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Taupo

Field Trip Guides

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Field Trip Guides – Contents

Field Trip 2

Geothermal Systems

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Aerial view of Champagne Pool area, note area of collapse craters to left.

Boiling spring, Waimangu

Mud Volcano, Waiotapu

Overview

This field trip will visit three geothermal systems Ohaaki-Broadlands, Waimangu and Waiotapu. Ohaaki-Broadlands is exploited to produce 108 MW of electrical energy from 17 bores. Waiotapu is an unexploited geothermal system and an array of surface features will be seen, characterised by moderate-large upflows of chloride waters and steam heated features. Small-moderate hydrothermal eruptions occurred in this area 600-700 years ago. Waimangu demonstrates the formation of surface features following a volcanic eruption through an existing geothermal system.

Field Trip Plan

Depart Conference Venue (0930h)

Stop at Ohaaki Power house overview (1000-1030h)

Visit Waiotapu Geothermal area (1100-1230h)
- Collapse craters
- Champagne Pool
- Mud Volcano

Lunch stop Lake Okaro (1300-1330h)

Visit Waimangu Geothermal area (1400-1600h)

Return Conference Venue (1700h)

Sketch map showing field trip route.

Geologic Setting of Hydrothermal Systems in New Zealand

The New Zealand lithosphere only began to develop as a separate crustal entity in the late Cretaceous early Tertiary when it broke away from the Gondwana supercontinent as the Tasman Sea opened (Sporli, 1987). New Zealand's Cenozoic history relates to its proximity to a major active boundary between the Indian and Pacific plates. Accurate reconstruction of the plate boundaries for most of this era is difficult, although several versions are published (e.g. Cole and Lewis, 1981; Ballance et a1., 1982; Brothers, 1984; Walcott, 1987). Hydrothermal systems occur throughout New Zealand (NZ Geological Survey 1974) with the large scale-high temperature systems restricted to the Taupo Volcanic Zone.

Taupo Volcanic Zone (TVZ)

The TVZ is a complex volcano-tectonic depression, filled with pyroclastic deposits and lavas, that is related to the westward dipping subduction zone of the Hikurangi Trough (Fig. 1). It extends offshore into the Tonga-Kermadec arc and marks part of the 'Pacific Rim of Fire'. Convergence along the Hikurangi Trough is increasingly oblique southward to form a transform plate boundary as delineated by the Alpine Fault in the South Island (Fig. 1).

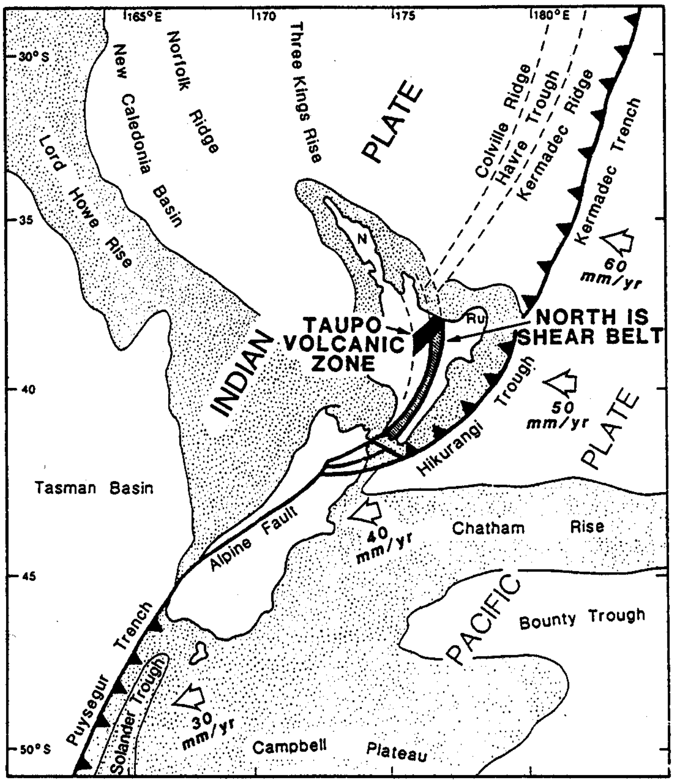

Figure 1. Location of New Zealand with respect to the Pacific-Indian plate boundary, with the stippled region representing continental crust. Arrows show motion of the Pacific Plate relative to the Indian Plate. From Cole (1990).

Tectonics

The Benioff zone dips at a very shallow angle west of the Hikurangi Trough but becomes steeper westward to where it lies at about 80 km depth beneath the TVZ (Fig. 2). An accretionary prism, comprising Tertiary and younger sediments, lies above the shallower Benioff zone. Bounding the accretionary prism to the west are the Axial Ranges which are made up of Mesozoic greywackes and argillites of the Torlesse terrane; the North Island Shear Belt comprises a set of dextral north-trending faults that cuts across them.

The TVZ lies adjacent to the Axial Ranges, about 250 km west of the Hikurangi Trough, and extends from White Island to Ohakune (Fig. 3). Its margins are defined by steep gravity gradients and distribution of volcanic vents, except to the northwest where it merges with the Coromandel Volcanic Zone (Rogan, 1982; Wilson et al., 1984). Northeast trending normal faults dominate the structural fabric, forming a series of horst and graben blocks. Block faulting, subsidence and thinned crust (15-25 km) are all products of extension which presently occurs at rates of 8-12 mm/yr across the TVZ (Stern, 1987; Darby et al., 2000). The oldest known volcanic rocks are about 1.6 ma (Pringle et al., 1992).

Volcanism

The TVZ can be divided into three segments based on the style of volcanism. The northern and southern segments are narrow (~30 km wide) and include the andesite volcanoes of White Island and Tongariro respectively. The central segment is broader (>80 km wide) and overwhelmingly dominated by rhyolite caldera volcanoes. An excellent description of their features and histories are supplied by Wilson et al. (1984, 1995) and Houghton et al. (1995), who compare the central segment to the Yellowstone system. Of the seven centres identified, Taupo and Okataina were recently active (Fig. 4). The 181 AD Taupo eruption was one of the most violent known eruptions in the world (Wilson and Walker, 1985); however, the youngest TVZ rhyolite erupted about 700 years ago at Okataina (Naim, 1989; Nairn et al., 2001, 2003; Leonard et al., 2002; Nairn, 2002). TVZ rhyolites are high in silica (70-75% SiO_2) and thought to originate from partial melting of the lower crust (e.g. Cole, 1990). Slight compositional variations between centres and between eruptive episodes, suggests that eruptions are associated with the generation of separate magma batches rather than the continuous evolution of a single magma chamber (Hochstein et al., 1993).

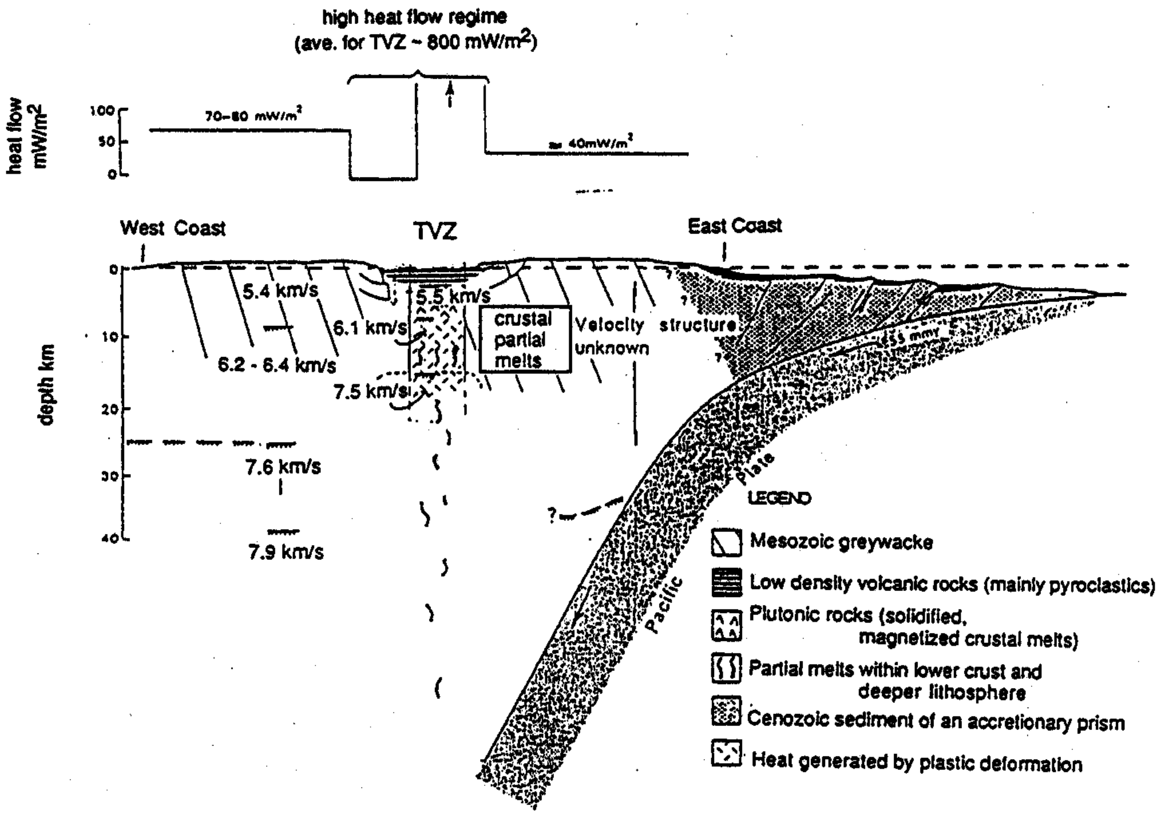

Figure 2. Cross-section showing the geophysical data and crustal structure relevant to plate convergence and subduction in the North Island. Modified from Stern (1987).

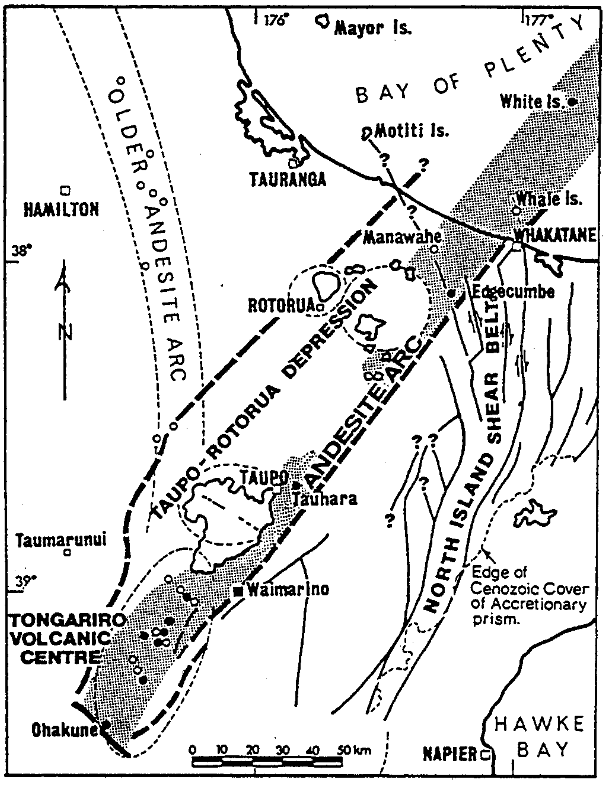

Figure 3. Location of the North Island Shear Belt (Axial Range) and the andesite-dacite volcanic centres in the Taupo Volcanic Zone. Open circles indicate andesite-dacite rocks >50,000 years old; closed circles indicate andesite-dacite rocks <50,000 years old. Modified from Cole (1990).

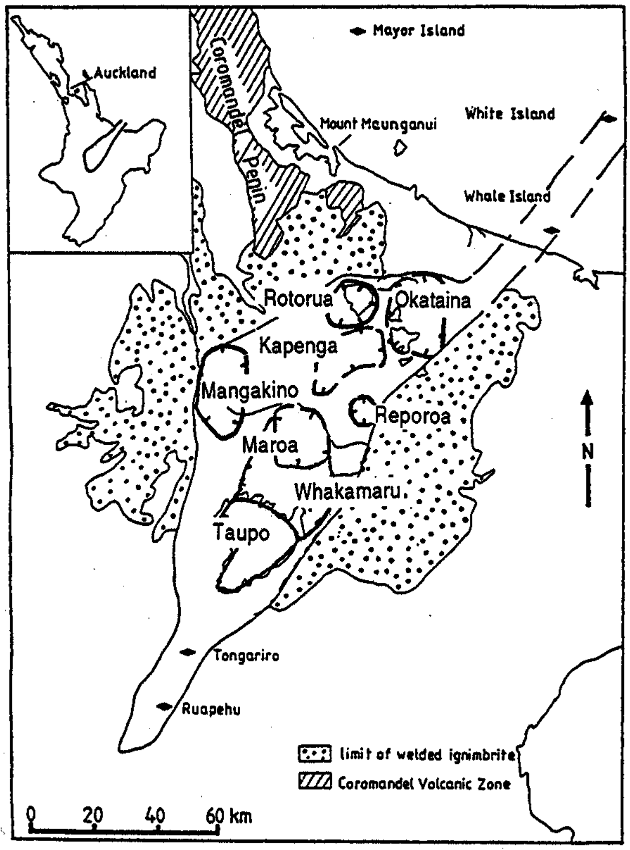

Figure 4. Location of rhyolite caldera centres and distribution of Quaternary welded ignimbrite deposits. Modified from Houghton and Wilson (1986).

Hydrothermal Activity

There are approximately 20 known hydrothermal systems[1], of which half have been explored by drilling down to a maximum depth of 2700 m (Fig. 5&6). In the central TVZ, hydrothermal systems are regularly spaced (10 to 20 km apart) and separated by zones of recharge. The main control on their distribution is uncertain though a few systems are clearly related to either major fault structures e.g. Orakeikorako, Te Kopia, Waikite or caldera boundaries e.g. Waimangu, Waiotapu (Wood, 1995). Most modern hydrothermal systems have been active for at least 10,000 years and possibly more than 300,000 years (e.g. Browne, 1979). The total estimated heat flow, due to hydrothermal convection, ranges between 2000 and 4000 MW (e.g. Allis, 1980; Stern, 1987; Hochstein et al., 1993), within an order of magnitude of that contributed by volcanism (last 200,000 years), 500 to 1000 MW (Hedenquist, 1986; Hochstein et al., 1993).

The source of the anomalously high heat flow, which is about four times greater than other regions of arc-related volcanism, is not fully understood. Some attribute the anomalous heat flow to crustal thinning and upwelling asthenosphere (e.g. Stern, 1987; Cole, 1990), whereas others suggest that the excess heat is generated by plastic deformation of ductile crust (Hochstein and Regenauer-Lieb, 1989; Hochstein et al., 1993). The answer appears to somehow relate to the unique location of the TVZ, situated near the transition between convergent and transcurrent plate boundaries.

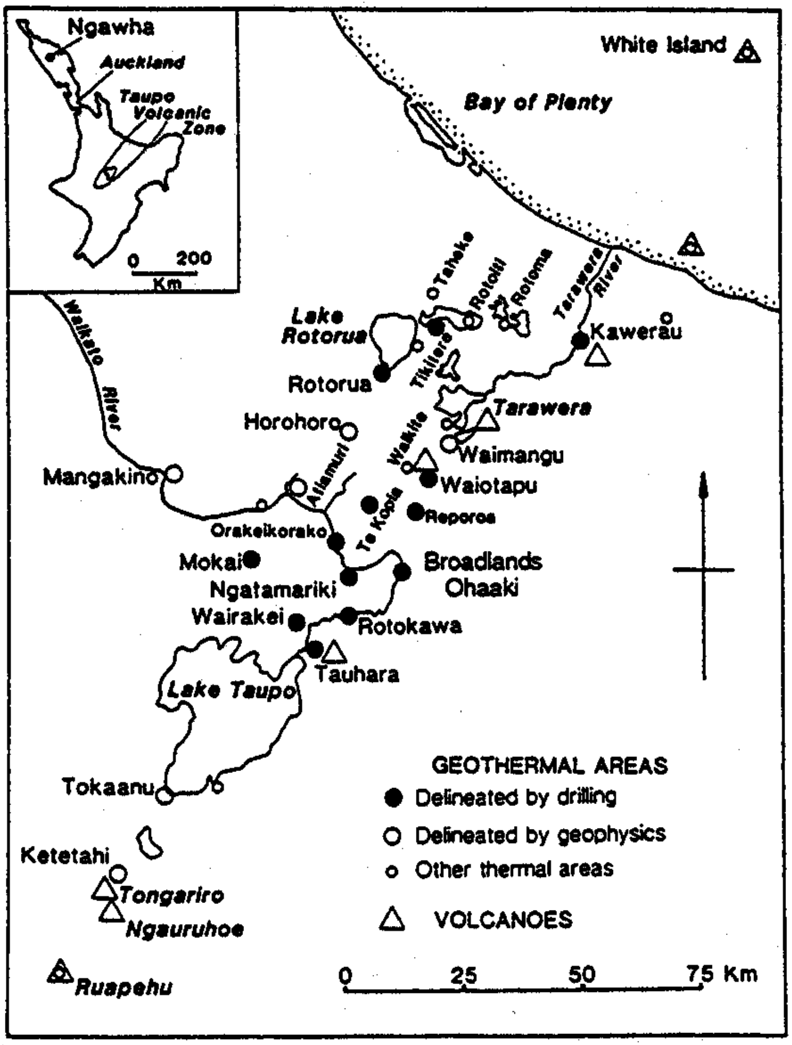

Figure 5. Distribution of active hydrothermal systems in the TVZ. From Hedenquist (1990).

[1]Individual systems are distinguished as having separate columns of hot water upflow, and the exact number depends on definition. Some located close together, e.g. Wairakei and Tauhara, are hydrologically connected at depth and they may comprise a single system (Allis et al., 1989). Further confusion derives from the absence of global criteria for distinguishing systems; e.g. the Yellowstone hydrothermal system has an areal extent similar to the central TVZ but is usually considered as a single system (Fournier, 1989).

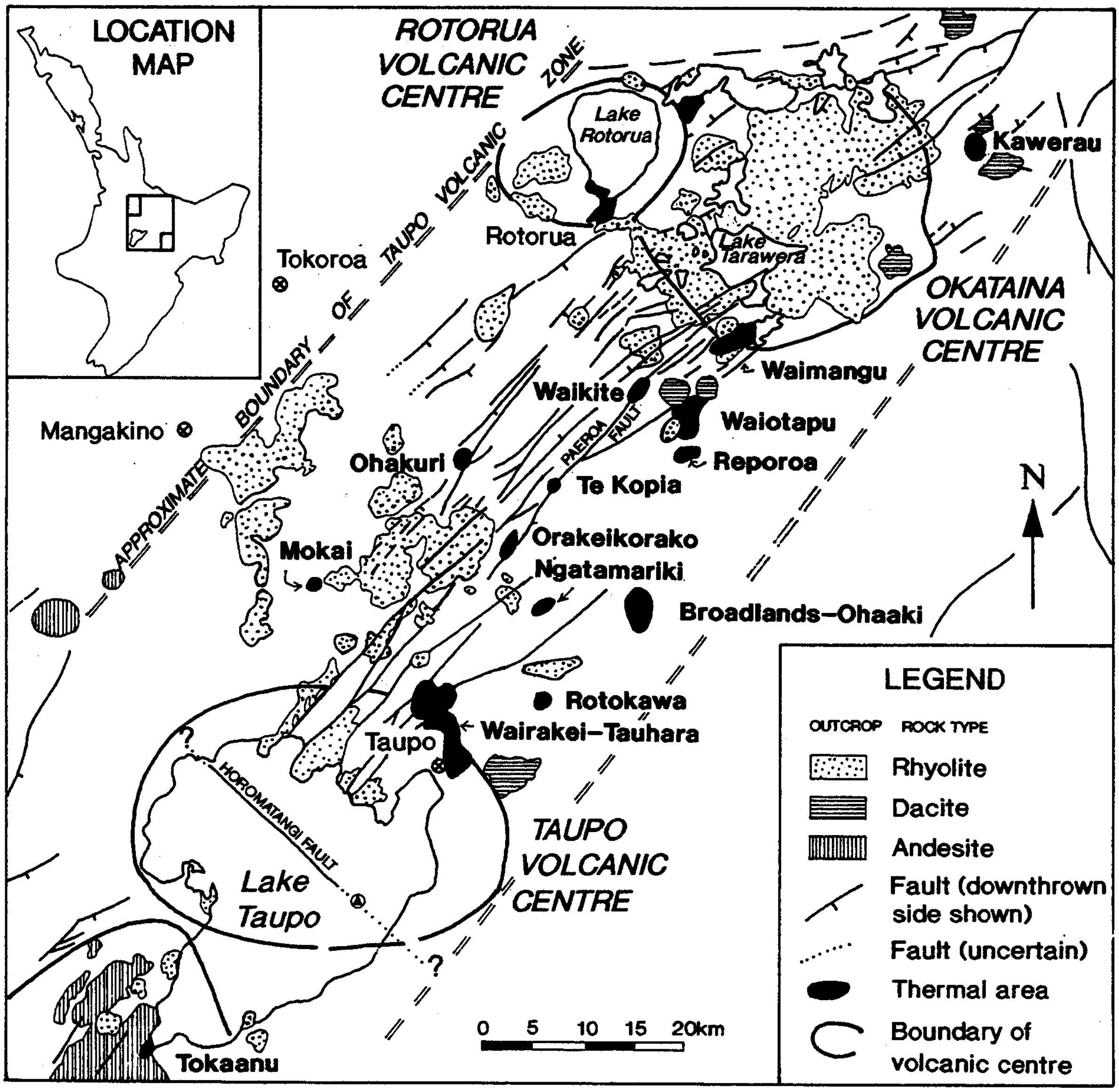

Figure 6. Map of the Rotorua-Taupo area showing the distribution of hydrothermal systems, lava type and structure. Modified from Cole (1990).

BROADLANDS-OHAAKI

Broadlands-Ohaaki (Fig. 7) is probably the most closely studied hydrothermal system within the Taupo Volcanic Zone in terms of its geology, fluid chemistry, isotope composition, hydrology, mineral-fluid equilibria and mineralisation (e.g. Grindley and Browne, 1968; Browne and Ellis, 1970; Browne, 1971; Giggenbach, 1971; Mahon and Finlayson, 1972; Wood, 1983; Lyon and Hulston, 1984; Hedenquist and Stewart, 1985; Hedenquist, 1990; Simmons and Browne, 1990; Lonker et al., 1990; Simmons and Christenson, 1994). This is primarily due to the more than 40 wells which were drilled since 1965. The deepest wells penetrate to 2500 m depth.

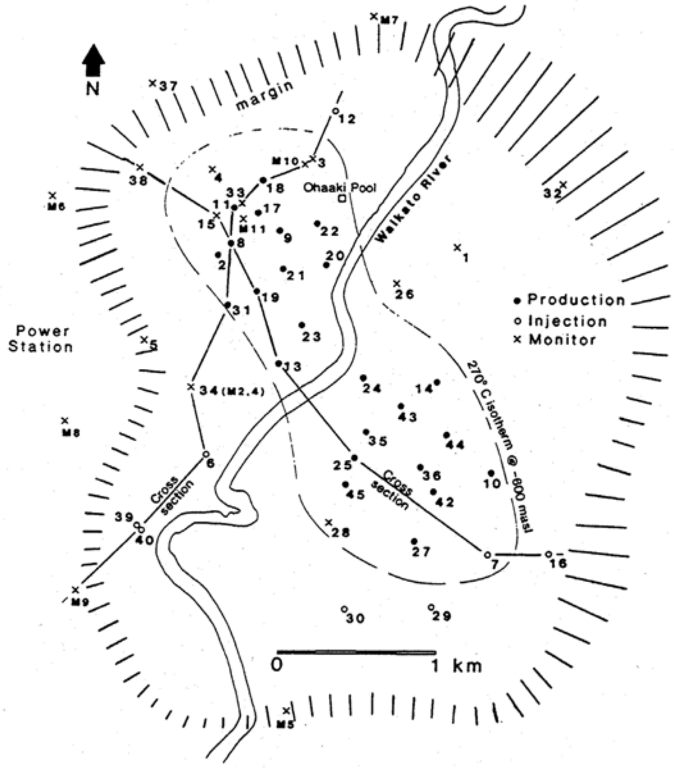

Figure 7. Location of geothermal wells and resistivity margin at Broadlands-Ohaaki. The 270°C isotherm shown is at ~900 m depth. From Hedenquist.

Broadlands-Ohaaki is situated on the eastern margin of the Taupo Volcanic Zone; however, its relationship to any of the postulated volcanic centres is uncertain (Wood, 1995). The Broadlands stratigraphy comprises a thick sequence of flat lying Quaternary to Recent rhyolites, dacites, andesites, air fall and water-lain tuffs, ignimbrites, and lacustrine tuffaceous sedimentary rocks (Table 1). These overlie Mesozoic basement greywacke and argillite rocks which were encountered by drill holes in the eastern part of the field (shallowest intersection is at 900 m); the basement surface dips generally westward. There is little surface expression of faulting, and structural features are inferred from stratigraphic relationships. Fractures extending into the basement probably act as the principal conduits for fluid flow.

Deep hydrothermal fluids are of neutral chloride-type and the hottest downhole temperature measured was 307°C. Figure 8 shows cross-sections through the system depicting its thermal structure and hydrology. There are two upflow zones located on both sides of the Waikato River. Fluids within these zones ascend with a vertical thermal gradient which corresponds to the boiling temperature of a H_2O-CO_2 fluid. Temperature inversions occur locally at the margins of the upflow zones, where cooler CO_2 rich steam-heated waters are diluting the ascending hydrothermal fluid. Acid-sulfate waters are present only in two small areas and do not occur below about 20 m.

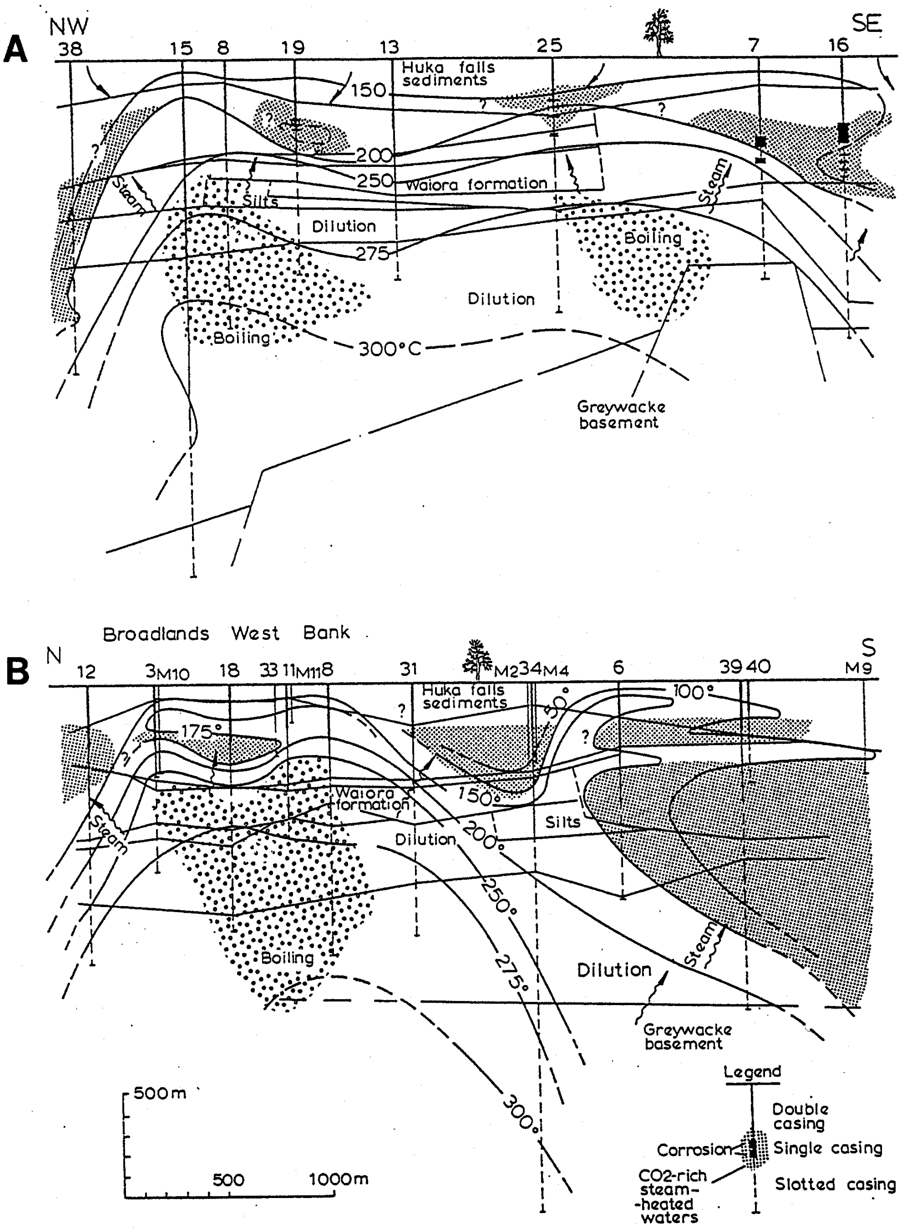

Figure 8. Northwest-southeast (a) and north-south cross-sections (b) through the Broadlands-Ohaaki system. Stipple pattern shows the distribution of CO_2 rich steam-heated waters; isotherms are also shown. From Hedenquist (1990).

Figure 9 shows the zonation of alteration minerals as a function of temperature. Hydrothermal alteration at ~150°C, which forms at shallow depths or on the margin of the system, is characterised by montmorillonite and interlayered montmorillonite-illite clays with local occurrences of mordenite, siderite, calcite, kaolinite, chalcedony, cristobalite and leucoxene. By contrast, hydrothermal alteration in the centre of the upflow at about 260°C is characterised by quartz, albite, adularia, K-mica, calcite, chlorite with rare epidote and wairakite. Disseminated sphalerite, galena, pyrite and chalcopyrite, with rare pyrrhotite, generally occur at depths below 500 m; however, in Br-16, sulfide occurrences extend from 280 to 1400 m (Browne, 1971). A geochemical study of trace elements, typically associated with epithermal Au-Ag mineralisation, indicated a zonation pattern with Au, As, Sb and Tl having greatest enrichments at shallow levels (200 to 400 m depth) whereas Ag, Se, Te, Bi, Pb, Zn and Cu are enriched at depth (Ewers and Keays, 1977).

Ohaaki Pool

Considering the size of the Broadlands-Ohaaki hydrothermal field, it is perhaps remarkable that its natural discharge features are so few. The Ohaaki Pool, with an area of 800 m^2 , was easily the largest of these and formerly discharged crystal clear chloride-bicarbonate water which deposited siliceous sinter. Overflows ceased once borefield production started. In 1989, the bottom of this pool was cemented, effectively blocking natural fluid flow. The water now filling the pool is runoff discharged from drillhole BR-22. For short periods (e.g. from 1957 to 1958), red-orange precipitate, rich in Sb, S, Au, Ag, Hg, Tl and As, deposited at the margins of the pool (Weissberg, 1969).

BR-22

In the early 1980's, Cu-Fe sulfide scale was discovered in wells 27 and 22 (Brown, 1986), coating black-pressure plates and the walls of pipes. This contained between 1.2 and 7.3% Au and up to 20% Ag. Brown (1986) calculated that the deep chloride fluid contained about 1.5 ppb Au, close to the maximum limit of gold saturation (~10 ppb) in solution as the bisulfide complex ($Au(HS)_2$) (Seward, 1973, 1982).

Electrical Production

The Ohaaki power plant has an installed capacity of 116 MW. This is comprised of two intermediate pressure steam turbine generator sets and two high pressure sets. The steamfield has 17 production wells, ranging in depth from 400 m to 3000 m and supply steam and water up to 280°C. There are 6 reinjection wells with an average depth of 1060 m (see also Appendix 1).

Table 1. Summary stratigraphy of Broadlands-Ohaaki.

Formation/unit	**Lithology**	**Max. Thickness (m)**	**Age (yr)**
Surficial deposits	pumice, alluvium, ash, sand, gravel, rhyolite and lapilli tuff	90	
Huka Falls	lacustrine silts and sands	350	~100,000 (?)
Ohaaki Rhyolite	biotite, hornblende, quartz, andesine rhyolite	450	
Waiora	pumice, lapilli tuff, locally water laid; low quartz content	380	
Broadlands Dacite	dense plagioclase-bearing dacite and andesite	490	
Broadlands Rhyolite	hard, flow-banded, spherulitic plagioclase-rhyolite	475	
Lower Siltstone	bedded tuffaceous siltstone and sandstone	115	
Rautawiri Breccia	lithic tuff and lapilli tuff	670	
Rangitaiki Ignimbrite	welded vitric tuff	410	
Ohakuri Group	crystal vitric tuff, locally welded	265	
Akatarewa Ignimbrite	welded lithic crystal tuff	215	
Waikora	conglomerate with greywacke and argillite clasts	130	
Torlesse Supergroup	greywacke and argillite (basement)	(?)	Jurassic

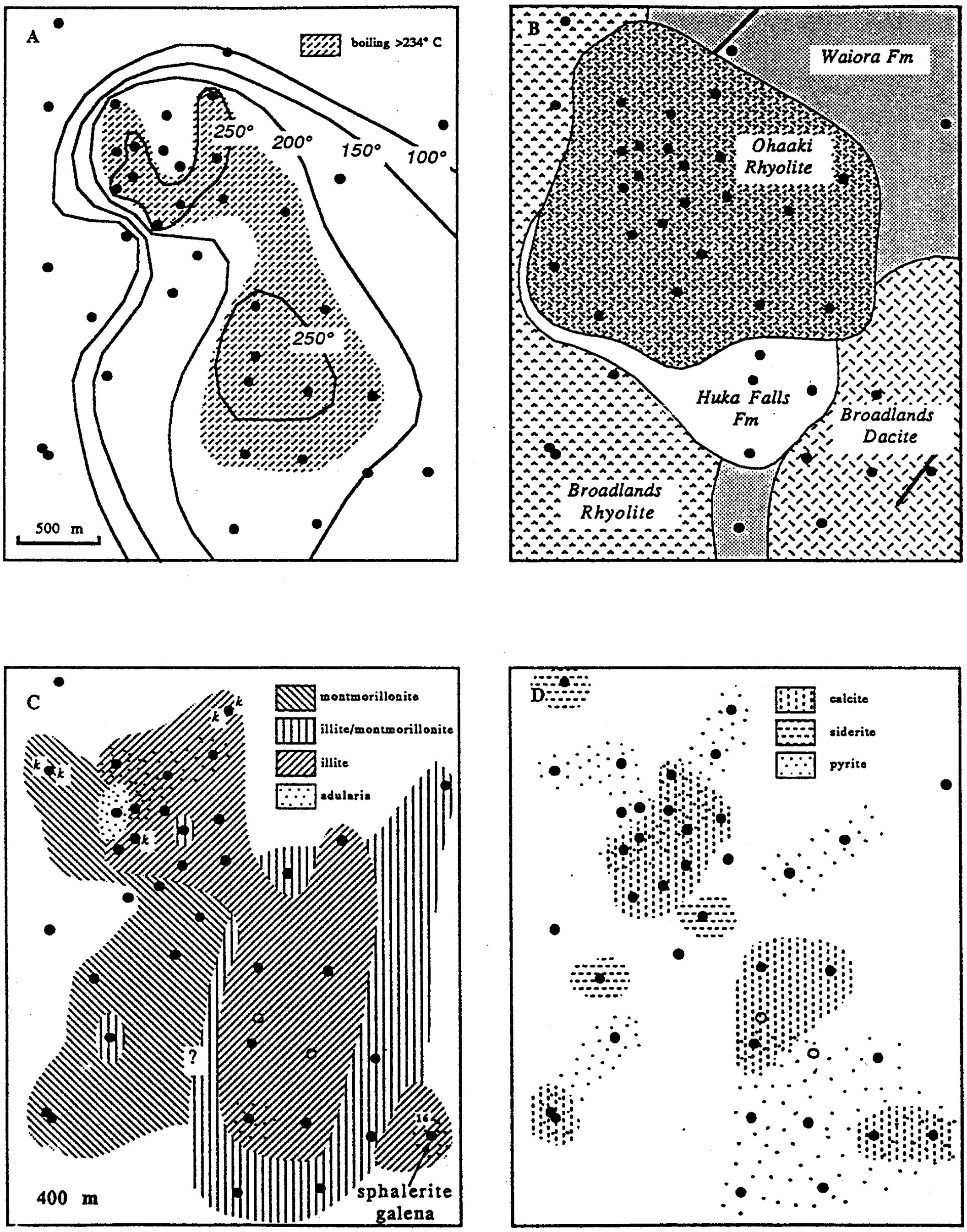

Figure 9. Plan views depicting, at approximately 400 m below the surface: A) temperature distribution and boiling zones, B) geology, C) clay and adularia distribution [k denotes occurrence of kaolinite], and D) carbonate and pyrite distribution.

WAIOTAPU

Waiotapu is located south of the Okataina Volcanic Centre, but its relation to recent volcanism is uncertain (Wood, 1995; Nairn, 2002). It has the largest area of surface thermal activity of any system in the TVZ (18 km^2 and 540 MWt). Seven holes penetrating to depths of 500 to 1100 m were drilled in near N-S alignment (Figs. 10 and 11), but due to poor discharge this field was never developed for production. Early geological and geophysical studies are described in DSIR Bulletin 155 (1963). More recently, Waiotapu has been studied with respect to its geochemical evolution and as an analogue to an active ore-depositing system (Hedenquist, 1983; Hedenquist and Henley, 1985; Hedenquist and Browne, 1989; Hedenquist, 1991; Giggenbach et al., 1994).

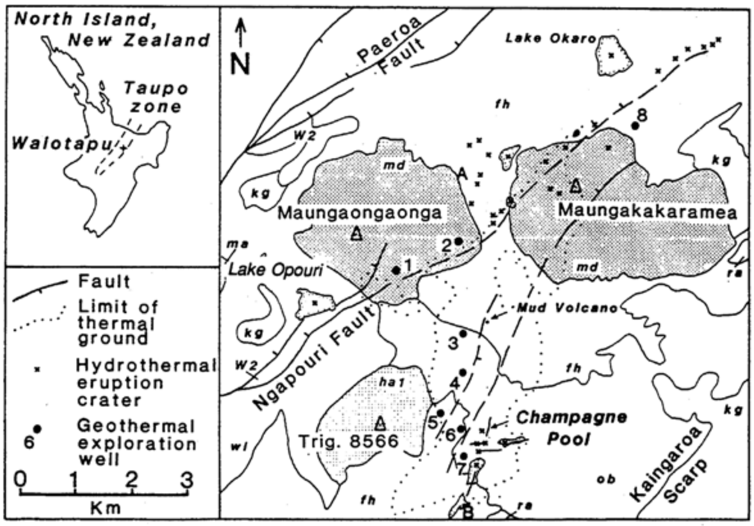

Figure 10. Simplified geologic map of the Waiotapu area; the unit abbreviations are keyed to Table 2. Also shown are the locations of drillholes (numbered) and hydrothermal eruption vents. From Hedenquist and Henley (1985).

The stratigraphy of the area comprises near flat lying felsic ignimbrites, tuffs, and lacustrine sedimentary rocks (Table 2, Fig. 12). Basement greywacke was not encountered in any of the drill holes. The northern part of the field is bounded by two dacite domes (Maungakakaramea and Maungaongonga) that rise 400 m above their bases, and a rhyolite dome (Trig 8566) lies west of the field. The principal structural feature is the Ngapouri Fault, a NE-SW trending splay off the Paeroa Fault which cuts between the two dacite domes (Figs. 10 and 11). Minor NNE trending faults are inferred from the alignment of thermal features in the central part of the field; further south, the apparent intersection of E-W and NNE-SSW trending structures coincides with four hydrothermal eruption craters. There are, in fact, more than twenty hydrothermal eruption craters and associated breccia deposits at Waiotapu (Figs. 10 and 11). Several ^{14}C age dates indicate that these eruptions took place around 7-800 years ago and were perhaps synchronous with rhyolite eruptions at Mt Tarawera, about 15 km north-east of Waiotapu (Lloyd, 1959; Grant-Taylor and Rafter, 1971; Hedenquist and Henley, 1985; Nairn et al., 2001; Leonard et al., 2002). Eruption craters are sometimes confused with collapse craters, which form due to dissolution, but the two can usually be distinguished from their crater morphology and the presence or absence of a breccia apron.

Waiotapu is characterised by a large area of steaming ground and fumarolic activity associated with collapse craters, mud pools and alteration due to acid-sulfate fluids, which form above the water table. Photographs, paintings and eyewitness descriptions of the 19th century indicate former widespread steaming ground on the flanks and near the summit of Maungakakaramea (Rainbow Mountain). This thermal activity has declined in the last 60 years but nevertheless is responsible for the noticeable variegated colours of rocks exposed there. Springs discharging chloride waters lie at the water table and deposit siliceous sinter, but many are diluted by bicarbonate or sulfate waters. The Champagne Pool is situated in the south-central part of the field and is the only feature from which undiluted chloride waters discharge.

The subsurface hydrology was deduced from drill hole data and spring chemistry (Hedenquist and Browne, 1989; Hedenquist, 1991). Deep fluids ascend along temperature and pressure gradients that are close to boiling in the vicinity of the Champagne Pool and near well 4. Temperature inversions at shallow levels (<300 m depth) encountered in wells 2 and 3, coupled with fluid chemistry, are interpreted to result from incursion of CO_2 rich steam heated waters (Hedenquist and Browne, 1989). The southern part of the field is dominated by a southerly outflow towards the Waikato River (Fig. 13). Spring waters are dominated by chloride with variable amounts of bicarbonate and sulfate.

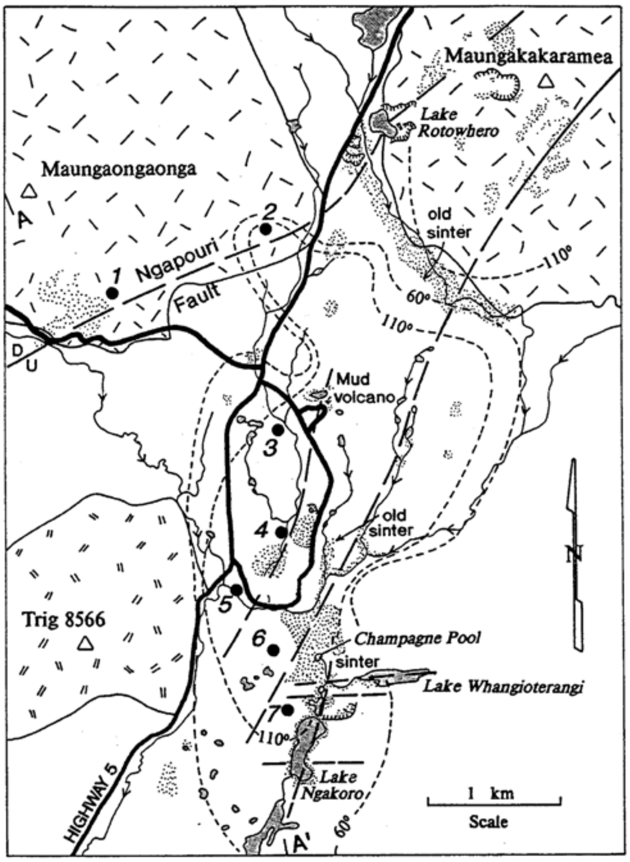

Figure 11. Map showing the location of the major thermal features at Waiotapu (after Lloyd, 1959).

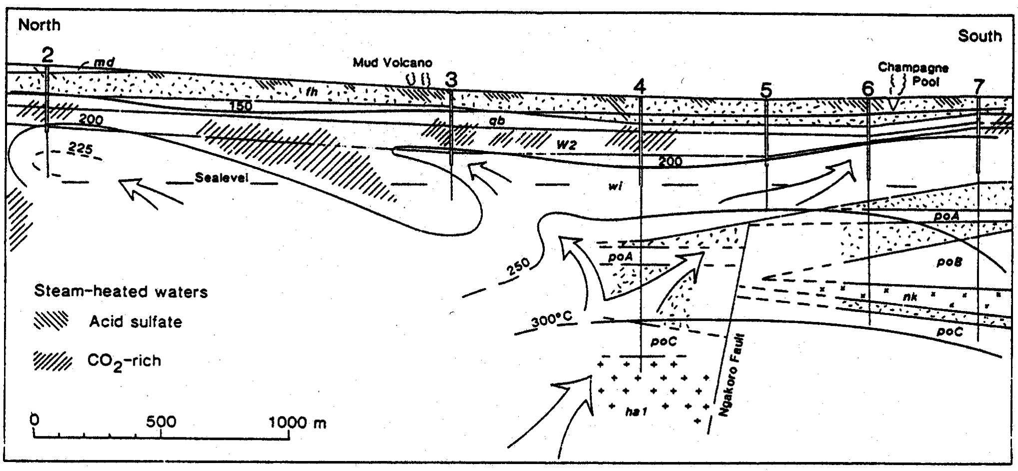

Figure 12. North-south section through the Waiotapu system, showing the geology, distribution of steam-heated waters, isotherms and flow paths of thermal fluids. (Hedenquist and Browne, 1989). Stratigraphic symbols keyed to Table 2.

Despite the large areal extent of thermal activity, unaltered rocks dominate surface exposures. Surficial hydrothermal alteration is restricted to steaming ground, bubbling mudpots and fumaroles, where alunite (natroalunite), kaolinite, amorphous silica, montmorillonite, cristobalite and native sulfur occur. Beneath the surface, acid-sulfate alteration is intense but is restricted to depths between 25 and 135 m (Figs. 14 and 15). At greater depth, minor mordenite exists but is superseded by laumontite at about 170°C, and montmorillonite is rare. The deep alteration assemblage (>200^{o}C) includes albite, adularia, K-mica, chlorite, epidote and wairakite. Pyrite is ubiquitous and pyrrhotite occurs below 400 m depth. Calcite, quartz and subordinate adularia fill fractures and veinlets.

Rare mineralisation in drill cores is characterised by disseminations of sphalerite, galena and chalcopyrite, but none reaches "ore" grade: gold and silver attain maximum concentrations of 0.2 ppm Au and 70 ppm Ag (Hedenquist and Henley, 1985). Spectacular mineralisation is seen in the Champagne Pool where orange precipitates, amorphous arsenic and antimony sulfur compounds, containing up to 80 ppm Au and 175 ppm Ag, are accumulating at the margins of the pool. Thallium and mercury attain 320 and 170 ppm respectively in the precipitates (Weissberg, 1969). These precipitates were not depositing in about 1930, so (A.P.G. Thomas, unpublished field notes). Hedenquist and Henley (1985) suggest that the subsurface environment beneath the Champagne Pool is a favourable site for precious metal deposition as here temperatures cool by boiling from 250° to 175°C. The Champagne Pool itself represents a unique environment of mineralisation in that dissolved CO_2 maintains sufficiently low pH to stabilise precipitation of amorphous arsenic and antimony sulfur compounds which then absorb Au and Ag from solution (Hedenquist and Henley, 1985; Renders and Seward, 1989; Webster, 1990).

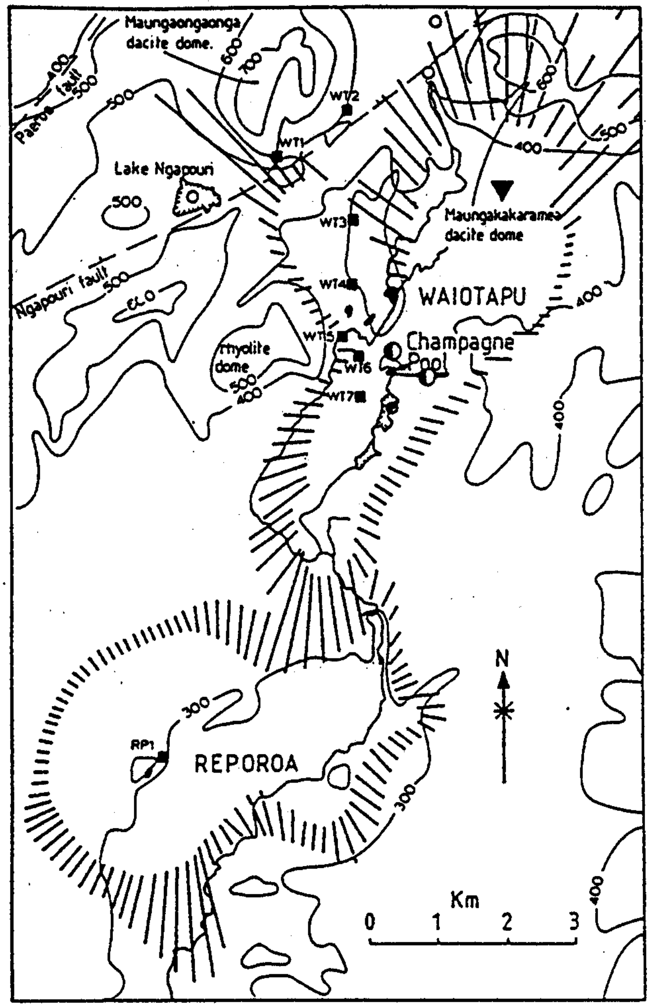

Figure 13. The <10 Ωm resistivity anomaly for the Waiotapu and Reporoa geothermal areas. The pattern indicates an outflow tongue of chloride water extending from Waiotapu to Reporoa (Healy and Hochstein, 1973). From Henley (1985).

Collapse Craters

From the tea rooms we cross the Waikokomuka Stream (Fig. 14, frontispiece). Tuffs exposed on the south bank are coated with a mixture of amorphous silica and alunite which precipitated directly from mixed acid-sulfate-chloride waters draining into the stream. Underlying this veneer the tuffs are silicified because of mixing between acid-sulfate and chloride waters at the water table. Unaltered Oruanui Ignimbrite crops out 2 m above stream level on the right side of the path; this contains numerous accretionary lapilli (pisolites).

Twenty metres further along the path is an area of collapse craters. Based on a conservative estimate, 70 million kg of rock (density=1.5 g/cc) were dissolved by acid-sulfate fluids to create unstable ground which then collapsed (Fig. 14). Ground surrounding the collapse craters contains cristobalite and sulfur, whereas alunite and kao1inite occur in mud pools on the crater floors. Notice how the ground resonates in places. Some of the deep craters (e.g. Rainbow Crater) contain a mixture of acid-sulfate and chloride waters, marking the location of the water table; other crater floors (e.g. Devil's Ink Pot) are perched above the water table and contain only acid sulfate waters. In the vicinity of the Devil's Ink Pot, the surface is littered with fragmentary lithic material which is the eruption breccia ejected from the hydrothermal vent now occupied by the Champagne Pool.

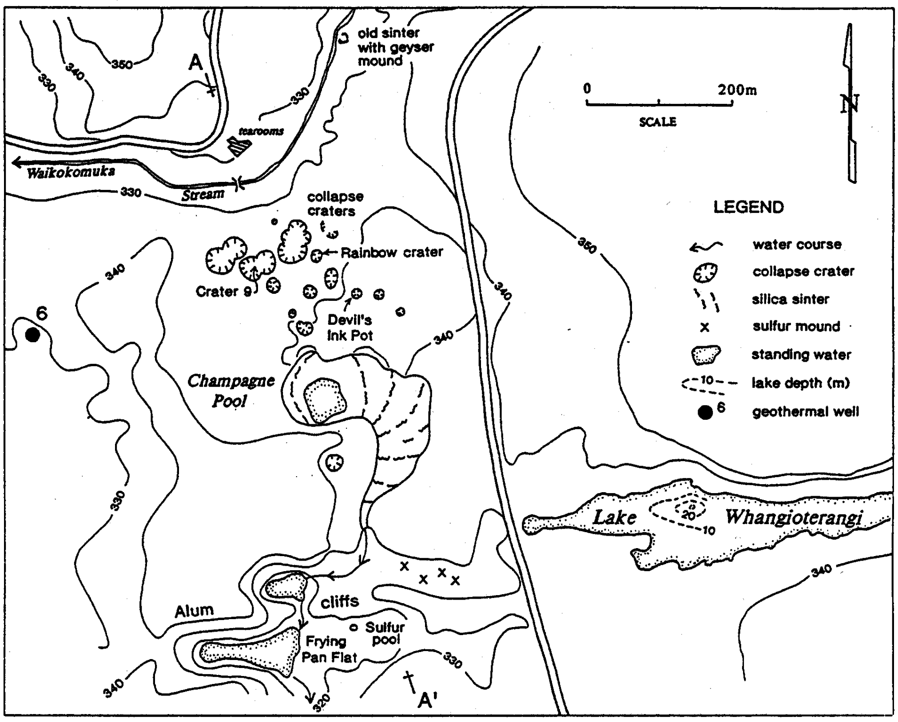

Figure 14. Location of thermal features in the vicinity of the Champagne Pool.

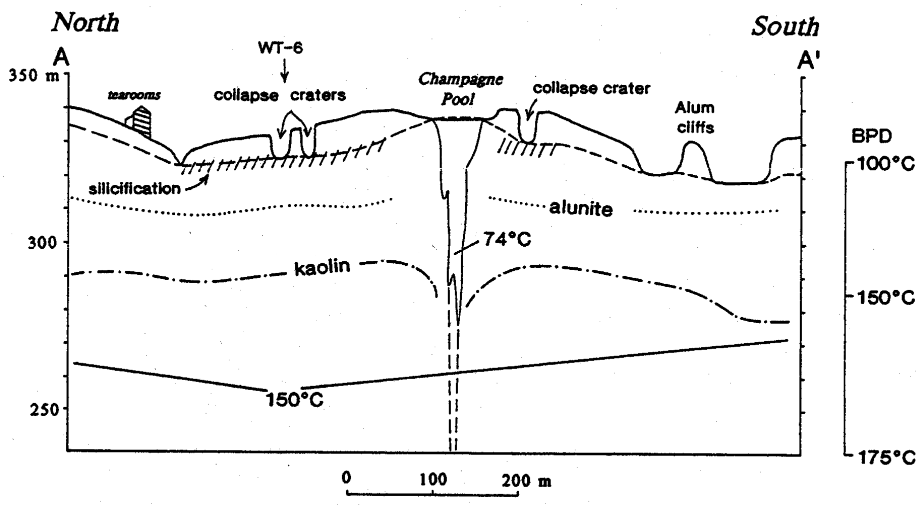

Figure 15. North-south cross section through the collapse crater-Champagne Pool vicinity, showing the water table and subsurface distribution of alunite and kaolinite. BPD is boiling temperature at depth indicated.

Champagne Pool

The Champagne Pool is a steep-sided, conical-shaped hydrothermal eruption crater 60 m deep (Fig. 14 and 15). An inferred stockwork fracture pattern in rocks below the pool forms a vertical conduit which taps deep reservoir fluids at ~230°C. Within the pool, the temperature is a constant 74°C from top to bottom because of rapid convection. Orange-coloured precipitates near the edge of the pool contain the amorphous arsenic and antimony sulfur compounds rich in gold and silver. The fluid effervesces CO_2 and bubbles nucleate at depths of only about 1 m below the surface. The high concentration of dissolved CO_2 results in a pH ~5.

Note that the water level in the Champagne Pool is about 10 m higher here than the surrounding vicinity. In exposures south of the Champagne Pool, hydrothermal eruption deposits overlie Taupo Pumice (186 AD). The breccia clasts are thought to derive from depths of <170 m; the large ballistic blocks are Oruanui Ignimbrite (Hedenquist and Henley, 1985).

Lake Whangioterangi (not visited)

The interesting feature here is the zone of upwelling in the centre of the lake (25 m deep), which is the surface expression of a sublacustrine spring. Molten sulfur occurs on the lake bottom.

Table 2. Summary stratigraphy of Waiotapu.

Formation/unit	**Lithology**	**Thickness (m)**	**Age (yr)**
Ash (fh)	at least five rhyolitic ash beds and interbedded alluvium	<10	186AD to c. 14,700
Oruanui [Wairakei Breccia] (th)	fine rhyolitic ash with abundant accretionary lapilli	<50	c. 22,600
Earthquake Flat Breccia (fh)	unwelded rhyolite pumice breccia, biotite-rich		c. 42,000
Huka Group (fh)	lacustrine silts and sands	40-120	100,000 to 400,000
Maungakakaramea Dacite (md)	lava domes and flows of dacite	up to 1000 (?)	c. 160,000
Kaingaroa Ignimbrite (kg)	upper welded lenticulite and lower unwelded breccia		
Matahina Ignimbrite (ma)	poorly welded pumiceous tuff		c. 200,000
Onuku Breccia Formation (ob)	pumiceous pyroclastics, reworked to silts, sandstones	~50	
Crystal-rich tuff (qb)	moderately welded quartzose, biotite ignimbrite		
Waiora Formation	pumiceous pyroclastics and lacustrine sediments of the (W2) lower Huka Group		
Haparangi Rhyolite (hal)	lava domes and flows of rhyolite, with intrusive equivalents	up to 1100	
Waiotapu Ignimbrite (wi)	moderate to highly welded quartz-poor lenticular ignimbrite	~250	
Ngakoro Andesite (nk)	augite-hypersthene intrusive (?) sill; no surface equivalent	50	
Paeroa Ignimbrite (po-A, B, -C)	three moderately welded ignimbrite sheets separated by tuff breccias	>100	300,000?
Torlesse Supergroup	greywacke and argillite (basement)		Mesozoic

Sulfur Mound Valley (not visited)

This is a drained western portion of Lake Whangioterangi. The yellow mounds consist of vesicular sulfur clasts and are interspersed among finely laminated beds of cristobalite; these are sublacustrine hydrothermal deposits. The vesicular sulfur clasts indicate that the sulfur was molten.

Mud Volcano (not visited)

At the turn of the century, this mud volcano was over 2 m high and its base had a diameter twice this. The mud contains kaolinite, opal CT, quartz and finely disseminated pyrite. The mud is 80-100^{o}C in places and the pH is 2.5.

WAIMANGU-ROTOMAHANA

I do not think that the impression made by this small dirty green lake, with its swampy shores and the dreary sombre treeless hills which surround it, overgrown merely with bracken, is in any way up to the expectation of the traveller who has heard so much of the lake's wonders. At least, that is how it was with us. The lake lacks all the qualities of a beautiful landscape. What makes it the most remarkable of all New Zealand lakes, one could even say one of the most remarkable places in the whole world, must be viewed at close quarters and lies mostly hidden from the newcomer's eyes. Only the steam clouds rising everywhere lead to the suspicion that there is really something to be seen here.

Hochstetter, 1864 (translation Fleming, 1959)

The Waimangu-Rotomahana hydrothermal system is located along the southern margin of the Okataina Volcanic Centre and is contained within a sequence of rhyolitic ignimbrites and lavas that were emplaced over the last 250,000 years. The southern part of the Haroharo caldera passes through the Waimangu-Rotomahana system, and this structure formed as a result of the eruption of more than 300 km^3 of mostly rhyolite magma (Nairn, 1986, 2002). The Okataina Volcanic Centre is the most recently active one in the TVZ with ignimbrite and dome building events occurring about 600 years ago within the Tarawera complex (Nairn et al., 2003). The youngest event was the 1886 basaltic eruption from a south-west trending line of vents, extending from the summit of Mt. Tarawera to the Waimangu Valley (Fig. 16).

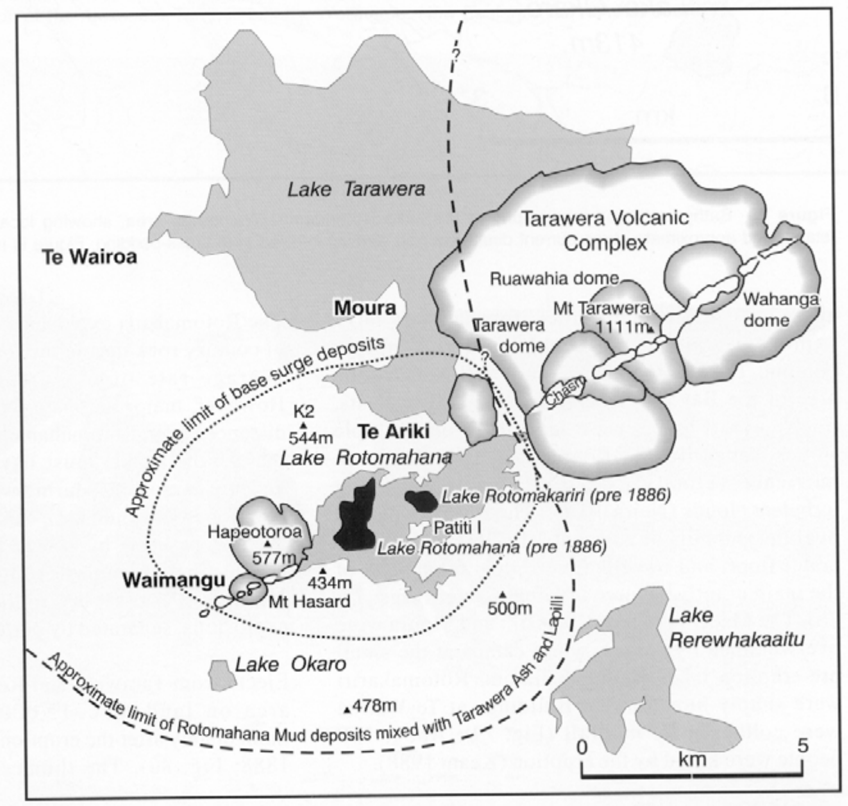

Figure 16. Map of the Tarawera-Rotomahana-Waimangu area showing the 1886 rift, Tarawera domes, limits of surge and airfall deposits and sites of pre and post eruption lakes (after Nairn, 2002).

Little is known about the deep subsurface geology and hydrology of Waimangu except that which can be deduced from the surface since there has been no drilling here (Simmons et al., 1993). Because of its special nature, none is likely. Thermal features at Waimangu are concentrated along the Waimangu and Lower Haumi Valleys, in a northeasterly alignment that parallels the 1886 Tarawera eruption vents (Fig. 17). Other thermal features occur along the western shores of Lake Rotomahana and are known as the "Steaming Cliffs". These features mostly discharge neutral chloride waters (85-100^{o}C) but there are also a few isolated localities of steaming ground where acid-sulfate waters exist. The chloride springs throughout the Waimangu Valley are surrounded by silica sinter aprons; however, these are small (~ few m^2 maximum), because of their youth. Chemical surveys of springs were described by Sheppard (1986), Keywood (1991), Simmons et al. (1993) and Simmons et al. (1994). Application of the K-Na and K-Mg geothermometers to spring waters indicates deep equilibration temperatures between 240^o and 260^{o}C.

Before 1886, the focus of surface activity was in the middle of the present day Lake Rotomahana (Fig. 16 & 17). Detailed descriptions and a map of the springs here as they appeared in 1859 were provided by Hochstetter (1964). At that time, Lake Rotomahana was much smaller an no more than a few metres deep; it was around this that thermal activity occurred (Fig. 17). Two prominent geysers, Otukapuarangi and Te Terata, fed the majestic Pink and White Terraces, respectively. These silica sinter terraces stepped down to the lake shore from about 20-25 metres above lake level and were the largest in New Zealand and perhaps the world. Analyses of water indicates that both Otukapuarangi and Te Terata discharged neutral chloride waters. A number of other near boiling springs, steaming ground and mud pools existed nearby (Hochstetter, 1864). The longevity of hydrothermal activity required to form the Pink and White Terraces, and the presence of both acid-sulfate and neutral chloride waters suggests that this area was situated above an upflow zone of boiling fluids in a hydrologic setting similar to that seen today at the Champagne Pool and Collapse Craters area of Waiotapu.

The Pink and White Terraces were destroyed in the early morning hours of 10 June, 1886 during a devastating fissure eruption of basalt magma. The eruption broke out on the summit of Mt Tarawera and activity migrated both northeast and southwest off the mountain into the Lake Rotomahana area.

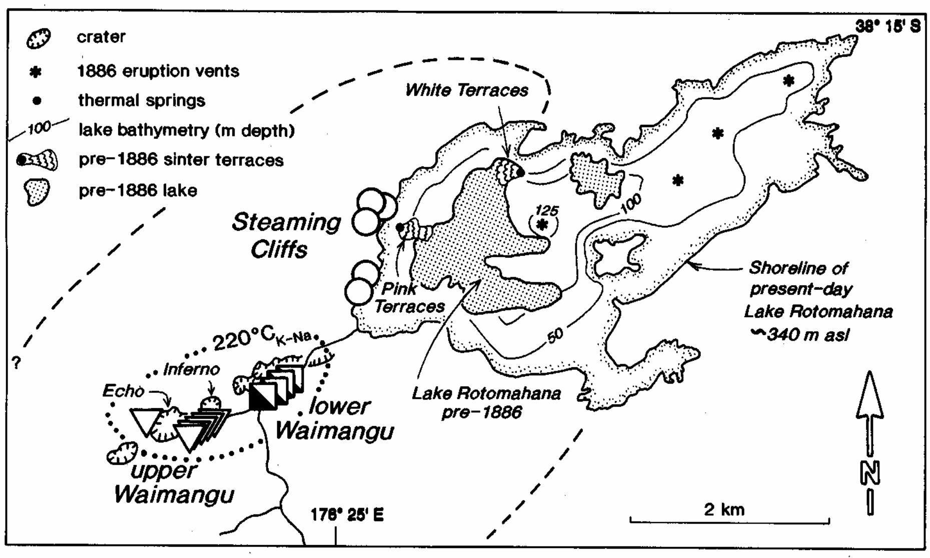

Figure 17. Location of present day thermal features and their relationship to the Pink and White Terraces and the pre-1886 Lake Rotomahana. The dashed line represents the 10 Ωm resistivity boundary (current electrode spacing 1100 m) delimiting the subsurface region occupied by chloride waters (Bennie et al., 1985). Dotted line represents 220°C isotherm based on K-Na geothermometer.

A phreatomagmatic phase ensued when basalt magma encountered the Rotomahana hydrothermal system resulting in violent explosions, as indicated by base-surge deposits, which dispersed very fine-grained material "Rotomahana Mud" up to several kilometres from source (Nairn, 1979). This phase was responsible for the deaths of 108 people. The eruption terminated before dawn, with its last phases forming the vents in the Waimangu Valley. It was at least five years after this eruption before any surface flows began in the Waimangu Valley.

Since the 1886 event, thermal activity at Waimangu has been characterised by episodic outbursts, including the Waimangu Geyser (Fig. 23), which played between 1901 and 1904, and the 1917 hydrothermal eruption from Echo Crater. The thermal instability of the area is attributed to the modification of surficial hydrology through the enlargement and deepening of Lake Rotomahana and formation of new fluid conduits. After the 1886 eruption, the shallow part of the Rotomahana hydrothermal system cooled due to shallow cold water influx, but since then it has been heating up (Simmons et al., 1993). Modern hydrology, hydrothermal eruptions and cyclic activity of the new crater lakes are described by Lloyd and Keam (1974), Scott and Lloyd (1982), Scott (1992, 1994).

Overview of the Waimangu Valley

Looking down the axis of the Waimangu Valley, we see Echo and Inferno Craters (Fig. 18) which are among the last vents that formed during the 1886 eruption. This lookout is near the site of the Accommodation House that was destroyed during a sequence of hydrothermal eruptions that originated from Echo Crater staring on 1 April 1917. The early phases of the 1917 eruption, which lasted three days, ejected material with a lateral trajectory that destroyed the Accommodation House and killed two if its occupants. Before this, the Echo Crater depression was infilled with alluvium washed from the surrounding slopes (devegetated by the 1886 eruption). Steam fumaroles dotted the surface of the depression, hence its name, Frying Pan Flat. The 1917 eruptions, however, ejected a large volume of unconsolidated and consolidated rock material. The new subcraters became a single lake by June 1918.

Southern Crater

This is the southernmost crater formed during the June 10 eruption. It contained boiling water when first seen after the eruption, but was dry soon afterwards. At various times since, however, a shallow lake has been present. Minor warm ground occurs at the eastern part of the crater. In the exposure opposite the Southern Crater lookout, Rotomahana Mud (1886) is overlain by Frying Pan Flat Breccia (1917), although their contact is difficult to see. Most of the walls are formed in Earthquake Flat Ignimbrite (60 ka).

Figure 18. View along the Tarawera vent lineation from Waimangu, across Lake Rotomahana, to Tarawera and Mt Edgecumbe. Photo D.L. Homer.

Echo Crater-Frying Pan Lake

Frying Pan Lake has a surface area of 38,000 m^2, and a volume of 200,000 m^3 (Figs. 19 and 20). The lake overflows continuously into Hot Water Creek draining from the northeast corner. The volume of water overflowing from Frying Pan Lake varies inversely with the water level in Inferno Crater, indicating that there is a subsurface hydrologic connection between them (Scott and Lloyd, 1982). Keam (pers. comm.) determined that the hottest region of the lake is located in the southwestern basin where surface lake temperatures are generally 8°C higher than the outlet, while the main body of the lake is 3°C higher (see also Mongillo, 1994). Diurnal temperature fluctuations of up to 6°C occur on fine sunny days. Scott (1992) reports a mean enthalpy of 749 ± 19 kJ^{-1} for the 1971-1990 period, having ranged from 722 to 791 kJ kg^{-1}.

The discharge temperature ranges from 42.1°C to 58.9°C, with the mean being 50.1 ± 0.8°C. Discharge fluctuations are influenced by both climate and hydrothermal processes. The mean daily discharge has ranged from 65.7 litre sec^{-1} to at least 219 litre sec^{-1}. There is a long term low amplitude variation in the discharge with a dominant periodicity of about 40 days. This is inversely related to the water level in Inferno Crater lake.

Iron-rich siliceous precipitates containing tungsten (up to 4 wt. %) are presently forming. Seward and Sheppard (1986) attribute this to adsorption of negatively charged tungstate ions onto positively charged ferrihydrite colloids. Associated elements including arsenic, antimony, phosphorous, molybdenum and vanadium are also enriched in the precipitates (Table 3).

Inferno Crater

The steep sides of Inferno Crater are carved out of the flank of the Mt. Haszard rhyolite dome (Fig. 18). The deepest part of the crater lies at its centre and is about 30 m below the highest water level (Keam, 1981a) (Fig. 21). Since the 1970s, the water level and temperature of water in Inferno Crater have been monitored (Scott and Lloyd, 1982; Scott, 1994). The water level of Inferno Crater's lake fluctuates over 8 metres with respect to overflow level over a period of 40 days (Fig. 22). When overflowing the lake has a volume of about 65 200m^3 and a surface area of 7,500 m^2 (about 20% of Frying Pan Lake). Scott (1992) reports an average enthalpy of 1197 ± 117 kJ kg^{-1} for the 1971 to 1990 period. Overflows typically last 51 hours, with a mean flow rate of 79.1 litres sec^{-1}. Temperature also fluctuates with water level and ranges from 35°C when the lake is low to about 70.6°C when the lake overflows (Fig. 22).

The water is an acid-sulfate chloride type (pH ~2.5, >800 ppm Cl) affected by oxidation (sulphide to sulphate) and evaporation. Its pale blue colour is almost certainly due to the presence of suspended silica.

Waimangu Geyser Site

This otherwise unremarkable place is the site of the Waimangu Geyser (Fig. 23). This spectacular geyser behaved in a cyclical manner and ejected a mixture of mud and water to heights of 100 to 460 m (hence its Maori name, meaning "black water"). The geyser followed a 36 hour cycle.

Lower Haami Valley (not visited)

A number of springs discharge neutral chloride waters here. Those at Iodine Pool and Warbrick Terrace have compositions which are believed to represent most closely the deep aquifer fluids. Warbrick Terrace has been artificially built up, but note the strange columnar shapes of silica and algae which grow from the bottom of the pool.

Table 3. Analysis of siliceous precipitates from (a) near outlet of Frying Pan Lake, (b) Warbrick Spring discharge apron, and (c) Bird's Nest Terrace near the mouth of Cold Water Stream; analyses are in mg/kg except where indicated. The temperature and pH and for the water at the point of sample collection. From Seward and Sheppard (1986).

	t (°C)	pH	Cr	Mo	W	As	Sb	Fe	Ge	Ag	Au
(a)	53	3.8	150	500	4.5%	8.8%	105	20.7%	5	2	0.03
(b)	68	6.6	100	-	0.05%	0.5%	55	28.7%	25	-	-
(c)	95	8.2	20	5	<0.001%	0.04%	12	4.0%	40	-	-

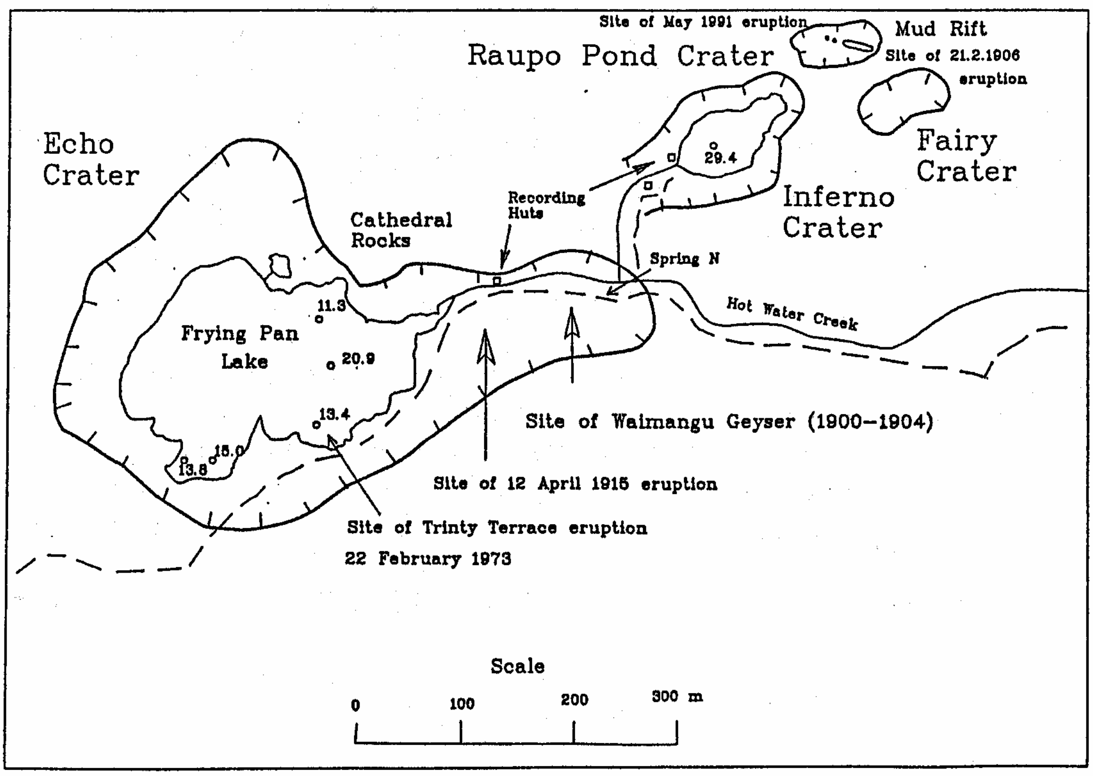

Figure 19. Sketch plan of Echo Crater and inferno Crater area. Numbers in the lakes are depths (after Keam, 1981a, b).

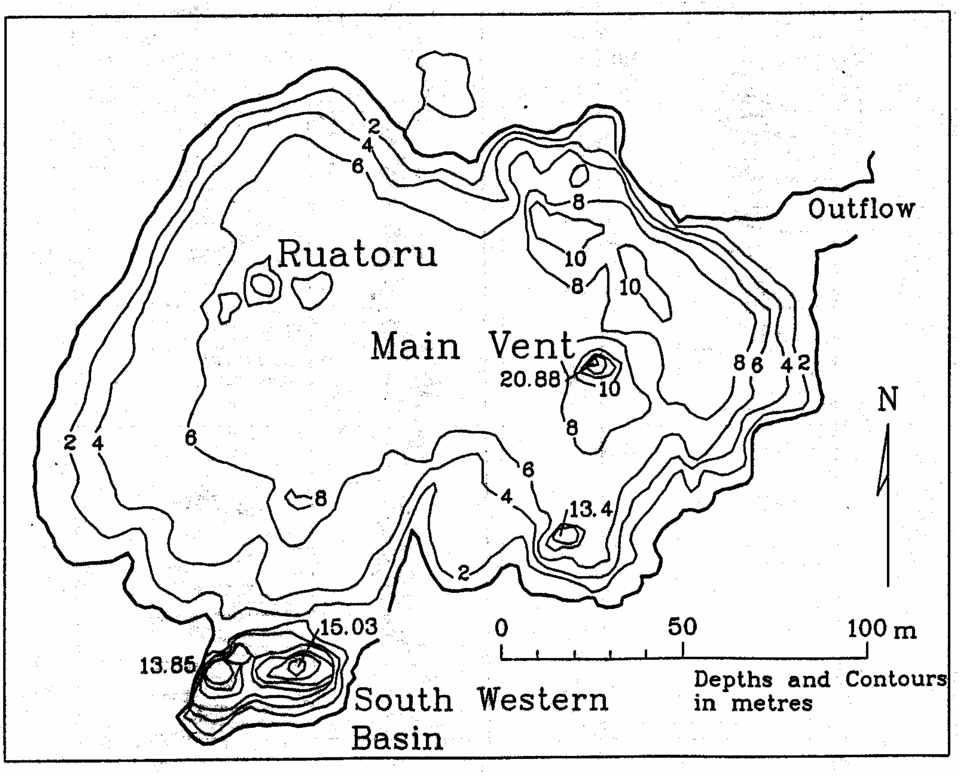

Figure 20. Simplified bathymetric map of Frying Pan Lake (after Keam, 1981b).

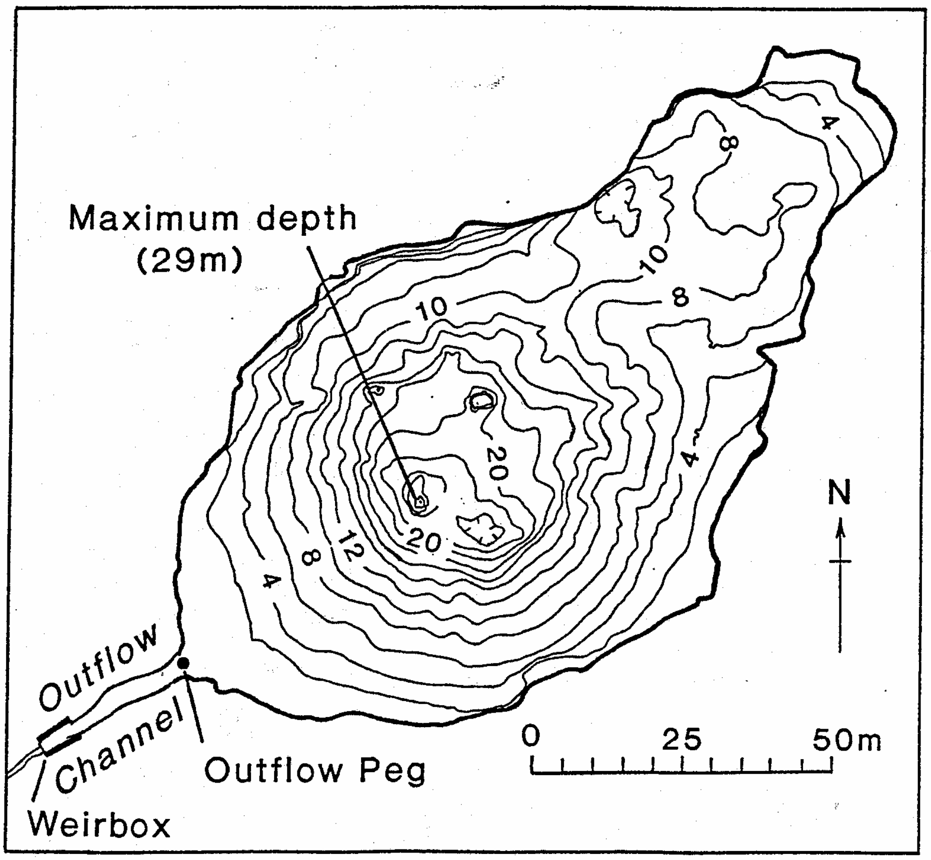

Figure 21. Simplified bathymetric map of Inferno Crater lake (after Keam, 1981a).

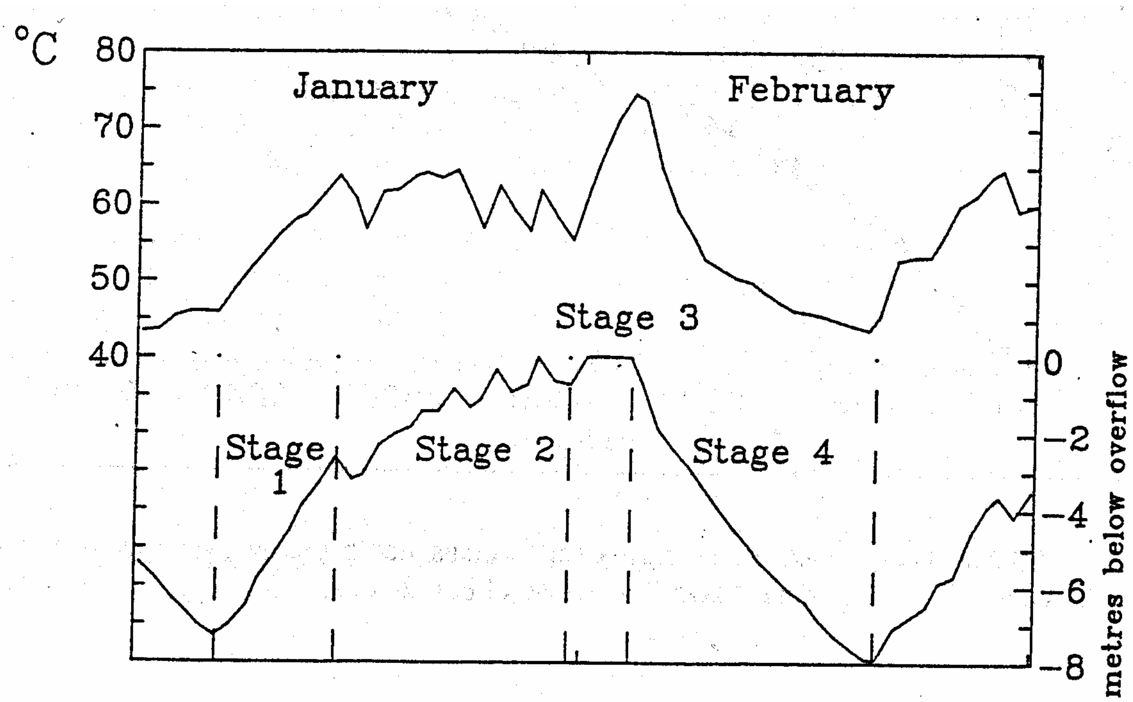

Figure 22. Temperature and water level of Inferno Crater lake for Jan-Feb 1973, showing the four stages of the cycle (Scott, 1994)

Figure 23. Waimangu geyser in eruption (Iles).

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APPENDIX 1
OHAAKI GEOTHERMAL POWER PLANT

Contact Energy Limited

Contact Energy Ltd is responsible for the operation of the Ohaaki Geothermal Power Plant.

Contact Energy Limited was formed on 1 February 1996 following a split of the generation assets of the Electricity Corporation of New Zealand Limited (ECNZ). This split formed two competing state owned electricity generating companies, Contact Energy and ECNZ.

Contact Energy owns and operates approximately 26% of New Zealand's total power generation capacity and produces about 25% of New Zealand's electrical energy. The company operates Clyde and Roxburgh hydro power stations; New Plymouth, Otahuhu, and Te Rapa thermal power stations; and Wairakei, Ohaaki and Poihipi geothermal power plants. Contact Energy also has an interest in two thermal power stations in Australia - Oakey in Queensland and Valley Power in Victoria.

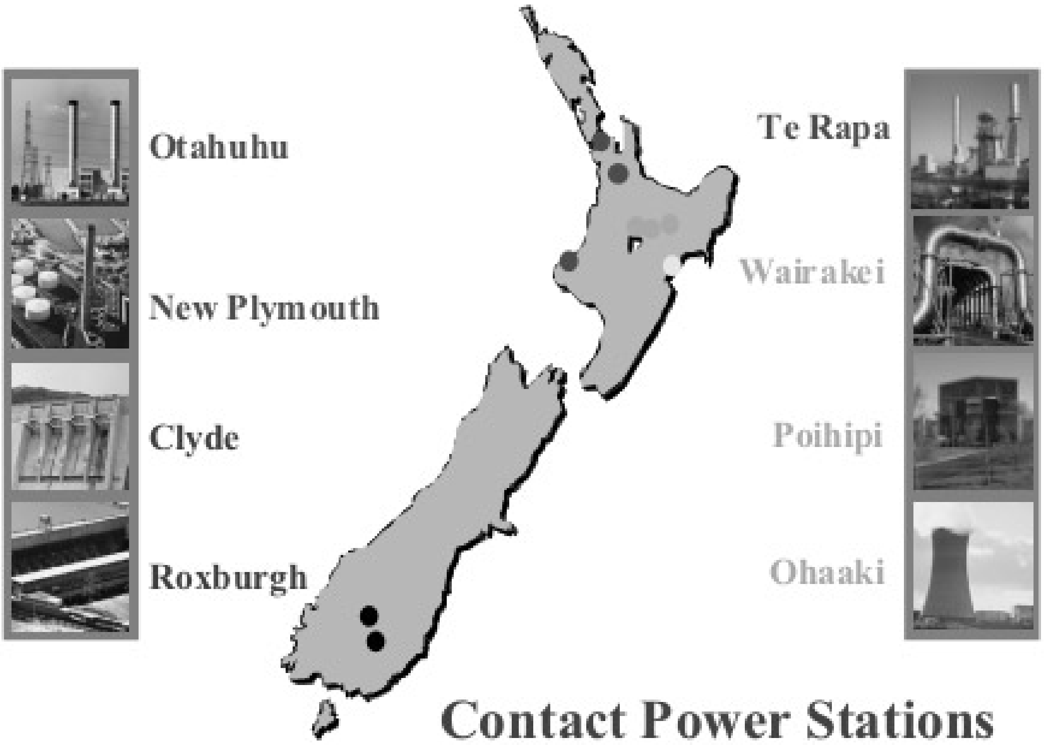

Figure 1. Contact Energy's New Zealand Power Plant Sites

Ohaaki Geothermal Power Plant

Government approval for the construction of the Ohaaki Geothermal Power Plant was given in 1982. The station, which is remotely controlled from Wairakei, has a gross installed capacity of 116 MW. This is comprised of two intermediate pressure steam turbine generator sets of 47 MW and two high pressure steam turbine generator sets of 11MW. Approximately 8 MW are required for auxiliary power, mainly for gas extraction, reinjection pumping and cooling water circulation. The net capacity of the station is 108 MW.

Electricity generation at Ohaaki started in the second half of 1988, all the generation sets were commissioned by May 1989, and the station was officially opened on 31 October 1989, by the Governor General, Sir Paul Reeves.

Steamfield

17 production wells, ranging in depth from 400m to 3,000m, currently supply hot geothermal water (up to ≈280ºC) from the underground geothermal reservoir for use at the Ohaaki Power House.
The geothermal water from a group of wells is fed to a common separation plant. There are two separation plants in the eastern steamfield and two in the western steamfield. A typical separation plant

Plate 1. Separation Plant

consists of a grouping of vertical cylindrical vessels up to 3 metres in diameter and 11 metres high with associated pipe work. The two phase flow from the wells consists of a mixture of water and steam. At the separation plant the two phases are separated in a two stage process to produce high (≈8 bar g) and intermediate (≈3.5 bar g) pressure steam and water.

Steam is piped via a network of insulated pipes to the Ohaaki Power House to drive the turbines.

There are 6 reinjection wells with an average depth of 1,060m. Separated geothermal water is pumped back into the ground through the reinjection wells at a pressure of 20 to 30 bar g and a temperature of ≈145°C. This temperature is greater than the silica saturation temperature for the water.

Power House

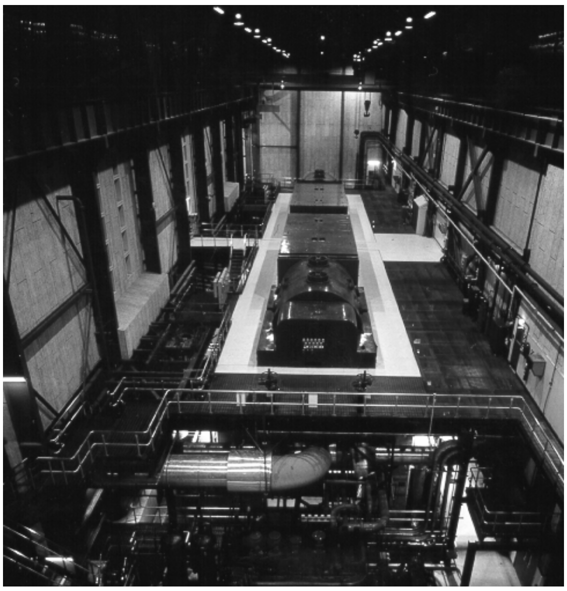

Plate 2 Intermediate Pressure Turbine Hall

The Ohaaki Power House has an installed capacity of 116 MW. This is made up of two 11 MW high pressure steam turbine generator sets (located within the "HP" Turbine House) and two 47 MW intermediate pressure condensing steam turbine generator sets (located in the "A" Station Turbine House). One intermediate pressure set is currently decommissioned due to the steam availability from the steamfield.

High pressure steam from the steamfield is passed into the two 11 MW high pressure steam turbine generator sets which convert the energy in the steam into electricity. Steam exits the turbines at a lower pressure and combines with intermediate pressure steam from the steamfield. This generates electricity as it passes through the 47 MW condensing steam turbine generator set. Efficient use of the steam in a condensing turbine is achieved by condensing the steam to water as the steam leaves the turbine. This is undertaken in a condenser where cooling water absorbs the heat energy in the steam passing out of the turbine, condensing it to water. Using a condenser enables significantly more energy to be extracted from a given amount of steam and hence improves the efficiency of the plant.

The condensed steam (condensate) mixes directly with the cooling water sprayed into the condensers and is drained into the Hotwell from where it is pumped back up to the cooling tower to be cooled down. This cycle is then continuously repeated. The heat energy gained by the cooling water as it passes through the condenser is transferred to the air passing through the cooling tower. Gas extracted from the condensers is discharged into the cooling tower plume.

Because the condensed steam mixes with the cooling water the volume of water in the cooling circuit increases. This surplus condensate is reinjected back into the ground.

The cooling tower is a visually dominant feature of the Ohaaki site. It is 105m high with a base diameter of 70m and a top diameter of 45m. The reinforced concrete shell is 160mm thick over much of its height. Its distinctive hyperbolic shape gives strength to the relatively thin walled structure. The height of the tower is designed to create a natural upward flow of air through the tower to enable the water to be cooled.

Transformers, which step up the voltage from 11 – 14 kV from the generators to the national grid voltage of 220kV, are located adjacent to the Power House.

A switchyard, owned by Transpower New Zealand Limited is located adjacent to the Power House. This provides the electrical connection to the National Grid.

The Ohaaki Geothermal Power Plant is operated from the Geothermal Group Control (GGC) at Wairakei using a supervisory computer system. The maintenance, management and support staff are based at Wairakei and visit Ohaaki as necessary to service the facility. Some 64 staff support the Ohaaki, Poihipi and Wairakei Geothermal Power Plants.

Production History

Figure 5.1 plots the energy produced from Ohaaki with time.

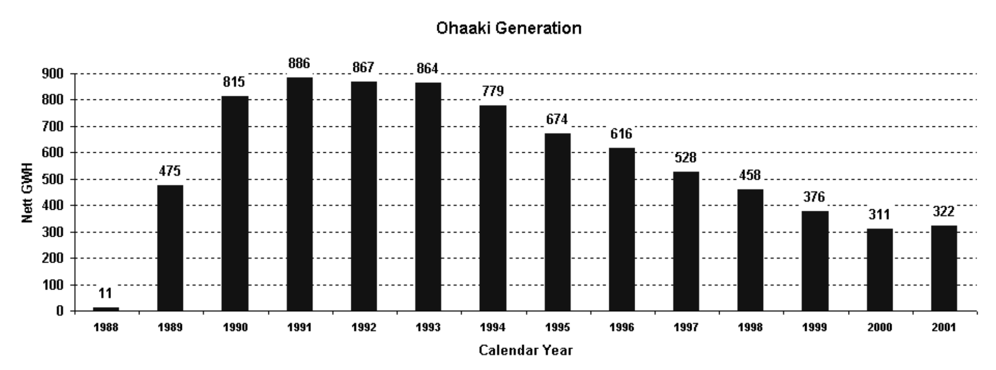

Figure 2 Ohaaki Generation

Contact energy is looking to target up to 70 Mwe gross production from the plant over a 15 year planning horizon. Additional drilling will need to be undertaken to achieve this level of production.

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