Stratigraphy of the Western Wairakei Geothermal Field: Insights from Recent Drilling in the Greater Te Mihi Area

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STRATIGRAPHY OF THE WESTERN WAIRAKEI GEOTHERMAL FIELD: INSIGHTS FROM RECENT DRILLING IN THE GREATER TE MIHI AREA

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SUMMARY – Since April 2005, nine geothermal wells (WK243-251) have been completed at Te Mihi, western Wairakei Geothermal Field. Shallow geological formations encountered during drilling are similar to other wells in the area, and comprise Oruanui Formation, Huka Falls Formation (including Rautehuia Breccia), Waiora Formation, Karapiti - 2A and - 2B Rhyolites. Beneath the Karapiti Rhyolites, a previously unknown stratigraphy has been encountered, including plagioclase-quartz-pyroxene phyric, coalesced rhyolite lavas (informally named Poihipi Rhyolite - 1 and - 2), that represent two of several domes underlying the Te Mihi area, welded and non-welded crystal-rich ignimbrite (informal name: Stockyard Ignimbrite), andesite lava and subordinate pyroclastic and volcaniclastic units. Interpretation of the units encountered by WK243-WK251 provides a framework for investigating production drilling targets, stratigraphic and structural controls on deep fluid flow in the western Wairakei Geothermal Field.

1. INTRODUCTION

The 'shallow' geology (to -500 mRL) of many wells in the Te Mihi sector, Wairakei Geothermal Field (Fig. 1) is well documented (Grindley, 1965; Steiner, 1977). However, since 1993, seven deep production wells (WK239, WK243-248) and nine shallow steam wells (WK236-238, WK240-242, WK249-251) have provided new information on the geology beneath Te Mihi, with WK247 and WK248 reaching 2768 mRF (-2246 mRL) and 1822 mRF (-1308 mRL) respectively. This paper details stratigraphic interpretations resulting from geothermal wells drilled at Te Mihi since April 2005, focussing on geological inferences and new formations encountered below -500 mRL.

2. TE MIHI STRATIGRAPHY

The geology of the upper ~600 m at Te Mihi area comprises generally flat-lying surficial tephra (pyroclastic ash and pumice-lapilli) and paleosol layers; Oruanui Formation (pumiceous non-welded ignimbrite, pyroclastic flow and fall units); Huka Falls Formation (poorly sorted lake sediments, comprising crystal-rich siltstone, pumice tuff, and intercalated mudstone layers of variable thickness); Rautehuia Breccia (volcanic breccia of crystal-rich pumice, rhyolite and sedimentary lithics in a vitric-crystal tuff matrix). Beneath the Huka Falls Formation there are Te Mihi Rhyolite lavas; Waiora Formation and intercalated Waiora Valley Andesite. The

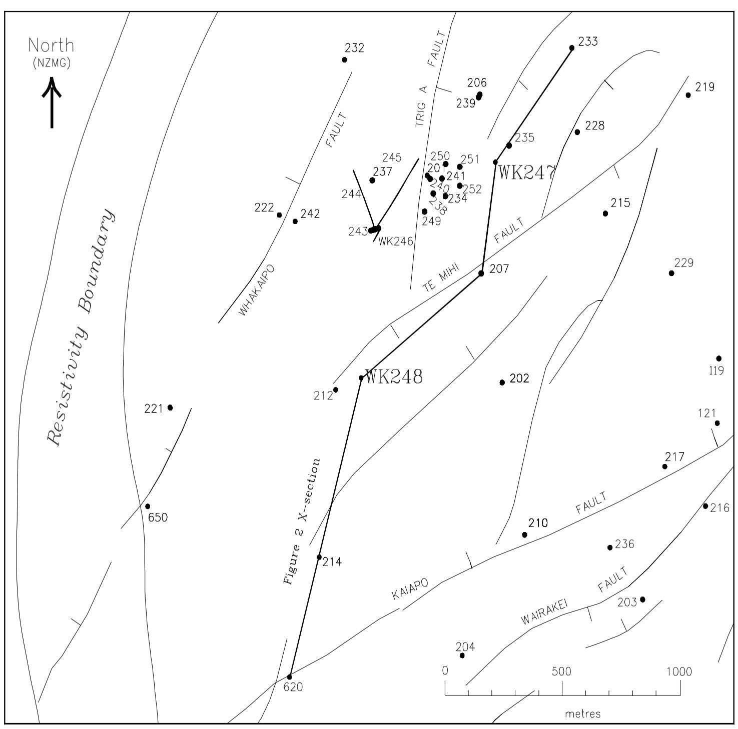

Figure 1. Well location map with mapped surface fault lines, Te Mihi sector, Wairakei Geothermal Field.

shallowest Waiora Formation in the Te Mihi area is medium grained vitric tuff (Wa_5 subunit; after Grindley, 1965), which in some areas grades downwards into tuff, silicified mudstone and sandstone (units Wa_4/Wa_3), and is elsewhere underlain by Karapiti 2A rhyolite breccia). These strata have previously been described for example in Grindley (1965), Healy (1965), Steiner (1977), Wood (1994), Bogie et al. (1995), Wood et al (1997) and most recently by Rosenberg (2006).

Below the Waiora Formation, WK243-248 wells encountered a series of rhyolite lavas, breccia and pyroclastic rocks, comprising:

Karapiti Rhyolites: The **Karapiti 2A Rhyolite** contains rare feldspar phenocrysts in a devitrified, fractured, hydrothermally altered matrix. The deep Waiora - Karapiti 2A boundary in WK248, compared to WK212 and WK221, may reflect bifurcation of the lava, caused by a topographic barrier, or a fault downthrown to the southeast.

Flow banded, sparsely spherulitic **Karapiti 2B Rhyolite**, has plagioclase, pyroxene and < 10 vol% quartz (despite the "quartz-free" criterion of Grindley, 1965) phenocrysts in a microcrystalline fabric, with inferred two-stage extrusion from a zoned magma chamber. The upper Karapiti 2B Rhyolite lava is auto-brecciated, which along with deeper cooling joint sets affords localised enhanced permeability.

Banded rhyolite encountered in WK247, several hundred metres from the inferred northern extent of Karapiti 2A, derives from **Karapiti 3 Rhyolite,** which was intersected in WK206 (probably also in blind drilled zones in WK235 and WK239). Its somewhat shallower occurrence, compared to Karapiti 2B in most Te Mihi wells, and absence in WK207 (Figure 2) precludes correlation with Karapiti 2B. A breccia of possible autoclastic origin, comprises the lower portion of the unit and consists of clast supported, brecciated flow-banded and porphyritic rhyolite, silicified vitric tuff, rare primary feldspar and quartz crystals.

Poihipi 1 Rhyolite Lava (NEW UNIT): The Poihipi 1 Rhyolite is petrologically distinct to the shallower crystal-poor Karapiti 2B Rhyolite lava, with common quartz, pyroxene and subordinate feldspar phenocrysts, with pumiceous, brecciated and flow-banded textures. The Poihipi 1 Rhyolite lava is characterised by strong propylitic-style alteration of its phenocrysts and groundmass.

Poihipi Rhyolite Breccia (NEW UNIT): This ~50 m thick clast-supported breccia, encountered in WK248 contains fragmented, angular feldspar-quartz-pyroxene phyric, pumiceous, porphyritic and flow banded (and veined) rhyolite lava lithics, minor silicified tuff clasts, feldspar, rare quartz and pyroxene crystals. It is spatially correlated with the enclosing rhyolite lavas, but has not been genetically linked to either one.

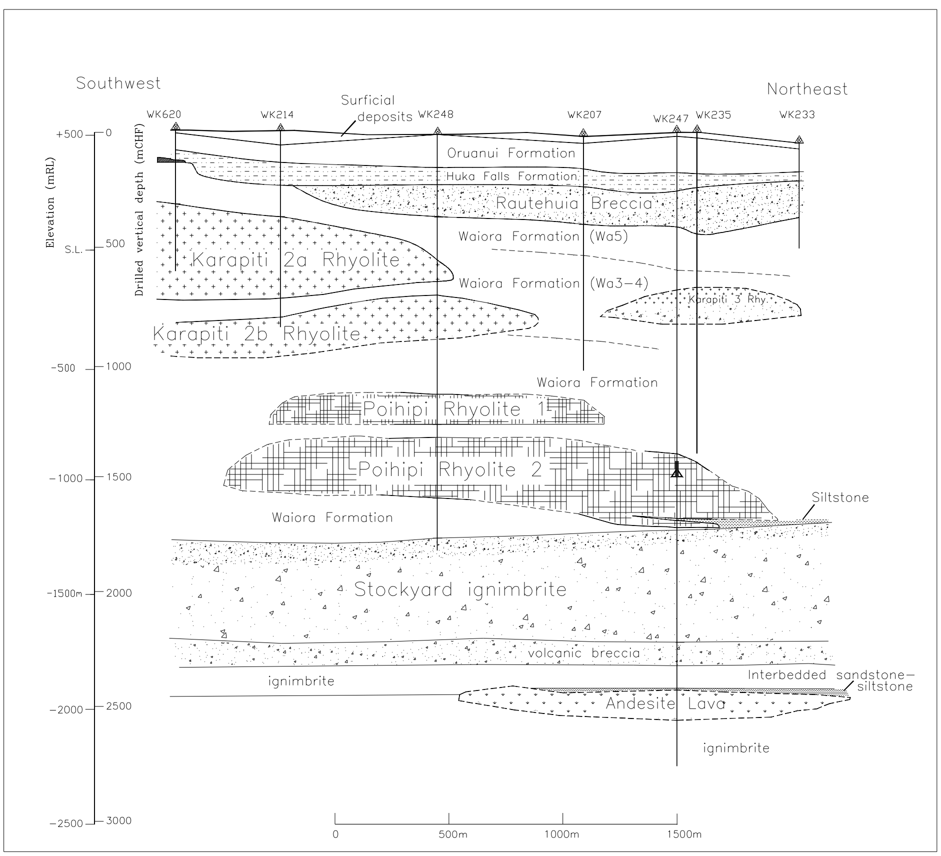

Figure 2. Geological SW-NE cross section through the Te Mihi area, Wairakei Geothermal Field.

Poihipi 2 Rhyolite Lava (NEW UNIT): Poihipi 2 Rhyolite is porphyritic feldspar-quartz-pyroxene flow-banded lava intersected by WK247 and WK248. Silicified, laminated siltstone occurs in WK247 between two rhyolite intervals, with the deeper lava having spherulitic and perlitic textures. The Poihipi -1 and -2 lavas may derive from separate eruption phases, and distinct vents.

Deep Waiora Formation: A pumiceous rhyolitic breccia has been intersected by WK248 (Figure 2), and is similar to the shallower Wa_4/Wa_3 Waiora Formation units, but appears to lack their mudstone - sandstone sedimentary component.

Stockyard Ignimbrite (NEW UNIT): Stockyard Ignimbrite, intersected by WK247 and WK247, is inferred to form an extensive sheet across the greater Wairakei area. The ignimbrite has inverse welding zonation: an upper densely welded sheet, has fiamme, perlitic and spherulitic textures, and is lithic poor and crystal-rich (volcanic feldspar, rare quartz and chlorite-altered pyroxene). A non-welded lower sheet contains plagioclase, quartz and relict pyroxene(?) crystals, common subangular pumice and minor rhyolite lava lithics. Hydrothermal alteration intensity is high through both welding zones. Stockyard Ignimbrite differs from Wairakei Ignimbrite mainly by its lack of abundant embayed quartz phenocrysts (cf. Browne, 1968) which characterise Whakamaru-type ignimbrites.

Volcanic Breccia (NEW UNIT): This intensely altered vitric-lithic breccia contains subangular pumice, rhyolite and silicified siltstone lithics. Volcanic quartz and rare feldspar are the dominant crystal components, in a fine ash matrix.

Ignimbrite (NEW UNIT): This intensely altered, partially welded, crystal-poor ignimbrite has yet to be correlated with any known ignimbrite at Wairakei. It contains subrounded pumice, angular chlorite-altered rhyolite, primary quartz, feldspar and relict mafic minerals (amphibole/pyroxene?) in an ash grade vitroclastic matrix.

Siltstone/Sandstone (NEW UNIT): This is a weakly laminated, silicified fine sandstone, with minor relict carbonaceous material, interbedded with massive or thinly bedded siltstone.

Andesite (NEW UNIT): Porphyritic andesite lava in WK247 has plagioclase, hornblende and clino-pyroxene phenocryst pseudomorphs in a trachytic feldspar matrix. By elevation and relative stratigraphic position, the lava could be a correlative of andesite lava drilled in WK121, but hydrothermal alteration obscures the rock texture and primary mineralogy that could provide definitive link.

Ignimbrite (NEW UNIT): The deepest unit encountered by drilling in the Te Mihi sector (in WK247) comprises a >200m-thick, intensely hydrothermally altered, partially welded, crystal-poor ignimbrite. The ignimbrite contains pumice, chlorite-altered rhyolite, sparse primary feldspar, quartz and ferromagnesian (relict amphibole and/or pyroxene) crystals in a fine ash matrix.

3. STRUCTURE

The Te Mihi-Wairakei-Tauhara area is crossed by numerous closely spaced, generally NE-SW trending, high angle normal faults (Figure 1). Their surface expression is usually eroded and/or obscured by recent volcanic products, but it is likely some of the inferred fault zones (in particular those active in late Quaternary time) persist to the greywacke basement, and may be zones for high permeability, and upward flow of reservoir fluids. Geodetic studies have shown crustal extension in the Taupo area is active at ~2-8 mm/yr, in a general NW-SE direction (Darby et al., 2000, Villamor & Berryman, 2001). This deformation is likely to provide and maintain fluid pathways along the fault zones.

An example is the informally named Trig-A Fault, the surface trace of which occurs between the WK243-245 and WK206/WK239 pad locations (Fig 1). Whilst the vertical offset along this fault is unknown, its surface scarp shows a normal sense of displacement (as do most other faults in the area). The dip angle of Trig-A Fault is also unknown, but is inferred to dip away from WK245, with possible intersections with WK206 and WK239 (for an inferred 70^o- 80^o dip) at ~+50 and -470 mRL respectively. However, whilst several feed zones occur in WK239, there is no direct evidence they coincide with a fault zone.

Although none of the recently drilled geothermal wells at Te Mihi (i.e. WK243-248) intersected known fault structures, discrepancies between wells in the depth and thickness of various units (notably otherwise near-flat lying pyroclastic deposits) could be explained by fault displacement and subsequent erosion.

4. PERMEABILITY

Measurements while drilling, and subsequent completion tests, have indicated a range of permeability targets in the Te Mihi area, including:

- zones of high permeability through the Waiora Formation, Karapiti 2A Rhyolite (which hosts the Poihipi steam zone), Poihipi 1 and 2 Rhyolite lavas. In the future, some wells could be designed to case off these zones, in favour of deeper intra-formational or fault-related permeability (i.e. at >1700 mRF);

- intra-formational permeability associated with sedimentary units, Stockyard Ignimbrite and deeper (un-named) volcaniclastic formations;

- formation contacts associated with the Waiora Formation and Stockyard Ignimbrite, and associated with andesite lava and deeper units;
- possible fault-related permeability encountered within the post-basement volcano-sedimentary stratigraphy, and/or basement

The rank, intensity and styles of alteration exhibited in the deep WK247 and WK248 wells are encouraging indicators of production potential. In these wells, the presence of epidote, wairakite, adularia and albite imply formation temperatures of at least 240° C and possibly > 260°C (cf. Steiner, 1977), which is consistent with measured downhole temperatures measured in the WK243-248 wells.

Mineral evidence concurs with chemical studies, which point to an upflow zone in the Te Mihi area (Glover and Mroczek, 1988), with temperatures >240°C below -600 mRL (Clotworthy, 2001). Recent production drilling to this and greater depths has confirmed >250°C reservoir temperatures in the Te Mihi area.

5. HYDROTHERMAL ALTERATION

With increasing depth, the hydrothermal mineral assemblages in Te Mihi core and drill cuttings increase in rank, and point to fluid-rock interactions below -600 mRL involving near neutral pH fluids, at temperatures of >235°C.

Low rank, argillic-type alteration occurs at depths shallower than ~125 mRL. Alteration is weak and characterised by smectite, calcite and pyrite. Smectite in the Wairakei geothermal system is inferred to form at <140°C (Browne and Ellis, 1970). An increase in alteration rank at ~0 mRL is recognised by the occurrence of interlayered illite-smectite, hydrothermal quartz, calcite and pyrite.

A transition to a higher rank propylitic-style alteration occurs from ~0 mRL, and is recognised by a secondary assemblage of quartz, illite, chlorite, epidote, pyrite and calcite, with variable amounts of adularia, albite, wairakite and titanite.

Epidote mineralisation is conspicuous within the Poihipi 1 and 2 Rhyolites, Waiora Formation and Stockyard Ignimbrite, and indicative of >235°C formation temperatures (possibly >260°C, Reyes, 1990). Epidote occurrences in WK247 above -200 mRL are representative of relict alteration event(s). The presence of clinozoisite and/or zoisite clusters that precipitated into cavities and veins indicate excellent permeability either presently and/or in the past. Wairakite, and plagioclase replaced by adularia also point to good permeability, and temperatures between 200 and 250°C (cf. Steiner, 1977). The occurrence of albite in some zones indicates somewhat lower permeability.

Mineral evidence points to overprinting in WK247 of its propylitic assemblage by a cooler

Table 1: Stratigraphy (to nearest 10 m) encountered by WK243-WK251, drilled at Te Mihi in 2005-07.

Thickness	Formation	Occurrence
10 - 20	Surficial Deposits	WK243-WK251
140 - 180	Oruanui Formation	WK243-WK251
0 - 80	Huka Falls Formation	WK243-WK251
140 - 170	Rautehuia Breccia	WK243-WK251
50 - 230	Waiora Formation (Wa_5)	WK243-WK251
90	Karapiti 2A Rhyolite	WK248
60 - 180	Waiora Formation (Wa_3-Wa_4,)	WK244-WK248
40 - 210	Karapiti 2B Rhyolite	WK244, WK245, WK248
150	Karapiti 3 Rhyolite + breccia	WK247
>500	Waiora Formation	WK247
130	Poihipi 1 Rhyolite Lava	WK248
60	Poihipi Rhyolite Breccia	WK248
270 - 280	Poihipi 2 Rhyolite Lava	WK247, WK248
10	Siltstone	WK247
30	Poihipi 2 Rhyolite Lava	WK248
180	Waiora Formation	WK248
>50 - 500	Stockyard Ignimbrite	WK247, WK248
100	Volcanic Breccia	WK247
100	Lithic Ignimbrite	WK247
10	Siltstone / Sandstone	WK247
130	Andesite Lava	WK247
>200	Ignimbrite (non-welded)	WK247

fluid with higher CO_2 concentration (characterised by illite-calcite mineral precipitation), and demonstrates that thermal (and chemical) fluctuations have occurred in the Te Mihi reservoir.

6. DISCUSSION

The geology of the upper 600 m at Te Mihi is well known, but drilling to >1500 m in 2005-07 has further refined the geology provided new insights into the *deep* stratigraphy in the Te Mihi area.

Many early wells at Te Mihi were too shallow to intersect the Karapiti 2A, 2B and 3 Rhyolites, so the lateral extent of those units was poorly constrained. However, new wells drilled at Te Mihi in 2005-07, have allowed their extent and thickness to be refined (Table 1; Rosenberg, 2006). Karapiti Rhyolite lavas constitute excellent shallow to mid depth drilling targets because they host 230-250°C fluid and generally have good permeability associated with auto-brecciated carapaces, cooling joints, and formation contacts.

The refined geometry of Karapiti 2B suggests the rhyolite may extend beyond the Wairakei field boundary (as also inferred for Karapiti 2A), and provides a potential conduit for cool(?) waters to ingress the geothermal field. If the Karapiti 2B Rhyolite lava does extend beyond the boundary of the Wairakei Field then the eastern or southern segments of the rhyolite are likely to be more prospective than western areas, as lower temperature, pressure and permeability conditions are more likely close to the field boundary.

The most significant geological outcome of drilling WK247 and WK248 (to -2246 mRL and -1308 mRL, respectively), was identification of a series of previously unknown volcanic formations, and confirmation that the greywacke basement occurs below -2250 mRL, more than 400 m deeper than previously known.

The new formations provide zones of deep intra-formational and contact-related permeability below -1200 mRL. Indeed, WK247 completion tests show feed points in the Poihipi 2 rhyolite lava and Stockyard Ignimbrite, which are potential production targets for future deep drilling in the Te Mihi area.

The Poihipi lavas are likely to be part of a series of coalesced domes spatially analogous to the clusters of rhyolite domes within the Maroa Volcanic Centre and Okataina Volcanic Centre. The geometry of the Poihipi rhyolite lavas can be inferred by analogy with these dome complexes, and their targeting could be undertaken by vertical wells without the need for deviated drilling. In the future, porosity and permeability measurements will be needed on Poihipi Rhyolite core to determine bulk rock properties. If the rhyolite is found to be dense and with low porosity, then fracture related feed zones could provide an explanation for feed zone distribution, with the entire formation (as opposed to its boundaries) being a production target. Based on the new deep stratigraphy, future deep drilling in the western Wairakei Geothermal Field is likely to encounter other rhyolite lavas, which would also constitute potential production targets.

The Stockyard Ignimbrite has an upper crystal-rich, densely welded zone (at least 60 m thick), characterised by extensive perlitic, fiamme and spherulitic textures (indicative of rapid cooling, devitrification and hydration; cf. McPhie et al., 1993); and a lower non-welded zone, of common volcanic quartz, plagioclase and ferromagnesian minerals, pumice and sparse rhyolite lava (40 m thick in WK247).

Based on its occurrence in WK247 and WK248, it is possible that the Stockyard Ignimbrite forms an extensive sheet at least 100 m thick beneath and probably beyond the Wairakei Geothermal Field. This is significant as intra-formational permeability has already been revealed by completion (spinner flow) tests, and the Stockyard Ignimbrite despite its poorly constrained extent, is therefore a production target. Permeable zones in underlying volcanic breccia and lithic ignimbrite have also been revealed.

Based on its primary mineralogy, the Stockyard Ignimbrite is distinct from the Waiora 1 and Wairakei Ignimbrites. The Wairakei Ignimbrite is one of the Whakamaru Group ignimbrites, and contains distinctive, large, embayed quartz phenocrysts that are absent in the Stockyard Ignimbrite. We infer from the dense and inversely zoned welding, that the ignimbrite was emplaced at very high temperature, and its occurrence beneath Wairakei is likely to be proximal to source.

To date, Te Mihi deep drilling has not encountered Wairakei Ignimbrite, Waikora Formation pebble conglomerate, or greywacke basement – all of which have been intersected at comparable elevations in eastern Wairakei, Ohaaki and/or Rotokawa Geothermal Fields. This suggests that major east-west structural discontinuities exist across the Wairakei region and while activated since ~320 ka they probably reflect older deep TVZ basement structure.

Correlation of the new rhyolites, pyroclastics and sediments with Waiora Formation has been made here, on the assumption that Wairakei ignimbrite lies beyond the currently drilled depth. However the alternative interpretation is their correlation with *pre*-Wairakei Ignimbrite, Reporoa Group (Gravley et al, 2006), assuming Wairakei ignimbrite has been entirely eroded.

If Wairakei ignimbrite and Torlesse greywacke are intersected in future exploration/production wells drilled to 3000m or deeper, their presence will prove extremely useful in refining seismic, magnetic, gravity and structural interpretations of the Wairakei Geothermal Field.

7. SUMMARY

Since April 2005, nine geothermal wells (WK243-251) have been completed in the Te Mihi area, western Wairakei Geothermal Field. WK247 is the deepest well yet drilled at Wairakei, to 2759 mCHF (-2246 mRL), and new formations were encountered below about -1200 mRL.

Drilling results from WK247 and WK248 have provided new information on the geology below ~1200 mRF. Beneath the Karapiti 2B Rhyolite lava are two previously unknown rhyolite lavas (Poihipi Rhyolite -1 and -2) which are distinct from Karapiti and Te Mihi-type rhyolite lavas previously described in the Wairakei Geothermal Field; a crystal-rich, inversely welded ignimbrite (Stockyard Ignimbrite); tuffs and volcanic breccia; and older volcanics (andesite lava and lithic ignimbrite) and volcaniclastic fine sediment.

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