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GEOPHYSICAL EXPLORATION FOR PROSPECTIVE GEOTHERMAL RESOURCES IN THE TARAWERA FOREST

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ABSTRACT

An integrated geophysical survey, involving resistivity, gravity and magnetic measurements, was conducted early in 1987 over a 300km2 area within and north of the Tarawera Forest, to investigate potential geothermal resources for Fletcher Challenge Ltd. Two significant anomalies have been delineated. The first is the Tikorangi resistivity and magnetic low, associated with the north-eastern boundary of the Haroharo Caldera and centered south of the Tikorangi solfataras. The second anomaly, which is situated within the Puhipuhi Basin, east of the caldera, is postulated to represent a separate but cooling geothermal system, with implications of possible epithermal mineralisation.

Interpretation of the gravity measurements has led to identification of a north-east trending graben passing through Lake Rotoma, and intersecting the Haroharo Caldera near Tikorangi. combined interpretation Of all available data resulted in a pre-drilling conceptual hydrological model for the Tikorangi system and a target for future exploration drilling.

INTRODUCTION

This paper presents the results of a geophysical investigation of prospective geothermal resources in and near the Tarawera Forest (between Rotorua and Kawerau) for Fletcher Challenge Ltd. Previous studies (Nairn, 1981, Yamada, 1985) provided encouraging evidence for the possible existence of a geothermal system in the area between Lake Rotoehu, Lake Rotoma, and the Tarawera River. Thermal manifestations, occur along the shores of both lakes, at Tikorangi, and within the Te Haehaenga Basin further south. The Puhipuhi Basin, south of the Tarawera River, was added to the area of interest because of evidence of intense alteration on Puhipuhi Hills, and the existence of the neighbouring Waiaute warm springs.

A number of previous geophysical surveys, conducted in this area, were used to guide the recent work. These included: an assessment of Okataina Volcanic Centre using gravity, seismic, resistivity and aero-magnetics (Rogan, 1980); a brief resistivity survey of the Rotoma-Tikorangi area by students from the Geothermal Institute (Doens, 1985, Kohpina, 1985); and a sequence of detailed aero-magnetic surveys flown over the Haroharo and Tarawera complexes (Salt, 1986). These are discussed in more detail by Hochstein et al. (1987). Late in 1987, another two Institure students (Ayala, Estrada) conducted follow-up resistivity and gravity work.

The geophysical studies described here include a gravity survey of 208 stations, a resistivity traversing survey of 278 stations (with AB/2 spacings of 500m and 1000m), 40 deep resistivity soundings, and some additional magnetic property measurements on surface rock samples.

GEOLOGY

Geological inferences suggest that the most promising geothermal prospects are located along the north-eastern boundary of Haroharo Caldera, which lies within the Okataina Volcanic Centre. The Haroharo and Tarawera complexes have been sporadically active for the last 250,000 years, most recently in 1886. This suggests that a magma chamber still underlies the caldera (Nairn, 1981). Important structural features of the caldera include its margin and the Haroharo and Tarawera vent lineations. As a result of multiple, shallow dip slumping, associated with the caldera margin, enhanced vertical permeability in the upper kilometre may be distributed over a broad zone. In addition, the underlying ring fault probably creates a deep zone of substantial permeability. Recent vents form two broad parallel lineations orientated at 50° which are probably associated with deep-seated basement fractures. The Haroharo vent lineation intersects the caldera boundary, at a position marked by Tikorangi, a small 5,000 year old rhyolite dome. Within the caldera there are very few mapped faults which is probably a function of the relatively young age of the surficial volcanics. However, outside the caldera, numerous north-east trending faults have been mapped, and many of these may also pass through the caldera, providing vertical permeability beneath the surficial volcanics.

The near surface geology of the Haroharo Complex consists of a relatively thick sequence of recent rhyolite lavas (approximately 5,000 to 9,000 years old), volcanic breccias and pyroclastics. East of the caldera boundary, the approximately 200,000 year old Haparangi rhyolites make up the Maungawhakamana massif and Rere hills bordering Lake Rotoma. To the south, the Puhipuhi Basin marks the site of a small depression or caldera now largely filled with lacustrine sediments and ignimbrites which were uplifted and altered by the emplacement of the Puhipuhi dacite volcano (160,000 years old). The Puhipuhi dacite is highly brecciated and has been intensely altered by acidic fluids to an assemblage consisting of an advanced argillic cap of alunite-cristobalite (opal) and pyrite, underlain by kaolinite and pyrite. Silica flooding is also common. This advanced argillic cap is typical of the surface expression of shallow boiling in epithermal environments, and it may be underlain by a paleo-boiling zone containing mineralisation. Gold and silver traces were reported by prospectors in the 1920's in opalised pyritised quartz veins. The lack of significant surface thermal features around Puhipuhi suggests that this prospect is probably a waning hydrothermal system.

The major thermal features of interest (see Figure 2) are located at Tikorangi (solfataras), Lakes Rotoma and Rotoehu (Waitangi and Otei Springs), in the Te Haehaenga Basin (Mangakotukutuku Spring), and west of Puhipuhi Hills (Waiaute Spring). Other nearby thermal features are located on the south eastern shore of Lake Okataina, Humphreys Bay of Lake Tarawera, and the Centre Basin of Lake Rotoiti. Descriptions of the major thermal manifestations are given by Nairn (1981) and Yamada (1985).

During the present geophysical survey another thermal feature was discovered in a swamp along Waterfall Road next to the Tarawera River (Grid: N77 993029). An extensive area of CO_2 degassing is associated with warm chloride fluids within the swamp. A maximum temperature of 30°C was recorded in mud at about lm depth. Measurements of flow rate and chloride concentration of the Tarawera River have identified a substantial increase in total chloride flux (about 150 gm/s) entering the river between the Tarawera Falls and the Waterfall Road bridge.

RESISTIVITY SURVEYS

Previous resistivity measurements in the area include an early DSIR traversing survey along State Highway 30 and six Schlumberger soundings, some dipole-dipole measurements and magneto-telluric soundings by Rogan (1980) along the Tarawera River. Rogan's models are reasonably consistent with subsequent resistivity sounding interpretations, although there is some doubt over the existence of a 1 ohm-m layer at 3 km depth near Lake Tarawera, which is based on one noisy dipole-dipole reading. A deeply penetrating magneto-telluric sounding located beside the outlet of Lake Tarawera revealed apparent resistivities of less than 10 ohm-m at a period of 10 seconds, increasing to more than 100 ohm-m at 200 seconds. Again reliable interpretation is hindered by noisy data and three-dimensional effects, but a simple layered model of the magneto-telluric curve suggests that if a 1 ohm-m layer exists at 2 to 3 km depth, then it is probably only about 500m thick and is underlain by much higher resistivities (in excess of 500 ohm-m). Geothermal Institute students Kohpina (1985) and Doens (1985) conducted a total of 10 soundings and 18 traversing measurements between Rotoma and the Tarawera River. These have been reinterpreted in conjunction with the recent resistivity survey.

The resulting apparent resistivity traversing contour maps reveal a complex zone of moderately low resistivities elongated in a north-south direction along the eastern caldera boundary (see Figure 1). The anomaly is bounded in most directions by resistivities in excess of 400 ohm-m. The low resistivity zones form two anomalies: the Tikorangi-Rotoma-Te Haehaenga anomaly and the Puhipuhi anomaly. The only zone of very low apparant resistivity (less than 10 ohm-m) is a 1.2 km^2 fan-shaped area north of the Tikorangi solfataras suggesting the existence of a shallow mineralised aquifer supplying the Waitangi and Otei Springs. The low resistivity corridor connecting the Tikorangi-Rotoma anomaly with the Te Haehaenga anomaly, is most obvious in the 1000m AB/2 data, which suggests the existence of a fairly deep connection. Soundings (with maximum AB/2 spacings of up to 1800m) located within the traversing anomalies confirm deep resistivities of 20 to 40 ohm-m in the Te Haehaenga Basin, and 3 to 20 ohm-m in the Tikorangi-Rotoma Valley. Several soundings located outside the anomalies recorded background resistivities at depth in excess of 500 ohm-m. Another broad zone of low resistivities lies to the south of the Tarawera River centred within the Puhipuhi Basin. This anomaly consists of apparent resistivities in the range of 20 to 50 ohm-m. Soundings within the basin confirm that deep resistivities approach constant values of 20 to 40 ohm-m. Resistivity cross-sections (Figure 3) have been prepared from the one-dimensional interpretations of soundings. The locations of

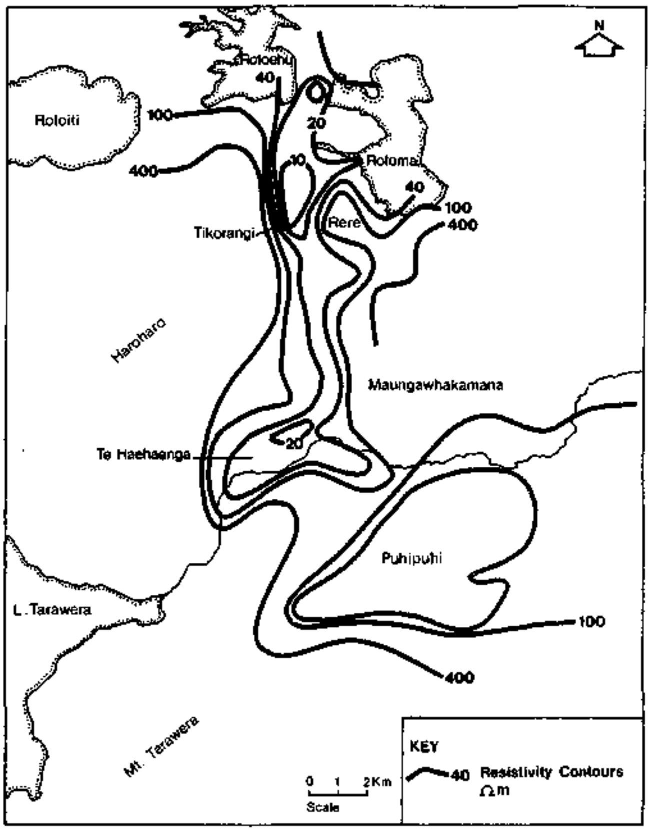

FIGURE 1:
Apparent Resistivity Contours : AB/2 = 1000M

the soundings and selected section lines are shown in figure 2. Interfaces between the layers are connected to portray subsurface variations in the factors that have caused the resistivity contrasts. In general, these factors are variations in porosity, temperature, saturating fluid mineralisation and intensity of clay alteration. Together, these factors can provide powerful indicators of the shallow hydrological processes occurring in a geothermal system, although care is necessary to avoid misinterpretations caused by combinations of alteration, porosity and fluid mineralisation contrasts without a corresponding change in temperature.

The first interface that appears in all the sections is closest to the surface, and probably represents the ground water table. It is marked by a contrast in resistivity of approximately one order of magnitude from several thousand ohm-m (unsaturated porous pyroclastics, rhyolites etc) to several hundred ohm-m (interpreted to be porous volcanics saturated with fresh ground water). As expected, the ground water table appears to be strongly controlled by the lake levels to the north (about 300m) and the Tarawera River elevation to the south (about 100m). Several soundings over the high elevation Haroharo Volcanic Complex reveal a ground water table close to lake level (about 320m elevation) suggesting that the top few hundred metres of this rhyolite complex is very permeable. This is supported by the absence of streams and surface erosion in this area of high rainfal1.

The resistivity of the ground water aquifer decreases dramatically to the north of the Tikorangi solfataras in the Rotoma Valley, where it is clearly affected by geothermal factors (elevated temperatures, mineralised fluids, and varying degrees of hydrothermal clay alteration). In the Te Haehaenga Basin there is also evidence of localised ground water contamination by geothermal products (possibly including rising

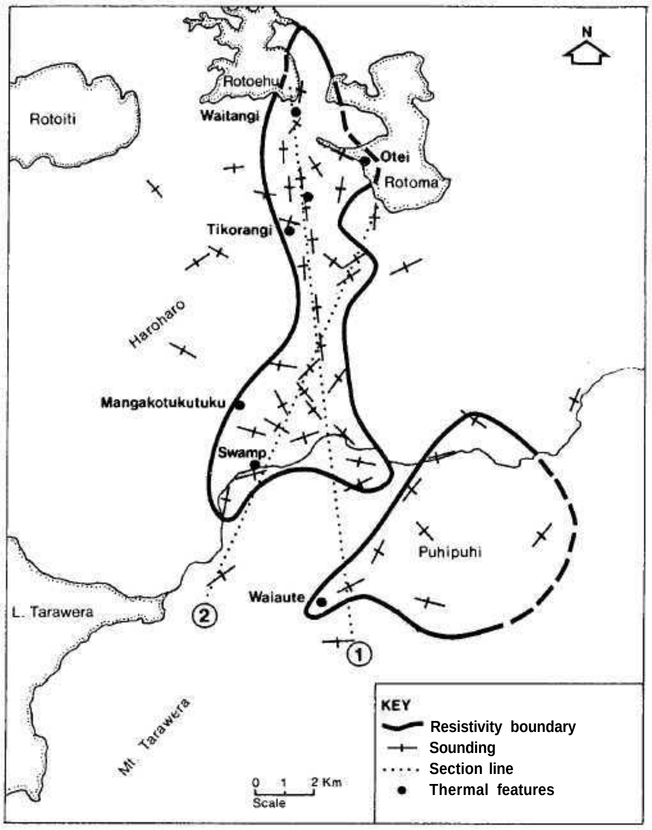

FIGURE 2:
Resistivity Soundings, Sections, and Boundary Locations

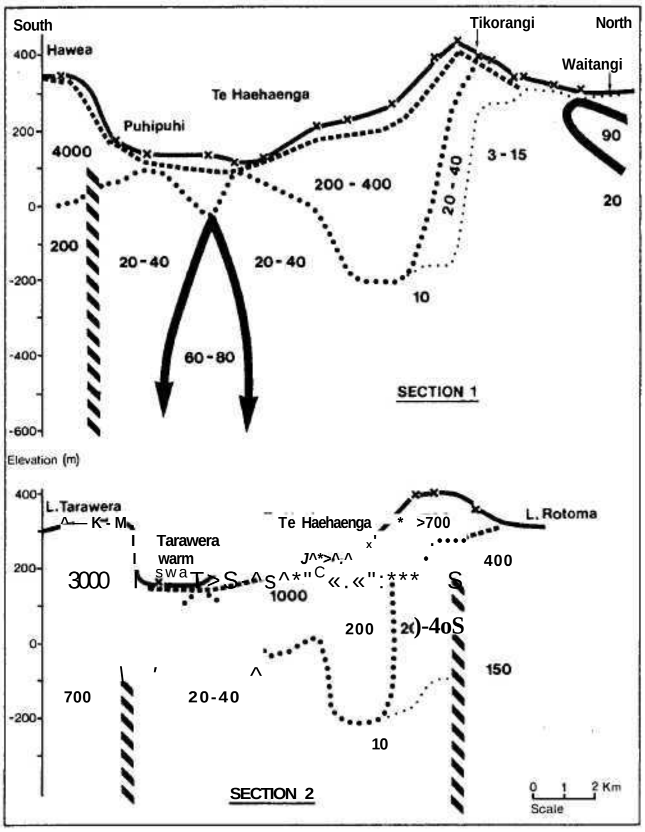

FIGURE 3:
Resistivity Sounding Sections
(average values in ohm-m)

steam and gas from a much deeper boiling geothermal aquifer), in the immediate vicinity of warm springs at Mangakotukutuku, and a warm swampy area along the Tarawera River. These localised shallow anomalies are probably related to structures allowing rapid vertical fluid convection. Nairn (1981) associates Mangakotukutuku Springs, for example, with localised north east trending faults. Also, a lineation in the apparent resistivity contours links the shallow anomaly near the Tarawera warm swamp with the NE trending Maungawhakamana fault.

The second resistivity interface that appears on all the sections marks the top surface of an intermediate low resistivity layer with values ranging from about 20 to 50 ohm-m. The major features identified by this interface are two large doming anomalies: one associated with the Puhipuhi Basin and dacite massif, and the other associated with Te Haehaenga Basin. Near Tikorangi, an intermediate-low resistivity layer can also be found- overlying deeper, very-low resistivity, particularly south of the solfataras. This is interpreted to indicate a zone of moderate to intense alteration, possibly saturated by a mixture of ground water and secondary fluids derived from boiling of a deeper, high-temperature mineralised aquifer.

The third interface, marks the top surface of formations with a resistivity of less than 20 ohm-m. This is interpreted to indicate the presence of intense alteration with associated aquifers of high temperature mineralised geothermal fluids, particularly where the resistivities are less than 10 ohm-m. The nature of these aquifers could be either primary neutral chloride fluids (most likely at depth) or secondary • mineralised fluids created by condensation of steam and gas into ground water (more likely at shallower levels). These shallow secondary fluids are usually acidic at source (ie: acid condensate fluids) but may neutralise along a flow path as a result of rock water reactions, and evolve into neutral sodium bicarbonate fluids possibly containing a moderate concentration of leached chloride ions. The chemical composition of Waitangi Springs, near Lake Rotoehu, fits this model, although there is also a possibility that these discharging fluids are a mixture of outflowing condensates, ground water, and primary chloride fluids, with the mixing process facilitated by deeply penetrating faults associated with the caldera boundary.

Another resistivity interface that has been identified in several soundings marks an increase in resistivity at depth to values in excess of 50 ohm-m. It is possible that this interface represents a resistivity basement caused by reduced alteration intensity and decreased porosity or temperature. Such basements can occur beneath lateral outflow tongues from a geothermal system and be diagnostic of a significant temperature inversion. This is not the only possible interpretation, however, because similar higher resistivity basements can occur within prograde high temperature systems as a result of significant reductions in porosity or changes in alteration type and intensity. Never-the-less, the location of these resistivity basements can assist in constructing conceptual geothermal models. The Puhipuhi and Te Haehaenga resistivity anomalies are separated by a steeply dipping basement of 60 to 80 ohm-m underlying several soundings. The Puhipuhi anomaly also appears to be constrained to the east, where one sounding reveals a high resistivity basement at about 800m below sea-level. This interface is probably true greywacke basement because its resistivity (144 ohm-m) is very similar to the basement resistivity of another sounding (135 ohm-m) located outside the Puhipuhi Basin, and the slope of the interpreted resistivity interface is consistent with a west dipping high-velocity seismic refractor identified by Rogan as greywacke basement.

Lateral resistivity contrasts that imply the existence of vertical boundaries to the geothermal system are also shown on the resistivity sections. These contrasts can be used, together with the apparent resistivity traversing contour maps, to obtain an approximate estimate of the size of the anomalies. The area of the Tikorangi-Rotpma-Te Haehaenga anomaly is approximately 40 km^2, and that of the Pjjhipuhi Basin anomaly is approximately 38 km^2.

GRAVITY SURVEY

The gravity method is frequently employed in geothermal exploration for two main reasons:

(i) to locate regions of subsurface densification caused by deposition of hydrothermal alteration products, and
(ii) to delineate major structures, such as grabens and calderas that could provide enhanced vertical permeability.

Hydrothermal densification has been clearly demonstrated at several New Zealand geothermal fields, notably Broadlands and Kawerau. Because densification is a time related process, there may be a relationship between the age of a hydrothermal system and its associated gravity anomaly.

Rogan (1980) has shown a clear correlation between a large negative gravity anomaly centred beneath the outlet of Lake Tarawera and the location of the Haroharo Caldera, with very steep gradients occurring near the caldera boundaries. Interpretation of the residual anomaly map consisted of a three-dimensional subsurface density model of the Haroharo Caldera structure, approximating an inverted cone extending to five kilometres depth. A mean density difference for the caldera infill of -0.5 gm/cm^3 was used, and a terrain density of 2.17 gm/cm^3 was chosen. Immediately east of Puhipuhi Basin, basement greywacke has been interpreted to occur at a level of 100m below sea level. Further north-east (through Kawerau) the greywacke surface becomes deeper and eventually it forms the Whakatane Graben (probably 2 km depth).

Rogan attributed a proportion of the 5 km thick cone of low density material underlying Lake Tarawera outlet to molten rhyolite because of the lack of a corresponding magnetic high in this area. By removing the effect of magnetised caldera infill (using an assumed 2.5 A/m average magnetisation in modelling of the aeromagnetic data), it was predicted that the resulting demagnetised low-density material (molten magma) has an upper surface at just 2.8 km depth, and a volume of 200 to 300 km^3 depending on the water content of the magma (wet magma has a lower density).

Stern (1982) conducted a very thorough reinterpretation of gravity data, supported by seismic refraction surveys and density determinations, covering the Central Volcanic Region, and encompassing the Okataina Volcanic Centre. He called into question the distinction between "volcanic cover" and "basement" because average measured densities of the volcanic fill approach those of greywacke at 2 to 3 kilometres depth. It was concluded, however, that major negative residual gravity anomalies in the Central Volcanic Region (such as Okataina) can be explained by large thicknesses of very low density pumice tuff or breccia in the top few kilometers of volcanic fill with a possible contribution from a deep body of low density molten rhyolite. Smaller residual anomalies can be accounted for by hydrothermal densification, or lateral variations in the relative thicknesses of tuff/breccia and lavas in the top kilometer of volcanic fill. It was also found that the average density of rhyolite samples is 2.27 gm/cm^3 and the average density contrast between infill volcanics and greywacke basement is -0.4 gm/cm^3.

In 1987, an additional gravity survey was conducted in order to provide more information on the area of prime interest for geothermal exploration, particularly Tikorangi, Rotoma, Te Haehaenga Basin and Puhipuhi. Standard corrections to the gravity measurements were applied, including instrument drift, earth tide, and terraia.corrections using a terrain density of 2.27 gm/cm^3. Elevations were determined using barometry, corrected for atmospheric pressure and temperature changes. Absolute gravity readings were obtained by tying the survey into previous gravity network stations. Residual gravity values were calculated by subtracting the regional gravity determined using a polynomonial given by Rogan (1980).

The additional gravity data have contributed useful new information, allowing a re-interpretation of the subsurface density structure beneath the Rotoma-Tikorangi areas, while at the same time confirming Rogan's large negative gravity anomaly centred beneath the eastern arm of Lake Tarawera. Where the data sets overlap there is an excellent match between the calculated gravity anomalies.

The most significant new feature to appear in the residual anomaly contour map (Figure 4) is a broad north-east trending graben structure extending beyond the north-eastern rim of the Haroharo Caldera, and passing through the southern basin of Lake Rotoma. Preliminary qualitative interpretation of this structure has been achieved using two-dimensional gravity modelling. The density model consists of a wedge shaped graben structure with a width at sea level of about 7 km, a basement depth of 1.3 km (below sea level) and a basement width of about 3 km. The density contrast used in the model is -0.4 gm/cm^3.

Some minor inflexions in the anomaly contours along the south-western shores of Lake Rotoma, and in the upper Rotoma Valley, suggest local variations in the densities of near surface lithologies. Near Tikorangi, in the Rotoma Valley, there appears to be a north-south trending zone of relatively low density, associated with the previously described low resistivity anomaly. This low density body beneath the valley is probably caused by a relatively thick sequence of high porosity tuffs and pyroclastics. These porous pyroclastics cause low resistivities when saturated with high temperature mineralised fluids. Therefore it appears that the shallow aquifers near Tikorangi reside in zones of relatively high porosity, and that deposition of alteration minerals has been insufficient to reduce the porosity and produce significant positive gravity anomalies. The implication of this model is that the shallow hydrothermal system at Tikorangi is relatively young because insufficient time has lapsed for the geothermal fluids to deposit significant quantities of minerals into available pore-spaces. This is consistent with the young age (5,000 years) of neighbouring volcanic vents (Tikorangi and Haroharo). However, the deep-seated hydrothermal system which feeds the shallow aquifers at Tikorangi may be much older.

A small positive gravity anomaly occurs along the eastern shore of Lake Rotoehu, north of the Waitangi Spring. This anomaly coincides with an outcrop of pre-caldera Hal rhyolite along the Haraharo Caldera boundary, and also lies northwest of the Rotoma Graben. It seems likely that high density basement lies close to the surface in this

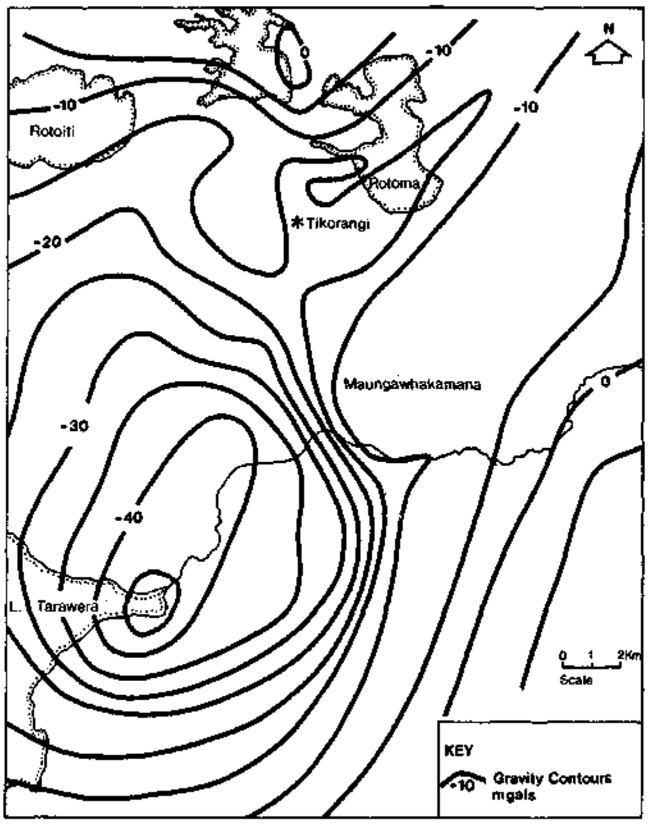

FIGURE 4:
Residual Gravity Anomaly Contours:
D = 2.27 gm/cm^3

area. Further north the residual gravity values decrease again, and it is likely that another depression filled with low density volcanics (about 1.7 km thick according to Stern, 1982) lies to the north of Lake Rotoehu.

The large negative residual gravity anomaly centred beneath the eastern arm of Lake Tarawera remains similar in shape to the anomaly contoured by Rogan (1980). Therefore, Rogan's three dimensional subsurface density model is accepted as a reasonable interpretation of the anomaly. This model includes a very steep boundary (70° dip) between Maungawhakamana and Te Haehaenga Basin. Interpreted depths to basement around the remainder of the caldera boundary vary from sea-level to 1 km below sea-level, with the exception of the upper Rotoma Valley where the caldera is intersected by the Rotoma Graben.

The broad intersection of these major structures, can be considered a prime location for enhanced vertical permeability at depth, suitable for the rapid establishment of a convecting hydrothermal system. The lack of discernable density increase associated with the low resistivity anomaly in this area, suggests that the shallow part of this system is relatively juvenile.

MAGNETIC SURVEYS

Magnetic surveys are often useful in geothermal exploration because magnetite is easily destroyed by hydrothermal alteration causing broad magnetic lows. To model magnetic anomalies with any confidence, knowledge of the magnetic vector direction as well as information on the magnetic properties of the rocks is required. Previous workers (Rogan, 1980, Salt , 1986) have used an average effective magnetisation of 2.5 A/m, which is summed from a normal remanent magnetisation of 2.2 A/m and an induced magnetisation of 0.3 A/m. However published data suggests that there is a wide range of rhyolite magnetisations within the Taupo Volcanic Zone. For example, Cox (1970) found an average effective magnetisation for Tarawera rhyolites of only 0.3 A/m. Therefore, it was considered prudent to add to the available data set by measuring remanent magnetisations and susceptibilities of local Haparangi rhyolite samples. The results still show a wide range in magnetisations, however the samples can be grouped into young rhyolites (less than 20,000 years old) with an average of 1.4 A/m., and old Haparangi rhyolites (greater than 200,000 years) with an average 4.5 A/m. The magnetic susceptibilities are very low and contribute about 0.15 A/m to the total effective magnetisation. (Because of the young age of the samples, the orientation of the remanent magnetisation vector is assumed to be normal, with a declination of 0° and a dip of -65°).

Early high-level aeromagnetic surveys flown at 1500m and about 4 km line spacing, were used by Rogan (1980), (assuming a magnetisation of 2.5 A/m) to obtain a depth to magnetic basement beneath the Okataina Volcanic Centre of 1.0 to 2.5 km. A comparison of the magnetic and gravity data was used to support the existence of a relatively shallow (2.8 km depth) magma chamber centered beneath the eastern arm of Lake Tarawera. However our results suggest that the range in calculated depths to magnetic basement could be a pseudo effect caused by substantial variations in magnetisation of the rhyolites.

In 1985 and 1986, Auckland University Geothermal Institute (Salt, 1986) conducted more detailed aero-magnetic surveys over the Okataina Volcanic Centre with a flight altitude of approximately 800m. Several positive anomalies, revealed in this survey, correlate with known volcanic features such as the young Haroharo vents and lava flows, and the older Haparangi rhyolites east of the caldera boundary (Maungawhakamana and Rere Hills). A large positive anomaly south of the Tarawera River has no obvious explanation at the surface, but correlates with high resistivities at depth (approaching 1000 ohm-m). It is interpreted, therefore, to indicate an unaltered buried dome or intrusive. Regions of zero magnetic response (when the negative dipole effect is taken into account) generally correspond with the low resistivity anomalies in the Rotoma, Tikorangi, Te Haehaenga and Puhipuhi basins, supporting the interpretation that hydrothermal demagnetisation is the principal cause of these magnetic lows. The centre of the strongest region of demagnetisation is the upper Rotoma Valley, approximately 2 kilometres SSE of Tikorangi where a 10 ohm-m anomaly lies at about 200m below sea level.

GEOTHERMAL RESOURCE MODEL

Based on the preceding arguments, an integrated exploration model of the geothermal resources in the project area is proposed. From the geology it is clear that the Okataina Volcanic Centre is relatively young, and that the associated Haroharo Caldera is underlain at some unknown depth by a large body of molten rhyolite, which constitutes the ultimate heat source for hydrothermal systems in the area. A broad zone of enhanced vertical permeability probably occurs along the caldera boundary. Within the project area, this forms a north-south trending zone from Lake Rotoehu through Tikorangi and the western flanks of Maungawhakamana. Large numbers of north-east trending structures also exist. These include numerous faults outside the caldera, the Haroharo vent lineation, and the newly described Rotoma Graben (from gravity interpretation). Vertical permeability is likely to be particularly high near the intersections of these sets of structures. The near-surface rhyolites of the Haroharo complex also have a high primary permeability allowing rapid downflow of recharging meteoric ground water. The ground water levels are generally controlled by the lakes to the north, and the Tarawera River to the south.

An assessment of the geothermal prospects in the project area is best treated by separation into two principal anomalies: Tikorangi-Rotoma-Te Haehaenga and Puhipuhi Basin.

The most prospective anomaly is associated with the Tikorangi solfatara field, which is the hottest known thermal feature (temperatures of at least 134°C at 30m depth). Large flowrate hot springs of diluted sodium-bicarbonate- chloride fluids occur about 3 km to the north and north-east of Tikorangi (Waitangi and Otei springs, respectively). These are thought to represent outflowing fluids which contain a significant proportion of neutralised condensates from the Tikorangi area. Fluid geothermometry suggests minimum temperatures of 200°C for the shallow aquifer supplying these thermal features. Gas isotope geothermometry suggests much higher temperatures at deeper levels.

The Tikorangi-Rotoma-Te Haehaenga resistivity anomaly covers an area of about 40 km^2, and is elongated along the caldera boundary between the Tarawera River and Lake Rotoehu. North of Tikorangi a small area of less than 10 ohm-m resistivities is interpreted to be caused by a shallow condensate aquifer. It has caused some hydrothermal alteration but insufficient mineral deposition to significantly reduce the porosity of the volcanic breccias and pyroclastics forming the aquifer. Soundings further north and north-east suggest that this shallow condensate aquifer feeds the Waitangi and Otei Springs. The area between Tikorangi and the head waters of the Kaipara Stream (labelled the upper Rotoma Valley) is underlain by a 10 ohm-m layer at about 200m below sea level, which is interpreted to represent a near-boiling geothermal brine. This area is the centre of a significant demagnetised zone, presumably the result of hydrothermal alteration. It also lies at the junction of two major structures identified by gravity : the Haroharo Caldera boundary, and a north-east trending graben through Lake Rotoma. These structures presumably provide the deep fracture permeability that has enabled rapid establishment of a high temperature convecting geothermal system.

Further south the Te Haehaenga Basin contains an upwelling resistivity anomaly of about 30 ohm-m, which approaches the surface near the Tarawera River and connects with the Tikorangi anomaly through the Kaipara Valley. The entire anomaly is demagnetised. The association of thermal fluids with the anomaly is confirmed by the presence of warm, dilute springs which are thought to be related to recent north-east trending faults allowing circulation and mixing of deeper outflowing geothermal fluids with a near-surface ground water aquifer. The Te Haehaenga anomaly is bounded to the south by a *very* high resistivity formation, coinciding with a positive magnetic anomaly which, by its shape, suggests the presence of an unaltered buried intrusive or dome.

The Puhipuhi Basin also contains a doming low resistivity anomaly with values of 30 to 40 ohm-m covering an area of about 38 km^2 and reaching highest elevations near the exposed acidic alteration on Puhipuhi Massif. The alteration assemblage is typical of the surface expression of a shallow paleo-boiling zone in an epithermal environment, which suggests that the Puhipuhi anomaly represents a waning hydrothermal system in the later stages of temperature decline. However, the possible association of the anomaly with the neighbouring warm Waiaute Springs implies the existence of some residual heat, with geothermometry predicting subsurface temperatures as high as 170°C. High resistivities and a positive magnetic anomaly beneath Hawea. road (to the south of Waiaute Springs) implies the absence of any substantial connection between this anomaly and Tarawera Volcano. A near zero residual magnetic field over the Puhipuhi Basin confirms that most of the volcanic material overlying the non-magnetic greywacke basement has experienced extensive hydrothermal demagnetisation.

In view of the geothermal resource models presented above, it is recommended that future exploration activity should concentrate on the most prospective area in the upper Rotoma Valley between Tikorangi and the head waters of the Kaipara Stream. The principal target is a *very* low resistivity formation occurring at about 200m below sea level. It is important to obtain information on the cause of this anomaly to test the proposed model. The information required includes subsurface temperatures, pressures, hydrothermal alteration, porosities, permeabilities, and if possible the chemical nature of the fluid.

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REFERENCES

Ayala, J., 1987 : Interpretation of 2-D resistivity structure of Tikorangi geothermal prospect. Geoth. Inst. Report 87.03.

Cox., A., 1970 : Remanent Magnetisation and Susceptibility of Late Cenozoic Rocks from N.Z. N.Z.J. Geology and Geophysics. Vol 14(1) : 192-207.

Doens, E.F., 1985 : Schlumberger Resistivity Sounds., Rotoma Geothermal Prospect. N.Z. Geotherm. Inst, Report Geotherm. 85.06.

Estrada, L., 1987 : Gravity survey at Tikorangi geothermal prospect. Geoth. Inst Report 87.07.

Hochstein, M.P., Yamada, Y., Kohpina, P., Doens, E., 1987 : Reconnaissance of the Tikorangi geothermal prospect, N.Z. Proc. 9th N.Z. Geothermal Worshop.

Kohpina, P., 1985 : Resistivity Traversing and Self Potential Surveys in Lake Rotoma Geothermal Prospect. N.Z. Geotherm. Inst. Report Geothrm. 85.14.

Nairn, I.A., 1981 : Geothermal Resources of the Okataina Volcanic Centre, N.Z. Geological Survey internal report.

Rogan, A.M., 1980 : Geophysical Studies of the Okataina Volcanic Centre. PH. D Thesis, Auck. Univ.

Salt, D.M., 1986 : Aeromagnetic survey of the northern Okataina Volcanic Centre and Study of Magnetometer Noise Characteristics. M.Sc Thesis, Physics Department, Auck. Univ.

Stern, T.A., 1982 : Seismic and Gravity Investigations of Central Volcanic Region, N.Z. Ph. D Thesis, Victoria Univ. Wellington.

Yamada, 1985 : Geological Reconnaissance Survey at Rotoma-Tikorangi Geothermal ARea. N.Z. Geotherm. Inst Report 85.29.