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RECONNAISSANCE AND FOLLOW-UP RESISTIVITY SURVEYING OF NEW ZEALAND GEOTHERMAL FIELDS

G.F. Risk

Geophysics Division, DSIR, Wellington, N.Z.

ABSTRACT

Geophysics Division's reconnaissance resistivity mapping programme which began in 1963 is planned to map all of the Central Volcanic Region (CVR) of New Zealand with fixed-spacing (AB/2 = 500 m or 1000 m) Schlumberger electrode arrays. With about half the CVR already covered, many geothermal fields have been identified, including some with only minor surface thermal manifestations. Since the planned areal coverage is only about one field station per square kilometre and, in some places, problems have been experienced because of either questionable data or data gaps over inaccessible regions, the reconnaissance maps indicate only the approximate outlines of the geothermal fields.

More detailed resistivity measurements have been done over many of the New Zealand fields being appraised for development to delineate the geothermal reservoirs more precisely. Several resistivity measuring techniques have been applied, with the multiple-source bipole-dipole method being most commonly used. For each field, a simplified interpretation of the resistivity data is given in the form of a lateral resistivity boundary zone which is inferred to represent the edge of the hot water reservoir.

RECONNAISSANCE RESISTIVITY MAPPING

It was recognised in the early 1950s (see, for example, Studt, 1951) that electrical resistivity prospecting methods had potential for delineating geothermal fields by utilising the property that the electrical resistivities of the hot clay-rich and saline-water-saturated rocks of hydrothermal reservoirs are much smaller than those of surrounding cold ground. However, technical difficulties caused by extremely high electrical resistance at the point of contact between electrodes and the pumice-rich ground held up implementation of the proposal. After much experimentation, the technical difficulties were overcome with the utilisation of high input impedance microvoltmeters by W.J.P. Macdonald (and colleagues) in the early 1960s, and a measurement programme finally got underway in 1963 (Banwell and Macdonald, 1965).

At first, the Wenner electrode array of four equally spaced (separation a ≃ 500 m) collinear electrodes was used, but this was soon replaced by a Schlumberger array with a spacing (from array centre to outside electrode) of AB/2 = 500 m. The two arrays are nearly equivalent. The 1970s saw the adoption of a more complicated arrangement of electrodes, which has been used since, and allows for simultaneous measurement with four Schlumberger-type electrode configurations; two symmetric, with AB/2 = 500 m and AB/2 = 1000 m; two asymmetric, with AB/2 = 500 m on one side and AB/2 = 1000 m on the other. Measurement redundancy in the system facilitates consistency checking which is useful for detecting errors in the measurements. A paper about to be published (Bibby, in prep.) gives full technical details of these methods.

Since the beginning of this project the aim has been to systematically map the Central Volcanic Region of New Zealand and the thermal zones in Northland. To date, about half of the area in question has been covered, with over 17 000 individual resistivity measurements having been made.

The aim has been to identify and roughly delineate all the hydrothermal systems within the region. Thus, it is principally a reconnaissance program in which much more emphasis is put on identifying resources than on accurately delineating them. Accurate delineation of fields is more effectively done by follow-up surveys on a field by field basis.

Figure 1 gives the coverage of the measurements made up to January 1985. Since then some of the gaps in map sheets T16 and U16 have been filled in, but several important regions are still to be comprehensively mapped.

These data are being published as a series of maps under the title "Electrical Resistivity Map of New Zealand". The pair of companion maps (AB/2 = 500 m and AB/2 = 1000 m) comprising map sheet U17 have already been published (Geophysics Division, 1985) to begin the series whose background and technical details are described by Bibby (in prep.).

Several important successes can be claimed for the project. More than 20 geothermal fields have been identified. While the existence of most of these fields was already well recognised prior to this work, none had been well delineated, and several of them, such as Broadlands/Ohaaki, Mokai and Ngatamariki, were thought to be only minor fields. The early impressions of rather limited resources were based mainly on the small extent and unspectacular nature of the thermal features, but this impression had to be revised when the reconnaissance resistivity mapping showed resistivity anomalies of up to 10 km^2 in area underlying the fields. Later drilling has verified the resistivity interpretations and proven the existence of large geothermal reservoirs at all three fields just mentioned.

Over the years, various technical and interpretational problems have beset the project. While, the main technical difficulties were overcome by 1963, occasional instrument malfunction (particularly in foggy or wet conditions) and operator error (inevitable with over 15 operators having been employed) have resulted in a few erroneous readings being put on file. Interference from buried metal pipes and stray electrical signals will, undoubtedly, have upset further measurements. In recent years, with the experience accrued and the better instruments and checking facilities now available, measurement accuracy (better than 5% for most measurements) is no longer a serious problem. Since making a measurement involves laying out between 1 and 2 km of wire in a nearly-straight line, some regions have proved immeasurable because of access difficulties, leaving gaps in the data set. When it comes to compiling a resistivity map from these data, some editing out of erroneous or questionable data will almost certainly be needed. This has proved a contentious issue with several approaches being advocated by different geophysicists, leading to the inevitable result that several versions of a map come into existence. It turns out, for most regions, that the broad features are in agreement, with only the details being in conflict. This further strengthens the view that these data are best suited for reconnaissance purposes and that any detailed appraisal of a field should be based on separate follow-up measurements.

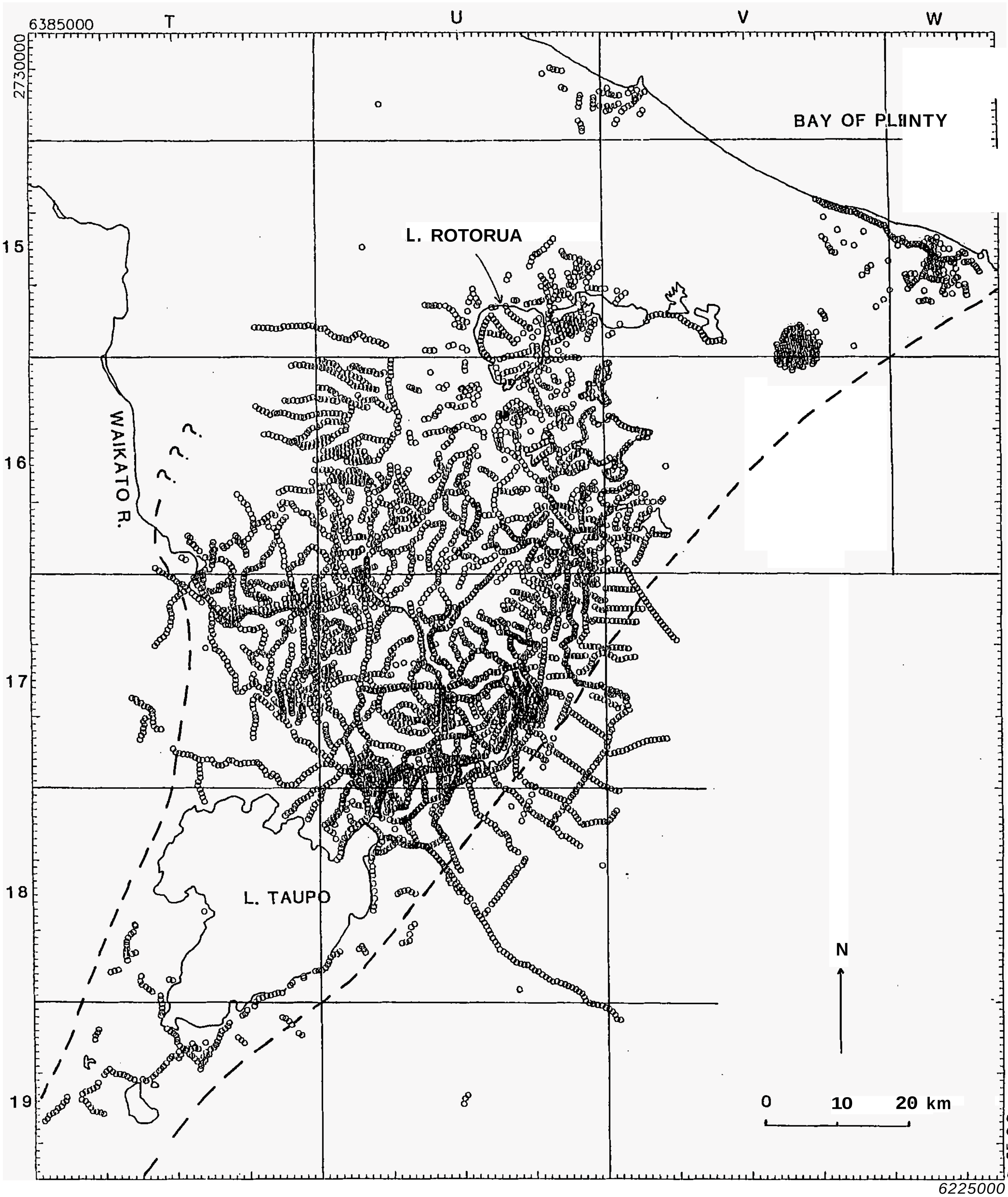

Fig. 1: Locations of resistivity measurements made between 1963 and January 1985 as part of the reconnaissance resistivity mapping project using either Wenner array (with spacing a = 550 m) or Schlumberger array (with spacing AB/2 = 500 m). Lettering at the edge of the map refers to the New Zealand Map Grid coordinates (in metres) and map sheet labels. Dashed lines indicate the approximate limits of the Central Volcanic Region.

Table 1: Major resistivity surveys of the Broadlands/Ohaaki geothermal field (1963-77)

Method		Date	Reference
a) Wenner traversing,	a = 550 m,	1963-66	Banwell and Macdonald (1965), Macdonald (1967)
b) Extension of Wenner traversing,	a = 500 m,	1967	Dawson (unpublished), Macdonald (1968), Risk et al. (1970)
c) Wenner survey,	a = 182 m,	1967	Gonzales, Dawson and Rayner (1968)
d) EM gun survey (shallow)		1967-68	Lumb (1968)
e) Multiple-source bipole-dipole surveys A & B		1968	Risk et al (1970)
f) Multiple-source bipole-dipole survey C		1969	Unpublished
g) Resistivity anisotropy survey D		1970	Risk (1975b)
h) Resistivity soundings		up to 1976	Risk (1975b), some unpublished
i) Boundary straddling bipole-dipole surveys H, XR, XS, XT		1975-76	Risk (1975a), Risk et al. 1977
j) Audio magnetotelluric tests		ca 1975	Whiteford (1975)

Other measuring techniques, such as the audio magnetotelluric method, have been tested and considered for use instead of Schlumberger traversing, but any advantages gained in speed of measurement seem to be outweighed by questionable accuracy. The Schlumberger array has the big advantage that, with centrally placed potential electrodes, it is relatively immune to errors caused by non-uniform ground. Present plans are to complete the project using the Schlumberger array.

DETAILED RESISTIVITY INVESTIGATIONS OF GEOTHERMAL FIELDS

After worthwhile energy-producing potential for a particular geothermal field has been established, there is usually a call for more detailed resistivity investigations to improve understanding of the extent and internal structure of the field. Separate studies involving other earth science disciplines are usually carried out simultaneously.

The investigations of the Broadlands geothermal field are a good example. The first few exploratory drillholes were sited using the Wenner-based reconnaissance resistivity surveys (Macdonald, 1967, see Fig. 2a) as a guide. By late-1967, eight 1-kilometre deep holes had been drilled, and the existence of a large high temperature geothermal reservoir proven. However, the drilling results also raised some problems. For example, hole BR6, in the southwest of the field, encountered rather low temperatures included two temperature inversion zones, implying that it lies closer to the edge of the field than expected. Thus, there was an obivous need for a better geophysical delineation of the field.

The first step taken was to repeat a few questionable Wenner measurements and to fill in, as much as was possible, gaps in the Wenner data set. While this revision improved the definition of the field, it was decided to experiment, at Broadlands/Ohaaki, with several measuring techniques to find the most appropriate method for delineating fields such as this. This exercise resulted in the surveys and experiments outlined in Table 1. Details of these experiments can be found in the publications referred to, and there is room here to cover only the main findings.

Attempts at unravelling details of the internal structure of the field with soundings and investigations of resistivity anisotropy produced some interesting results but they had little impact on well-siting and the development of the field.

The main achievement of these experiments was in determining the lateral extent of the low resistivity region, and hence the hydrothermal reservoir. The most successful experiments were those listed as *(e)* and (i) in Table 1. The vital feature of the measurement process which allowed the edge of the low resistivity zone to be pinpointed was to arrange for the current flow pattern to cross the edge of the geothermal field nearly perpendicularly. Of the experiments mentioned in Table 1, item (i) (Risk el al., 1977) proved to be the most effective in this regard, with its use of the "boundary straddling" technique which has one current electrode inside the field and the other outside. However, fieldwork with this method was cumbersome and slow, and it has not been applied to other New Zealand fields.

Instead, the multiple-source bipole-dipole technique, listed as item (e) on Table 1, has been generally adopted for the delineation of geothermal fields. Details of the technique are summarised in Bibby and Risk (1973), Bibby (1977). In brief, three independent current flow patterns are made to pass through the survey area from a current transmitter sited a few kilometres outside the field. Mobile receiver units measure the received signals at many points in and around the field. At each measurement point, three apparent resistivities corresponding to different current flow directions are obtained. These are computer analysed to reveal horizontal resistivity changes. In New Zealand, to date, this technique has been applied to the Broadlands/Ohaaki, Mokai, Ngawha, Wairakei, Rotokawa and Ngatamariki fields.

CONCEPT OF A LATERAL RESISTIVITY BOUNDARY

After a geothermal field has been surveyed with several different resistivity methods, there will inevitably be some apparent conflicts between the resulting resistivity maps. This can cause confusion, particularly to non-geophysicists. Several examples have been recorded where a particular resistivity contour (usually the 5 Ωm contour) has quite wrongly been taken as representing the edge of the field. To overcome this problem, the current practice in New Zealand is for the geophysicist to produce a simplified interpretation of all available resistivity data which will include a lateral resistivity boundary zone representing the edge of the field and, perhaps, an indication of how the boundary changes with depth.

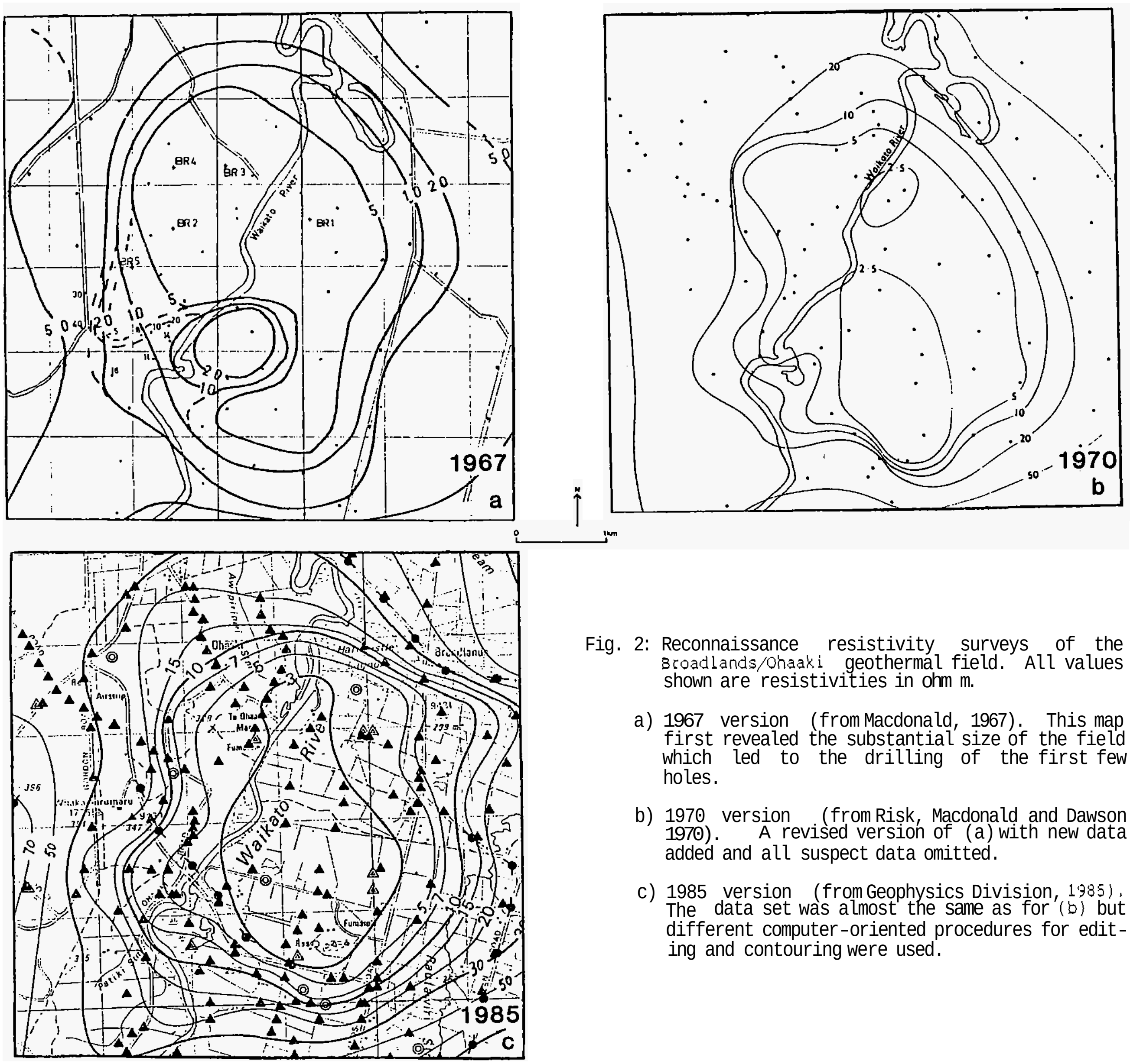

Fig. 2: Reconnaissance resistivity surveys of the Broadlands/Ohaaki geothermal field. All values shown are resistivities in ohm m.

a) 1967 version (from Macdonald, 1967). This map first revealed the substantial size of the field which led to the drilling of the first few holes.

b) 1970 version (from Risk, Macdonald and Dawson 1970). A revised version of (a) with new data added and all suspect data omitted.

c) 1985 version (from Geophysics Division, 1985). The data set was almost the same as for (b) but different computer-oriented procedures for editing and contouring were used.

This simplified interpretation aims at classifying the average ground resistivity inferred from the data (to depths of about 1 km) into three categories: low, intermediate, and high. The resistivity values defining the categories usually vary from field to field; for example, at Broadlands/Ohaaki they are: low <8 Ωm; intermediate 8-25 Ωm; high ≥25 Ωm. A map is prepared showing the horizontal extent of the three zones. If, in the vicinity of the intermediate zone, few data exist, or if there are apparent conflicts between data sets, the width of the intermediate zone is increased to accommodate the implied uncertainty.

It has been demonstrated in several geothermal fields in the Central Volcanic Zone that the inner region (low resistivity zone) can be safely interpreted as representing the hot water reservoir with temperatures in excess of 200°C. The outer region is inferred to be cold, while the intermediate zone, referred to as the lateral resistivity boundary zone, may have either hot, warm, or cold temperatures. The lateral resistivity boundary zone is taken to represent the edge of the hot water reservoir down to about 1 km. The width of the zone reflects the uncertainty implied as to the location of the edge of the geothermal field.

SUMMARY OF BROADLANDS/OHAAKI DATA

In order to illustrate the points made earlier, the following gives a summary of the resistivity surveys made over the Broadlands/Ohaaki field. Figures 2 and 3 show reproductions of published maps rearranged to a common scale and cut-up.

Reconnaissance surveys

Figure 2 shows progressively updated versions of the reconnaissance traversing resistivity measurements made with Wenner and Schlumberger arrays. Figure 2a shows the original version (June 1967) from Macdonald (1967). Some time later it was found that instrument problems had caused some erroneous readings to be included in the vicinity of the closed 20 Ωm contour to the south of the field. After revision, the 1970 version in Fig. 2b was compiled from a total of about 180 measurements. With the same data set, the contours have been recently reassessed and redrawn for the map covering the whole of the Wairakei-Broadlands region (Map Sheet U17, Geophysics Division, 1985) from which Fig. 2c is taken.

Remembering that the three maps on Fig. 2 represent reconnaissance surveys, their differences are not very significant. They clearly identify the low resistivity region and approximately outline it.

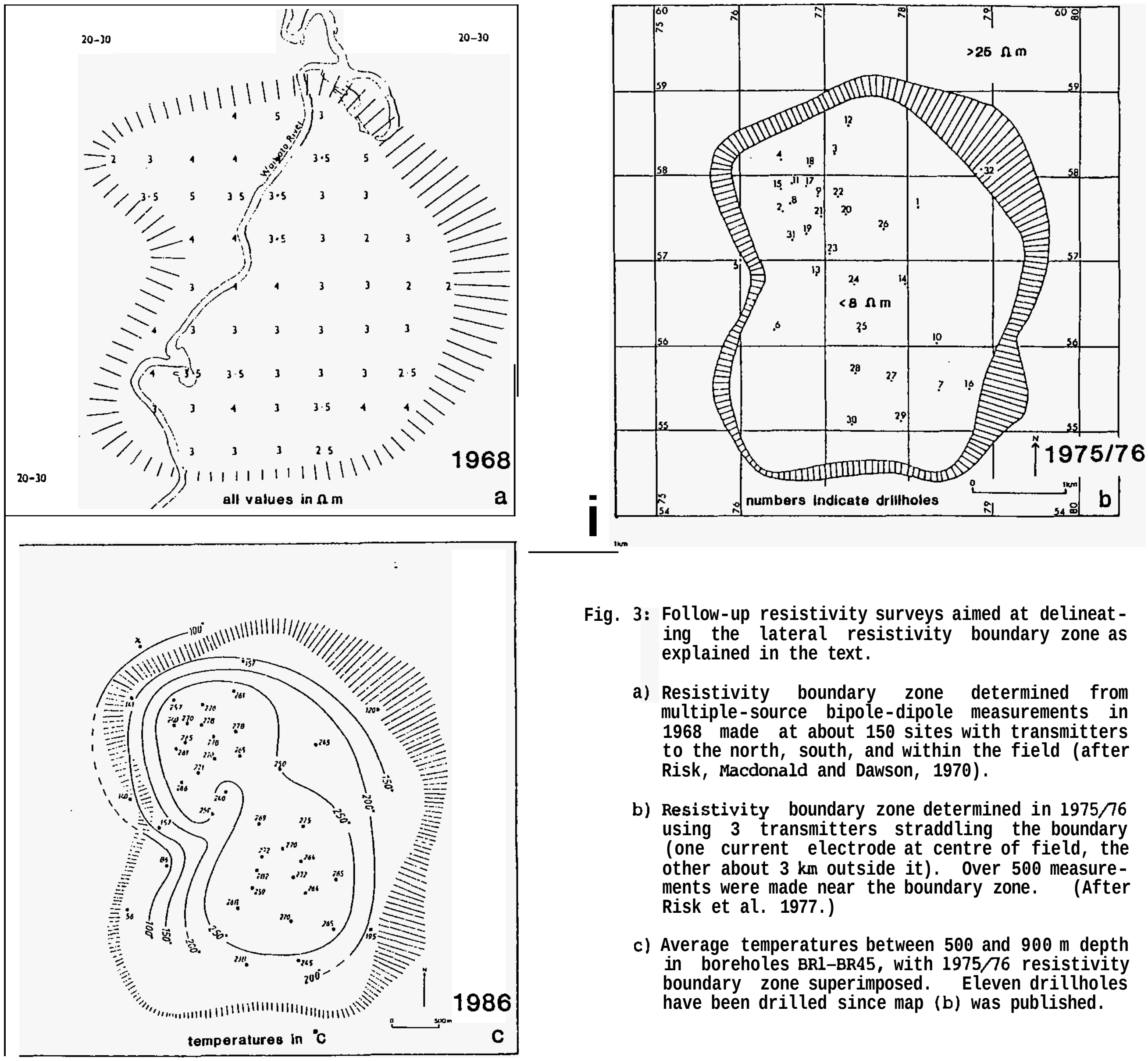

Fig. 3: Follow-up resistivity surveys aimed at delineating the lateral resistivity boundary zone as explained in the text.

a) Resistivity boundary zone determined from multiple-source bipole-dipole measurements in 1968 made at about 150 sites with transmitters to the north, south, and within the field (after Risk, Macdonald and Dawson, 1970).

b) Resistivity boundary zone determined in 1975/76 using 3 transmitters straddling the boundary (one current electrode at centre of field, the other about 3 km outside it). Over 500 measurements were made near the boundary zone. (After Risk et al. 1977.)

c) Average temperatures between 500 and 900 m depth in boreholes BR1–BR45, with 1975/76 resistivity boundary zone superimposed. Eleven drillholes have been drilled since map (b) was published.

Detailed follow-up resistivity surveys

The follow-up work was done in two stages as illustrated in Fig. 3. Apparent resistivities were measured in 1968 at about 150 sites in and around the Broadlands/ Ohaaki field using the multiple-source bipole-dipole technique. These data were analysed to produce the resistivity boundary map shown in Fig. 3a. Until about 1976, this map was considered the best outline of the field to depths of about 1 km but, in the light of later measurements (Fig. 3b), the eastern boundary seems to have been placed too far to the east.

In 1975/76, a further survey using the boundary-straddling technique (Risk et al. 1977) was undertaken to obtain a more precise location of the lateral resistivity boundary zone. Effort was concentrated on the boundary region itself with over 500 measurements being made within about 1 km of the boundary. The resulting resistivity boundary map, shown here as Fig. 3b, was adopted superseding the 1968 outline. It was reproduced on the official MWD field plan of Broadlands/Ohakki (8/1427/00/1804), and is still the best available resistivity boundary map.

Figure 3c gives contours of average temperatures in drillholes between 500 m and 900 m depth superimposed on the 1975/76 resistivity boundary outline. Although there are very few holes outside the resistivity boundary zone, the pattern of temperatures is generally consistent with the inferred resistivity interpretation (to depths of the order of 1 km). The only significant discrepancy occurs in the southwest where temperatures are colder than predicted. It is noteworthy that data from the 11 holes drilled since Fig. 2b was published fit the pattern quite well.

FUTURE POSSIBILITIES

With the reconnaissance resistivity mapping presently covering only about half the Central Volcanic Region, as shown in Fig. 1, it is clearly worthwhile to complete the project. The main areas with poor coverage lie in the north and south of the region. After filling these gaps there is a good chance that some major geothermal fields may be found in places where only minor thermal features are presently known. Exploitation of such fields, should they be proven, has the attraction that, being little known (like Mokai), they should be relatively immune to cultural, tourist or environmental objections.

In areas where the reconnaissance mapping has revealed large-sized low resistivity anomalies, consideration must be given to undertaking drilling, follow-up resistivity work, or other investigations. At the moment there are several geothermal prospects (Te Kopia, Atiamuri, Horohoro, Mangakino) where a limited

Table 2: Assessment of coveroye of major New Zealand geothermal fields by reconnaissance and follow-up resistivity surveys (✓ means satisfactory)

Field	No. of drillholes deeper than 500 m	Reconnaissance resistivity surveys	Detailed follow-up resistivity work	Comments
Wairakei	ca 93	J	J	noisy environment
Broadlands/Ohaaki	43	J	J	well covered
Kawerau	2H	AB/2 = 500 m only	none	limited coverage
Ngawha	13	J	J	poor resistivity contrast
Waiotapu	7	J	none	large area
Rotokawa	7	J	J	
Mokai	6	J	✓	
Ngatamariki	4	J	J	
Tauhara	4	partial coverage	none	access difficult near Mt Tauhara
Orakeikorako	4	partial coverage	small amount	protected field

amount of investigation has been done, but it is too early to decide whether or not the prospects contain significant geothermal resources. Investigations in these fields should continue in line with the availability of funds and the degree of success achieved as the work progesses.

The fields which have traditionally been considered to contain exploitable energy resources comprise another major category. Table 2 lists the fields which have been investigated by four or more deep (>500 m) drillholes, although some of these are currently classified as protected fields. The point at issue is to assess whether sufficient resistivity exploration has been done to date.

Table 2 indicates that resistivity coverage (both reconnaissance and follow-up) is adequate for the Wairakei, Broadlands/Ohakaki, Ngawha, Rotokawa, Mokai and Ngatamariki fields. Coverage is not complete at Orakeikorako, and no follow-up work has been done at Waiotapu, but both fields are protected at present. The fields most deserving attention are Kawerau and Tauhara. Reconnaissance coverage has been hampered by access problems over nearby volcanoes (Mt Edgecumbe and Mt Tauhara), and no significant detailed follow-up resistivity studies have been attempted. Clearly more work is needed.

CONCLUSION

Reconnaissance resistivity prospecting has proved valuable for identifying geothermal fields and, in particular, for demonstrating the presence of significant previously unrecognised resources at some fields. The problem of accurately delineating particular fields with resistivity techniques is best done with separate follow-up surveys designed for the purpose. This can lead to the definition of a lateral resistivity boundary zone which can be inferred to represent the edge of the hydrothermal reservoir. While lateral resistivity boundary zones are often somewhat over-simplified interpretations, they have enjoyed wide use in New Zealand as the best available way of indicating the inferred size and extent of partly explored geothermal fields.

ACKNOWLEDGEMENT

I acknowledge the contribution many Geophysics Division staff members have made over the years to the geothermal resistivity project, particularly that by W.J.P. Macdonald G.B. Dawson and H.H. Rayner who got the project underway in the early 1960s.

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