EXAMINATION OF HEAT FLOW AND RESISTIVITY VALUES AT THE BOUNDARIES OF THE GEOTHERMAL SYSTEM BENEATH LAKE TAUPO, NORTH ISLAND, NEW ZEALAND

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Both the heat flow and resistivity anomalies associated with the hydrothermal system near the Horomatangi reefs in Lake Taupo have abrupt boundaries. A simple thermal model of the boundary to the hydrothermal system, assuming only conductive heat transfer, cannot produce the abrupt horizontal rate of change of heat flow observed, and implies a non-conductive thermal regime. This suggests that cold groundwater adjacent to the hydrothermal system is being drawn into the hydrothermal system producing the abrupt change in heat flow. By analogy the narrow resistivity boundaries observed at several of the TVZ's geothermal fields may also mark areas where the cold groundwater is entering or is being entrained into the convecting geothermal fluids.

INTRODUCTION

The Taupo Volcanic Zone (TVZ) in the North Island, New Zealand (Figure 1) is characterised by extensive rhyolitic volcanism, associated ignimbrite eruptions and a large number of high temperature geothermal fields. The most recent ignimbrite eruption in the TVZ occurred about 1800 years ago from a vent near the eastern shore of Lake Taupo near the Horomatangi reefs (Wilson and Walker, 1986). A resistivity survey of Lake Taupo (Caldwell and Bibby, 1992) has outlined the extent of a hydrothermal system that now occupies the vent area of this eruption. Although in its present form the hydrothermal system can only have existed for the last 1800 years the resistivity anomaly associated with the system is similar to the anomalies found at other geothermal systems elsewhere in the TVZ. By applying marine heat flow measurement techniques to this system it possible acquire detailed heat flow data needed to investigate the physical processes occurring at the boundary to this hydrothermal system. Such investigations are much more difficult to undertake at the geothermal systems found elsewhere in the TVZ.

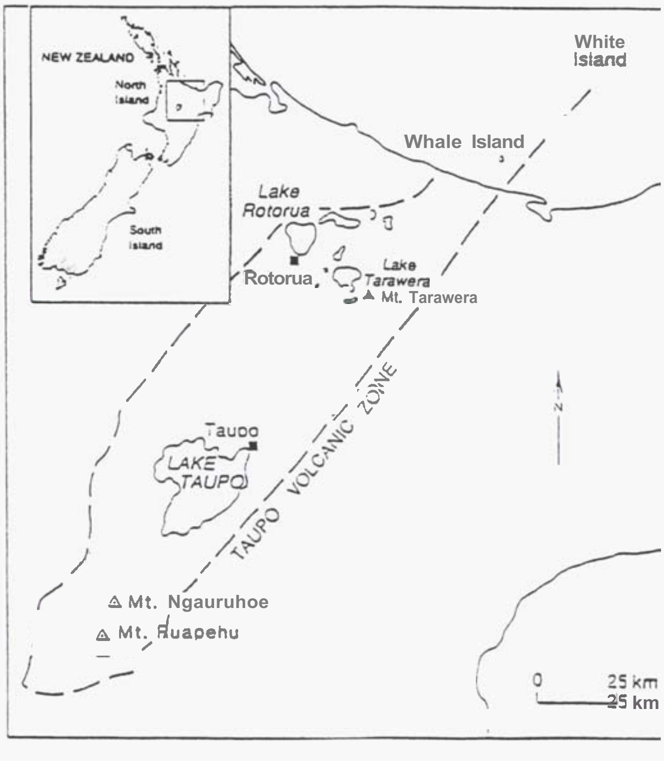


Figure I - Map showing the location of take Taupo and the Taupo Volcanic Zone, North Island of New Zealand.

RESISTIVITY

The extent of the hydrothermal system near the Horomatangi reefs became clearer after a waterborne resistivity survey (Caldwell and Bibby, 1992). A map showing the results of this survey is reproduced in Figure 3. The apparent resistivities were measured using an equatorial dipole-dipole array with each dipole of the array being towed behind separate small boats (Caldwell and Bibby, 1992). Individual measurements of apparent resistivity were made at 10m intervals and then averaged to give independent estimates of resistivity every 150 m. These are estimates were used to derive the contour map (Figure 3). The most prominent feature of the resistivity data is the low resistivity area that surrounds the Horomatangi reefs.

HEAT FLOW

The first investigation of the heat flow in Lake Taupo was made by Calhaem (1973) who measured conductive heat

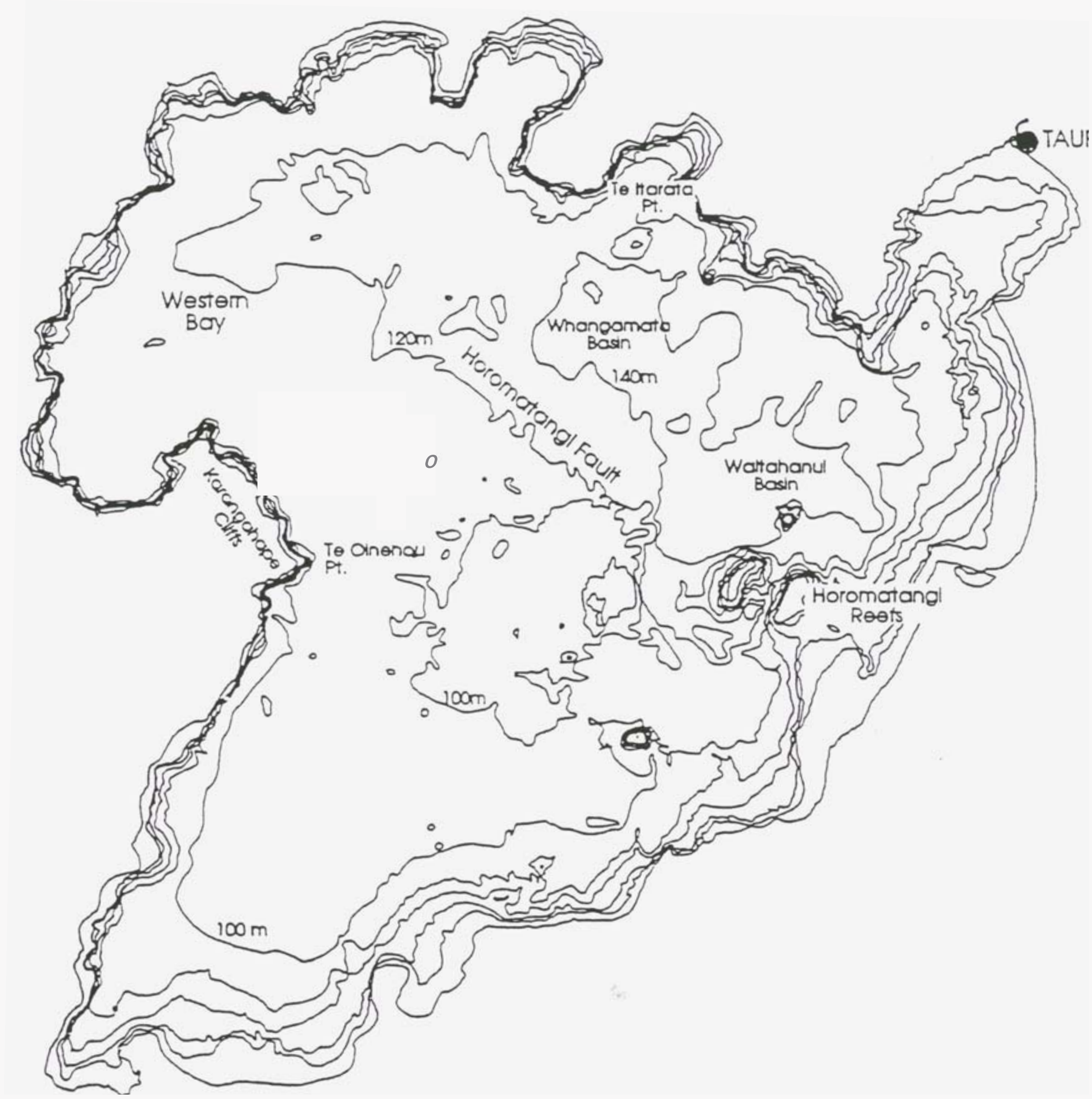


Figure 2 - Map showing the bathymetry (m) of Luke Taupo. The vent area of the Taupo eruption about 1800 b.p. lies in rhe region of the Horomatangi Reefs, Wilson and Walker(1986).

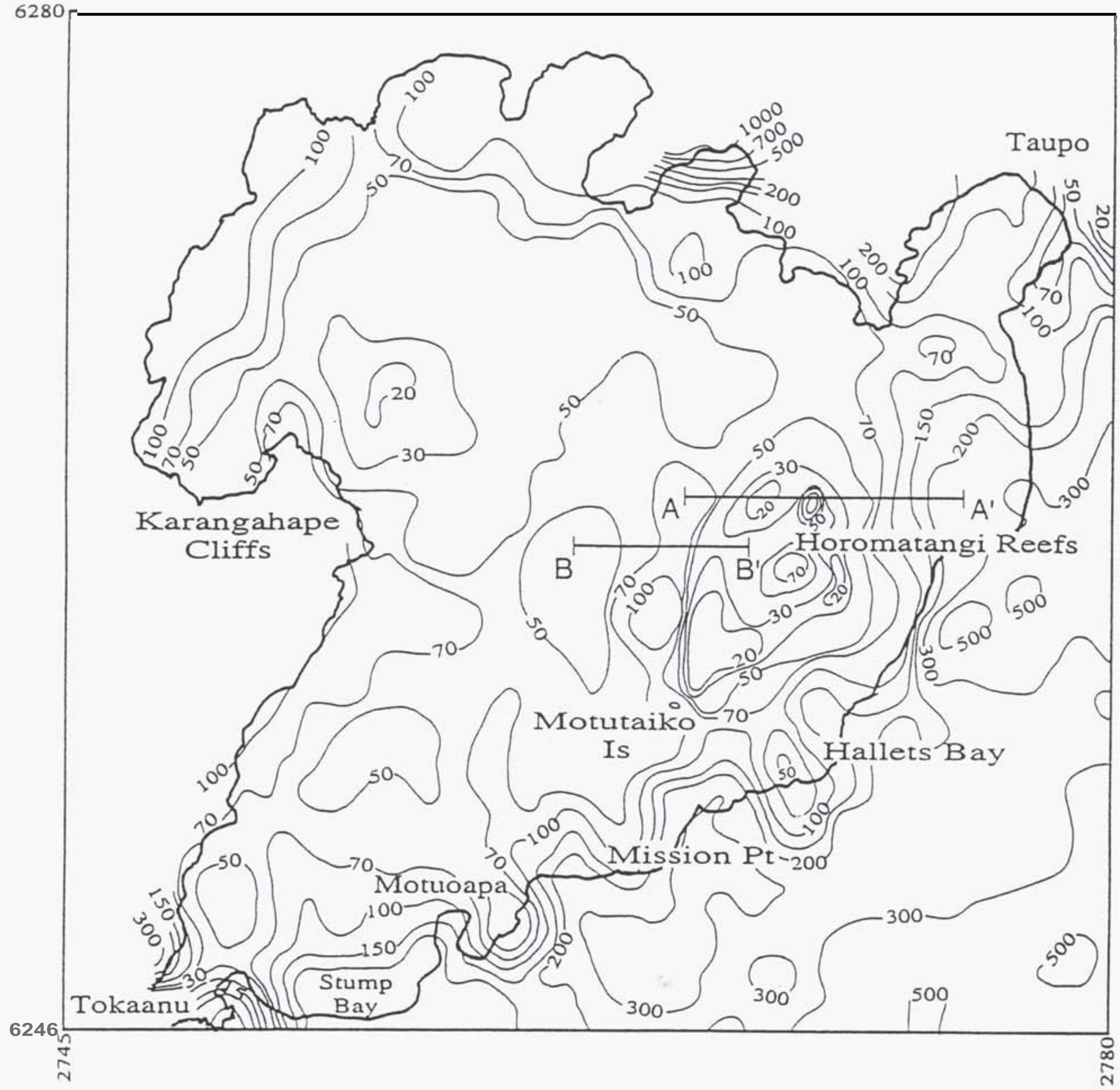
flow in the sediments at 63 sites scattered over the area of the lake. This survey identified four areas of abnormally high heat flows, the largest occurring near the Horomatangi reefs (Figure 2). Gas bubbles can also be observed at the lake surface this vicinity and were attributed by Northey (1983) to underlying geothermal activity.

The results from a recent heat flow survey at 76 sites using a 2 metre long temperature probe (Whiteford (1992, 1994) are shown in Figure 4. The values of heat flow are estimated to have an uncertainty of about 100 mW/m^2.

Although the distribution of heat flow measurements is sparse compared with the resistivity measurements, there is good agreement between the heat flow and resistivity maps. In particular, the area near the Horomatangi reefs and the less pronounced low resistivity anomaly north west of the Karangahape Cliffs have abnormally high heat flows. Also, the two heat flow measurements at the margins of the higher resistivity area at the centre of the Horomatangi low resistivity anomaly have intermediate values consistent with the higher resistivity. A less apparent but important feature of the heat flow results is the large area that has an abnormally low (<50 mW/m^2) heat flow. Low heat flows observed elsewhere in the TVZ have been attributed by Studt and Thompson 1969 to the downward flow of cold ground water that ultimately supplies the water discharged in the geothermal fields.

HEAT FLOW AND RESISTIVITY PROFILES

One of the characteristics of the resistivity anomalies associated with hydrothermal systems in the TVZ is the abrupt decrease in resistivity that occurs at the margin of the geothermal fields (for example Bibby et al., 1994). Two profiles showing the heat flow and resistivity along lines crossing the boundary of the hydrothermal system near the Horomatangi Reefs, are shown in Figure 5.



'igure 3 - *Apparent resistivity map of Lake Taupo (Caldwell and Bibby, 1992) showing the two lines (AA', BB') along which* ıe *profiles of resistivity and heat flows have been plotted in Figure 5 .*

'he locations of these lines, AA' in the north, and BB' in the outhwest (BB'), are shown in Figure 3.

'he heat flow measurements on the northern profile, AA' in 'igure 5a, all lie within 500m of the line along which the orresponding resistivity measurements were made, that is long the line midway between the two dipoles used for the esistivity measurements. The most prominent feature of the pparent resistivity data on this profile, Figure 5a, is the arrow peak in the centre of the profile. This feature in the esistivity data is due a lava pinnacle that occurs in the lake .oor (see Figure 2) about 2 lan north of the Horomatangi eefs, (Caldwell and Bibby, 1992). This profile is not erpendicular to the western boundary of the low resistivity one and the change in resistivity, from about 100 Ohm-m to ess than 50 Ohm-m, may be more abrupt than is suggested y the apparent resistivity values shown in Figure 5a. The hange in apparent resistivity at the western end of the rofile is mirrored in the heat flow values which rise abruptly from near zero to greater than 500 mW/m^2. In the east the heat flow values are too widely separated to determine whether not a similar abrupt change in heat flow occurs. Any such abrupt increase would also lie to the west of the obvious step that occurs in the apparent resistivity data.

The line of closely spaced heat flow measurements made to the south west of the Horomatangi reefs (Figure 4) unfortunately does not follow a line of resistivity measurements. Data from this line has therefore been projected onto the line of resistivity measurements (BB' in Figure 3) and is shown in Figure Sb. Although, the resistivity contrast at the boundary of the hydrothermal system is smaller on this line than that to the north and south the correlation between the rapid eastward increase in heat flow and decrease in resistivity in Figure 5b is again very good.

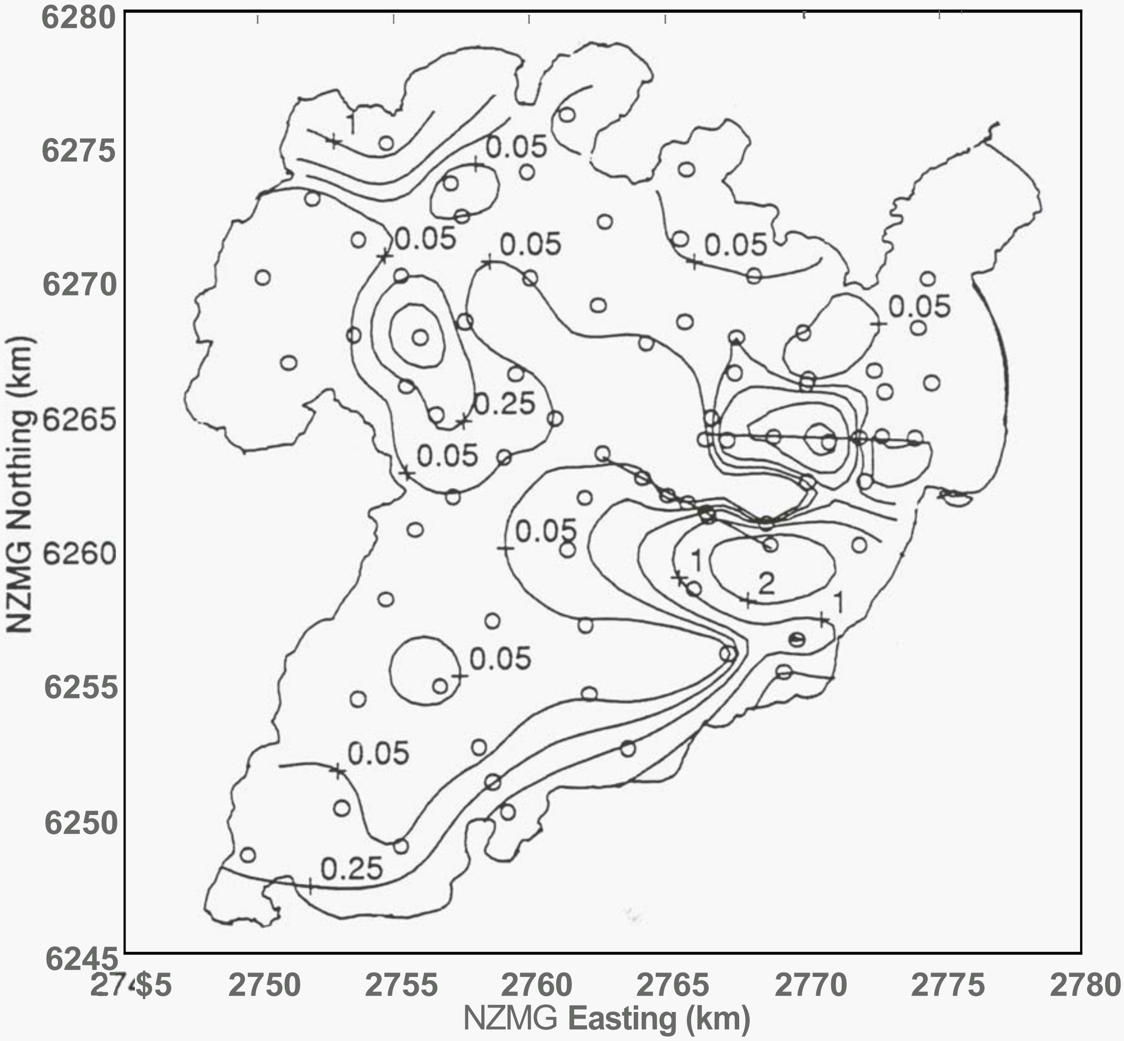


Figure 4 - Contoured heat flow values (W/m^2) for Lake Taupo. The contours are at 0.05, 0.25, 0.5, 1, & 2 (W/m^2). The positions of the heat flow values are shown as open circles. For reference the best fit straight lines through the heat flow measurements used in each of the two profiles in Figure 5 are shown.

DISCUSSION

In order to see if conductive heat transfer across the boundary of the geothermal system could produce the abrupt change the **observed** heat flow, the theoretical heat flow was calculated for a simple two-dimensional model of the hydrothermal system using a thermal modelling program (Lee, 1980). **A** cross section though this model and the calculated heat flow at the surface are shown in Figure 6. Constant temperature boundary conditions were imposed at the surface (10 "C) and bottom (200"C) at a depth of 5 km. Boundary conditions at the left and right edges of the modelled area assume that the horizontal heat flux is zero. An isothermal region, temperature 200 °C, extending from 0.2 km below the surface to the bottom of the model represents the coiumn of convecting fluids. The lake sediment covering the floor of the lake is represented by a 0.1 km thick layer of thermal conductivity 0.8 W/(m°C). Below this layer the thermal conductivity is assumed to be 2.5 W/(m°C). The very high heat flow (1150 mW/m^2) above the 200°C region drops rapidly as the boundary is crossed. **At** 0.5 km from the boundary the heat **flow has** decreased to less than 500 mW/m^2 but does not approach the background value for the model (91 mW/m^2) until about 3 km from the edge of the **200** °C isothermal region, Figure 6a.

The measured heat flow values, shown in Figure 6a, are plotted on the model profile. The location of the heat flow values relative to the boundary was determined by using the resistivity data to determine the position of the boundary of the geothermal system. The boundary **was** assumed to occur at the point at which the resistivity **first starts** to rise. **As** can be seen in Figure 6a the observed heat flow values decrease more rapidly than the results of the conductive model falling to very small values within a 1 km of the resistiviry boundary.

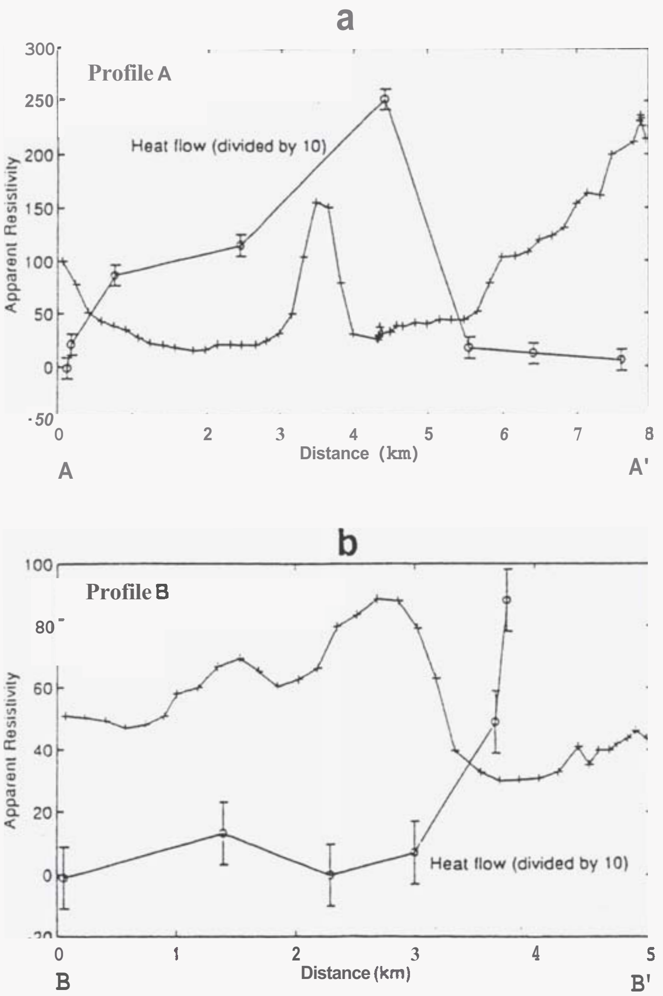


Figure 5 - Heat flow and resistivity values along the lines shown in Figure 3. The heat flow values, in mW/m² , have been divided by 10 so that they can be shown on the same graph as the apparent resistivity. Heat ***flow*** *error bars are 100 mW/m² . Figure 5a and Figure 5b* ***show*** *respectively the northern (AA') and southern (BB')profiles.*

The model demonstrates that the change in heat flow at the boundary of the hydrothermal system is too steep to be accounted for in terms of conductive heat transfer for a geologically reasonable choice of boundary conditions.

Over much of the lake floor the observed heat flows are small. The low heat flows observed suggest that a slow downward flow of water is occurring in these areas, as has been suggested for other regions in the TVZ (Studt and Thomson, 1969). To suppress a normal conductive heat flux, typically about 70 mW/m^2 for the New Zealand region, requires a downward flow equivalent to a few millimetres per year per unit area. The abrupt change in heat flow near the edge of the hydrothermal system, cannot realistically be accounted for in terms of conductive heat transfer and suggests that there is also a component of inflow into the hydrothermal system. **Thus,** rather than marking a permeability barrier, the narrowness of the boundary is evidence of the flow or entrainment of surrounding cooler water into the hydrothermal system.

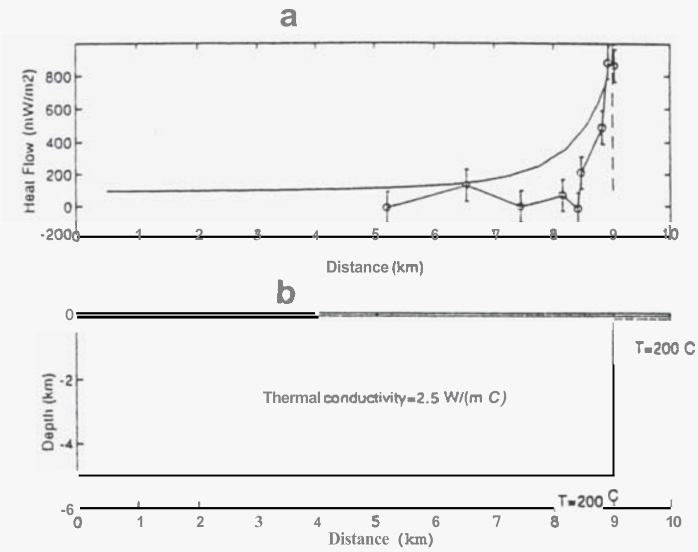


Figure 6 - Calculated and observed heat ***flow*** *are shown in Figure 6a as a function of distance from the hydrothermal system boundary (see text). Figure 6b shows the two dimensional conductive model used in the calculation.*

CONCLUSION

The rapid change in observed heat flow that takes place at the resistivity boundary marking the edge of the Horómatangi hydrothermal system suggests that the boundaries to the hydrothermal system are open to (lateral) fluid flow, and suggests that the margins **of** hydrothermal systems are not areas of low horizontal permeability. The permeability inside and outside this hydrothermal system in Lake Taupo may or may not be different.

Narrow resistivity boundaries have been observed at several of the geothermal fields in the TVZ, eg the southern margin to the Ohaaki geothermal field (Risk 1983) and the south western boundary to the Kawerau geothermal field (Allis et al. 1993). If our interpretation of the data from Horomatangi can generalised then sharp resistivity boundaries may **mark** areas in which cold ground water is being drawn into the geothermal field.

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REFERENCES

Allis, R.G., Christenson, B.W., Nairn, I.A., **Risk, G.F.** and White, S.P. (1993). The natural state of the Kawerau geothermal field. *Proc. 15th New Zealand Geothermal Workshop*, 227-233.

Bibby, H.M., Caldwell, T.G. and Risk, G.F. (1994). Resistivity evidence for an independent geothermal field at Reporoa. *Proc. 16th New Zealand Geothermal Workshop*, this volume.

Caldwell, T.G. and Bibby, H.M. (1992). Geothermal implications of resistivity mapping in Lake Taupo. *Proc. 14th New Zealand Geothermal Workshop*, 207-212.

Calhaem, I.M. (1973). Heat flow measurements under some lakes in the North Island, New Zealand. PhD Thesis. Department of Physics, Victoria University of Wellington, New Zealand.

Lee, T.C., Rudman, A.J., Sjoreen, A. 1980: Application of finite-element analysis to terrestrial heat flow. Department of Natural Resources, Indiana Geological Survey Occasional Paper 29, State of Indiana, USA. 53pp.

Northey, D.J. (1983). Seismic studies of the structure beneath Lake Taupo. PhD Thesis, Victoria University, Wellington, New Zealand.

Studt, F.E. and Thomson G.E.K. (1969). Geothermal heat flow in the North Island of New Zealand. *N.Z. J. Geol. Geophys. 12*, 673-683.

Risk, G.F. (1983). Delineation of geothermal fields in New Zealand using electrical resistivity prospecting. *Proc. 3rd biennial conference of the Australian Society of Exploration Geophysicists*, 147-149.

Whiteford, P.C. (1992). Evidence for geothermal areas beneath Lake Taupo from heat flow measurements. *Proc. 14th New Zealand Geothermal Workshop 1992*, 185-188.

Whiteford, P.C. (1994). Heat flow in the sediments of Lake Taupo, New Zealand. *Tectonophysics, Elsevier*, in press.

Wilson, C.J.N. and Walker, G.P.L. (1986). The Taupo eruption, New Zealand. I. General Aspects. *Phil. Trans. R. Soc. London.* A.314, 199-228.