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ELECTRICAL RESISTIVITY SURVEY OF THE WAIRAKEI GEOTHERMAL FIELD

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ABSTRACT

Resistivity surveys of the Wairakei geothermal field were made during 1978-83 using the Schlumberger and multiple-source bipole-dipole techniques. The Schlunberger measurements used electrode arrays with AB/2 spacings of 500 m and 1000 m, while the multiple-source bipole-dipole survey used a current transmitter placed in high resistivity ground about 6 km north of the field. From the measurements, a resistivity boundary zone defining the lateral transition from low (5 to 10 Ωm) to high (>100 Ωm) resistivity rock at about 0.5 to 1 km depth has been inferred. In the area of about 20 km², enclosed by the boundary zone, temperatures above 135°C exist in all the holes penetrating deeper than 700 m. Resistivities in the eastern and northern corners of the field are lower than the average within the field.

INTRODUCTION

During the period 1963-65, a resistivity survey of the area in and around the Wairakei geothermal field was made using the Wenner array with electrodes at equally spaced intervals of 1800 ft (549 m). The results, published as a contour maps by Banwell ard Macdonald (1965) and Hatherton, Macdonald and Thompson (1966) are given here in Fig. 1. The emphasis in that survey was to prove that the centre of the geothermal field had low resistivity values (<5 Ωm), rather than to accurately delineate the lateral limits of the low resistivity body associated with the field.

In the late 1970s several development proposals for Wairakei highlighted the need for a more detailed resistivity map. Between 1978 and 1983 a new resistivity survey of the Wairakei field and its surrounds was made using the Schlunberger array of electrodes with spacings of AB/2 = 500 m and AB/2 = 1000 m. It was thought to be both impracticable and unprofitable to repeat or extend the 1963-65 Wenner measurements. In June 1982, another resistivity *survey* using the multiple-source bipole-dipole array was made over the northern part of the field and its environs.

In addition, six Schlumberger resistivity soundings were made at the sites shown in Fig.4, but they provided little useful information owing to the high noise levels, and are not discussed here.

Full details of this work, including lists of the resistivity measurements. can be found in Risk *et. al.* (1984). The present paper is intended to make available a readily accessible *summary* of the data, and in particular, to present the inferred location of the lateral resistivity boundary zone representing the edge of the hot hydrothermal reservoir.

SCHLUMBERGER RESISTIVITY SURVEYS

At each measurement site four apparent resistivity measurements were made. For the first, the current electrodes were symmetrically sited a distance for the second, the arrangement was similar but with AB/2 = 1000 m. For the other two, the current electrodes were asymmetrically arranged at distances of 500 m and 1000 m on either side of the array centre. The symmetrical arrays provide the most readily interpretable information, while the data from the asymmetrical arrays have been mostly used in checking for measurement errors.

The Wairakei area proved to be a difficult place to make accurate resistivity measurements with the Schlumberger array. Strong background electrical noise levels exist in some places, probably caused by radiation from the power station, from electrical transmission lines, and from electric fences on nearby farms. Man-made conductive objects in contact with the ground, such as the steam pipes and well casings, sometimes have a shorting effect which can disturb the natural resistivity structure in the ground and cause anomolous apparent resistivities to be measured . In some places, such as near the main stem pipes, the apparent resisitivities observed were found to have been disturbed by as much as an order of magnitude.

The task of editing out erroneous or doubtful measurements has been one of the main considerations in preparing the apparent resistivity maps. in Figs 2 and 3, the measurements are presented in three categories. Measurements depicted as "R" have been rejected on the grounds that they *are* severely disturbed and *are* obviously erroneous. The other stations have the measured apparent resistivity values (in Ωm) shown alongside the sites. Those shown in the smaller italic lettering together with a question mark *are* of doubtful reliability, and most of them are likely to be wrong. The remaining measurements appear to be reliable, but when the ubiquitous nature of the disturbances caused by electrical noise and extraneous conductors is taken into account, some of these must inevitably be in error as well. With most of the erroneous data. the nature of the interference is such that the apparent resistivities are likely to have been over-estimated.

As well as showing the apparent resistivity values for, respectively, AB/2 = 500 m and AB/2 = 1000 m, Figs 2 and 3 show bars to indicate the orientations of each leg of the electrode array on either side of the centre. The data are contoured at logarithmically spaced intervals between 20 and 100 Ωm, but reliable contours could not be drawn in the regions with apparent resistivity less than 20 Ωm or more than 100 Ωm due to the scatter of the data.

Within the area of about 20 km² enclosed by the 20 Ωm contour and the river, apparent resistivities are mostly between 3 and 10 Ωm. Hot thermal ground exists over much of this area and all the drillholes penetrsting below about 300 m encounter temperatures above 100°C. Outside the 100 Ωm contour, apparent resistivities as high as about 800 Ωm are observed. No known hot springs or areas of hot ground occur in the outer zone and in three drillholes there (see Fig. 11) encounter temperatures below 40°C in the upper 500 m. Thus, there is a good inverse correlation between apparent resistivity measured with the Schlumberger array and temperature within a few hundred metres of the

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A comparison of the areas enclosed by the 20 Ωm contours on Figs 2 and 3 shows that there are more very low apparent resistivity values (3 to 6 Ωm) on the AB/2 = 500 m map than on the AB/2 = 1000 m one. This implies that resistivity increases with depth within the field, but to some extent, the trend could be caused by the greater susceptibility to disturbance by noise of the longer spaced array. The large scatter of apparent resistivity values observed within the field with both arrays makes a quantitative analysis of the data impractical. However, since errors due to noise usually result in higher rather than lower apparent resistivities, the lowest values are thought to be the most reliable. Thus, representative values of 3 to 5 Ωm for the AB/2 = 500 m survey, and 4 to 7 Ωm for the AB/2 = 1000 m survey are obtained for the low resistivity region.

The western edge of the low resistivity region extends about 1 km further west on the AB/2 = 1000 m map (Fig. 3) than on the AB/2 = 500 m map (Fig. 2). This difference is probably caused by variations of water level and surface elevation. Static water levels in the most westerly bores (on the elevated ground) are about 100-300 m below the surface, much deeper than in the east. For example. at bore 221 near the junction of Poihipi and Oruanui Roads, the static water level is about 220 m below ground surface. The ground above this level is expected to be largely drained ol water and probably relatively cool. Thus, the upper 200 m, or so, of ground is likely to exhibit a high resistivity, which will cause the AB/2 = 500 m apparent resistivities to be higher than the AB/2 = 1000 m values.

The north-eastern boundary, which runs parallel to State Highway 1, is about 0.5 km further towards the centre of the field on the deeper penetrating AB/2 = 1000 m pattern (Fig. 3). This is consistent with bore-hole measurements in the area which show that temperatures reach maxima close to the surface and monotonically decline at greater depths. Thus, the surface layers are more conductive than the deeper ones.

The Wenner array with electrodes spaced at a = 1800 ft = 550 m, wed by Banwell and Macdonald (19651 and their co-workers (Fig. 11, should give similar apparent resistivities to those measured with the Schlunberger array with AB/2 = 500 m. In fact, although there is broad agreement, some details are in conflict, as is discussed below.

MULTIPLE-SOURCE BIPOLE-DIPOLE SURVEY

Following the established practice for the resistivity exploration of New Zealand geothermal fields, a survey using the multiple-source bipole-dipole technique was undertaken to provide a "second opinion". Compared with the Schlumberger surveys, deeper penetration is possible, measurements can be made at logistically difficult sites, a greater immunity can be expected from electrical noise and disturbances caused by pipes and conductive objects, and the suite of data can be processed using more sophisticated analysis techniques.

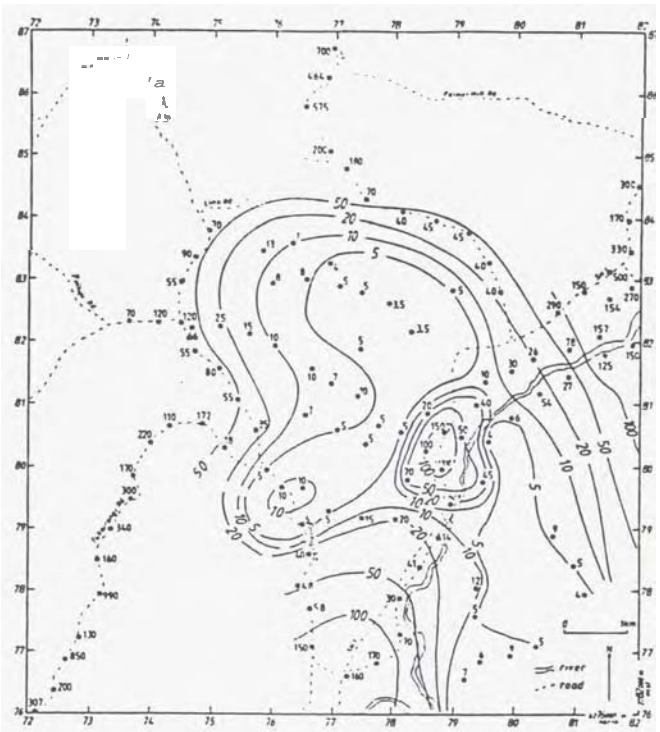


Fig. 1: **Apparent resistivities measured between 1963** and 1965 with **Wenner** array of **electrode spacing a = 1800 ft (= 550m). Contours from Banwell** and **Macdonald (1965).**

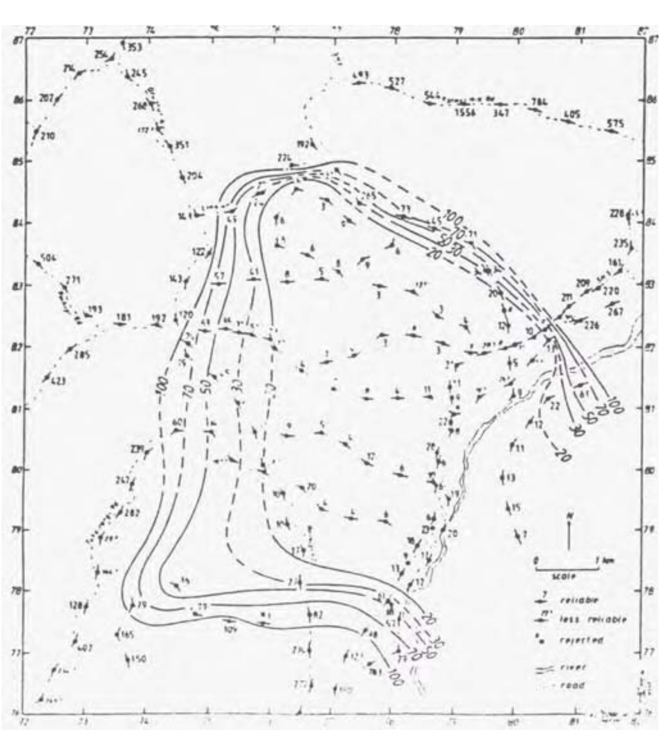


Fig. 2: Schlumberger apparent resistivities (in Ωm) for AB/2 = 500m. Bars

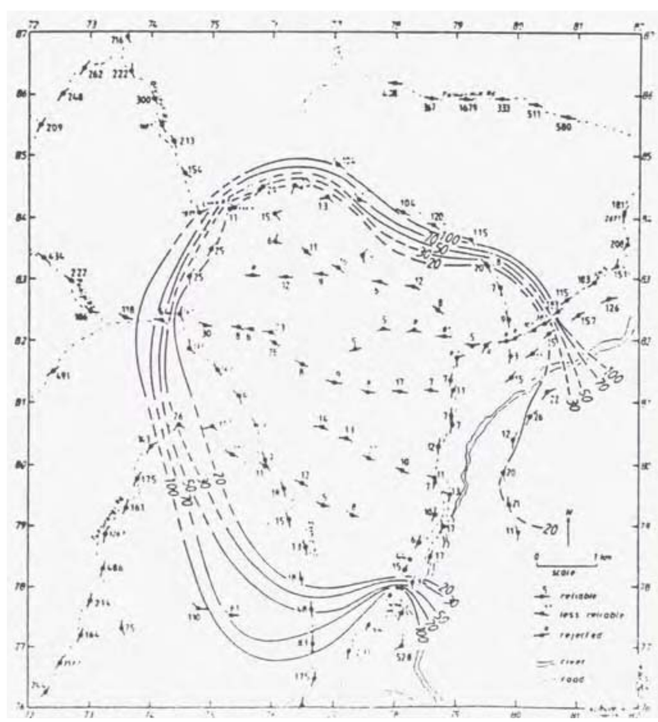


Fig. 3: Schlumberger apparent resistivities (in Ωm) for AB/2 = 1000m. Bars

The measurement technique follows the scheme first used at the Broadlands geothermal field by Risk *et. al.* (1970) and the data analysis was done using the steps outlined by Bibby and Risk (1973) and Bibby (1977). Current was injected into the ground sequentially through three 4 km long current bipoles (labelled A, B, and C in Fig. 41, situated on high resistivity ground about 6 km from the northern edge of the Wairakei geothermal field. An asymmetric square waveform was used with peak-ta-peak amplitude about 22 A and period 30 s. The signals were measured at the receiver sites shown in Fig. 4 wing receiver unit3 comprising two perpendicularly aligned grounded dipoles, between SO and 100 m long, connected to electronic consoles.

Maps of apparent resistivity at the receiver sites for current sources A, B and C, derived using the equations developed by Risk *et. al.* (1970) and Bibby and Risk (1973), are shown in Figs 5, 6 and 7, respectively. Short bars show the azimuths of the measured electric fields,

Dependence on source orientation can be eliminated by combining the three *measured* electric field strengths uith their corresponding (uniform field) current density vectors to form an apparent resistivity tensor. This was done for the Wairakei data using the scheme outlined by Bibby (1977). Figures 8 and 9 show contour maps of the rotational tensor invariants P_1 and P_2 (see Bibby, 1977 for definition of P_1 and P_2). These parameter3 have the dimensions of ohm metres and, for practical purposes, can be thought of as apparent resistivities averaged over azimuth, using two different averaging schemes. Figure 10 displays the data in an alternative uay using the elliptical representation of the apparent resistivity tensor. The principal axes depicted by the kite-like figures give a pictorial indication of both the magnitude and azimuth of the maximum and minimum apparent resistivities.

MAIN FEATURES OF MULTIPLE-SOURCE BIPOLE-DIPOLE DATA

All 3ix maps (Figs 6 to 10) of multiple-source bipole-dipole apparent resistivities show large values (>70 Ωm) outside the field beyond its western, northern and eastern edges, in agreement with the Schlumberger measurements. In the north and east a sharp resistivity boundary is evident between these high values and the lover values within the geothermal field: but there is an indistinct boundary on the western side, and the southern portion was out of range of the transmitter.

Within the Field, the multiple-source bipole-dipole survey has revealed some details not detected by the Schlumberger surveys. Two zones of very low apparent resistivity (mostly less than 20 Ωm) occur on *each* of the maps (Figs S to 10). One is in the north of the field near Link Road and the other in the east near the junction of State Highways 1 and 5. Intermediate apparent resistivity values (15 to 30 Ωm, see Fig. 9) were recorded in a narrow region linking the two lows, and in a band on the western side of the field which appears to link the northern low with the environs of Karapiti. The central part of the field including the main borefield area has higher apparent resistivities (30 to 80 Ωm) on each of the maps.

A striking feature of Fig. 10 is that, within the Wairakei field, strongly anisotropic ellipses are observed, aligned with their resistive (major) axes in a north-west to south-east azimuth. In seeking an explanation for this, the influence of the near-vertical resistivity boundary at the edge of the field was investigated by modelling the field as a low-resistivity body shaped as a hemispheroid and as a slab bounded by a vertical boundary of infinite length. Although neither model produced apparent anisotropy as pronounced as that observed, it is reasoned that a model comprising a low-resistivity body, elongated in the north-west to south-east direction, and situated over the region encompassing the two resistivity lows would produce a pattern of apparent anisotropy similar to that observed. Current would tend to be channeled along the axis of the body, causing enhancement of both the electric fields and the apparent resistivities in that direction.

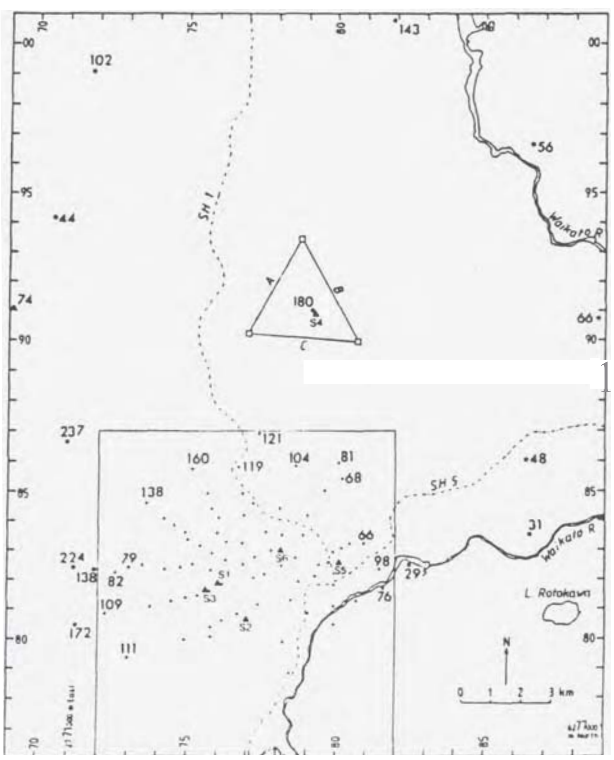


Fig. 4: Location of transmitter and receiver sites near Wairakei for multiple source bipole-dipole measurements. A, B, C represent the three bipolar current sources (transmitters) and the dots are receiver sites. Inset shows area covered by Figs 1, 2, 4-11, A1. Numbers by the more remote receiver sites are P_1 apparent resistivities in ohm m. (see Fig. 8). Resistivity sounding sites are shown as small

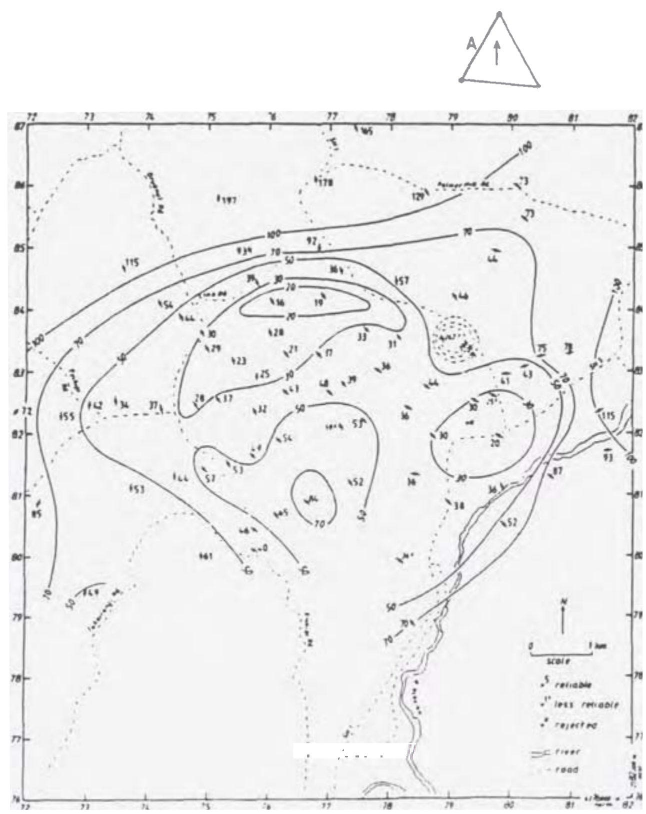


Fig. 5: Apparent resistivities (in Ωm) for current source A (shown in Fig. 4) of multiple source bipole dipole survey. Bars indicate azimuths of

LATERAL RESISTIVITY BOUNDARY

The main aim of the resistivity interpretations given here is to attempt to delineate the boundary between the high and low resistivity regions over the deeper parts of the main aquifer at levels between about sea-level and 400 m below sea-level (i.e. about 500 to 900 m below ground surface). It is from this range of levels that most of the hot water is drawn from the field.

A hatched annulus has been drawn on Fig. 11, enclosing an inner region where resistivities at the levels just mentioned are low (5 to 10 Ωm) and temperatures are inferred to be high (above about 150°C). In the region of high resistivity outside the hatching, temperatures are inferred to be low (less than 100°C). The hatched zone itself has intermediate resistivity values and it is uncertain whether hot or cold temperatures should be expected there. The position of the hatching was chosen mainly from consideration of the data on Figs 2, 8 and 9, but weight was also given to some other maps (Figs 5, 6, 7, 10) displaying the other parameters obtained from the multiple-source bipole-dipole survey. Data from the AB/2 = 500 m Schlumberger survey, shown on Fig. 2, was not given much weight because the depths probed would have been mostly shallower than 500 m.

Figure 11 also shows the locations of drillholes penetrating deeper than 700 m and their temperatures averaged between 500 and 900 m depth. Shallower drillholes are also shown, but without temperatures. There is a good inverse correlation between the patterns of highs and lows of temperature and resistivity. All the wells in low resistivity ground inside the hatching have mean temperatures above 170°C, except WK301 (drilled in 1984 in the south-east of the field) whose provisional average temperature is 83°C after only six weeks of heating following drilling. Throughout the western portion of the main borefield and the northern part of the field, mean temperatures are consistently between 245 and 260°C. The two deep bores in the high resistivity region outside the hatching have low mean temperatures (≤41°C), while an intermediate mean temperature (97°C) was observed in the well within the hatched resistivity boundary zone itself. Thus, the hatched resistivity boundary zone in Fig. 11 appears to separate the region which is hot down to about 900 m from the colder surrounding regions.

NORTHERN RESISTIVITY LOW

With a greater density and a better coverage of measurement points in the north and north-west of the field than had been possible with the 1960s Wenner measurements (Fig. 1), it now appears that the low resistivity region extends about 1 km further to the north and north-west than had previously been thought the case. The apparent resistivity maps obtained from the multiple-source bipole-dipole survey (Figs 5-9) all show a major resistivity low, just inside the field, on the south side of Link Road between State Highway 1 and Oruanui Road. Thermal activity at the surface has been occurring in the area in question for a long time (see Grange, 1955, map 4). This observation, together with the fact that the resistivity low is more prominent in the deeper penetrating multiple-source bipole-dipole surveys than on the shallow Schlumberger surveys suggests that the resistivity anomaly extends from the surface down to at least 1 km in depth. True ground resistivities within the low are inferred to be 5 to 10 Ωm within a few hundred metres of the surface.

The relationship of this northern resistivity low to local geologic structures in the area is uncertain, but there are some noteworthy geologic features nearby. North-south geological cross-sections of the field (see, for example, Grindley, 1982: Healy, 1984) show, that the depth to the top of the Ohakuri formation rapidly shallows (by 700 m) towards the north of the field, with an accompanying thinning of the ignimbrite. Although the location and strike of this feature is ill-defined, and its interpretation uncertain, it seems likely that the zone where the ignimbrite is thinnest (Ohakuri formation shallowest, only 1000 m deep) will approximately coincide with the resistivity low. Perhaps the two are related. The Huka Falls Formation is thicker in this vicinity and might also contribute to the low.

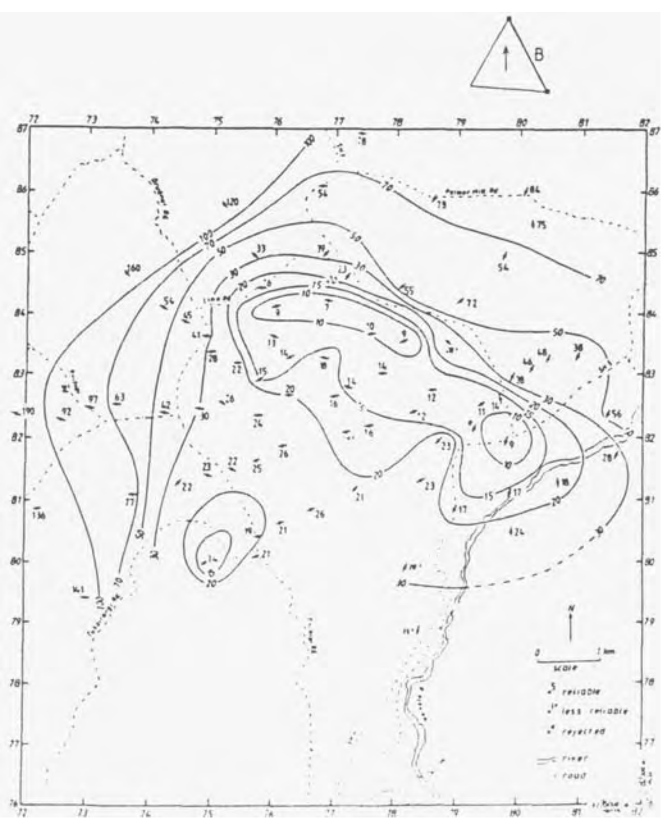


Fig. 6: Apparent resistivities (in m) for current source B (shown in Fig. 4)

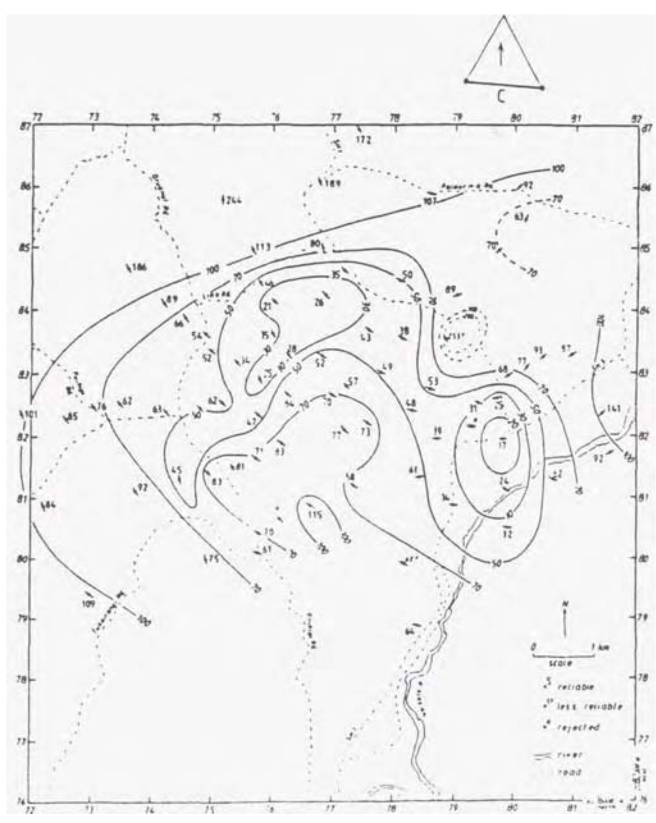


Fig. 7: Apparent resistivities (in m) for current source C (shown in Fig. 4) of multiple-source bipole-dipole survey. Bars indicate azimuths of

It is commonly held (see, for example, Grant, 1982) that the major deep feed for the Wairakei field occurs as an upflow in the north-west, but because there are few drillholes there, it3 position is not uell defined. The resistivity boundary outlined in Fig. 11 sets northern and western limits to any upflow uithin 1 km or so of the surface. Some modelling has been done in an attempt to determine what happens at deeper levels. Interpretations deduced from several different approaches have the common feature that the resistivity *boundary* is steeply dipping to the north.

The only holes drilled within a kilometre of the northern resistivity boundary are three shallow ones (small dots on Fig. 11), less than 320 m deep: all three encountered temperatures above 200°C. The three most northerly of the deep holes (WK 205, WK 219 and WK 222) all have average temperatures lover the 500-900 m depth range) higher then 250°C (see Fig. 11). Further drillholes are needed in this northern zone to explore the area and define the northern limit of the high temperature region.

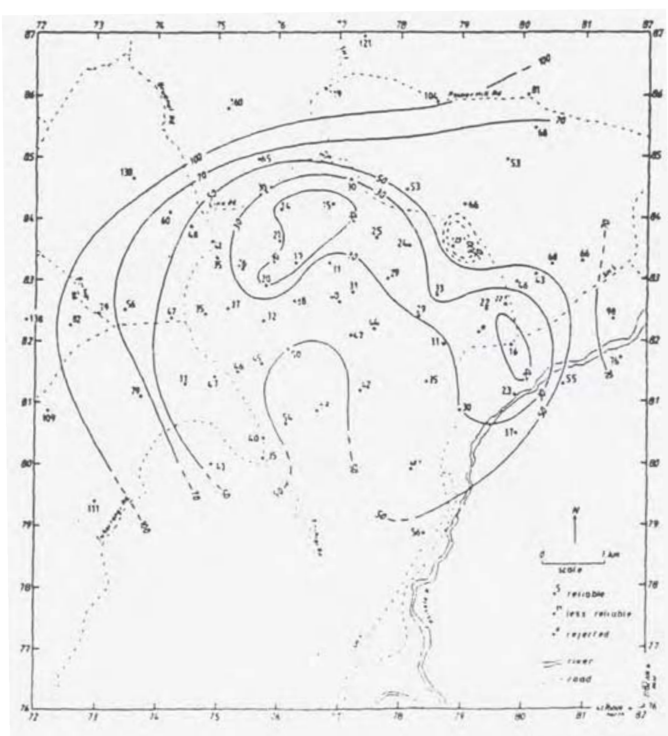
OTHER INTERPRETATIONS OF THE DATA

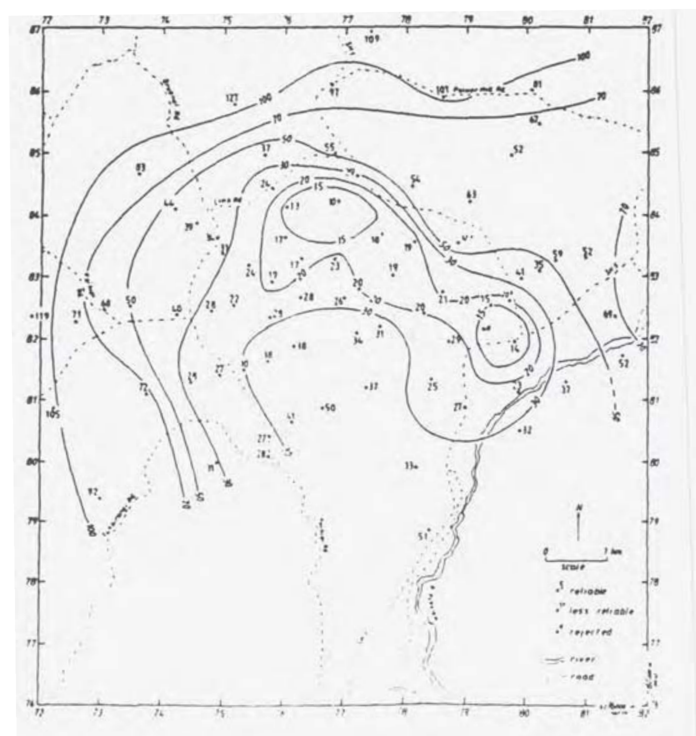
The region around the intersection of state Highways 1 and S is now interpreted as being uithin the main zone of low resistivity (3 - 10 Ωm), since low values were obtained from both the recent Schlunberger (Figs 2 and 3) and the multiple-source bipole-dipole surveys. The Wenner data *are* regarded as unreliable in this area. Temperatures in the seven drillholes (numbers WK2, WK10, WK23, WK33, WK35, WK36, WK301) located between the eastern part of the main borefield and the resistivity boundary (Fig. 11) reach maxima of only 90°C to 190°C, but most of the holes are quite shallow. Since none of the temperatures found so far (including those in WK301, over 1450 m deep) i3 above 200°C, it seems that this region is a peripheral part of the field, perhaps an outflow zone. At first site, the lou apparent resistivities obtained from the multiple-source bipole-dipole survey (Figs 8 and 9), being comparable in magnitude with those measured in the

of 101°C at 375 m, and 138°C at 1450 m) seem to rule o this possibility. It must be bourne in mind th measurements are not very reliable in this area awing the high noise level emanating from the power station.

In the vicinity of the main borefield (shown as t zone of close-spaced bores on Fig. 11), the Schlumberg results (Figs 2 and 3) show that, within a few hundr metres of the surface, resistivities are the same (3 5 Ωm) as in other parts of the field. Howeve resistivities obtained with the deeper penetrati mltiple-source bipole-dipole survey are abo 50 percent higher than those from the resistivity lo in the north and east (see Figs 8 and 9). Why th borefield shows up as a saddle region of intermediat resistivities joining the two lows is not clear at th stage. A thick layer of resistive stem in the uppe parts of the reservoir is a possible cause, or th observation could be related to the relative thinning o the Huka Falls Formation (less than 100 m thick), or th relative shallowing (600 m deep) of the Wairake ignimbrite.

The Karapiti thermal area lies in the south-west o the Wairakei field to the north-east of bore WK208 (th bore shown in Fig. 11 with a temperature of 171°C). Schlunberger apparent resistivities (Figs 2 and 3) are low (between 5 and 10 Ωm), reflecting the near surface thermal activity. The multiple-source bipole-dipole survey did not extend as far south as Wapiti, but quite high apparent resistivities (30 to SO Ωm in Fig. 9) were obtained over a 2 km stretch of countr immediately north of the Karapiti thermal area. To th north-west, a tongue of slightly lower apparent resistivity (25 to 30 Ωm in Fig. 9) appears to lead fro the northern resistivity low to the Karapiti region. I the Karapiti activity is being fed from a deep hot water source in the north-west of the field, as many believe, this tongue may represent the path. Since bores close to the resistivity tongue all encounter thick formations of rhyolite likely to be quite permeable, the argument that the tongue represents a flow path seems tenable.





The Tauhara geothermal field lies adjacent to the Wairakei field on its south-eastern side. Monitoring of pressures at deep levels in bores in the two fields indicates that they are hydraulically connected, but the aquifers forming the connection have not been accurately delineated. From the Wenner resistivity survey of Banwell and Macdonald (1965), (Fig. 1) the 2 km wide band of low apparent resistivity in the south-eastern corner of the Wairakei field was interpreted as the aquifer of hot water connecting the fields, with the high resistivity zone near the Huka Falls acting as a barrier to flow over the middle of the hand. The Schlumberger surveys (Figs 2 and 3) show a similar low resistivity band which is slightly wider (3 km) but has no high resistivity zone near the Huka Falls. Thus, there now appears to exist a continuous connection over a span of about 3 km, but doubts still exist about the reliability of many of the measurement3 in the region.

CONCLUSION

The recent resistivity surveys have provided a more detailed interpretation of the location and lateral extent of the resistivity bourdary of the Wairakei geothermal field (Fig. 11) than had previously been available. One of the more important findings is the inference that the field extends northwestward at least 1 km beyond the region investigated by deep walls. Further drilling in this area seems justified.

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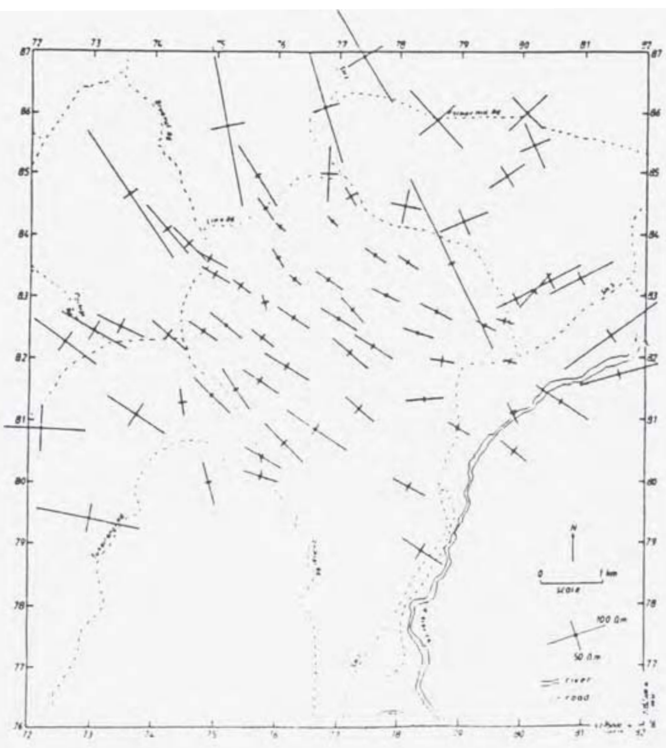

Fig. 10: Plot of maximum and minimum principal axes of the apparent resistivity tensor in the elliptical representation

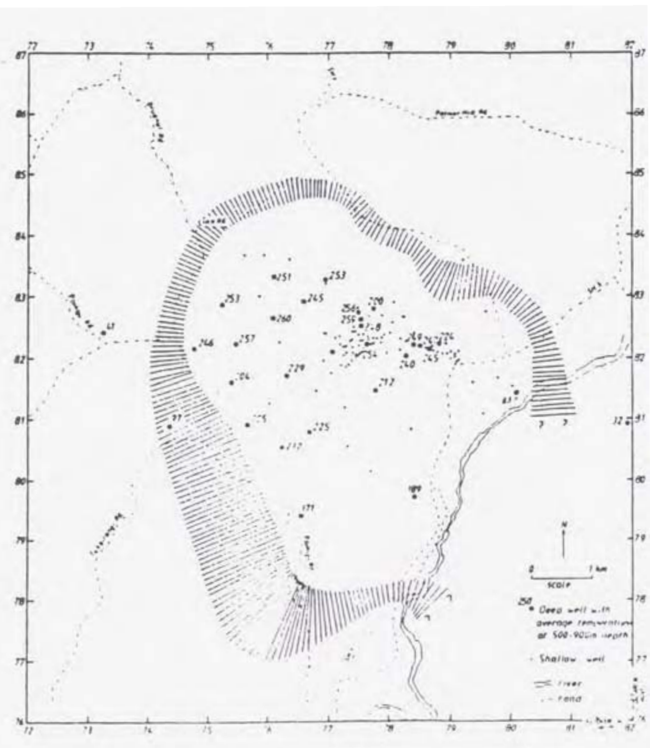

Fig. 11: Comparison of average borehole temperatures and inferred resistivity zones in the 500-900 m depth range. Low resistivities (<10 Ωm) are inferred inside the hatched boundary, high resistivities (>100 Ωm) outside, and intermediate values within the hatching itself. (Dots