THE BASEMENT AT KAWERAU GEOTHERMAL FIELD

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SUMMARY - Kawerau and Ohaaki geothermal fields have regional similarities - both occur close to the east margin of the TVZ, have shallow basement, and are not associated with a major rhyolitic caldera. The Kawerau basement slope into the TVZ is half as steep as at Ohaaki, and the south to north drop could be accommodated on two major faults. Predicting basement permeability fiom fault patterns is difficult, and may lead to erroneous well targeting. Kawerau greywackes belong to Waioeka petrofacies of the Torlesse, and have more plagioclase, but less quartz and argillite than the Axial-A petrofacies greywackes of Ohaaki. Because of this, the Kawerau basement may sustain open fiactures to greater temperatures and depths than Ohaaki basement.

1. INTRODUCTION

In a review of the basement geology and structure of geothermal fields in the Taupo Volcanic Zone (TVZ), it was noted that the Mesozoic Torlesse terrane greywacke/argillite rocks were commonly penetrated at production drilling depths in only the two most easterly fields, Ohaaki and Kawerau (Wood, 1996). Attention was focussed on Ohaaki where, in 1994-1995, long-throw deviated drillholes into the basement demonstrated poor production permeability in the Torlesse terrane rocks. At Ohaaki only 1 of 18 wells penetrating the basement has been sufficiently permeable to sustain production (BR43). By contrast, 8 of the 17 basement-penetrating wells at Kawerau have been permeable, with some very large producers (eg KA21), though in general the Kawerau basement rocks are considered to be largely impermeable (Allis *et al.,* 1993).

Although both fields are less than 10 km fiom the eastern boundary of the TVZ, they are 65 km apart (Fig. 1) and the basement rocks, though superficially similar, have different compositions and belong to separate subterranes of the Torlesse (Mortimer, 1995). Greywacke composition is unlikely to influence permeability at different localities at production drilling depths. However, in the deep systems where T>350°C such factors may influence the depth of the brittle-plastic transition, the extent of open fissuring, and hence the efficiency of heat extraction by circulating fluids. Also, the ability of the greywacke basement to sustain open fractures at high temperatures may be affected by its bulk grain size (argillite content) content.

In this paper we present new petrographic data on Kawerau basement rocks, discuss the nature of their permeability, and compare and contrast with Ohaaki. The work is part of an ongoing study to discover more about the deep geothermal resources of the Taupo Volcanic Zone.

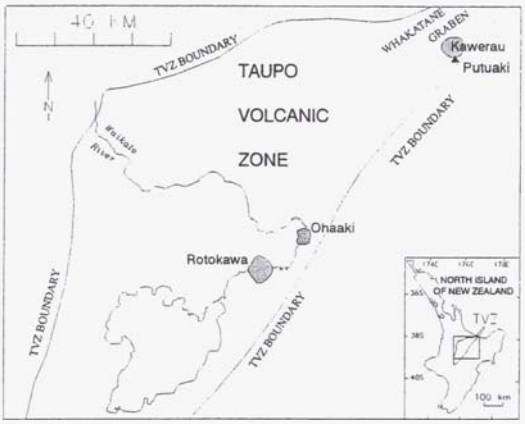


Figure 1 – Map of Taupo Volcanic Zone showing locations of geothermal fields with Torlesse terrane basement.

2. KAWERAU AND OHAAKI

2.1 Regional Setting

Kawerau and Ohaaki have certain regional characteristics that set them apart from other major geothermal fields in the TVZ (with the possible exception of Rotokawa; Fig. 1).

Unlike most geothermal fields in the rhyolite-dominated central part of the TVZ, neither

Ohaaki nor Kawerau are located within, or on the faulted margins of one of the large rhyolite calderas (Wood, 1995). Kawerau is 10 km NE of the very active Haroharo Caldera in Okataina Volcanic Centre, while Ohaaki lies respectively 5 km south and 10 km east of the indistinct margins of the inactive Whakamaru and Reporoa calderas.

2.2 Basement Faults

Kawerau and Ohaaki occur where the basement profile has been represented as a series of stepped blocks, faulted down towards the centre of the TVZ. In both fields, downhole temperatures suggest mass flow of hot fluids fi-om depth occurs in the SE where the basement is at its highest elevation, field pressures are highest, and there is evidence of a shallow magmatic heat source (Allis *et al.,* 1993 fig. 7; Wood, 1996 fig. 4; Christenson *et al.,* 1998).

At Ohaaki the basement falls at 570 m/km to the NW, with a total displacement of ~1300m, that can be accommodated on as few as three faults (Wood, 1996). The situation at Kawerau may be similar, and it has been suggested that NE-trending normal faults bound a series of blocks that are back-tilted to the SE (Allis *et al.,* 1993). However, drillhole evidence is not convincing, and it is hard to locate basement faults from surface morphology with accuracy. Fig. 2A shows contours on the basement surface dropping fi-om south to north with a maximum displacement of 570 m (260 m/km or 15°, only half as steep as at Ohaaki). There are two zones where the slope steepens to about 30°, separated by a nearly flat-lying zone in the centre of the field with an average slope of ~5°. The steep zones probably represent large faults with an approximate position as shown on Fig. 2A.

This simple picture of basement faulting contrasts strongly with the complexity of the fault network (Fig. 2B) assumed by earlier authors (Nairn, 1986; Nairn & Beanland, 1989) and later modified for geothermal field management purposes (eg Stevens & Koorey, **1996).** Fig. 2B shows a series of faults with a dominant NE-SW (45°) strike. Parallel fault zones in the area of KA21-KA36-KA37 are assumed to be significant targets for production drilling. Allis *et al.,* (1993) show basement faults as extending through the 0.33Ma Rangitaiki Ignimbrite, but no further (to *–600* m depth). A similar situation was reported at Ohaaki where movement on the major basement faults appears to have ceased shortly after the 0.33Ma "Whakamaru Group" catastrophic eruptions that produced the Rangitaiki Ignimbrite (Wood, 1996).

The location of basement faults has important management implications, for Kawerau is said to lack extensive permeable stratigraphic aquifers.

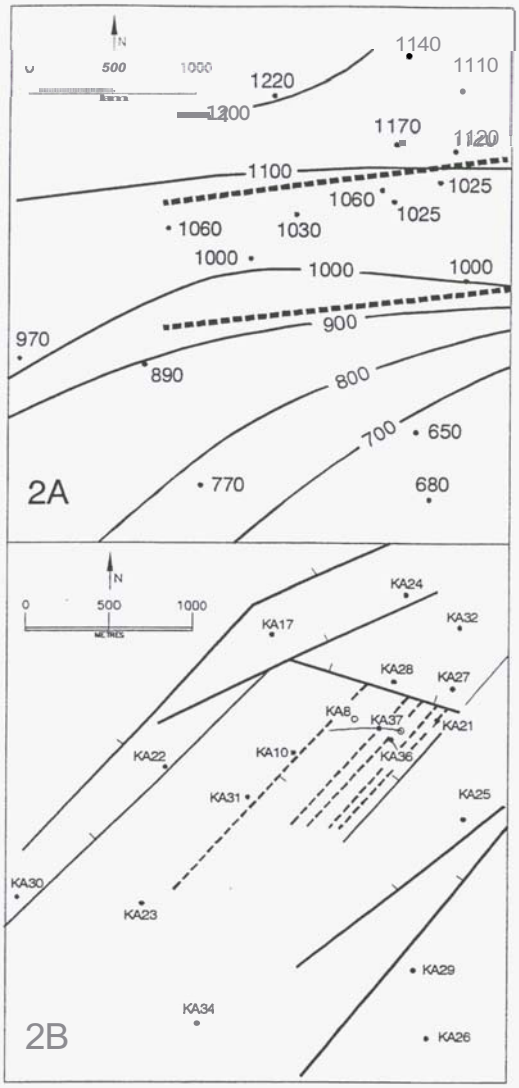


Figure 2 - A: Contour map of basement elevations (m bsl) in Kawerau drillholes. Dashed lines show possible locations of basement faults. B: Previously inferred fault map (see text for sources) and well numbers.

However, the regular **45"** fault pattern does not conform with the slope of the basement surface, and is at variance with the dominant 055°-065° **(ENE)** trend of the most accurately measured faults in the area - those that ruptured during the 1987 Edgecumbe earthquake. The closest of these surface breaks to Kawerau (Rotoitipakau Faults, Onepu Fault and Te Teko Fault; Beanland *et al.,* 1989 fig. 1A) occur en echelon in an E-W zone from 2.5-5 km north of the centre of the geothermal field. Beanland *et al.*, state that the Edgecumbe event was typical of normal faulting events expected in the TVZ. Thus, although no ruptures were seen directly in the geothermal field, the **055°-065°** fault strike presumably is representative of active faulting across a wide area of the Whakatane Graben, including Kawerau. Two possibilities arise: either the allegedly 045"-dominant fault trend relates to an

early tectonic regime that was more northerly oriented than the modem active faulting in the Whakatane Graben, or it does not represent the true fracture pattern at Kawerau.

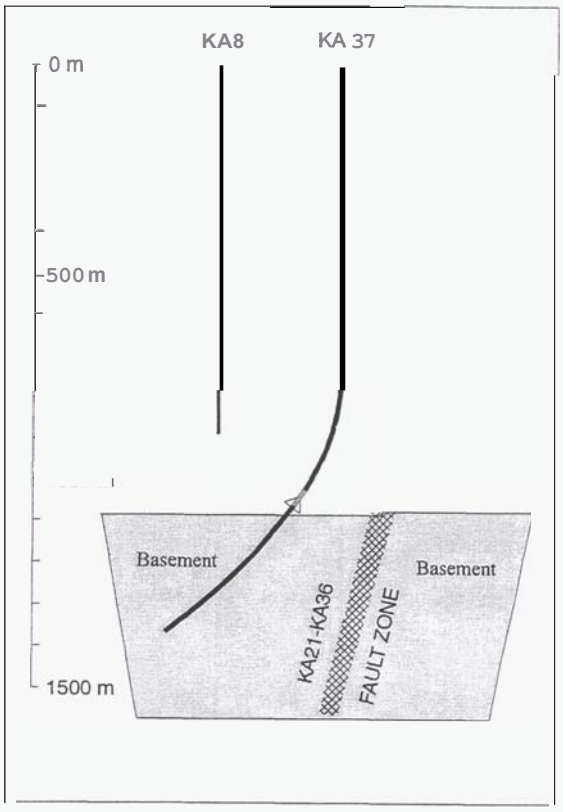
3. BASEMENT FAULTS AS TARGETS

3.1 Locating Faults

Finding permeable faults in a TVZ geothermal field is largely a hit-or-miss procedure. Geological formations at depth in TVZ volcanic terrane often have naturally steep slopes (buried volcanoes, calderas, river valleys), and formation contacts determined fkom drill logs often have unavoidably large errors (±5m minimum). Hence, stratigraphic information is rarely good enough to determine the presence of a fault, let alone its dip and displacement. Surface fault traces are sometimes obvious, but usually only the approximate position of a fault can be fixed, and then with no indication of dip angle. Investigations of the Edgecumbe Fault showed that in the top *2* km under the Rangitaiki Plains, the fault plane dip in the basement was about 55" or shallower, curving towards vertical only in the top 100m or so (Beanland *et al.,* 1989; Nairn & Beanland, 1989; Woodward, 1989). However, most geological analyses have assumed high dips for faults in TVZ geothermal fields (eg 80° for Kawerau, in Allis *et al.,* 1993). The difference between 55° and 80° could represent hundreds of metres drilling for a vertical well targeted at a basement fault plane, even with the rare luxury of an accurately fixed surface trace to measure from.

32 Recent Basement Drilling

The uncertain trends of concealed faults and the large range of possible dips, means attempts to determine fault attributes by linking permeable zones in adjacent wells, may lead to the wrong conclusions. The history of drilling in KA21-36-37 area (Fig. **2B)** provides a case example of such difficulties of interpreting basement faulting, and hence of tapping into faults with precision. In 1975, KA21 intersected two feed zones within 150m below the basement surface and became a large and reliable producer. In 1991 when extra steam supply was needed, KA36 was drilled 300 m SW of KA21 and deviated to intersect the same faults, which were assumed to strike at 045°. Again, two feed zones were found, though 70-120 m deeper. Interference tests were carried out with KA21 on discharge, and pressure drawdown confmed the wells were connected (Stevens & Koorey, 1996). The authors emphasised the importance of such measurements because when used with a wellbore simulator, the net steam gain could be calculated for any new well ***tapping the same fault structure:*** important information indeed, but dependent on knowing which fault is



'Figure3 – Schematic profile of well KA37.

which. In fact, Stevens & Koorey correlated the basement faults in KA36 with permeable zones in the volcanic cover in KA21, as follows:

Feed Zones (m depth); basement *italicised*

KA21	KA36
800	*1150*
935	1300
1080	
1180	

This correlation was based (Lynell Stevens pers. com. 1998) on an a ***priore*** geological assumption that the KA21 800 m feed must be fault controlled and connected to the upper basement feed in KA36 (Nairn & Wood, 1991). This led to the conclusion that KA36 had not been drilled deep enough to reach the projected KA21 basement faults which remained a viable target for future redrilling. However, if it is assumed the hydrological connection between KA21 and KA36 is actually **via** the basement, the connecting fractures must strike ~048°-063°, consistent with the strikes of Edgecumbe earthquake fault ruptures. Importantly, if KA36 should fail, redrilling deeper is no longer a viable option.

In 1993 KA37 was drilled from 70 m NE of KA36 on a westward deviation to intersect basement fkactures postulated to be feeding high enthalpy "primary" fluids to the volcanics penetrated by KA8 (Christenson, 1987). Despite

passing more or less beneath KA8 on its way laterally through 270 m of greywacke (Fig. 3), the well was impermeable. Perhaps the deep feeder channels discharging primary fluid to the KA8 area associated with the northern postulated major basement fault described earlier (Fig. 2A). KA37 track was sub-parallel to that fault, so could not have penetrated it. If the KA21-KA36 fault (more likely, zone of fault fractured rock) has a strike of say 55°-60°, it projects close beneath KA37 (Fig. 3), suggesting the well could be renovated by redrilling on a deviation to ESE.

4. BASEMENT PETROGRAPHY

4.1 Waioeka Petrofacies

Absar & Blattner (1985) reported on basement mineralogy at Kawerau, but their data are at variance with Waioeka petrofacies (Mortimer, 1995). In particular, the type Waioeka sandstones (greywackes) are dominated by andesitic volcanic clasts, and have low-moderate quartz (4-20%), but Absar & Blattner make no mention of lithics, give higher **quartz** values (10-33%) and list 3-19% K-feldspar, which seems unlikely in andesite-derived sandstones. Therefore we have re-examined the mineralogy of 35 basement cores from 17 wells. The data below confm that Kawerau basement comprises Late Jurassic-Early Cretaceous Waioeka petrofacies sandstones (volcanic litharenite) with abundant volcanic clasts, moderate quartz, and little K-feldspar.

The dominant lithology is a medium grained (0.25-0.5mm) sandstone composed of subangular volcanic clasts (mainly andesite lavas with rare rhyolite), minor argillite and chert, and detrital plagioclase (abundant), **quartz** (subequal with plagioclase in fine-grained sandstones), minor perthitic K-feldspar, biotite, epidote, and rare muscovite. The andesite lava clasts show felted or pilotaxitic textures with laths of plagioclase, and intergranular chlorite. Rhyolite clasts are identified from relict spherulitic textures in very fine grained devitrified glass. Possible ignimbrite with relict welded texture is present in several thin sections. Clasts and lenses of carbonaceous argillite occur in minor amounts in all samples, and **as** discrete laminae interbedded with fine-grained sandstone in KA34/1443m. Chert is a minor constituent in most samples. The medium-grained sandstones are clast-supported and matrix-poor (–5%); the matrix being clay/silt altered to illite-chlorite-quartz.

The least-altered Kawerau samples are very similar to pristine Waioeka greywackes which outcrop east and north of Kawerau. Samples of litharenite from Hendersons Quarry (15km ENE) and Camerons Quarry (28km NNW) are medium or coarse grained sandstones composed of subangular clasts of altered andesitic volcanics, and minor argillite, chert and rhyolite, with abundant plagioclase and quartz, and minor K-feldspar (microcline), augite, biotite, chlorite, epidote and rare muscovite **as** the detrital minerals. They are clast supported and matrix poor (–5%). The andesitic clasts are all altered to chlorite-rich assemblages and some plagioclase clasts are partly altered to illite, suggesting that the parent volcanic rocks were already altered. This alteration contrasts with scattered cavities filled with calcite±chlorite deposited during low-grade burial metamorphism.

Modes of least-altered volcanic litharenite (Tab. 1) show the dominance of volcanic lithic fragments, and the low matrix proportion. However, it is often difficult to distinguish lithic material from matrix because of the alteration. In comparison, a typical greywacke **from** Ohaaki basement is lithic-poor, matrix-rich and quartz-rich, typical of the sandstones (feldsarenites) of the Torlesse Axial-A petrofacies (Mortimer, 1995). The Ohaaki greywackes are also fine-grained and interbedded with argillite, whereas the Kawerau samples are dominantly medium-grained sandstones with only a minor argillite content.

Table 1: Modal composition of basement greywacke from Kawerau (KA) and Ohaaki (BR)

Well No	KA17	KA28	KA32	BR47
depth	1452m	1448m	1424m	1607.5m
	%	%	%	%
Volcanic	58.6	58.8	52.0	7.8
Argillite	4.0	0.2	1.0	2.0
Chert	1.2	1.6	1.6	1.0
Quartz	11.0	8.8	13.2	32.8
Plagioclase	19.4	24.8	24.6	21.8
K-feldspar	0.2	0	0.2	0.2
Biotite	0.2	1.0	0.6	2.0
Others	1.0	1.6	1.4	1.4
Matrix	4.4	3.2	5.4	31.0
Total %	100.0	100.0	100.0	100.0

Analyses by counting 500 points per thin section

Palmer et al. (1995) list chemical analyses of 4 samples **from** Kawerau and Camerons Quarry, and 2 from Ohaaki. Anhydrous SiO_2 ranges from 64-65.3 **wt%** for Kawerau compared with 69.4 and 72.8 **wt %** for Ohaaki, and the former have significantly higher Al_2O_3. The compositions are consistent with the Kawerau and Camerons samples being richer in felsic volcanic and plagioclase clasts, and are consistent with the regional petrological differences between the Waioeka and Axial-A facies (Mortimer 1995).

4.2 Hydrothermal v. Pristine Greywacke

All Kawerau samples are hydrothermally altered; mostly moderately (30-60%), but some intensely

(60-80%). Chlorite is the main hydrothermal mineral, but in the intensely altered samples illite becomes dominant. Calcite and fine grained hydrothermal epidote are common and tend to be antipathetic. Minor fine-grained titanite and pyrite are usually present. Plagioclase within andesite clasts or as discrete grains is partly to largely replaced by illite or less commonly by albite. It is totally replaced by adularia in the most intensely altered samples. Detrital biotite is partly replaced by chlorite. Most of the samples have mm-scale veinlets filled by a variety of hydrothermal minerals: calcite ± wairakite ± chlorite ± pyrite, epidote ± pyrite ± wairakite, or illite. Quartz veinlets are rare.

Comparison with compositionally similar, but not hydrothermally altered litharenites at Hendersons and Camerons quarries indicates that some of the chlorite and illite alteration is inherited and/or related to regional low-grade metamorphism. These Waioeka petrofacies litharenites also contain minor calcite, chlorite and zeolite filling small cavities, and minor detrital epidote and augite (replaced by chlorite at Kawerau). However, the abundance of veinlets is the main signature of hydrothermal reaction.

5. DISCUSSION

The depth to which hydrothermal convection occurs in the rocks beneath a geothermal field is determined by temperature, lithology, water content and strain rate, which control the location of the transition zone between the brittle-fracture and plastic-flow regimes (Nielson, 1994; Fournier, 1991). Studies in volcanic/geothermal areas suggest the transition coincides with the base of the seismogenic zone, coincident with the 350°C isotherm (Hill, 1992; Smith & Braile, 1994). Robinson (1989) reported the base of the seismogenic zone of the Edgecumbe earthquake and aftershocks to be about 9 km, except near Kawerau geothermal field and adjacent Putauaki (Mt Edgecumbe at the SE resistivity boundary of the field), where there was a seismic gap. He accepted the gap may have been coincidental, but raised the possibility that the rocks beneath the volcano and geothermal field were too hot and ductile to sustain seismic slip. Measured subsurface temperatures support the interpretation, though brittle fracture obviously occurs throughout the productive borefield. Impermeable wells in the south within 1.5 km of the nearest vents on Putauaki exceed 315°C (Allis *et al.,* 1993), suggesting the 350°C isotherm could be as shallow as 2km below sea level.

Lithology is also important, and Wood (1996) recognised that the different Torlesse petrofacies of the Kawerau and Ohaaki basements could influence the temperature at which ductile behaviour occurred. *Quartz* becomes ductile at lower temperatures than plagioclase, so all other factors being equal, the brittle-plastic transition should occur at lower temperatures (shallower?) in the quartz-rich Ohaaki basement, than in the relatively quartz-poor/plagioclase-rich Kawerau basement.

Both microscopic and macroscopic observations on core fi-om Ohaaki suggest there is a higher proportion of argillite laminated with the Axial-A petrofacies greywackes. Nielson (1994) noted at Valles Caldera that shale (argillite) deformed plastically when granite remained brittle, and by analogy, indurated sandstone should also be more brittle than argillite. Wood (1996) noted that argillite was in total only a minor component of the Ohaaki basement (~3%), but occurred in fine partings. It was evident that shear had occurred along sandstone/argillite contacts. Thus, at higher temperatures, much strain could be accommodated by slippage of ductile argillite laminae, rather than by cracking the dominant sandstone.

In theory, brittle fracturing should allow convecting fluids to penetrate deeper into hotter Waioeka than Axial-A greywackes. This does not imply that the deep basement above the transition zone at Kawerau is necessarily permeable enough to be economically productive, but there should be more efficient transfer of heat into the exploitable shallower levels, with resultant higher enthalpy fluids.

No existing wells at either Kawerau or Ohaaki penetrate deep enough into hot basement to test this hypothesis. Even in the hot, unproductive basement in south Kawerau, thin sections show the rocks contain veinlets filled with hydrothermal quartz and calcite, providing evidence of brittle fracture. However, the time may come when the shallow magma-ambient zones believed to exist beneath Putauaki, and SE Ohaaki provide an incentive for exploration.

6. CONCLUSIONS

The Torlesse terrane basement at Kawerau comprises Waioeka petrofacies volcanic litharenites (greywacke sandstones).

The basement slopes down into the TVZ from south to north, and most of the fall could be accommodated across two large buried faults. There is little stratigraphic evidence for a complex 045"-oriented fault pattern, and the orientation of productive fractures may be consistent with the ~055-065° trends of active faults in the Whakatane Graben.

The ductile-brittle transition should occur at lower temperatures/shallower depths in the quartz-rich argillite-bearing Axial-A petrofacies

greywackes of Ohaaki, than in the Waioeka petrofacies rocks of Kawerau.

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