POROSITY AND PERMEABILITY IN THE BASEMENT ROCKS AT THE KAWERAU AND OHAAKI GEOTHERMAL FIELDS, NEW ZEALAND

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SUMMARY – Porosity and permeability of Torlesse basement rocks and volcano-sedimentary sequences at Ohaaki and Kawerau were studied by direct porosity measurement and petrography of blue-epoxy impregnated thin sections. Thin sections show greywacke has near-zero primary porosity; Waikora Formation conglomerates have open pores between greywacke and argillite clasts; pumiceous Ohakuri Group volcaniclastics have greater porosity. Secondary porosity occurs in hydrothermal leach cavities in all lithologies. Clay minerals have intracrystalline microporosity. Basement porosities are generally <10%, but the Waioeka petrofacies greywackes of Kawerau have a greater porosity range than the Axial-A petrofacies greywackes of Ohaaki. Fracture-vein networks and microcracks could account for the higher Kawerau porosities, and where connected would provide some permeability. Oxygen isotope shifts in Kawerau greywackes are positively correlated with porosity. Porosity measurements indicate that at Ohaaki, pre-330 ka volcaniclastic formations have similar fluid storage capacity to the younger Rautawiri Breccia aquifer, but less than the shallow Waiora Formation aquifer.

1. INTRODUCTION

Mesozoic Torlesse terrane greywackes and argillites have been extensively drilled at Kawerau and Ohaaki geothermal fields (Fig.1), where they form the basement beneath the Quaternary deposits of the Taupo Volcanic Zone (TVZ).

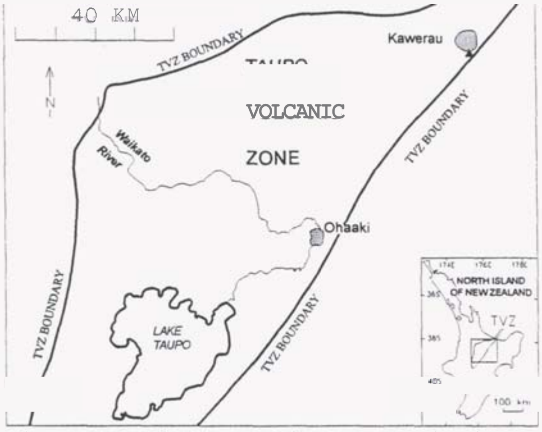

Figure 1. Outline map of the Taupo Volcanic Zone showing the location of Kawerau and Ohaaki geothermal fields.

Wood (1996), Wood & Brathwaite (1999), and Wood et al. (2001) documented the lithological and structural controls on basement permeability in these fields, and showed the greywackes contain significant volumes of hot fluid. However, there is a lack of information on where this fluid is held. Is it mainly in open fractures, in pores between and within mineral grains, or a combination of these? Porosity and permeability are essential properties of reservoir rocks in geothermal fields. Pores between and within mineral or rock grains provide storage space for fluids and the ratio of the volume of spaces to the bulk volume of the rock is its porosity. Permeability is provided by fractures and interconnection of pore spaces and is required for movement of fluids through the rocks.

Two objectives of the current study were to compare the measured porosity of the Kawerau and Ohaaki basement rocks, and by using petrographic techniques, to determine where both porosity and permeability are located on a microscopic scale. The porosity values were also compared with ^{18}O-compositions, which are ideally a measure of the degree of fluid/rock interaction.

Most geothermal production in the TVZ comes from volcanic/volcano-sedimentary aquifers deposited since the Whakamaru ignimbrites eruptive episode at –330 ka (Wilson et al., 1995). The older TVZ strata between the Whakamaru ignimbrites and the basement are poorly known, but do contain units that are lithologically similar to the shallow aquifers. We have compared the porosity of selected deep and shallow beds at Ohaaki, to see if the pre-330 ka deposits have similar storage capacity to the young aquifer rocks.

Here we summarise data for 53 samples from the Ohaaki and Kawerau fields. Individual porosity and oxygen isotope values along with petrographic descriptions are available from the authors on request.

2. POROSITY

Primary porosity in volcaniclastic and sedimentary rocks is provided by spaces between mineral or rock clasts. Secondary porosity results from leaching of unstable minerals during hydrothermal alteration, such as in the partial replacement of calcic plagioclase by adularia.

Mineralogical and textural controls on the location and geometry of the porosity were observed from petrographic examination of thin sections impregnated with blue epoxy. This is a commonly used technique in hydrocarbon reservoir rocks, in which porosity is subdivided into macroporosity (>16 µm) and microporosity. Macroporosity mainly consists of intergranular holes. Microporosity occurs as micropores in clay minerals, such as illite and chlorite, and can be observed by staining and/or scanning electron microscopy. Microcracks, defined as discontinuous (<20 mm in length) fractures which are less than 0.5 mm in width, are another contributor to secondary porosity in the basement rocks.

2.1 Primary intergranular porosity

Because of induration and alteration, the greywacke sandstone .basement rocks at Kawerau and Ohaaki appear to have near-zero intergranular porosity. The spaces between mineral and lithic grains are filled with recrystallised matrix of illite and chlorite. However, intergranular porosity is locally present in conglomerate from the Waikora Formation at Ohaaki (Fig. 2A) and siltstone clasts in tuff (BR15-1591m) from the Ohakuri Group. Pumice lenticules show possible primary porosity as irregular-shaped areas up to 0.2 mm in length in a few samples of welded ignimbrite (eg BR12-1275m) from the Ohakuri Group.

2.2 Secondary porosity.

In the volcanic and volcaniclastic lithologies, secondary pore spaces of significant size consist of leach cavities in calcic plagioclase and primary mafic minerals and of vugs associated with vein or cavity filling by hydrothermal quartz or epidote. Leach cavities in plagioclase are the most common and occur as semi-rectangular-shaped holes up to 0.2 mm in length (Fig. 2B) in crystals of plagioclase that is replaced by hydrothermal albite or adularia. The semi-rectangular shape clearly follows the crystal structure of the original plagioclase. Leach cavities associated with former mafic minerals are more diffuse, such as small pore spaces associated with chlorite replacing former pyroxene crystals in BR1-1397m. Examples of hydrothermal minerals partly filling vugs include quartz (BR14-1186m) and epidote (BR26-1159m, Fig. 2C).

Intercrystalline porosity occurs as micropores in clay minerals, such as illite and chlorite, but it may not be significant in providing permeability because of the small size of the pores and their lack of connectivity. Microporosity is observed as a diffuse pale blue colour filling micropores that do not extend through the full thickness of the thin section. This microporosity is common in hydrothermal illite and chlorite, and in microcrystalline glass in tuffs and ignimbrite. In many cases the hydrothermal illite is replacing pumice clasts in tuffs (eg BR1-1125m). In other samples the microporosity is localised in former glass shards **(Fig. 2D).**

3. PERMEABILITY

Interconnected intergranular pores, as noted above, provide primary permeability. However, in geothermal fields, secondary fracturing, such as open fault zones and breccia zones produced by hydraulic fracturing (Grindley & Browne, 1976) provide much of the permeability. Fig. 2E illustrates a network of veins, which represent filling of a fault-fracture mesh in litharenite from Kawerau.

Interconnected microcracks may also be a provider of permeability in geothermal reservoirs (Wajima et al., 2000). Microcracks, as discontinuous subparallel or intersecting fractures, were observed in plagioclase grains (Fig. 2F) and in wairakite veins from several litharenite samples at Kawerau.

4. POROSITY MEASUREMENTS

Apparent porosity (the volume of pores interconnected with the sample surface and penetrable by water) was measured on 53 selected samples of pre-330 ka rocks, by standard hydrostatic weighing methods. New data were combined with old data (for Ohaaki wells only) from the GNS rock properties database. Table 1 summarises the data. The porosities of Waioeka lithofacies (see Wood & Brathwaite, 1999 for lithofacies descriptions) basement greywacke cores at Kawerau range from 2.3 to 18.4% (25% had >10%) and shows a general positive correlation with the microscopically observed porosity.

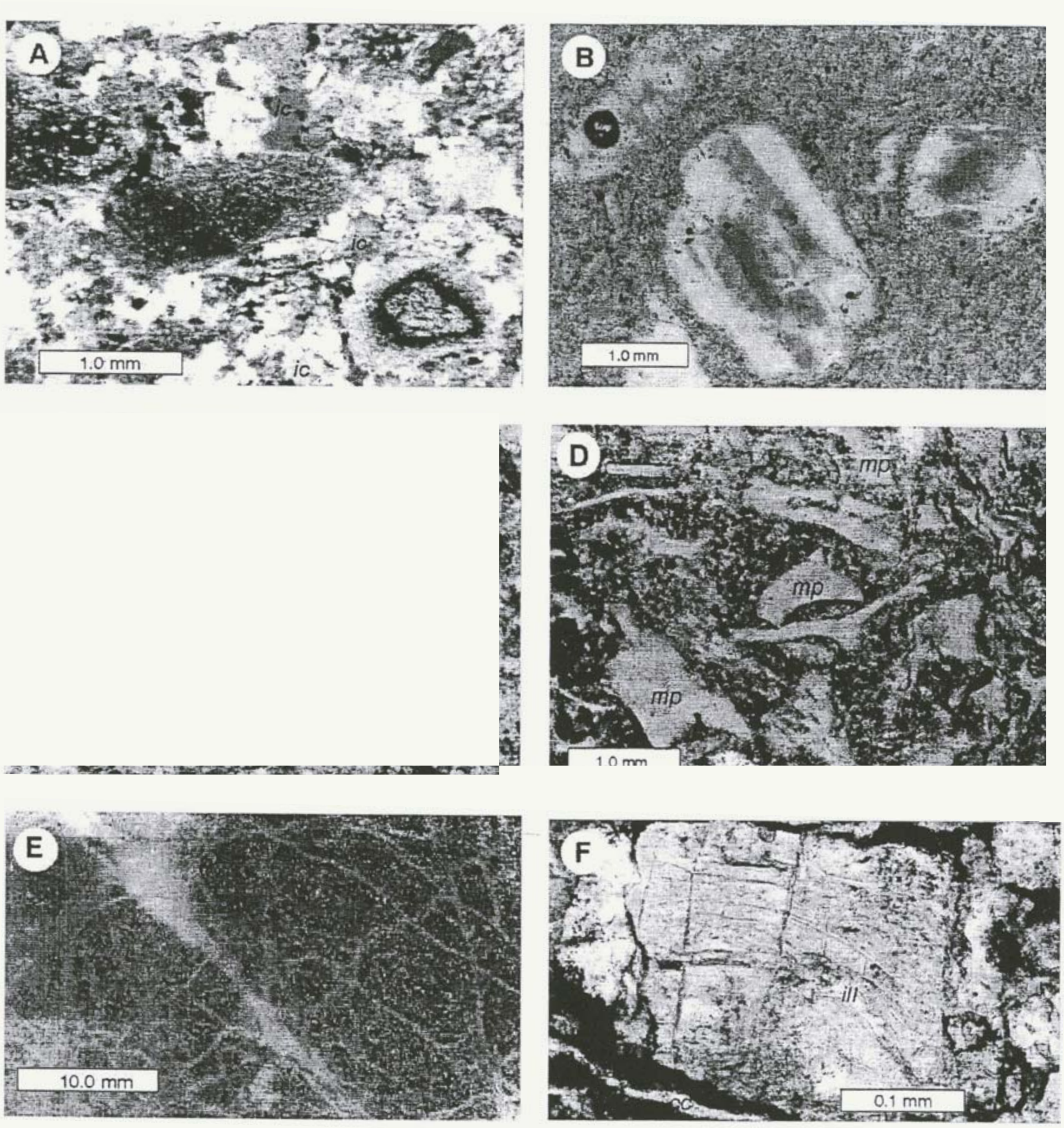

Figure 2. Photomicrographs of porosity and permeability. **A:** Interclast pores *(ic)* between sandstone clasts (Waikora Conglomerate, BR24-1255m). **B**: Leach cavities (medium grey) in plagioclase crystals (ignimbrite BR37-1370m). C: Radiating crystals of hydrothermal epidote partly filling a vug (medium grey) in volcaniclastic sandstone (Waikora Conglomerate, BR26-1159m). D: Microporosity (*mp*, pale grey) in glass shards (ignimbrite, BR32-1089m). E: Mesh of illite-epidote-calcite veins in hydraulic fracture breccia (litharenite, KA36-1075m). F: Microcracks cutting illite (*ill*) veinlets in altered plagioclase grain, with adjacent calcite (cc) vein (litharenite, KA38-1240m).

Axial-A lithofacies greywacke cores from Ohaaki have the same mean porosity as Kawerau greywackes (Table 1), but only 5% exceeded 10% porosity, which is consistent with the limited microporosity observed in these samples.

Fig. 3 shows greywacke porosity against core depth for the two fields. There is no significant correlation of porosity with depth, except that the two relatively shallow cores from Kawerau also have the highest porosity.

Table 1: Porosity % of some Ohaaki formations, Kawerau basement, and surface outcrops. SD = standard deviation; N = number of analyses.

	Post-330 ka Aquifers		330 ka	Pre-330 ka Formations		Torlesse "basement"		
	Waiora Formation	Rautawiri Breccia	Rangitaiki Ignimbrite	Ohakuri Group	Waikora Formation	Ohaaki Axial-A	Kawerau Waioeka	Surface outcrops
Mean	33.0	24.9	13.2	20.9	14.5	6.5	7.2	1.7
SD	8.1	7.5	7.7	6.8	6.6	2.7	4.5	0.75
N	64	124	65	33	25	22	24	13

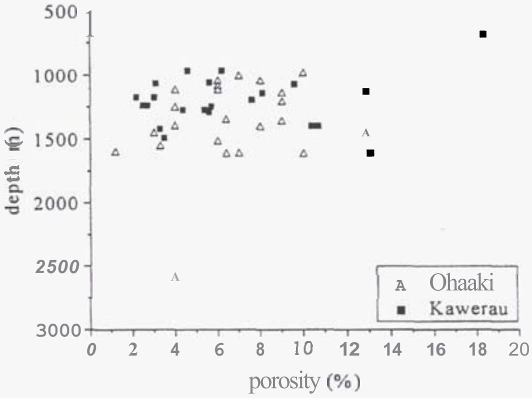

Figure 3. Porosity v. depth of Torlesse basement greywackes from Ohaaki and Kawerau.

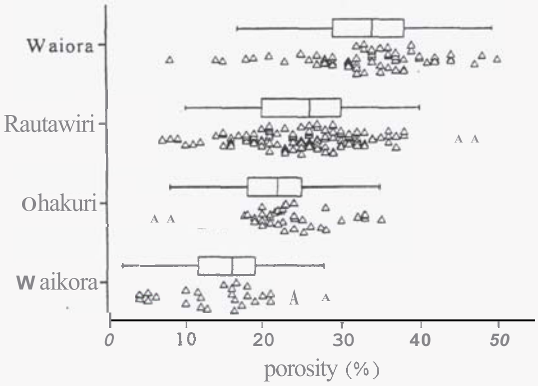

Figure 4. Porosity of Ohaaki Pre-330 ka formations (Ohakuri Group and Waikora Formation) and Post-330 ka aquifers (Waiora Formation and Rautawiri Breccia).

Greywacke cores from both fields have much higher porosity than similar Torlesse rocks in outcrops just east of the TVZ from the Kaimanawa Ranges north to the Bay of Plenty coast (Table 1). The Torlesse rock masses would initially have had similar physical properties, so it seems likely that the greywackes at Kawerau and Ohaaki have higher porosity (and presumably permeability), because of increased hydrothermal microfracturing in the tensional stress regime within the TVZ. As discussed before (Wood & Brathwaite, 1999), the Kawerau Waioeka facies basement may be more susceptible to brittle fracture at elevated temperatures than Ohaaki Axial-A facies, which may contribute to the greater abundance of higher porosity samples at Kawerau. Hydraulic fracture breccias were observed in core from Kawerau (Fig. 3E) and similar fault-fracture breccias occur in basement greywacke at Kuaotunu, Coromandel Peninsula (Rowland & Sibson, 1998). This type of breccia is a manifestation of the fluid-driven meshes of Sibson (1996) that are considered to form channels for large-volume fluid flow in extensional tectonic settings such as the TVZ.

The two main stratigraphic production aquifers at Ohaaki are the Waiora Formation and Rautawiri Breccia. Both contain primary volcaniclastic beds interlayered with reworked epiclastic units. Their absolute ages are uncertain, but Rautawiri Breccia lies directly on the 330 ka Rangitaiki Ignimbrite, and is separated from the younger Waiora Formation by a minimum of –30 m of siltstone. Ohakuri Group is an informal name used for beds of similar lithology to the Waiora Formation and Rautawiri Breccia, that lie between the Rangitaiki Ignimbrite and the basement. Ohakuri Group strata are interbedded with conglomerates of the Waikora Formation, comprising mainly greywacke-argillite pebbles in a sandy tuffaceous matrix.

Porosity data are given in Table 1. The Waiora Formation has highly significantly greater porosity than the equivalent lithological formations, the Rautawiri Breccia and the Ohakuri Group. The latter two formations are similar, though Rautawiri Breccia porosity is slightly higher. As could be expected, the Waikora Group conglomerates are transitional between Ohakuri Group and Torlesse basement. Unlike the Torlesse greywackes, none of these formations crop out at the surface. The porosity relationships show clearly in “box and whisker” plots (Fig. 4). In these plots the box extends from the 25* to 75th percentiles around the median, and the whiskers are two standard deviations from the mean. The **Y-axis** scatter for each formation is depth related.

5. OXYGEN ISOTOPES

Absar and Blattner (1985) and Blattner et al. (1994) suggested that past flowpaths in the basement rocks of geothermal fields could be defined from the isotopic shift of whole rock oxygen isotope values. They inferred that lower values (<7 ‰ for andesite and ignimbrite, <10 ‰ for greywacke) have been shifted down by interaction with meteoric waters and that these depleted values correlated with permeable zones.

As a test of this hypothesis, selected samples of basement rocks from Kawerau and Ohaaki were analysed for oxygen isotopes using a conventional BrF_5 extraction of silicates. The $\delta^{18}O$ values range from 11.7 to 4.0‰ in samples of volcanic litharenite from Kawerau. The values that are significantly down shifted from unaltered litharenite at about 12‰, show a positive correlation with measured and observed porosity. However, the results for samples from Ohaaki are inconsistent. Two samples of greywacke have $\delta^{18}O$ values of 5.4 and 6.0‰, which are anomalously low in relation to their low porosities (3.0-6.4%) and only weak to moderate alteration. In contrast, samples of ignimbrite are anomalously high (7.8-9.4‰) in relation to their porosities (12-33%) and intense alteration.

6. DISCUSSION & CONCLUSIONS

It is generally believed, but rarely proven, that a geothermal well must intersect a fault fissure to provide enough permeability to sustain production. However, fissures in impermeable rock can be vulnerable to scaling and mechanical blockage, and consequent rapid decline in output. The ideal situation occurs when faults or other extensive fissures are located in porous strata with high storage capacity and extensive micropermeability. The Waiora Formation is such an aquifer that has produced well at Wairakei and Ohaaki (Wood, 1994), and the lithologically similar Rautawiri Breccia at Ohaaki has been productive for 213 of the wells to penetrate it. In contrast, Kawerau lacks extensive stratigraphic aquifers, and production from Quaternary formations is said to rely on fractures in impermeable lavas and ignimbrites (Allis et al., 1993).

Beneath the Quaternary, the Mesozoic Torlesse basement has considerable fault-controlled permeability at Kawerau; yet has virtually zero productivity at Ohaaki. Such geological variability at fields which appear similar on a gross scale make it difficult to extrapolate potential geothermal capacity in as yet unexploited areas of the TVZ. Lawless (2002) produced an estimate of the high-temperature resource capacity of all TVZ fields using void space as one of the input parameters. The void space estimates have a large variance, and for fields with shallow basement, include large volumes of rock with poorly known porosity and permeability characteristics. We hope the data in this paper may help refine resource capacity estimates in future, particularly where basement is involved.

The very low porosity of surface Torlesse greywacke in comparison with cored geothermal basement may be misleading. Surface samples were selected from solid unfractured rock, whereas core is often fractured. In this respect., the porosity values of core greywacke are likely to be more representative of the bulk void space in the basement than the outcrop samples are of the bulk Torlesse at the surface. Observed microporosity in the quartz-rich Ohaaki greywackes is very low and associated mostly with clay minerals (chlorite and illite). At Kawerau, the volcanic clast-rich greywackes are variable with nil porosity seen in about 25% of thin sections, while thin fractures associated with veins occur in the rest.

Although the porosities of the different basement lithofacies are similar, our results suggest that the Waioeka (Kawerau) greywackes are more susceptible to microfracturing than the Axial-A (Ohaaki) rocks. In turn this could result in greater brecciation when stressed, and consequent higher permeability and fluid-feed into productive fractures. Basement petrography and microporosity measurements may offer a predictive tool if greywackes are penetrated in as yet undeveloped fields near the eastern TVZ boundary (eg Tauhara). Thus, if an exploratory drill hole penetrated Axial-A lithofacies greywackes, the Ohaaki experience would suggest that production drilling into the basement would be unprofitable, and should be avoided.

The pre-330 ka Ohakuri Group volcaniclastics at Ohaaki have similar mean porosity to the younger Rautawiri Breccia aquifer, but are interbedded with Waikora Formation conglomerates with much reduced porosity. Unlike the post-330 ka strata above the Rangitaiki Ignimbrite, which field-wide are mostly 800-1100m thick, the strata between the Rangitaiki Ignimbrite and the basement vary in thickness from zero in the SE to >970m in the *NW*, making it hard to correlate individual permeable Ohakuri Group units, and hence to predict their depth and thickness, especially in the *NW* where they are most likely to be productive.

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