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The Natural State and Response to Development of Kawerau Geothermal Field, New Zealand

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ABSTRACT

Kawerau field has been supplying steam to a pulp and paper mill for process heat and power since 1957. The highest measured temperatures, pressures and chloride concentrations occur in the south of the field towards the volcanic cone of Putauaki, consistent with deep upflow from this location. Although the field has a low resistivity anomaly of 19-35 km² in area at about 500 m depth, most surface thermal activity and the present production borefield are located in less than half this area. Negligible long-term pressure changes have occurred at production depths due to a net mass withdrawal of around 1,000 t/h over the last 10 years. A total pressure decline of around 3 m (0.3 bar) is estimated from changes in elevation of flowing hot springs. This appears to have caused a 10 km² subsidence anomaly of between 10 and 30 mm/y which is centred on the northern boundary of the field. Some of the early shallow production wells suffered rapid invasion by cool waters, but present production from around 1 km depth is relatively stable, exhibiting some gradual cooling and dilution trends. Apart from some silica precipitation in one well, few problems have been encountered during the 5 years of reinjection into a shallow aquifer overlying the production reservoir.

Investigations into using the geothermal energy at Kawerau for power or process steam began in the early 1950s, and the first geothermal steam was supplied to a pulp and paper mill in 1957. Separated geothermal steam has been largely used for process heat, with excess steam utilised for electricity generation (up to 8 MW). As the plant expanded, the demand for geothermal steam also increased, and the field is now supplying around 300 ton/hour to the mill. Separated water is used in two small binary power plants (total output of 6 MW) as well as a greenhouse. 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, relatively shallow wells developed casing cement problems, suffered cold water invasion, and have been grouted up. Reinjection of separated geothermal water began in 1991. At present, 300 t/h of geothermal water is reinjected into a shallow aquifer located above the production aquifer, using two wells. An additional 900 t/h of separated water is discharged into the Tarawera River.

This paper is one of several companion papers in this volume reporting on aspects of the natural state and development of Kawerau field. They expand and update two earlier review papers (Wigley and Stevens, 1993; Allis et al., 1993), and are largely based on scientific and engineering compilations which have recently been lodged in the public domain in support of resource consent submissions (e.g. Allis et al., 1995). This paper focuses on physical aspects of the natural state of the field, and the subsurface effects of development. Companion papers address the geology and geochemistry (Christenson), reservoir modelling (White et al.) and engineering aspects of the field development (Bloomer; Lichti and Wilson).

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.
Allis

Figure 1. Locations of main thermal areas (stippled), production borefield (open circles), exploration wells (dots), reinjection wells (crosses), the resistivity boundary zone, and the approximate location of the subsidence anomaly. A-B is the line of the cross-section. 'x' is Umupokapoka.

vents (Figure 1). The springs and seepages were concentrated along the banks of the Tarawera River, and around the southern shore of Lake Rotoitiipaku 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 northwest side of Kawerau town. The only other thermal features are weak steam and 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 hot lakelet with a significant overflow around the turn of the century, but by 1952 it had become a sintered lake bed with numerous bubbling hot pools and little outflow.

Studt (1958) attributes the loss of Umupokapoka hot spring to downcutting of the Tarawera River at Kawerau by 3 m 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).

Studt's 1952 survey of thermal activity has been the only systematic assessment of the heat flow of Kawerau field, but it was limited to the Onepu thermal area. The main hot spring area adjacent to Lake Rotoitiipaku 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 Rotoitiipaku, 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 Rotoitiipaku. 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. An additional 50 MW of subsurface outflow to the north of the field has also been postulated by Allis et al. (1993), based on anomalous boron concentrations in the groundwater north of the field. Assuming all this heat originates from a deep upflow of 300°C water, a deep mass upflow of ca. 100 kg/s is implied. These figures are similar in magnitude to many of the geothermal fields of the Taupo Volcanic Zone.

Subsurface Area of the Field

Although the surface activity at Kawerau is mostly concentrated in a 2 km² 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 resistivity surveys of Kawerau field were relatively shallow-penetrating, and limited in the area surveyed. These measurements suggested a field area of around 10 km² at about 250 m depth, roughly centred on the Tasman mill (Macdonald et al., 1970).

More recent resistivity measurements suggest a much larger field area 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 = 500 m and 1,000 m), 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 encloses an area of between 19 and 35 km², depending on whether the inner or outer edge of the boundary zone is included (Allis et al., 1995). A significant finding of the new resistivity survey has 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. Apparent resistivities with AB/2 = 1,000 m are mostly less than 20 ohm m for a distance of more than 3 km to the east of the Mill (Figure 2). Comparison of the AB/2 = 500 m and AB/2-1,000 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, there has been no drilling to test the geothermal potential beneath the eastern half of the low resistivity anomaly.

Reservoir Characteristics

Exploration drilling has confirmed early geophysical interpretations of a sequence of Late Quaternary volcanics overlying greywacke basement at around 1 km depth. The coalescing rhyolite domes, andesite lava, ignimbrite flows and intervening sediments and tuff typically result in stratigraphically controlled, high horizontal permeability in a few key units. Local temperature inversions frequently occur on drillhole temperature logs, even in the shallow upflow zone, indicating that aquifers containing cross-flowing cool groundwater merge with the rising geothermal water (Figure 3a). This is especially pronounced at less than 500 m depth. Fracturing is the main source of high permeability at greater depth. Deep hot water apparently rises on a few, widely spaced faults within the basement. The best production well at Kawerau, well 21 (up to 150 t/h of separated steam), intersects a major, northeast-trending faultzone in the basement around 1,100 m depth.

Temperature

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 (Figure 3a). This is confirmed by the temperature contours at 1 km depth shown in Figure 4.

In the central borefield, deep production temperatures are consistent with boiling of CO₂-bearing fluids (Christenson, this volume). Around the northern borefield, temperatures appear to be lower than the boiling point conditions, although the
two phase conditions. Boiling point conditions are also present in shallow aquifers (especially at elevations 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. The high-temperatures in the south of the field suggest the deep heat source for the field could be beneath Putauaki. This is a relatively young volcano (most of the cone is <5,000 years old) compared to the age of hydrothermal activity in the field (>300,000 years, Browne, 1979).

**Pressure**

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 3b). 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 100 kg/s at 300°C over an area of 1 to 2 km² implies an average vertical permeability of 10 to 20 md (below 500 m depth; the calculation assumes simple darcy flow; modified from Grant et al. 1982). This is smaller than the values determined from interference testing, 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 permeability. 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 with cold groundwater. The reason for the change in permeability around 500 m depth may be the preponderance of tuff and sediments acting as an aquiclude separating the shallow and deep parts of the reservoir. More details on the results of interference testing and numerical simulation of the field hydrology is given by White et al., (this volume).

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 below about 1 km depth (Figure 3a). The higher pressures could be influenced by the increased head associated with groundwater recharge into the elevated volcanic complex of Putauaki.

**Geochemistry**

The chemistry of Kawerau field fluids has many similarities to that found at Ohaaki and Rotokawa fields on the eastern side of the Taupo Volcanic zone (Christenson, 1987 and this volume). The downhole chloride concentrations in exploration wells decrease northwards across the main borefield, confirming the dominance of mixing and dilution with groundwater in an outflow zone extending to over 1 km depth (Figure 4). Consideration of chloride-enthalpy trends suggests the deep parent water feeding the main production borefield could have a chloride concentration of around 900 mg/kg, and an enthalpy of over 1,400 kJ/kg (over 310°C). Gas concentrations are variable due to the boiling and/or dilution history of the waters, and range up to 0.8% CO₂ and 0.02% H₂S by weight in the production borefield feedzones. This is discussed in more detail by Christenson (this volume). The gas content caused calcite scaling in production wells to be a problem in the early development years but this has been largely overcome by the injection of antiscalant below the flash level of production wells (Bloomer, this volume).

**Effects Of Development**

The rate of mass withdrawn from production wells at Kawerau has increased from relatively small values in the late 1950s, to 1200 ± 80 t/h (± 1 s.d., based on annual average values) during the last 10 years (6/1986 - 6/1996). Shallow reinjection began in 1991, and has averaged between 200-300 t/h for the last 4
years. The net mass withdrawal from the field has therefore been around 1000 t/h since the mid 1980s. The average enthalpy of the production fluid has remained close to 1200 kJ/kg, equivalent to a liquid feed temperature of 270°C. Significant variations in this average enthalpy occurred during the 1960s when some of the shallow production wells temporarily developed excess enthalpy during a period of local pressure drawdown. Subsequently, the effects of invading cooler waters depressed the average discharge enthalpy until production was shifted to greater depth.

The average net mass flow from the borefield of around 1000 t/h compares with the natural geothermal flow inferred from thermal activity of the order of 300-700 t/h, depending on whether unmixed 300°C water, or diluted 150°C water is being considered. These figures would suggest that significant development impacts should have occurred. In fact, any changes have generally been small or negligible, causing suspicions that the natural flow of the field is larger than initially inferred from thermal activity.

Pressure Changes

The long-term pressure drawdown at Kawerau field appears to have been within measurement error of most downhole logging runs (<±1 bar). Continuous pressure monitoring in selected wells has confirmed that the largest producers cause pressure changes elsewhere in the production borefield of up to 1 bar as a result of opening or closing wells. The excess vertical pressure gradient over a hydrostatic gradient below 500 m depth has therefore persisted with time (Figure 3b), and deep reservoir water still flows upwards to charge the shallow aquifers and to appear as seepages along the banks of the Tarawera River. This was confirmed by an airborne infra-red survey in 1992. These hot spots extended downstream to the northerm, outer edge of the resistivity boundary crosses the river (Figure 1).

Intensive monitoring of the hot groundwater aquifer within the production borefield has occurred since 1991 so that the effects of shallow reinjection could be studied. Prior to the start of reinjection, the local groundwater level in wells M1-M4 varied between 18 and 22 m above sea level, with the adjacent Tarawera River level at 17 m asl. These wells had maximum depths of 110-140 m, and maximum temperatures of between 120 and 170°C. The pattern of water level changes since 1991 shows that the water table has varied by up to two metres due to the combined effects of nearby shallow injection, varying rainfall, varying infiltration from surface hot water disposal, and any production-induced effects (Figures 5 and 6).

A quantitative analysis of the causes of the water level fluctuations has not been attempted, but qualitative interpretation of the short period changes in response varying flow rates in reinjection wells M1 and 38 indicates changes of between 0.5 and 1 m. The water level in M3 is now below the original, pre-reinjection level of 20 m asl, so a decline of between 0.5-1 m between late 1991 and late 1996 appears to have affected this well (it is 250 m from M1). There is no evidence for large temperature changes in M3, and the other groundwater monitors do not show the same water level decline. Since M3 is the hottest of the groundwater wells, it is possible that it is more sensitive to deep pressure changes, and may be indicating a deep change of 0.05 - 0.1 bar in the last 5 years.

As mentioned above, changes in hot spring activity this century have been caused by down-cutting of the Tarawera River, and by the dumping of mill waste over the hot spring area adjacent to Lake Rototipaku. However some chloride-bearing groundwater still flowed out onto the sinter of the old Umupokapoka pool during the 1950s, so the hot groundwater table was then probably close to the local ground level of 23 m asl. The groundwater level in M2, adjacent to Umupokapoka, has remained between 19.8 and 20.8 m asl during the 1990s, so a groundwater level fall of around 3 m appears to have occurred as a result of field development. This is a minimum estimate because separated water from well 35 discharged onto the Umupokapoka sinter for many years and may have recharged the local groundwater aquifer. Subsequently, reinjection into the adjacent well 38 (liner between 157-380 m depth) could be helping to sustain groundwater levels. Groundwater level changes have probably been much smaller than 3 m in areas away from the Onepu thermal area, where temperatures are cooler, and levels have been sustained by the regional, cold groundwater table.

Temperature Changes

Long-term temperature changes at Kawerau field are not well documented, due to factors such as the effects of interzonal flow in wells, progressive calcite scale effecting feedzone depths, and local cooling induced by drawdown of cooler waters with production, especially in the shallower wells. Such wells have been cemented up, but the thermal effects of cold water invasion are probably still present. Strong dilution trends accompanied the progressive demise of these wells, with downhole chloride concentrations decreasing from initial values of around 900 mg/kg to 400-600 mg/kg, and temperature decreases of around 50°C before abandonment of the wells (Allis et al., 1995).

The present production wells are much more stable, indicating slow cooling trends of up to 0.5°C/year, and chloride dilution trends of the order of 10 mg/kg/year. These trends have been used to calibrate the numerical simulation of the field response to development (White et al., this volume) and are discussed in more detail by Christenson (this volume).

Subsidence

Precise relevelling of benchmarks throughout Kawerau field and the surrounding countryside since 1970 have revealed a stable pattern of anomalous subsidence in a 10 km² area centred on the northern part of the field. Here benchmarks have been subsiding at rates of up to 30 mm/y (Figures 7 and 8). This stable pattern was dramatically interrupted on 2 March, 1987 when a shallow earthquake with an epicentre near Edgecumbe, 15 km north of the field, caused most of the field to suddenly subside by between 200 and 270 mm (Allis et al., 1995). Although the associated ground shaking (up to MM9) caused much damage
Figure 5. Trends in groundwater levels in response to reinjection into well M1 since 1991, and into both M1 and 38 since 1993. Well locations shown on Fig. 6 (data supplied by Downer Energy Services Ltd).

Figure 6. Location of features in the production and reinjection borefield.
Allis by between 200 and 270 mm (Allis et al., 1995). Although the associated ground shaking (up to MM9) caused much damage throughout the Bay of Plenty and to the mill on Kawerau field, the actual subsidence caused little direct damage. Subsidence rates rapidly returned to their pre-seismic pattern after the earthquake.

The earthquake demonstrated that tectonic subsidence is superimposed on any anomalous subsidence caused by geothermal development, and care is needed interpreting such anomalies. Geologic evidence suggests that the Whakatane graben, in which Kawerau field is situated, is subsiding by an average of several mm/y, but this occurs intermittently. In the subsidence map for the post-seismic period 1988-1994 (Figure 8), tectonic effects are present to the northeast of the field, where subsidence of between 5 and 9 mm/y extends over a large area. Comparisons with a map of pre-seismic subsidence (1976-1986; Allis et al., 1995) shows rates of <5 mm/y over the same area. The area of anomalous subsidence which appears to be associated with Kawerau field is defined on Figure 8 by the 10 mm/y contour in the north, and by the 5 mm/y contour in the south. This is the outline of the subsidence anomaly shown on Figure 1.

The subsidence anomaly includes the main thermal outflow of the field (i.e. the Onepu thermal area) and the production borefield. Subsidence anomalies in outflow zones have also occurred at Wairakei-Taupara, and Ohaki fields as a result of shallow pressure drawdown due to development (Allis, 1982). Although the evidence for pressure drawdown at Kawerau is only inferred from changes in hot spring activity, the similarity in the locations of subsidence anomalies in other developed fields strongly suggests a causal link. The horizontal subsidence gradients adjacent to subsidence maxima at Kawerau suggest compaction at shallow depth. A well specifically designed to identify the compacting horizon has confirmed that in that area the compaction is occurring beneath the bottom of the well (>83 m depth). The compaction zone may coincide with the hot

![Figure 7](image-url) **Figure 7.** Trends in representative benchmarks at Kawerau field. The step in the trends in March, 1987, occurred at the time of the Edgecumbe earthquake. The benchmarks are located in Figure 6.

![Figure 8](image-url) **Figure 8.** Annual average subsidence around Kawerau field for the period 1988-1994. Additional benchmark data is available within the production borefield area but has been omitted for clarity. Note that there is a regional subsidence anomaly of up to 5-9 mm/y northeast of the field, probably due to residual ground settlement after the 1987 Edgecumbe earthquake. The fine dashed line are topographic contours; the hatching is the resistivity boundary.
groundwater aquifer at 100-200 m depth and could be due to high compressibility of its host formation, the Rotoiti breccia.

**Reinjection**

The reinjection history at Kawerau field has already been discussed above, and is summarized in Figure 5. The injection flow rate into M1 has declined since 1991, with the average injectivity decreasing from around 35 t/h/bar to 25 t/h/bar. Deposition of silica is thought to be the main reason. Brief periods of discharge of M1 temporarily improved the injectivity, but so far have been unable to slow the longterm decline trend. The reinjection water in M1 originates from deep wells 21 and 27, having exited a separator at around 180°C, and then flowed through a binary power plant where it cools to around 120°C. This is 20°C below the silica saturation threshold of around 140°C, so some silica precipitation problems were expected. The temperature at injection depths is over 30°C higher than the injection temperature, but potential increases in permeability with time due to the effects of cooling appear to have been outweighed by the effects of silica precipitation.

In contrast to M1, the injectivity of well 38 has increased with time. The injection flow rate has increased from 150 to 200 t/h with constant wellhead pressure since 1993, and the injectivity has increased from 17 to 22 t/h/bar. The reinjection water is at 180°C having come directly from the separator receiving fluid from production wells 19 and 35. This temperature is 28°C above silica saturation. The injectivity increase with time is attributed to the effects of cooling and contraction of the country-rock at loss zone depths (temperature originally >200°C).

Pressure interference between shallow reinjection and shallow monitor wells tapping the hot water in the Onepu thermal area had been confirmed during earlier reinjection tests, and are clearly evident on Figure 5. Several tracer experiments with fluorescein, radio-active iodine and SF₆ have proved to be inconclusive, and generally shown no returns to either deep production wells or shallow monitor wells. Positive results from a 1991 fluorescein test soon after reinjection start-up in M1 showed returns in M3 and M4, but subsequent tests have been unable to duplicate the results (Wigley and Stevens, 1993). However, steadily increasing chloride concentrations in M2, M3, and several other groundwater monitor wells from initial values of 300-400 mg/kg to 500-600 mg/kg in 1996 strongly suggests that reinjection fluid (1,000 mg/kg Cl) is mixing with the groundwater zone. M4 is an exception to the above trend, with Cl increasing from 300 to 350 mg/kg during the first year of reinjection into M1, but since then it has steadily decreased to around 200 mg/kg. Because of the well's location on the “upstream” side of the Onepu thermal area and the two injection wells, this could be another indication of gradually decreasing upflow of deep reservoir water into the shallow aquifer. Further monitoring is needed to clarify the main factors controlling the groundwater in the Onepu thermal area.

**Concluding Comments**

Resistivity surveys suggest that Kawerau field could have a total area of 19 to 35 km². The productive potential of most of this area is unproven and unknown, with the present production borefield producing from about 2 km² around the Onepu thermal area, and interference effects evident over about 10 km². 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 points to a balance at the moment between relatively small pressure effects due to production, and sustained natural upflow of geothermal fluid to groundwater aquifers. Despite the complicating effects of shallow reinjection in the Onepu thermal area, small effects of gradually decreasing upflow appear to be occurring. These include subsidence on the northern side of the field, and possible water level decline and shallow chemistry changes. A substantial increase in production will cause greater pressure drawdown, increasing the possibility of downflows from the groundwater aquifer as has occurred at Wairakei-Tauhara and Ohaaki fields near their original outflow zones. Significant new production will probably require both a major expansion in the area of production wells and reinjection of all the additional mass withdrawal. The potential for interference between existing and new production and reinjection wells, together with the need to mitigate environmental impacts, will best be achieved through unified management of the borefield.

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