Proceedings 9th NZ Geothermal Workshop 1987

MAGNETIC MODELLING OF THE OLKARIA GEOTHERMAL FIELD, KENYA.

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Abstract

Threedimensional modelling of aeromagnetic data from Olkaria geothermal field has indicated a large zone, 20 km x 8 km, of reduced magnetisation, orientated ENE-WSW across the N-S trending Rift Valley. This zone, modelled as extending from 500m to 4 km below the surface, appears to be further subdivided into three parts, of approximately equal area, but with different magnetic characteristics. The central part broadly coincides with the zone of surface manifestations, and a typical rock resistivity of 30 ohm-m. The western body, with a significantly lower magnetisation, is close to the rift escarpment in a zone characterized by no surface manifestations but a typical resistivity of 5 ohm-m at depths greater than 500m. The eastern body, also with lower magnetisation, is in an area that has not been surveyed by other geophysical techniques.

Introduction and Geology

Exploration of the Olkaria geothermal field, located in the Rift Valley, Kenya (Figure 1), began in the 1960's, and has led to the commissioning of a 45 MW power station and plans for further power station developnient of up to 240 MW. More than 25 wells have been drilled in the East Olkaria Borefield, and at least 10 exploration wells covering an area of 50 km^2.

Aeromagnetic surveys have been used to investigate the structure of a number of geothermal fields worldwide. The rationale behind these surveys is the expectation that hydrothermal alteration at upper levels of the geothermal system will be manifested as demagnetised zones. However, this interpretation is complicated by the common Occurrence of acidic volcanics, with reduced magnetisation, which can produce a similar magnetic signature (Soengkono, 1985, Henrys and van Dijck, 1987).

An aeromagnetic survey of the Olkaria geothermal field was carried out by Geosurvey for the Kenya Power Company in February 1986. E-W traverse lines, at 1 km spacing, were flown at a height of 300m above the surface, with N-S tie lines every 5 km. Measurements were made at a constant sampling spacing of 20m. Navigational and location equipment included barometric and radar altimeter, doppler radar, and a 35mm navigation camera.

Standard data processing, including flight path recovery, IGRF removal, filtering of both the magnetic and altimetric data, and adjustments by network analysis on the traverse and tie line intersections were carried out by Geosurvey. The adjusted magnetic values and their coordinates were then gridded at a mesh spacing of 250m, with data between flight lines interpolated using a cubic spline. Contour maps of this data, as well as data upward continued by 750 m, were supplied to the client. Because of the low magnetic latitude of the area (- 20^0) and the cast-west flight direction, reduction to pole was not possible.

The area around Olkaria is covered by a thick (up to 300m) surface cover of young (Quaternary) ash and pyroclastics overlain by obsidian and comendite flows. This cover effectively masks most of the regional structure in the area. Clay and silt-rich lake sediments have been postulated to exist in the area, based on resistivity data, but lithological analysis of well cores and cuttings have found no evidence to support this.

In the East Olkaria Borefield, the surficial pyroclastics, with a thickness of approximately 200m, are underlain by sub-horizontal intercalated rhyolite, trachyte and basalt lavas, comendites, tuffs and pyroclastics, with trachyte lavas dominant by volume. In the western part of the field, the subsurface rocks are similar to those of the eastern borefield, except that basalt and rhyolite lavas dominate.

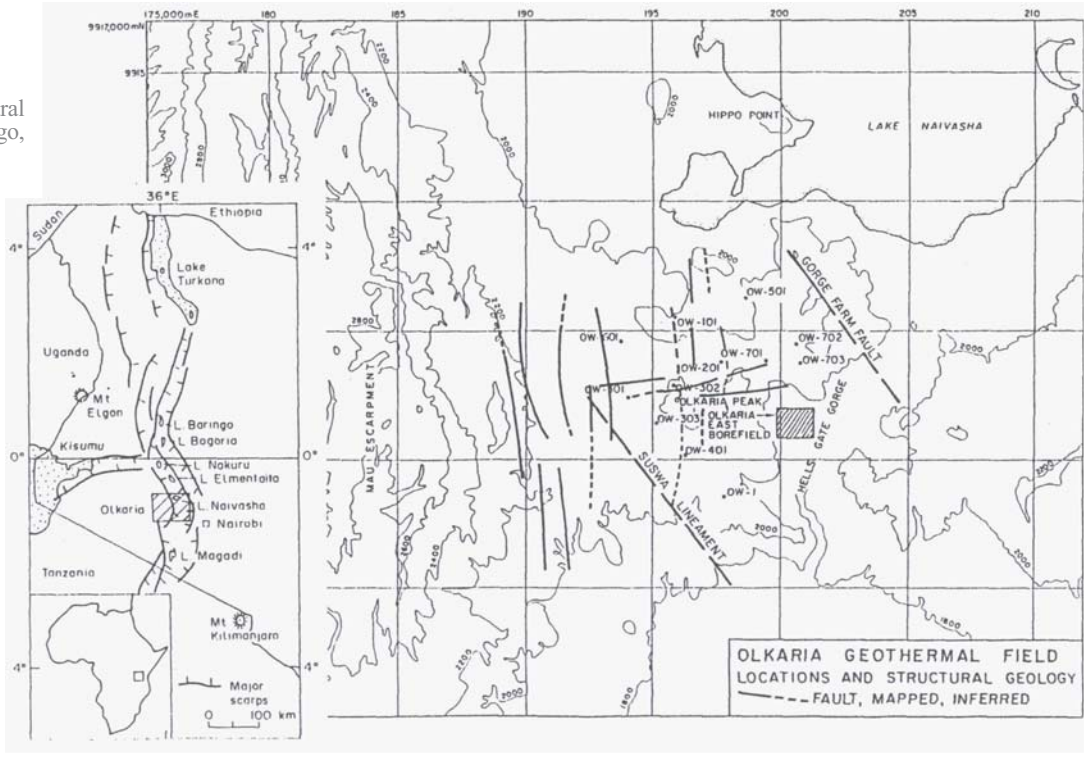

Figure 1.

Locations and Structural Geology (after Odongo, 1984,1987).

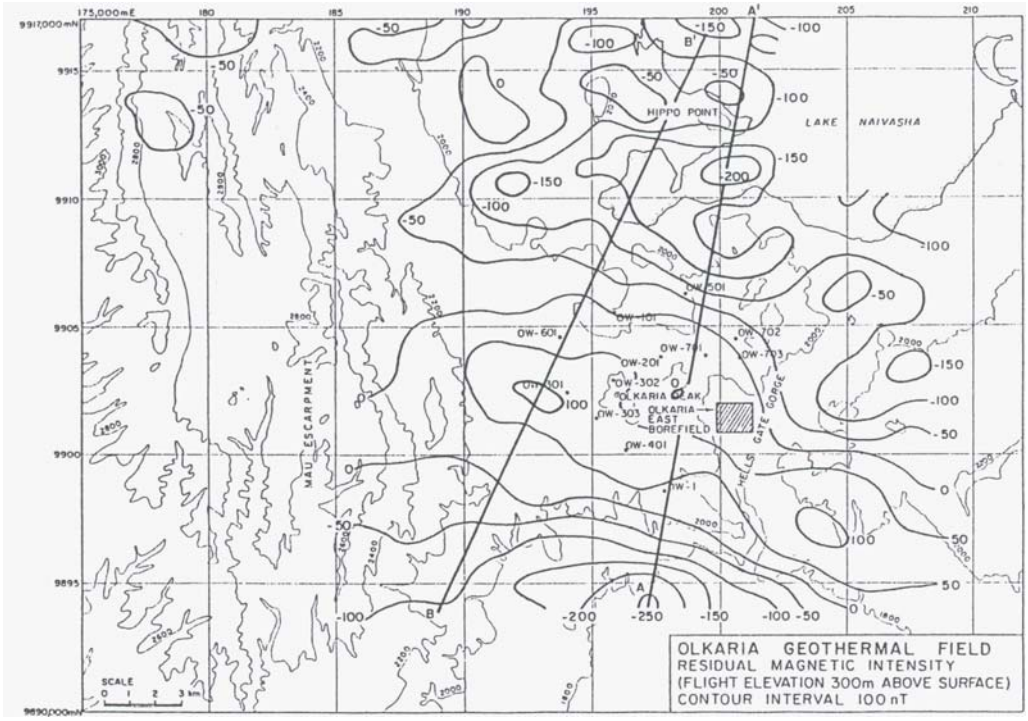

Figure 2.

Residual Magnetic Intensity.

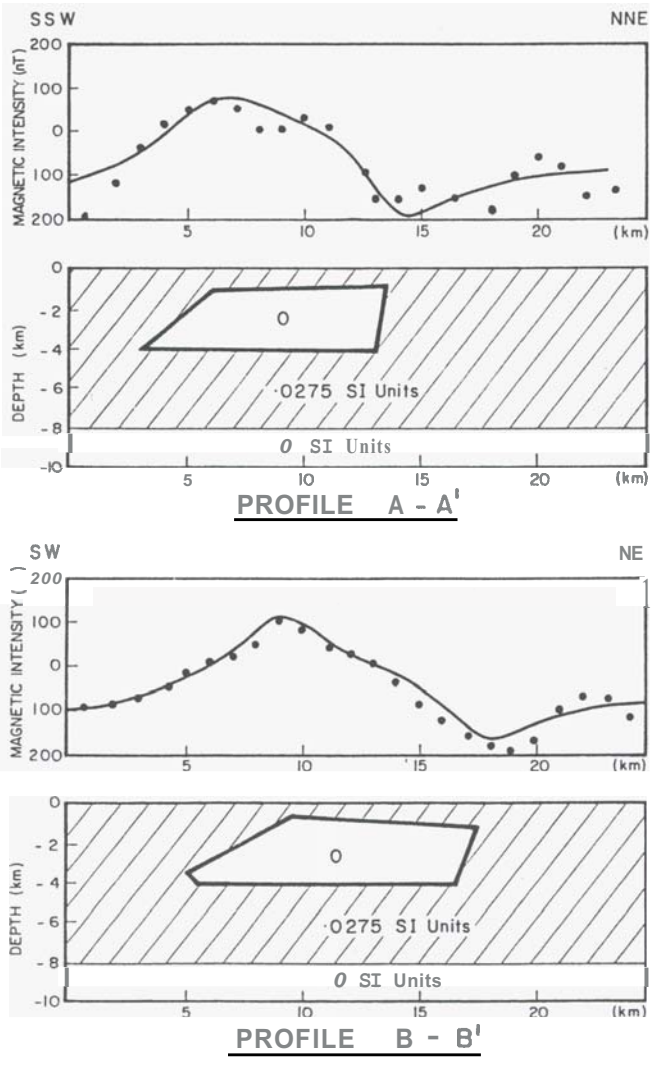

Figure 3.

2D modelling on selected profiles.

The predominant fault trend of the area is north-south, parallel to the alignment of the Rift Valley at this point. However, regional NW-SE lineaments are observed (Figure 1), as well as the WSW-ENE Olkaria Fault just to the north of Olkaria Peak, which is considered to control the two upflow zones of the system (at wells OW-301 and OW-701).

Analysis

The residual magnetic contour map (Figure 2) shows a broad positive anomaly trending WNW-ESE across the Rift Valley. Two peaks to +100 nT are observed within this anomaly, to the west and south-east of the East Olkaria Borefield. The total area enclosed by the 0 nT contour exceeds 120 km^2. A strong negative anomaly to - 250 nT is observed to the south, and another to -225 nT to the north. The rift valley escarpments are characterised by very subdued magnetic anomaly patterns, as is the zone within the positive anomaly.

The first step in the analysis procedure was to estimate the effect of the topography on the observed magnetic anomalies. To do this, the magnetic variation near a prominent topographic feature in the survey area (Olkaria Peak) was matched by trial-and-error selection of magnetic susceptibilities, using a 3D prism-based topographic modelling program. The prism depth was to a plane at 1500m a.s.l (approximately 500m below surface), chosen to coincide with the typical depth at which intense rock alteration was observed (Browne, 1981).

It was found (van Dijck, 1986) that topographic effects could not be responsible for more than minor detail within the overall anomaly pattern. In the absence of measured data at the time, a magnetic susceptibility of 0.02 SI units was chosen, which resulted in a satisfactory fit of the embayment in the magnetic anomaly pattern to the east of Olkaria Peak, as well as causing the "pinching-in" of the broad positive anomaly south of the borefield. This susceptibility has been used in the subsequent 3D modelling presented in this paper. However, measurements have since shown that Olkaria Peak rhyolite has a considerably lower susceptibility, which suggests that the anomaly pattern in this area may have a cause other than topography.

A number of profiles were then selected across the anomaly to carry out 2D modelling. Examples are given in Figure 3, for the profiles indicated in Figure 2. Again, a trial-and-error procedure was adopted, using magnetisation contrasts considered to be typical of the observed rock types within a geothermal environment. The size, shape, location and magnetic properties of the bodies were then used as a basis for a comprehensive 3D modelling exercise, considered necessary because of the

significant three-dimensionality of the anomaly pattern, especially to the south and north-east.

Three-dimensional modelling was carried out using a method based on polygonal laminae to form the various magnetic bodies. A total of five bodies were considered in the final model (Figure 4). The broad positive magnetic anomaly extending across the geothermal field required three contiguous bodies of decreased magnetisation to obtain an adequate fit to the data. As the cental portion of this anomaly is enhanced by the positive lobe associated with the strong negative anomaly to the south, the central body was required to be rather less demagnetised than the bodies located to the east and west. To the south, and on the shores of Lake Naivasha to the north, two relatively small normally magnetised bodies were located. The calculated magnetic response of these bodies is shown in Figure 5, and includes the effect of topography at a susceptibility of 0.02 SI units.

The bodies were modelled using magnetisation contrasts relative to average Rift Valley volcanics, rather than magnetic susceptibilities. Relative to the surrounding country rock. the values used were:

Eastern less magnetised body:	-0.6 A/m
Western less magnetised body:	-0.5 A/m
Central less magnetised body:	+0.32 A/m
Normally magnetised bodies:	+1.5 A/m

If it is assumed that the eastern body is completely unmagnetised, the equivalent magnetic susceptibilities of the various bodies, in the absence of any remanent magnetisation, would be:

Eastern body:	0 x 10^{-3} SI units
Western body:	4 x 10^{-3} SI units
Central body:	10 x 10^{-3} SI units
Surroundings:	22 x 10^{-3} SI units
Magnetised bodies:	78 x 10^{-3} SI units

Magnetic modelling using relative rather than absolute magnetic parameters can result in a level shift of the magnetic response, although the shape of the anomaly is not affected. Such a level shift can be observed in the response of the model (Figure 5), as compared with the measured data (Figure 2). However, the magnitude of the level shift depends on the effective magnetic depth of the surroundings, and 2D modelling showed that a reasonable adjustment of this level could be obtained by having an overall niagnetic depth of 8 km below surface. It is surmised that temperatures exceed the Curie point for the rocks in question at these depths.

Discussion

The three less magnetised bodies are modelled from 500m below surface, to a depth of 4km. The depth to the top surface was chosen at the level where significant rock alteration was observed in well cores (Browne, 1981), and which also coincided with the top of the deep low resistivity layer. The thickness of the bodies is not well defined as the modelling process is fairly insensitive to model variations at this depth. Generally, the bodies have vertical sides, apart from some shallow lobes on the western body extending to the southwest, and a stepped structure at shallow levels on the north of the eastern body. The lateral boundaries of the bodies are poorly constrained, in. particular those trending north-south, but measured resistivities, together with well data, have been used as a guide.

The central body is observed to coincide fairly well with the known geothermal field, as delineated by exploration wells and surface manifestations, and other geophysics. The subsurface resistivity in this area, below 400m, is typically 25 to 35 ohm-m, with a thickness of at least 1500m. To the north and north-east, the indicated magnetic boundary appears to be correlated with a deepening of this resistivity layer, although data is a little sparse to establish this precisely. To the south and east, there is little resistivity data because of the rugged country, but it is observed that the first exploration well, OW-1, which was abandoned after reaching a depth of 1000m because of low temperatures, is located outside the postulated body. The surface manifestations near OW-1, used to locate this well, are all at a fairly constant elevation, and are most likely the expression of a shallow outflow from the north. Also, well OW-401, with rather cooler temperatures than more northerly exploration wells, is located very close to the southern boundary of the demagnetised body.

The western body extends from the central region to beneath the first step of the western rift escarpment. This whole region is characterised by a quite different resistivity structure to the central zone, with a low resistivity layer of typically 5 ohm-m beneath a resistive overburden of at least 500m thickness. The eastern margin of this resistivity regime is well established, and coincides with the boundary of the western body, although the anomaly pattern is fairly insensitive to boundary adjustments in this area.

The southern and western resistivity boundaries are poorly known, due to access difficulties. In the north, the low resistivity structure appears to extend outside the limits of the demagnetised body, although this interpretation is based on a single sounding.

Virtually no resistivity measurements have been carried out within

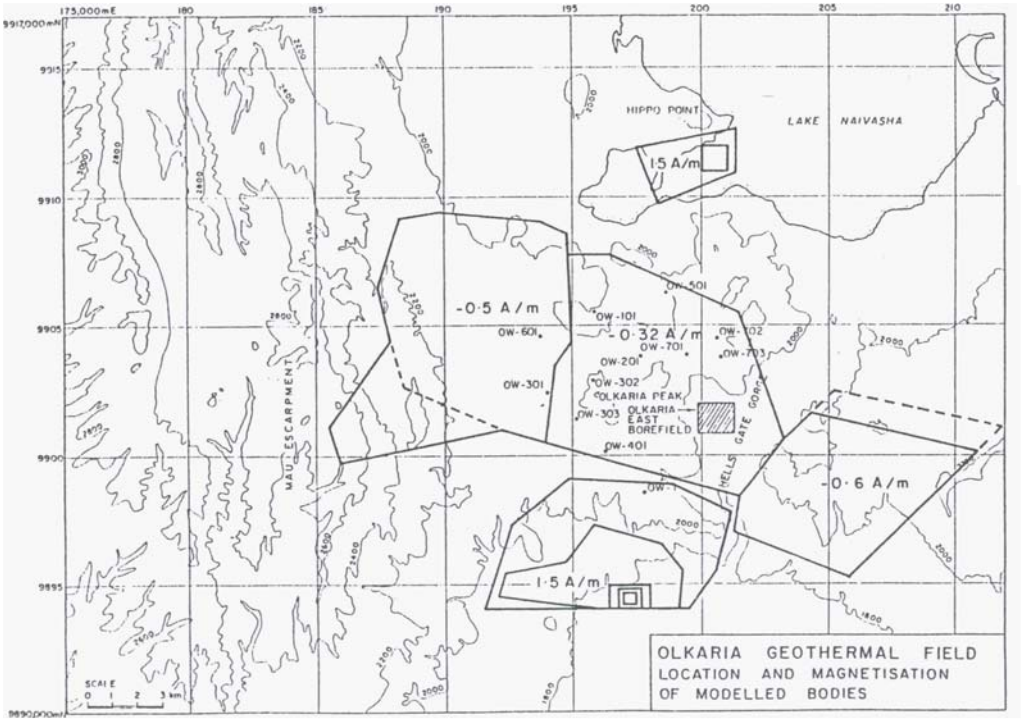

Figure 4.

Results of 3D modelling.

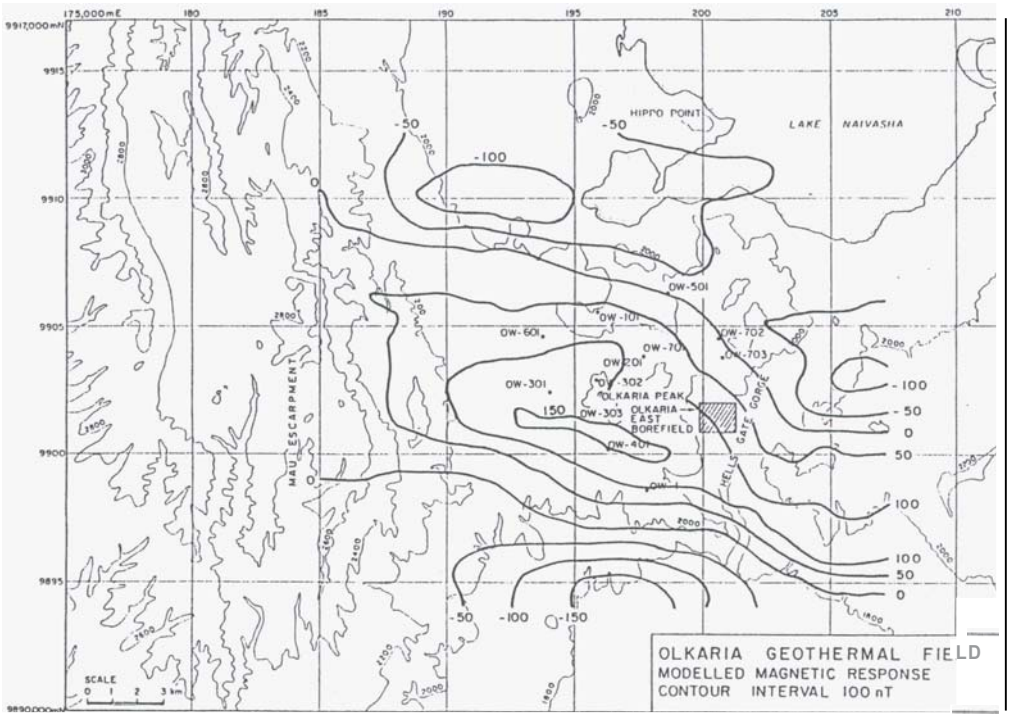

Figure 5.

Magnetic response of 3D modelling.

the eastern zone, because of the ruggedness of the terrain. Therefore, the boundaries of the modelled demagnetised body have been principally determined by goodness of fit with the measured data. However, one resistivity traverse line has extended to the northern boundary of this body, and the last measurement shows an atypical low resistivity of 15 ohm-m at 1000m AB/2.

The normally magnetised body to the south narrows to a vertical plug near the surface. This plug coincides exactly with a localised positive gravity anomaly, unfortunately not defined to the southwest because of the survey limits. The deeper part of the body correlates reasonably well with a more widespread positive Bouguer anomaly in the area, although the rapid topographic variation and the absence of substantial density data makes gravity interpretation difficult. It is thought that this body represents a gabbro intrusive. The northern boundary of this body is very close to the central demagnetised zone, and in fact may be a permeability barrier forming the southern limit of the Olkaria geothermal field.

In the north, another magnetised body is located in Lake Naivasha, just south of Hippo Point. No other geophysical measurements have been carried out in this area.

A substantial number of relative magnetic susceptibility and remanent magnetisation measurements have been carried out on surface samples and well cores from the Olkaria area. These indicate that measured remanent magnetism of all samples are very small and were neglected in any modelling exercise. Virtually all of the susceptibility samples are from within the geothermal field, so that it is difficult to assign a magnetic susceptibility to the rocks surrounding the area. Average measured values are as follows:

Olkaria Peak Rhyolite:	1.5 x 10-3 SI units
All other Rhyolites:	0.5 x 10-3 SI units
Tuffs Hells Gate gorge:	2.0 x 10-3 SI units
Agglomerate Hells Gate	7.2 x 10-3 SI units
Rhyolite/Tuff cores:	0.6 x 10-3 Si units
Trachyte cores:	0.3 x 10-3 SI units
Basalt cores (all wells):	39 x 10-3 SI units
Gabbro cuttings (OW-11):	20 x 10-3 SI units

It can be seen that the measured magnetic susceptibilities are generally quite low, consistent with the requirement of reduced magnetic susceptibilities in the central ma. Even the basalts have reasonably low values compared with typical examples elsewhere (Hunt and Smith, 1981). However, confirmation of the postulated susceptibilities of the modelled bodies must await magnetic parameter measurements on rock samples from the area surrounding the central area.

Conclusions

Modelling of the aeromagnetic data from the Olkaria geothermal field has indicated the presence of a large body of varying degrees of reduced magnetisation, trending ENE-WSW across the Rift Valley. Compared with quite rapid intensity changes in other parts of the survey area, the subdued variation in the magnetic anomaly pattern over this body indicates a fairly uniform rock magnetisation, which could be caused by general demagnetisation from widespread hydrothermal alteration.

The central portion of the body, strongly correlated with the geothermal field, as defined by exploration wells and a characteristic rock resistivity of 30 ohm-m, is likely to be caused also by the lithology of the area (eg rhyolites, and other acid volcanics), as well as demagnetisation of hydrothermal alteration. The extent of this body corresponds quite well with the caldera structure proposed in Svanbjornsson et al (1983).

The western part of the body is rather more problematical to explain. Western wells (OW-301, OW-601) indicate that basalts are more common and that the magnetite within the basalts is at least partially altered to non-magnetic minerals. Also, the measured susceptibility of the basalts are relatively low. This, coupled with the presence of persistent low resistivities at depth, strongly suggests that the geothermal system extends to the west, under a thick impermeable surface cover that prevents surface geothermal manifestations.

If this hypothesis is true, the greater degree of demagnetisation, together with less clear evidence of a distinct lithological regime correlated with the modelled western body, suggests that the intensity of alteration is likely to be greater than in the central area. However, an alternative explanation is that saline sediments, both conductive and non-magnetic, have been laid down against the escarpment, thus forming both geophysical anomalies.

The eastern body, almost unexplored by other geophysical techniques, lies between Olkaria field and the recent Longonot volcano, which has fumaroles within its crater. The one tantalising low resistivity value on the northern boundary of the postulated body, together with its location, suggests that there may be a geothermal extension to the east. However, a recent deep resistivity sounding near the centre of this body indicates 30 ohm-m at depth, similar to the central region.

The exact cause of this very large body of reduced magnetisation remains unknown. More resistivity measurements to test the boundaries of the postulated body to north and south may clarify some aspects However, full elucidation will probably come only when the proposed exploration well, 2km further west than OW-301, is finally drilled.

Acknowledgements

Kenya Power Company is thanked for its kind permission to publish this paper.

Bibliography

Browne, P.R.L., 1981: Petrographic study of cuttings from 10 wells drilled at Olkaria geothermal field, Kenya. Report for KPC.

Henrys, S.A., and van Dijck, M.F., 1987: Structure of concealed rhyolites and dacites in the Broadlands - Ohaaki geothermal field. Proc of 9th New Zealand Geothermal Workshop, Geothermal Institute, University of Auckland.

Hunt, T.M., and Smith, E.G.C., 1981: Magnetisation of some New Zealand igneous rocks. Journal of the Royal Society of New Zealand. V 12, No 2, pp 159-180.

Odongo, M.E.O., 1984: Geology of Olkaria geothermal field. KPC internal report.

Odongo, M.E.O, 1986: Geology of the Olkaria geothermal field. Geothermics, V 15, No 5/6.

Soengkono, Suprijadi, 1985: Magnetic study of the Mokai geothermal field. Proc of 7th New Zealand Geothermal Workshop, Geothermal Institute, University of Auckland.

Svanbjornsson, A., Matthiasson, J., Frimansson, H., Arnorsson, S., Rjornsson, S., Stefansson, V., and Saemundsson, K., 1983: Overview of geothermal development at Olkaria in Kenya. Proc. 9th Workshop, Geothermal Reservoir Engineering. Stanford University.

van Dijck, M.F., 1986: Preliminary interpretation of aeromagnetic data from the Olkaria geothermal field, Kenya. Report No. 86:23. Geothermal Institute, University of Auckland.