GEOTHERMAL IMPLICATIONS OF RESISTIVITY MAPPING IN LAKE TAUPO

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ABSTRACT - A waterborne DC resistivity survey of Lake Taupo was conducted in early 1992 using a towed electrode may. A large area of low apparent resistivity forming a moat-like feature around the Horomatangi Reefs was observed. This area is known to mark the vent of the Taupo eruption about 1800 years ago. The low resistivity is interpreted as the signature of a hydrothermal system lying within the collapse structure formed by this eruption. The reefs appear to form a 'plug' within this structure with geothermal fluid entering the lake in an annulus surrounding the reefs. A less distinct area of low resistivity occurs near the mouth of Western Bay and may also mark the site of an eruption, perhaps the Oruanui Ignimbrite about 22000 years ago.

INTRODUCTION

Conventional long wire DC resistivity measurements have been used extensively for resistivity mapping in the Taupo Volcanic Zone (TVZ) over the past 25 years (Bibby 1988). The majority of measurements have been made using Schlumberger arrays supplemented with older Wenner array data and waterborne resistivity measurements using anchored Schlumberger arrays measured in some of the lakes of the region. For example the published 1:50000 apparent resistivity map of the Wairakei region (Geophysics Division, DSIR, 1985) contains data measured using anchored arrays in Lake Ohakuri (Bennie and Stagpoole 1985). Waterborne measurements using this technique is for logistic reasons very difficult in water depths much over 30m. This has effectively restricted such measurements to shallow lakes or to near shore areas. Unfortunately, the largest lake in the region, Lake Taupo, is deeper than 100m for most of its area (Irwin 1972).

Experimental work using an electrode array towed at the surface has shown that with careful electrode design it is possible to measure electric field strengths down to the order of 5μV/m. With this development a survey of Lake Taupo using towed arrays became feasible. Indeed, a resistivity survey using a towed array offers the possibility of collecting data at much greater densities and much more rapidly than land based DC resistivity surveys. Apparent resistivity data collected using a towed array in Lake Rotorua was included in the resistivity survey of the Rotorua area (see Bibby et al. 1992).

RESISTIVITY MEASUREMENTS

The electrode array used for the resistivity survey consisted of two 150m long dipoles towed in parallel behind small boats, each boat separated by 500m, forming an equatorial dipole-dipole array. In practice, it is very difficult to maintain an ideal array configuration and the array geometry will vary from the ideal along each survey line. A sketch showing an imperfect equatorial dipole-dipole array is shown in Figure 1. Data analysis for the non ideal case presents little problem as long as the array geometry is well known.

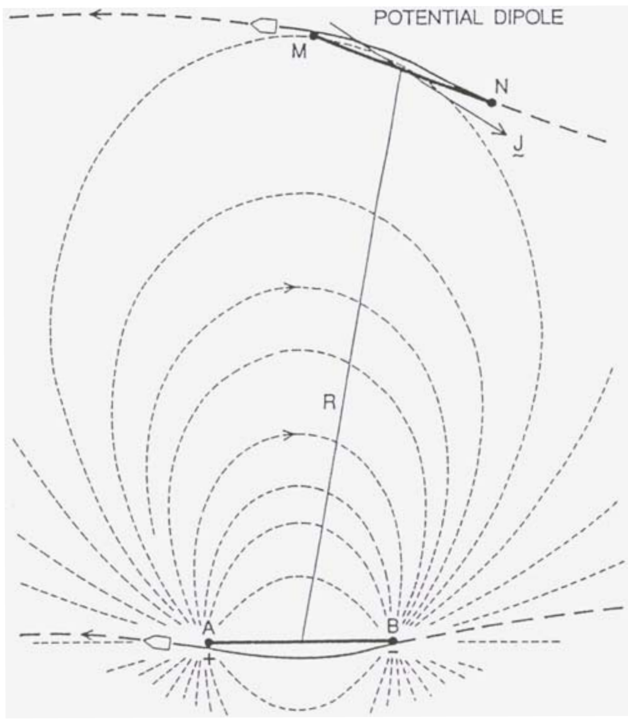

Figure 1. The equatorial dipole-dipole array used during the waterborne resistivity survey in early 1992. The fine dashed lines show the lines of current flow for a uniform resistivity half space. The electrodes forming each dipole are mounted on cables, shown as solid lines, towed behind each boat.

Navigation was controlled using Global Positioning Satellite (GPS) receivers on each boat and positions were recorded, using laptop computers, at 10 second intervals, corresponding to a distance interval of about 25m at the towing speed used. By fitting a smooth curve to the individual GPS position estimates the relative positions of the electrode dipoles can be determined as a function of time to much better accuracies than the individual GPS fixes.

Current was supplied using a standard 200W DC resistivity power supply with the current being reversed at 4 second intervals. Potential differences were recorded continuously using a digital data acquisition system sampling at 20Hz. These data were also stored on standard 720KB floppy disks using a laptop computer. Peak to peak voltages at each current switch were determined by least squares fitting a square wave of known phase but unknown amplitude to segments of voltage data, 2 seconds long, centred on each current reversal. The data processing scheme is shown schematically in figure 2. Using this method it is possible to estimate the apparent resistivity at 4 second intervals, a distance of about 10m, along each survey line.

Uncertainties in the apparent resistivity estimates have two main sources, the error in the least squares fit to the voltage data and the uncertainty in the relative orientation of the two dipoles. The error in the potential difference, which can be estimated directly from the least squares fitting procedure used to determine the signal amplitude, reflects the noise present in the voltage data. The noise level depends mainly on the state of the lake surface, calm conditions having the lowest noise. Uncertainties produced by positioning errors depend upon the particular array configuration. These are small when the array is nearly ideal but become large when the angle between the potential dipole and the uniform half space current density, shown as the vector J in Figure 1, exceeds more than about 45 degrees. The uncertainty introduced by the geometry can be derived directly from the uncertainty in the relative positions of electrodes which is estimated to be about 10m.

CONTOURING PROCESS

In order to computer contour the waterborne resistivity data, means of the individual apparent resistivity measurements, weighted according to their uncertainty, were calculated at 150m intervals along each survey line. This data set was then combined with the available 500m Schlumberger array data measured on the eastern side of the lake and with waterborne measurements made with anchored Schlumberger arrays in shallow water. Older Wenner array data around the Tokaanu area was also used. Anchored array data is available only in the areas to the south east of the Horomatangi Reefs, around Motuoapa and along the southern shores of the lake in Stump Bay. The combined data set was contoured using a method similar to that described in Bibby (1988). Figure 3 shows the positions of both the land based and waterborne measurements used to derive the apparent resistivity contour map shown in Figure 4.

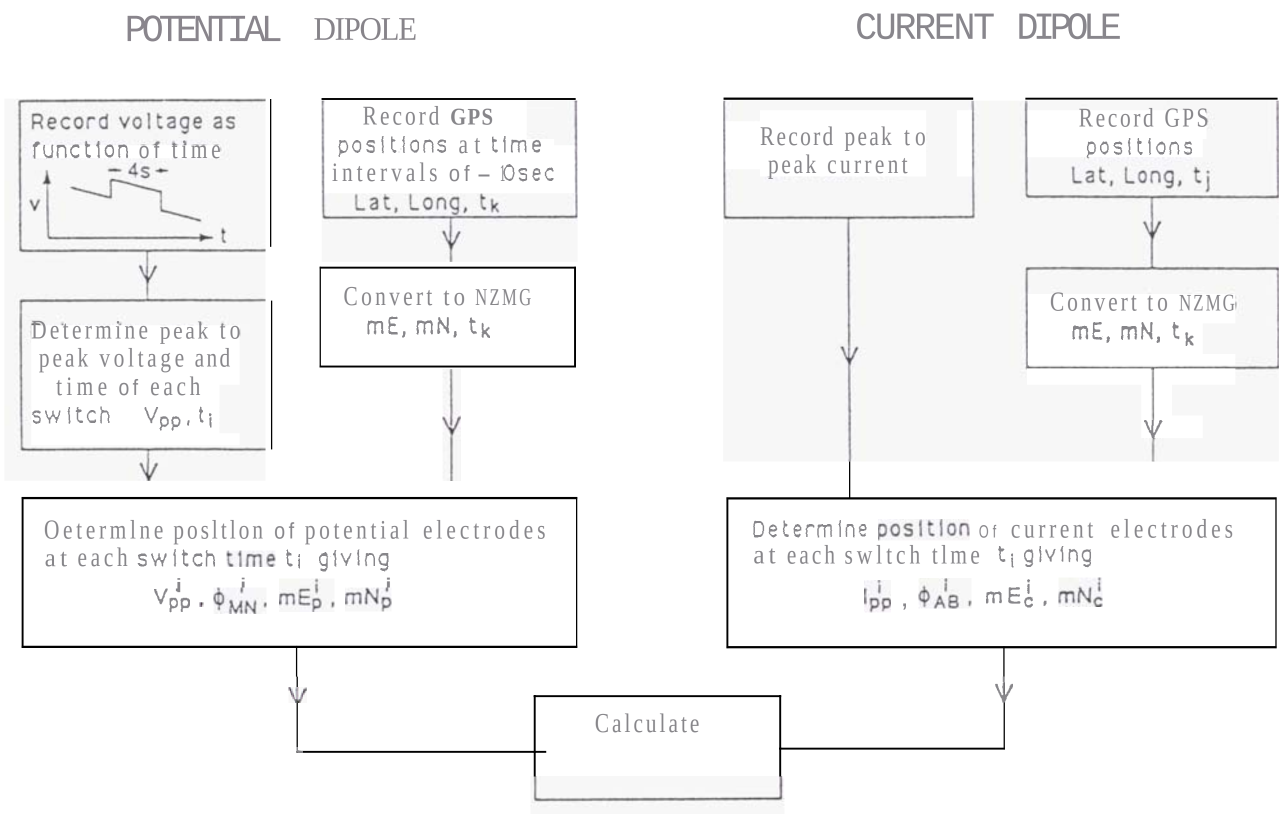

Figure 2. Schematic diagram showing the method used to analyse the resistivity data from the towed electrode array.

Combining apparent resistivity data measured with different electrode geometries is not strictly valid as different arrays will give different apparent resistivities depending on the

Figure 3. The map shows the positions of the resistivity measurements used to compile the contour map shown in Figure 4. These measurements are made up from three different data sets: measurements made on land using Schlumberger and Wenner arrays, waterborne measurements using anchored Schlumberger arrays with the electrodes placed on the lake bottom and waterborne measurements using a towed equatorial dipole-dipole array.

sub surface resistivity distribution. However, for the special case of measurements made on a horizontally layered media apparent resistivities measured with the equatorial dipole-dipole and Schlumberger arrays are the Same if the dipole separation is equal to half the current electrode separation for the Schlumberger array (Zhody, 1978) as is the *case* here. The greatest difference in apparent resistivity will occur in areas of abrupt lateral resistivity change. Data measured with anchored Schlumberger arrays overlaps with the towed array data only in the area south east of the Horomatangi Reefs and any direct conflict between the two sets of measurements will be restricted to this area. In fact, contours derived using only the waterborne equatorial array data, not shown here, were in excellent agreement with the Schlumberger data. This suggests good compatibility between the two data sets. Good compatibility was also observed during the resistivity work conducted on Lake Rotorua reported in Bibby et al. 1992.

RESULTS AND DISCUSSION

Crucial to any discussion of the apparent resistivity data is the effect of the overlying water layer. Lake water resistivities and surface temperatures were measured periodically during the course of the survey. The measured surface resistivities were remarkably uniform with a value of about 80 Ωm. This value is however unrepresentative of the bulk resistivity of the lake water. In late summer a thin layer at the surface of the lake reaches a temperature of nearly 20°C. Correcting the observed surface resistivity for the estimated mean temperature of the lake, about 11°C, shows that the resistivity of the lake water is about 100 Ωm.

Any DC resistivity measurement can be thought of as providing an estimate of the mean resistivity of the material beneath the array. For the equatorial dipole-dipole and Schlumberger arrays discussed here the nominal penetration depth of the arrays is 500m, however more realistically the arrays are sensitive only down to depths of about 300m. For example, with a lake depth of 100m the observation of an apparent resistivity of 50 Rm implies the underlying 100 to 200m of material would have a mean resistivity of slightly less than 50 Rm due to the effect of the overlying 100 Ωm water. The greater the resistivity contrast between the water and the underlying material the greater the effect.

As can be seen in figure 4 apparent resistivities over much of the lake are less than 70 Rm, suggesting the sediments on the lake floor have resistivities significantly lower than the lake water. This is interpreted to be due to the effect of the clay content of of the lake sediments, these sediments accumulating in the deeper parts of the lake. Apparent resistivities in the shallower areas, depths less than about 100m, are generally greater than 100 Rm.

Horomatangi Area

As can be seen in Figure 4 an area of apparent resistivity less than 30 Ωm forms a moat-like feature, open to the west, surrounding a central more resistive area coinciding with the Horomatangi reefs. The low resistivity moat forms part of a larger area with apparent resistivity less than 50 Ωm stretching from Motutaiko Island in the south to about 4km north of the Horomatangi reefs. The small area of high resistivity about 2km north of the Horomatangi reefs coincides with a pinnacle-like feature in the bathymetry, known as the Waitahanui Bank.

The western boundary to this area of low resistivity is remarkably abrupt, the apparent resistivity decreasing in a distance of about 400m by more than half an order of magnitude to values of about 15 Ωm. The resistivity of the material underlying the lake in this area is approximately 10 Ωm if allowance is made for the overlying layer of 100 Ωm water more than 100m thick. In other areas of the TVZ such low values of resistivity are associated with the geothermal fields as indeed are abrupt changes in apparent resistivity. Thus we infer that the large area of low apparent resistivity surrounding the Horomatangi reefs marks the near surface expression of a large hydrothermal system centred on the reefs.

Lake bottom temperature gradient measurements reported in Calhaem (1973) as conductive heat flows are in good agreement with this inference, high temperature gradient measurements occurring within the low resistivity area. These results have been confirmed by recent heat flow measurements by Whiteford (1992). Northey (1983) also observed an area of gas discharge from a point about 2km south of the reefs in the area of low resistivity.

The higher resistivities associated with the reefs suggest that these features contain less geothermal fluid and are less hydrothermally altered than the surrounding material. This is consistent with the view that the reefs are juvenile features, almost certainly lavas (rhyolites) extruded in the dying stages of the Taupo eruption about 1800 years b.p., (Wilson and Walker 1985). We suggest that the inferred hydrothermal system lies within and is confined to a collapse structure associated with this eruption or sequence of eruptions. The reefs *appear* to form a 'plug' within a more permeable zone formed by the disrupted material of the collapse structure. Hot fluid thus enters the lake in an annulus surrounding the reefs causing the observed pattern of apparent resistivity. The sharp western boundary in the resistivity is interpreted to coincide with the western edge of a collapse structure marked by a *scarp* like feature that can be seen on the map of the lake bathymetry, Irwin (1972).

South Eastern Margin

Two localised areas with intermediate values of apparent resistivity occur near the south eastern shore of the lake in relatively shallow water. The Southern most of these two anomalies can be identified with the Motuoapa Hot springs, see Bibby et al. 1991. Recent heat flow measurements, Whiteford this volume, show that the northern anomaly, near Hallets Bay, has a very high heat flow. The indentation in the contours to the north of Mission point suggests the possible existence of another area of hydrothermal activity in the lake floor. Evidence to support this interpretation comes from reports in several newspapers, NZ Herald 1963 and NZ Geological Survey files, of what may have been a hydrothermal eruption in this area in 1963. The size of the resistivity anomalies associated with these inferred hydrothermal areas is very much smaller than is typical for geothermal systems elsewhere in the TVZ. In our opinion these areas are probably not mature geothermal systems in the sense of Wairakei or Ohaaki. Proximity of the northern two areas to the most recent vent of the Taupo Volcano suggest they may be related to the recent volcanism. The nature of any such relationship is unclear.

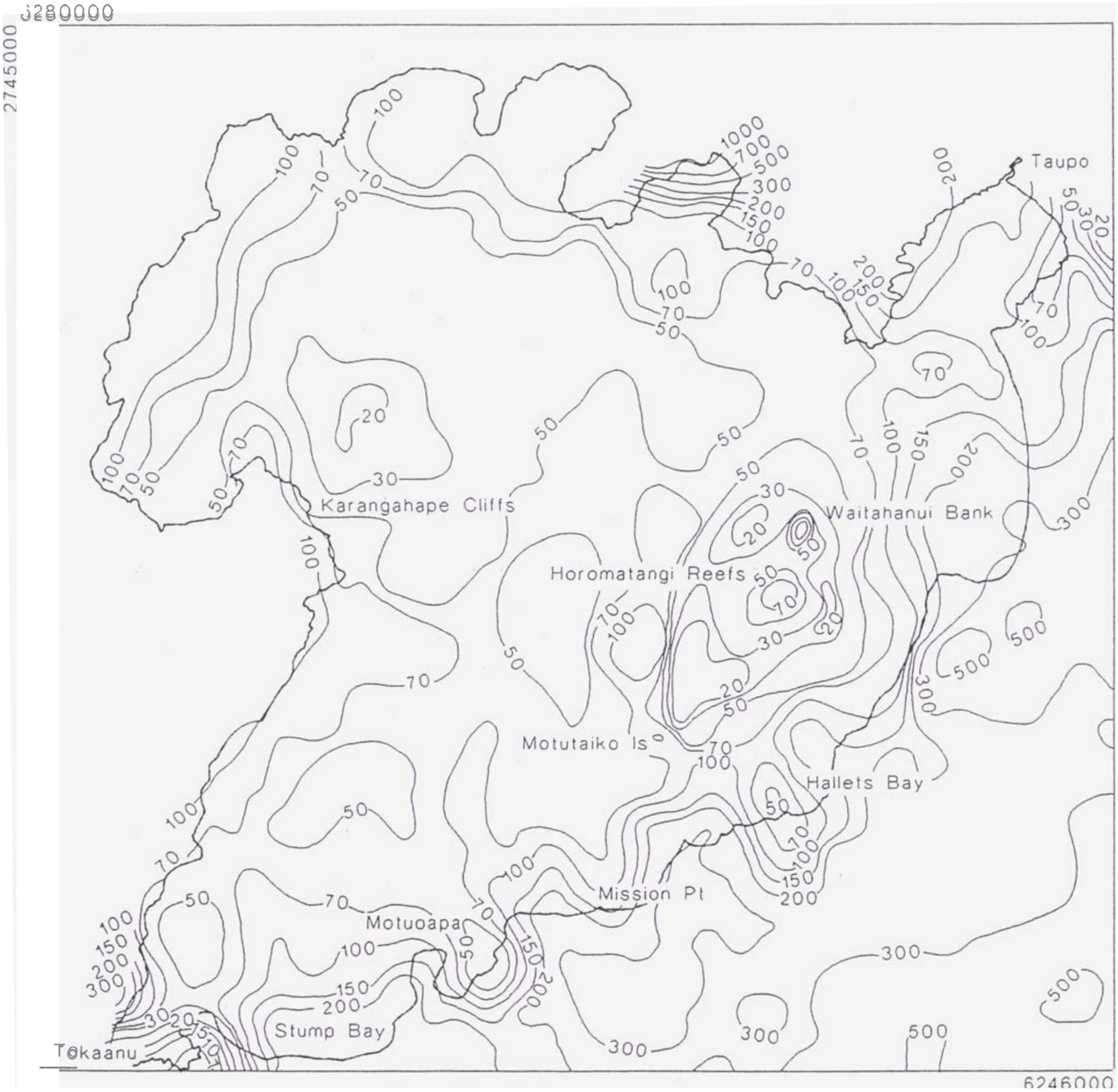

Figure 4. Apparent resistivity contour map of Lake Taupo. The contour interval is logarithmic with six contours per decade.

North Western Area

Resistivities in the north western part of lake are, except for the shallower areas, less than 50 Ωm. Within this region an area with apparent resistivity less than 30 Ωm occurs about 3km north east of the Karangahape Cliffs. No anomalously high heat flows were reported in this area by Calhaem (1973). However, Whiteford 1992, reports that this area has slightly higher than normal flows suggesting that a hydrothermal source for this anomaly cannot be entirely ruled out. Alternatively, the low apparent resistivity observed here may simply be the product of a greater thickness of clay rich sediments or an increased concentration of clays in the sediments.

Western Bay appears to be the western half of a collapse caldera that must have resulted from a large eruption centred somewhere within the northern part of Lake Taupo. The most obvious candidate being the eruption about 22000 years ago of the Oruanui Ignimbrite. It is thus tempting to make the analogy with the Horomatangi area and interpret the low resistivity as the signature of a hydrothermal system, possibly now largely extinct, that was active within the collapse structure. The analogy is even more striking if the large positive magnetic anomaly lying just to the north of this area, Roberts and Williams (1966), is interpreted as rhyolitic lavas that were extruded from the vent area and now lie buried beneath material from the Taupo eruption.

Tokaanu

The apparent resistivity map (Figure 4) shows the low resistivity associated with the Tokaanu geothermal field extending at least 1km north from shore line. However, the contours in this area are based entirely on a few Wenner measurements made on shore and the southern most waterborne line nearly 5km to the north. Given the interpolation distance and the smoothing used in the computer contouring process these contours should not be considered to be a reliable representation of the northern boundary of the Tokaanu geothermal field.

CONCLUDING REMARKS

The coincidence in position between the resistivity anomaly at Horomatangi and the most recent vent of the Taupo Volcano suggests the possibility that some of the other geothermal fields in the TVZ may also be located in or near the vent areas of other large eruptions. If the interpretation of the Horomatangi reefs acting as a plug is also correct then this model offers a plausible explanation for the occurrence of rhyolites at the margins of some of the geothermal fields e.g. the Karapiti rhyolite at Wairakei.

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