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APPLICATION OF MAGNETIC METHOD TO ASSESS THE EXTENT OF HIGH TEMPERATURE GEOTHERMAL RESERVOIRS

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ABSTRACT

The extent of thermally altered rocks in high temperature geothermal reservoirs hosted by young volcanic rocks can be assessed from magnetic surveys. Magnetic anomalies associated with many geothermal field in New Zealand and Indonesia can be interpreted in terms of thick (up to 1 km) demagnetized reservoir rocks. Demagnetization of these rocks has been confirmed by core studies and is caused by hydrothermal alteration produced from fluid/rock interactions. Models of the demagnetized Wairakei (NZ) and Kamojang (Indonesia) reservoirs are presented which include the productive areas.

Magnetic surveys give fast and economical investigations of high temperature prospects if measurements are made from the air. The magnetic interpretation models can provide important constraints for reservoir models. Magnetic ground surveys can also be used to assess the extent of concealed near surface alteration which can be used in site selection of engineering structures.

INTRODUCTION

Almost all geophysical methods have been used to assess geothermal systems, the success (or failure) of each method depends on the geological and hydrological setting as well as the type of the geothermal system. This paper reviews application of the magnetic method for study of high temperature (high T) geothermal systems in young (Quaternary) volcanic rocks. Investigation techniques that can be used to estimate reservoir extent and for mapping surface hydrothermal alteration are discussed with reference to case histories. Application of the magnetic method to assess crustal temperature structures, i.e. Curie point depths (e.g. Laughlin, 1982), is not discussed here.

The size of a geothermal reservoir is an important constraint for any conceptual model of a geothermal prospect and for resource assessment. The likely lateral extent of a geothermal reservoir can usually be assessed in moderately steep terrain from geophysical surveys, since significant contrast in physical parameters exist between reservoir rocks and the surrounding country rocks as a result of fluid/rock interactions. In many geothermal prospects, fluids also affect the ground surface. For such prospects, the size of a geothermal field can often be obtained from a study of surface manifestations, including mapping of altered ground. However, in most volcanic settings, hydrothermally altered rocks are hidden by vegetation or a weathered layer, or else covered by younger deposits of tephra and alluvium. Since thermally altered ground also exhibits physical parameters which differ with respect to those of unaltered ground, geophysical investigation methods can be used to detect such ground even where concealed.

HIGH-T GEOTHERMAL RESERVOIRS HOSTED BY YOUNG VOLCANIC ROCKS

Almost all volcanic rocks are magnetic because they contain small amounts of primary magnetic minerals (mainly magnetite and titanomagnetite). The total magnetization of volcanic rocks (in the range of 0.5 to 10 A/m) is given by the vector sum of induced and remanent magnetization. Induced magnetization depends on the magnetic susceptibility of the rocks (which is proportional to the volume fraction of magnetic minerals present) and the magnitude of the earth's magnetizing field. Remanent magnetization is the result of a complex unbalanced domain structure within the magnetic minerals and exists even where the magnetizing field is absent; rocks with remanent magnetization in the opposite direction to the present day earth's magnetic field are termed "reversely magnetized" rocks. In many liquid dominated geothermal fields, hydrothermal processes alter magnetite and titanomagnetite to almost non-magnetic minerals, such as pyrite, leucoxene, or hematite (Browne, 1994). Such processes cause the volcanic rocks to become partly or completely demagnetized and a significant magnetization contrast exists between the reservoir rocks and the unaltered volcanic rocks outside it.

Residual magnetic anomalies associated with a thick layer (0.5-1 km) of demagnetized rocks in the upper part of high T reservoir can usually be recognised from airborne magnetic data if larger areas surrounding the geothermal prospect are also covered by the survey and no reversely magnetized rocks (age ≥0.7 M yr) occur inside and outside the reservoir. Algorithms suitable for 3-D magnetic modelling of hydrothermal demagnetization zones are available (for example, Barnett, 1976). In large volcanic fields associated with so-called "active margins", regional effects of deeper seated magnetic bodies can cause a shift of residual magnetic anomalies. Assessment of such a regional field is required to obtain a representative "zero level" value for the residual bipolar anomalies; this can be obtained from the analysis of pronounced, isolated "topographic anomalies" outside the prospect, or by simultaneous analysis of first order residual anomalies observed at a higher level and extended to non-magnetic basement rocks (Hochstein and Soengkono, 1994).

Demagnetization of volcanic rocks by fluid/rock interaction is a complex process which depends on parameters controlling the stability of the primary magnetic minerals, like pH and temperature of fluids, joint permeability, fluid movement, etc. In an oxidizing environment, magnetite can be stable which explains why volcanic rocks on top of a high T reservoir and at levels above shallow boiling can retain their magnetization (Hochstein and Soengkono, 1994). Elsewhere the same rocks forming pronounced topographic highs (volcanic domes) may be completely demagnetized by interaction with shallow, acid condensates as hematite and limonite replace primary magnetic minerals.

Demagnetization by hot fluid/rock interaction is cumulative and irreversible. Demagnetized rocks therefore occur in extinct geothermal systems, a phenomenon now used to explore for epithermal mineral deposits. Cumulative demagnetization of active systems may also reflect the control of paleo-permeability and paleo- subsurface fluid flow patterns. In some cases demagnetization can affect large areas outside the present day high T reservoir, thus causing some rather indistinct magnetic anomaly patterns (Hochstein and Soengkono, 1994). In the following two case histories, demagnetization is clearly restricted to the productive area of high T reservoir and where the geometry of the demagnetized reservoir can be used for modelling it.

Kamojang Geothermal Field

The Kamojang Geothermal Field is located in West Java, Indonesia. It is a vapour dominated system hosted by a sequence of young, dominantly andesitic volcanic rocks (e.g. Hochstein, 1976; Dench, 1980; Grant *et al.*, 1982). The reservoir is capped by a thick (about 300-350m) condensate layer in which temperature increases from about 100° C at the top to about 235° C at the bottom.

An airborne magnetic survey was conducted in 1986 at 2500m asl altitude (about 900m above mean terrain), covering the Kamojang and the nearby Darajat fields. A representative "zero level" value of the residual anomalies was obtained from topographic modelling (Suranto, 1987). The residual magnetic anomalies over the Kamojang field are presented in Figure 1 which shows a magnetic low centred on the field as delineated by DC-resistivity surveys. At Kamojang, where the magnetic inclination is about -35°, the centre of the magnetic low has been shifted north of the centre of the anomalous body. There is no evidence that rocks within or outside the Kamojang reservoir are reversely magnetized. The residual anomalies were interpreted using 3-D magnetic modelling (Soengkono *et al.*, 1988). The interpretation shows that the magnetic low can be explained by a thick demagnetized volcanic body in the southern part of the Kamojang field (see Figure 1) at depths below 300m (Figure 2). This is supported by core studies (Figure 3) which show that between about 300 and 1000m depth most cores are significantly demagnetized. The demagnetized rocks lie now within the vapour dominated reservoir below the condensate layer. However, the widespread occurrence of replacement and vein calc-silicates in the vapour dominated reservoir indicates that demagnetization took place when Kamojang was a liquid-dominated system (Hochstein and Soengkono, 1994). Cores taken from the surface to 300m depth and below 900m depth are still magnetic.

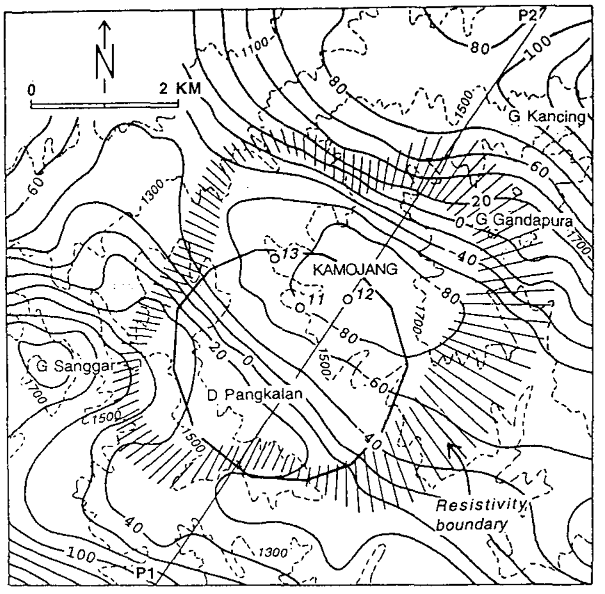

Figure 1. Residual total force anomaly (solid contours, 20 nT interval) at 2500m asl over the Kamojang Geothermal Field, West Java, Indonesia. The topography is shown by broken contours (interval 200m). The demagnetized body below 300m depth is outlined by the polygon. Numbered circles are wells referred to in Figure 3 (from Soengkono *et al.*, 1988).

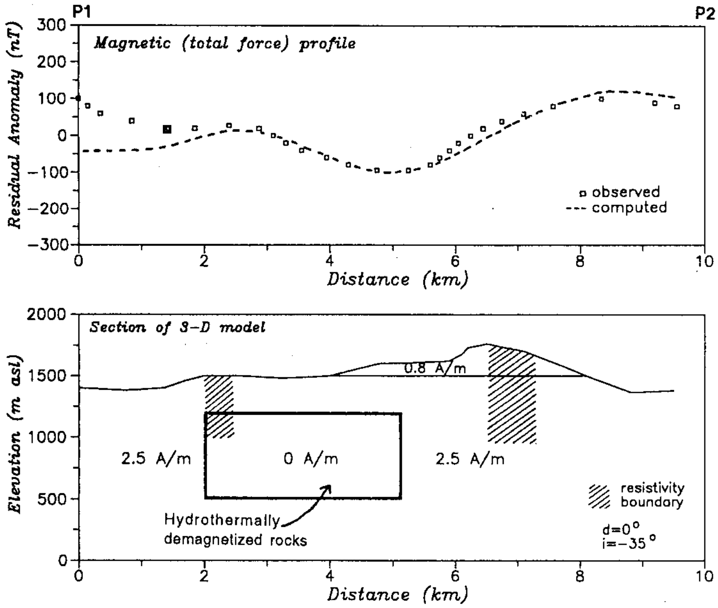

Figure 2. Observed and computed anomalies of profile P1-P2 (see Figure 1) together with interpreted cross section (taken from Soengkono *et al.*, 1988).

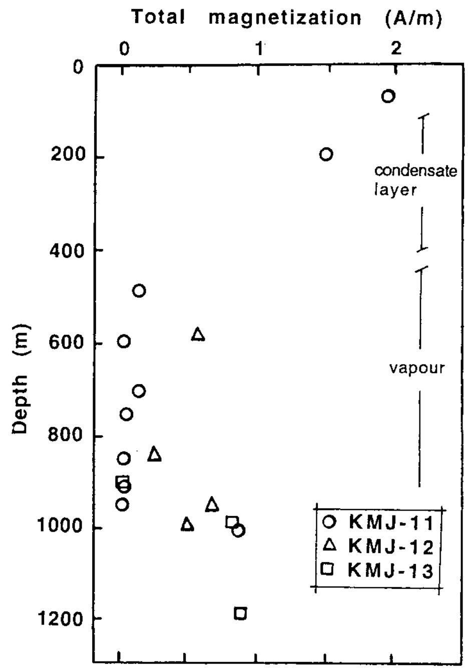

Figure 3. Plot of total magnetization of cores from Kamojang wells against depth (modified from Soengkono *et al.*, 1988). Well localities are shown in Figure 1.

Assuming that fluid characteristics remain about constant at the same level throughout the reservoir, it can be inferred that demagnetization has been controlled by the (paleo-) permeability of the rocks. Based on this inference, Soengkono *et al.* (1988) suggested that parts of the Kamojang reservoir which lie outside the demagnetized body, but still within the resistivity boundary, should exhibit a lower permeability. Figure 4 shows that the demagnetized reservoir encompasses the Kamojang borefield and wells with low productivity (i.e. KMJ- 9, 13, 25, 12, 7, 20 and 32) are indeed located close to the boundary of the magnetic model. Reservoir modelling by Saptadji (1987) also indicates that the permeability of volcanic rocks outside the Kamojang borefield is low.

Wairakei Geothermal Field

The Wairakei Geothermal Field is part of the large Wairakei-Tauhara hot water dominated system in the Taupo Volcanic Zone (TVZ), Central North Island, New Zealand. The geothermal reservoir stands in a sequence of young, dominantly rhyolitic volcanic rocks (Steiner, 1977). The Wairakei field has been exploited since 1950s and is now probably one of the best studied geothermal systems in the world.

The Wairakei Field was covered by a low level (760m asl; about 300m above mean terrain) airborne magnetic survey conducted in 1984 by staff of the Geothermal Institute. Residual anomalies were computed by removing the normal field, defined by the International Geomagnetic Reference Field (IGRF) of Malin and Barraclough (1981), and reducing the regional field

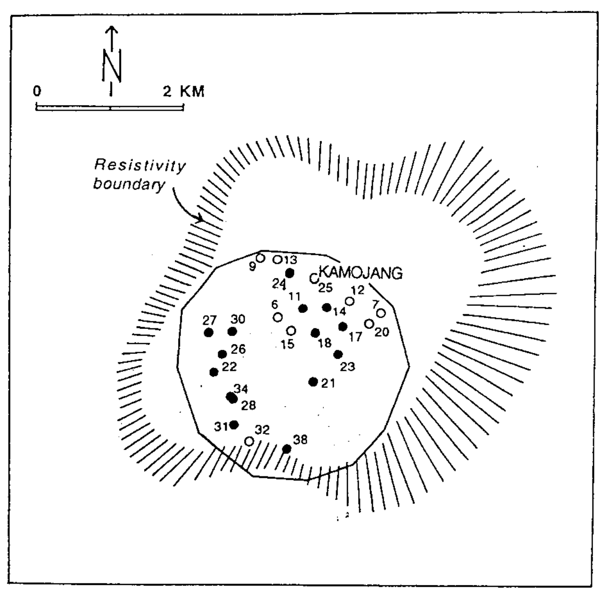

Figure 4. Map showing the extent of demagnetized rocks (thick polygon) and locality of Kamojang production wells with mass flowrate ≥30 t/h (solid circle) and ≤30 t/h (open circle).

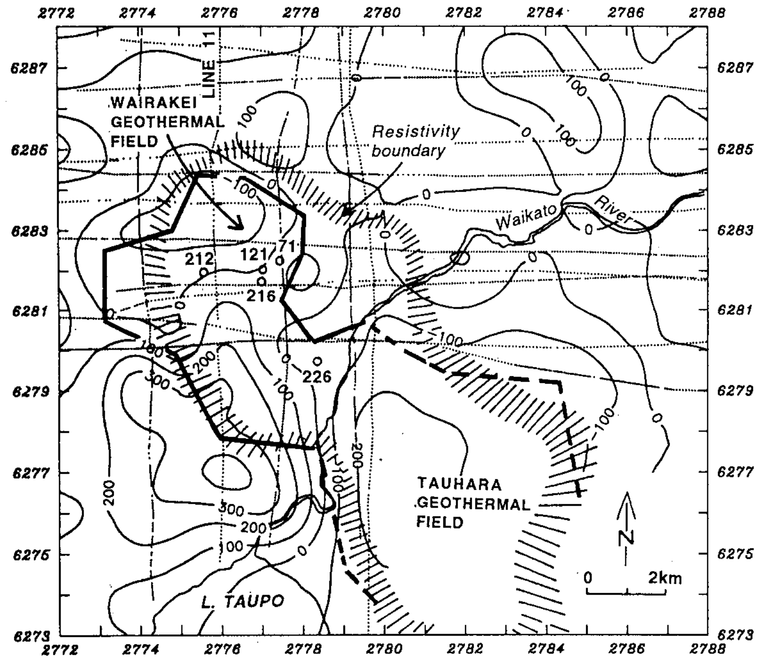

Figure 5. Residual total force anomaly (solid contours, 100 nT interval) at 760m asl over the Wairakei Geothermal Field, Central North Island, New Zealand (modified from Soengkono and Hochstein, 1992). The demagnetized body below sea level is outlined by the thick line. Numbered circles are wells referred to in Figure 6. Flight lines of the survey are shown by the dotted lines.

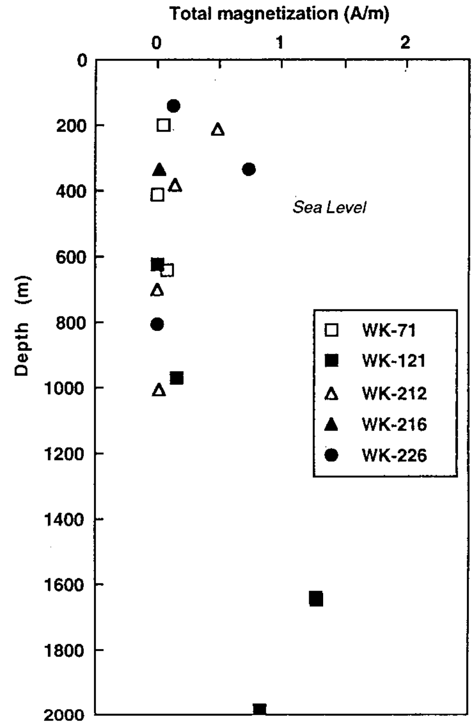

Figure 6. Plot of total magnetization of cores from Wairakei wells against depth. Well localities are shown in Figure 5.

caused by deeper seated magnetic bodies beneath the TVZ (Soengkono and Hochstein, 1992). Residual anomalies are presented in Figure 5 which shows the presence of a distinct magnetic low in the northwestern part of the Wairakei field as defined by the resistivity boundary. The data in Figure 5 also indicate a second magnetic low associated with the Tauhara Field, although this field is not fully covered by the survey. A large magnetic high (max. amplitude c.400 nT) occurs to the south-west of the field; its northeast extension separates the magnetic low in the northwestern part of the Wairakei Field from that over the Tauhara Field. There is no evidence of any reversely magnetized rocks in the Wairakei area.

A study of cores from several wells was conducted by Lampoonsub (1987). This (Figure 6) showed that cores taken from below sea level (c.450 m depth) are almost completely demagnetized. Some cores from higher levels are magnetic and not greatly affected by hydrothermal alteration; cores taken from below 1000m depth also have retained their magnetization. A similar pattern was found at Kamojang in West Java, Indonesia (see Figure 3) and in the Mokai geothermal field, about 25 km north-west of Wairakei (Soengkono, 1985).

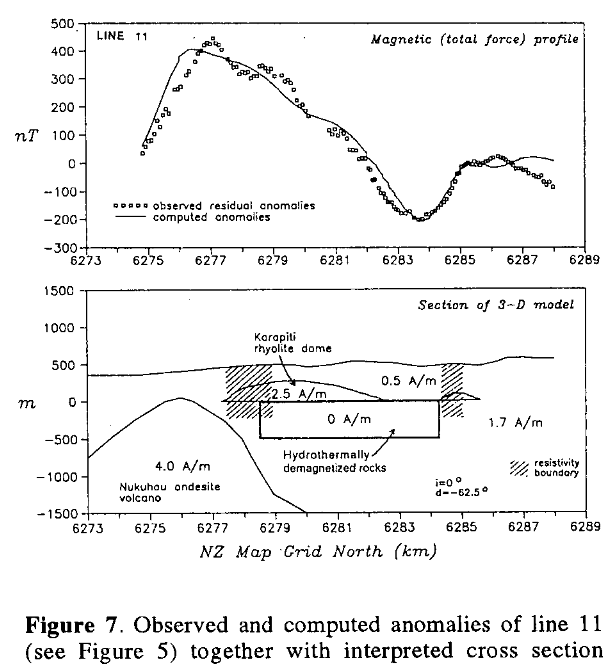

Figure 7. Observed and computed anomalies of line 11 (see Figure 5) together with interpreted cross section (taken from Soengkono and Hochstein, 1992).

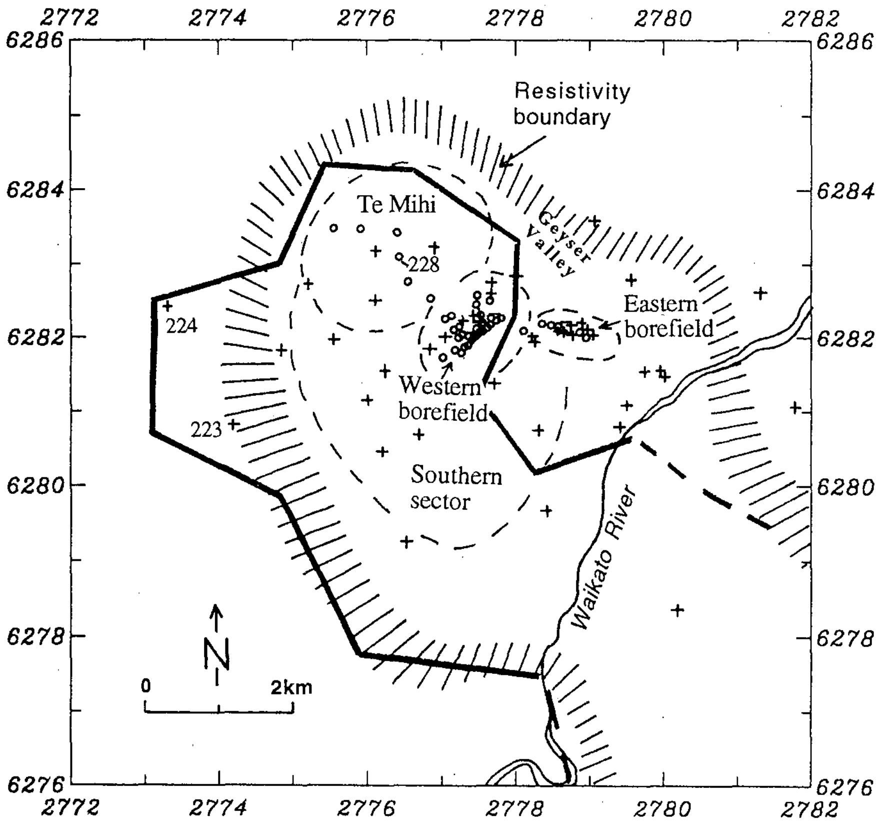

Figure 8. Map showing the extent of demagnetized rocks (thick line) and locality of Wairakei production wells (open circles) and investigation wells (crosses).

A 3-D magnetic model of the Wairakei geothermal field (see Figure 5 and 7) was constructed by Soengkono and Hochstein (1992) which includes hydrothermally demagnetized rocks to about -500m below sea level (450-950m depth from the surface). A concealed rhyolite dome (Karapiti Rhyolite) still retains its magnetization; a large concealed andesite strato volcano to the south-west of the Wairakei field (not reached in any drillholes) is also highly magnetic.

The magnetic model (Figure 8) shows that the demagnetized reservoir covers the Te Mihi sector, the main western bore field, and the southern sector of the Wairakei field, but not the smaller eastern borefield. Well 228 drilled in the Te Mihi area (Figure 8) is one of the large producing wells in this field, with a production of 90 t/h dry steam (Grindley, 1986). Based on pressures, temperatures and fluid constituents of wells drilled in the Te Mihi sector, Grant (1982) inferred that a major upflow occurs beneath this area. In the natural state hot fluids must have flowed laterally to the east of the area now occupied by the western and eastern borefields and towards Geyser Valley (now called Wairakei Valley). If this interpretation is true, we can explain the lack of demagnetization in the eastern part of the Wairakei field in terms of this being a very young outflow region.

The demagnetized rocks extend also outside the western resistivity boundary of the Wairakei Field. Well 223 lies over this extension and has temperatures up to 100° C at 600m depth. Well 224, which is located outside the resistivity boundary but still within the extension of demagnetized body, is cold; core studies (Lampoonsub, 1987) show that the rocks from well 224 are not greatly altered, but they have relatively low remanent magnetization. The cause of this primary low remanent magnetization is still unknown.

MAPPING OF CONCEALED SHALLOW ALTERATION

For detection of shallow hydrothermal demagnetization patterns, airborne magnetic data are usually not very useful, since the magnetic signal associated with such rather thin near-surface anomalous bodies is rapidly attenuated with height. However, near surface alteration zones can often be detected by ground magnetic surveys, particularly when the gradient of magnetic field components is measured during the survey.

The phenomenon that volcanic rocks at the top of some high T systems have been partially demagnetized is a recent discovery. No systematic studies of shallow cores and outcrops have been made yet. If magnetite were stable in an oxidizing environment, such shallow demagnetization should not occur. However, the two case histories presented below show that demagnetization of

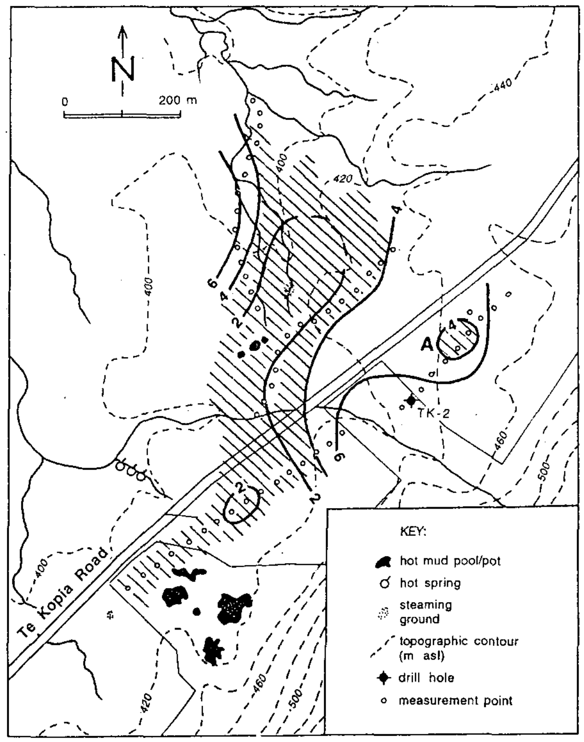

Figure 9a. Horizontal magnetic gradient (solid, thick contours) over the northern part of Te Kopia geothermal field, Central North Island, New Zealand; contour values are in nT/m (modified from Nguyen Hong Bang (1993) and Perez-Ramos (1993)). Areas where the gradient is ≤4 nT/m (zones of near surface alteration) are hatched .

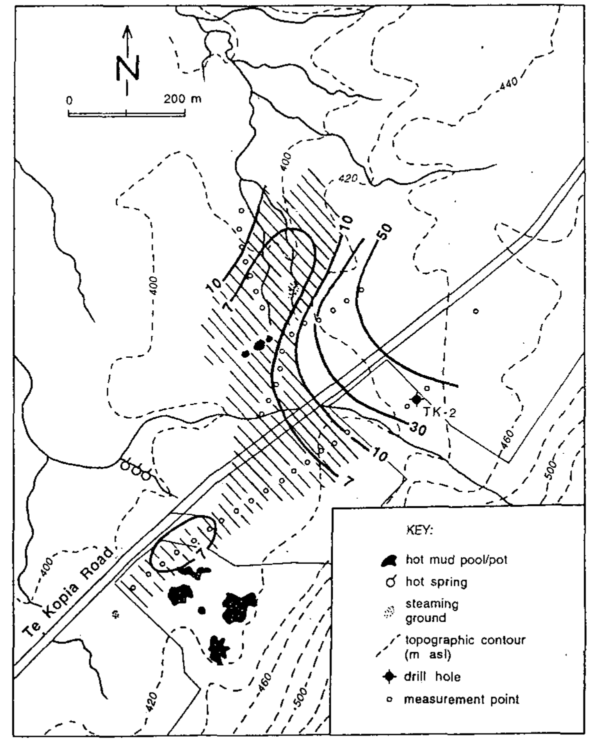

Figure 9b. Apparent resistivity measured using a Schlumberger array with AB/2=60m (solid, thick contours) over the same area shown in Figure 9b; contour values are in Ω-m (modified from Nguyen Hong Bang (1993) and Perez Ramos (1993)). Area where the apparent resistivity is ≤10 Ω-m (zones of near surface alteration) is hatched.

shallow rocks is common. At present we believe that the phenomenon is caused mainly by the same process which causes demagnetization of high standing surface extrusions, namely demagnetization induced by acid steam condensates.

Northern Te Kopia Geothermal Field

The Te Kopia Field lies about 25 km north east of the Wairakei Geothermal Field. Present day thermal activity consists of fumaroles, mud pools, steaming ground and some hot springs. Two deep exploratory wells have been drilled which show that the geothermal reservoir lies in a sequence of rhyolitic pyroclastics and lavas (Bignall, 1991) which outcrop in places.

Ground magnetic gradient measurement together with Schlumberger resistivity traversing (AB/2 spacing of 30 and 60m) were conducted in 1993 in the northern part of the Te Kopia field (Nguyen Hong Bang, 1993; Perez-Ramos, 1993). Results of these surveys are presented in Figures 9a and 9b. The figures show that low apparent resistivity values (≤10 Ω-m for AB/2=60m), which indicate the presence of electrically conductive altered ground, are clearly associated with low values of the horizontal magnetic gradient (≤ 4 nT/m). In Figures 9a and 9b, the hatched pattern indicates the likely extent of the altered ground which is now covered by soils or thin layers of pumice; samples taken from 1 m depth show that hydrothermal alteration indeed occurs beneath a thin unaltered cover. A small area with low magnetic gradient to the north of well TK-2 (indicated by A in Figure 9a) coincides with a zone of high apparent resistivity values (Figure 9b). A similar phenomenon occurs in the Northern Tokaanu-Waihi field and a possible explanation is given in the following section.

Northern Tokaanu-Waihi Geothermal Field

The Tokaanu-Waihi prospect is an undeveloped geothermal field located near the southern shore of Lake Taupo, about 45 km southwest of the Wairakei Geothermal Field. The area is mainly covered by young andesite flows of the Tongariro Volcanic Centre (Grindley, 1960). Two larger areas with hydrothermal activity occur in this field - the Tokaanu thermal reserve near Tokaanu village and the Hipaua thermal area in a rugged area in the north. In addition, several discharges of hot water occur along Lake Taupo shore line near the Waihi village.

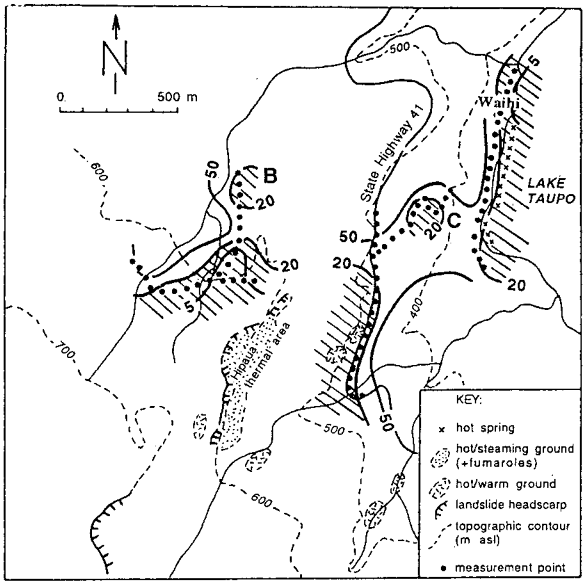

Figure 10a. Horizontal magnetic gradient (solid, thick contours) over the northern part of Waihi-Tokaanu geothermal field, Central North Island, New Zealand; contour values are in nT/m (modified from Siripongsatian, 1994). Areas where the gradient is ≤20 nT/m (zones of shallow alteration) are hatched.

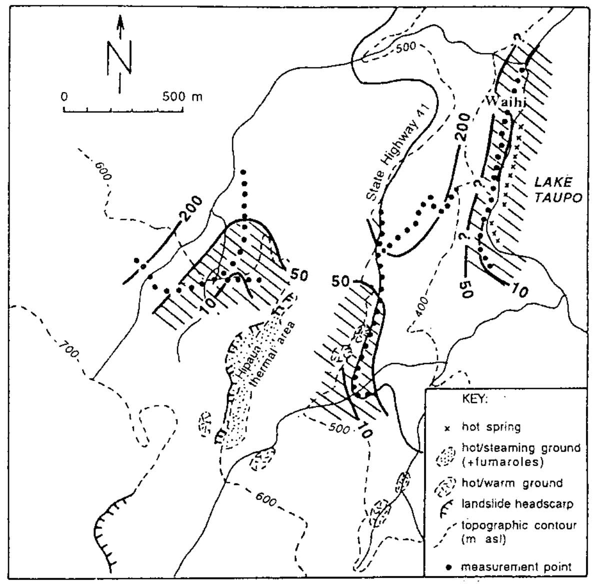

Figure 10b. Apparent resistivity measured using the Schlumberger array with AB/2=60m (solid, thick contours) over the same area shown in Figure 10a; contour values are in Ω-m (modified from Munyithya, 1994). Area where the apparent resistivity is ≤50 Ω-m (zones of shallow alteration) is shown hatched.

Ground magnetic gradient measurements and resistivity traversing using AB/2 spacing of 50 and 100m were conducted in the northern part of the Tokaanu-Waihi geothermal field in 1994 (Munyithya, 1994; Siripongsatian, 1994). Correlation between apparent resistivity and magnetic gradient values (Figures 10a and 10b) shows a pattern similar to that observed at Te Kopia (discussed in the previous section). However, the interpreted near surface alteration zones (Figures 10a and 10b) appear to be associated with higher values of both magnetic gradient and apparent resistivity in comparison to those at Te Kopia. At Tokaanu-Waihi, areas with near-surface alteration are marked by a magnetic gradient ≤20 nT/m and an apparent resistivity ≤50 Ω-m. It is possible that the difference in magnitude of magnetic gradient and shallow apparent resistivity in both areas reflect the level of boiling. At Te Kopia boiling temperatures occur at shallow depths (probably 10 to 30m) whereas beneath the highstanding Hipaua area at Tokaanu-Waihi boiling occurs at depths >100m (Severne and Hochstein, 1994).

There are two small areas (B and C in Figure 10a) with magnetic gradient values ≤20 nT/m which are not associated with low apparent resistivity values. As mentioned in the previous section, one such area also occurs at Te Kopia. As magnetite and titanomagnetite are the first minerals to be altered in NZ prospects by hydrothermal activity (Browne, 1994), it is possible that a shallow hydrothermal alteration process has started in these areas, which has altered the magnetic to non-magnetic minerals, but which has not produced a sufficient amount of clay minerals to cause the rocks to become electrically conductive. Thus, the phenomenon of smaller areas with low magnetic gradient but high apparent resistivity values may indicate an initial stage of alteration. An anomalous ground temperature at 1 m depth of more than 1° C above ambient also occurs in area B in Figure 10a (Munyithya, 1994).

SUMMARY AND DISCUSSION

Geophysical investigations using airborne magnetic surveys are useful to assess the lateral extent of many high temperature geothermal reservoirs in young volcanic rocks. Airborne magnetic surveys can be used to quickly investigate a large prospect area with access problems. Interpretation of residual airborne magnetic anomalies can often provide models that show the extent of hydrothermally demagnetized rocks and concealed paleo-permeability structures. In active geothermal fields, the presence of thick and extensive demagnetized rocks can indicate areas of high reservoir permeability and upflow regions, as shown by the discussion of two high T reservoirs which are presently exploited (Wairakei and Kamojang). However, hydrothermal demagnetization is an irreversible process and demagnetized bodies interpreted from the residual magnetic data also reflect hydrothermal past activity.

Studies of two NZ geothermal prospects (Te Kopia and Tokaanu-Waihi) show that ground magnetic surveys can be used to detect and map the distribution of concealed near-surface alteration. At Tokaanu-Waihi, thermally altered ground beneath steeper terrain is unstable (Severne and Hochstein, 1994) and should be avoided by construction site.

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