Geophysical techniques for low enthalpy geothermal exploration in New Zealand

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Introduction

Shallow warm water resources associated with low enthalpy geothermal systems are usually difficult to explore using geophysical techniques, mainly because the warm water creates insufficient physical changes to the host rocks to be detectable. In addition, often the system also has a limited or narrow size.

This paper presents case studies of geophysical exploration of shallow warm water systems over a variety of settings in New Zealand (mostly over the North Island), with a variable degree of success. Locations of study areas are shown in Figure 1.

Shallow temperature measurements

A simple and direct method for the exploration of warm water systems is shallow ground temperature measurements. Ground temperature variation over the Naike hot springs (Figure 1) is shown in Figure 2*a*. It suggests a relationship between the ground temperature and Faults II and III which were mapped by Siswojo *et al.* (1985) from an examination of aerial photographs.

The occurrence of thermal water near Whitford (Figure 1) at South Auckland was revealed during the drilling of a few shallow wells (<80 m) for a farm water supply. The existence of this thermal water was also shown by subsequent ground temperature measurement across the area.

At Pipiroa (Figure 1) temperatures at 1 m 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 (22–26°C) or gas discharges had been noted.

At least five hot springs occur along the south-eastern shore of Mokoika Island (Figure 1) in Lake Rotorua. Results of shallow ground temperature measurements clearly indicate two favoured sites for accessible shallow hot water resources.

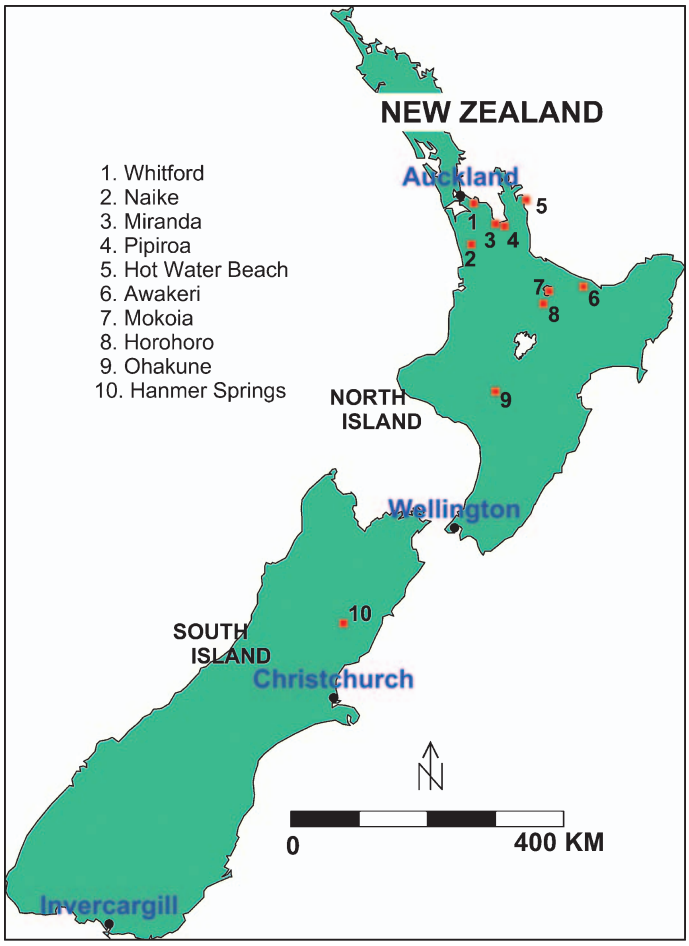

Fig. 1. *Location map of the study areas.*

Gravity method

The gravity method is often used as a structural technique for the exploration of New Zealand warm water systems.

At Naike, residual gravity data (Kasonta, 1984) appear to indicate the deepening of greywacke basement under the overlying Tertiary rocks (see Figure 2*c*), but show no obvious correlation with the thermal springs. A correlation between residual gravity anomaly and faults II and III seems to occur close to the greywacke basement outcrop, but this is questionable because of the limited number of measurement sites.

Detailed gravity measurements over the Whitford warm water prospect (Chen, 1990) did not show any obvious relationship with the inferred fracture zone in this area as suggested by various DC resistivity surveys (Mohamed, 1988; Yang, 1989; El-Shariff, 1990).

At Awakeri (Figure 1) 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 (Bromley *et al.*, 2003).

Direct current (DC) resistivity survey

Direct-current (DC) resistivity measurements using a variety of electrode arrays have been the most common method for the exploration of low enthalpy geothermal resources in New Zealand.

At Naike, Schlumberger DC apparent resistivity data appear to indicate the deepening of greywacke basement under the overlying Tertiary rocks (consistent with the gravity data), but show no obvious correlation with the thermal springs (see Figure 2*b*).

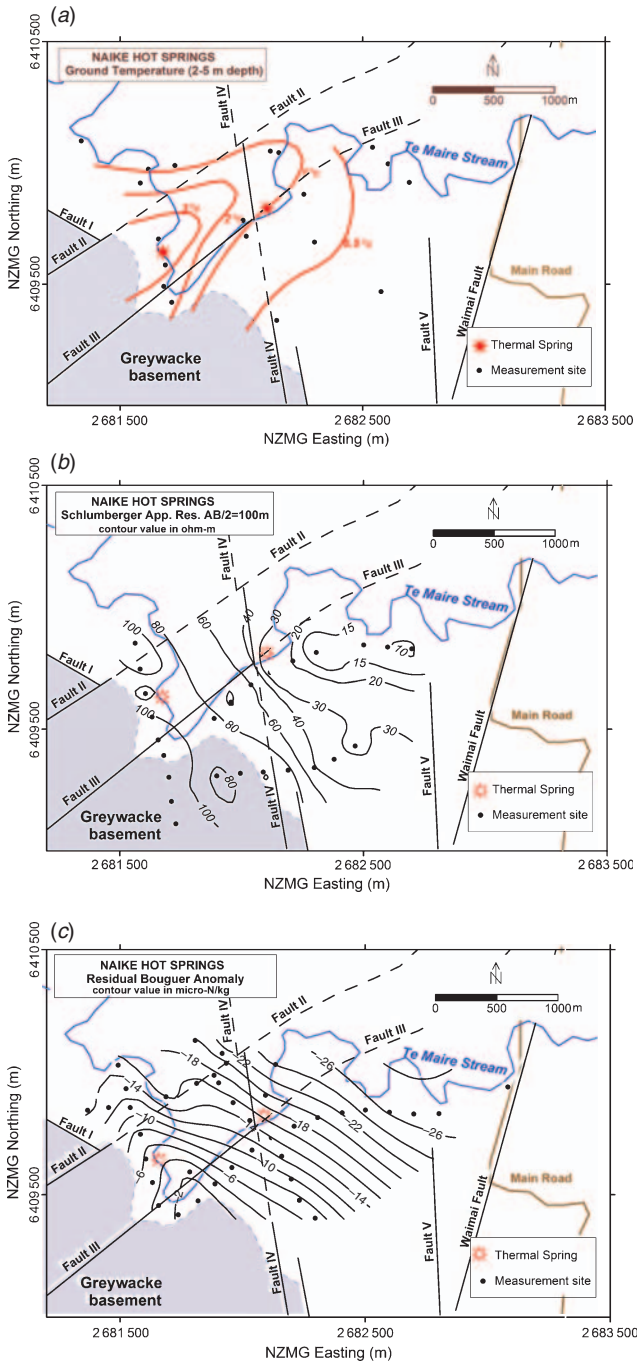

Fig. 2. *Ground temperatures (a), Schlumberger app. resistivity (b) and residual Bouguer anomaly (c) of the Naike hot springs (from Simandjuntak, 1983; Kasonta, 1984; Siswojo* et al.*, 1985).*

Apparent resistivity tensor measurements, together with ground temperature survey and borehole temperature data suggest the presence of a zone of NNW oriented basement fractures associated with the warm water at Whitford (Boedihardi and Hochstein, 1990). The existence of such a fracture zone is also supported by a circular Schlumberger electrical sounding (CES) carried out by Yang (1989).

DC resistivity measurements using Schlumberger array were carried out across the Miranda hot springs (Figure 1) by Sudarman (1982). Figure 3 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 = 300 m). The further decrease of apparent resistivity to the east may indicate the influence of seawater. 2D interpretation of the Schlumberger traversing data, combined with 1D 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 Figure 3) was interpreted by Sudarman (1982) as a possible deep structural scarp that may be associated with the Miranda hot springs.

At Hot Water Beach (Figure 1) on the eastern coast of Coromandel Peninsula, Schlumberger resistivity traversing (AB/2 = 500 m) indicated low apparent resistivity values of 5–19 ohm-m (relative to background values of 50–60 ohm-m)

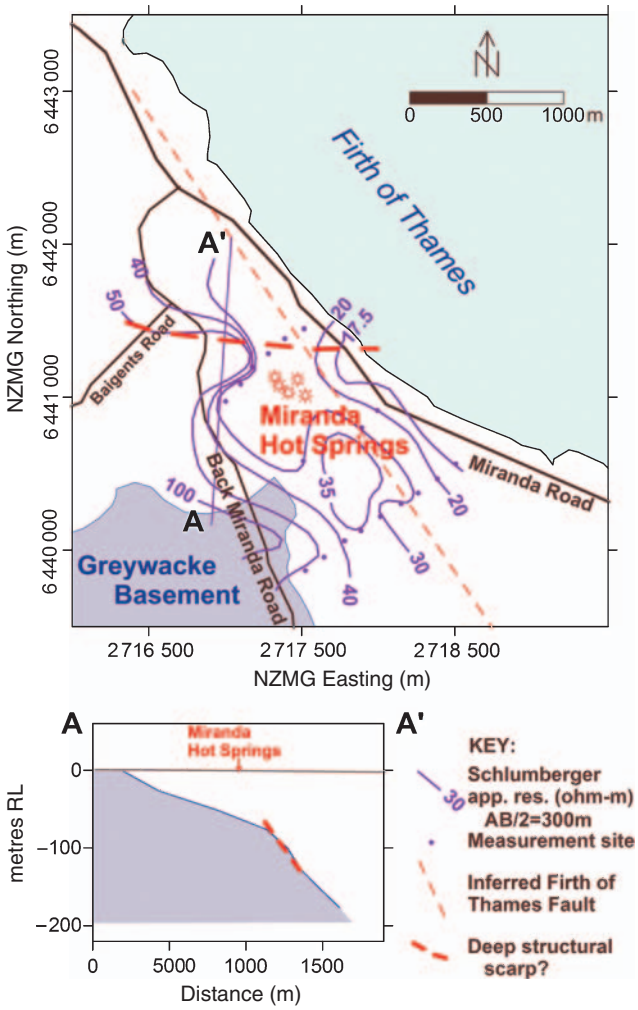

Fig. 3. *Results of a DC resistivity survey over the Miranda hot springs (from Sudarman, 1982).*

associated with 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 500 m for the thermal alteration anomaly.

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 at Awakeri (Bromley *et al.*, 2003).

In the South Island, hot springs at Hanmer (Figure 1) occur in an alluvium-filled depression (about 60 m 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 100–120°C. Resistivity gradient array and VES soundings (Bennie and Graham, 2001a) were interpreted to indicate the presence of a shallow low resistivity layer (20–40 m thick of 30 ohm-m). 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.

Electromagnetic (EM) survey

More recently, resistivity investigations using shallow magnetotellurics (MT), controlled source audio magnetotellurics (CSAMT) and transient electromagnetic (TEM) methods have also been used to explore the shallow warm water systems in New Zealand.

MT soundings were made near Miranda hot springs (Bennie and Graham, 2001b). Resistive (300–500 ohm-m) greywacke basement was modelled at depths of 100–200 m, 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.

At Pipiroa (between Miranda and Thames, see Figure 1), GNS undertook a TEM resistivity sounding during September 2005 in the vicinity of a capsicum producing greenhouse to search for evidence of a hot water resource. The result 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.

Along the south-east shoreline of Mokoia Island (Lake Rotorua), 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. The TEM sounding showed a low resistivity layer of 5–10 ohm-m, presumably caused by geothermal fluid or clay, within the upper 50–100 m depth. The shallow MT soundings recorded at frequencies from 8 kHz to 4 Hhz, showed a consistent pattern of low resistivities near the surface (10–30 ohm-m) underlain by a higher resistivity layer (100–300 ohm-m).

CSAMT measurements along a NW profile were conducted through the 11 hectare Horohoro property of Plenty Flora Ltd (see Figure 1 for location), with the purpose of testing the

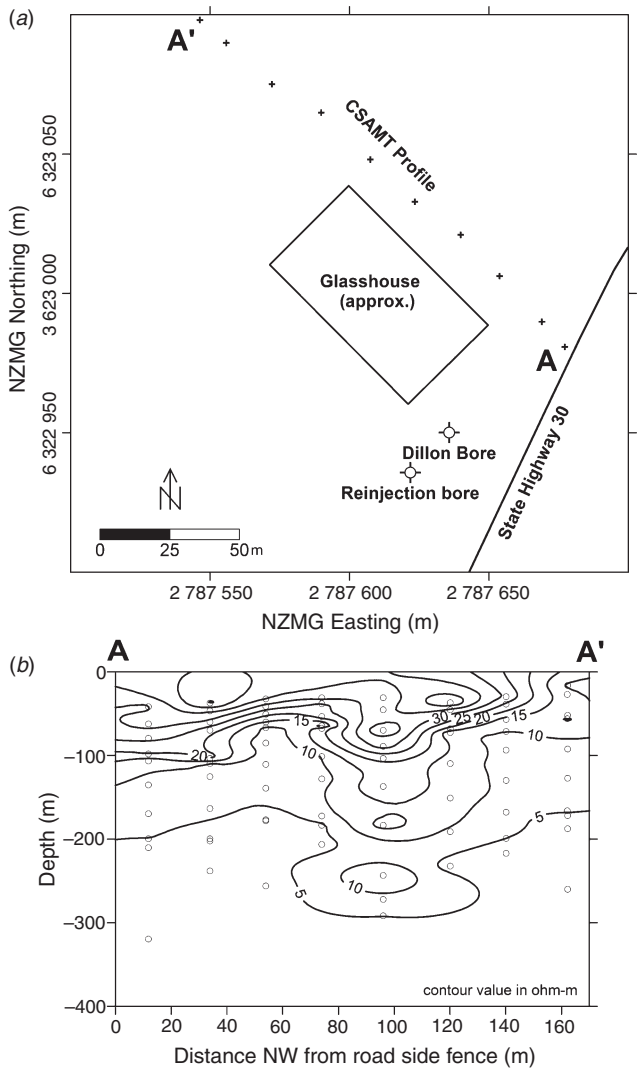

Fig. 4. *Map of CSAMT resistivity profile line location and boreholes (a) and CSAMT resistivity cross-section along line A-A′ (b), Plenty Flora Ltd, Horohoro.*

resistivity method for targeting hot water resources in the depth range of up to 300 m. The CSAMT resistivity cross-section along the profile is shown in the lower part of Figure 4. The profile shows a low resistivity layer below about 100 m depth near the road (SH30), sloping up to about 50 m 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 96 m) has anomalous high resistivities at depths from about 50 m to 270 m. 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 at the Plenty Flora area proves the presence of a lateral subsurface flow of hot geothermal water, centred at about 200 m 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 (96 m from the road). The target depth would be 200–250 m. If drilling is undertaken, cuttings from the

hole should be studied for evidence of silicification and fracturing.

Conclusions

The works described in this paper have 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 have different thickness, but the gravity method is generally ineffective at identifying the actual warm water reservoir.

DC resistivity methods provide a practical means of locating warm water resources or associated hydrothermal clay alteration, but they are usually less efficient at resolving narrow target structures.

CSAMT, TEM and shallow MT have advantages in terms of efficiency of 3D data collection and improved resolution of subsurface resistivity structure (to about 300 m depth). However, it should be noted that such EM methods are always highly susceptible to local electrical noise sources.

Highly conductive clays of thermal or non-thermal origin create penetration depth limitations and interpretation difficulties for the resistivity methods. Interpretation of resistivity anomalies needs to be treated in a site specific manner.

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