A THERMAL AREA BENEATH LAKE ROTOMAHANA OUTLINED BY SEDIMENT TEMPERATURE MEASUREMENTS

P.C. WHITEFORD[1] AND D.J. GRAHAM[2]

[1]Institute of Geological and Nuclear Sciences Ltd., Wellington
[2]Institute of Geological and Nuclear Sciences Ltd., Wairakei

Abstract - Temperature measurements made at a depth of 1 m in the sediments at the bottom of Lake Rotomahana in October 1992 showed elevated temperatures in the south-western half of the lake and normal temperatures in the north-eastern half. Temperatures greater than 1 ^{o}C above bottom water temperature occur over an area of 4.3 km^2, which is just over half of the lake: Within this anomaly, temperatures of greater than 5 ^{o}C above bottom water temperature occur in two areas, one in the west which is contiguous with the thermal activity on the shore, and the other in the southern part of the lake which appears to be a separate entity. The 1 m temperature measurements confirm the existence of a significant area of thermal activity beneath Lake Rotomahana.

INTRODUCTION

Lake Rotomahana is situated within the Taupo Volcanic Zone of the North Island New Zealand about 22 km southeast *of* Rotorua (Fig I). To the 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, and is a well known tourist spot for viewing thermal activity. Five km to the northeast is the Tarawera volcano which erupted in 1886 causing the **loss** of 108 lives.

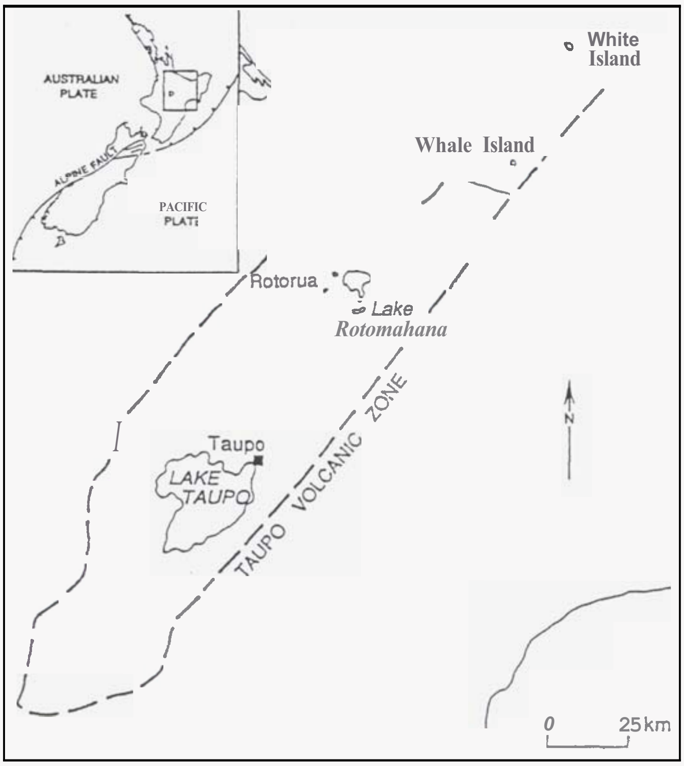

Fig 1. Map showing the location of Lake Rotomahana in the North Island of New Zealand.

Before 1886, there were two small lakes in the area now occupied by Lake Rotomahana (Lakes Rotomahana and Rotomakariri), and Rotomahana was the most intensely active hydrothermal field in the Rotorua region (Scott 1992, Nairn 1989). During the Tarawera eruption a 17 km long fracture formed extending from Mt Tarawera through Lake Rotomahana to the Waimangu thermal area. Violent steam and lava eruptions deepened and enlarged these two small lakes to form Rotomahana Crater, which was the site of vigorous steam emission until it filled with water to form Lake Rotomahana as it is now. The famous Pink and White Terraces were destroyed in the 1886 eruption and Lake Rotomahana now covers the sites of these terraces.

Lake Rotomahana has no outlet, and the lake level increases noticeably after rainfall. The lake covers an area of 7.95 km^2 , has a maximum length of 6.2 km and width of 2.8 km, and a maximum depth of 125 m (Irwin, 1975). The lake bathymetry is show in Fig 2.

Present-day thermal activity near Lake Rotomahana occurs mainly along the western shore of the lake where there are extensive tracts *of* altered ground, fumaroles, boiling springs, geysers, and also along the southern shore of the lake where minor hydrothermal activity in the form of warm and hot springs occur close to lake level (Nairn 1989). Activity close to the lake fluctuates with lake level. Although Nairn (1989) reports large upwellings of hot water in the lake 10-20 m offshore as indicating the locations of major submerged hot springs, no upwellings were observed during the execution of this survey. In the eastern part *of* the lake there is no surface thermal activity apart from a discharge of cold gas rising through the lake at one spot.

Jolly (1968) noted that the lake was 3 ^{o}C warmer than nearby Lake Tarawera (I km to the north), and attributed this to the explosive origin of the lake but the actual heat source was not investigated. Jolly (1968) found no significant spatial variation in bottom water temperatures. Irwin (1968) however observed high water temperatures at the lake bottom at three sites in water about 80 m deep in the southern part of the lake (Temperatures of 23.3 °C, 23.9 °C, 37.7 °C, see Fig 2 for location of the sites). Isothermal water from 1 m above the bottom to within **40** m of the surface. At 60 other measurements sites, distributed with even and relatively dense coverage, the water was isothermal (15.8 °C) from a depth of **40** m to the bottom. Irwin (1968) also noted that lake temperature was **4** to 5 °C higher than similar nearby lakes, which he attributed to local heat input from the lake floor.

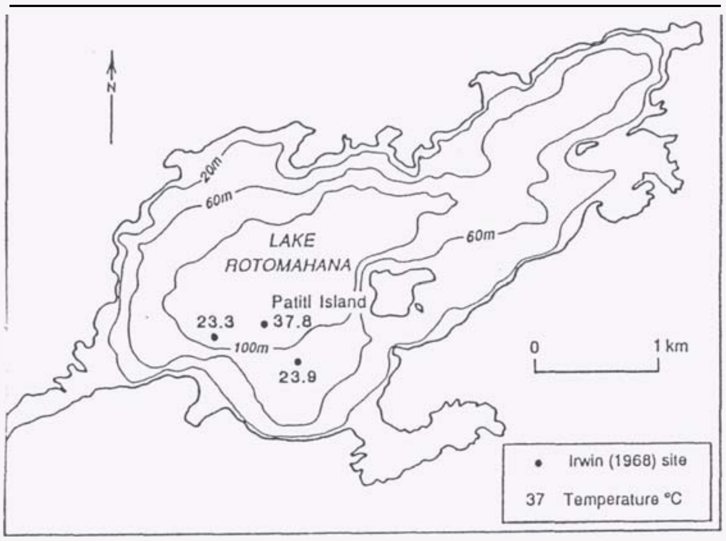

***Fig* 2.** *Map showing the bathymetry (m) of Lake Rofomahana, and showing the location of the three sites where Irwin **(7968)** measured high bottom water temperatures. The temperatures are also shown.*

Waterborne resistivity measurements made in shallow waters near the shore (Bennie et al. 1985) show low resistivities (2 to 11 ohm.m) west of Patiti Island, and higher resistivities (16 to 56 ohm.m) east of Patiti Island. The low resistivities are indicative of subsurface thermal conditions. Resistivities of less than 10 ohm.m cover an area comprising the lake west of Patiti Island and the Waimangu thermal area for a distance of 3 km south-west of the lake. Bennie et al (1985) refer to this low resisitivity area as the Waimangu Geothermal field.

In the present study, a series of temperature measurements were made in the bottom sediments of Lake Rotomahana to delineate areas having temperatures above ambient, which may indicate the presence of thermal activity. The measurements were made in the lake-bottom sediments using the marine technique (Lanseth, 1965) in which a temperature probe is dropped and forced to penetrate into the sediments and a (near) vertical temperature profile measured. At the time of preparing this manuscript the measured values of thermal conductivities of the sediments were not available, and hence the calculation of heat flow is not possible. However calculation of heat **flows** will be the subject of a later study.

The method of measuring temperatures just below the surface (usually 1 m depth), is a technique that has been used quite widely in the Taupo Volcanic Zone to delineate near-surface thermal areas (Thompson et al 1961, Thompson 1968, Dawson et al 1970, Allis 1979a, Allis 1979b). Temperatures of more than 1 °C above ambient at a depth of 1 m are common in thermal areas 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). The 1 m temperatures are commonly presented as temperature contour maps. At the Wairakei Geothermal Area in 1960 the 1 °C above ambient temperature contour enclosed an area of 8.5 km^2 (Thompson et al 1961) while at the Broadlands Geothermal Area in 1967 the area of elevated ground temperatures was less (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.
While the 1 m temperatures from the bottom of the lake cannot be compared directly with the 1 m temperatures obtained on land because of the different physical environment, both outline the areas with elevated temperature in the same manner.

Temperature Probe

The temperature probe (Fig 3) consists of a stainless-steel strength member, 2m in length, with thin stainless steel tubing containing the temperature sensors mounted parallel and alongside. Above this is a large diameter cylindrical steel case containing a water-tight recording instrument. The probe

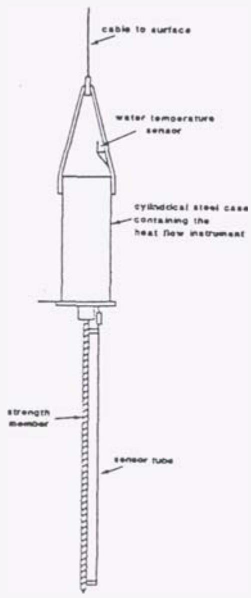

Fig* 3. *A *schematic diagram of the temperature probe.*

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 Celcius but it is possible to resolve 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 the measured angle of penetration and the spacing of the sensors in 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.

MEASUREMENTS

Temperature probe measurements were made between 21 to 30 October 1992 at 28 sites (Fig 4) distributed as uniformly as possible over the lake . The measurements were made from a 5 m runabout boat, which utilised a special derrick and motorised hydraulic winch 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 which was mounted in the boat.

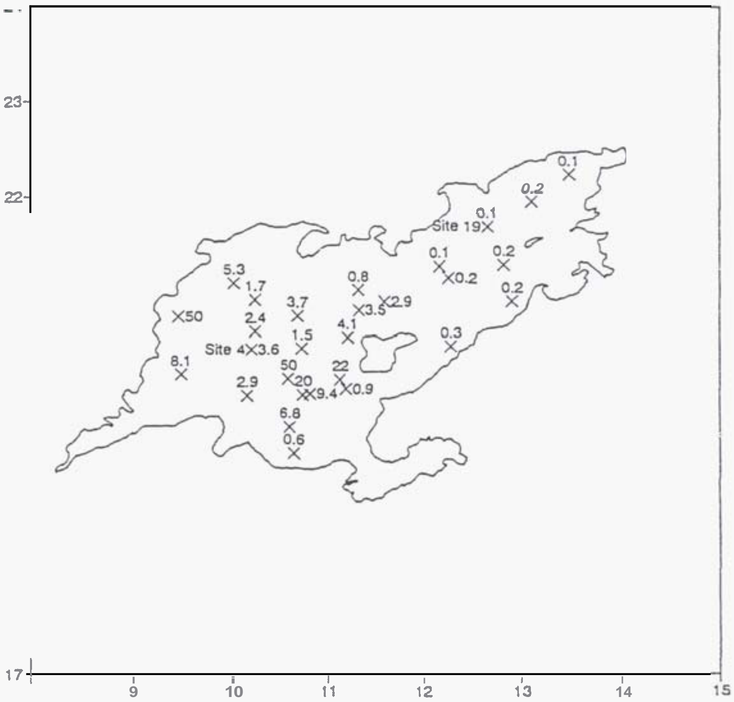

Fig 4. Map showing the location of the measurement sites in Lake Rotomahana and temperatures above bottom water temperature (°C) at 1 m depth. The two sites referred to in Fig 5 (sites 4 and 79) are numbered. The axes show the NZMS262 map grid wifh tick marks at 1 km intervals.

SEASONAL WATER TEMPERATURE CORRECTIONS

The bottom water temperatures of Lake Rotomahana, like most similar lakes, vary seasonally resulting in an annual temperature cycle. Jolly (1968) and Irwin (1968) noted that Lake Rotomahana exhibits a distinct thermocline (i.e. has a layer of warm water near the surface) throughout spring, summer and autumn. and this was also observed in measurements reported here. The bottom water temperature of lakes which exhibit a distinct thermocline usually has 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). This annual bottom water temperature change occurs uniformly over all of the lake, as at any one time the lake bottom waters are close to isothermal (Jolly 1968, Irwin 1968), as was confirmed in these measurements. This annual temperature cycle is conducted down into the sediments as an attenuating temperature wave which changes the sediment temperatures. This change is uniform over the lake and does not alter the temperature pattern obtained from a 1 m temperature survey, however the absolute values of temperature are altered. To obtain the sediment temperatures which would have existed in the absence of the annual bottom water temperature cycle a correction was calculated using Fourier analysis of the annual cycle (Whiteford 1992) and applied to the sediments temperatures. The correction factor, calculated for the time of the measurements, was 0.4 °C. The bottom water temperature at the time of the measurements was 12.8 °C.

RESULTS

After the measured sediments temperatures were corrected for annual bottom water temperature changes, and for non-vertical penetration of the temperature probe into the sediments, the temperatures at a depth of 1 m in the sediments were obtained by interpolation using a least squares method from the sediment temperature profile to an accuracy of better than $\pm$0.1 °C. The temperature above bottom water temperature at a depth of 1 m rounded to the nearest 0.1 °C is plotted for each site in Fig 4.
Two typical sediment temperature profiles are shown in Fig 5, one for a site in a thermal area where the deepest probe measured 11 °C above bottom water temperature (site 4, Fig 4), and the other in an area which was not thermal where the deepest sensor measured only 0.37 °C above bottom water temperature (site 19, Fig 4). At many sites the cylindrical steel case of the temperature probe penetrated into the sediments as well as the 2 m probe, and the deepest sensor was more than 2 m deep; for example the deepest sensor at site 4 (Fig 5) penetrated to just over 3 m and that at site 19 *to* 2.5 m. It can be seen that these profiles are close to linear.

The 1 m depth sediment temperatures are plotted on a map in Fig 6 as contours at 0.5,1,2,5, and 10 °C above bottom water temperature. In the north-eastern half of Lake Rotomahana temperatures are mostly about 0.1 °C above bottom water temperature, which are approximately normal temperatures, i.e. the value expected when there is no thermal activity. In the south-western half temperatures are all above normal, with most being well above normal. In two areas, temperatures in excess of 5 °C above bottom water temperature occur, one in the southern part of the lake to the south-west of Patiti Island, and the other by the western shore. Temperatures of about 50 °C

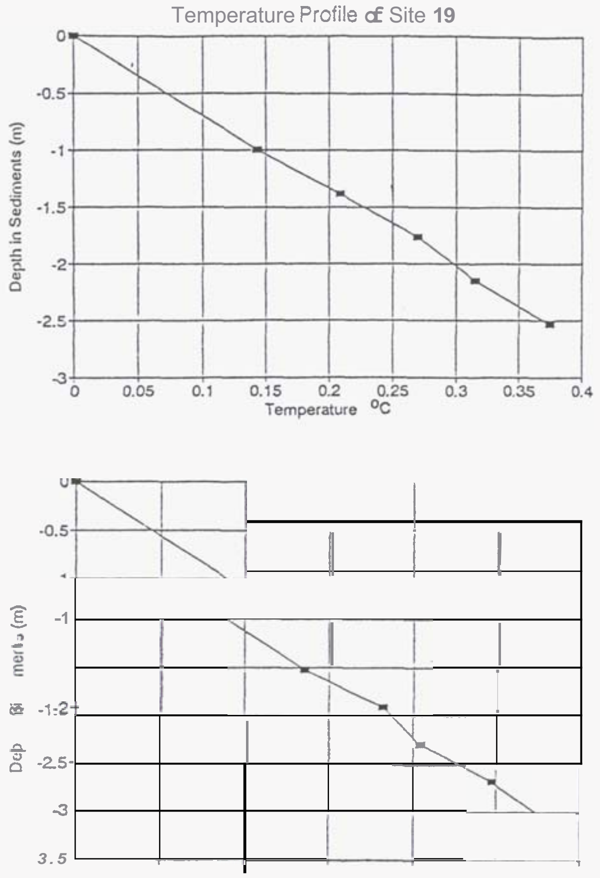

Fig 5. Typical sediment temperature profiles, relative to bottom water temperature, measured by the temperature probe in Lake Rotomahana.

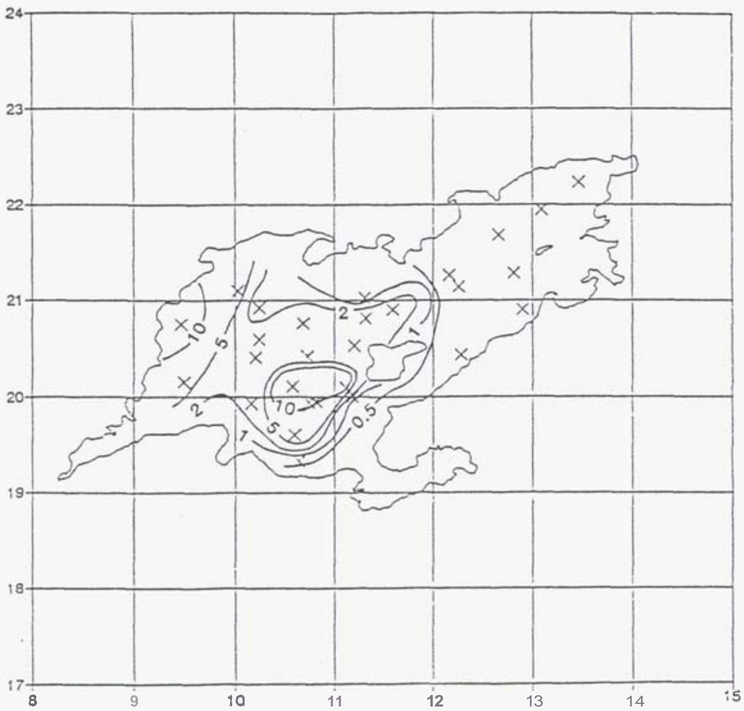

Fig 6. Contoured temperatures (°C) above bottom water temperature at a depth of 1 m in the sediments of Lake Rotomahana. The contours are at 0.5,1,2,5,&10 °C. The axes show the NZMS262 map grid.

above bottom water temperature were in the centre of each of these two areas. However the temperatures at these spots may be even higher than 50 °C above bottom water temperature because of larger errors in measuring such high temperatures; the deeper sensors of the temperature probe went offscale and the 1 m temperature was estimated by extrapolation of temperatures measured by the shallow sensors.

DISCUSSION

The temperatures measured at Lake Rotomahana range from normal (about 0.1 °C) to 50 °C above bottom water temperature, and higher temperatures probably occur but were not measured because the temperature recorder went off scale. An area of 4.3 km^2 was enclosed by the 1 ° (above bottom water temperature) contour, which is just over half of the area of the lake.

These temperature measurements confirm the presence of thermal activity beneath the south-western half of Lake Rotomahana. This area of elevated temperatures approximately coincides with the deep crater formed in the 1886 eruption and which is now the southwestern part of Lake Rotomahana This was also the site of the previous Lake Rotomahana, which, presumably, originated in a crater formed during an earlier eruption. Hence it is likely that the thermal activity has been in this locality for many centuries. The 0.5 °C (above bottom water temperature) contour divides the thermal activity in the southwest of the lake from the normal temperatures in the north east. Temperatures 1 °C (above bottom water temperature) or greater do not extend to the lake shore except in the west, and the 1 °C and 2 °C (above bottom water temperature) contours and possibly the 0.5 °C (Fig 6) approximately follow the bathymetry (Fig 2). The 5 °C and 10 °C (above bottom water temperature) contours do not follow the bathemetry.

The western high temperatures area (Fig 6) is over the site of the famous Pink Terrace (which was destroyed in the 1886 eruption) and is adjacent to thermal activity on the western shore of the lake which extends north from the adjacent Waimangu thermal area and which consists of hot springs, fumaroles, geysers, and hot ground along the western shore of the lake (Scott 1992, Nairn 1989).

The high temperature anomaly in the southern lake appears to be a separate entity and not connected with onshore thermal activity. Two of the three anomalously high bottom water temperatures measured at the top of the sediments by Irwin (1968) lie within this southern area and the third lies just on the edge. The hottest value (of 37.8 °C) measured by Irwin lies beside the 50 °C (above bottom water temperature) site measured in this survey.

The areas of elevated 1 m depth temperatures approximately coincide with the values of resisitivity less than 10 ohm.m measured by Bennie et al (1985). No resistivity measurements were made in the deep water of Lake Rotomahana; they were made only in the shallow water near the lake edge and on land. The temperature measurements suggest that the low resistivities would occur in throughout the south-western Lake Rotomahana. Bennie et al (1985) refer to the low resistivity area as the Waimangu geothermal field.

These measurements cannot be compared directly with the land based 1 m temperature surveys because of the different physical environments. With the land measurements pressure is close to 1 atmosphere and the ground may not be saturated with water, whereas the sediments at the bottom of the lake at a depth of 80 to 100 m are at a pressure of about 10 atmospheres and are completely saturated. The high water content alters the thermal conductivity and diffusivity and therefore the conduction characteristics (Dawson et. al. 1970). In thermal ground the mechanism of heat transfer changes from conduction to convection (of vapour) at a temperature of about 70 ^{o}C (Allis 1979b), whereas in the lake the sediments act as an impermeable layer and conduction is likely to persist at higher temperatures. At all the sites the measured temperature profiles are linear and temperature gradients are large in the hot areas, confirming conductive conditions. If convection were occurring the temperature gradient would probably be very small and non-linear.

It is of interest to note the results obtained from the land-based 1 m surveys. At the Wairakei Geothermal Field the range of temperatures was higher than at Lake Rotomahana, with the highest temperatures reaching about boiling point, i.e. 100 ^{o}C (Thompson et al 1961). An area of 8.5 km^2 was measured with temperatures over 1 ^{o}C above ambient temperature. At the Broadlands Geothermal Field Thompson (1968) did not list the discrete 1 m depth temperatures, but the temperature contours, at 5 ^{o}C and 10 ^{o} above ambient temperature cover a similar range to those at Lake Rotomahana (which are 0.5,1,2,5 and 10 ^{o}C above bottom water temperature).

Because a significant area of Lake Rotomahana has elevated sediment temperatures it seems likely that a geothermal field exists beneath the lake. It is thought to be connected with the Waimangu thermal system to the southwest of the lake. The two areas with very high temperatures are probably features where hot fluids are close to the bottom of the lake. Such high temperature areas of discrete size within a geothermal field are common features of a geothermal field, whereas at depth the temperatures are expected to be more uniform.

ACKNOWLEDGMENTS

The writers wish to thank G.F. Risk, R.G. Allis, and H.M. Bibby for helpful criticisms of this manuscript

REFERENCES

Allis, R.G. (1979a). Thermal history of the Karapiti Area, Wairakei. *Report* 737. 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.

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

Dawson, G.B., 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 utilisaion of geothermal resources,* Pisa, 22 Sept - 1 Oct 7970. vol. 2, pp 466-473.

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

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.

Scott, B (1992). Waimangu a volcanic encounter. Published by Waimangu Volcanic Valley, Rotorua, New Zealand.

Thompson, G.E.K., C.J. Banwell, G.B. Dawson, D.J. Dickinson (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. *Geofhermics,* vol. 21, pp. 75-88.