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BASEMENT GEOLOGY AND STRUCTURE OF TVZ GEOTHERMAL FIELDS, NEW ZEALAND

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SUMMARY - The basement beneath the volcanic and sedimentary deposits in geothermal fields in the Taupo Volcanic Zone is a potential, but poorly understood resource for future deep production. **A** basement exploration drilling programme carried out by ECNZ (now Contact Energy Ltd) at Ohaaki showed that greywacke-dominated Torlesse Terrane is permeated by hot fluids to depths of 2000 m below sea level, but has poor permeability even where cut by major faults. **A** rhyolite dyke drilled 575 m below the basement surface may have intruded a fault plane and sealed permeability at that point. Greywacke-dominated basement probably does not extend more than 10 km beyond the eastern margin of the TVZ at Ohaaki. Hot plutons (granite and minor diorite), and metamorphosed Torlesse Terrane intruded by dyke complexes may comprise the basement further west in the Whakamaru caldera area.

1. INTRODUCTION

As heat and fluid are mined from the shallow volcanic sequences of geothermal fields in the Taupo Volcanic Zone (TVZ), the underlying, poorly permeable basement will become an important production target. The success of the strategy will be determined by the productivity of natural fractures, and our ability to find them. Contact Energy Ltd recently carried out a basement drilling programme at Ohaaki. This paper reports on the geological information gathered, and discusses wider aspects of the nature of the TVZ basement.

2. BASEMEN" IN THE TVZ

Rocks lying beneath the Quaternary volcanic and sedimentary sequences of the TVZ have been penetrated at Rotokawa, Ohaaki, Kawerau and Ngatamariki (Fig.1). The first three fields lie close to the eastem boundary of the TVZ, and in each case, the basement rocks are Mesozoic sandstones (greywacke) and argillite of the Torlesse Terrane (Mortimer, 1995), which crop out in the Huiarau and Ikawhenua Ranges to the east.

Resistivity modelling over the area including Ohaaki and Rotokawa (Risk *et al.,* 1993, 1994) indicates that the Torlesse greywackes lie buried a few 100 metres beneath the ignimbrites of the Kaingaroa Plateau as far west as the Kaingaroa Fault, which effectively defines the east side of the TVZ. The 5-10 km wide fault zone comprises a series of normal faults which progressively drop the basement westwards to a depth of at least 2 km below sea level (-2000 mRL). Further west there is a pronounced lateral change from high to low resistivity over the Taupo-Reporoa Basin (Bibby *et al.,* 1995) which suggests that the Torlesse Terrane may be missing or completely changed in character. Drillhole data provide support for the resistivity model. Thus the basement gradient at Ohaaki (570m/km) would drop the surface to below -4000 mRL at 10 km west of the TVZ boundary. The gradient is less at Kawerau (260m/km), but is consistent with a basement surface not deeper than -2500 mRL in the Whakatane Graben (Nairn and Beanland, 1989).

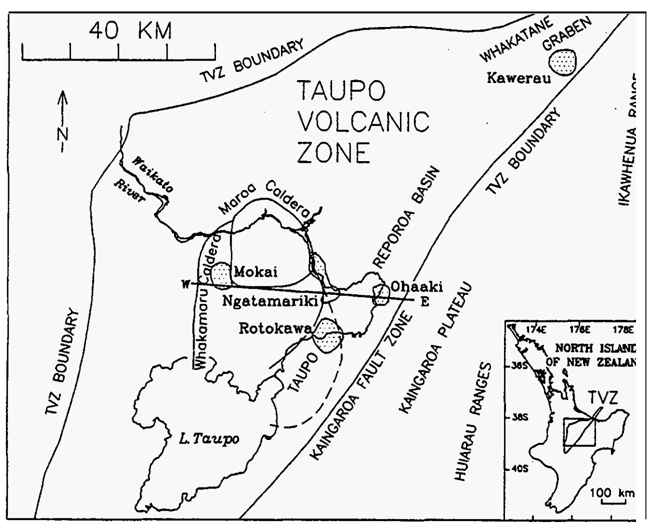

Figure 1 - Outline map of Taupo Volcanic Zone showing locations of some geothermal fields (stippled), calderas, and the W-E geological cross-section (Fig. 6).

Igneous basement has been drilled only at Ngatamariki (15 km from the eastern boundary of the TVZ), where well NM4 reached 2742 m depth (-2392 m **IU)** and bottomed in 100 m of diorite, assumed to be part of an intrusive pluton (Browne *et al.*, 1992) emplaced prior to 0.33 Ma.

3. THE OHAAKI EXPERIENCE

Prior to 1994, 16 vertical wells had penetrated a total of 3 km of Torlesse Terrane basement at Ohaaki (Fig. 2). With the exception of BR34 which was drilled through 1 km of greywacke down to -2274 mRL, the average penetration depth was only –130 m. A 3D view of the basement (Fig. 3) shows how the surface falls from SE to NW over the buried scarps of two major basement faults (Faults A and B) which comprise part of the Kaingaroa Fault Zone (Risk et *al.*, 1993).

Fault B trends SW-NE parallel to the TVZ boundary, but the downthrow side of Fault A is defined only by BR15, and its SW - NE orientation is presumed. Fault C is poorly defined, but also has a westerly downthrow. BR16 stratigraphy suggests that Fault D drops the basement in the SE comer of the field down to the SE by at least 200 m, in a contrary sense to the general westward downthrow into the TVZ. All the faults appear to dislocate the Rangitaiki Ignimbrite, and possibly the overlying Rautawiri Breccia. Younger formations are not noticeably affected, suggesting that most movement occurred prior to about 0.3 Ma.

The greywacke has a poor production record. Circulation losses while drilling in the basement were recorded in BR10, BR42 and BR43 (at 72 m, 185 m and 20 m below basement surface respectively), but only BR43 could sustain production. None-the-less, the basement is hot and potentially productive. The modelled temperature of the basement surface (Fig. 3) is below 200°C only in the southwest where it was penetrated by reinjection well BR39. In the productive part of the field (the area inside the 260°C isotherm at -600 mRL in Fig. 2A), it is mostly at 280-300°C. A hot-spot occurs on the scarp face of Fault A. Figure 4 is a geological cross-section from BR16 to BR34, overlaid on a thermal cross-section. A thermal plume rising into the volcanics from the basement in the vicinity of Faults B and C is clearly shown.

A 3-well, deviation drilling programme to explore basement production potential was designed by Contact Energy Ltd (then ECNZ). The well trajectories were aligned approximately E-W, targeted to penetrate the major fault zones at points where the predicted temperature exceeded 280°C. Two of the wells, BR47 and BR49, were located on the eastern (Broadlands) side of the field and drilled respectively westward and eastward through the basement at its highest elevation. BR48 was drilled on the Ohaaki side of the Waikato River eastward into the scarp face of the western fault.

BR47 (Fig. 5) penetrated 1691 m of basement, terminating at -2000 mRL (1295-2986 m drilled depth); BR49 penetrated 1633 m of basement, terminating at -1780 mRL (1160-2793 m drilled depth). BR48 probably penetrated about 100 m into basement around -1500 mRL, but complete drilling circulation losses prevented geological sampling.

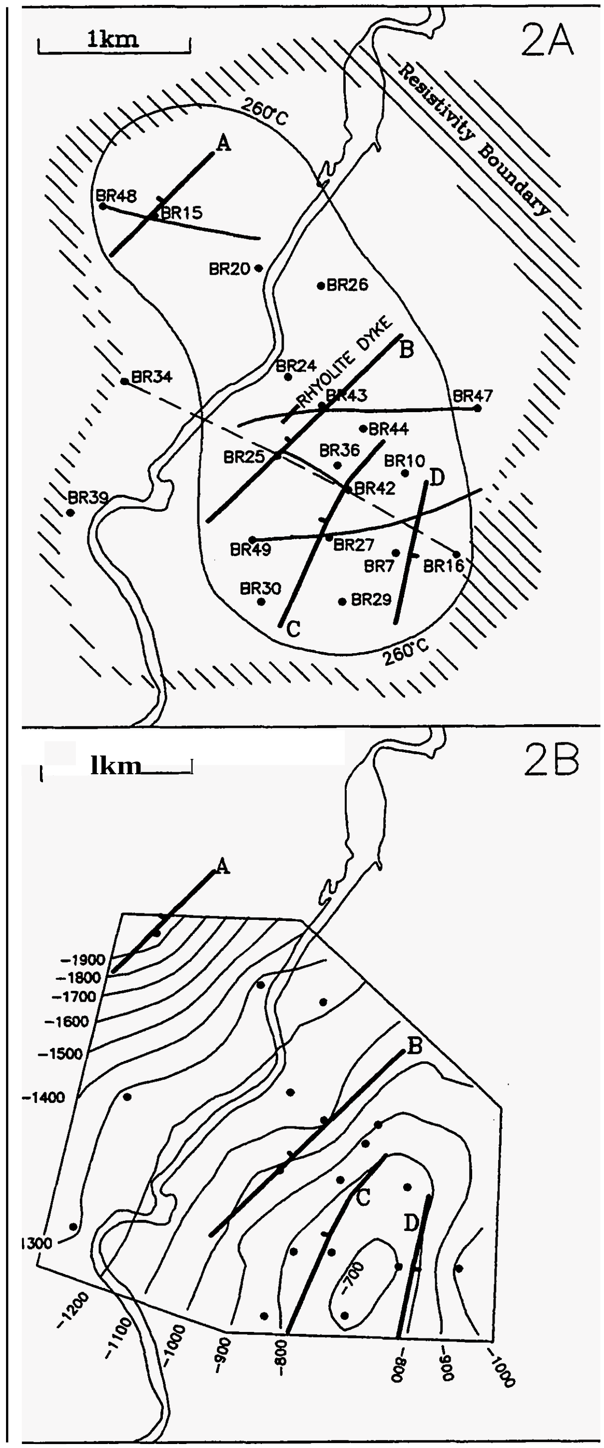

Figure 2 - Ohaaki geothermal field showing (A) resistivity boundary, 260°C isotherm at -600 mRL, faults (A-D), well locations, rhyolite dyke intersected by BR47, and cross-section line of Fig. 4: (B) contours on basement surface in mRL, and data points used to define the surface. Polygon outlines the block shown in Fig. 3.

4. NATURE OF THE BASEMENT

The basement beneath the SE sector of the field consists almost entirely of interbedded sandstone and subordinate (–3%) argillite. Thin argillite partings in sandstone are common. The best sample of continuous core yet obtained from the pre-TVZ basement (from ~-1300 mRL) was recovered from BR47. It comprises mostly hard, grey, medium-fine grained greywacke sandstone with partings of grey-black argillite. The sandstone contains abundant detrital quartz, and is correlated with Axial A petrofacies Torlesse Terrane (Mortimer, 1995). Much of the core is massive greywacke with thin (≤1 mm) argillite partings on a mm to cm scale. Argillite beds are more common in the lower part of the core and show 45° (relative to core axis - true orientation unknown) bedding planes with greywacke. Argillite is cut by fine (<1 mm) chloritic strings lying subparallel to the bedding. Contacts between argillite and greywacke are commonly sheared and micro-brecciated with chloritic slickenside caused by post-depositional movement between argillite at greywacke. The fracture pattern showed no preferred orientation - some are parallel to bedding planes, others orthogonal, and others cross-cutting. Veins (≤2 mm) filled wholly or partly with hydrothermal minerals are commonly oriented subparallel to the core axis. They are lined with epidote ± calcite and filled with later-stage quartz, calcite and chlorite, and smaller amounts of illite, pyrite, sphalerite and galena. Hydrothermal quartz, chlorite and pyrite also occur in the crush zones between greywacke and argillite beds. Pyrite is particularly common in association with argillite.

The hydrothermal mineral assemblage is much the same as that in the deeper parts of the volcanic sequence at Ohaaki (Browne and Ellis, 1970; Lonker *et al.*, 1990). These authors emphasised the rare Occurrence of epidote in the shallower part of the system, a consequence of high CO_2 concentrations in the fluids and preferential stability of calcite. Epidote appears to be more abundant in the basement, and was the first mineral to form on the vein walls, though it is commonly inter- and over-grown with calcite. Significantly, the basement vein mineralogy lacks adularia, which typically occurs with quartz at all depth levels in highly permeable zones in the overlying volcanic aquifers.

Cuttings from BR47 and BR49 were very fine grained (<3 mm), preventing recognition of anything other than gross hydrothermal structure. However, calcite, epidote, quartz and pyrite were present throughout the basement, in quantities similar to those found in cuttings at the core depth. This implies that the whole mass of the basement is pervasively fractured and mineralised on a decimeter to metre scale. Nowhere were the minerals common enough to suggest the wells passed through zones of intense fracturing and mineralisation. Prismatic quartz crystals occurred in BR49 at 2340 m (~-1800 mRL) where there must have been open cavities at least 2 mm wide, but neither here nor at any other depth where enhanced mineralisation was noted, was there enhanced permeability. It would appear that the greywacke/argillite basement is soaked in geothermal fluid, but has little connected permeability.

4.1 Rhyolite Dyke

The only certain occurrence of a volcanic feeder dyke yet encountered within the TVZ basement is in BR47 (Fig. 5). Cuttings of rhyolite, sandwiched between greywacke, were returned from 2468-2487 m (about -1700 mRL). At this point, the well had penetrated ~1170 m of basement and was 575 m vertically below the basement surface. The orientation and thickness of the dyke cannot be measured directly. It occurs at the point where BR47 was predicted to pass through Fault B (Fig. 2A). Assuming the dyke intruded the zone of weakness provided by the fault, and the fault dip is ~75°, the true dyke thickness is about 10 m.

Thin sections of cuttings (maximum size ~2 mm) show the rock originally comprised phenocrysts of plagioclase, quartz, and possibly hornblende, with accessory FeTi oxide, zircon and apatite set in a very variable matrix. The matrix is mostly fine-grained with little recognisable fabric. Microgranular texture predominates in the shallower cuttings, but deeper, micropoikilitic (snowflake) texture is common, consisting of zones of optically continuous quartz heavily charged with illitised feldspar, chlorite and obscure dusty matter. In places, the included matter is flow-aligned such as seen commonly in rhyolite lava glass. Rarely the texture is coarser, when it shows micrographic or mosaic texture. Similar textures are common in glassy rhyolitic rocks which have devitrified during slow cooling, such as in the centre of thick welded ignimbrites (Lofgren, 1970; McPhie *et al.*, 1993). Less commonly the rhyolite matrix appears to show weak vitroclastic texture typical of eruptive deposits. The lack of coarse-grained plutonic texture, and the rare presence of apparent eruptive textures suggest that the dyke discharged at the surface, causing degassing and vesiculation down to at least the level penetrated by the drillhole.

The hydrothermal alteration of the rhyolite is consistent with the surrounding greywacke. Plagioclase is partly altered to albitekquartz, calcite, epidote and illite. Hornblende(?) is replaced by chlorite, or quartz+epidote. The matrix contains albite, chlorite, leucoxene-sphene, pyrite, illite, calcite and rare sphalerite. The primary rhyolite mineralogy has not been established well enough to allow correlation with eruptive units at Ohaaki, but the composition is similar to parts of the Rautawiri Breccia formation.

4.2 Ohaaki Interpretation

BR47 was impermeable throughout the basement, including the rhyolite dyke believed to occupy the plane of Fault B. BR43 also intersected Fault B at a point ~500 m up the fault plane from the BR47 intersection and only 20 m into the basement; here at ~-1150 mRL, the fault is productive. BR49 crossed a permeable zone about 80 m below the basement surface (~-815 mRL), interpreted as Fault B, but no permeability was recorded corresponding to Fault C, despite mineralogical evidence for open fractures at the appropriate depth.

The Ohaaki experience suggests that the basement is pervaded by fractures containing geothermal fluid, but major permeable pathways are either narrowly confined or non-existent. If the latter is true, the geothermal aquifers in the TVZ volcanic cover must be recharged by diffuse leakage through the basement surface. However, the presence of a hot-spot on Fault A scarp, a thermal plume located above Faults B and C, and shallow intra-basement permeable zones in at least two wells, is evidence that faults do provide enhanced permeability, even if the channels have limited lateral extent. It is possible that Fault B was sealed in parts by the intrusion of rhyolite magma.

Finding and exploiting these channels is necessary if deep production is to succeed, but it is clearly a difficult proposition. The Ohaaki wells were deviated at a high-angle (up to 55° from vertical) to increase the chances of penetrating steeply dipping faults, but at the risk of passing through the faults in too short a distance, at an impermeable point. *An* optimum strategy would be to drill a deviated well down along the fault plane close to the strike direction, to give both lateral and vertical continuous penetration. However, this would require fault attitudes to be known with an accuracy far beyond present knowledge.

5. A GEOLOGICAL TRANSECT

Fig. 6 shows a speculative cross-section through Ohaaki, Ngatamariki and Mokai. From east to west, the transect crosses the Kaingaroa Fault Zone where Torlesse Terrane basement is progressively thrown down to the west in accordance with the Risk *et al.* (1993) resistivity model, and observed geology in Ohaaki drill holes. A postulated diorite pluton beneath eastern Ohaaki, represents a heat source that generates fluids with an "andesitic" signature (Giggenbach, 1995), consistent with the presence of a buried, young (< 0.3 Ma) andesitic volcano centred in the SE (the "Broadlands Dacite", now known to consist mainly of andesite: C.P.Wood unpublished data).

The western edge of the high-resistivity Torlesse Terrane corresponds to magnetic anomalies which Soengkono (1995) interpreted as hot plutons with tops at ~-4000 mRL. They are shown extending as far west as Ngatamariki where drilling proved a relatively shallow dioritic pluton surrounded by a metamorphic aureole. West of Ngatamariki, the transect is dominated by the large, 0.33 ka, Whakamaru caldera. Granite plutons occupy the centre of the caldera and lie beneath Maroa Caldera just north of the Transect (Fig. 1).

Mokai is a typical low-gas "rhyolitic" system (Giggenbach, 1995), possibly sustained by heat associated with the Whakamaru and Maroa caldera plutonic episodes, and located where caldera fractures (of both calderas) provide deep access for groundwaters (Wood, 1995). The deepest rocks recovered from Mokai (MK5 at -2143 mRL) are reworked rhyolitic pyroclastics of pre-Whakamaru Ignimbrite age (C P Wood, unpublished data). They are hydrothermally altered, but show no sign of thermal/pneumatolytic effects that could relate to plutonic intrusions. The depth to which early TVZ deposits of this type extend is completely unknown. Remnants of metamorphosed Torlesse Terrane may be present at depth in the western part of the transect, where multiple dyke intrusion is likely.

6. DISCUSSION

The deep limit of hydrothermal convection is the transition zone between the brittle fracture and plastic flow regimes in stressed rocks (Nielson, 1994; Fournier, 1991), and is controlled by temperature, rock lithology, water content, and strain rate. Temperature is a major determinant, and studies in volcanic/geothermal areas have determined the base of the seismogenic zone (the brittle-plastic transition) to coincide with the 350°C isotherm (Hill, 1992; Smith and Braille, 1994).

However, as Bibby *et al.* (1995) have pointed out, the host rock temperature at depth within a convecting geothermal plume is controlled by the circulating fluid, and the temperature gradient is low. This suggests the vertical extent of the exploitable (convective) part of a geothermal system may be determined less by the depth of its heat source, and more by factors that control the ability of the host rocks to sustain open fractures, such as lithology and strain rate.

It has been shown (Sibson, 1984; Foumier, 1991) that because quartz becomes ductile at a lower temperature than plagioclase feldspar, the brittle-plastic transition occurs at a much lower temperature in granite than quartz diorite. Thus, under conditions of a high-geothermal gradient (125°C/km), normal faulting and strain rate similar to that measured in the TVZ (10^{-14} s^{-1}, Darby & Meertens, 1995), the transition occurs at ~300°C in "wet" granite, and at ~400°C in "wet" quartz diorite. In a convecting system where T>300°C and the geothermal gradient is low, a temperature difference of 100°C could represent 2-3 km depth range.

Plutons beneath the rhyolitic, central TVZ are expected to be granitic. Hence convection in TVZ systems may not extend as deep as in areas dominated by andesite volcanism. However, the only plutonic rock yet drilled in the TVZ is in fact quartz diorite at Ngatamariki (Browne *et* al., 1992). Possibly this is anomalous, and may imply that the Ngatamariki geothermal system penetrates deeper than average in the central TVZ.

Basement rocks with very different lithology have differing brittle-plastic characteristics. For instance, in a Valles Caldera well, a bed of impermeable shale at about **2.5-3.0** km depth could not sustain open fractures, whereas deeper granite remained brittle and permeable even at 340°C (Nielson, **1994).** Similarly, the Torlesse Terrane is more likely to suffer plastic deformation than massive coarse-grained plutonics under the same P/T conditions. Within the grossly homogeneous Torlesse Terrane there are regional petrofabric variations that could influence its ability to hold open fractures.

The Torlesse Terrane rocks are dominated by indurated, massive sandstones, which appear monotonously similar, but in fact belong to different petrofacies (Mortimer, **1995).** At Rotokawa and Ohaaki, the sandstones are quartz-rich Axial petrofacies with a "rhyolitic" composition **(SiO_2 70-80%).** At Kawerau they are quartz-poor, volcanolithic-rich Waioeka petrofacies of "andesitic" composition **(SiO_2 60-64%).** All other factors being equal, the brittle-plastic transition should occur at higher temperature (deeper) in the quartz-poor Waioeka basement (or its metamorphosed equivalent). Hence Kawerau presents a better prospect for deep basement production than Ohaaki or Rotokawa.

6. ACKNOWLEDGEMENTS

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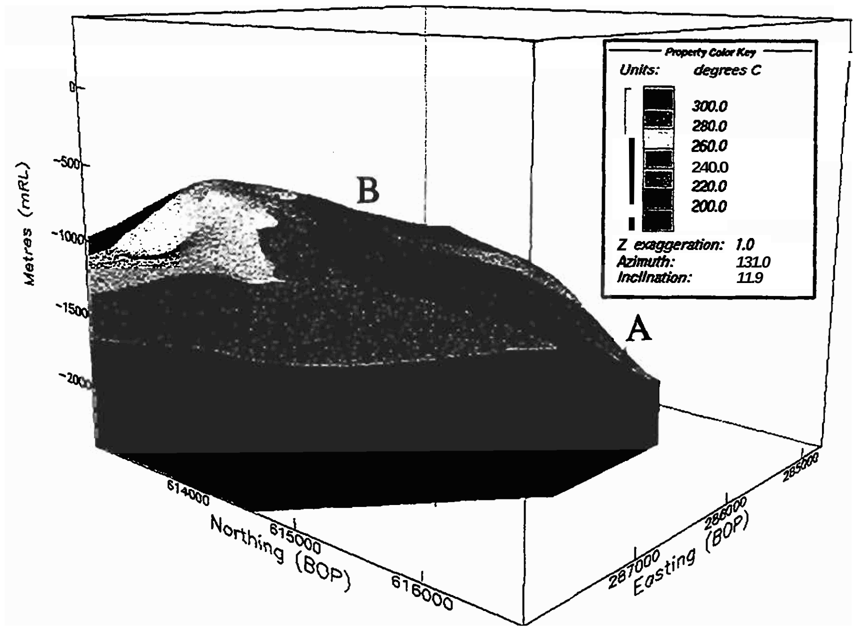

Figure 3 - 3D model of Ohaaki basement coloured according to temperature. Block outline is shown on Fig. 2B.

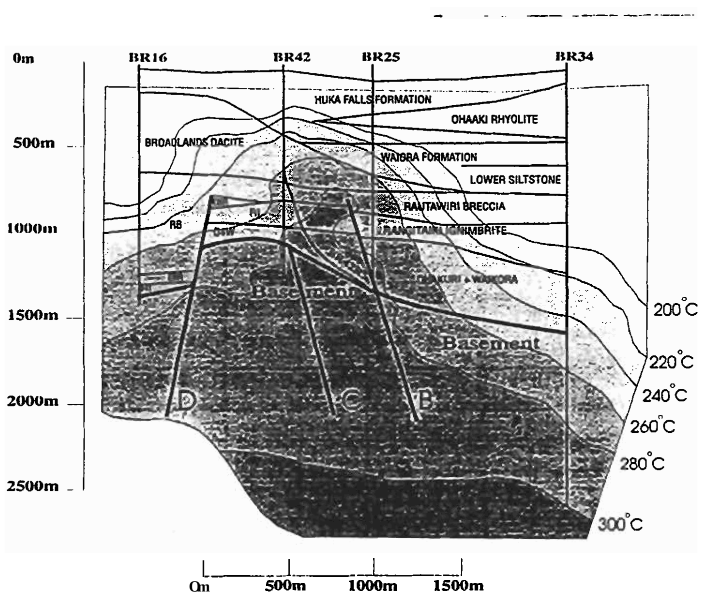

Figure 4 - Geological and thermal profile from BR16 to BR34. Section line is shown on Fig. 2A.

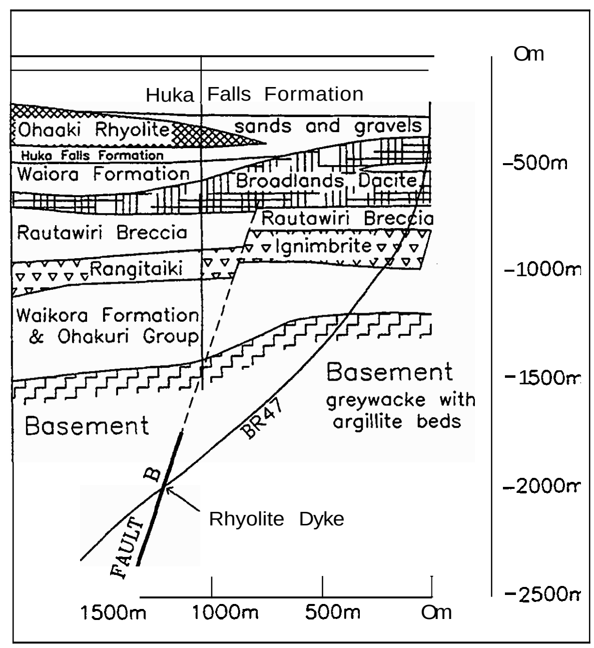

Figure 5 - Geological profile in plane of deviated well BR47

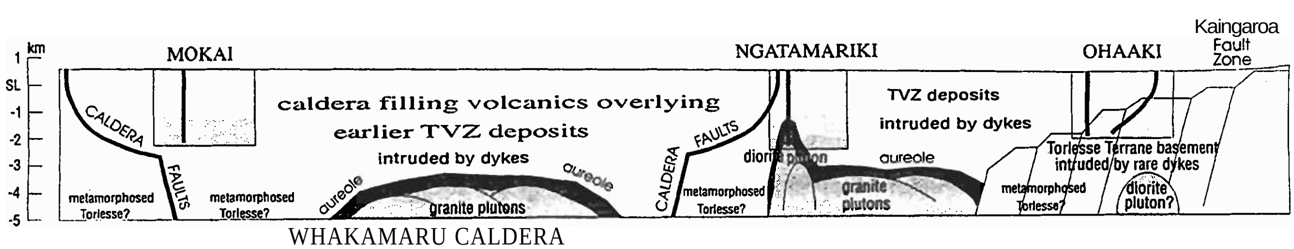

Figure 6 - Speculative schematic geological cross-section through Mokai, Ngatamariki and Ohaaki geothermal fields. Section line is shown on Fig. 1. Vertical and horizontal scales are equal.