THE WAIORA FORMATION GEOTHERMAL AQUIFER, TAUPO VOLCANIC ZONE, NEW ZEALAND

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SUMMARY - The definition and usage of "Waiora Formation", an important geothermal aquifer in the Taupo Volcanic Zone, is reviewed. Problems arise in defining the upper and lower stratigraphic boundaries of the formation at Wairakei and Ohaaki. In particular, the distinction between Waiora Formation and Huka Falls Formation (an aquitard) becomes blurred away from the type locality, while ignimbrites comprising the oldest member of the formation at Wairakei may be correlated with a completely separate unit at Ohaaki, the Rautawiri Breccia. Much stratigraphic information is hidden in hydrothermally altered Waiora Formation strata that may hold the key to elucidating geological structure across field boundaries at Wairakei-Tauhara, Rotokawa and Ohaaki, particularly if widespread units such as the Kaingaroa Ignimbrite can be identified within the fields.

1. INTRODUCTION

The prime objective of geothermal-field geology is the construction of a stratigraphic and structural framework in which strata are documented as a sequence of correlatable units whose physical and hydrological characteristics are known and predictable. Borefield stratigraphies have been set up to serve exploration and development purposes for most fields drilled in the Taupo Volcanic Zone (TVZ), but there has been little success in correlating these local stratigraphies with the surrounding Surface geology, or between geothermal fields. Two obvious factors that have slowed progress in this direction are the lack of deep drillholes outside the geothermal areas, and the intensity of hydrothermal alteration, which precludes easy identification and correlation particularly between geothermal aquifer rocks and Surface formations. In this paper I review the status of one such important geothermal aquifer, the Waiora Formation, which occurs in many TVZ geothermal fields, and may prove to be the key to deciphering the geology and structure across field boundaries in the TVZ.

2. DEFINITION AND USAGE

The Waiora Formation was formally defined by Grindley (1965) in his seminal bulletin on the Wairakei Geothennal Field, as those pyroclastic rocks, ignimbrites and interbedded sediments lying between the top of the Wairakei Ignimbrites and the base of the Huka Falls Formation in drill hole WK213 (the type section). He further defined Huka Falls Formation as the sediments and pyroclastic rocks between the top of the Waiora Formation and the base of the Wairakei Breccia in WK213. Together, the Waiora and Huka Falls Formations comprised the Huka Group. Waiora Formation was subdivided into five members. The oldest (Member 1) and youngest (Member 5) are dominated by ignimbrites, whereas Members 2, 3, and 4 consist mainly of water-laid siltstones, tuffaceous sandstones and coarser pumiceous deposits (so-called "pumice breccias"). Rhyolite lavas interbedded with the sediments and pyroclastic rocks were arbitrarily excluded from the Waiora Formation. Recent radiometric dates (Houghton et al., 1994) show the Huka Group was deposited from ~0.31 Ma (Wairakei Ignimbrites) to 22.6 ka (Wairakei Breccia = Oruanui Formation).

Steiner (1977) largely ignored Grindley's stratigraphic framéwork in favour of numbered volcanic and sedimentary units based on the lithological, petrological and genetic characteristics of the rocks. In doing so, he implicitly recognised that the whole of the drilled sequence represented a continuous process of volcanic and sedimentary accumulation in the subsiding TVZ graben, broken by intermittent periods of erosion. Steiner did not correlate his units directly with Waiora Formation members, but he did note the important stratigraphic break above the lowest ignimbrites (Grindley's Member 1 = Steiner's Units 19-21) and suggested the Waiora Formation base be revised upwards to exclude them (Steiner, 1977).

Healy (1984) reviewed the geology of Wairakei Geothermal Field, and attempted to reconcile Grindley and Steiner's different approaches by correlating their Waiora and Huka Falls Formation sequences in well WK213. He concluded that Steiner's Units 13 and 16 were the same strata, corresponding in part or whole to Grindley's Members 2, 3 and 4, thus emphasising the difficulties of identification and correlation presented by highly altered tuffs.

The most recent summaries of Wairakei geology are in Electricity Corporation of New Zealand's resource-consent application documents (C P Wood, unattributed chapters on "Geology" in ECNZ 1990, 1992). Here it was recognised that Steiner's unit system came closest to the ideal of a

ECNZ, 1990		Steiner, 1977	Grindley, 1965
Huka Falls Formation		Huka Falls Formation	Huka Falls Formation
West	East	Units 4,5,6	hu 1,2,3,4
sediments	sediments		
Rautehuia	Nffs		Top of Waiora Fmn
Breccia	sediments		
Top of Waiora Fmn Waiora Formation wa5		Unit 7 (Ignimbrite I) units 9,10,11	wa5 mostly ignimbrites and Nffs
wa4	Unit 12a (Karapiti II) Haparangi Rhyolite (Karapiti Rhyolite hak)	Unit 13a	wa4 mixed sediments and Nffs
wa3		Units 13a,b,c	wa3 mixed sediments and tuffs
wa2		Units 13c,d, and 16	wa2 tuffaceous sediments
		Base of Waiora Fmn	
wa1 Base of Waiora Formation		units 19 and 21	wa1 ignimbrites Base of Waiora Fmn
Wairakei Ignimbrite		Wairakei Ignimbrite	Wairakei Ignimbrite

Table 1 - Outline of Huka Group stratigraphy showing approximate correlations between Steiner (1977) and Grindley (1965) and ECNZ (1990 useage. Note: Wairakei Ignimbrite is not part of the Huka Group.

practical stratigraphy for geothermal field management purposes, but the complexities of Wairakei geology and difficulties in correlating hydrothermally altered rocks precluded its easy adoption. Table 1 gives a brief *summary* of Huka group stratigraphy at Wairakei.

3. WAIRAKEI AND TAUHARA

The use of "Waiora Formation" as an identifier for a wide lithological and genetic variety of strata has advantages and disadvantages. It is simple to apply and acts as a convenient hold-all for the rather nondescript sequence of beds located above the distinctive Wairakei Ignimbrites. Characteristics such as density, permeability and hardness *can* be assigned en bloc for modelling purposes, and as a guide for drilling. However, the fact that the formation is not lithologically distinctive *can* lead to false correlations and misinterpretation of stratigraphy and structure.

3.1 Rhyolites

Grindley (1965) considered rhyolites drilled at Wairakei to be intrusive, and excluded them from the Waiora Formation. However, the main mass of rhyolite (Karapiti rhyolite) is now thought to be a buried lava dome (Healy, 1984; ECNZ, 1990, 1992) that may have associated coeval tephras and rhyolitic breccias which would be included in the Waiora Formation. There is little logic in excluding rhyolitic lava flows from the Waiora Formation, while including rhyolitic ignimbrite flows, though there is a practical advantage. Large rhyolite domes usually have distinctive lithology and hydrology, and their boundaries are easily located in drillholes, allowing their shapes to be modelled (ECNZ, 1992) with reasonable accuracy.

3.2 Waiora Formation Top

The fact that the top of the Waiora Formation is defined as the base of the Huka Falls Formation (and vice-versa) has caused confusion with correlations in some wells, since both formations contain lithologically similar sediments and tuffs, and the boundary between them is diachronous (Grindley, 1965). For instance, at the site of well WK227 outside the geothermal field boundary near the centre of the Taupo-Reporoa depression, Huka Group siltstones are thicker than at the type section (WK213) where pumiceous sandstones and breccias predominate. Grindley et al., (1966) logged the top of the Waiora Formation at -95m RL in WK227, whereas Steiner (1977) concluded that Huka Falls Formation siltstones continued to -308m RL and lay directly on Unit 19 ignimbrite (Waiora Member 1); by his definition, the Waiora Formation was absent (see Fig.1).

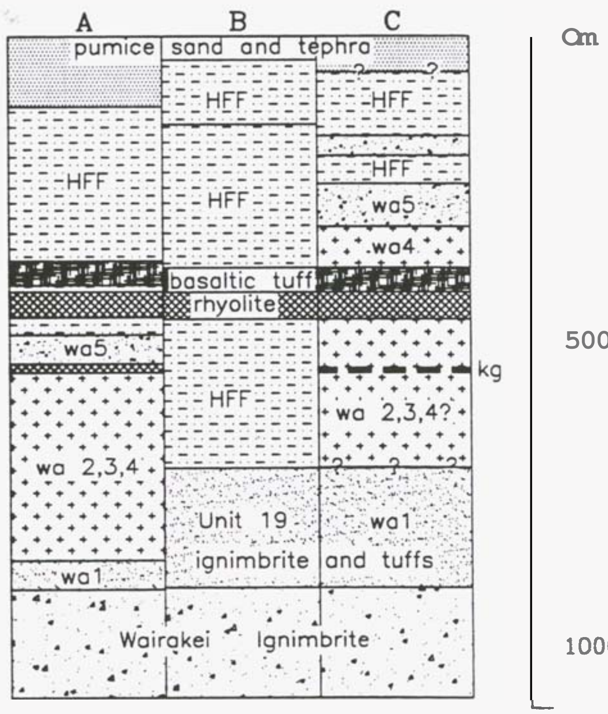

Figure 1. Alternative stratigraphic logs of WK227 drillhole. A = Grindley et al. 1966: B = Steiner, 1977: C = this paper. Ground level is 402 m above sea level. HFF = Huka Falls Formation siltstones. wa = Waiora Formation. kg = Kaingaroa Ignimbrite.

Some 3.5 km SW of WK227, the northernmost Tauhara geothermal exploration well (TH2) penetrated a complex sequence (924 m thick) of predominantly fine-grained Huka Group tuffs and sediments interbedded with brecciated rhyolite lavas, terminating in Waiora Member 1 ignimbrites. Grindley et al. (1966) considered the Huka Falls Formation/Waiora Formation contact to be at -84m RL, similar to WK227. I have used drill logs, cores, cuttings, and petrographic data to reinterpret the stratigraphy of WK227 and TH2, and consider the top of the Waiora Formation is at higher elevations (158m RL in WK227; tentatively in the 182-120 mRL range in TH2). Data from these and other Wairakei drillholes were then used in conjunction with seismic reflection profiles (confidential to ECNZ) to produce the contour map of the base of the Huka Falls Formation (i.e. top of Waiora Formation) shown in Fig. 2 (reproduced from ECNZ 1992). The contours define a subcircular depression centred at -20 m RL beneath the Waikato River. It has the form of a large, volcanic explosion crater, and hence may possibly be the source of some of the youngest Waiora Formation pyroclastics (Member 5).

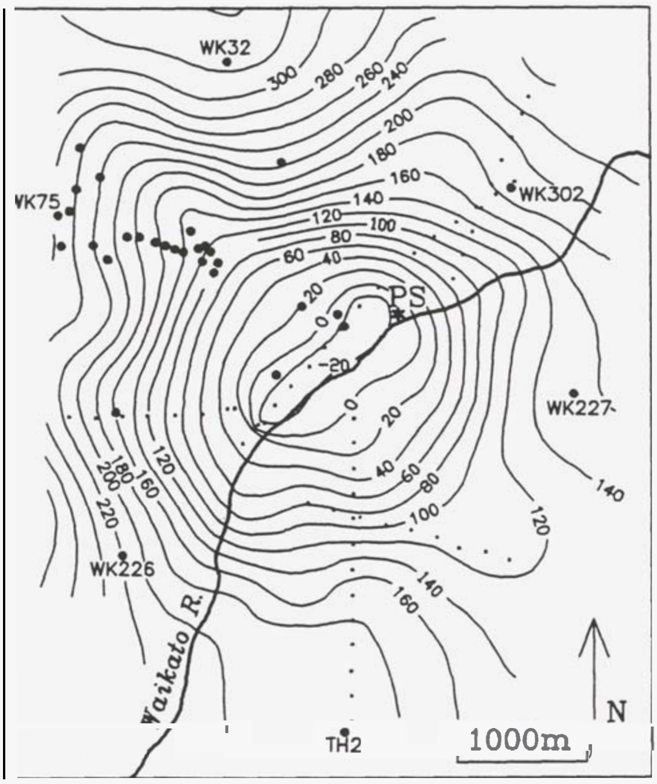

Figure 2. Contours in mRL (relative to sea level) on the base of the Huka Falls Formation in the Wairakei-Tauhara area. Large dots are drillholes (some peripheral wells are labelled to aid location), small dots are positions on seismic reflection profiles. PS is Wairakei power station.

Of particular note is the discovery of Kaingaroa Ignimbrite in the Waiora Formation at 550 m in WK227. The 0.24 Ma Kaingaroa Ignimbrite from Reporoa caldera at the northern end of the Taupo-Reporoa depression (Nairn et al. 1994), also occurs in WK302 (ECNZ, 1992) 1.6 km NNE of WK227. Surely this distinctive welded ignimbrite also occurs in Waiora Member 2-4 beds within Wairakei field, but has not yet been recognised because of hydrothermal alteration.

3.3 Waiora Formation Base

Wairakei Ignimbrite is considered to be a member of the Whakamaru-group ignimbrites (Wilson et al. 1986) erupted in the 0.31 - 0.35 Ma period (Houghton et al. 1994). Over a wide area Wairakei Ignimbrite is immediately succeeded by up to three sheets of ignimbrite (Member 1 of Grindley, 1965; Units 19 and 21 of Steiner, 1977) which exceed 250 m in wells WK37, 60, 266 and TH2 (ECNZ, 1992) up to a maximum of 435 m in WK301 where Wairakei Ignimbrite is missing. The great thickness of these ignimbrites suggest they came from a series of caldera-forming eruptions, so soon after the massive discharges of rhyolite magma (≥ 1000 km³) in the Whakamaru-group ignimbrites episode that the question arises if they are in fact late-stage members of the group. They have a similar phenocryst mineral assemblage as Wairakei Ignimbrite (plagioclase, quartz, hypersthene, hornblende, rare biotite) but in different proportions; unlike typical Whakamaru-group members they are not quartz-rich. No correlations with outcropping post-Whakamaru-group ignimbrites are evident. Unless the Waiora Formation is formally redefined to exclude the Member 1 ignimbrites (Steiner's suggested revision was informal), the base must remain as an arbitrary boundary between two sequences of voluminous, and possibly related ignimbrite sheets.

3.4 The Waiora Aquifer

Grindley (1965) observed that most production at Wairakei came from thick pumice breccias of the Waiora Formation, particularly where cut by faults; overlying Huka Falls Formation mudstones capped the aquifer. After more than 25 years of exploitation the observation remains true, and almost all production still comes from the Waiora Formation, particularly from near its upper and lower contacts (ECNZ, 1992). However, the coarse permeable pumice breccias of the Wairakei area appear to be replaced by finer-grained tuffs and sediments in the Taupo-Reporoa basin where the Waiora Formation "aquifer" resembles the Huka Falls Formation "cap-rock". A thorough review of Huka Group stratigraphy in the SE Wairakei - Tauhara area is needed if its potential for production and reinjection is to be realised.

4. BEYOND WAIRAKEI

Waiora Formation is rarely exposed in the TVZ, but was considered by Grindley (1965) to constitute the major part of the deposits filling the Taupo-Reporoa depression (Fig. 3); the overlying Huka Falls Formation crops out more widely. The definition of Waiora Formation can be widened beyond the bounds of Wairakei geothermal field by making its base equate to the top of any of the Whakamaru-group ignimbrites, particularly the Whakamaru and Rangitaiki ignimbrites which are probably direct correlatives of the Wairakei Ignimbrites. Locating the top of the Waiora Formation outside Wairakei is more difficult. The base in

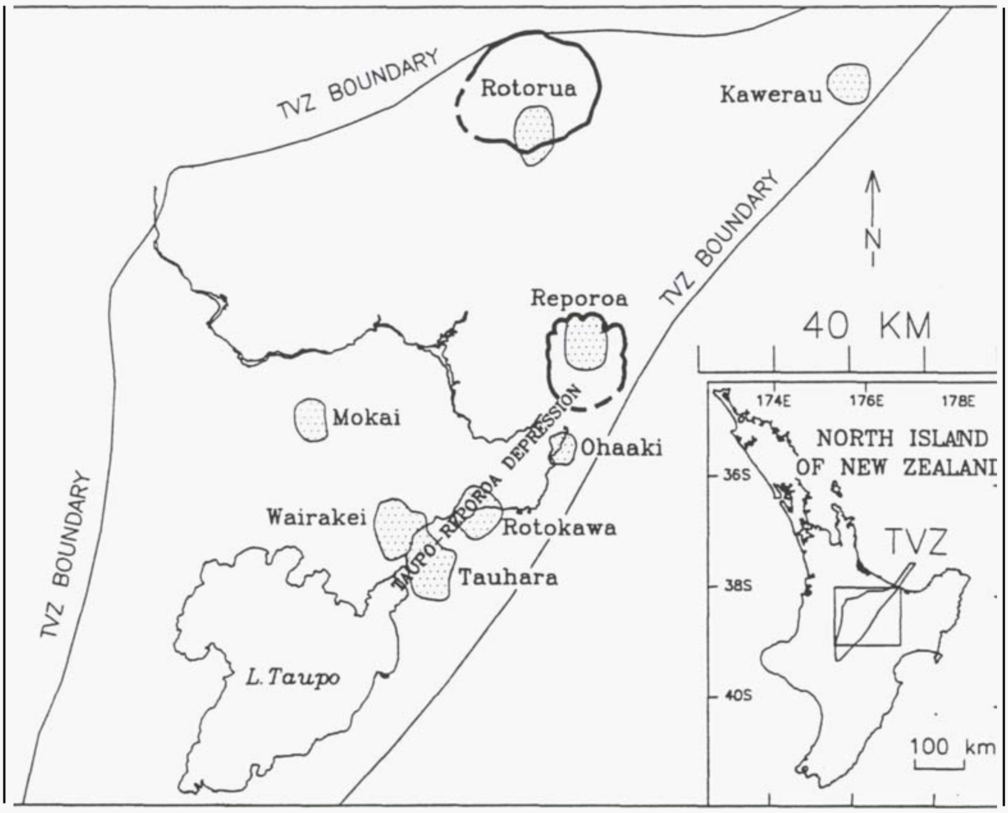

Figure 3. Outline map of Taupo Volcanic Zone (TVZ) showing locations of several geothermal fields (stippled areas), and the Taupo-Reporoa Depression. Rotorua and Reporoa calderas shown as heavy solid-dashed lines.

effect is a chronological boundary because it is defined in relation to an ignimbrite, whereas the mutually dependent base of the Hika Falls Formation and top of the Waiora Formation float in time. In practice, the Hika Falls Formation is taken to be a lithological unit of muddy lacustrine sediments encountered at shallow depths in a geothermal field, whilst any underlying tuffs are assigned to the Waiora Formation, despite the fact that the middle unit of the Hika Falls Formation at Wairakei is an ignimbritic pumice breccia. While this approach has facilitated geothermal exploration, potential stratigraphic information in the Waiora Formation has been lost, so obscuring its importance in the development of the TVZ as a whole. In particular, some of the many voluminous, wide-spread ignimbrites erupted from TVZ calderas (Houghton et al. 1994) during the –300 000 year history of the Hika Group should be present in the Waiora Formation. Some, such as the Matahina at Kawerau, the Mamaku at Rotorua, and the Mokai at Mokai, have been recognised at shallow depths and close to source, but the occurrence of Kaingaroa Ignimbrite in the Waiora Formation on the perimeter of Wairakei field suggests that this and other ignimbrites await discovery following detailed analysis of hydrothermally altered Waiora tuffs.

4.1 Rotokawa and Ohaaki

Rotokawa is one of the few areas where Waiora Formation tuffs, ignimbrite and sediments have been mapped at the surface (Grindley, 1961). In drillholes, Waiora Formation comprises up to *500* m of undifferentiated silicic pyroclastic rocks interbedded with rhyolite lavas (Browne et al. 1992). No intra-formational correlations with nearby Wairakei are known.

At Ohaaki, petrological and stratigraphic logs of drillholes indicate a simple division of Huka Group into Hika Falls and Waiora Formations with no intra-formational subdivisions (Browne, 1971; MWD, 1977; Wood, 1983). However, between the base of the Waiora Formation and the top of the Rangitaiki Ignimbrite (correlated with Wairakei Ignimbrite) are the Lower Siltstone and Rautawiri Breccia, both of which would be included within Waiora if Grindley's (1965) "Wairakei" definition were strictly applied. The Rautawiri Breccia occurs fieldwide and consists of 90 - 350 m of heterogenous ignimbritic tuffs and breccias, with significant permeability. The petrography and stratigraphic position of the Rautawiri Breccia suggest it may be correlated with the Waiora Member 1 ignimbrites at Wairakei. The Lower Siltstone occurs only in wells west of the Waikato River, and has a maximum thickness of 170 m in BR34 where it is overlain by Waiora Formation tuffs. It represents a period of quiet lacustrine deposition following prolonged voluminous ignimbrite eruptions, and probably correlates with the siltstone-dominated Waiora Member 2 at Wairakei. Waiora Formation proper at Ohaaki comprises bedded, water-laid pumice tuffs, ignimbritic breccias and thin sediments, mostly 80 - 200 m thick, but exceeding 350 m in the north of the field. The beds occur in all wells except in the SE and SW where the formation wedges out on the flanks of the buried

Broadlands Dacite and Broadlands Rhyolite lava domes. Waiora Formation is a significant production aquifer though less important than at Wairakei. Overlying the Waiora tuffs are up to 400 m of Huka Falls Formation siltstones and minor interbedded pumice tuffs. Waiora Formation at Ohaaki has not been correlated with any of the formation members at Wairakei.

A surprising feature of the post-Rautawiri Breccia stratigraphy is the lack of correlated ignimbrites, particularly the 0.24 Ma Kaingaroa Ignimbrite from Reporoa caldera just 15 km to the north. Kaingaroa Ignimbrite occurs at Wairakei within the Waiora Formation so is likely to be represented by some part of the formation at Ohaaki.

4.2 Reporoa and Rotorua

The stratigraphic sequences drilled in the Reporoa and Rotorua geothermal fields exemplify the localised accumulation of ignimbrite, bedded tuffs and lacustrine sediments in calderas which collapsed during the period of Waiora Formation deposition at Wairakei.

Drillhole RP1 in the middle of Reporoa caldera (Nairn et al. 1994) bottomed in Kaingaroa Ignimbrite at 1340 m depth after penetrating Huka Falls Formation siltstones, rhyolite lavas, and 415 m of Waiora Formation tuffs (Wood, 1994). The tuffs represent a period of rapid erosion and deposition in the deep basin caused by caldera collapse. They are texturally and lithologically similar to Waiora Formation tuffs at Ohaaki and Wairakei, but probably do not extend beyond the caldera confines, though the shallower Huka Falls Formation siltstones are probably part of a continuous belt of lake deposits in the Taupo-Reporoa depression.

Shallow (< 300 m) wells in the east of Rotorua geothermal field passed through up to 235 m of water-laid siltstones and tuffs, into the 0.22 Ma Mamaku Ignimbrite (Wood, 1992). Deposits of the 22.6 C^{14}ka Oruanui eruption occur at the surface, so the whole drilled sequence, including Mamaku Ignimbrite, could be classed as Huka Group. Thompson (1974) mapped siltstones in Rotorua basin as Huka Group, but there seems little point in introducing the term "Waiora Formation" for tuffs which have no clear stratigraphic connection with the deposits in the Taupo-Reporoa basin.

5. CONCLUSIONS

The Waiora Formation needs to be reviewed and the hidden details of its stratigraphy revealed, especially in the Wairakei-Tauhara area where future development of the geothermal resource for production or reinjection to the south and east of the Waikato River will depend on a better understanding of the stratigraphy. Revised stratigraphy of two wells in this area (WK227, TH2) suggests that the distinction between the Waiora Formation aquifer and Huka Falls Formation aquitard becomes blurred in the middle of the Taupo-Reporoa basin. The base of the Huka Falls Formation is shallower than previously drawn, but the pumiceous tuffs of the Waiora Formation are finer grained, muddier and less permeable than in the Wairakei borefields.

Widely spread ignimbrites were erupted in the TVZ while the Waiora and Huka Falls Formations were accumulating, and though some occur in each formation, none have been correlated with exposed ignimbrites of known age and source. Conversely, Kahgaroa Ignimbrite has been logged in Waiora Formation in holes peripheral to Wairakei geothermal field, but not inside the field nor in Ohaaki wells. Detailed petrological work is needed to identify this and other ignimbrites in their altered state: they may be the key to interpreting the geological structure of the field boundaries. The ignimbrites that comprise the oldest member of the Waiora Formation (wa 1) at Wairakei are possible correlatives of the Rautawiri Breccia in Ohaaki wells. Their thickness and distribution suggest they are the products of a major caldera-forming eruption of unknown provenance.

In recognition of the fact that the Huka Falls and Waiora Formations are neither lithologically nor genetically distinct, it was suggested (ECNZ, 1990) that Waiora Formation be informally redefined to include all strata deposited in the time interval between the top of the Wairakei Ignimbrite and the top of the youngest Waiora Member 5 ignimbrite (Unit 7, or Ignimbrite I of Steiner, 1977). In the type section (WK213) the boundary is in the same place as before. This redefinition is more consistent because distinctive ignimbrites are used as "time-planes" to mark both top and bottom of the formation. However, it would be difficult to apply outside Wairakei where the upper ignimbrite has not been identified. In the wider context of the history of the TVZ and its geothermal fields, the main problem with the Waiora Formation is not in how it is defined, but in what is hidden between its boundaries.

6. ACKNOWLEDGEMENTS

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