NE-oriented elongated resistivity anomaly is a wide boundary zone of changing resistivity where the electric field directions resulting from oblique current flow were deflected from their normal (isotropic) orientations by up to +/- 15 degrees. These changes, as observed at 20m intervals along profile lines, were relatively smooth, implying gradational lateral changes in thermal clay alteration and temperature. The resistivity tensor ellipses were aligned along the axis of the linear resistivity anomaly when inside it, and perpendicular to the structure when outside it.

5. 2 Mokoia

Mokoia Island in Lake Rotorua contains at least 5 lake-edge hot springs (up to 61 ^{o}C) along its southeastern shoreline (as revealed by infrared images), including the famous Hinemoa pool that features in the Maori love story of Hinemoa and Tutanekai. The chemistry of this 55 ^{o}C spring source shows it to be dilute, neutral pH, Na-HCO$_3$ water with a chloride content (in February 2003) of 69 mg/kg.

Along the south-east shoreline, shallow scalar MT resistivity soundings and a TEM sounding were recorded by GNS in order to determine the local subsurface resistivity structure and to assist with planning possible direct use of hot water as part of a proposed outdoor educational facility (Te Kura Kaupapa Maori O Ruamata). Two profiles of temperature measurements at 1m depth and at 50m spacings were also obtained (Fig. 8). The most favoured sites for accessible shallow hot water resources were clearly indicated by the temperature peaks.

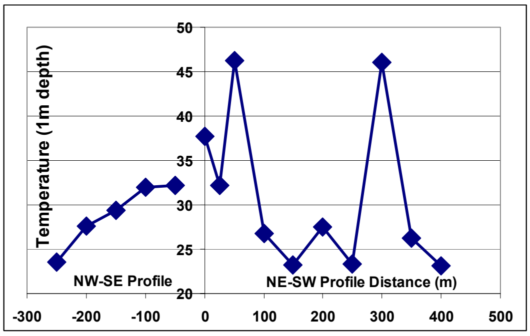

Figure 8. 1m deep temperature profiles (0 = the eastern point of Mokoia island)

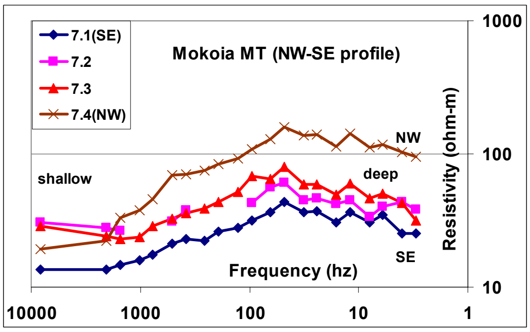

Figure 9. Measured apparent MT resistivities versus decreasing frequency (increasing depth), at 50m intervals along NW-SE profile (1st profile in Fig. 8) showing lowest resistivities at the SE end where 1m temperatures are higher.

The TEM sounding, located at 400m on the NE-SW profile in Fig. 8, showed a low resistivity layer of 5-10 ohm-m, presumably caused by geothermal fluid or clay, within the upper 100m depth. The shallow MT soundings (Fig. 9), recorded at frequencies from 8 kHz to 4 Hz, showed a consistent pattern of low resistivities near the surface (10 to 30 ohm-m) underlain by a higher resistivity layer (100-300 ohm-m). This is presumably related to the rhyolitic core of Mokoia island. Resistivities at the lowest frequencies (<10 Hz) showed decreasing values indicating possible geothermal reservoir conditions at greater depths (~1km). Lateral resistivity gradients showed a consistent decrease towards the eastern-most point on the island.

5. 3 Horohoro

A CSAMT resistivity profile was conducted by GNS in April 2006 through the 11 hectare Horohoro property of Plenty Flora Ltd, with the purpose of testing the resistivity method for targeting hot water resources in the depth range of up to 300m. The property is inside the Horohoro resistivity anomaly (less than 30 ohm-m at AB/2=500m). An existing 300m deep borehole, “Dillon bore”, located near the main highway at the south-west corner of the property (Fig. 10) provides about 3m^3/hr artesian hot water from below the casing (at about 190m depth). The flowing bore water is weakly mineralised (125 mg/kg chloride). This water is used to heat a glasshouse before disposal into a 45m deep borehole located about 20m to the southwest. The geology of the main borehole consists of Huka Falls mudstone formation to 190m underlain by hard ignimbrite to at least 300m. Downhole temperature logging showed a linear, conductive temperature gradient, (which indicates low permeability), rising to a maximum of 115 ^{o}C at about 180m depth, then an inversion from 240m to 300m at 75 ^{o}C (hole bottom). This inversion probably indicates that a separate aquifer of cooler fluid underlying the hot water aquifer is flowing in laterally through the base of the ignimbrite layer, possibly from the cooler edges of the geothermal system.

The signal source for the CSAMT measurement was generated by a high capacity transmitter injecting up to 12.5 amps of current into a remote, 1.7 km long grounded dipole (NW-SE orientation), located about 7 km to the south-west of the study area. Measurements were conducted along a NW profile at about 20m intervals (Fig. 10). An orthogonal NE dipole was also tested at station 100m, but the results were not useable because the signal to noise ratio was too low. Natural source MT data were also un-useable because of local electrical noise sources. A CSAMT resistivity cross-section along the profile is shown in Fig. 10.

The profile shows a low resistivity layer below about 100m depth near the road (SH30), sloping up to about 50m depth near the NW end. This low resistivity layer (less than 10 ohm-m) can be attributed to geothermal fluids and/or hydrothermal clay alteration occurring within and beneath a conductive, clay-rich mudstone layer. The 5th dipole (centred at 96m) has anomalous high resistivities at depths from about 50m to 270m. This is possibly caused by silicification of the fractured mudstone and ignimbrite formations. It may indicate the presence of higher permeability. Therefore, greater fluid flow may naturally pass through the rock in this vicinity.

Given that the existing well proves the presence of a lateral subsurface flow of hot geothermal water, centred at about 200m depth, then the presence of an isolated more-resistive anomaly within an otherwise low resistivity layer throughout this site suggests that the best place to drill a new investigation borehole would be at this local anomaly, near the centre of the 5th dipole (96m from the road). The target depth would be 200-250m. If drilling is undertaken, cuttings from the hole should be studied for evidence of silicification and fracturing.

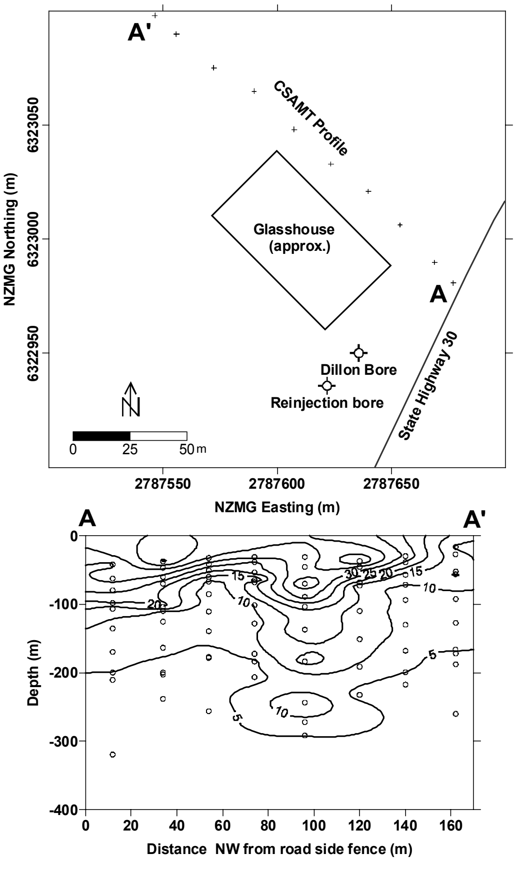

Figure 10. Map of CSAMT resistivity profile line location and boreholes (a) and CSAMT resistivity cross-section along line A-A’ (b), Plenty Flora Ltd, Horohoro.

5. 5 Ohakune (SW of TVZ)

At an Ohakune property (Park Avenue) a 600m deep borehole was drilled in 2005, in the hope of encountering hot waters associated with the nearby Ruapehu volcano for use in spa-pools. The hole was completed from top to bottom in Tertiary papa mudstones and sandstones. Initial indications suggested that subsurface temperature gradients were normal. Magneto-telluric and TEM soundings were conducted by GNS around Ohakune to see if these would assist in locating promising local geological structures or hot water aquifers.

Electro-magnetic noise from residential sources and from the electrified main trunk railway line significantly degraded the quality of the data. 3D and static shift distortions were also observed. Some of these distortions might be related to dykes or plugs of volcanic rock (associated with volcanic craters near Ohakune). However, there were no indications in the data of any low resistivity anomalies (< 25 ohm-m) in the area. (Tertiary mudstones typically have a resistivity of about 30 ohm-m at ambient temperature). The underlying resistive greywacke basement was modelled at depths of about 700m to 1200m in the Ohakune area. It was concluded from these results that the chances of encountering hot waters in this area are small.

6. SOUTH ISLAND

6. 1 Hanmer Springs

Hot springs at Hanmer occur in an alluvium-filled depression (about 60m thick) between greywacke ranges. As with all South Island hot springs, the origin of the hot water is tectonic, resulting from convective circulation of meteoric water along active faults, to about 3-4 km depth, where temperatures are 100 to 120^{o}C. Resistivity gradient array and VES soundings (Bennie and Graham, 2001b) were interpreted to indicate the presence of a shallow low resistivity layer (20 to 40m thick of 30 ohm-m) beneath the Hanmer Springs hospital grounds and golfcourse area surrounding the baths complex. The resistivity of the spring water itself is 5 ohm-m while that of background cold water is 200 ohm-m. The low resistivity layer could therefore represent porous sediments saturated with the thermal fluid and/or an associated clay-rich unit.

DC resistivity data were collected using various current dipoles for different effective probing depths. The deeper gradient-array resistivity information suggests that the deep upflow zone at Hanmer (where apparent resistivity values are lowest), is located south of the baths complex, and that it is oriented approximately east-west. This zone coincides with a recent fault scarp and is presumed to be associated with a deeply penetrating fault zone of crushed greywacke basement rock. In the sediments above the greywacke, the hot water upflow zone (of lowest resistivity) is in the immediate vicinity of the bore supplying the baths complex, and is elongated NE-SW.

Probable distortions to the measured resistivities in the urban environment were noted. These included the effects of buried pipes and grounded fences. They were revealed by using two orthogonal current sources to produce different current flow directions through the target area.

7. CONCLUSIONS

A comparison of the results of temperature gradient, gravity and resistivity trials over shallow hot water (low enthalpy) resources, conducted in a variety of New Zealand settings, and using a variety of methods, including DC and EM (TEM and MT) resistivity surveys, has provided us with several conclusions. Shallow temperature methods are useful where the hot water resource is close to the surface and is not masked by overlying aquifers of cold groundwater. Gravity anomalies can be interpreted in terms of subsurface structure, where formations of different density are vertically displaced, but the gravity method is generally ineffective at identifying fractured parts of fault zones that are permeable to fluid flow.

DC resistivity methods (especially tensor-gradient and Schlumberger array) provide a practical means of locating hot water resources or associated hydrothermal clay alteration, but they are usually less efficient at resolving narrow target structures. CSAMT and shallow MT have advantages in terms of efficiency of 3D data collection and improved resolution of subsurface resistivity structure (to about 300m depth), but are highly susceptible to local electrical noise sources. All the resistivity methods suffer from distortions caused by earthed metal structures. Highly conductive clays of thermal or non-thermal origin create penetration depth limitations and interpretation difficulties. Therefore, interpretation of resistivity anomalies must be treated in a site specific manner. In some settings a narrow resistive structure may indicate a fault-controlled zone of silicification within an otherwise impermeable clay-rich layer. In other settings, a permeable fault zone may contain conductive thermal fluids or clays within an otherwise resistive host rock. Where structure is 3-dimensional, a full tensor approach may be necessary in order to usefully resolve contrasts in formation resistivities.

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