THE NATURAL STATE OF KAWERAU GEOTHERMAL FIELD

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SUMMARY - Kawerau is a relatively large geothermal field sited on the northeast boundary of the Taupo Volcanic Zone. Subsurface temperatures range to over 315°C, with the highest measured temperatures occurring in the south of the field towards Putauaki (Mt Edgecumbe). The highest pressures and in situ chloride concentrations are also towards the south of the field, consistent with deep upflow from this location. Resistivity surveys find a low resistivity anomaly of 19 - 35 km^2 in area at about 500 m depth associated with the field. However most surface thermal activity is located in **less** than half this area, and the productivity of much of the resistivity anomaly is unproven. The natural surface heat flow from thermal activity is estimated to be about 100 MW(th), with possibly an additional subsurface outflow of the order of 50 MW(th). This outflow may be the cause of anomalous boron and chloride concentrations in groundwaters on the Rangitaiki plains 5-10 km north of the field.

INTRODUCTION

Kawerau geothermal field is the most northeasterly of the major land-based geothermal systems in the Taupo Volcanic Zone, being situated about 15 km from the Bay of Plenty. The field lies between the andesite volcano of Putauaki (Mt. Edgecumbe), and the rhyolite/dacite domes known as the Onepu hills, and is centred on the flood plains of the Tarawera River (Figure 1). Although its natural thermal activity has not been regarded as having having spectacular tourist values like many other fields in the Taupo Volcanic Zone, one of its hot springs, Umupokapoka, features in the Maori legend of Ngatoroirangi and his sisters who created New Zealand's geysers and volcanoes.

In 1951 and 1952, the **DSIR** and Ministry of **Works** carried out scientific surveys and shallow drilling to investigate the geothermal potential of Kawerau Field for either power production or process heating. One year later, Tasman Pulp and Paper Company decided to site a mill on the field, partly because of the possibility of using the geothermal energy. **The** drilling of geothermal production wells for Tasman began almost immediately, with the first geothermal steam supplied to the mill in 1957. The steam supply system was fully operational by 1961. Geothermal steam was largely used for process heat, with excess utilised for electricity generation (up to 8 MW). As the plant expanded] the demand for geothermal steam also increased, and is now around 300 tonnes/hour. Over **40** geothermal wells have been drilled since the 1950s, although usually not more than 6 have been in production at any one time. Many older wells developed casing cementing problems and have been cemented up, while others are used as investigation and monitor wells. Field monitoring has become increasingly important since testing of long-term reinjection of separated geothermal water began in 1991. A more detailed review of past development, and future scenarios for the field is given by Wigley and Stevens (this volume).

NATURAL THERMAL FEATURES

Early this century, the surface features at Kawerau included hot springs, seepages and associated sinters, altered and steaming ground with small fumaroles, and hydrothermal eruption vents (Figure 1). The springs and seepages were concentrated along the banks of the Tarawera River, and around the southern shore of Lake Rotoitipaku in what has been called the Onepu thermal area. Patches of steaming ground occur on the hills 1 - 2 km southwest of the Onepu thermal area, and on the west side of Kawerau town (known as Ruruanga thermal area). The only other thermal features are gas emissions in marshlands towards the east of the field, marked on some old topographic maps as the "boiling lake" area.

The natural heat and mass flows from geothermal fields are a minimum indicator of the size of the field, and provide important constraints for reservoir models which attempt to predict the effects of production and reinjection. In the **case** of Kawerau field, there is a large uncertainty because it is clear that hot spring activity has declined significantly this century due to both natural and man-made causes. Umupokapoka was described as a lakelet having "a large spring yielding 300,000 gallons" in a Colonial Laboratory Report in 1904. Macpherson (1944) surmised that this was **a** daily output (i.e. 1400 m^3/day, or 16 l/s). By the time of Macpherson's (1944) study, Umupokapoka hot spring could not be identified, and Studt's (1958) publication of his 1952 survey suggested that the feature had become a sintered lake bed with numerous bubbling hot pools. The inferred flow from Umupokapoka around the turn of the century was almost twice that observed flowing from all springs in 1952. Note that although some investigation drilling of the field was occurring in 1952, significant discharges from wells did not occur until 1953-54. Studt (1958) attributes the loss of Umupokapoka hot spring to downcutting of the Tarawera River at Kawerau by 3m between 1920 and 1950. The lowered river level also lowered the adjacent groundwater level, and decreased hot spring flows from the field (and also removed the risk of repeated flooding, apparently common at earlier times this century).

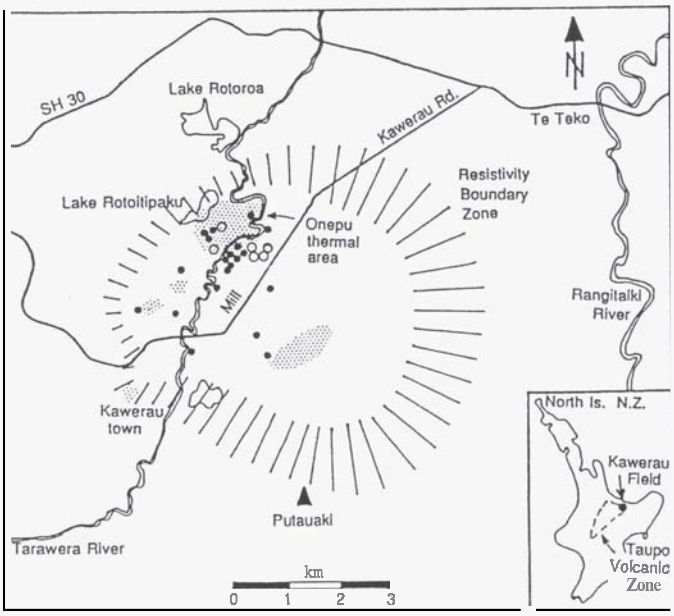

Figure 1. Locations of the main thermal areas (stippled), production borefield (open circles), exploration wells (dots), and the resistivity boundary zone of Kawerau Field at about 500 m depth.

Studt's 1952 survey has been the only systematic assessment of the heat flow of Kawerau field, but was limited to the Onepu thermal area. The main hot spring area adjacent to Lake Rotoitipaku has since been covered by sludge waste from the Tasman mill, and the springs have become inaccessible. The most active thermal areas in 1952 were around the southern rim of Lake Rotoitipaku, and the northern margin of the former Umupokapoka, with the total outflow being 9 l/s. The total heat flow from the Onepu thermal area was estimated to be close to 100 MW (thermal), dominated by 70 MW from seepage into the Tarawera River (0.8°C rise in temperature) and over 10 MW of evaporative heat loss from Lake Rotoitipaku. Although the heat output from the steaming ground south of the Onepu thermal area was not included, consideration of the total area of steaming ground, as well as the uncertainties in Studt's heat flow estimates (likely to be at least 25%), means that a total natural heat flow value of around 100 MW for Kawerau field is the best estimate available.

This heat flow estimate does not consider natural outflows which do not reach the ground surface in the field. The increase in chloride concentration with increasing depth in Kawerau wells indicates that dilution due to mixing with cross-flowing groundwater is an important process in the shallow levels of the reservoir at Kawerau. Elevated boron (and other elements) in groundwater wells on the Rangitaiki plains 10 km north of Kawerau field may be due to subsurface outflow from the field merging with the shallow aquifers. The surface heat flow of 100 MW is therefore a minimum figure. For the shallow geothermal aquifer at Kawerau (at several hundred metres depth) the 100 MW heat flow therefore implies a mass flow of 170 kg/s, assuming an average temperature of around 150°C, and an enthalpy of 600 kJ/kg. At greater depth, this heat flow implies a mass upflow of about 80 kg/s of water with an enthalpy of 1300 kJ/kg (290°C), prior to dilution with groundwater. These figures are of the same order as the other geothermal fields of the Taupo Volcanic Zone.

SUBSURFACE AREA OF THE FIELD

Although the surface activity at Kawerau is mostly concentrated in a 2 km^2 area, resistivity surveying has revealed that the subsurface geothermal fluid is much more extensive. Resistivity surveys exploit the large contrast between the low resistivity characteristic of the interior of geothermal fields, and much higher resistivity frequently characteristic of surrounding cold groundwaters. Early (1969-70) resistivity surveys of Kawerau field were relatively shallow-penetrating, and limited in the area surveyed. These measurements suggested a field area of around 10 km^2 at about 250 m depth, roughly centred on the Tasman mill (Macdonald et al., 1970).

More recent resistivity measurements indicate an even greater area of geothermal fluid at greater depth (Figure 2). By analysis of the location and the width of the transition from low resistivity to high resistivity made with varying electrode spacing (AB/2 = 500m and 1000m), a boundary zone can be defined. This is the hatched zone depicted in Figure 1, and it usually represents the transition from geothermal to non-geothermal conditions at about 500 m depth. Variations in the width of the boundary zone could be caused by factors such as the presence of a low permeability barrier separating hot and cold waters over a narrow zone, a broad zone of mixing between hot and cold waters, a sloping boundary zone with increasing depth, or just imprecise or widely spaced measurements.

The new boundary zone of Kawerau field shown in Figure 1 encompasses an area of between 19 and 35 km^2, depending on whether the inner or outer edge of the boundary zone is included. A significant finding of the new resistivity survey has

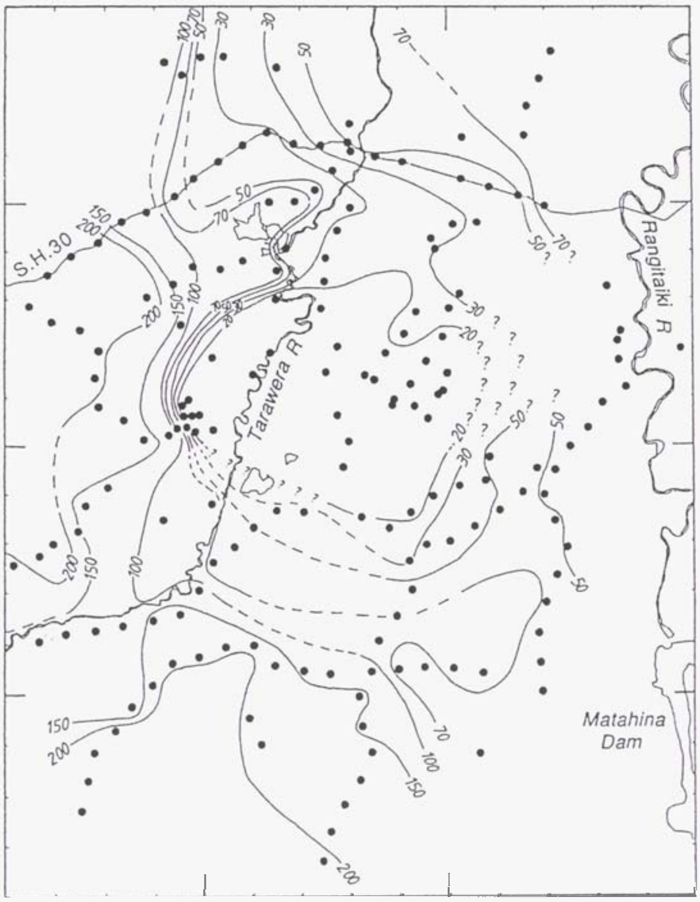

Figure 2. Contours of apparent resistivity (in ohm-m) using Schlumberger electrode spacing AB/2 = 1000 m (nominal). Contours are dashed where data is in doubt or not available.

been a major eastward extension of the low resistivity region to cover a large area of ground to the east of the Mill and north of Putauaki (Mt. Edgecumbe). Apparent resistivities with AB/2 = 1000 m are mostly less than 20 ohm m for a distance of more than 3 km to the east of the Mill (Fig. 2). Comparison of the AB/2 = 500 m and AB/2 = 1000 m resistivity survey data indicates that resistivity decreases with depth, suggesting that geothermal conditions may exist at deeper levels, and thus may represent a major addition to the presently proven geothermal resource. However, no drilling has been done to test this suggestion and there is little direct evidence, such as high temperatures at the surface, to support it (other than minor activity at the "boiling lake" area).

Low resistivity to the north and northeast of the main thermal areas are consistent with a northward subsurface outflow of thermal fluids from Kawerau field. Supporting evidence may come from the shallow groundwater wells 5 to 10 km north of the field with anomalous temperature, chloride and boron values indicative of dilute and cooled geothermal water (Bay of Plenty Regional Council Technical Report #2, 1991). This is discussed in more detail below.

GEOLOGICAL CONTROLS ON THE RESERVOIR

Kawerau geothermal field lies at the southern end of the Whakatane graben, where the northeast-striking rift of the actively spreading Taupo Volcanic Zone intersects the north-south trending major strike slip faults of the North Island shear belt (Nairn and Beanland, 1989). Within the Whakatane graben, Mesozoic (~120 million years) greywacke basement rocks have been down faulted to 1 - 2 km below sea level during the last million years. The resulting basin has been infilled by Quaternary volcanic rocks and sediments mostly derived from the large Okataina and Taupo volcanic centres to the south. The Okataina volcanic centre has been the main external focus of volcanic activity affecting the Kawerau area during this period. A small volcanic centre has also existed at Kawerau, where eruptions have occurred from sometime before 400,000 years ago, through to about 2500 years ago at Putauaki (Mt. Edgecumbe). The Kawerau field is sited where the main drainage channel from the Okataina volcanic centre debouches into the Whakatane graben. Major rivers have commonly flowed through the Kawerau area, carrying sediments from this volcanic centre.

Drillhole stratigraphy shows that the basement greywacke surface is step-faulted down to the northwest on northeast-trending normal faults to form a series of southeast-tilted fault blocks (Figure 3). These probably plunge to the northeast in a structural pattern similar to that of the regional geology. Some northwest-trending cross-faulting also occurs. Much of the displacements occurred before the deposition of many of the overlying volcanic units, because the displacements decreases upwards along fault planes. Some of these faults have been intersected by drillholes, and they are now production drilling targets both above and within the basement. The locations of many faults in the field are still not precisely known, so the fault pattern depicted in Figure 3 has to be interpreted cautiously.

Kawerau field appears to lack extensive permeable aquifer beds and drillhole production relies on intersecting fractures in otherwise impermeable ignimbrite, rhyolite, andesite and greywacke basement. The Kawerau Andesite is an example of a hard, dense volcanic unit of very low intrinsic permeability but in which development of fractures has formed a reservoir of good lateral permeability. Other volcanic units at Kawerau tend to be permeable only where they are hard enough to support open fractures, i.e. in strongly welded ignimbrites or

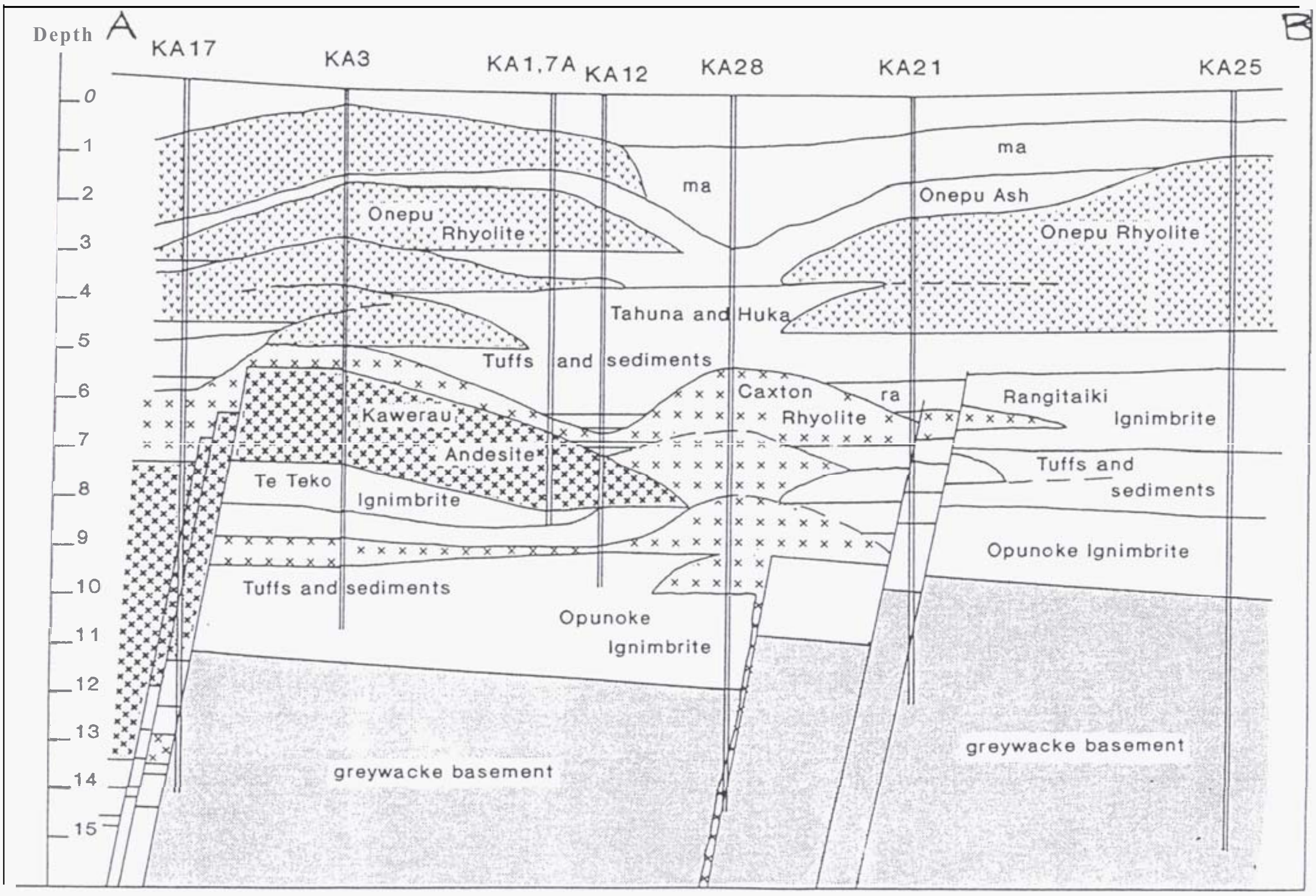

Figure 3. Schematic west-east cross-section through the centre of the production borefield showing the effects of faulting on structure. Horizontal and vertical scales equal; depths in 100 m intervals.

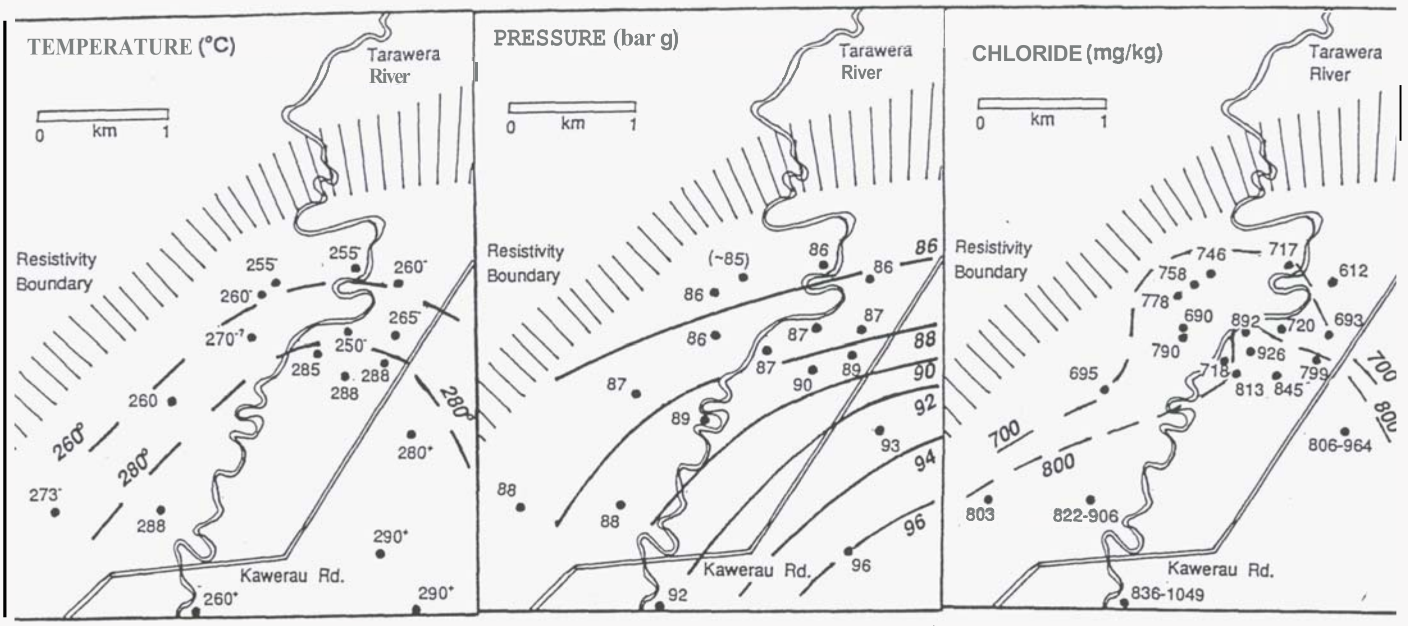

Figure 4. Pattern of temperature (°C), pressure (bar g.) and in situ chloride (mg/kg) variations at approximately 1000 m below sea level in Kawerau field. A minus or plus sign after the temperature indicates whether the temperature at greater depth is decreasing or increasing respectively. Hatching is the resistivity boundary shown in Figure 1.

massive lithoidal rhyolite lavas. Particularly important in terms of an aquiclude are sequences of sediments, ash and explosion breccias centred at about 500 m depth , and interfingering between rhyolite lavas and ignimbrite across the main production borefield area. interference testing between shallow and deep wells indicates that these volcanic sediments have relatively low permeability, and separate near-surface geothermal waters from deeper production fluids. An absence of Matahina Ignimbrite, which appears to be an aquiclude in the east of the field, may contribute to the location of surface thermal activity in the northwest of the field.

In summary, the geohydrological model derived from Kawerau drillhole data suggests that the deep hot water moves upwards through the greywacke basement along a small number of widely spaced active fault fractures of high local permeability within otherwise largely impermeable basement. These fault planes pass up into the cover beds where hot water spreads laterally into permeable zones of the subhorizontally stratified volcanics and sediments. Mixing occurs with cooler waters entering the field along the shallow-dipping cover bed strata. The intrusion of cooler waters gives rise *to* common temperature reversals in wells, and falling temperatures and enthalpies during shallow production. The highest temperatures occur in the south of the field, and suggest a deep source for the field in this region. Putauaki (Mt Edgecumbe) is relatively young (most of the cone is <5000 years old) compared to the age of hydrothermal activity in the field (>300,000 years, modified from Browne, 1979). Putauaki may be a recent extrusion from a shallow magma body located in the south of the field, which has also been a heat source for the geothermal system.

SUBSURFACE TEMPERATURES

Kawerau Field contains some of the hottest temperatures measured in New Zealand geothermal fields - ranging to over 315°C in southern wells towards Putauaki, at depths greater than 1 km. In the main production borefield, temperatures are typically in the range 260 - 290°C at production depths. Towards the north, a temperature inversion appears to be present below about 700 m depth suggesting an outflow of geothermal water towards the north, at or above this level. This is confirmed by the temperature contours at 1 km depth (Figure 4). A common characterisic at Kawerau Field is for small temperature inversions to be present, particularly in the upper few hundred metres. These are indicative of interfingering, cross-flowing cooler waters, and mixing of geothermal and cold groundwater.

In the central borefield, deep production temperatures *are* consistent with boiling of CO_2-bearing fluids. Around the northern borefield, temperatures appear *to* be lower than the boiling point conditions, although the effect of varying gas content may be important in causing local, two phase conditions. Boiling point conditions are also present in shallow aquifers (especially above 60 mbsl) overlying the production borefield area. Two phase conditions may be more extensive in the hotter, deeper parts of the field inferred to be present further south.

SUBSURFACE PRESSURES

Although shallow pressures around the main production borefield appear to be consistent with hot hydrostatic conditions with depth below the Tarawera River level, below about 500 m depth, pressures exceed hydrostatic by 6 to 12 bar (Figure 5). The amount of excess pressure appears to increase with increasing depth, indicative of the driving force causing the fluid upflow in this region. Assuming the excess pressure gradient to be 7% above the hydrostatic gradient, a mass upflow of 80 kg/s at 290°C over an area of 1 to 2 km^2 implies an average vertical permeability of 10 to 20 md (below 500m depth; the calculation assumes simple darcy flow modified from Grant et al. 1982). This is smaller than the values determined from the interference testing (discussed below), because it represents only the vertical component of permeability, and because it is an average value and therefore may not be representative of local fracture permeablity. The permeability at less than 500 m depth appears to be significantly higher than this average value because of the smaller excess pressure gradient, and much greater mass flows due to mixing and dilution with cold groundwater. The reason for the change in permeability around 500 m depth may be the preponderance of tuffs and sediments acting as an aquiclude separating the shallow and deep parts of the reservoir.

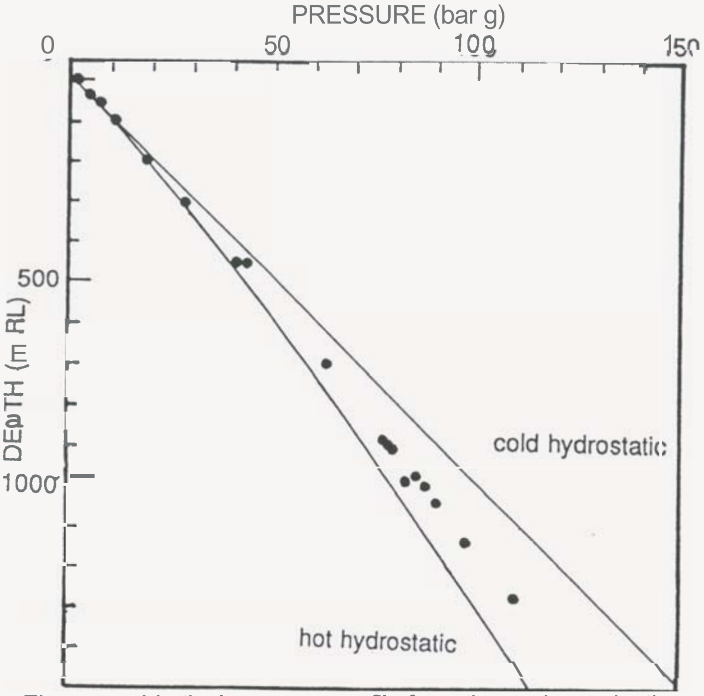

Figure 5. Vertical pressure profile from the main production borefield area of Kawerau field. Pressures significantly exceed hot hydrostatic below about 500 m bsl, with the excess pressure increasing with increasing depth.

Kawerau Field has a pronounced horizontal pressure gradient across the drilled part of the field at around 1 km depth (Figure 4). The gradient of around 5 bar/km trends north to northwest, with highest pressures being closest to Putauaki. This high pressure region in the southeast of the drilled part of the field appears to have low permeability, but very high temperatures. It is not known whether the higher pressures here are influenced by the increased head associated with groundwater recharge into the elevated volcanic complex of Putauaki.

GEOCHEMICAL CHARACTERISTICS

The chemistry of Kawerau field fluids has many similarities to that found at Ohaaki and Rotokawa fields and has been discussed in detail by Christenson (1987). A comparison of the chloride and enthalpy measurements of the Kawerau geothermal waters demonstrates that mixing with adjacent, cold meteoric waters is the dominant cooling process in much of the drilled part of the field (Figure 6). The deep parent water of the main production borefield could have a chloride concentration of around 925 mgkg, and an enthalpy of over 1400 kJ/kg (over 310°C), based on the mixing line shown in Figure 6. Uncertainties in the slope of the mixing line contribute to uncertainties in the chloride and euthalpy of deep parent water. The temperature of over 310°C is at the upper end of estimates derived from the K-Na-Mg geothermometers. Local boiling is occurring beneath some of the production borefield, but the overlying, shallow aquifers have largely evolved by cooling and dilution as a result of mixing with near surface, cold waters. Some of the surface waters in thermal areas adjacent to the Onepu hills have been steam-heated, whereas many of the original hot springs and seepages around Lake Rotoitipaku and the Tarawera River show evidence of near-surface boiling and steam loss.

When the best estimates of the undisturbed reservoir chloride concentrations from production wells are mapped (Figure 4), a pattern very similar to the temperature and pressure trends emerges. This is confirmation of the geohydrological model which has the deep source of the geothermal waters in the south of the field, and a northward outflow with mixing of surrounding cold waters (Figure 7).

Gas concentrations vary across the borefield due to the effects of boiling and mixing with dilute waters. In general, marginal fluids which are dilute with respect to chloride, are enriched in CO_2 relative to their least mixed counterparts in the centre of the borefield. After correction for the possible effects of excess enthalpy in the well discharges, the fluid at feedzone depths in the production borefield ranges up to 0.8% CO_2 and 0.02% H_2S by weight. This implies an unboiled deep parent fluid with CO_2 and H_2S contents of 2.8 and 0.03 weight % respectively, for a deep temperature of 315°C. Boiling of this fluid would occur at around 2 km depth, assuming the pressure - depth relationship observed beneath the production borefield. This gas content indicates that the Kawerau fluids are more similar to Broadlands-Ohaaki and Rotokawa, than to Wairakei and Mokai geothermal fluids.

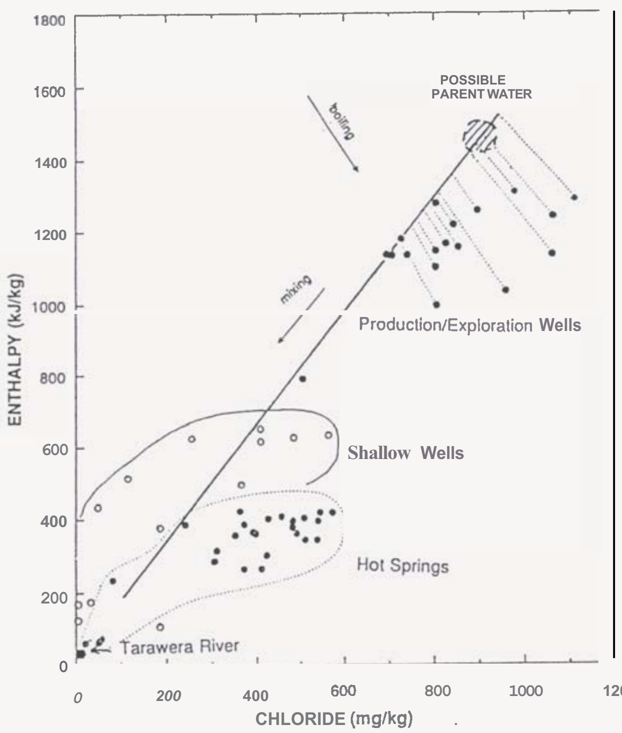

Figure 6. Chloride - Enthalpy relationships for shallow and deep waters from Kawerau field. Line is a theoretical mixing model between a deep parent fluid and cold surface water. Departures from the line may be interpreted in terms of steam loss (boiling), or steam heating.

The groundwaters of the Rangitaiki Plains may contain geochemical evidence of a significant subsurface outflow northwards from Kawerau field. In particular, boron concentrations are anomalously high, reaching 3 mg/kg in groundwater between 20 and 60 m depth, about 10 km north of the field (Figure 8). Groundwater Consultants (N.Z.) Ltd (1984) interpret this as geothermal water mixing with the groundwater, but the Bay of Plenty Regional Council Technical Report #2 (1991) has also suggested groundwater interaction with peat as a possible cause of the high boron levels.

Comparison of chloride/boron ratios in the groundwater and the geothermal water suggest a link, with the groundwaters having a molar ratio of 3 - 10, which is similar to the deep geothermal waters and the hot springs at Kawerau (5 - 7). The Awakeri hot spring also has a Cl/B ratio of 4. In contrast, sea water has a Cl/B ratio of over 1000, so groundwater contamination from this source is usually distinctive (e.g. there is evidence of this in some groundwater wells near the Bay of Plenty coastline and around Whakatane).

As mentioned above, there is resistivity evidence of northward outflows from Kawerau field, and for the field to extend east-west a distance of up to 7 km (at depth), from over 1 km west of the Tarawera River to about 2 km west of the Rangitaiki

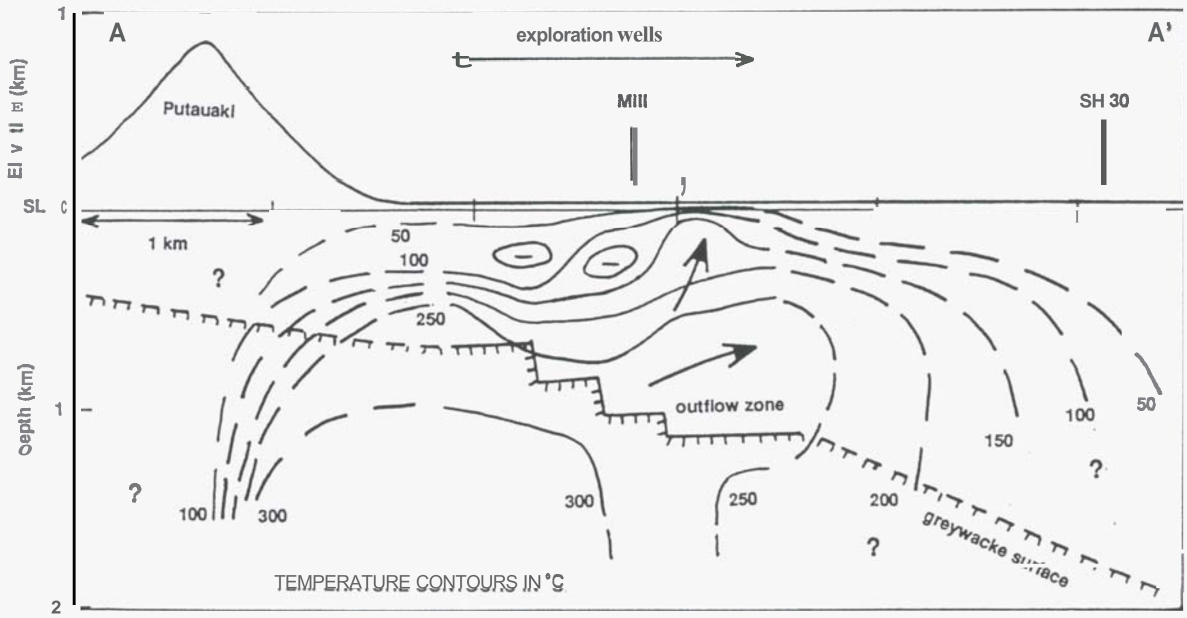

Figure 7. Speculative north-south cross-section across Kawerau field consistent with the subsurface trends in temperature, pressure, and chemistry of the fluids. Transect A-A' is located on Figure 8.

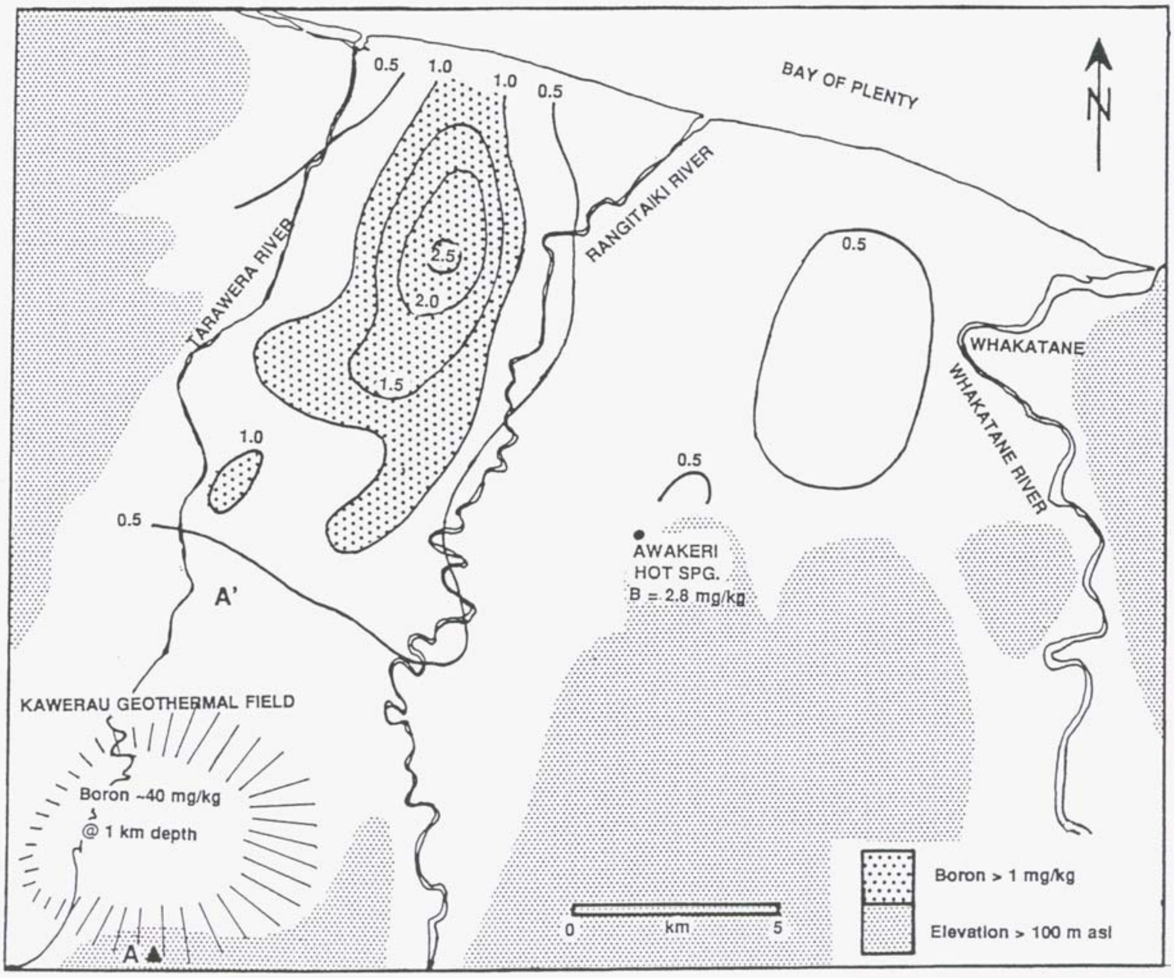

Figure 8. Location of Kawerau field in relation to the boron anomaly in groundwater on the Rangitaiki Plains (modified from Bay of Plenty Regional Council Technical Report #2, 1991). The source of most of the boron may be outflowing geothermal water from Kawerau field (hatching is resistivity boundary).

River. This is a similar width to the boron anomaly in the groundwater north of the field. Although not conclusively proven, there appear to be several indicators pointing to a major subsurface outflow from the field. If so, this natural outflow(s) is has long had a major impact on the water quality of the Rangitaiki Plains. It is important to note here that because the net rate of extraction of geothermal fluid from production wells now exceeds the likely deep inflow to Kawerau field, the subsurface outflow has probably reduced significantty, and a long term improvement in groundwater quality may occur. The time scale for the flow across the plains is unknown. The groundwater flux across the Tarawera-Rangitaiki Plains has been estimated by Groundwater Consultants (N.Z.) Ltd (1984) as 40 Mm^3/y (with large uncertainty). If this flux has an average boron concentration of 1 mgkg due to mixing with Kawerau geothermal water with an original concentration of 40 mg/kg at depth beneath the field, then the subsurface outflow from the field would be 50 kg/s. This estimate has an uncertainty of at least a factor of 2. Further investigation into the possible geothermal component in the groundwater, and the origins of such a component, are needed.

PERMEABILITY

The geological evidence when combined with the productivity of deep wells suggests that major fractures and fault zones are the main cause of high permeability in Kawerau field. Interference and tracer testing of both shallow and deep wells have constrained the variation in permeability in the vicinity of the production borefield, and assisted in the definition of a numerical model of the fluid flow processes occurring in the reservoir. The results from these tests are consistent with there being an unconfined shallow geothermal aquifer in the field extending from the surface to about 400 m depth with transmissivities (permeability-depth), of the order of 400 to 1600 darcy-metres, and storativities of 2 - 7 x 10^{-7} mPa^{-1} (above the 1 km^2 area of the borefield). Over the time scale of testing (typically days to months), variations in production rates from the deeper reservoir do not affect the shallow aquifer (and vice versa). The base of this aquifer appears to correspond to low permeability sediments (Huka Group) which are common between 400 - 600 m depth.

At production depths (typically 900 to 1500 m) significant interference effects are detectable over at least the width of the production borefield. Modelling of the responses suggests similar transmissivities to the shallow aquifer, with the responses influenced by fracture flow within the reservoir. A substantial recharge coefficient of 3 - 70 x 10^{-7} $m^3Pa^{-1}s^{-1}$ is implied by the modelling of this data (c.f. Wairakei where the recharge coefficient is 6 - 12 x $10^{-7}m^3Pa^{-1}s^{-1}$). The size of the deep reservoir is difficult to determine from the interference modelling because of the influence of fractures on fluid flow, but an area in excess of 10 km^2 appear to be indicated. This reservoir largely coincides with greywacke basement.

CONCLUDING COMMENTS

Resistivity surveys suggest that Kawerau field could have a total area of 19 to 35 km^2. The productive potential of most of this area is unproven and unknown, with the present production borefield producing from about 2 km^2, and interference effects evident over about 10 km^2. Notwithstanding these uncertainties, comparisons with other geothermal fields in the Taupo Volcanic Zone suggest that Kawerau field is a major geothermal resource. The available evidence based on 40 years of production, however, points to the need for a shift in the location of the production borefield (or a major expansion in its area), if a largescale Increase in development is to occur.

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