Proceedings 18th NZ Geothermal Workshop 1996

THERMAL ACTIVITY BENEATH LAKE TARAWERA, NEW ZEALAND, OUTLINED BY TEMPERATURE MEASUREMENTS

P.C. WHITEFORD', D.J. GRAHAM[2] AND G.F. RISK'

[1] Kelbum Research Centre, IGNS, Wellington, NZ
[2] Wairakei Research Centre, IGNS, Taupo, NZ

ABSTRACT - Temperaturc soundings to ca. 2m dcpth have been made into the bed of Lake Tarawcra at 45 sites. Temperature differences between lake bottom and lm depth were determined by interpolation after correction for seasonal and measurement-related disturbances. Thermal activity is indicated by temperatures anomalies (elevated by up to 1^{o}C above lake floor temperature) in a zone close to the northern coast, and in another in the south of the lake near Lake Rotomahana. Slightly anomalous temperatures (by up to 0.36 ^{o}C) are found near the western shore of the lake. These temperature anomalies are smallcr than those of thermal areas under Lake Rotorua and Lake Rotomahana, survey previously.

INTRODUCTION

Lake Tarawera is situated in the Taupo Volcanic Zone (TVZ), North Island, New Zealand, about 18 km southeast of Rotorua City (Fig. 1). It is surrounded by five other lakes: Okataina, Okareka, Tikitapu, Rotokakahi and Rotomahana. The main geothermal and volcanic features in the vicinity lie on the south side of Lake Tarawera. Mt Tarawera, 4 km southeast of the lake, is an active volcano which last erupted in 1886 causing the loss of 108 lives. About 6 km southwest of the lake is the Waimangu thermal area which contains active thermal features such as hot or boiling pools, silica deposits, steaming cliffs, and hot ground. The Waimangu area and the western half of Lake Rotomahana, together, have a total natural heat output estimated to be 510 MW (Bibby et al., 1995), which classes them as a major geothermal system.

L. Tarawera covers an area of 41 km^2, has a maximum length of 11.4 km, a maximum width of 9.0 km, and a maximum depth of 87.5 m (Irwin, 1975). Most of the central lake is over 80 m deep (Fig. 2). At the eastern end the outlet of the lake flows into the Tarawera River. The only significant river discharging into the lake is the Wairoa Stream at the western side, but water from Lake Rotomahana (elevation 337 m) may seep through to Lake Tarawera (elevation 299 m), as Lake Rotomahana has no surface outlet. Lake Rotomahana is about 3 ^{o}C warmer than Lake Tarawera.

Present-day thermal activity occurs in three zones along the shorelines of Lake Tarawera (Nairn, 1989). In two of the zones, one on the northern shore near the southeastern arm of Lake Okataina, and the other in the east, activity is minor. The only intense surface activity occurs on the southern shore near Lake Rotomahana.

Waterborne resistivity measurements made in the shallow waters near the shore of Lake Tarawera (Bennie *et al.*, 1985) show low resistivities (10 to 30 Ωm) indicative of subsurface thermal conditions in the southern inlet. Bennie *et al.* note that this resistivity low is the northern part of the large area low associated with the Waimangu geothermal area. Resistivities of about 30 Ωm. were also measured in the part of the northern shore near the southeastern arm of Lake Okataina. Elsewhere around the edge of the lake resistivities are high (50 to 200 am).

The fist heat flow measurements in Lake Tarawera were made by Calhaem (1973). His 10 measurements showed zones of elevated heat flow in the southern inlet and in the northern part of the lake near Lake Okataina. Calhaem's temperature probe consisted of two temperature sensors

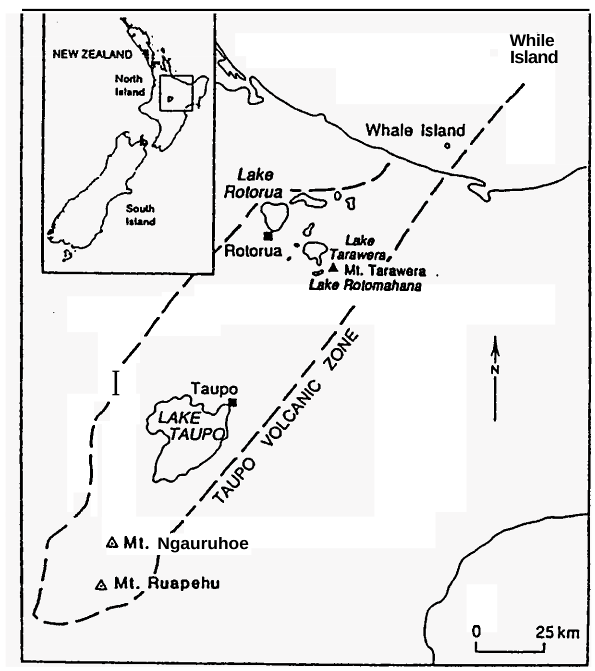

Fig. 1. Luke Tarawera lies within the Taupo Volcanic Zone in the North Island of New Zealand.

1.5 m apart, from which only a single temperature difference could be obtained. Neither the angle of penetration of the probe nor the bottom-water temperatures could be measured. Hence, it was not possible to correct for skew penetrations, and very difficult to estimate how deep the probe had penetrated into the sediments. Significant errors can be introduced if these parameters have values different from those assumed in the analysis.

In the present study, temperature profiles in the sediments at the bottom of Lake Tarawera were made to about 2 m depth at 45 sites. From these, the temperatures at a depth of 1 m in the sediments were interpolated. We have previously (1992) used the same technique for measuring temperature gradients and heat flow at Lake Rotomahana (Whiteford & Graham, 1993). The measurements were made using the marine technique (Langseth, 1965) in which a temperature probe (Fig. 3) is dropped from the lake surface and forced to penetrate into the sediments. After the temperatures have come to equilibrium, a (near) vertical temperature profile is measured by the fives temperature sensors along the probe. Thermal conductivities are also measured allowing heat fluxes to be calculated. But, at the time of preparing this manuscript, the thermal conductivities were not available, and hence calculations of heat flow must be left as the subject of a later paper.

Since we have used more up-to-date equipment and have a greater density of measurement sites than those of Calhaem (1973), we have been able to outline the temperature anomalies in more detail. Our temperature probe measured the depth of penetration, the lake-bottom temperature and the angle of repose of the probe, enabling corrections to be made for these parameters. During the 4 years prior to the measurements, bottom-water temperatures of the lake had been monitored, and variations of these temperatures were used to correct for the seasonal changes. The use of the actual lake bottom-water temperatures allows more accurate corrections for the seasonal variations to be made than can be obtained with a theoretical model of the variations, as used by Calhaem (1973).

Surveys of near-surface temperatures (usually 1 m depth) have long been used on land in the TVZ for finding and outlining thermal areas (Thompson et al., 1961; Thompson, 1968; Dawson et al., 1970; Allis, 1979a; Allis, 1979b). Temperatures of more than 1 °C above surface ambient at 1 m depth usually indicate thexmal activity while temperatures of over 50 °C above ambient occur in areas of intense thermal activity. Above about 70 °C the mode of heat transfer in the ground changes from conduction to convection (Allis, 1979b). At the Wairakei geothermal field, the 1 °C above ambient temperature contour encloses an area of 8.5 km^2 (Thompson et al., 1961), while at the Broadlands geothermal field there is also a significant area of elevated ground temperatures (Thompson, 1968). Since 1970, aerial infra-red surveying has superseded temperature surveying for mapping thermal ground, but this latter method is unsuitable over lakes except where the water is very shallow.

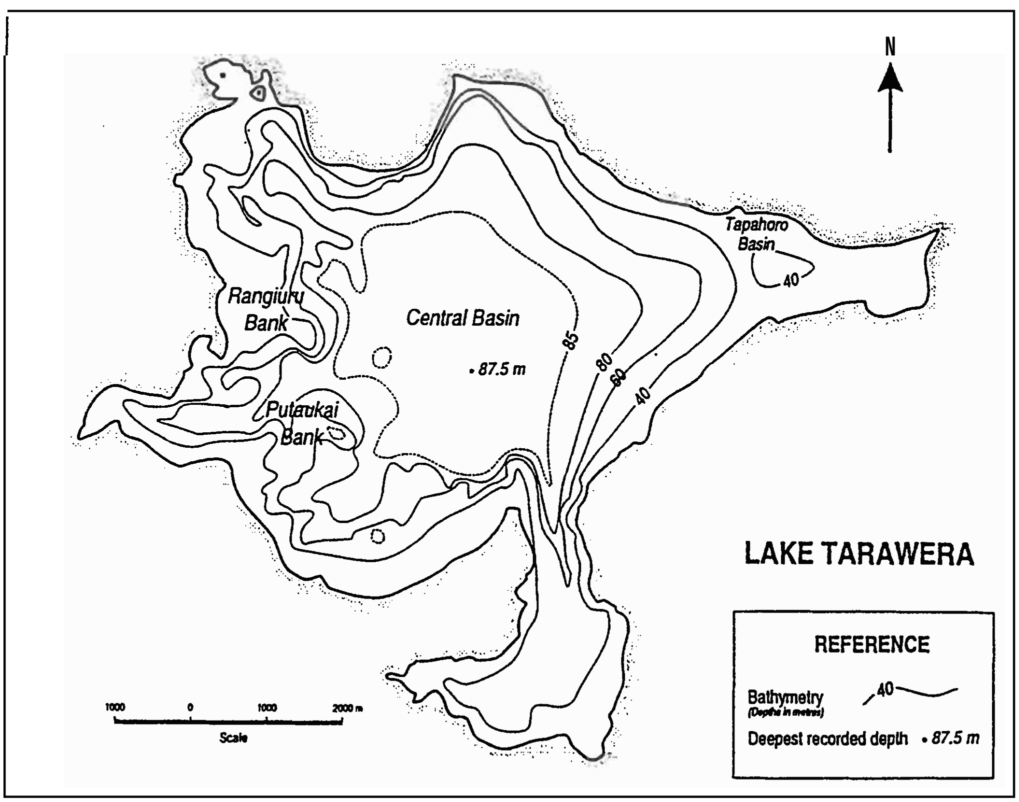

Fig. 2 . Map showing the bathymetry (in m) of Lake Tarawera.

TEMPERATURE PROBE

The temperature probe (Fig. 3) consists of a stainless-steel strength member, 2m in length, with a thin stainless steel tubing containing the temperature Sensors mounted parallel and alongside. Above this, there is a large diameter cylindrical steel case containing a water-tight recording instrument. The probe weighs 70 kg. Five Sensors within the stainless steel tubing measure the sediment temperatures, and a sixth, located above the cylindrical case, measures the bottom-water temperature. The temperatures are measured to an absolute accuracy of a few hundredths of a degree Celsius, but it is possible to resolve temperature differences of a few thousandths of a degree. Inside the case are two orthogonal tiltmeters which measure the angle of the probe relative to the vertical. This enables the vertical spacing between the sensors at the time of a measurement to be calculated using a correction based on the angle of repose and the spacing of the sensors along the probe. Measurements are stored in digital form in solid state memory within the instrument until the probe is brought on board the boat, and then the data are transferred to a computer for analysis and permanent storage.

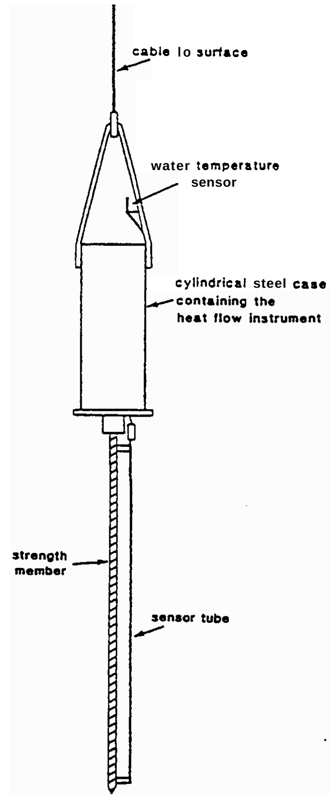

Fig. *3. Schematic diagram of the temperature probe.*

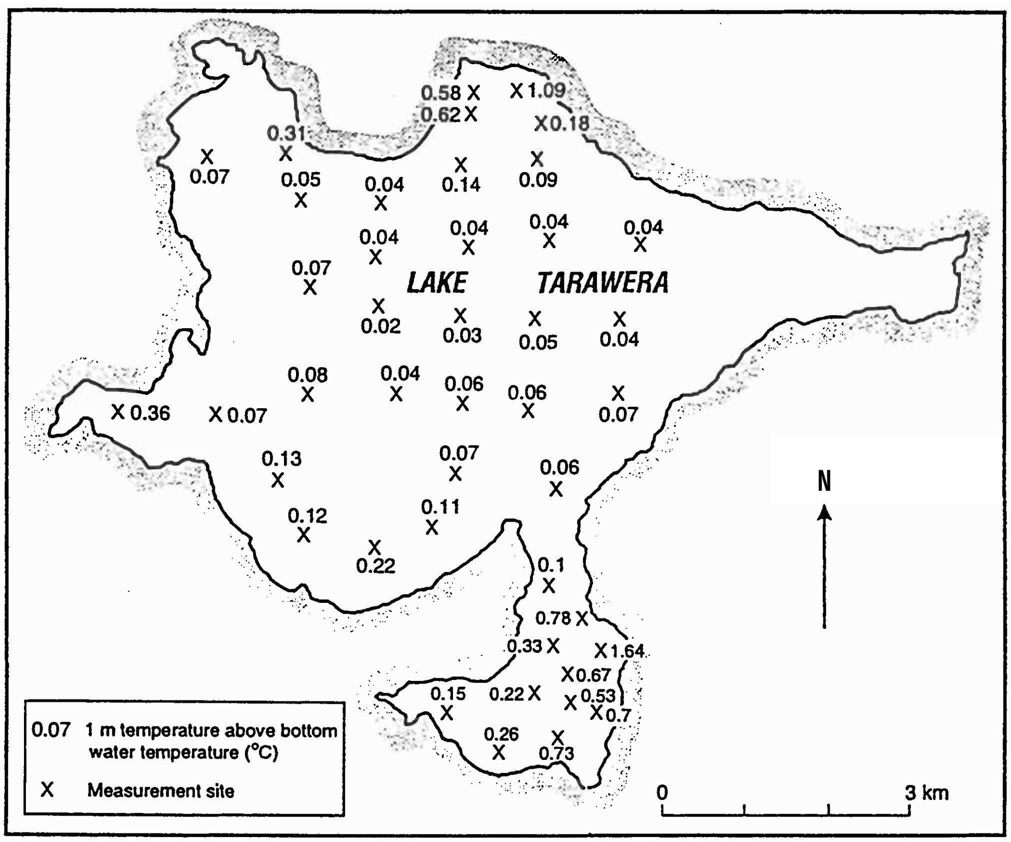

Fig. 4. Map showing temperature anomalies at I m depth, measured relative to bottom-water temperature.

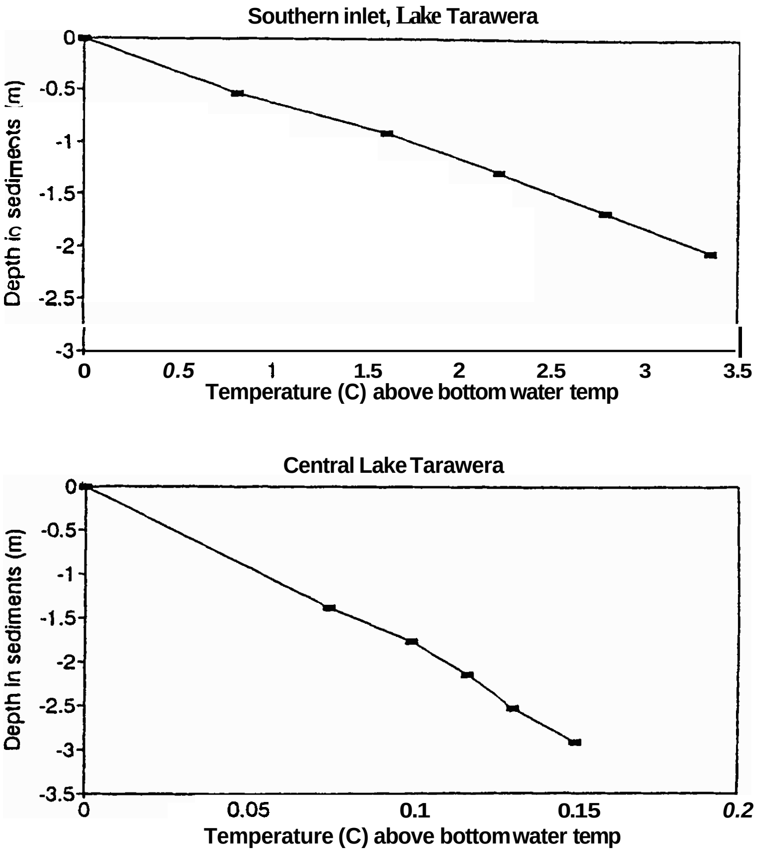

Fig. 5. *Typical temperature profiles through sediments at bottom of L. Tarawera. Temperatures are presented relative to bottom-water temperature.*

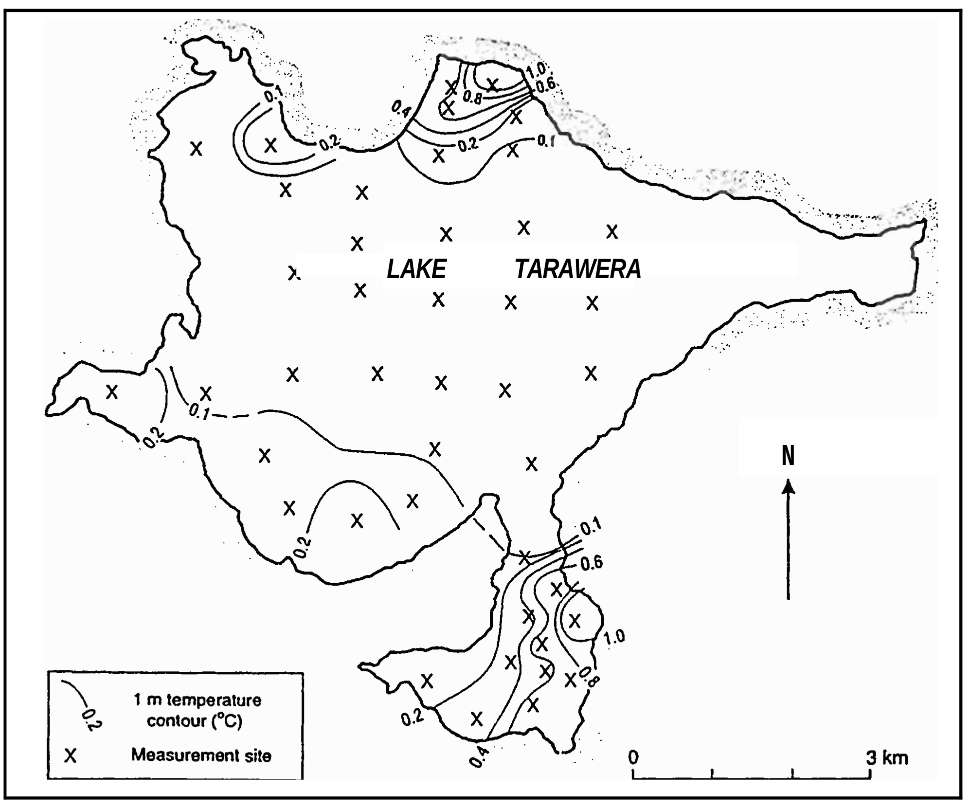

Fig. 6. *Contours of temperatures (in °C) at 1 m depth relative to bottom-water temperature. The contours are at 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0 °C.*

MEASUREMENTS

Temperature measurements were made between 19th and 23rd February 1996 from the 6-metre vessel ***Rukuwui*** at 45 sites (Fig. 4) distributed as uniformly as possible over the lake. The ***Rukuwui*** has a special derrick and a motorised winch with a mechanical clutch for lowering and raising the temperature probe. The location of each site was determined to an accuracy of about 40 m by a *Magellan* GPS navigation system mounted in the boat.

SEASONAL TEMPERATURE CORRECTIONS

The bottom-water temperatures of Lake Tarawera, like most similar lakes, vary seasonally, resulting in an annual temperature cycle. Jolly (1968) and Irwin (1968) noted that Lake Tarawera, like other lakes in the area, exhibits a distinct thermocline (i.e. has a layer of warm water near the surface) throughout spring, summer and autumn. The existence of this themocline was confirmed by our measurements. The bottom-water temperatures of lakes exhibiting such thermoclines usually reach a maximum in early winter, and a minimum at the end of winter (Irwin, 1968), thus giving an annual cycle which looks like a saw-tooth function (Calhaem, 1973). These temperature variations occur uniformly over the lake; at any one time the water at lake bottom is nearly isothermal (Jolly, 1968; Irwin, 1968), as our measurements confirmed. As part of our programme of measurements, the annual cycle of bottom-water temperature was determined by repeat measurement at two sites in the lake throughout the 4 years prior to measuring the temperature profiles. The annual temperature cycle propagates down into the sediments as an attenuating temperature wave. The correction needed to obtain the temperatures which would have existed in the absence of the seasonal temperature cycle was calculated at each site using Fourier analysis of the annual temperature cycle (Whiteford, 1992).

The temperatures were also corrected for deviations of the attitude of the probe from the vertical. Then, the temperatures at 1m depth in the sediments were obtained to an accuracy of better than ± 0.01 °C by interpolation, using a least squares method. The differences between the temperatures at 1m depth and those at the lake bottom, rounded to the nearest 0.01 °C, are plotted for in Fig. 4.

RESULTS

Two temperature profiles through the sediments, typical of the data, are shown in Fig. 5. One was measured at the site in the southern inlet where the highest 1m temperature was recorded (1.64 °C above bottom-water temperature, Fig. 4), and the other in the center of the lake where the 1m temperature is 0.05 °C above bottom-water temperature (Fig. 4). It can be seen on these profiles that temperature varies nearly linearly with depth, as expected for steady-state conductive flow.

At many sites, the probe penetrated into the sediments by more than the 2 m length of the temperature extension, thus burying part of cylindrical steel case. The deepest temperature sensor was sometimes as deep as 3.0 to 3.5 m. For example, at the site in the center of the lake, the deepest sensor was 3.0 m deep (Fig. 5).

The temperatures at 1m depth over most of the central part of the lake lie between 0.04 and 0.07 °C above bottom-water temperature (Fig. 4). Since there is little or no thermal activity in this part of the lake, these values provide a background temperature level. The temperatures are plotted in Fig. 6 as contours ranging from 0.1 to 1.0 °C above bottom-water temperature. Temperature differences above about 0.1 °C appears anomalous and may indicate thermal conditions in the bed of the lake. Temperatures above 0.1 °C occur in the south-western part of the lake near the shore, in the southern inlet and near the northern shoreline adjacent to the southeastern arm of Lake Okataina. The highest 1m deep temperature anomalies (ca. 1.0 °C above ambient) occur at the eastern sides of the latter two areas.

DISCUSSION

The temperatures anomalies measured at Lake Tarawera at 1m depth range from 0.02 °C to 1.64 °C. An area of about 9 km^2 (22% of the lake) showed temperatures anomalies greater than 0.1 °C. These measurements confirm the presence of significant thermal activity beneath Lake Tarawera, as first reported by Calhaem (1973) and outline in better detail the two main areas of activity. A third area with elevated temperatures is revealed by this survey along the south and southwest of the lake where Calhaem's measurements gave little detail.

The areas of elevated 1m depth temperatures approximately coincide with the values of low resistivity measured by Bennie *et al.*, (1985). Since no resistivity measurements have been made in the deep water of Lake Tarawera the two data sets can be compared only in the shallow water near the lake edge and on land.

The highest 1m temperatures in Lake Tarawera (ca 1.6 °C above bottom-water temperature) are not as high as those observed in Lake Rotorua (4.1 °C; Whiteford, 1992), and Lake Rotomahana (37.8 °C; Whiteford & Graham, 1993). This indicates that the geothermal areas beneath Lake Tarawera are not as vigorous as those beneath Lakes Rotorua and Rotomahana.

The 1m deep temperature beneath a lake floor cannot be compared directly with the land based 1m temperature surveys because of differences between the two physical environments. With the land measurements, pressure at 1m depth is close to 1 atmosphere and the ground is often not be saturated with water, whereas the sediments at the bottom of the lake, at depths of 80 to 100 m below the surface, are at about 10 atmospheres pressure, and will be completely water-saturated. This high water content affects the thermal conductivity and diffusivity and thus alters the conduction characteristics (Dawson et. al., 1970).

At 1m depth in thermal ground on land, the mechanism of heat transfer changes from conduction to convection (by vapour) at a temperature of about 70 °C above ambient (Allis, 1979b), whereas in the lake, the sediments tend to act as an impermeable layer impeding convection; thus conduction is likely to persist at temperatures higher than 70 °C. At all the sites, including the hot areas, linear temperature gradients were found, confirming conductive conditions. If significant convection were occurring, very small and non-linear temperature gradients would be expected.

A comparison of the 1m deep temperatures from Lake Tarawera with those from previous land-based surveys shows significant differences. At the Wairakei geothermal field the range of temperatures encountered at 1m depth was greater than at Lake Tarawera, with the highest temperatures reaching close to boiling point, i.e. 100°C (Thompson et al., 1961). An area of 8.5 km^2 was found with temperatures over 1°C above ambient surface temperature. At the Ohaaki (Broadlands) geothermal field, Thompson (1968) shows large areas enclosing within temperature contours at 5°C and 10°C above ambient surface temperature. Thus, as expected, the temperatures in 1m depth in these land based fields are significantly greater than those at the bed of Lake Tarawera.

The zones of anomalous 1m depth temperatures in Lake Tarawera indicate the existence of thermal conditions beneath the lake. The anomalous zone of slightly elevated temperatures in the southern arm of the lake appears to be an extension the Waimangu-Rotomahana thermal system. But, since the temperatures are only a few degrees above background this region appears to be a peripheral part of the thermal system.

The temperature anomaly in the northern part of Lake Tarawera was first noted by Calhaem (1973) and appears related to thermal phenomena is the region described by Nairn (1989). The nature and extent of this thermal activity appears to be little known and warrants further investigation.

ACKNOWLEDGMENTS

The writers wish to thank H.M. Bibby for helpful discussions, and Carolyn Hume and Michelle Fraei for preparation of diagrams. This paper is IGNS contribution No. 966. The work was supported by funding from the Foundation for Science, Research and Technology.

REFERENCES

Allis, R.G. (1979a). Thermal history of the Karapiti Area, Wairakei. ***Report*** 137. Geophysics Division, D.S.I.R., Wellington, New Zealand.

Allis, R.G. (1979b). Heat flow and temperature investigations in thermal ground. ***Report*** 135. Geophysics Division, D.S.I.R., Wellington, New Zealand..

Bennie, S.L., Stagpoole, V.M. and Bibby, H.M. (1985) Waterborne resistivity measurements in the Rotorua lakes area of New Zealand. ***Report*** 206. Geophysics Division, D.S.I.R., Wellington, New Zealand.

Bibby, H.M., Glover, R.B. and Whiteford, P.C. 1995. The heat output of the Waimangu, Waiotapu-Waikite and Reporoa geothermal systems (NZ): Do chloride fluxes provide an accurate measure? ***Proceedings of the 17th New Zealand Geothermal Workshop 1995***, 91-97.

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

Dawson, G.B. and Dickinson, D.J. (1970). Heat flow studies in thermal areas of the North Island of New Zealand. ***Proc. U.N. Symp. on the development and utilisation of geothermal resources,*** Pisa, 22 Sept - 1 Oct 1970. vol. 2, pp 466-473.

Irwin, J. (1968). Observations of temperatures in some Rotorua lakes. ***N.Z.J. Marine & Freshwater Research,*** 2, 591-605.

Irwin, J. (1975). Checklist of New Zealand lakes. ***New Zealand Oceanographic Institute Memoir*** 74, New Zealand Department of Scientific and Industrial Research, Wellington. New Zealand.

Jolly, V.H. (1968). The comparative limnology of some New Zealand lakes. ***N Z J. Marine & Freshwater Research,*** 2, 214-259.

Langseth, M.G. (1965). Techniques of measuring heat flow through the ocean floor. In ***Terrestrial Heat Flow,*** W.H.L. Lee, editor, Geophysical Monograph Series number 8, American Geophysical Union, pp 58-77.

Nairn, I.A. (1989). Geology of Mount Tarawera, Geological Map of New Zealand, 1:50 000, Sheet V16 AC, New Zealand Geological Survey, D.S.I.R., Lower Hutt, New Zealand.

Thompson, G.E.K., C.J. Banwell, G.B. Dawson and Dickinson, D.J. (1961). Prospecting of hydrothermal areas by surface thermal surveys. ***United Nations Conference on New Sources of Energy,*** G/54, 25 pages.

Thompson, G.E.K. (1968). Ground temperatures at a depth of one metre. ***Report*** 49. Geophysics Division, D.S.I.R., Wellington, New Zealand.

Whiteford, P.C. (1992). Heat flow in the sediments of Lake Rotorua. ***Geothermics,*** vol. 21, pp. 75-88.

Whiteford, P.C. and Graham, D.J. 1993. A thermal area beneath Lake Rotomahana outlined by sediment temperature measurements. ***Proceedings of the 15th New Zealand Geothermal Workshop*** 1993, 213-217.