GEOPHYSICAL STUDY OF THE NORTHERN PART OF
TE KOPIA GEOTHERMAL FIELD, TAUPO VOLCANIC
ZONE, NEW ZEALAND

S. SOENGKONO1, S. ARUNACHALAM1, FATKHAN1, N.H. BANG1
AND G.S. PEREZ-RAMOZ1

1Geothermal Institute, The University of Auckland, Auckland, NZ

SUMMARY • Geophysical surveys were carried out in 1993 and 1997 to investigate the northern part of the Te Kopia geothermal field (central North Island of New Zealand). The surveys consisted of Schlumberger electrical resistivity mapping using small array spacings (AB/2 of 60 m and 30 m), Schlumberger vertical electrical sounding, ground magnetic gradient survey, and temperature measurements at 1 m depth. The results indicate a zone of warm ground associated with low-resistivity and low-magnetic gradient extending from the North Lakes (main surface manifestation area) and Road Springs, through the Murphy Hill area (mud craters and steaming ground), towards the Murphy's Farm Springs near the northern boundary of the field. This thermally active alteration zone probably indicates a path of near surface thermal waters which is controlled by a set of small, en echelon faults. Such a shallow hydrology of thermal waters is sensitive to minor movements of the faults which can trigger thermal perturbations such as those occurred in late 1993 - early 1994.

1. INTRODUCTION

The Te Kopia geothermal field is a high-temperature field in the Taupo Volcanic Zone (TVZ), situated about midway between Taupo and Rotorua. It is one of three geothermal fields that are located along a major NE trending fault system, the Paeroa Fault Zone (Fig. 1). The Te Kopia field has extensive surface manifestations which include fumaroles, pools and craters containing hot mud and acid sulphate waters, steaming ground, hot/warm ground and a widespread hydrothermal alteration. Most of these manifestations occur along the scarp of the Paeroa Fault Zone, but a small group also exist on the downthrown (NW) side of the fault a few hundred metres from the base of the scarp. In addition, there are two groups of hot springs on the downthrown side of the Paeroa Fault Zone discharging acid-chloride and chloride-bicarbonate waters.

Two wells were drilled in mid-1960s at Te Kopia to depths of about 945 m (TK1) and 1250 m (TK2). Both wells penetrated a sequence of ignimbrites and lavas which have been described by Grindley (1965) and Bignall (1991, 1994). The maximum temperature measured in these wells was 238 °C in TK1 and 227 °C in TK2 (Bignall, 1994).

The northern part of Te Kopia was investigated in 1993 and 1997 using a variety of geophysical measurements comprising Schlumberger resistivity mapping with small array spacings (AB/2 of 60 m and 30 m), Schlumberger vertical electrical sounding (VES), ground magnetic gradient survey, and temperature measurements at 1 m depth. Results from these investigations are presented in this paper.

2. THE EXTENT OF TE KOPIA FIELD

The Te Kopia field has been investigated by a reconnaissance electrical resistivity mapping using the Schlumberger array with spacings (AB/2) of 1000 m and 500 m (Geophysics Division of DSIR, 1985a; 1985b), and was covered by an aeromagnetic survey at ca. 760 m RL (Soengkono, in prep.).
resistivity mapping showed a resistivity low at the Te Kopia field, indicating the existence of electrically conductive hydrothermal alteration products (clays) and mineralized thermal waters (Bibby et al., 1994). The aeromagnetic data exhibit negative residual magnetic anomalies over Te Kopia, which can be interpreted as effects of hydrothermally demagnetized reservoir rocks (Hochstein and Soengkono, 1997).

A resistivity boundary of the Te Kopia field has been inferred from the DSIR electrical resistivity data (Soengkono, in prep.) and is shown in Fig. 2, together with contours of residual aeromagnetic anomalies over the geothermal field. The extent of hydrothermal demagnetization of the Te Kopia reservoir, inferred from a preliminary 3-D interpretation of the residual aeromagnetic data, is also shown in Fig. 2.

Both the resistivity boundary and the magnetic interpretation results in Fig. 2 suggest that the Te Kopia reservoir has a greater extent than that indicated by the area of surface manifestations. A more detailed study of the resistivity, aeromagnetic, and topographic data (Soengkono, in prep.) has suggested that the Te Kopia geothermal reservoir is influenced by two sets of geological structures (faults and fractures) trending in the NE and NW directions, respectively.

3. SURFACE MANIFESTATIONS AT THE NORTHERN PART OF TE KOPIA FIELD

Fig. 3 shows the distribution of active Surface manifestations at the northern part of Te Kopia field. The North Lakes are part of the main surface manifestations of Te Kopia, consisting mainly of mud and acid sulphate pools and craters. The Road Springs consists of two hot springs and some seepages along a small stream which discharge clear but acid waters (pH=2-3) with slightly elevated chloride levels (about 30 ppm) at an average temperature of 97°C (Karouaz, 1997). Murphy hill is a mound of about 8 m high, occupied by three mud-craters (numbered I, II and III in Fig. 4) which are aligned in the NE direction. Steaming ground and a small steam vent occur near a stream about 100 m north of the Murphy Hill. At the Murphy’s Farm springs about 600 m to the north of Murphy Hill, a group of hot springs occurs on a steep bank of a small river discharging near neutral (pH=6-7) chloride-bicarbonate waters at an average temperature of 60°C (Glover et al., 1992; Bignall

Figure 2. Map of Te Kopia geothermal field showing the area of surface manifestations (shaded and bounded by dashed line), hot springs (hatched open circles), wells TK1 and TK2 (solid circles), resistivity boundary (light shade), contours of residual aeromagnetic anomalies at ca. 760 m RL (values in nT), the inferred extent of hydrothermal demagnetization of reservoir rocks (thick, dashed polygon), and Schlumberger VES sites 100, 200 and 300 (solid triangles).

Figure 3. Map of the northern part of Te Kopia field showing the surface manifestations and geophysical measurement sites.

3.1 Changes of thermal activity

Changes of thermal activity occurred in the northern part of Te Kopia field in late 1993 - early 1994 which have been reported by Browne et al. (1994). Some additional data from our observations related to these changes are described below.

During our field work in August 1993, the three mud craters at Murphy Hill were vigorously boiling (surface temperature about 98°C) and lumps of hot mud were occasionally discharged from craters I and III and deposited up to 2 m distance from the edge of the craters. Browne et al. (1994) reported that the mud craters were still very active during November 1993 - February 1994; ground vibrations caused by the activity were felt occasionally up to 100 m away. However, the craters became less active during the following few weeks and by the end of March 1994 the mud had thickened and the ground vibrations had significantly reduced. No further observation was recorded until August 1997 when we did our second field work in the area. By this time, only crater II showed signs of activity (small discharges of gas/steam with surface temperature of about 70°C); the other two mud craters had dried out, although their near surface temperatures were still above ambient, i.e. 32°C (mud crater I) and 26°C (mud crater III). In contrast, we found a small (0.5 m diameter) boiling mud pot about 15 m NNE of crater III, which did not exist in 1993.

In August 1993, we did not notice any sign of thermal ground in the area surrounding Murphy Hill. However, by the end of 1993 vegetation dieback was noticed in the area to the west of Murphy Hill by Browne et al. (1994) who conducted three subsequent monthly ground temperature surveys in mid-January, February, and March 1994. The surveys showed the development of thermal ground in this area where anomalous ground temperatures up to 84°C (1 m depth) were measured. Browne et al. (1994) also reported that ground temperatures were variable during the three months period of their surveys, but without any simple pattern of changes. More than three years later (August 1997) we conducted a similar temperature survey but covering a smaller area NW of Murphy Hill craters. Our measurement results are presented in Fig. 4 together with those from the March 1994 survey made by Browne et al. (1994). It can be seen in Fig. 4 that changes of ground temperatures continued between March 1994 and August 1997. In the area SW of mud craters, the ground had significantly cooled, from 95-97°C in March 1994 to about 30°C in August 1997. In contrast, about 30 m to the NW, the ground temperatures had increased, from 62-78°C in March 1994 to 85-97°C in August 1997, suggesting an apparent northward shift of the activity.

Figure 4. Ground temperatures (1 m depth) in the Murphy Hill area in March 1994 (upper figure) and August 1997 (lower figure). Temperatures ≥70°C are indicated (shaded). A new mud pot (did not exist in 1994) is indicated by the star symbol in the lower figure.
Signs of thermal stress on vegetation were also noticed in the Pine Plantation area (Fig. 3) by Browne et al. (1994) in late 1993 (simultaneously with the ground temperature changes in the Murphy Hill area). Their three subsequent monthly temperature surveys in this area recorded the development of about 800 m² thermal ground where temperatures up to 86°C were measured in some 1 m depth holes. Browne et al. (1994) have suggested that the thermal perturbations in the Murphy Hill and Pine Plantation areas might have been initiated by two medium sized earthquakes (magnitudes of 4.3 and 4.5 on Richter’s scale) that occurred in the Te Kopia area on 28 and 29 November 1993.

4. SCHLUMBERGER VERTICAL ELECTRICAL SOUNGING (VES)

Vertical electrical sounding (VES) using the Schlumberger array were conducted in 1997 at three sites: 100, 200 and 300 (see Figs. 2 and 3). The purpose of the soundings was to investigate shallow hydrology of the survey area.

A small dc-current source (transmitter) powered by a car battery was used to inject electrical currents into the ground through a series of current electrodes A and B (metal spikes) to a maximum AB/2 spacing of 200 m. Voltage differences between potential electrodes M and N (each made of Cu metal immersed in a porous porcelain pot containing CuSO₄ to minimise polarisation by the ground) in response to the injected currents were measured using a Fluke digital multimeter. Apparent resistivities were computed using the standard equation for the Schlumberger array (eg. Dobrin and Savit, 1988).

The sounding curves are presented in the upper part of Fig. 5 which include apparent resistivity data interpolated from the DSIR Schlumberger resistivity maps for AB/2 of 500 m and 1000 m. The lower part of Fig. 5 shows 1-D interpretations of the sounding curves. The results suggest that a layer of low electrical resistivity (about 7 ohm-m) exists beneath sounding sites 200 (at 34 m depth) and 100 (at 14 m depth). It is possible this low resistivity layer contains electrically conductive mineralised thermal water, since it is closer to the surface (14 m) at site 100 which is located only about 100 m from the Road Springs (Fig. 3). No layer of low electrical resistivity is indicated by sounding 300, which suggests that there is no direct (straight line) hydrological link at a shallow level (≤60 m depth) between the Road Springs and the Murphy’s Farm springs.

Figure 5. VES curves from measurements made at sites 100, 200, and 300 (upper figure) and their 1-D interpretations (lower figure).

5. SHALLOW RESISTIVITY MAPPING, MAGNETIC GRADIENT MEASUREMENT, AND GROUND TEMPERATURE SURVEY

A combined survey of resistivity mapping using the Schlumberger array with spacings (AB/2) of 60 m and 30 m, horizontal magnetic gradient measurement, and determination of temperature at 1 m depth was carried out in 1993 along three traverses in the study area (see Fig. 3). The main purpose of this combined survey was to investigate the extent of near surface hydrothermal alteration and its relationship with present day thermal activity.

The resistivity mapping was carried out using the same set of equipment (current transmitter and digital multimeter) used for the Schlumberger VES. Contours of apparent resistivities measured using AB/2=60 m are shown in Fig. 6, which indicate the distribution of ground electrical resistivity to a depth
of about 30 m. The surface manifestations at North Lakes and Murphy Hill are all located inside a resistivity low (apparent resistivity <10 ohm-m) which can be interpreted as a zone of electrically conductive altered ground.

The magnetic gradient measurements were made using an ELSEC 820 proton magnetometer. The magnetic gradient at a survey station was determined by measuring total force magnetic field strengths (in nT) above the station and at 5 m distances to the north and to the east of the station. As the total time required for a complete measurement at one station is less than 5 minutes, diurnal correction was not necessary for the magnetic readings. Components of horizontal magnetic gradient (nT/m) in the NS and EW directions were computed from the differences of magnetic readings divided by the distances and the results were used to determine the (total) horizontal gradient by a vector summation.

Horizontal magnetic gradient is sensitive to variation of ground magnetisation. Over an area where near surface rocks are mostly non-magnetic, such as a thermally altered ground, the horizontal magnetic gradient would have a low value. To reduce the effects of thin (<1 m) cover of unaltered (magnetic) younger volcanic products (mainly the 1,800 years old Taupo ignimbrite), the magnetic sensor was always placed at about 2.5 m above the ground. The zone where values of horizontal magnetic gradient are less than 4 nT/m is shown (shaded) in Fig. 6, which coincides with the electrically conductive altered ground indicated by the resistivity mapping.

The temperature survey was made by temperature measurements in 1 m depth holes drilled using a hand auger. The aim of the survey was to delineate zones of thermal (warm) ground where temperatures are above the ambient.

The ambient temperature at shallow depths (<5m) is affected by quasi-periodic temperature variations (mainly annual/seasonal temperature variations), and therefore are seasonally variable. Neglecting effects of diurnal or monthly (short-term) variations, the shallow ground temperature can be expressed by the equation:

$$ T(z,t)=aT_0+\Delta T_{cool}[-z/(a/2\omega)^2]cos[\omega t-z/(a/2\omega)] $$

where $z$ is depth (m), $a$ is temperature gradient ($^\circ$/m) associated with conductive heat flow, $T_0$ is the mean annual temperature ($^\circ$C), $\Delta T_{cool}$ is the amplitude of seasonal temperature ($^\circ$C), $\omega$ is the fundamental radian frequency (= 2\pi rad/year or 2\times10^7 rad/sec), $t$ is the time (s) from maximum peak of temperature (summer), and $a$ is the thermal diffusivity (m$^2$/s) of the ground (Hochstein, 1995).

Figure 6. Map of the northern part of Te Kopia field showing the surface manifestations (see Fig. 3 for explanation), a zone of low (<4nT/m) horizontal magnetic gradient (shaded), contour lines of Schlumberger apparent resistivity for $\Delta R/\rho = 60$ m (thick, solid lines; ohm-m), and contour lines of 1 m depth ground temperatures (thick, dashed lines; $^\circ$C).

The To and $\Delta T_{cool}$ measured at the Taupo NZED station (about 40 km south of Te Kopia; elevation 376 RL) are 11.9 and 5.4 $^\circ$C, respectively (Rwegoshora, 1995). Assuming an atmospheric temperature gradient of $-7$ $^\circ$/C/km (Hochstein, 1995), To at Te Kopia (400 m RL) is about 11.7 $^\circ$C. The normal (undisturbed) temperature gradient (a) is about 0.03$^\circ$/C/m and the average thermal diffusivity (a) of the ground in the TVZ is about 0.4x10^{-6} m$^2$/s (Hochstein, 1995). Hence, according to equation (1) the ambient temperature at Te Kopia (1 m depth) during the survey (conducted in the month of August when $t$ = 7 months, or 1.8x10^7 s) was about 8.5 $^\circ$C.

Contour lines for 7$^\circ$C, 10$^\circ$C and 20$^\circ$C ground temperatures across the survey area are shown in Fig. 6. The 10$^\circ$C contour lines delineate an approximate boundary of thermal (warm) ground in the study area, where temperatures at 1 m depth are well above the ambient temperature (8.5$^\circ$C). The thermal ground follows the zone of shallow alteration indicated by the resistivity mapping and magnetic gradient survey.
6. DISCUSSION

Ground magnetic gradient survey is a simple method of geophysical exploration which can be done rather quickly even in a moderately steep terrain. The results in Fig. 6 show that electrically conductive altered ground in the northern part of Te Kopia field are associated with low horizontal magnetic gradients (≤4 nT/m). Hence, these results have shown that a ground magnetic survey can be used to detect and map the distribution of near-surface alteration.

Fig. 6 also shows that the alteration zone indicated by the resistivity mapping and magnetic gradient survey in the north Te Kopia area, which extends through active thermal manifestations (from the North Lakes area and the Road Springs, through Murphy Hill, towards the Pine Plantation thermal ground and the Murphy’s Farm Springs), also coincides with the thermal (warm) ground delineated by the temperature survey. Hence, the alteration zone, which is still thermally active, indicates a path of near-surface thermal waters. The path does not follow a simple straight line (see also previous discussion on Schlumberger VES interpretation), probably because it is structurally controlled by a set of small, en echelon faults. Such an interpretation is consistent with the occurrence of thermal perturbations in late 1993 following two medium sized local earthquakes, since such a shallow hydrology of thermal waters would be sensitive to minor movements of the faults triggered by the earthquakes.

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