RE-INTERPRETATION OF RESISTIVITY DATA OVER THE OLKARIA GEOTHERMAL PROSPECT (GREGORY RIFT, KENYA)

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ABSTRACT

The apparent resistivity pattern of the Olkaria Field is not as well defined as that of other hot water systems standing in volcanic rocks. Attempts to delineate the lateral extent of the reservoir by resistivity measurements (using arrays with a nominal depth penetration of 750 to 1000 m) produced the confusing picture that several smaller areas with apparent resistivities of 10-20Ωm occur over an area of about 100 km^2. Until recently these structures were interpreted as "upflow centres" with the present bore field lying over one of these centres.

A recent re-interpretation of the resistivity data has produced a significantly different resistivity model. Analysis of older Schlumberger soundings has shown that an unbroken layer of lake sediments (5 - 10Ωm) underlies most of the prospect and separates a non-coherent sequence of surface volcanics (50 - 500Ωm) from older volcanics (≈30Ωm) forming the upper reservoir. At greater depth (>1.5 km) the whole Olkaria Field is underlain by a coherent low resistivity structure. The new model shows that the Olkaria system covers a much greater area (≥80 km^2) than previously thought. The Olkaria Field is an example of a hot water system in volcanic rocks which does not exhibit very low resistivities usually found elsewhere over systems in a similar hydrological-geological setting.

INTRODUCTION

The Olkaria Geothermal Field is the first geothermal prospect in Africa which is being developed for production of electric power. It is a high temperature, water-dominated field with two-phase flow zones (Grant and Whittome, 1981). Surface manifestations, covering an area of about 35 km^2, and a natural heat loss of about 400 MW, point to a large reservoir at depth.

Dipole-dipole resistivity surveys have been used rather extensively to explore the resistivity structure of the Olkaria prospect (Noble and Ojiambo, 1976; Bhogal, 1980). The method was used to overcome problems related to apparently "erratic" results of earlier-made Schlumberger soundings (Furgerson, 1972) which could not be correlated with an earlier geological model of the field (McNitt, 1976). Dipole-dipole resistivity data were compiled in "pseudo"-resistivity sections and apparent resistivity maps. These maps showed that the pattern of apparent resistivity contours for shallow penetration (AB = MN = 250 m, n = 2), and for deeper penetration (n = 8) is rather similar (Bhogal, 1980). As three separate areas with intermediate apparent resistivities (10 to 20Ωm) were outlined (see Fig. 1), it was inferred that these areas outline "upflow" centres, i.e. they represent separate reservoirs. As two productive exploratory wells were drilled in two of these centres (X-2 and OW-2 in Fig. 2), the model could hardly be rejected. However, there were indications that the model of individual "upflow" centres was open to criticism. Apparent resistivities, based on the Schlumberger array data, showed a quite different contour pattern (Bhogal, 1980); furthermore, the distribution of fumaroles and steaming ground shows no correlation with the areas of rather low apparent resistivities (≈20Ωm) in any of the resistivity maps (see Fig. 1).

These discrepancies did not greatly affect the initial stage of the development of the field, when 14 production wells were drilled in an area of less than 1 km^2 in the immediate vicinity of exploratory well OW-2. However, the production of nearly all later wells was found to be rather moderate, equivalent to about 2 MW_1 (Grant and Whittome, 1981). For further development, other parts of the field have to be exploited. The question therefore had to be answered as to whether the model of separate upflow centres holds, and whether the resistivity data contain information about other structures which could be selected as drilling targets.

EARLIER INTERPRETATIONS OF DIPOLE-DIPOLE PSEUDO-RESISTIVITY SECTIONS

The resistivity model of the Olkaria Field mentioned in the introduction was based essentially on a qualitative interpretation of the pattern of apparent resistivities. A quantitative interpreta- of the dipole-dipole data was undertaken much later by Ndombi (1978) and by Ross et al. (1979).

Any quantitative interpretation of dipole-dipole pseudoresistivity sections in terms of 2D or 3D models is limited by problems common to

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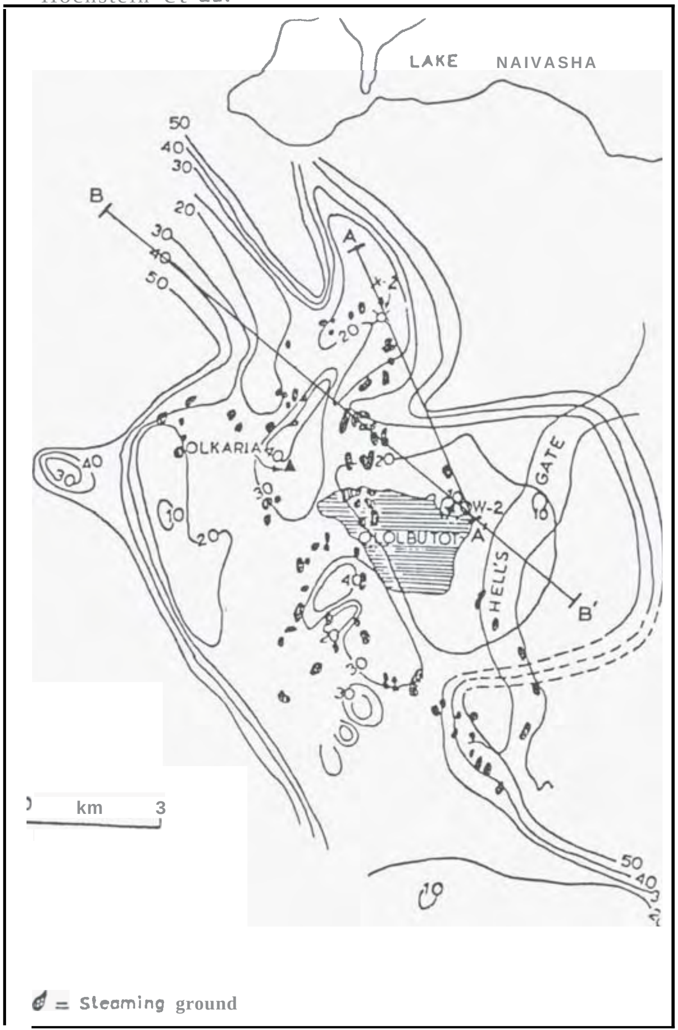


Fig. 1: Apparent resistivity contour map from dipole-dipole surveys (AB = MN = 250 m; n = 8), Olkaria Geothermal Field. (All contours give apparent resistivity in Ωm)

interpretations of all potential fields, namely that numerous models can be obtained which fit the same set of data unless realistic restraints are incorporated. Interpretations of dipole-dipole data encounter the additonal problem that observed apparent resistivities are strongly affected by resistivity inhomogeneities beneath the current dipole in contrast to central field gradient methods (i.e. Schlumberger array). Unfortunately, inhomogeneous near-surface rocks are common in all thermal areas, a point which has apparently been overlooked by investigators who have promoted the application of dipole-dipole methods in geothermal exploration.

Ndombi (1978) attempted to model one dipole-dipole resistivitiy section lying immediately to the SW of the Ololbutot obsidian flow (see Fig. 1) in terms of simple "block" structures using the programme of Dey and Morrison (1976). A moderate fit between observed and computed data was obtained although the fit is biased in terms of a deeper NS-trending, low resistivity dyke structure beneath a NS-trending line of fumaroles. The concealed dyke structure, in turn, was derived from a questionable interpretation of residual gravity anomalies (Ndombi, 1981; Hochstein, 1981). In view of this, Ndombi's dipole-dipole interpretation is open to criticism, although certain features of his model are similar to those suggested already by Furgerson (1972), namely an extensive near-surface low resistivity layer (10 - 15Ωm) and mean resistivities of 10 to 35Ωm for the shallow reservoir at 200 to 1000 m depth.

A more detailed interpretation of all dipole-dipole pseudoresistivity sections along 153 line km (24 profiles) of the Olkaria Field was undertaken by Ross et al. (1979). The data were also interpreted in terms of a 2D-resistivity block structure using an interactive finite element method with 70 x 13 mesh points for each model (Killpack and Hohmann, 1979). Because of the limited horizontal extent of the mesh, several overlapping models were required to obtain a true resistivity section along any given profile. An example of the model along line 2 (position indicated in Fig. 1) is shown in Fig. 2. This section was chosen because it is controlled by deep drillholes at each end; in addition, Schlumberger soundings (Furgerson, 1972) had been made at about 1 km intervals along the line. If one compares computed (Fig. 2b) and observed (Fig. 2c) resistivity data, one can see that the agreement is poor; the agreement for overlapping segments is also poor. Unusual features in the model in Fig. 2a are the highly complex resistivity structure in the upper 400 m and the non-coherent structure below 400 m depth where low resistivity bodies between adjacent profiles could. hardly be fitted into any coherent structure. As no similar complex resistivity structure had been reported for other hot water reservoirs it was difficult to accept the interpretation models of Ross et al. without reservation.

INTERPRETATION OF SCHLUMBERGER SOUNDINGS

A number of Schlumberger soundings (up to AB/2 = 2700 m) had been made by Furgerson (1972) during the earlier exploration phase of the Olkaria Field. Furgerson had also presented resistivity sections for the field based on standard sounding curve interpretation. His sections indicated a shallow, coherent, low resistivity layer (7 - 20Ωm) which was underlain by rocks with intermediate resistivities (20 to 30Ωm) in the SE part of the prospect. There was no evidence for any extensive low resistivity structure at intermediate depths (300-1000 m) nor for any steeply-dipping resistivity boundaries in the sections by Furgerson. However, these sections could not be correlated with any structure in the sections by Ross et al (1972). Both interpretations were checked by using the original data to find out the likely cause of this lack of correlation.

We started by re-interpreting all sounding curves which had been observed over the Olkaria area (total of 42) including some later soundings which had been undertaken by Bhogal (pers. corn.).

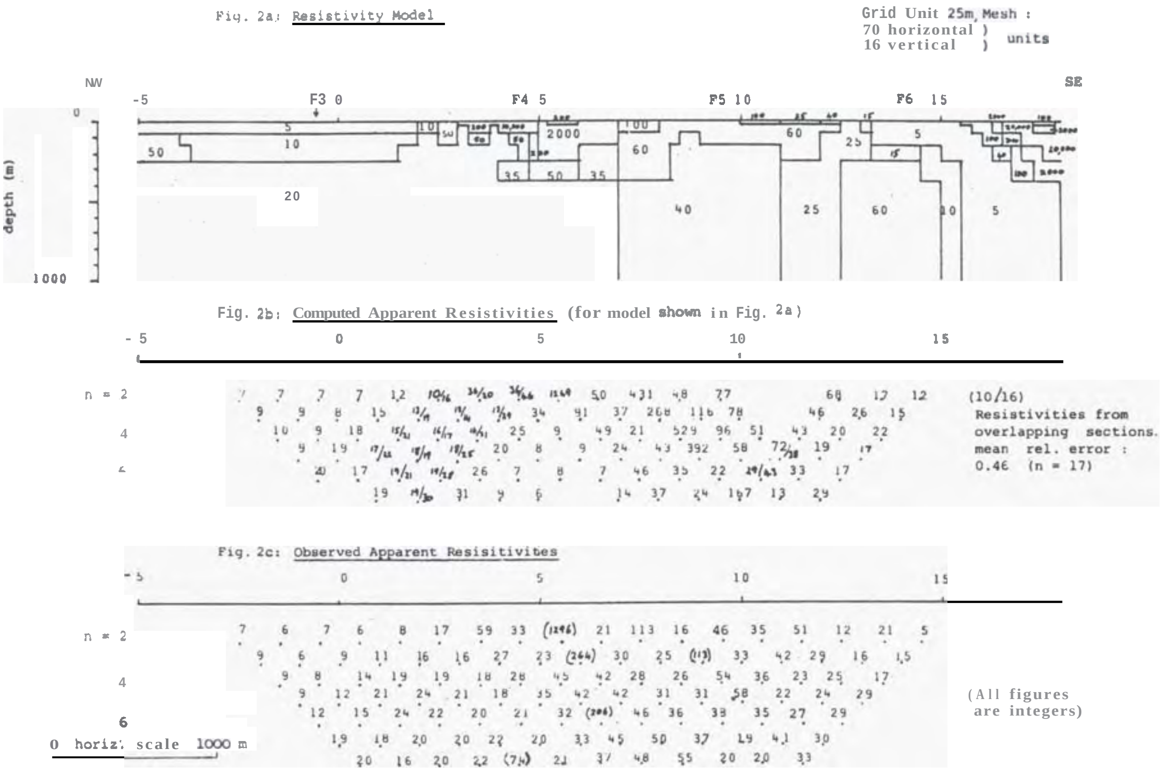


Fig. 2: Observed and computed resistivities for dipole-dipole line 2, Olkaria Field (taken from Ross et al., 1972). The position of the line (A-A') is shown in Fig. 1.

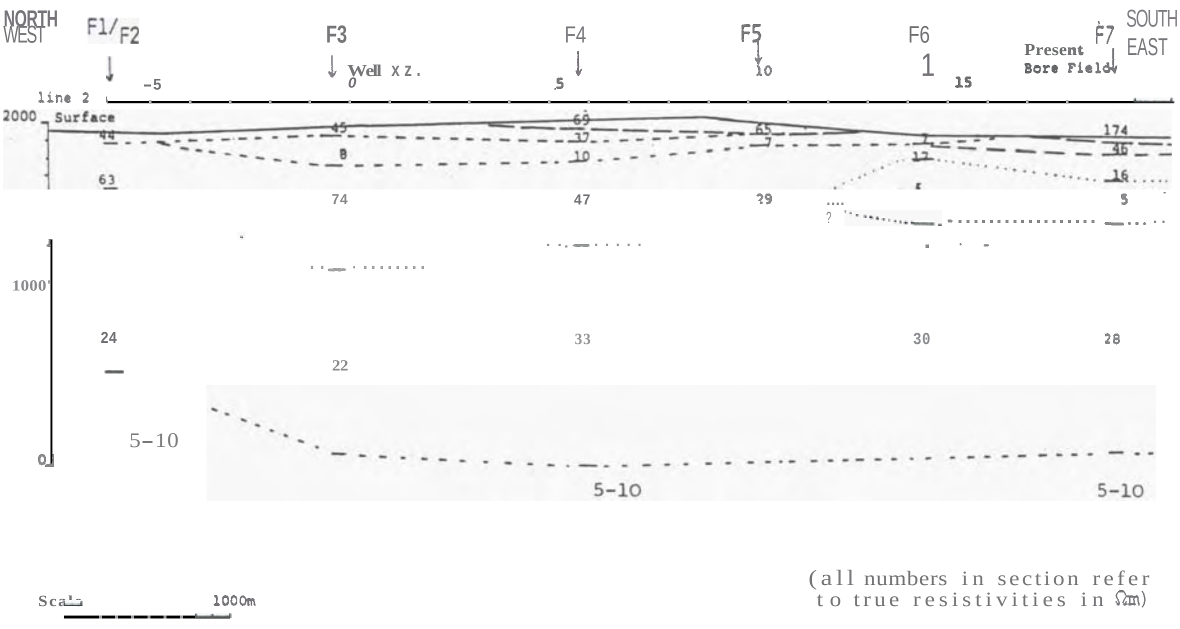


Fig. 3: Resistivity model for dipole-dipole line 2, Olkaria Field; the section is based on the interpretation of Schlumberger soundings taken at stations F1/F2, F3, F4, F5, F6 and F7 marked in the figure.

Standard inversion programmes (Ghosh, 1970; Zohdy, 1975) were used to obtain stratified resistivity sections which turned out to be quite similar to those of Furgerson. The 2D-effect of these sections was found to be rather small when theoretical resistivities of equivalent sections were re-computed for a few selected spacings. An example of a re-interpreted resistivity section along line 2 is shown in Fig. 3; some of the original sounding curves upon which the section is based are shown in Fig. 4. The slightly different resistivities for the deeper coherent layers were later combined into layers with constant resistivity using the equivalence theorem, which hardly affects the overall structure. The re-interpretation of sounding curves from other parts of the field produced sections similar to that shown in Fig. 3. The exercise showed that:

(a) there, is a coherent, near-surface resistivity layer (7 - 10Ωm) which can be traced over the E part of the field (E of Olkaria Volcano).

(b) Beneath this 100 - 150 m thick near-surface layer occur rocks with intermediate resistivities of 50 to 60Ωm, which decrease to about 30Ωm below about 500 m depth.

(c) The resistivity of rocks above 500 m depth increases laterally in the western part (up to about 200Ωm); the thickness of rocks with about 30Ωm also decreases in the W and NW part of the field.

(d) A coherent low resistivity substratum (about 5-10Ωm) occurs beneath the whole field and forms a doming structure in the NW part. The deeper substratum is indicated by decreasing resistivities at AB/2>2000 m in most sounding curves (see Fig. 4).

(e) Apart from the near-surface layer and the deeper substratum there are no other low resistivity structures at intermediate depth; the lens-shaped low resistivity structure at 250 to 500 m depth beneath the present bore field might be a pseudostructure, as it can only be recognised in one sounding (F7).

A schematic cross-section of the gross resistivity structure of the Olkaria Field along a NW-SE profile is shown in Fig. 5. It can be seen that the resistivity structure in the NW part of the field differs significantly from that in the SE part.

GEOLOGICAL STRUCTURE AND RESISTIVITY STRUCTURE OF THE OLKARIA FIELD

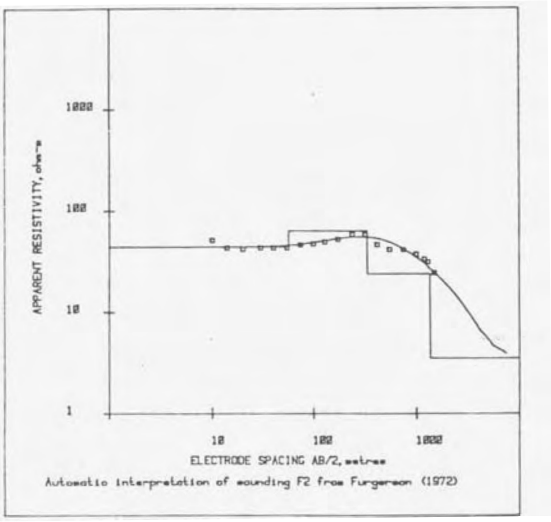
Recent geological mapping has shown that a 100 to 150 m thick near-surface layer of silty lake sediments occurs to the E of Olkaria Volcano (M.O. Odongo, pers. comm.). The layer can be identified from cuttings in the drillholes, but it also outcrops in some part of the field (at sounding station F6, for example, in Fig. 3), in the foothill region of Olkaria Volcano and in the cliffs of the Ol' Njorowa Gorge where this layer was first described by Thompson and Dodson (1963). The low resistivity near-surface layer could clearly be correlated with a layer of lake sediments which can be used as a marker horizon which separates non-coherent recent surface volcanic rocks (rhyolite lavas and pyroclastics, trachyte lavas with rather high resistivity of 50 to 500Ωm) from older basalts, rhyolite lavas and trachytes encountered between 200 and 1500 m depth in the production wells of the borefield and in exploratory well X-2. These older volcanic rocks generally exhibit true resistivities of about 30Ωm below 500 m depth. There is no information available which might explain the nature of the low resistivity rocks at 250 to 500 m depth beneath the borefield. No drillhole has yet encountered the deep low-resistivity substratum.

COMPARISON OF DIPOLE-DIPOLE MODELS AND SOUNDING MODELS

The simplified geological structure can be used to explain the apparent resistivity patterns in dipole-dipole resistivity maps such as that shown in Fig. 1. It was found from the re-interpreted sounding sections that lower apparent resistivities were usually observed with the dipole-dipole arrays over parts of the field where the low resistivity lake sediments are rather thick and are near the surface or outcrop at the surface. Higher apparent resistivities in these maps can be correlated with areas where the recent surface volcanics are thick and/or where the lake sediments are absent. The apparent resistivity maps give little information, therefore, about the deeper resistivity structure of the Olkaria reservoir, and the hypothesis that there are individual "upflow" centres beneath parts of the field with somewhat lower apparent resistivities in these maps can be rejected. As there is no evidence for a coherent, shallow, low resistivity layer (lake sediments) in the interpretation models of Ross et al. (1979) (see Fig. 2), the near-surface structure of these models is open to criticism. However, we could not ignore the possibility that some of the deeper structures in the dipole-dipole models were real, since concealed structures with vertical boundaries are difficult to detect with Schlumberger arrays.

The re-interpreted resistivity sections obtained from sounding data were therefore approximated by block structures, and theoretical resistivities were computed for the dipole-dipole profiles using the finite element method of Dey and Morrison (1976). The computation exercise was restricted to a few profiles where the terrain effect is small.

An example of such re-interpretation for line 2 is shown in Fig. 6. It can be seen that the chosen resistivity structure is similar to that obtained from the interpretation of the sounding curves shown in Fig. 3. Only moderate fits were obtained, however, which for deeper penetration (n = 4 to 8) are slightly better than those obtained by Ross et al. The fit between observed and theoretical data could not be improved by changing the deeper structure, although some improvement was noticeable when the surface resistivities near the current dipole were changed.



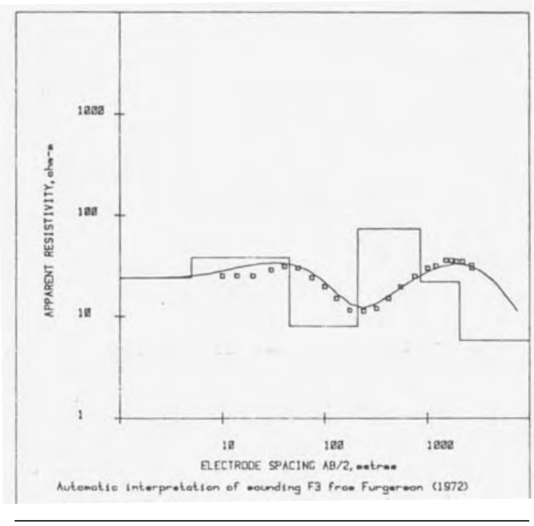


Fig. 4: Observed (squares) and computed apparent resistivities at stations **F2** and **F3,** line **2,** Olkaria Field (see Fig. 3); the stepped line gives the true resistivity versus depth function. (Lake sediments *are* absent beneath **F2** but fully developed at F3).

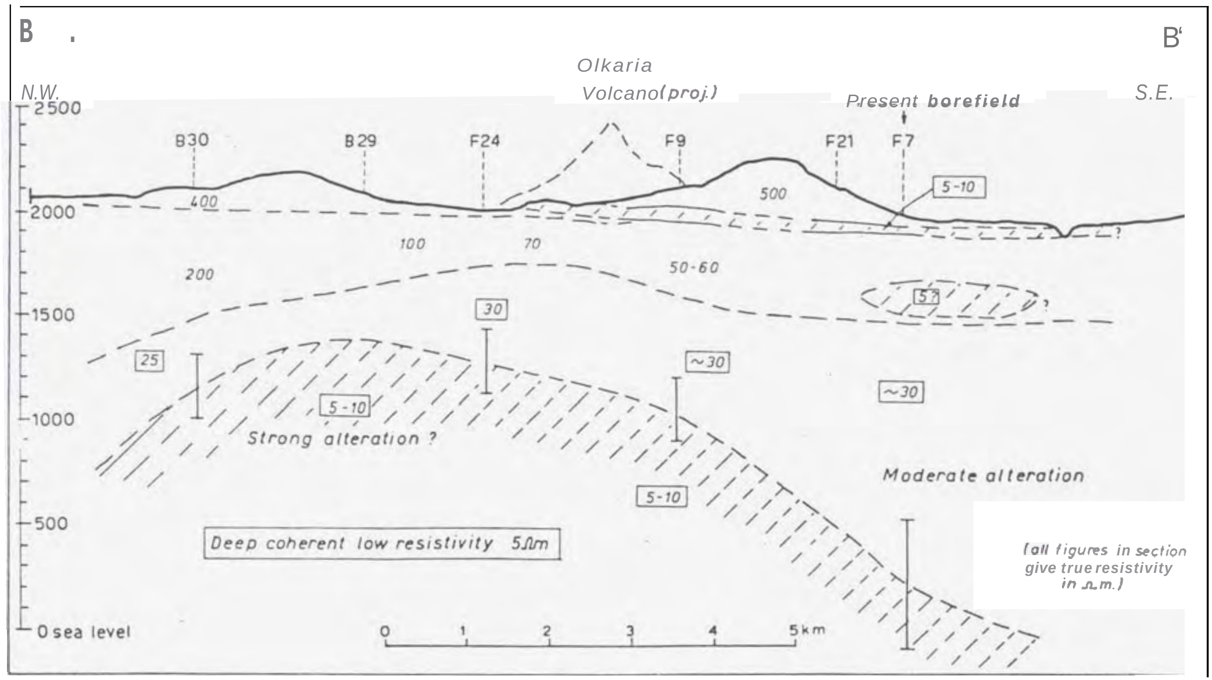


Fig. 5: Idealised resistivity cross-section (NW-SE) through central part *of* Olkaria Field. (The error bars indicate uncertainty in level of low resistivity substratum). The position of the section (B-B') is shown in Fig. 1.

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The re-interpretation of the dipole-dipole data showed that:

1) in the presence of an inhomogeneous surface layer it is almost impossible to obtain significant information about the deeper resistivity structure of a geothermal system from a quantitative interpretation of dipole-dipole pseudoresistivity sections.

2) Details in these sections at greater dipole-dipole spacings are always distorted by near-surface inhomogeneities: this also explains why at Olkaria the apparent resistivity pattern in dipole-dipole maps at smaller spacings (n = 2) is similar to that observed for larger spacings (n = 8).

3) No interpretation of dipole-dipole data should be attempted without adequate and detailed infomation about the near-surface resistivity structure beneath the current electrodes.

The re-interpretation of the dipole-dipole data over the Olkaria Field has shown that the interpretation models by Ross et al. are questionable and that shallow and deeper resistivity structures in these models are mostly pseudostructures. The assessment of McNitt (1976), that. only dipole-dipdle surveys were useful for the exploration of *the* Olkaria system, is wrong. We know now that the original geological model of the Olkaria Field, which did not allow for the unbroken low-resistivity lake sediments, was at fault, and that the dipole-dipole data are "erratic", not the Schlumberger sounding data.

DISCUSSION

A re-interpretation of resistivity data over the Olkaria Field has led to a revision of the gross resistivity structure of the field. Evidence has been presented which shows that most of the prospect is covered by non-coherent, recent volcanics of variable thickness with intermediate to high resistivities (up to 500Ωm), which are underlain by a coherent layer of lake sediments of unusually low resistivity (5 - 10Ωm). Variation in thickness 'of these two layers causes the phenomenon of a highly inhomogeneous surface layer which strongly affects the value of the apparent resistivity of arrays with large spacings. The pattern in apparent resistivity maps predominantly reflects the structure of this inhomogeneous surface layer; the pattern is not related to the deeper resistivity structure. Dipole-dipole data are especially affected by the near-surface inhomogeneities.

The only reliable information about the resistivity structure of the volcanics below the lake sediments comes from Schlumberger soundings which show that the reservoir rocks in the E part exhibit unusually high resistivities of about 50 - 60Ωm down to 500 m depth, and about 20 to 30Ωm below 500 m depth. Such high values have never been reported previously for volcanic reservoir rocks of a hot water system where resistivities of about 5Ωm are usually encountered. It appears that the resistivity of the rocks between 200 and 1000 m depths increases only gradually near the margin of the field which cannot therefore be clearly delineated by resistivity data; this finding also has not been reported previously for other hot water systems. The only information which can be used to define the size of the Olkaria Field is the extent of the deeper low resistivity substratum (about 5 to 10Ωm) which could be traced over an area of about 80 km^2. It is possible that this substratum extends much further.

No convincing explanation can yet be given for the rather high resistivity of the reservoir rocks lying between the low resistivity substratum and the lake sediments. The reservoir rocks are less porous (3 - 12%, Hochstein, 1981) and less permeable (Grant and Whittome, 1981) than reservoir rocks in N.Z. hot water systems, which would explain a somewhat higher formation factor of these rocks especially if their rank of alteration is moderate. Using a qualitative assessment we could not find much evidence for a significantly higher alteration of rocks at 250 - 500 m depth where a 5Ωm layer might occur beneath the production field, although many rocks encountered in the production wells are altered. Presence of steam also increases the resistivity of reservoir rocks (Hochstein, 1980), but the steam phase is certainly not dominant in the Olkaria reservoir apart from a steam layer at 600 to 800 m depth (Grant and Whittome, 1981).

Combining all arguments, it was inferred that reservoir rocks in other parts of the field with resistivities similar to those at 500 to 1500 m depth in the present production field should exhibit similar production characteristics. To test the hypothesis that higher permeabilities might be encountered in the low resistivity substratum, drilling of deep (2500 m) exploratory wells was proposed. The drilling of the first deep exploratory well has started recently.

If production of these wells proves to be significantly higher, and if production can be obtained from deeper feed zones, the doming structure of the low resistivity substratum in the W part of the field might define the target for the next development phase of the Olkaria Field.

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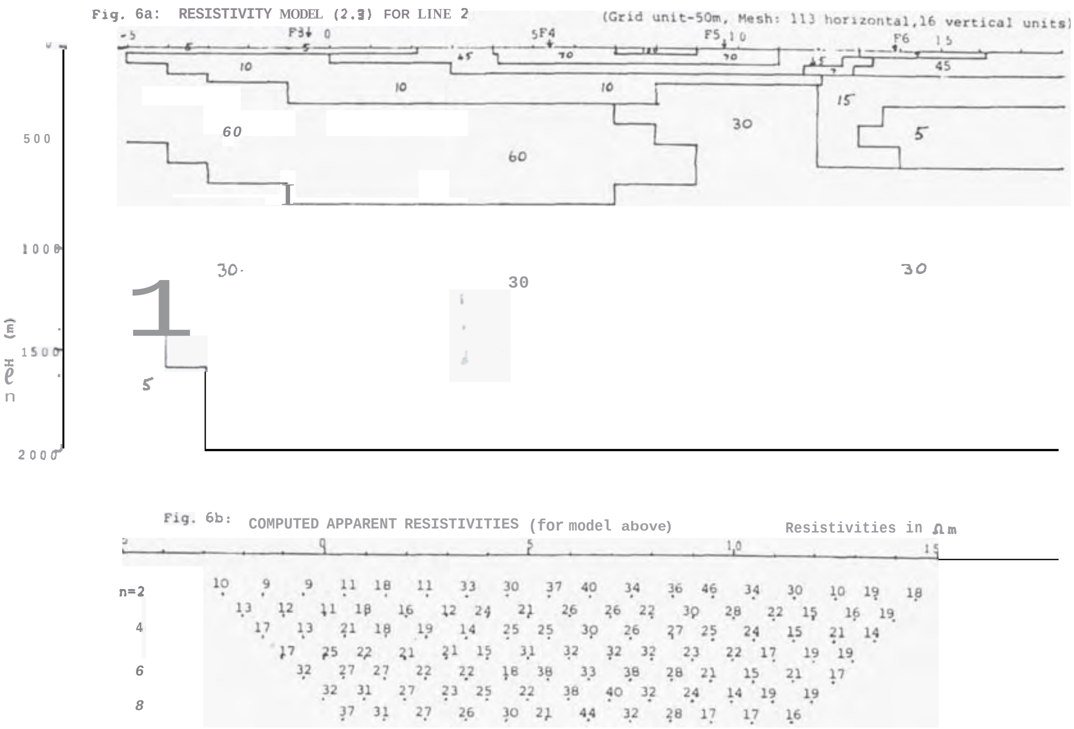

Fig. 6: Re-computed apparent resistivities for dipole-dipole line 2, Olkaria Field. (Model in Fig. 6 was adopted from section shown in Fig. 3). Computed resistivities in Fig. 6b should be compared with observed values for the same line shown in Fig. 2b.

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