INFLUENCE OF LARGE-SCALE RESISITIVTY SETTING ON INTERPRETATION OF RESISTIVITY WITHIN GEOTHERMAL AREAS

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ABSTRACT – Resistivity surveys using the Schlumberger traversing and multiple-source bipole-dipole methods show a sharp NNE trending discontinuity in electrical resistivity marking the margin between the eastern side of the Central Volcanic Region and the Kaingaroa Plateau which represents a 5 - 10 km wide band of normal faulting. South of Reporoa, the resistivity discontinuity coincides with the mapped position of the Kaingaroa Fault Zone, but further north it cuts beneath the comer of the Kaingaroa Plateau several kilometres east of the mapped positions of the Kaingaroa Fault and *Scarp*. Three distinct resistivities zones exist in the region: 350 - 1500 for the greywacke rocks beneath the Plateau, about $30\,\Omega$m for the volcanic fill of the Taupo-Reporoa Basin, and 2 - 5 Ωm for the geothermal fields.

Results from three multiple-source bipole-dipole surveys at Ohaaki using sources within the field, just outside the field, and 15 km away on the Kaingaroa Plateau show that the P_2 tensor apparent resistivity invariants measured in the Same resistivity zone as the current source are close in value to actual ground resistivities. But 'static shifts' of apparent resistivity occur when the receiver is in a different zone from the source. The very large 'static shifts' (an order of magnitude) observed in and near the Ohaaki Field from the source on the Kaingaroa Plateau are due to the influence of the large-scale lateral resistivity discontinuity at the edge of the high resistivity region beneath the Kaingaroa Plateau.

INTRODUCTION

While most of the resistivity surveying in the Central Volcanic Region (CVR)of New Zealand undertaken since the 1960s has been aimed at finding and delineating relatively shallow resistivity anomalies associated with geothermal fields, some of the surveys have investigated the larger-scale resistivity signatures caused by deeper structures related to the volcanism, faulting and plate tectonic processes. Data from these two classes of surveying cannot be satisfactorily interpreted independently. For example, computer modelling shows that apparent resistivities from large-scale regional surveys using the multiple-source bipole-dipole method are strongly dependent on both the large-scale lateral resistivity variations and the smaller-scale geothermal anomalies occurring in the region. The converse is also true; apparent resistivities measured in and near geothermal fields depend on the regional and deeper resistivity structure of the area. Correct interpretation of these sorts of data requires both an appreciation of the nature of the problem and sufficient knowledge of the local and regional resistivity structures to allow corrections to be made.

In this paper, we first discuss the interpretation of a resistivity survey designed to investigate the eastern margin of the CVR. This is marked by a large-scale 2-D resistivity discontinuity which has a strong effect on the apparent resistivities measured within the Taupo-Reporoa Basin. We then address the problem of assessing regional influences in interpreting ground resistivity structure in and near a geothermal field. As an example, we compare results from several resistivity surveys made at Ohaaki using the same measurement technique, but with the transmitter sited in
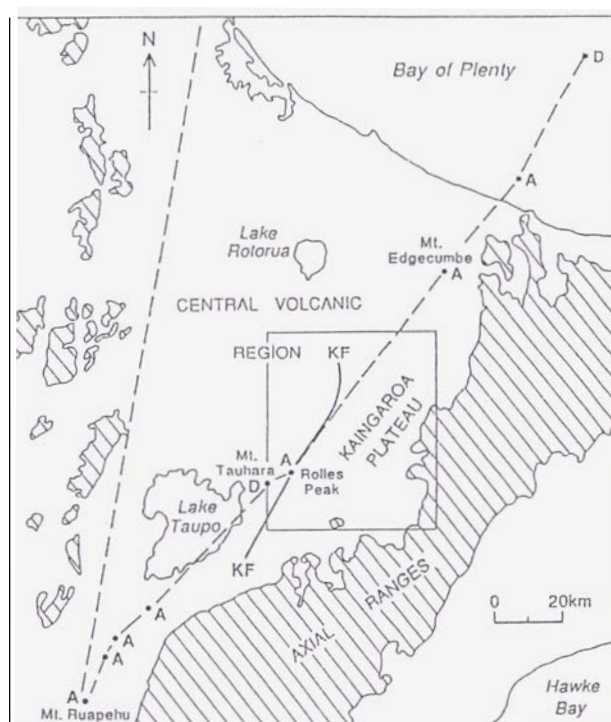

Fig. 1: The Central Volcanic Region is defined by the two dotted lines enclosing the centres of active volcanism. Dotted line to the east links the easternmost quaternary andesite (A) and dacite (D) volcanoes. Western margin is approximate. KF indicates mapped position of Kaingaroa Fault. Shaded areas indicate outcropping greywacke-argillite basement rocks. Outline indicates region of study shown in later figures.

different environments. This demonstrates that it is vital to make allowance for the effects of large-scale regional resistivity structures while interpreting ground resistivities within and near the field.

GEOLOGICAL SETTING

The Central Volcanic Region of New Zealand (Fig. 1) is a wedge-shaped zone of quaternary volcanism lying over the convergent margin formed from the collision of the Pacific and Australian Plates. The thick near-surface cover of ignimbrites and recent volcanics, which extends well beyond the CVR itself onto the greywacke basement rocks to the east and west, has proved an impediment to precise definition of the positions of the margins of the CVR.

Westward downfaulting of the greywacke basement rocks (Figs 1 & 2) marks the eastern margin of the CVR. Further east on the Kaingama Plateau, both drilling data and seismic exploration (Dawson and Hicks 1980, Macdonald and Hatherton 1968) show that greywacke lies at only about 200m depth. West of the fault zone, logs of drillholes in the Rotokawa and Ohaaki Geothermal Fields show the greywacke to be vertically offset by more than 1000 m. The fault zone appears to consist of a series of steps rather than just a single large fault. Interpretations of gravity data in the vicinity of Ohaaki support this view (Hochstein and Hunt 1970).

Lying to the west of the Kaingaroa Fault Zone, the Taupo-Reporoa Basin is filled to depths of up to 2000 m by a sequence of volcanic sediments. Several geothermal fields occur along the length of the Basin (Fig. 2).

RESISTIVITY SURVEYS

Fig. 3 shows the results of resistivity profiling with a Schlumberger array of spacing AB/2=1000 m over the western part of the study area (Geophysics Division DSIR, 1985).

In 1991, a multiple-source bipole-dipole resistivity survey (survey 'AA') was made over the study area using a transmitter on the Kaingaroa Plateau (site on Fig. 2). This survey employed the multiple-source bipole-dipole technique in a format that was first developed in New Zealand in 1968 (Risk et al 1970; Bibby and Risk 1973). The transmitter current supply was sequentially connected to three separate current bipoles (electrode pairs A, B and C in Fig. 2). Current was injected in turn into each pair for 4.5 minutes, with a half-minute break between pairs. Thus, the cycle of transmissions for A, B, and C was completed in a total of 15 minutes. The electric fields resulting from the current flow were measured at 220 receiver sites throughout the study area.

Following the theory of Bibby (1977, 1986), the data obtained from the three sets of transmissions can be combined to form a 4-element apparent resistivity tensor for each measurement site. Tensors such as these can be displayed in various ways some of which utilise the fact that the tensors possess rotational invariants with the same dimensions as resistivity. Values obtained for the invariant referred to as P_2 are shown in Fig. 4. An alternative graphical representation is given in Fig. 5. This shows each tensor as an ellipse for which the length of a diameter

in a particular direction is proportional to the apparent resistivity that would be measured when the electric field is aligned in that direction.

The broad features of the resistivity data can be seen on Figs. 3 and 4, which show summaries of the Schlumberger and multiple-source bipole-dipole resistivities, respectively. The dominant feature on both maps is the nearly linear NNE trending boundary separating the high resistivity values observed on the Kaingaroa Plateau from the much lower values obtained in the Taupo-Reporoa Basin to the west. The geothermal fields of the Taupo-Reporoa Basin also stand out, characterised by their very low resistivity values.

RESISTIVITY INTERPRETATION

Kaingaroa Plateau and Scarp

In the interpretation of the apparent resistivities measured with the multiple-source bipole-dipole method it is important to first determine the resistivity structure near the current transmitter. For survey 'AA' with the source on the Kaingaroa Plateau, the high apparent resistivities (>300 Ωm on Figs. 3 & 4) measured on the Plateau must be largely due to the greywacke basement rocks since they are found at about 200 m depth. By assuming the structure under the Plateau can be taken as horizontally layered, the apparent resistivity invariants shown in Fig. 4, which increase with distance from the transmitter, can be treated as a resistivity sounding. Inverting these data suggests that the greywacke has a resistivity of about 350 Ωm to about 4 km depth, below which it increases to about 1300 Rm. This interpretation is consistent with that derived from magnetotelluric data (Ingham 1991).

The western edge of the Kaingaroa Plateau is marked electrically by an abrupt drop in the values of the P_2 resistivity invariant. On the two southern lines crossing the scarp (WW' and XX, Fig. 5) the drop in P_2 begins near the topographic scarp and continues westwards for about 5 - 10km before the curves level out at resistivity values of 150 - 200 Ωm on the floor of the Taupo-Reporoa Basin. This slow decline in resistivity is not consistent with a single sharp vertical resistivity boundary, but suggests that the basement rocks dip to the west or are step-faulted across a broad zone. From theoretical models of two-dimensional structures such as this, the point at which the curve levels off marks the bottom of the sloping interface. Thus, there is a clear suggestion that the Kaingaroa Fault Zone exists as a series of down-stepping faults over a horizontal distance of 5 - 10km.

The apparent resistivity ellipses shown in Fig. 5 exhibit a clear change in orientation at the resistivity discontinuity marking the eastern edge of the zone of normal faulting. This behaviour is consistent with model studies which show that, in the high resistivity zone near a resistivity boundary, the ellipses become rotated as the boundary is approached, such that the major axes of the ellipses become nearly perpendicular to the discontinuity. To the west, within the low resistivity zone, the areas of the ellipses rapidly decreases, as observed in Fig. 5, and the major axes of the ellipses rotate and tend to align parallel to the discontinuity.

North of Reporoa, a change in direction occurs in the mapped position of the Kaingaroa Fault (Fig. 2). Yet on
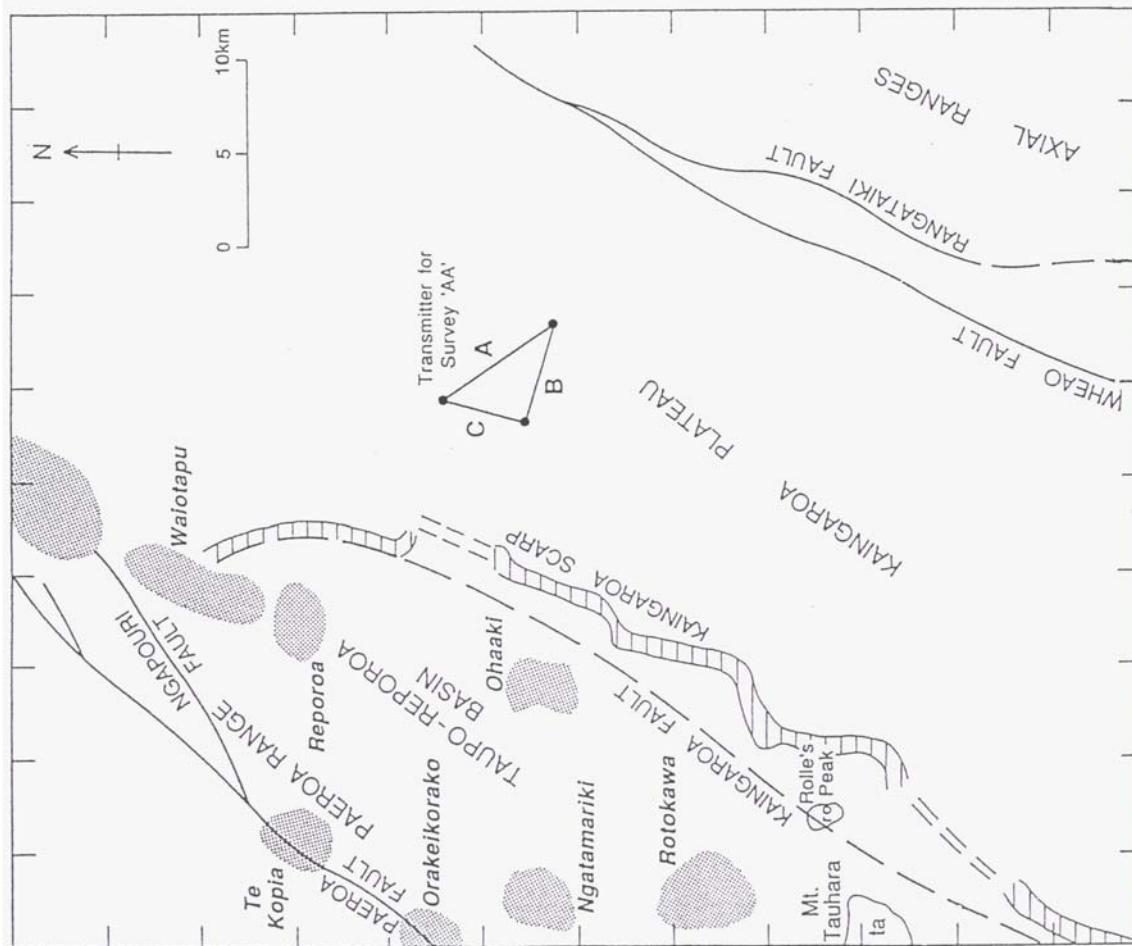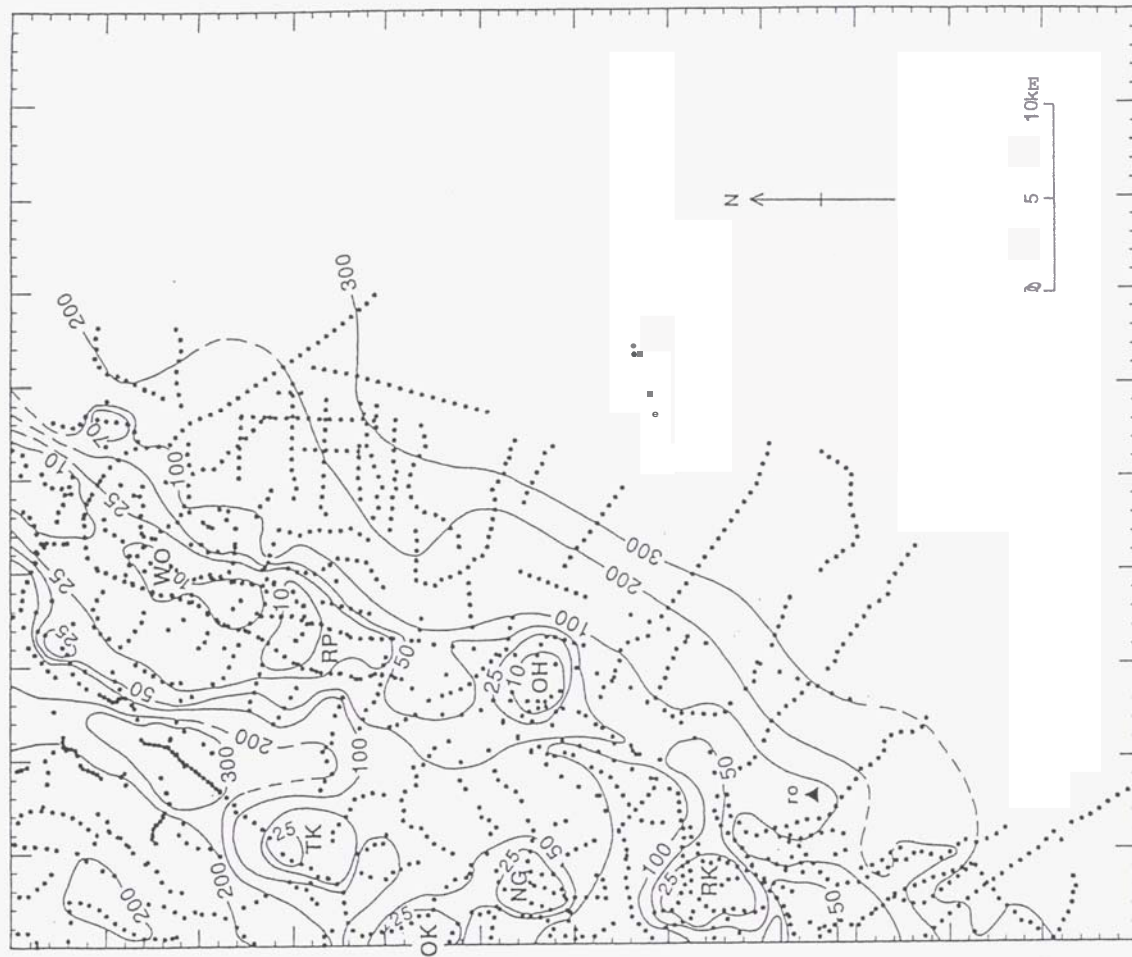
Fig. 3: Contours of apparent resistivity (in ohm-m) made with Schlumberger array of electrode spacing AB/2 = 1000 m. Dots indicate measurement sites. Geothermal Fields are indicated as follows: WO Waiotapu; RP Reporoa; OH Ohaaki; RK Rotokawa; NG Ngatamariki; OK Orakei-korako; TK Te Kopia. Rolles Peak is indicated ro.

Fig. 2: Locations of transmitter for survey 'AA', major faults, physiographic features, geothermal fields and other structures.

lines **YY'** and **ZZ'** (Fig. **5),** the points at which the resistivity drop is first seen are located well to the east of the topographic **scarp** and the mapped position of the Fault. These points form the segment **NN'** on Fig. **5** which aligns with the NNE trend-line of the corresponding onset of the resistivity drop on the southern lines, suggesting that the topographic scarp does not mark the edge of the zone of normal faulting on the northern transect. We conclude that the position at which the greywacke begins to drop is masked from view by several hundred metres of overlying Kaingaroa Ignimbrite on this line. The lack of faulting visible on the surface suggests that its last major downwarping of the greywacke occurred before the emplacement of the Kaingaroa Ignimbrite about **240,000** years ago **(Nairn 1989).**

Resistivity in the Taupo-Reporoa Basin

It is clear from the shallow traversing measurements (Fig. 3) that a large contrast exists between the resistivities of the near-surface **rocks** of the Kaingaroa Plateau and those of the CVR. At the surface in the Taupo-Reporoa Basin, apparent resistivities are of the order of $50 - 70\,\Omega m$. However, even the Schlumberger resistivity measurements give a clear indication that, outside of the geothermal systems, resistivity decreases with increasing depth (e.g. Bibby **1988).** Indications of the resistivity values at depths between **1** to 2 kilometres can be obtained from the multiple-source bipole-dipole measurements made to investigate individual geothermal systems. Data from the investigation of the Ohaaki Field quite clearly indicate that at depth the resistivity within the Taupo-Reporoa Basin, outside of the geothermal fields is about $30\,\Omega m$ (Risk et al. **1970,** Bibby **& Risk 1973).** Surveys in other parts of the Taupo-Reporoa Basin show similar findings.

The influence that the regional structure has on the values of apparent resistivity is clearly seen in Fig. **4.** South of Ohaaki in the Taupo-Reporoa Basin away from the geothermal fields, apparent resistivities are of the order of **150 - 200 Bm,** much higher than the true ground resistivity in this vicinity, which is about $30\,\Omega m$. This is not an indication of higher resistivity at greater depth under the Basin, as indeed modelling has demonstrated. The high values of apparent resistivity result from the influence of the very large resistivity discontinuity between the greywacke rocks under the Kaingaroa Plateau and the volcanics of the Taupo-Reporoa Basin. Since current always preferentially flows within a low resistivity zone, a large fraction of the current from the source on the Kaingaroa Plateau is drawn into the basin, increasing the electric field in this region by a factor of about **7.** Simple modelling of the region confirms this enhancement of current, and the consequential increase in apparent resistivity.

This enhancement of apparent resistivity produced by regional structures can be thought of as analogous to the 'static shift' problem commonly encountered in magnetotelluric exploration. In both cases all values of apparent resistivity in the affected region become enhanced (or diminished) by a similar amount, producing a parallel offset of the resistivity sounding curve.

Ohaaki Geothermal Field

Within the broad structure of the Taupo-Reporoa Basin, the

geothermal fields (Fig. 2) appear as localised zones where resistivity is further reduced below its average value for the Basin itself. Thus, the geothermal fields, with typical electrical resistivities in the range $2 - 5\,\Omega m$ are embedded within the volcanics of the Taupo-Reporoa Basin with resistivities of $30 - 50\,\Omega m$. In turn, the Basin lies adjacent to the very large-scale structure of the Kaingaroa Plateau and the eastern greywacke ranges which have resistivities of the order of $1000-1500\,\Omega m$. For a small-scale resistivity survey with relatively shallow penetration the regional structure can be ignored, but as depth of investigation increases, regional structures becomes increasingly important.

The influence on apparent resistivity values of both the scale of a survey and the placement of the current electrodes is demonstrated by comparing the results from three multiple-source bipole-dipole surveys of the Ohaaki Geothermal Field. While the earlier surveys, 'A and **'C',** were made in **1968-69** (Risk et al. **1970)** before the tensor analysis techniques had been developed, the measurement methods used were essentially the same as used in **1991** for Survey 'AA', allowing tensor analysis to be applied and comparisons to be made.

Fig. 6a, b, and c shows the results of the three surveys plotted in the form of the elliptic representation of the apparent resistivity tensor. Fig. 6a shows those from survey 'C' made with current electrodes at the centre of the Ohaaki Field. By way of comparison, Fig. 6b shows results over the same area from survey 'A', for which the current electrodes were placed just outside the field in higher resistivity ground. The corresponding data from survey 'AA' with current electrodes **15** km away on the Kaingaroa Plateau are shown in Fig. 6c. Note that the resistivity scale of the ellipses is different by factors of **50:100:200** between Fig. 6a, b and c, respectively. Typical apparent resistivities near the centre of the field are 2, **8,** and **40** Ωm, respectively, compared with true shallow ground resistivities of $2 - 5\,\Omega m$. These differences in apparent resistivity can be clearly seen in Fig. **7** which shows the tensor invariant apparent resistivity (P_2) plotted along a south-north profile through the centre of the field.

When the current electrodes are placed in the low resistivity ground within the geothermal field (Fig. 6a), the P_2 values measured within the field are close to the true near-surface resistivity and the Schlumberger resistivity measurements (Fig. 3). This agrees with the results of modelling (Bibby & Hohmann, in press) which show that, generally, the P_2 tensor invariant apparent resistivities measured in the same region as the source are representative of the actual resistivity of the rocks in that region. Because current preferentially flows in the low resistivity zone, not much current crosses the boundary. Thus, outside the boundary, electric fields and hence apparent resistivities **(7-10 Ωm)** are low, and less than the true resistivities outside the field. Although plotted on a log scale on Fig. **7,** a small jump of apparent resistivity can be seen at the boundary, but the contrast is small, and with this current electrode placement the boundary is poorly resolved. It is noteworthy that the ellipses in Fig. 6a are oriented with their major axes parallel to the boundary, typical of the transition from low resistivity to high resistivity (Bibby **1986).**

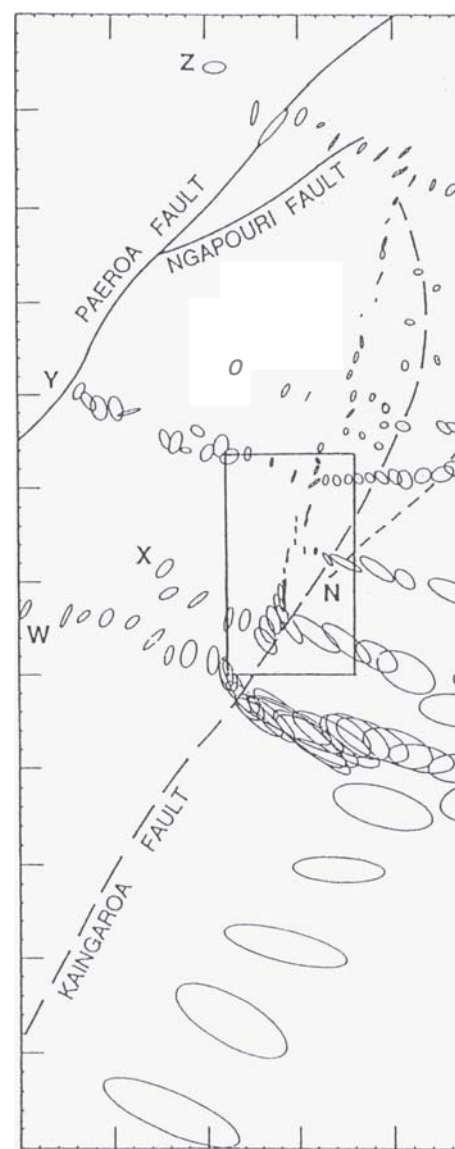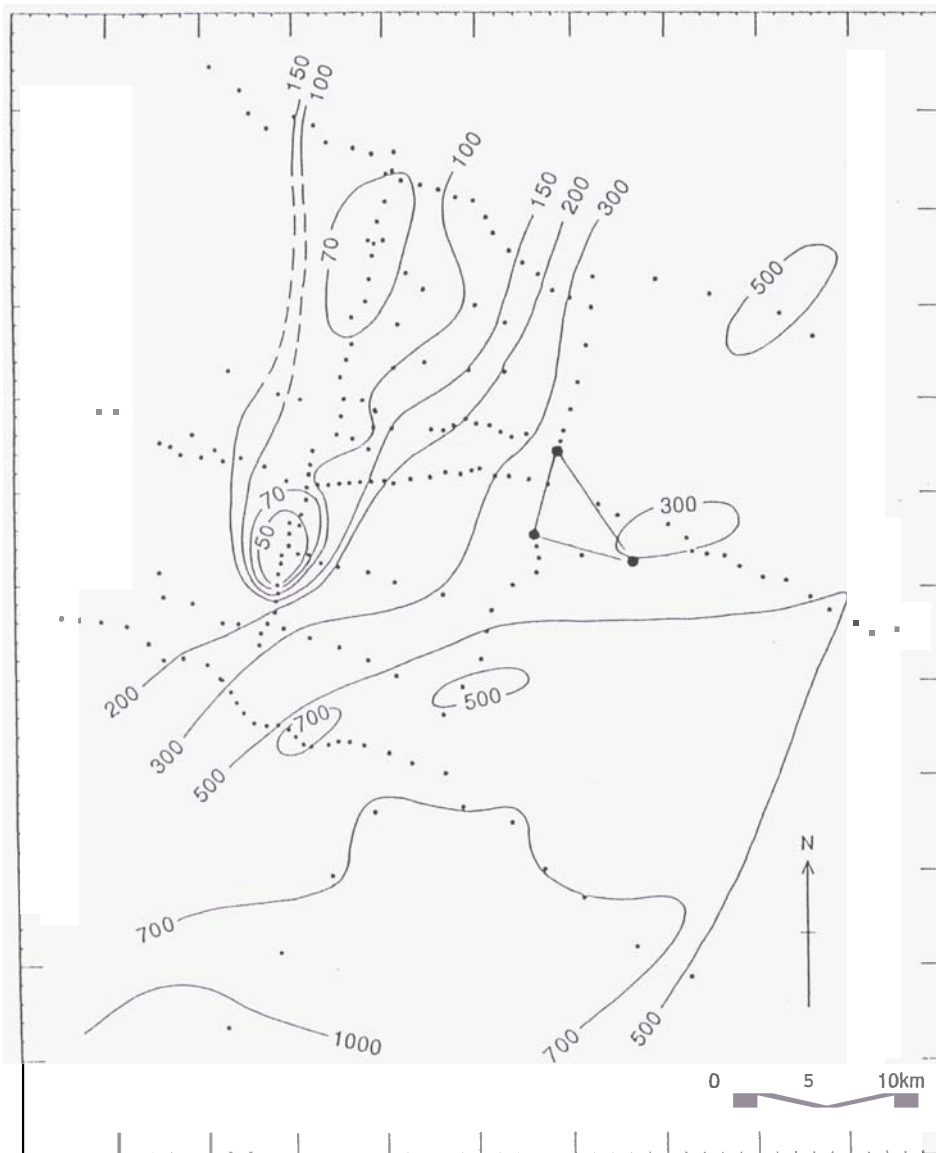With the current electrodes placed outside but near the field

Fig. **5:** *Apparent resistivities tensors fo...*
The length of a diameter in a particula...
the apparent resistivity that would be m...
is aligned **in** *that direction according t...*
indicate major faults.   NN' shows infer...
of CVR.   Outline indicates coverage Jo...

as in survey 'A (Fig. 6b), extra current is drawn across the boundary into the low resistivity material within the field. Once again, representative P_2 apparent resistivities are obtained in the same region as the source, in this case, the deeper parts of the region immediately surrounding the field, which therefore, has resistivities of about $30\,\Omega m$. However, now the values of P_2 inside the field no longer typify the rocks there; the enhanced current flow within the low resistivity zone results in increased values of apparent resistivity by a factor of more than 2 (Fig. 7). The enhanced current flow across the boundary causes a large apparent resistivity contrast which makes the boundary easier to determine than in the previous case. The boundary zone is clearly outlined by changes of the size, shape and orientation of the apparent resistivity ellipses (Fig. 6b). Immediately outside the boundary, the major axes of the ellipses lie perpendicular to the discontinuity, and the ellipses exhibit the largest eccentricity. These features can be used to both locate the boundary of the field, and indicate its strike.

The most dramatic influence of structure on the apparent resistivity values is seen in the third example (survey 'AA') where the current source is outside the Taupo-Reporoa Basin on the Kaingaroa Plateau. Again, the least disturbed apparent resistivities are measured in the Same region as the current source, namely, the values of $300 - 1500\,\Omega m$ representing the greywackes of the Kaingaroa Plateau. There are now three levels of apparent resistivity, corresponding to the three regions dominated by the greywackes, the volcanic fill, and the geothermal fields. With the current source situated in the highest resistivity zone, current is drawn into the two low resistivity zones to a larger extent. For measurements within the Ohaaki Geothermal Field (Figs. 6c, 7) there are consequently two processes of enhancement of the electric field, one from the regional structure, and the second from the geothermal field itself. A large contrast of apparent resistivity across the boundary will still be expected, indicating the position of the boundary, but the P_2 values measured within or near the field will be very much greater than the actual resistivity of the ground below the measurement points. The results from survey 'AA (Fig. 7) bear this out. Within the geothermal field, P_2 apparent resistivity values are about $40\,\Omega m$, compared with $2 - 5\,\Omega m$ for the local rocks, with values outside the field of about $200 - 300\,Qm$, compared with actual values of about $30\,Rm$. The similar shapes of the curves on Fig. 7 show that the dominant influence of having a distant source and significant regional structure is the 'static shift' in the resistivity values. The profile measured with the distant source is nearly parallel to that measured with the close source, but is shifted upward, with all apparent resistivity values increased by a nearly constant factor (of $7 - 10$).

The sharp boundary zone outlined on Figs. 6 and 7 is consistent with the near surface resistivity boundary of the Ohaaki Field defined by Risk et al. (1977) using a different resistivity array with relatively shallow penetration. The profile of P_2 for survey 'AA' also clearly shows a smooth decrease in apparent resistivity as the boundary of the field is approached from the outside. This decrease is consistent with previous studies (Bibby 1978) which show that the area of the low resistivity zone associated with geothermal fields in the CVR increases with depth below the fields. Detailed interpretation of these data in terms of the geometry of the deep field is the subject of ongoing research.

CONCLUSION

In investigations using electrical resistivity methods to seek information over large regions, it is essential to be aware of the influence that large-scale lateral resistivity structures have on the measured values of apparent resistivity. The demonstration using data from the Ohaaki Geothermal Field with current sources in the field, near the field and on the Kaingaroa Plateau, shows that the largest 'static shifts' arise mostly from the influence of the lateral resistivity discontinuity at the edge of the high resistivity region beneath the Kaingaroa Plateau. A smaller contribution comes from the disturbance caused by the low resistivity material of the geothermal field itself. Such 'static shifts' appear to be a little-recognised feature of all electrical resistivity measuring techniques. For correct interpretation of apparent resistivities from regional surveys in the Central Volcanic Region, or even of data from local surveys for assessing the geothermal fields, knowledge of the regional resistivity setting is essential. Only after regional influences have been removed from the measured apparent resistivities by detailed computer modelling, can the resistivity values of the structures present be determined.

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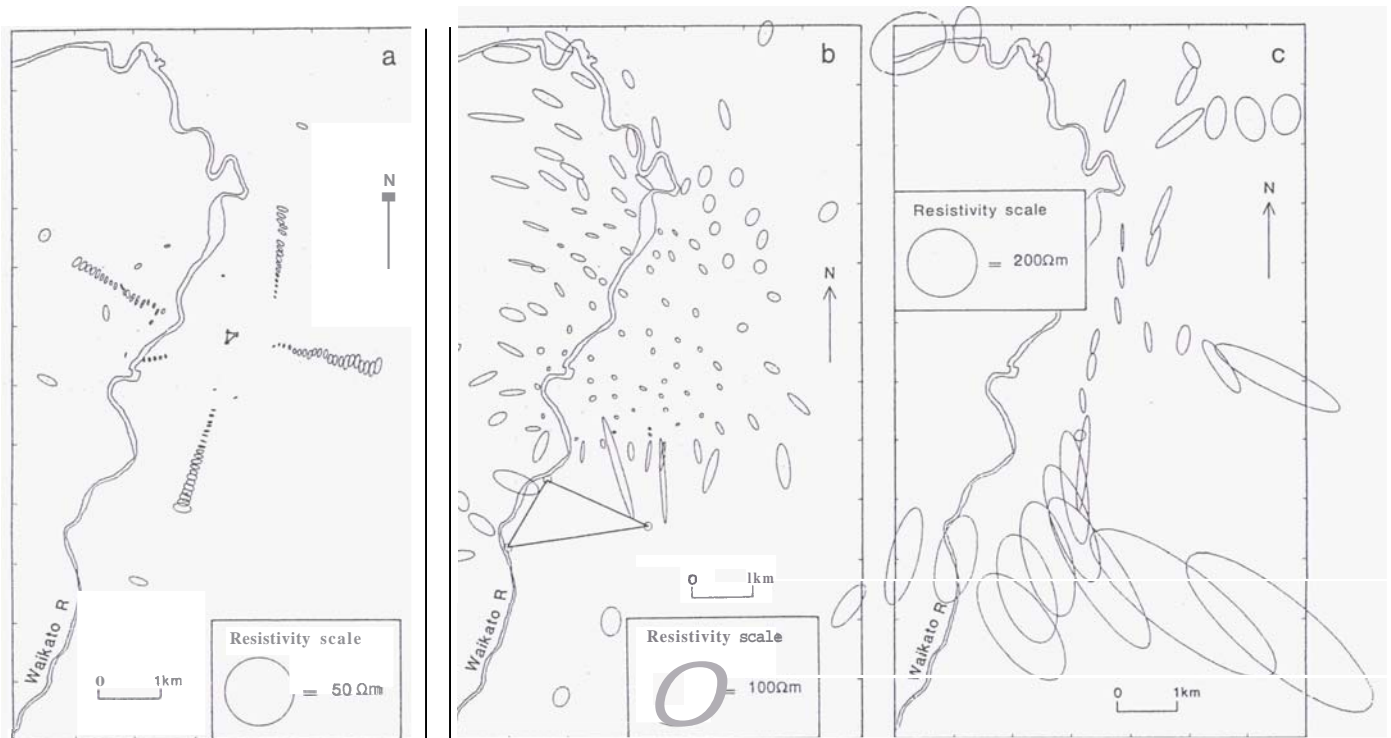
Fig. 6: *Apparent resistivity tensor ellipses at Ohauki Geothermal Field. Resistivity scales differ for each map.*
a) Survey 'C', transmitter at centre of field, apparent resistivity inside field about 2 ohm-m;
b) Survey 'A', transmitter outside but near the field, apparent resistivity inside field about 8 ohm-m;
a) *Survey 'AA', transmitter on Kaingaroa Plateau, 15 kni away, apparent resistivity inside field about 40 ohm-m.*
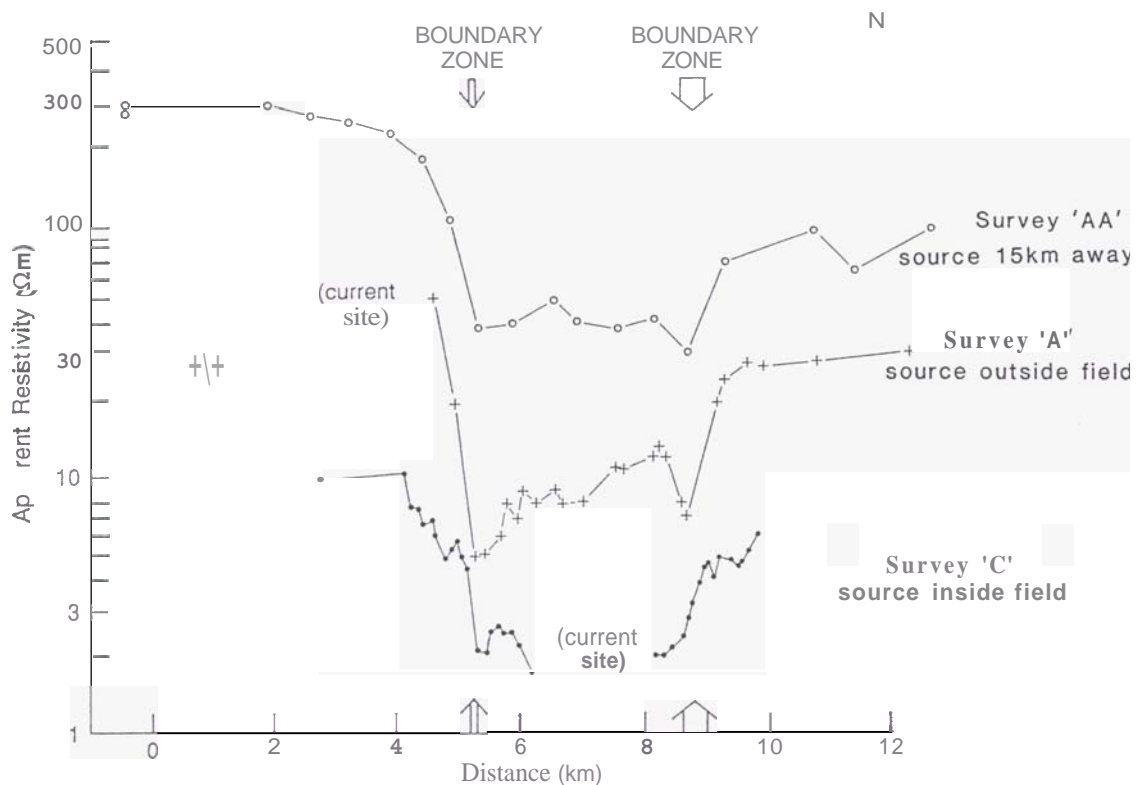

Fig. 7: *Tensor invariant P2 apparent resistivities along NS line through Okaaki Geothermal Field.*
Large static shifts occur, depending on placement of current electrodes.

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