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THE ROTORUA GEOTHERMAL FIELD, NEW ZEALAND: ITS PHYSICAL SETTING, HYDROLOGY, AND RESPONSE TO EXPLOITATION

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Abstract—Rotorua geothermal field contains New Zealand's only area of geyser activity that has not been significantly affected by power developments. Geophysical and geochemical investigations of the field indicate that it has an area of 18-28 km^2 at about 500 m depth, and a natural heat flux of 430±30 MW. About a third of its area and over half its heat and mass flux occur beneath the southern end of Lake Rotorua. Aquifer pressure beneath much of Rotorua City is controlled by the lake level, and is uniform due to high permeability in the rhyolitic host rocks. Pressure in the high temperature zone in the south east of the field is about 1.5 bar higher than in the rhyolite, and is controlled by the elevation of the main discharges in the geyser area. Although significant natural changes in the geyser activity at Rotorua have occurred historically, the progressive decline of spring and geyser outflows observed since about 1970 was caused by increasing withdrawal from wells tapping geothermal fluids at up to 300 m depth beneath Rotorua City. Detailed monitoring during the 1980s showed that aquifer pressure head was varying by up to 1 m in amplitude in response to a seasonal drawoff from wells of 290 to 360 kg/s, and average head was declining by over 0.1 m/y. Enforced closure of wells within 1.5 km of the geysers has resulted in a recovery of over 2 m, and the geyser activity being rejuvenated.

INTRODUCTION

Rotorua geothermal field contains New Zealand's one remaining area of major geyser activity. The field is situated near the northwestern edge of the late Quaternary rhyolite volcanism of the Taupo Volcanic Zone (Fig. 1). Although there are over 20 geothermal fields with natural heat outputs typically between 100 and 400 MW(thermal) in the zone, only three have been noted for their outstanding geyser activity this century: Wairakei-Tauhara, Orakeikorako, and Rotorua. During the 1950s and 1960s, the extraction of subsurface fluid for geothermal power caused the demise of geyser activity at Wairakei, and the flooding of many of the geysers at Orakeikorako resulted after the construction of a hydroelectric dam. These events, and the growing use of the subsurface geothermal fluids beneath Rotorua, heightened public sensitivity to the values of New Zealand's remaining geyser field. Concern increased during the 1980s with the failure of some of the Rotorua geysers and nearby hot springs. Fears that the geysers would be lost if exploitation of the field continued, resulted in the government-enforced closure of wells in 1987.

The geysers and thermal waters of Rotorua have always been highly valued. The thermal activity has a special place in Maori culture, being used for bathing, cooking, heating, and processing a range of natural products, and is listed among their *taonga* or most prized possessions. Since European settlement of the region in the early 1800s, the geysers have gained world renown (Donaldson, 1985; Cody and Lumb, 1992) and Rotorua has become one of New Zealand's major

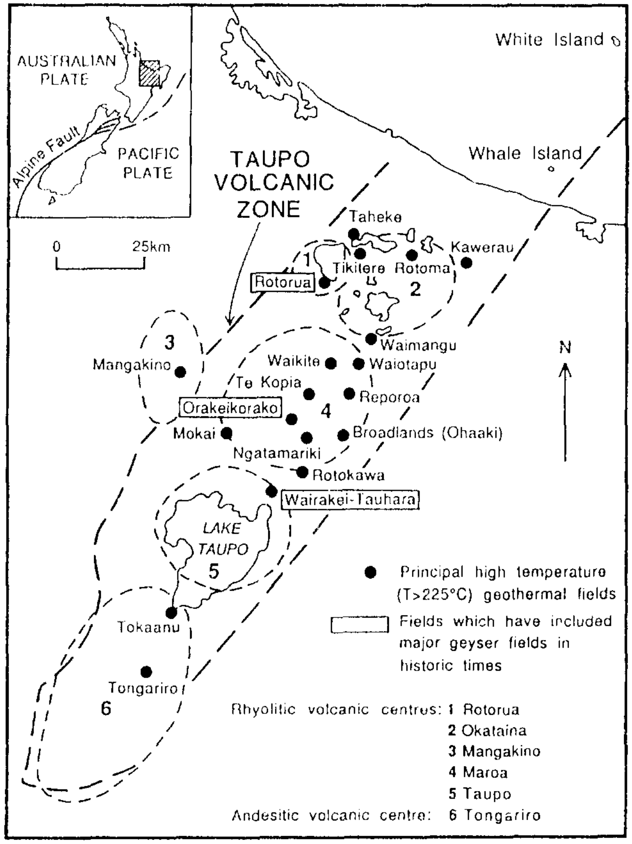

Fig. 1. Distribution of the major volcanic centres, geothermal fields, and geyser areas in the Taupo Volcanic Zone (TVZ) of New Zealand. The outlines of the TVZ and the volcanic centres are after Cole (1990).

tourist destinations. The geyser activity is concentrated in the Whakarewarewa thermal area (Fig. 2), near the southern end of Rotorua city, with Pohutu geyser being the most spectacular and regular performer for most of this century (Cody and Lumb, 1992). However, other thermal areas containing a mix of hot springs, pools, mudpots, steaming ground or gas vents also occur adjacent to Whakarewarewa in the Arikikapakapa golf course, further north around the southern shores of Lake Rotorua (Ohinemutu, Government Gardens, and Ngapuna), and in the floor of Sulphur Bay, Lake Rotorua (Fig. 2).

Many of Rotorua's residents have taken advantage of the geothermal waters by drilling wells to extract the hot fluids. These fluids were used for both domestic and commercial heating, with some of the largest commercial users being Government Department offices, hospitals and major tourist hotels (Task Force, 1985). The first geothermal wells in Rotorua were drilled during the 1920s, with close to 750 wells whose date of drilling is recorded, having been drilled since then (Fig. 3). Some of these were replacement or standby wells, and some wells were not replaced after casing failures or blockages, so the actual number of wells in use reached a maximum of around 500 in 1985. At that time, the total well discharge was estimated to be 25 000 t/day (290 kg/s) during summer months, rising to 31 000 t/day (360 kg/s) during winter months. Only 5% of the discharge fluids were estimated to be reinjected to production depths (typically 100 - 200 m). Most of the waste liquid was being put into shallow soak holes (<20 m depth) and, contravening a local

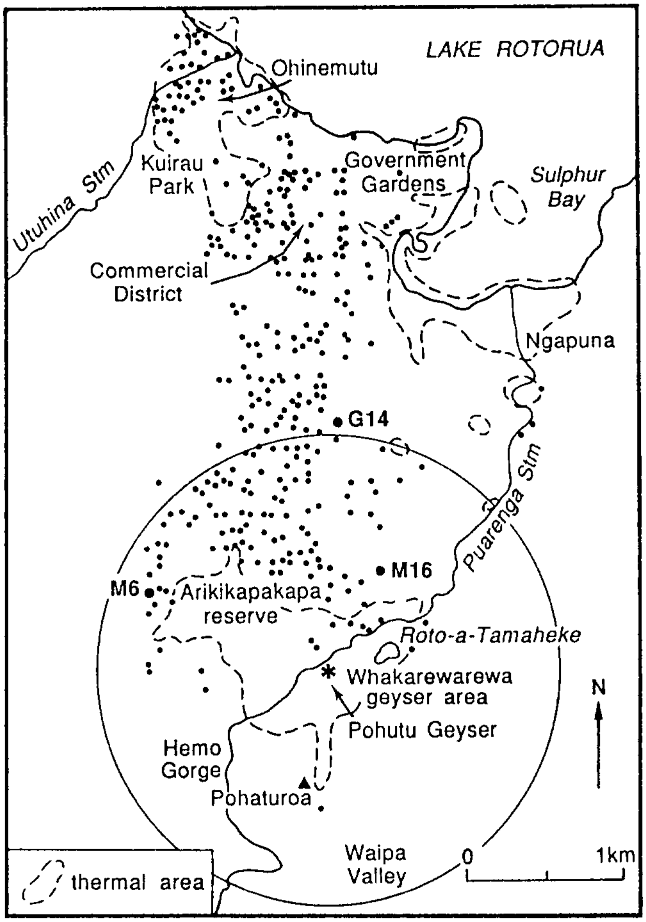

Fig. 2. Distribution of geothermal wells in use in 1985 (after Monitoring Programme, 1985), and the main areas of thermal activity (mapped by Mongillo and Bromley, 1992) in the Rotorua geothermal field. Special features and wells referred to in the text have been labelled.

by-law, into the storm water drains. Approximately half the fluid extracted was for residential use and half for commercial use. However, because many wells in the residential sector were shared by several households, 1500 of the total 1840 geothermal users were residential. The dominant commercial sector user in 1985 was tourist accommodation which used 20% of the total discharge (Task Force, 1985).

The effect of the bore closure programme, when all wells within 1.5 km of Pohutu geyser were cemented up (mostly during 1987), and a charging regime for remaining well discharges was implemented, was a reduction of the total well discharge to about 30% of 1985 levels by 1989 (Fig. 3; Timpany, 1990). The average summer drawoff in 1990 is estimated to be 10 280 t/day (118 kg/s) increasing in winter by 1040 t/day (12 kg/s). The commercial sector now accounts for 68% of the total discharge, and the reinjected mass has risen to 31% of the discharge (Timpany, 1990). The net mass withdrawal from the field in 1990 has therefore decreased to close to 20% of the 1985 level.

Fluid pressure beneath Rotorua has recovered about half the inferred drawdown caused by a combination of exploitation and a long-term decrease in rainfall prior to the mid 1980s (Bradford,

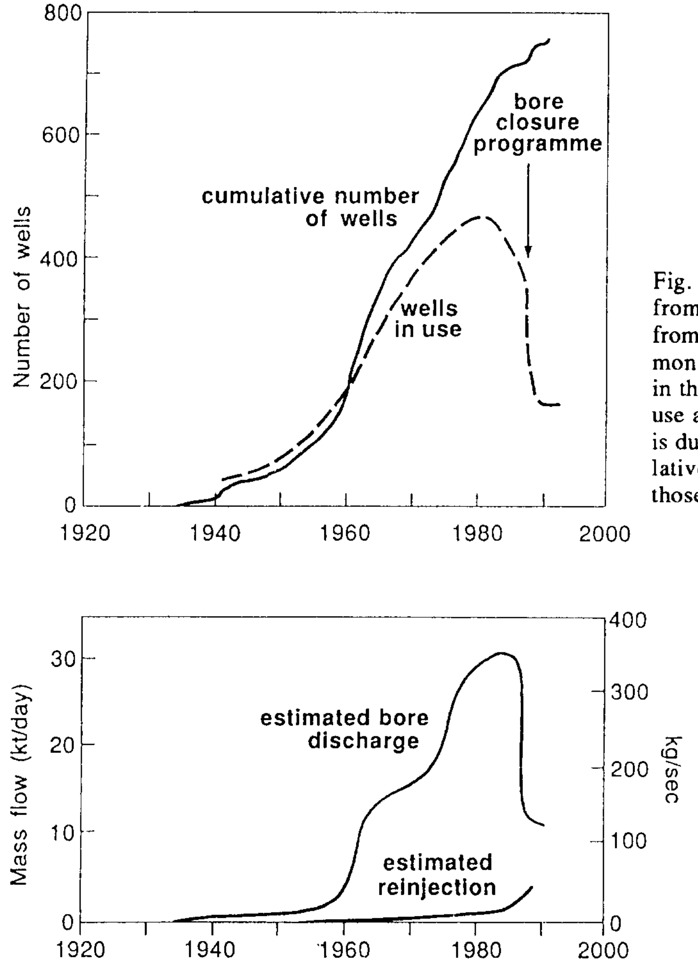

Fig. 3. Pattern of geothermal fluid use from wells in Rotorua City (derived from Timpany, 1990; and data from the monitoring programme). Differences in the curves for the number of wells in use and the cumulative number of wells is due to different data sets. The cumulative number of wells includes only those where exact date of drilling is known.

1992b). The geyser activity and hot springs have been rejuvenated with some springs overflowing for the first time in over 30 years (Cody and Lumb, 1992). The response of the geothermal field to exploitation and its subsequent recovery are reviewed in more detail below.

The primary purpose of this paper is to provide a synthesis of the extensive research carried on Rotorua geothermal field over the last 10 years. Results from the intensive monitoring of the field and from the investigation of geothermal fluid use at Rotorua during the mid 1980s were published as two major reports (Task Force, 1985; Monitoring Programme, 1985), but these were not widely distributed, even within New Zealand. Since then, the Department of Scientific and Industrial Research (DSIR) has focussed geothermal research on resolving some of the uncertainties that existed about the Rotorua geothermal field in order to improve understanding of its physical characteristics and its response to exploitation. The scope of this paper is limited to highlighting what we consider to be the most important features influencing the behaviour of the field. Extensive reference is made to the other papers in this special issue of Geothermics.

PHYSICAL SETTING AND SIZE OF FIELD

Key features of the regional setting of the Rotorua field are depicted in Fig. 4. The field is situated towards the southern margin of a basin which is up to 25 km in diameter, and largely

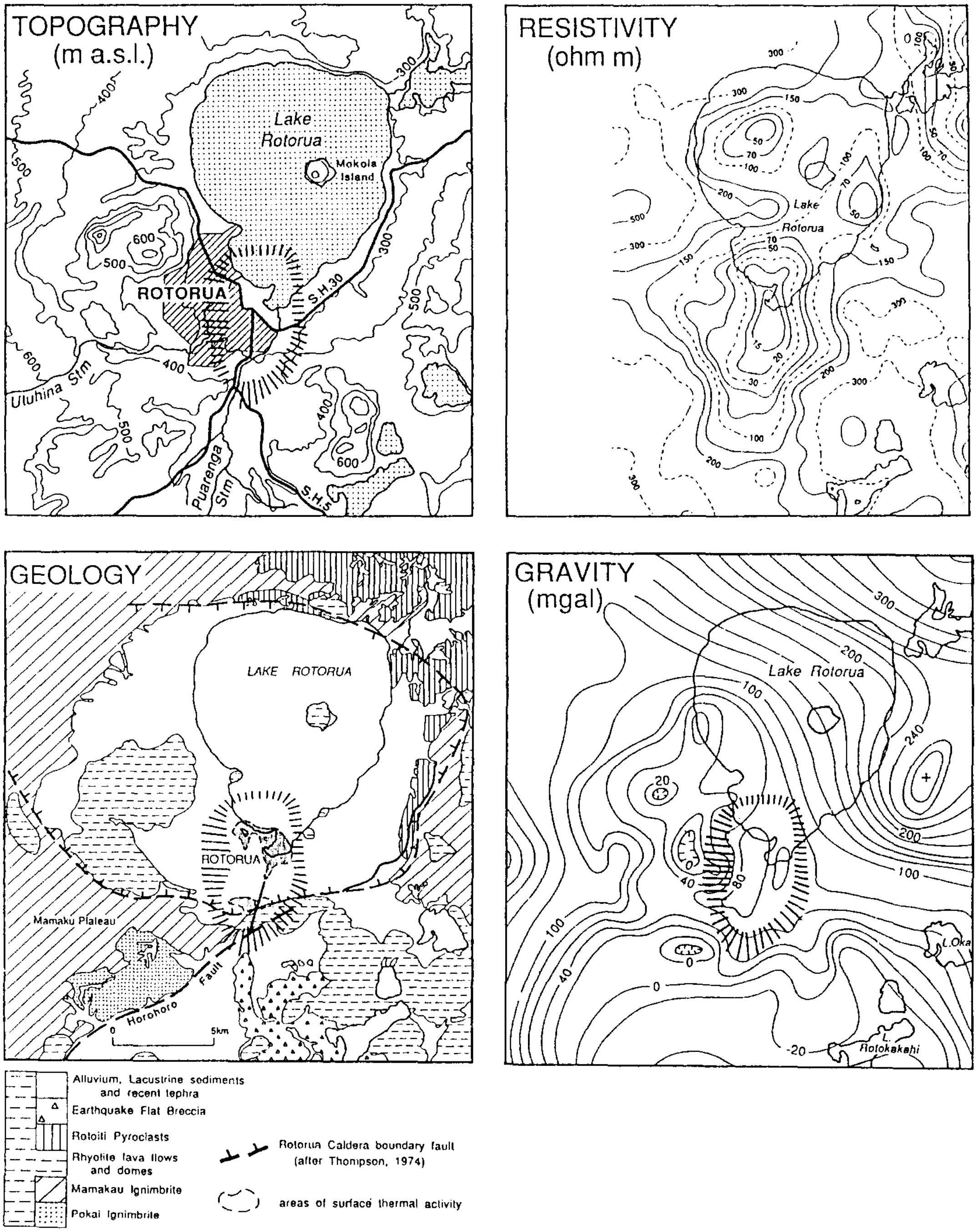

Fig. 4. Maps depicting aspects of the physical setting of Rotorua field. All maps have the same scale; the distance bar is shown in the geology map. The resistivity is from Schlumberger traversing at 1 km electrode spacing (AB/2; Bibby *et al.*,1992). The gravity is from Hunt, (1992), and the geology is from Wood, (1992). The zone of radial hatching is the boundary zone of the field, as interpreted from the resistivity by Bibby *et al.* (1992).

coincides with the Rotorua Caldera (Thompson, 1974; Wood, 1992). The caldera is thought to have been caused by the eruption of 300 km^3 of rhyolitic magma which formed the Mamaku Ignimbrite about 140 000 years ago (Wilson *et al.*, 1984). The eastern, southern and western margins of the basin surrounding Lake Rotorua rise to over 600 m above sea level (asl), whereas the northern margin is less than 500 m asl, and the outflow of the lake is to the northeast at 280 m asl. Lake Rotorua is relatively shallow for its size, with a maximum depth of 40 m. Rhyolite domes erupted about the time of the caldera formation, or soon after, creating local topographic relief within the basin. Mt. Ngongotaha, about 7 km west of Rotorua city, is the highest such dome, rising to over 750 m asl (Fig. 4).

In view of the large outflow from the Rotorua geothermal field into the lake, the lake level is probably the main cold water pressure control for much of the field. There is evidence of silica deposits at higher elevations on the southwest side of the field, coinciding with a period when the lake level was at 370 m asl 50 000 to 22 000 years ago (Wood,1992). Present thermal activity ranges in elevation from less than 100 m above lake level south of Whakarewarewa, to the floor of Lake Rotorua, at about 10 m below lake level.

Electrical resistivity surveying reveals that the area of the geothermal field at around 500 m depth is between 18 and 28 km^2 (Bibby *et al.*, 1992), and that it extends 2 km northwards into the southern end of Lake Rotorua, and 2 km south of Whakarewarewa (Fig. 4). This area is similar to that of many of the major geothermal fields in the Taupo Volcanic Zone. A comparison between measurements made using the 500 m Schlumberger array spacing and the more deeply penetrating 1000 m array indicates that the resistivity boundary zone is nearly vertical along the eastern and northern sides of the field. In the south, the low resistivity appears to be more extensive with increasing depth, whereas along the western boundary, the boundary zone may be more complex, appearing to move inwards with increasing depth. However, a well in the west shows a layer of warm water overlying a colder region below, and the boundary at depth is probably close to vertical. The resistivity anomaly becomes more clearly elongate with increasing depth, with its major axis striking almost due north, suggesting that the upflowing geothermal fluids at about 1 km depth may be controlled, or influenced, by a north-south structural feature such as a fault zone.

The resistivity surveys also delineate low resistivity anomalies coinciding with the Tikitere geothermal field 15 km to the northeast, and a possible geothermal field beneath the floor of Lake Rotorua, southeast of Mokoia Island (Bibby *et al.*, 1992). A third low resistivity anomaly is centred in the northwest part of Lake Rotorua but lake-bottom, conductive heat flow measurements (Whiteford, 1992) indicate this not to be associated with thermal activity. However, conductive heat flow values of more than 1 W/m^2 confirm the northward extension of the Rotorua field into Lake Rotorua, and the presence of a thermal anomaly southeast of Mokoia Island. The conductive heat output from the the Mokoia-east Lake Rotorua thermal anomaly is about 10 MW (Whiteford, 1992). The only known surface manifestations of the latter anomaly are a hot pool on Mokoia Island (Hinemoa Pool, temperature, 54°C; chloride, 66 mg/kg), and two areas of warm seepages on the eastern shore of Lake Rotorua, close to the low resistivity anomaly offshore (Lake Rotokawa, temperature, 57°C; chloride, 179 mg/kg; Giggenbach and Glover, 1992).

The possibility that the Mokoia Island-east Lake Rotorua thermal anomaly could be an outflow zone of the Rotorua geothermal field has been considered by Bibby *et al.* (1992) and several others. On balance, the lack of very low resistivity linking the two thermal areas, and the presence of a magnetic high, perhaps indicative of relatively unaltered rhyolite, between the thermal areas, point to unrelated areas of thermal activity. In addition, the centre of the low resistivity anomaly associated with the Mokoia-east Lake Rotorua thermal area has an apparent resistivity of close to 50 ohm m (Fig. 4), whereas in the area of the known outflows into Lake Rotorua from the Rotorua field, the resistivity is less than 20 ohm m. The sediments over most of the Mokoia-east

Lake Rotorua thermal anomaly may be sufficiently thick to form an impermeable cap preventing fluid outflow through the floor of the lake. If so, the bulk of the geothermal fluid flowing into Lake Rotorua is likely to originate from Rotorua field, around the southern end of the lake.

A detailed study of the fluxes of geothermal indicators such as chloride into, and out of, Lake Rotorua shows that only 40% of the chloride can be attributed to land-based discharges (Glover, 1992). The total geothermal heat output, derived from the chloride flux out of the lake of 0.54 kg/s, is 470 MW. This assumes the chloride originates from a deep geothermal source with a chloride concentration of 1250 mg/kg and an enthalpy of 1085 kJ/kg, consistent with the well and spring data (Stewart *et al.*, 1992; Giggenbach and Glover, 1992). If as argued above, almost all the chloride in Lake Rotorua is from the Rotorua geothermal field, then about 60% of the outflow of geothermal fluid from that field is through the lake floor.

A complicating factor for estimating the undisturbed natural chloride and heat flux for the Rotorua system is the extent of waste geothermal discharges from wells entering the lake through undetected outflows. Glover (1992) estimates that this could have been a maximum of 0.125 kg/s chloride in 1985, diminishing to a maximum of 0.032 kg/s in 1989. This is equivalent to a maximum of about 20% of the total flux based on the 1985 figure or a maximum of about 4% for the 1989 figure. The chloride flux survey was carried out over 1989-90, and the lake has a 550 days residence time. Given all the uncertainties, and the compensating relationship between the natural mass outflow and the drawoff/discharge from wells, the natural heat flux from Rotorua field is likely to be in the range 430±40 MW.

Based on the above analysis, the chloride flux indicates a deep geothermal upflow rate of 400 kg/s (± 10%) of 250°C water with 1250 mg/kg Cl, or around 700 kg/s of water at 150°C with 700 mg/kg Cl at shallower depth, assuming dilution with cold groundwater is the dominant cooling mechanism. These figures confirm that the field is significantly larger than that indicated by the land-based outflows known at the time of the monitoring programme in the mid 1980s, when the drawoff from wells was 330±30 kg/s. This is about half the inferred natural flux of geothermal fluid at typical production depths, perhaps providing a qualitative answer as to why the geysers were not more severely affected by the exploitation.

In addition to the resistivity and chloride evidence for the extent of geothermal discharges from Rotorua field through the floor of Lake Rotorua, seismic reflection profiling also detected anomalies (Davy, 1992). A strong, shallow lakefloor reflector masked deeper reflections, and local pock marks on the lake floor were interpreted to be due to the presence of gas-charged sediments over much of the southern part of the lake. Because the reflection survey was limited to the southern part of the lake, it is not known whether the anomalies occur only in the vicinity of the geothermal field, or whether they are a general feature of Lake Rotorua sediments.

Direct drillhole evidence for major faults controlling the location of the upflow of fluids in the Rotorua geothermal field is lacking. The southern boundary of the Rotorua Caldera as described by Wood (1992) crosses through the middle of the resistivity anomaly, but the north-south orientation of the resistivity anomaly, and a southeast to northwest gradient of fluid pressure at 100 to 200 m depth within the field (Fig. 5) do not support the caldera boundary fault being a dominant factor controlling fluid flow. Across the boundary fault zone, which includes subparallel "inner caldera" faults, the Mamaku Ignimbrite is down-thrown to the north by around 400 m over a 3 km distance (Wood, 1992). In the vicinity of Ngapuna, the upper surface of the ignimbrite is about 200 m below lake level. It should be noted here that there is no gravity "signature" of the type generally regarded as typical of a caldera boundary. The question as to whether the Rotorua field lies close to the margin of a typical caldera must remain unanswered, but Wood (1992) provides the interesting variant of a "hinged" collapse region.

A second major fault zone which may be relevant to the location of Rotorua field is the Horohoro fault (Fig. 4). The surface trace of this northeast-trending, southeast-dipping fault crosses the southern resistivity boundary and ends near the caldera boundary. A NNE-trending splinter from this fault is marked by thermal ground south of Pohatoroa hill and passes through Roto-a-Tamaheke, an overflowing lakelet at the northeast end of the Whakarewarewa geyser area (Wood, 1992). The lakelet dominates the heat flow from Whakarewarewa (33 MW, or 40% of the total heat flow from Whakarewarewa in 1985, Cody and Simpson, 1985), and nearby springs have the highest chloride concentrations at Whakarewarewa (> 800 mg/kg Cl, Glover, 1985). It is not known whether the Roto-a-Tamaheke fault completely crosses the caldera boundary fault zone. Simpson (1985) has suggested that there is a slight easterly offset at an inner caldera fault, and a second fault (named the Ngapuna Fault) continues trending NNE into Sulphur Bay. The presence of the Ngapuna fault remains conjectural (refer to Wood, 1992, for location), although a seismic reflection line crossing this region suggests at least 4 minor faults (Lamarche, 1992).

HYDROLOGICAL CHARACTERISTICS

During the 1980s in particular, a massive amount of data on the physical and chemical characteristics of the wells and springs of Rotorua field was collected as part of the Rotorua Geothermal Monitoring Programme. The extent of information available on the field is unusual because, although there are several hundred wells, they are mostly concentrated within only 10 km^2 of the 18 to 28 km^2 area of the field, and almost all are less than 300 m deep. There is, therefore, a very large amount of data available for a relatively shallow, horizontal slice of part of the field, but very poor information on the depth dimension of the field, especially when compared to many other fields in New Zealand which are drilled to 1.5 to 2.5 km depth. This limits the accuracy of even conceptual hydrological models of the field which usually indicate the location of an "upflow zone" at several kilometres depth, and the location of boiling and dilution processes in "outflow zones" typically within a kilometre of the surface.

A selection of critical physical and chemical data from wells and springs of Rotorua field is mapped in Fig. 5. Temperatures and pressures are plotted at a constant elevation of 180 m asl, which corresponds to 100 m below lake level. Most wells penetrate this datum, and although care is needed when interpreting downhole data from wells whose feedzones are at greater depth, the resulting maps are considered, for the purposes of this paper, to be more instructive than maps on a laterally varying datum such as a stratigraphic, permeable geological unit. The distribution of wells (Fig. 2) gives an indication of the density of data across the maps; data is scarce towards the cooler margins of the field. This is critical south of Whakarewarewa thermal area, where there are only two wells, about 1 km further south in the Waipa valley.

The temperature map (Fig. 5a) shows a roughly north-south trending anomaly which coincides with the zone of lowest resistivities. There are two temperature maxima indicating areas of upflow at 180 m asl: one including Whakarewarewa geyser area, and one centred on Kuirau Park near the crest of the northern of two rhyolite domes whose extent and location are shown in Fig. 5b. The north dome rises to 280 m asl, the south dome to 240 m asl. The role played by the rhyolite domes in the hydrology of the Rotorua geothermal field is discussed by Wood (1992).

The two low temperature embayments into the main thermal anomaly (northeast of Whakarewarewa and south of Kuirau Park) appear to be due to two different causes. The cool embayment on the west side of the field, south of Kuirau Park, coincides with the saddle between the two rhyolite domes underlying Rotorua city (Wood, 1992). This also overlaps the region of anomalously high tritium ratios in well discharges (Stewart *et al.*, 1992 and Fig. 5d) and low soil gas flux (Finlayson, 1992). The uppermost 40 m of the domes are very permeable, and constitute the main aquifer for most production wells. However, many wells in the central city area have temperature inversions, which have been attributed to cooler fluids moving laterally from

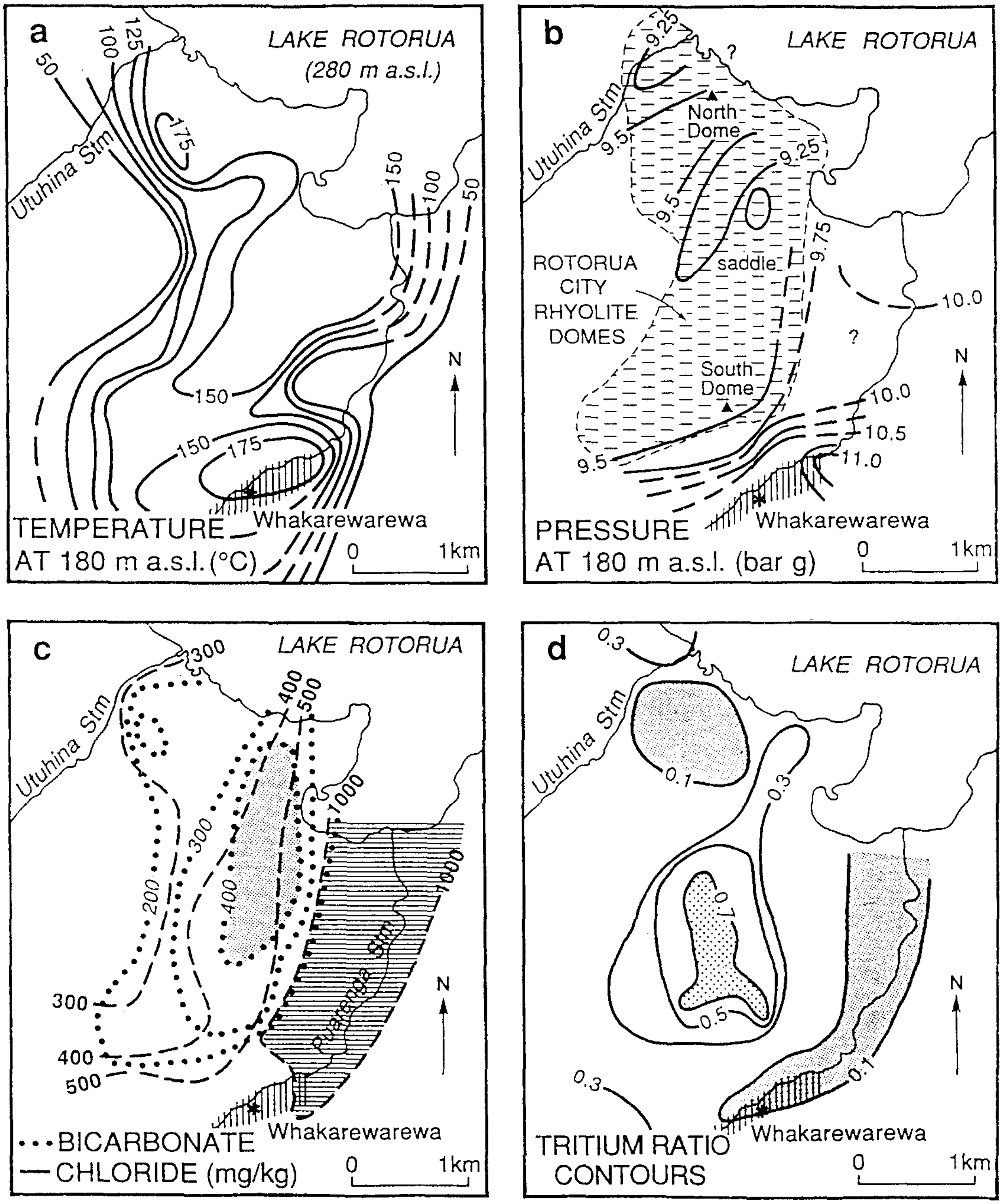

Fig. 5. Hydrological characteristics of the Rotorua field. The temperature and pressure contours are derived from Grant *et al.*, (1985); the bicarbonate, chloride and tritium ratio contours are from Stewart *et al.*, (1992). The vertical stippling on all four maps shows the extent of the Whakarewarewa geyser area, with Pohutu geyser marked as a star.

the west within the rhyolite (Wood, 1992). All the above factors are consistent with the mixing of shallow groundwater with geothermal fluids in the west-central part of the field, producing temperatures which are significantly below the boiling point between 180 m asl and the ground surface.

The eastern embayment of cooler temperatures occurs where the main hot Mamaku Ignimbrite aquifer is situated deeper than 180 m asl, and is overlain by less permeable sediments. In fact, the highest temperatures measured in the field (200 - 210°C at 50 m asl) have been measured in a well near Ngapuna. Thus, at greater depth, thermal boundary along the eastern side of the field appears to be situated further east than indicated in Fig. 5. It probably lies east of the Puarenga Stream at more than 200 m depth.

Pressures at 180 m asl are fairly uniform over a large part of Rotorua City, with the highest pressures occurring towards the southeastern side of the field (Fig. 5b, derived from Grant *et al.*, 1985). The region of uniform pressures (9.5±0.25 bar gauge) includes the rhyolite aquifer, and indicates relatively high permeability. This is confirmed by interference tests indicating transmissivities of the order of 100 darcy metres (Grant *et al.*, 1985). The occurrence of extensive outflows from Rotorua Field into Lake Rotorua suggests a highly permeable connection at shallow depth. The equivalent cold water pressure at 180 m asl due to Lake Rotorua is 10.0 bar, so if the rhyolite aquifer was in good communication with the lake, at or beneath that datum (i.e. 100 m below lake level), then the aquifer would be underpressured and could be invaded by lake water. The stable isotopes from springs and well waters show that this is not the case (Stewart *et al.*, 1992). However, the 9.5 bar hot water pressure in the rhyolite aquifer is exactly balanced against the lake if the communication is near the ground surface at lake level, and the average temperature in the hot water column above 180 m asl is 110°C. In the vicinity of the north dome, the aquifer pressure probably exceeds that beneath the lake, whereas around the saddle between the domes, both lower pressures and temperatures suggest that a zone of relative underpressuring existed in 1985. This is an area of major drawoff from wells so the lower pressure is likely to be a drawdown effect. The same explanation probably applies to the other low pressure anomaly around Ohinemutu. Measurements made since the period of bore closure (1986-87) show that temperature-adjusted water levels of wells tapping the rhyolite aquifer are now typically in the range 280±1 m asl (i.e. lake level). This applies to wells up to 3 km south of the lake (e.g. M6; discussed later), appearing to confirm high permeability within the aquifer, and indicat ing that much of the aquifer is in good communication with the lake.

At the north end of the Whakarewarewa thermal area, the pressure and temperature conditions suggest up to 15-18 m of head relative to lake level. This is where the highest chloride concentrations within the geyser area occur, and where heat and chloride outflows are greatest (Roto-a-Tamaheke lakelet, Cody and Lumb, 1992). The elevation of the static water levels of the Pohutu-Te Horu geyser feature and Roto-a-Tamaheke lakelet are at 296-297 and 296 m asl respectively. The nearby monitor well M16 also has a static head of 295 m asl (measured in 1990). Since these heads are the highest measured in the Rotorua field, the outflows at Whakarewarewa clearly represent a major pressure control point for the field. The temperatures and pressures near Whakarewarewa indicate two-phase conditions, consistent with the main, land-based upflow at a few hundred metres depth being located near here. Two-phase conditions may also exist further to the northeast towards Ngapuna, but may be restricted to greater depth, beneath sediments covering the geothermal aquifer which, here, lies within the Mamaku Ignimbrite. Further north, near the mouth of the Puarenga Stream, there are no wells, but there is a boiling, overflowing pool with the highest chloride concentration of any natural feature in Rotorua (Giggenbach and Glover, 1992). The chemistry of this feature suggests that the fluid feeding it has cooled predominantly by steam loss along its upflow path, which in turn suggests two-phase conditions. The geothermal inflows to Sulphur Bay detected by the airborne infrared survey (Mongillo and Bromley, 1992), together with the occurrence of high chloride features around the southern margin of the bay are possibly consistent with a major upflow zone beneath the bay. The floor of the bay is pock marked with crater-like depressions, eruptions of steam and water have been reported occasionally from the middle of the bay and the adjacent land area has had numerous hydrothermal eruptions throughout historic times (Cody, pers. comm.), all of which suggest extensive two-phase conditions at shallow depth.

The shallow upflow zone implied by the temperatures beneath Kuirau Park may be a consequence of high vertical permeability within the steep western flank of the rhyolite, rather than an indicator of much higher temperatures at greater depth. Quartz-silica and K-Mg geothermometers imply equilibrium temperatures of 170-220°C for the west Rotorua waters in contrast to 240-270°C waters for east Rotorua (Giggenbach and Glover, 1992). The observed maximum temperatures beneath Kuirau Park fall within this range, and as mentioned above, temperature inversions with depth are not uncommon within the rhyolite. The slightly higher pressures close to the crest of the north dome compared to those at Ohinemutu and the commercial district (+0.25 bar) can be fully accounted for by a +20°C anomaly existing between 80 and 180 m asl in a local upflow zone beneath the dome.

Pronounced east-west gradients are found in the chemistry of the Rotorua fluids (Glover and Heinz, 1985; Taylor and Stewart, 1987; Giggenbach and Glover, 1992; Stewart *et al.*, 1992; Graham, 1992). Three chemical components, chloride, bicarbonate, and tritium are presented in Fig. 5(c and d) to summarize the major hydrological characteristics revealed by these studies. The higher temperature, higher pressure fluids beneath the eastern side of the field are chemically distinct from the fluids beneath west Rotorua, displaying higher chloride and rubidium concentrations, lower bicarbonate, boron and lithium concentrations, low tritium and high strontium isotopic ratios.

When considered together with the relative abundances of certain gases (CO_2, N_2, Ar, He), the chemical signature of all Rotorua fluids is similar to fluids from other geothermal fields in the western side of the Taupo Volcanic Zone (e.g. Wairakei, Mokai, Orakeikorako; Giggenbach and Glover, 1992). That is, their chemistry is consistent with fluids which have circulated deep into crust that is characterised by active basalt-rhyolite volcanism, in contrast to fluids which have interacted with a region influenced by active andesitic volcanism. Giggenbach and Glover (1992) conclude that the east Rotorua fluids have the most extreme basalt-rhyolite magmatic signature of any of the Taupo Volcanic Zone geothermal discharges. In particular, the east Rotorua fluids have very low relative concentrations of CO_2, N_2, and low B/Cl ratio.

A fundamental hydrological question raised by the chemical differences between east and west Rotorua is whether they have arisen at relatively shallow depth (e.g. the order of 500 m) by differences in steam loss, mixing with groundwater, and interaction with different host rocks, or whether the differences have been generated at much greater depth. Stewart *et al.* (1992) present the shallow model; Giggenbach and Glover (1992) suggest a deeper origin for the two fluids but neither estimate is precise enough to draw a clear distinction between them. In both cases groundwater is expected to penetrate to considerable depth and the Stewart *et al.* model involves rock-water interactions which could occur deeper than the 500 m given by them. The B/Cl ratio, which is usually invariant with changes in steam loss or groundwater dilution, decreases by a factor of three between east and northwest Rotorua. This is the clearest indication that a chloride water flowing from east to west across the Rotorua field, undergoing simple processes of steam loss and/or mixing with groundwater, cannot explain the chemical differences (Glover, 1967).

Chloride-enthalpy considerations reinforce this conclusion (Fig. 6). The observed high temperature fluids beneath northwest Rotorua (i.e. beneath Kuirau Park) are 180°C and have chloride concentrations less than 400 mg/kg, compared to 200°C and >1000 mg/kg respectively beneath east Rotorua. The northwest Rotorua fluids at production depths (<300 m) clearly have excess heat for the observed chloride content compared with the higher pressure fluids of east Rotorua. This heat is unlikely to have been derived from mixing with a steam-heated groundwater. As already discussed, there is little evidence to support a major zone of two-phase conditions below 180 m asl in west Rotorua. The simplest hydrological model is for the excess heat to be derived

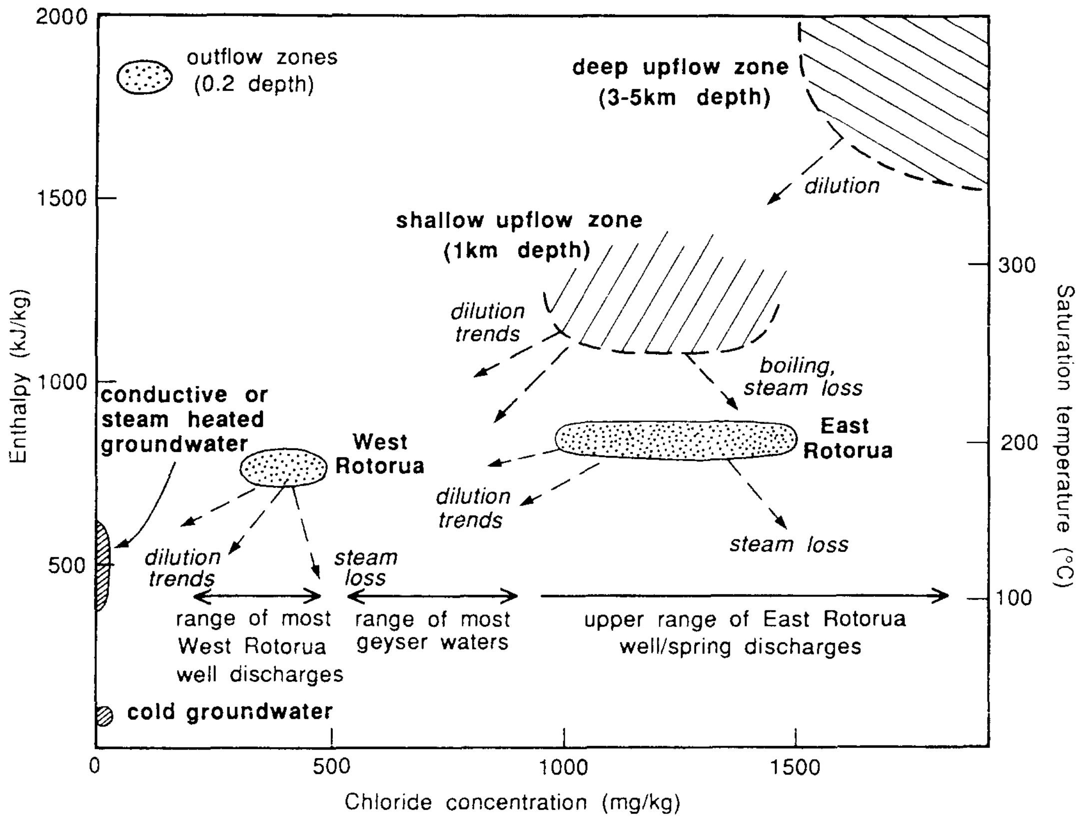

Fig. 6. Summary of the chloride-enthalpy relationships of the Rotorua geothermal fluids. The stippled zones of east and west Rotorua are based on observed data. The diagonally hatched zones are inferred partly from the K-Na-Mg geothermometers and the isotope geothermometers (Giggenbach and Glover, 1992; Stewart *et al.*, 1992).

by conductive heating of groundwater on the west side of the field before it mixes with hot chloride water at depth. If so, this implies that the western side of the field may be gradually cooling. Low tritium in the groundwater (Stewart *et al.*, 1992) suggests that its flow is slow, so that if such cooling occurs it will be on a much longer time scale and is probably at much greater depth than any changes induced by exploitation over the last decade. Conductive heating of fluid on the west side of Rotorua field was a feature of the mathematical model of Burnell, (1992).

Giggenbach and Glover (1992) argue that the chloride-bicarbonate fluids of west Rotorua have interacted more extensively with their host rocks than the east Rotorua fluids. The longer residence time and lower temperatures in the upflow on the west side of the field has enabled the conversion of dissolved CO_2 to HCO_3. Some of the other chemical differences may have resulted from interaction with differing host rocks. At drilled depths, rhyolite is predominant in the west, ignimbrite and shallow sediments are predominant in the east. The eastern fluids may also have interacted with metasedimentary basement rocks at much greater depth, based on their unexpectedly high $^{87}Sr/^{86}Sr$ ratios (Graham,1992).

Neither the Stewart *et al.* (1992) "shallow" hydrological model nor the Giggenbach and Glover (1992) "deep" model explain all of the major differences across the field. The "shallow" model appears to have difficulty providing the excess heat for the observed chloride content seen in the west Rotorua fluids, particularly if there is a significant natural mass flux through this part of the field. The "deep" model which requires lateral differences to extend to several kilometres depth may overstate the geographic separation between the two main fluid types. The maximum bicarbonate concentrations occur 1 km east of the Kuirau Park upflow zone, within a kilometre of the eastern, high-chloride fluids. If bicarbonate production requires prolonged interaction with the host rocks, then it is difficult to explain a bicarbonate maximum so close to the eastern upflow zone, rather than being centred on the western side of the field in the vicinity of the Kuirau Park upflow area. The ^{13}C (CH_4-CO_2) isotopic evidence for a uniform gas source beneath the east-central part of the field (Stewart *et al.*, 1992) suggests that the bicarbonate concentrations may have a much closer link to the eastern upflow zone than that suggested by Giggenbach and Glover (1992). It seems likely that some of the bicarbonate is a consequence of mixing with shallow, steam-heated waters, overlying a two-phase zone associated with the eastern upflow zone. However, none of these models completely excludes the others.

A more detailed understanding of the hydrological relationships between the east and west Rotorua fluids is likely to remain uncertain given the absence of deep well data. Fig. 6 summarizes the main processes thought to be occurring beneath the field. Although scant, the isotopic data implies temperatures of the order of 350°C, perhaps existing at depths of 3 to 5 km. The ascending fluid cools predominantly by mixing with adjacent "groundwaters" until around 250°C when first boiling occurs at around 0.5 km depth. Some of these "groundwaters" may be low-chloride waters which have been resident at several kilometres depth for a sufficiently long time to become conductively heated to around 150°C prior to mixing with the rising plume of geothermal water. Chloride concentration in the main upflow zone at 0.5 to 1 km depth in Fig. 6 is shown with a broad range to reflect the uncertainty in compositions and fluid flow processes. Shallower than 0.5 km, the east Rotorua fluids evolve through boiling and steam loss, with varying degrees of dilution depending on location. However, the geyser waters at Whakarewarewa are a result of major dilution of the east Rotorua parent fluid at 200 m depth. The west Rotorua fluids are also dominated by dilution processes, with possibly steam-heated waters being the diluting fluid in the central part of the field, and cold, or conductively heated groundwaters causing dilution on the west side.

EFFECTS OF EXPLOITATION AND WELL CLOSURES

With the growth of Rotorua City over the geothermal field during this century, the impacts on the natural activity have progressed from obvious modifications of the outflow channels to enhance either the availability of hot water (usually for bathing purposes) or the frequency of geyser eruptions, to the drilling of an increasing number of wells for extracting the underlying hot water. In addition to the trend of increasing exploitation of the geothermal water (until 1986/87), there appear to have been significant natural changes in thermal activity, particularly in the Whakarewarewa geyser area. One of the problems researchers have had with the thermal activity at Rotorua has been trying to quantify the likely causes of change. Little quantitative monitoring was carried out prior to the early 1980s.

Detailed reviews of all known changes in thermal activity at Rotorua are contained in Donaldson (1985) and Cody and Simpson (1985). This information is updated and summarized in two other papers in this issue (Cody and Lumb, 1992; Bradford, 1992a), so comments in this paper are kept to a minimum. A theoretical analysis of geyser eruption dynamics of Pohutu during the mid 1980s, also provides critical information on the subsurface fluid state and the physical characteristics of the plumbing beneath the geyser (Weir *et al.*, 1992).

Although Pohutu Geyser dominates the thermal activity at Whakarewarewa today, this was not the situation earlier this century. During the 1930s, Pohutu had a period of dormancy for almost

3 years, and prior to this eruptions appear to have been erratic except for a period of several years late last century when eruptions were artificially stimulated twice every 24 hours. However, around the turn of the century, other geysers within 300 m of Pohutu were noted for their spectacular eruptions (Cody and Lumb, 1992). By 1970, Pohutu was the major geyser attraction at Whakarewarewa and it was more active than ever previously observed. Up to this time, the only notable springs in Rotorua Field clearly affected by drawoff from wells and pumping was Rachel Spring, in the Government Gardens near the commercial district, and (temporarily in the 1940s) the Roto-a-Tamaheke outflow. In both cases, the springs were supplying public bath complexes.

During the 1970s and early 1980s, a sequence of failures or abnormal behaviour of the surface activity occurred which cumulatively can be linked to the increasing effects of drawdown. These include:

- Pohutu Geyser: after 1982, very short (5 to 10 minutes) eruptions became common. "Full column" discharges uncharacteristically degenerating into low energy, splashing displays after the first 2 to 5 minutes of eruption were noted in 1986;
- Te Horu Geyser (a large geyser vent next to, and connected to Pohutu): stopped overflowing and erupting in 1972, and its water level had fallen several metres by 1987;
- Waikorohihi Geyser (next to, and connected to Pohutu): abnormally long periods of dormancy developed in 1985/86 (20 to 35 hours compared to the usual 1 hour);
- Hot springs near the outlet of Roto-a-Tamaheke: overflow ceased in 1983, and the residual water decreased in temperature and chloride content. The heat flow from Roto-a-Tamaheke in 1984 was estimated to be about half a 1967/69 estimate of 60 MW;
- Papakura Geyser (400 m southwest of Pohutu, on bank of Puarenga Stream): its continual, splashing eruptions observed throughout this century ceased in 1979, and its water level receded to 2 m below overflow (0.4 m below stream level) in 1986;
- The total heat flow from all thermal activity at Whakarewarewa is estimated to have decreased since 1967/69 by 30%, to around 150 MW in 1984.
- Kuirau Lake (in Kuirau Park) developed an erratic, very weak overflow (0 to 5 l/s) of neutral pH water in the 1970s and 1980s. Its historic behaviour has been variable, possibly due to its location close to the area of maximum drawoff.

Public concern during 1979 and 1980 over the threat to the geyser activity resulted in a ban on drilling (other than replacement wells) within a 1.5 km radius of Pohutu Geyser (Fig. 2). Later in 1980, the New Zealand Government agreed to set up a programme to monitor the geothermal field to determine the major factors affecting the geyser activity and to provide a baseline for future field management. The drilling of monitor wells, and the installation of automatic data-loggers on wells and key thermal features were carried out between 1982 and 1984. In addition to the Rotorua Geothermal Monitoring Programme, a Task Force was set up in 1983 to establish the extent of drawoff from wells, and to investigate ways of reducing that drawoff through improvements in efficiency and engineering.

By 1985, it was realised that pressure within the field was varying seasonally by around 0.05 bar (over 0.5 m of head) in response to a drawoff of 25 000 t/day (290 kg/s) during summer, rising to 31 000 t/day (360 kg/s) during winter (Fig. 7; Bradford, 1992b). By comparing the seasonal pressure and drawoff changes, Grant *et al.*, (1985) estimated the total drawdown due to the drawoff to be 2 to 4 m. This is in the same range as the changes in head determined from a careful selection of old and new drillhole data, which indicated up to 7 m of head decline due to exploitation in the south of the field (near Arikikapakapa), reducing to no change in the north near the lakeshore (Simpson, 1983). A more careful analysis of the seasonal pressure fluctuations and their relationship to total drawdown is given by Bradford (1992b).

By late winter 1986, aquifer pressures had fallen to their lowest levels since the monitoring programme began (Fig. 7), despite widespread publicity and advice on the need for conservation

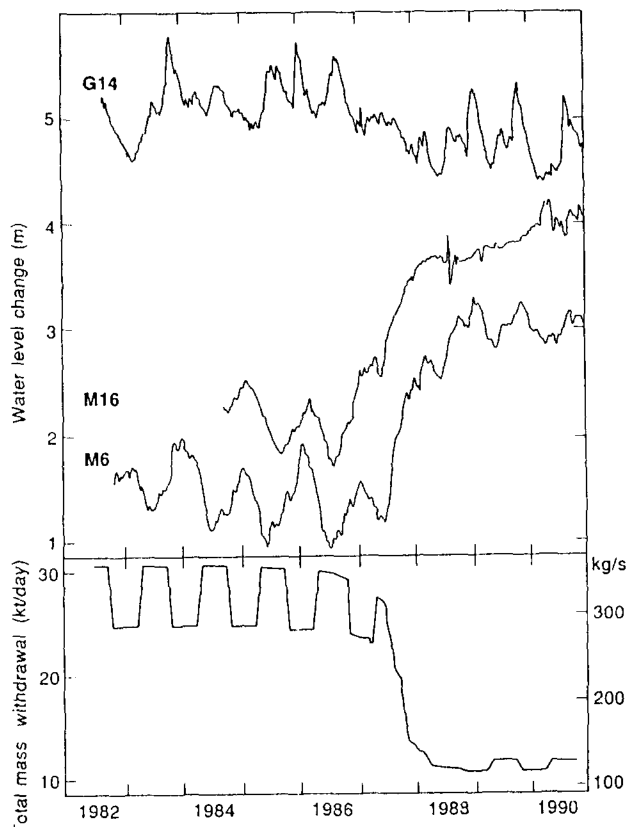

Fig. 7. Examples of the response of monitor wells to the simplified, total mass withdrawn from wells at Rotorua field (adapted from Bradford, 1992b). The water level change curves have a different datum for each well. The location of the wells is shown on Fig. 2.

and on ways to improve efficiency and minimise waste heat, and despite the ban on the drilling of new wells within 1.5 km of Pohutu Geyser (Fig. 3 shows the long-term trend in fluid withdrawal). The annual rate of head decline during the mid 1980s appeared to be at least 0.1 m/y, and this was occurring both in the higher pressure zone close to the geyser area and in the lower pressure zone beneath most of Rotorua City. Due to the deleterious changes in thermal activity summarised above, the monitoring programme recommended to central Government that urgent action was needed to prevent further deterioration of the geyser activity at Whakarewarewa. As a result, the Government invoked its statutory authority and ordered the closure of all wells within 1.5 km of Pohutu Geyser, at the same time implementing a charging regime for extracting geothermal fluid from the remainder of the field.

Because of massive public protests and resistance from well users, including a legal challenge to the Government's right to cement up wells, it was not until mid 1988 that all closures had been effected. The net mass withdrawn from the field decreased to around 20% of the 1985 level by 1990 (Timpany, 1990), and the recovery in aquifer pressure coincided with the start of closures in 1987 (Fig. 7; Bradford, 1992b). The recovery of head in the few monitor wells remaining after the closures appears to have stabilised at between 1.5 and 2.0 m. This is significantly less than the 2 to 4 m predicted by the linear extrapolation of the seasonal variations. Explanations for the smaller than expected pressure recovery are: decreased groundwater recharge due to a long-term decrease in rainfall since the 1960s and increased runoff associated with urban growth; and a long-term component to the recovery which may still be occurring, as a result of the long-term drawdown (Bradford, 1992b).

The recovery in the thermal activity has been dramatic. Pohutu Geyser resumed longer duration, full column, high energy eruptions by 1989, with short (<5 minute) eruptions rare (Cody and Lumb, 1992). Another geyser close to Pohutu (Kereru) began erupting in 1987 for the first time in 10 years, and has continued its activity ever since. The brief resumption of activity of two other geysers at Whakarewarewa in December, 1987, after many years of dormancy, is attributed to coinciding favourable factors (rainfall, a local earthquake, and rising aquifer pressure; Cody and Lumb, 1992). Roto-a-Tamaheke, the hot lakelet at the northeast end of Whakarewarewa increased its mass and chloride outflow by around 50% during 1986 and 1987, although the increase in heat flow appears to have been more gradual, continuing up to 1990 (Bradford, 1992a). The prolonged rise in heat flow is to be expected because of the buffering effect of the subsurface rock on a changing boiling point for depth relationship. In downtown Rotorua, Rachel Spring (in the Government Gardens) resumed intermittent, boiling, overflow in late 1988 and has continued this state since then. Apart from two periods of overflow in 1964 and 1966, the spring had not overflowed for 80 years (Cody and Lumb, 1992). In Kuirau Park, Kuirau Lake has resumed a strong overflow (40 - 60 l/s) of alkaline, hot water, which had not been observed since the 1940s (ibid.). A nearby hot spring also resumed flowing in early 1989 for the first time in about 30 years.

DISCUSSION

The conflicts throughout the 1980s between widespread public concern that the unique geyser activity at Rotorua was being harmed and faced imminent extinction, and the rights of Rotorua residents to use the hot water that existed under their property, created immense pressure on scientists and engineers involved in the investigation and monitoring of the geothermal field. Geothermal activity is naturally variable, and sensitive to many factors such as long-term rainfall, changes in groundwater recharge, changes in aquifer pressure due to erosional downcutting or surface flooding at the main outflow points, and changes in subsurface permeability, especially at times of earthquakes or hydrothermal eruptions. All the above factors were known to have occurred historically in the Rotorua geothermal field, making it very difficult to identify and quantify unequivocally the cause(s) of changes in thermal activity that had been occurring since the early 1970s. Within three years of the detailed monitoring investigations being started it was clear that aquifer pressure was responding directly to seasonal changes in the rate of fluid extraction from wells, that the total amount of fluid being extracted was of the same magnitude as that flowing naturally from land-based thermal activity, and that the geothermal aquifer had been drawn down by about 5 m in the south of the field, and the annual average head was declining by at least 0.1 m/y.

The reports of the monitoring programme and the task force investigating the use of geothermal fluids in Rotorua recommended that the geyser activity could be sustained if major inefficiencies were eliminated in the way the geothermal fluid was used, so that the amount of fluid withdrawn could be significantly reduced (Monitoring Programme, 1985; Task Force, 1985; Freeston and Dunstall, 1992). The reports recommended an annual reduction in the drawoff rate of 4000 - 5000 t/day for 3 years, concentrating on wells in the southern part of the field closest to the geysers. This would have reduced the extraction of fluid by about 50% after 3 years. About one year after the reports were published, only minor reductions in fluid extraction had been achieved, and aquifer pressures in the winter of 1986 declined to the lowest values ever measured. Many well users disputed the findings of the reports, and probably general apathy, together with outright resistance to spending money on closing some wells and modifying others to achieve the recommended efficiencies, resulted in inaction. The subsequent decision by central Government to enforce total closure of all wells within 1.5 km of Pohutu Geyser inevitably became the only way to achieve a rapid reduction in fluid withdrawal close to the geyser area. However, even with the legal and financial resources of central Government, the closures took almost two years to be completed.

Ironically for the well users, the recommendations of the Rotorua Geothermal Monitoring Programme and the Task Force had been relatively moderate, permitting some geothermal withdrawal near the geyser area, but with special controls to minimise the impact on the geothermal aquifer. Although the eventual decision to enforce closure of all wells was described by the well users as being draconian, and an over-reaction by central Government and its scientific advisors, the indisputable recovery of the geyser activity and other thermal springs around Rotorua City has demonstrated that the decision was the correct one. A unique geyser field is now protected from subsurface human interference for the benefit of future generations.

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