Geology of the Wairakei-Tauhara Geothermal System, New Zealand

Greg Bignall, Sarah Milicich, Ernesto Ramirez, Michael Rosenberg, Geoff Kilgour, Andrew Rae

Private Bag 2000, Taupo, Wairakei Research Centre, GNS Science, New Zealand

g.bignall@gns.cri.nz

Keywords: Geology, stratigraphy, structure, Wairakei-Tauhara geothermal system, Taupo Volcanic Zone

ABSTRACT

In the last 4 years to mid 2009, more than 45 geothermal wells (i.e., production, shallow (<600 m deep) steam, injection and exploration) have been drilled by Contact Energy Ltd. in the Wairakei and Tauhara Geothermal Fields. New information on the stratigraphy below ~1500 m drilled depth at Wairakei (including the deepest well WK247, drilled to 2759 mCHF VD; -2246 mRSL), and previously unexplored parts of the Tauhara Geothermal Field, has prompted a revision of their geology and stratigraphic nomenclature. Shallow formations comprise Oruanui Formation, Huka Falls Formation (including Rautehuia Breccia), Waiora Formation (5 members), Karapiti (2A, 2B, 3) Rhyolites and Wairakei Ignimbrite (Whakamaru Group). The previously unknown deeper stratigraphy (below -1000 mRSL) comprises plag-px phyric rhyolite lava (Poihipi Rhyolite), and several welded and non-welded pyroclastic units of the Tahorakuri Formation (including previously unrecognised Stockyard ignimbrite member). The inferred depth to the greywacke basement is >400 m deeper at Wairakei (below -2250 mRSL) than previously believed, whereas it has now been encountered by deep drilling (in TH17) from -1484 mRSL in the NE sector of Tauhara.

Interpretation of recent drilling results by GNS Science, complemented by detailed petrology, provide a geological framework for identifying future drilling targets. Whilst fault zones provide up-flow channels, we now appreciate intra- and inter-formational permeable zones provide major inflows to the production wells, and an important control on lateral fluid flow at Wairakei and Tauhara. Hydrothermal mineral studies confirm a prograde trend in alteration rank and intensity with depth, and point to thermal and chemical change in the western Wairakei-Tauhara system that has created a lower temperature mineral overprint of the early propylitic assemblage, whilst conditions at the eastern boundary of the system have long term stability. Defining the nature and extent of the geological formations, and lithological / structural controls on permeability, has proven invaluable to understanding the hydrology of the geothermal system and essential to the continued long-term, sustainable utilisation and management of the resource.

1. INTRODUCTION

In this paper, we review geological results from recent (2005-09) drilling at the Wairakei-Tauhara Geothermal Field (Figure 1). The stratigraphic units in the district and the structures that shaped them, represent close to 2 million years of geological evolution near the eastern edge of the Taupo Volcanic Zone (TVZ) (Wilson et al., 1995; Spinks et al., 2005). This evolution encompassed regional tectonism, both catastrophic and local scale volcanism, and sedimentation.

Defining the nature and extent of the formations encountered by drilling is key to understanding the hydrology of the system. Knowledge of the strata and structures at Wairakei-Tauhara has evolved during the 50 years of resource development, with more than 45 production and injection wells drilled at Wairakei and Tauhara in 2005-2009. Since 2005, well drilling to >1500 m depth (below -1000 mRSL) has provided new insights into the deep stratigraphy of Te Mihi area (western Wairakei), and eastern/northeastern parts of Tauhara. The new insights include a series of previously unknown deep volcanic formations; intersection of the greywacke basement at -1484 mRSL in the NE part of the Tauhara Geothermal Field (TH17); at Wairakei the basement is now known to occur below –2250 mRSL (i.e., >400 m deeper than previously estimated).

2. STRUCTURE AND TECTONICS

Regional gravity and magnetic studies (e.g. Stagpoole and Bibby, 1999) have indicated the Wairakei Geothermal Field is located over a broad, deep depression in the greywacke basement, filled by low-density pyroclastics and sediments. Whilst geothermal drilling and geological mapping has largely confirmed the gravity structure, a 3-D interpretation of the strata at Wairakei remains somewhat ambiguous due to the complex lateral and vertical extent and variations in lithology and thickness (Hunt et al., 2009).
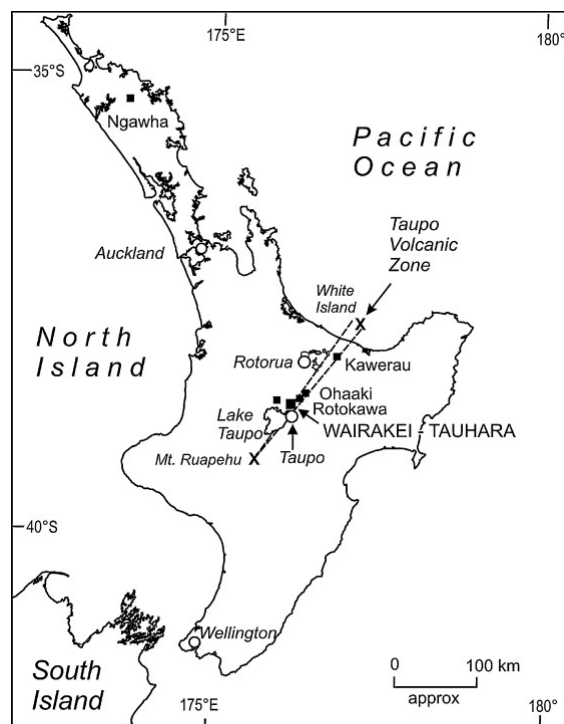

Figure 1: North Island, New Zealand. Taupo Volcanic Zone, Wairakei-Tauhara Geothermal Field, and other geothermal plants (from Hunt et al., 2009).

Bignall et al.

The Wairakei-Tauhara area is crossed by numerous closely spaced, NE-SW trending, high-angle normal faults (Figure 2). Ground rupture has occurred in the area, for example on the Kaiapo Fault during the 1922 and 1983 Taupo earthquake episodes (Grindley and Hull, 1986), and has maintained some scarps. Surface fault traces, however, are typically eroded and/or obscured by recent volcanic products. The fault zones (particularly those active in the late Quaternary) are likely to have influenced the upward flow of reservoir fluids at Wairakei.

Geodetic studies show active crustal extension in the TVZ area of ~2-8 mm/yr, in a NW-SE direction, although stress accommodated between rift segments may allow oblique (NE-SW) extension (Rowland and Sibson, 2004). This deformation, accompanied by fault activation, may have helped to maintain fluid pathways in competent host rock (greywacke, lava, welded ignimbrite), and allow geothermal fluid to be diffused through less competent pyroclastic strata.

Grindley (1965) suggested feed zones in Wairakei wells correlate with fault zones, and breccia/slickenside textures in cores from several wells support this assertion. However, although fault-related permeability within the volcano-sedimentary strata is possible, it remains unproven. In recent Wairakei-Tauhara drilling, permeable zones cannot be ascribed to faults mapped at the surface, nor are they marked by distinctive clastic fabrics in well cuttings. Measurements during drilling, and subsequent completion tests, indicate a range of highly permeable points or zones. Intra-formational permeability is associated with sedimentary units and deep volcaniclastic formations (e.g. in the Stockyard Ignimbrite of the Tahorakuri Formation). Permeability at formation contacts is commonly associated with the Waiora Formation, and in deep wells, with andesite lava, Stockyard Ignimbrite and undifferentiated pyroclastic units of the Tahorakuri Formation.

3. STRATIGRAPHY

In this paper we review the geological framework of the Wairakei-Tauhara geothermal system, updating Rosenberg et al (2009) with information from wells drilled in the area in 2009, and describing the host rocks and their general hydrological role. The distribution and thickness of a number of extant formations has been updated, and is summarised in Figures 3 and 4.
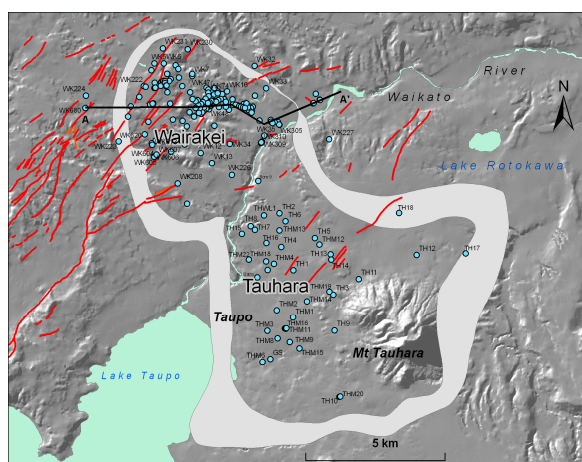

Figure 2: Digital terrain map of the Wairakei–Tauhara area, showing resistivity-defined field boundary; NE-oriented active faults (http://data.gns.cri.nz/af/), **geothermal wells (circles), and a cross-section**

line (A-A') for Figure 4 (after Rosenberg et al., 2009).

3.1 Greywacke Basement

Jurassic volcaniclastic sandstones of the Torlesse Terrane are the geological basement of the Taupo Volcanic Zone, and host the deep heat and fluid sources of its geothermal systems. There is no greywacke outcrop within 30 km of Taupo and although it has not yet been drilled at Wairakei (where the deepest well reaches -2246 mRSL), greywacke was intersected in one well at Tauhara (at -1484 mRSL in TH17, in the NE part of the field).

The regional basement structure (Rowland and Sibson, 2001), combined with basement surface contours, from drill hole data at Rotokawa and Ohaaki Geothermal Fields (Rae et al., 2007), suggest a NE-striking, westward-deepening, basement graben likely exists beneath Wairakei-Tauhara.

3.2 Reporoa Group (Formerly Ohakuri Group)

Previously, "Ohakuri Group" was used for all pyroclastic, volcaniclastic and sedimentary rocks (except greywacke conglomerate) pre-dating >320–340 ka Whakamaru Group ignimbrites in Wairakei drillholes. This name has been superseded by *Reporoa Group* (Gravley et al., 2006), which contains two members: the Tahorakuri and Waikora Formations. The Tahorakuri Formation, >1100 metres thick in some Wairakei wells, consists of pumiceous lithic tuff with intercalated partially welded ignimbrite. The tuff is variously composed of pumice, rhyolite lava, siltstones and rare to minor greywacke fragments, as well as altered plagioclase and ferromagnesian crystals in a fine matrix. The informally-named Stockyard Ignimbrite, a densely welded ignimbrite, is a sub-unit of the Tahorakuri Formation. The other member of the Reporoa Group, the Waikora Formation, is a litho-stratigraphic term for greywacke pebble conglomerate that either underlies, or is intercalated with, the Tahorakuri Formation.

The Stockyard Ignimbrite was first drilled in 2007 in the western Wairakei borefield (Bignall et al., 2007). The densely-welded ignimbrite has perlitic, fiamme and spherulitic textures, and crystals of plagioclase and pseudomorphed ferromagnesian minerals. It is inferred to have been emplaced at high temperature, and at Wairakei is proximal to source. Although only encountered in wells in western Wairakei, it is likely to constitute an extensive (>100 m thick) sheet beneath, and extending beyond, the Wairakei Geothermal Field. The Stockyard Ignimbrite overlies thick sequences of non-welded tuff, silicic tuff, breccia, rhyolite and andesite lavas, that were previously assigned to a lower, "unwelded Stockyard Ignimbrite" or Waiora Formation (Rosenberg et al., 2009). However, these units are now recognised as being part of the Tahorakuri Formation. Whilst the extent of the Stockyard Ignimbrite remains poorly constrained, its occurrence is significant as good intra-formational permeability has been revealed by geothermal well completion tests.

3.3 Wairakei Ignimbrite (Whakamaru Ignimbrite)

Wairakei Ignimbrite is a crystal-rich, moderately welded member of the >320–340 ka Whakamaru Group of ignimbrites, which erupted during the TVZ's most intense episode of caldera volcanism (Houghton et al., 1995).

It was previously indicated (Rosenberg et al., 2009) that Wairakei Ignimbrite had not been encountered by Wairakei wells west of a line joining WK219, WK215 and WK204. However, recent drilling at Te Mihi in 2009 showed

Wairakei Ignimbrite is more than 50 m thick in WK259. This prompted a reinterpretation of age relations and geological controls on the distribution of Waiora and
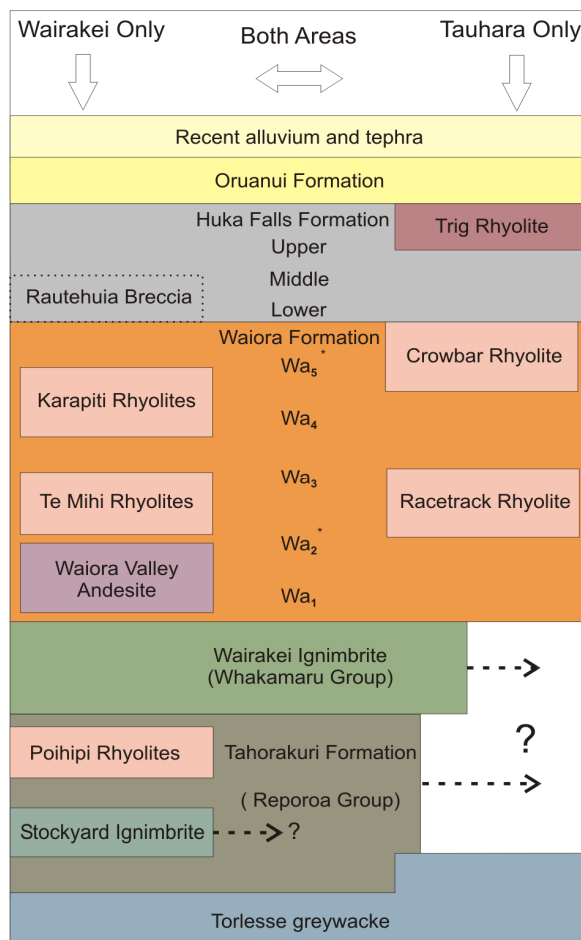

Figure 3: Stratigraphic units penetrated by Wairakei and Tauhara wells (after Rosenberg et al, 2009).

Tahorakuri units and fluid flow in the area. The ignimbrite does not occur in wells adjacent to the Wairakei Power Station (e.g., WK301), but it has been confirmed east of the power station (e.g., WK305) (Figure 2). At Tauhara, Wairakei Ignimbrite occurs in TH12 (<-1425 mRSL), 6 km east of WK305, but is absent in TH9 and TH10 (drilled to ~ -1800 mRSL) to the south, implying continuity to the east, but not to southern parts of Wairakei-Tauhara (Figure 2).

The geometry of the ignimbrite in western Wairakei can be explained by a cumulative vertical displacement of several hundred metres, and slip rate of ~5 mm/year (Villamor and Berryman, 2001), on a narrow fault zone coincident with the Kaiapo Fault. This structural feature is too far west to equate with the Whakamaru Caldera boundary proposed by Wilson et al. (1986, 1995). An alternative explanation assumes the Wairakei Ignimbrite was eroded in areas to the west prior to, or during, accumulation of the Waiora Formation. To the east, close to the Wairakei Power Station, Wood et al. (1997) suggested the discrepancy between the stratigraphy in WK301 and WK305 reflects displacement on a listric fault associated with the Whakamaru Caldera.

The absence of Whakamaru Ignimbrite in some Tauhara wells (e.g., TH9, TH10), but presence in TH12, indicates a broad set of fault structures likely controls the geometry of the Wairakei Ignimbrite, and that the structures continue

eastwards across the Wairakei-Tauhara area. A suggested structural arrangement, with horst and graben elements, is one whereby an upfaulted block of Wairakei Ignimbrite is bounded to the west and east by elongate fault controlled basins (Figure 4).

The extent and thickness of the Wairakei Ignimbrite and its permeability structure are not well known. Some wells (e.g., WK305 and WK307, near the Wairakei Power Station) have good fracture controlled permeability, whereas no significant permeability occurs in 970 m drilled in WK121. It is likely that a combination of fractures and intraformational pathways control fluid flow in the Wairakei Ignimbrite. Indeed Bixley et al. (2009) suggest most liquid production in the Western Borefield comes from near the contact with Waiora Formation. In outcrop, Whakamaru Ignimbrites have sub-vertical, 1-3 m wide spaced columnar cooling joints, which at depth may still provide vertical and lateral flow paths. At Wairakei-Tauhara the fracture network is likely a modification of the joint arrangement, enhanced by tectonic strain, or locally inhibited by hydrothermal mineral deposition.

3.4 Waiora Formation

The Waiora Formation is a thick sequence of volcanic deposits, with interlayered mudstones and sandstones. The formation occurs at Wairakei and Tauhara, and is generally correlated between fields, although not all members are present in both. The thickest package of Waiora strata (>2100 m) is in the SE part of Tauhara (TH9 and TH10) and thinnest (~400 m) in the Western Wairakei Borefield. The formation comprises all strata, except rhyolite (Haparangi Rhyolite Group, of Grindley 1959) and andesite lavas (Waiora Valley Andesite), between the top of the Wairakei Ignimbrite and the base of the Huka Falls Formation (HFF).

At its reference locality (WK213), Grindley (1965) logged five litho-stratigraphic members: ignimbrite and tuff (Member 5, Wa_5); interbedded breccia, tuff, sandstone and siltstone (Members 3, Wa_3; and 4, Wa_4); siltstone (Member 2, Wa_2); non-welded/welded ignimbrite (Member 1, Wa_1) that may be petrogenetically related to the underlying Wairakei Ignimbrite (Wood, 1994). However, it is difficult to distinguish these five members across the Wairakei-Tauhara Geothermal Field, yet whilst some of Grindley's logs have proven to be incorrect, they are a useful starting point for establishing stratigraphic correlations.

With the exception of delineating the Member 1 ignimbrites, in our opinion textural variety has made Grindley's (1965) 5-member subdivision of the Waiora Formation almost impossible to apply at Tauhara. The distinction between the upper layers of the Waiora Formation and the overlying HFF is especially difficult as the upper Waiora Formation at Tauhara contains more fine-grained muddy beds and fewer coarse volcanic horizons. This formation boundary is most likely gradational in space and time. Between the Waiora 1 ignimbrites and the fine-grained Lower HFF-upper Waiora sequence, coarse bedded tuffs, breccias and sediments are correlated as a composite Member 3-4 unit.

Whilst Waiora Formation accumulation started ca. 320 ka ago, the duration of its formation is poorly constrained by the ages of its constituent units, and overlying HFF. No geochronology study of Waiora Formation ignimbrites or lavas has been undertaken, and there is clearly a need to define the genetic linkages to better understand the evolution of the volcanic and hydrothermal systems.
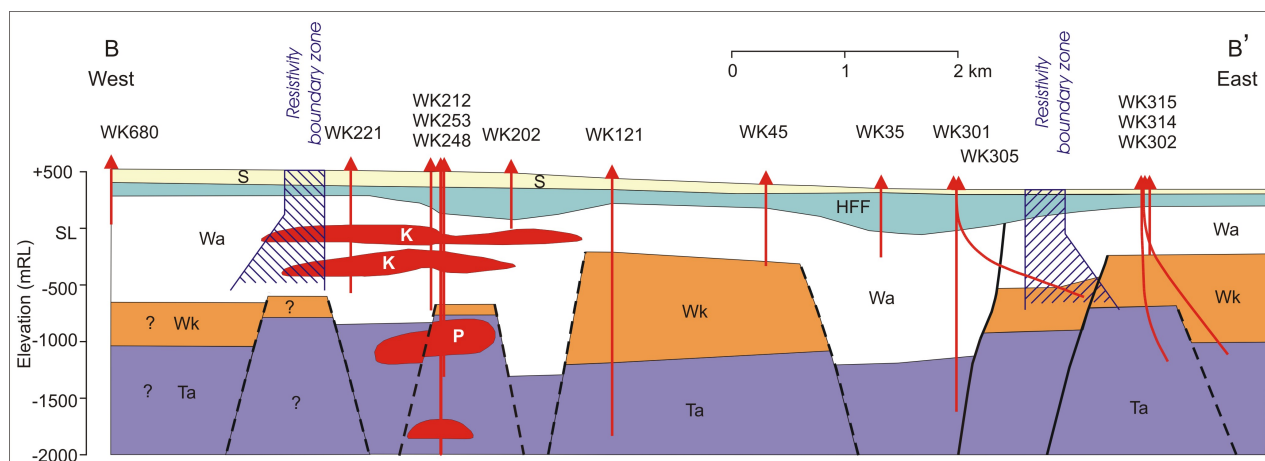
Figure 4: Structural 2D interpretation of the Wairakei Geothermal Field (from Rosenberg et al., 2009). Section line (B-B') is shown in Figure 2. Faults are simplified (inferred as dashed) to highlight the controls on thickness of Waiora Formation and Wairakei Ignimbrite. Abbreviations: Superficial (S); Huka Falls Fm. (HFF); Waiora Fm. (Wa), Karapiti (K) and Poihipi Rhyolites (P); Wairakei Ignimbrite (Wk) and Tahorakuri Fm. (Ta). mRL: metres with respect to sea level.

No one horizon within the Waiora Formation is most productive, although temperature maxima occur in breccias of Wa_3 and Wa_4 in many wells. Member 5 ignimbrite at the top of the Waiora Formation is an important steam-filled aquifer at Te Mihi, whilst Wa_2 has lower permeability and forms local aquicludes. The spatial extent and controls of permeability of the Waiora Member 1 ignimbrites have yet to be determined; although feed zones appear to be strongly influenced by welding zone or flow unit boundaries.

3.5 Waiora Valley Andesite

Andesitic lava and breccia (up to 50 m thick) overlying Wairakei Ignimbrite are named Waiora Valley Andesite. These lavas were extruded in at least two discrete, short-duration episodes of volcanism, from an eruption centre probably located in the Western Borefield/Te Mihi area. They are not related to deeper and older andesite lava in nearby Rotokawa Geothermal Field (Arehart et al., 1997).

3.6 Rhyolite Lavas

Rhyolite lavas and associated breccias, which occur as a spatial clustering of domes in the Te Mihi area (Figure 4), are an important component of the Wairakei-Tauhara stratigraphy and hydrology. The thickness of the lavas vary, and point to prolonged, yet local, silicic volcanism that pre-dated the ~0.32-0.34 Ma Wairakei Ignimbrite (i.e., Poihipi Rhyolite), occurred throughout the accumulation of the Waiora Formation (e.g. Te Mihi and Karapiti Rhyolite at Wairakei; Crowbar and Racetrack Rhyolite at Tauhara) and continued until more recent volcanic events (e.g. c. 28ka Trig rhyolite) (Figure 3).

The largest and hydrologically most significant rhyolite is the Karapiti Rhyolite (Grindley, 1965), which is now known as Karapiti 2A Rhyolite (to distinguish it from discrete Karapiti 2B and Karapiti 3 lavas). Karapiti 2A has the form of a lava dome, which extruded into a broad basin in which Waiora Formation was accumulating. It extends from the Waikato River to the western resistivity boundary, at least as far as WK224. It is thickest in WK208 (~490 m), and extends southwards, and across to Tauhara (Figure 5). Karapiti 2A is permeable, and a storage for low-pressure single-phase steam in the Poihipi area. It has good fracture permeability, particularly in its brecciated margins.

South of Te Mihi, impermeable Rautehuia Breccia laps the Karapiti 2A, to impound the low-pressure steam and form a barrier that separates the high pressure Te Mihi steam zone, from the Southern steam zone (Figure 5). Here, early wells that penetrated the rhyolite had temperature inversions that pointed to cool water flowing through the lower layers of the rhyolite. Clearly, the Karapiti 2A in this area has good permeability, but no production capability.

Since mid-2005, nineteen wells have been drilled in the Te Mihi area (thirteen to >1100 m depth). Seven wells intersected Karapiti 2B, of which three intersected both Karapiti 2A and 2B (separated by Waiora Formation). Whilst the surface geometry and lateral extent of Karapiti 2B is now better defined, its bottom surface is still poorly constrained. Karapiti 2B Rhyolite is less than a quarter of the known area of Karapiti 2A (Figure 5), and less than half as thick, but is a production target as it is hot and permeable.

Flow-banded rhyolite in WK247, several hundred metres from the inferred northern extent of Karapiti 2A, is Karapiti 3 Rhyolite. Its shallow occurrence, compared to Karapiti 2B in most Te Mihi wells, but absence in WK207, precludes correlation with Karapiti 2A. A basal breccia of autoclastic origin consists of clast-supported, brecciated, flow-banded and porphyritic rhyolite, and silicified tuff. Predating the
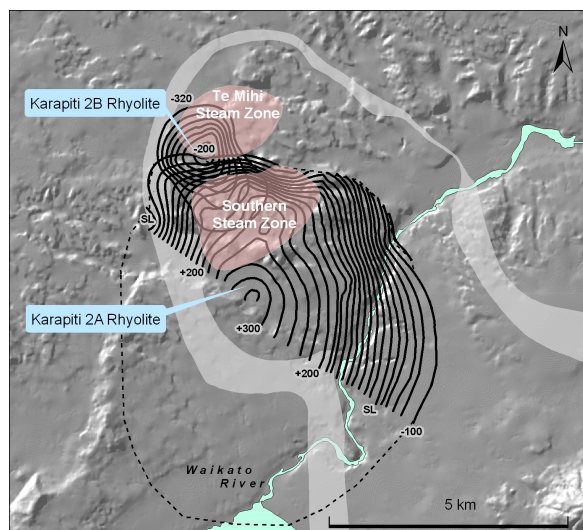
Figure 5: Wairakei map with contoured upper surface (20 m intervals) of Karapiti 2A and 2B Rhyolite lavas, steam zones and resistivity-defined field boundary. Dashed curve represents inferred extent of Karapiti 2A lava; SL: sea level (Rosenberg et al., 2009).

Karapiti Rhyolites and occurring beneath the Wairakei Ignimbrite are previously unknown rhyolite lava and breccia units of the Poihipi Rhyolite. This is a porphyritic (plagioclase-pyroxene) flow-banded, spherulitic and perlitic lava, up to ~480 m thick including a brecciated carapace, that was intersected by WK247, WK248, WK253, WK258 and WK260 (at Te Mihi).

Since 2005, more than 13 geothermal wells have been drilled at Tauhara, and several intersected rhyolite, with five new lava bodies and possible silicic (rhyolite) intrusions (dykes?) revealed in TH9 (Milicich et al., 2009) and TH18 (Ramirez et al., 2009). The ~300-m thick, porphyritic, spherulitic and flow-banded Racetrack Rhyolite Lava (Rosenberg et al., 2009) occurs beneath Waiora Wa$_{3-4}$ tuff and breccia (Figure 3) in TH11, TH12, and TH18. The lava has no known correlatives outside Tauhara. Parts of the lava are hyaloclastic, but most have spherulitic and flow banding textures typical of subaerial extrusions. Also at southern Tauhara is the 350-m thick, porphyritic, spherulitic- to flow-banded Crowbar Rhyolite Lava (Rosenberg et al., 2009) which lies beneath HFF siltstone and Waiora Formation tuff (Figure 3).

3.7 Huka Falls Formation
The Huka Falls Formation of Grindley (1965) includes all lacustrine sediments and water-deposited tuffs between the base of the Oruanui Formation and top of the Waiora Formation. Prior to the Oruanui eruption at Taupo volcano, HFF accumulated in a long-lived shallow basin stretching >50 km from modern Lake Taupo to Waiotapu (20 km SE of Rotorua).

The HFF has not been dated, but its age has been inferred from pollen assemblage ages (late Castlecliffian to early Hawera Stage; Grindley, 1965) and bracketed by radiometric ages of the 26.5 ka Oruanui Ignimbrite and 230 ka Kaingaroa Ignimbrite (Houghton et al, 1995). The minimum formation age is 28 ka, based on correlation of Trig 9471 and Rubbish Top dome rhyolite (Charlier et al., 2005), with ~28 ka old Poihipi tephra (Sandiford et al., 2001). At Hipaua dome, megaliths of thinly-bedded siltstone lithologically correlated with HFF, have been enveloped by endogenous growth of 190-ka dacite (Wilson et al., 1995). The megaliths are evidence part of the HFF is at least 190 ka old (Rosenberg and Kilgour, 2003).

Although facies architecture is complicated, a three-unit division of HFF is applied across the Wairakei-Tauhara Geothermal Field. This is comprised of an *Upper HFF* unit that is a combined equivalent of Grindley's Hu3 and Hu4 units; a *Middle HFF,* being Hu2; the *Lower HFF,* the same as Hu1. Complications with this scheme arise in some wells, with a coarse tuffaceous sandstone, or coarse pumice-lithic breccia, lithologically akin to Waiora Formation, occurring beneath Middle and Lower HFF lacustrine mudstone and sandstone. However, this unit is not present everywhere, and the Lower HFF does not form a continuous layer across Wairakei-Tauhara.

From the Eastern Wairakei Borefield to Tauhara, mudstone, siltstone, and coarse-to-fine sandstone of the Upper and Lower HFF, are separated by unconsolidated (>200 m thick at the Wairakei Power Station) pumice-vitric tuff and pumice conglomerate, derived from reworked ignimbrites. This Middle HFF unit of vertically and laterally variable lake-deposited material thins to the north, west and south, and is absent where underlying Karapiti 2A Rhyolite lavas reach high elevation. Indeed, the Karapiti 2A dome likely acted as an island around which the tuff and sediment accumulated. In southern parts of Wairakei, the sediments and tuff lap against the rhyolite, but do not to cover it.

The HFF is hydrologically important, as it typically has low permeability and acts as an aquitard separating hot fluid in Waiora Formation from shallower groundwater. However, whilst Upper and Lower HFF behave as aquicludes, within them, the Middle HFF pumice tuffs are highly permeable and form an important aquifer. At Wairakei, Middle HFF contains hot water, but at the field margin, such as near the Wairakei Power Station, well temperature profiles indicate the unit allows cool water to penetrate the field boundary.

3.8 Rautehuia Breccia
In the Te Mihi area, Healy (1984) recognised a volcanic breccia (previously thought to be a hydrothermal eruption breccia or landslide deposit) of poorly sorted angular lithics (including mudstone and sandstone from a pre-existing lake) embedded in an unstructured silty matrix. The breccia has a minimum thickness of ~30 m (commonly 100-150 m) and volume of >500 x 10^6 m^3 and is now informally called Rautehuia Breccia (ECNZ, 1990). The Rautehuia Breccia is significant in the NW part of the Wairakei field because it restricts the Te Mihi (high-pressure) steam zone to the underlying Waiora Formation. It may also help to confine the Southern (low-pressure) steam zone in the Karapiti area, where the breccia laps up against the northern side of the permeable, steam-bearing Karapiti 2A Rhyolite.

We suggest the breccia represents an eruption event involving hydrothermal and volcanic (magmatic) activity – perhaps with large-scale collapse and debris/pyroclastic flow. Browne and Lawless (2001) suggest it may be a composite of several units. Structural contours of the bottom surface of the Rautehuia Breccia show the deposit filled deep locally sinuous depressions that appear to have been valleys eroded into the Waiora Formation.

3.9 Other units

Trig Rhyolite Formation
Trig 9471 rhyolite (Graham and Worthington, 1988) and Rubbish Tip dome (Charlier et al., 2005) are small,

coalesced rhyolite domes that occur on the western edge of Mt Tauhara. Both are crystal rich lavas, with a plagioclase + quartz + pyroxene + hornblende + biotite phenocryst assemblage, and discrete isotopic signature (Sutton et al., 1995), prompting their grouping as Trig Rhyolite. Breccia from the rhyolite was encountered in TH3, and coherent lava up to 100 m thick was intersected by TH9, TH11 and TH14. The extent of the dome(s) is ~5 km^2 and its minimum volume is 0.5 km^3. The lava occurs above HFF, and by correlation with the Poihipi tephra (~28 ka) is the youngest rhyolite at Wairakei-Tauhara (Figure 3).

Oruanui Formation

Wairakei Breccia (Grindley, 1965), Wairakei Formation (Self and Healy, 1987), Wairakei Lapilli Tuff (Steiner, 1977) and Oruanui Formation (Wilson, 1993) are synonyms for products of a catastrophic eruption beneath a former Lake Taupo some 26,500 years ago (Wilson, 1993). The formation, produced by a single eruption episode, comprises several pyroclastic density–current deposits interbedded with ash tuff units of airfall and/or flow origin (Wilson, 2001). A fine ash tuff that contains accretionary lapilli (pisolites) occurs at the base of the formation.

At Wairakei-Tauhara, the Oruanui Formation refers to all of its constituent layers, not to single airfall or flow units to which previous names relate. The sequence is lithologically well defined, and up to 170 m thick in northwest Wairakei, where hydrothermally altered ignimbrite is commonly exposed. Elsewhere, it rarely exceeds 120 m thickness.

Mt Tauhara Dacite

Mt Tauhara is a composite volcano constructed from coalesced dacite lava domes, breccia and locally distributed pyroclastic deposits (Graham and Worthington, 1988). Lava from the Hipaua dome has been dated (190 ka; Wilson et al., 1995), but other (undated) domes are physiographically younger (Graham and Worthington, 1988). There is evidence in TH3 cuttings that debris from an early-erupted dacite was incorporated into HFF. All dacitic lava, pyroclastic or epiclastic debris layers in geothermal wells north, northwest and south of Mt Tauhara post-date HFF and Trig-type rhyolite lavas, and provide potential pathways for cold meteoric water into shallow aquifers.

Superficial deposits

Most outcrops in the Wairakei-Tauhara area comprise young pyroclastic fall and flow units, and their sedimentary or pedogenetic derivatives. The superficial deposits are subdivided into material related to the 1.8 ka Taupo eruption (Wilson, 1993), and layers that pre-date that eruption but post-date the Oruanui Formation, including pyroclastic fall units and non-welded ignimbrite of the Taupo eruption, fluvial and lacustrine pumiceous sand and alluvium. Locally there are surficial hydrothermal eruption breccia deposits (Browne and Lawless, 2001).

The post-Oruanui sequence includes surface mantling of volcanic ash and pumice fall units, derived from small- to moderate-scale silicic magma eruptions (Wilson, 1993), intercalated paleosol horizons, and locally dispersed basaltic tephra and cryptotephra from andesitic sources (Mts. Ruapehu, Egmont/Taranaki, Tongariro). Sedimentary and aeolian sequences are also recognised. Some beds within the superficial deposits are permeable and contain shallow groundwater aquifers, both cold and thermal (e.g., Taupo and Oruanui tuffs form perched geothermal reservoirs that supply many domestic hot water bores in Taupo Township).

4. HYDROTHERMAL ALTERATION

Hydrothermal alteration at Wairakei-Tauhara follows a prograde trend of increasing rank and intensity with depth.

An argillic-type alteration assemblage (smectite, calcite ± pyrite, ± illite-smectite) affects most surficial and near-surface units at Wairakei-Tauhara. Alteration intensity ranges from weak in the Oruanui Formation, to moderate and high in the HFF. Smectite presence infers formation temperatures <140°C (Browne and Ellis, 1970). An increase in alteration rank is recognised by the occurrence of interlayered illite-smectite, hydrothermal quartz, calcite and pyrite, followed by trace illite, chlorite, and epidote.

Propylitic alteration predominates in Waiora Formation strata and rhyolite lavas. It is recognised by the presence of chlorite, quartz and epidote, and variable abundances of albite, adularia, clinozoisite, zoisite, wairakite and titanite. Wairakite is a useful indicator of formation temperature, as it typically forms at temperatures >210°C (Steiner, 1977). Epidote occurs as vein-filling euhedral crystals, but is more common as a replacement of primary minerals and rock matrix. Albite commonly replaces primary plagioclase. Adularia implies deposition in a high-permeability environment, with vein adularia pointing to boiling conditions, at >230°C (White and Hedenquist, 1990) and as a replacement of feldspar.

The highest rank assemblage, including epidote and prehnite indicates that, either presently or in the past, fluid-rock interaction occurred with near-neutral (to slightly acidic) pH fluids at >240°C -280°C. Measured downhole temperatures in many wells match these inferred conditions.

Examination of samples from wells recently drilled at Te Mihi reveal an illite-calcite assemblage overprinting hydrothermal albite and adularia; illite replacing chlorite; and corroded epidote crystals in a calcite-altered matrix. The mineral changes imply the CO_2 content of the hydrothermal fluid has increased, resulting in the deposition of carbonate, and that illite has become stable instead of the hydrothermal feldspar (i.e. albite and adularia) and chlorite. Shallow occurrences of epidote (e.g. in WK247 above -200 mRSL) also point to relict alteration event(s). The shift from albite/adularia to illite stability reflects decrease of temperature and/or pH of the circulating hydrothermal fluid (Browne, 1978). Such mineralogical changes are evidence of thermal and chemical evolution in the western Wairakei Borefield, whilst the eastern part of the field has remained relatively static.

5. GEOLOGICAL QUESTIONS

After more than fifty years of drilling and development for power generation, gaps still remain in our geological knowledge of the Wairakei-Tauhara geothermal system.

As Rosenberg et al. (2009) outline, initially there was no need to drill very deep wells at Wairakei, since steam or two-phase flows could be tapped at a few hundred metres depth. In the 1970s and 1980s, drilling typically stopped at 1200 ft (~365 m) or 1500 ft (~460 m), near the (apparently impermeable) top of the Wairakei Ignimbrite, particularly since shallower feed zones were tapped in the Waiora Formation. So, whilst geological data above ~0 mRSL is abundant, it comprises only a small part of the resource.

In the last 5 years, it has been more common at Wairakei to complete new geothermal production and injection wells to >1500 m drilled depth (i.e. to about -1000 mRSL). Whilst stratigraphic correlations are still unclear between many

wells, recent drilling has extended what is known of deep geology of the system.

It is not known, however, why the Wairakei-Tauhara geothermal system is in its specific location. Resistivity data has been used to model the system (Bibby et al., 2009), and its shape reflects separate Wairakei and Tauhara reservoirs that coalesce within the top 2-3 km of volcanic strata. Seismic and resistivity modelling reveal thinned crust, and a possible magmatic source at 10-15 km depth beneath the Wairakei region (Bibby et al., 2009), but the reason why magmatic heat is focused at Wairakei-Tauhara has not been resolved.

The inferred TVZ fault structure and kinematics, supported by surface fault mapping at Wairakei-Tauhara, point to the location of the geothermal system being influenced by oblique extension. However, the surface distribution of faults at Wairakei-Tauhara appears no different to the area west of Wairakei, where there are no geothermal manifestations, and no obvious clues for distinguishing any specific structural control. Active extension across the Taupo Fault Belt (Rowland and Sibson, 2001) is likely to maintain hydrothermal flow paths, but how the local stress field influences permeability distribution is not known.

Although geochronological studies are now underway, the age of the main aquifer and aquitard rocks in the Wairakei-Tauhara system is still very poorly constrained. Better age control will greatly help to understand how the hydrothermal system has evolved. Combined with complementary fluid-rock interaction studies, we will be better placed to infer the longevity of the system, and the timeframe for high-temperature TVZ geothermal systems to become established or recover after major periods of local or regional volcanism.

Dating strata of the HFF and Waiora Formation is key in establishing the volcanic and tectonic history of the sedimentary basin that hosts the system, and relevant to the volcano-tectonic history of extension in the central TVZ. There are many dated and/or chemically correlated rhyolite lavas (e.g. Sutton et al., 1995; Ramirez et al., 2009) associated with the Taupo and Maroa volcanic centres, and one or more are likely to be genetically related to major pyroclastic units of the Waiora Formation (i.e., Wa_1 or Wa_5). New isotope geochronology techniques, such as Uranium-series dating of zircon bearing lava and ignimbrite units (Charlier et al., 2005; Wilson et al., 2008) overcomes the effect of alteration of feldspar and ferromagnesian minerals that makes conventional argon-argon or potassium-argon dating techniques inapplicable for geothermal reservoir rocks. Major advances in understanding the geology and hydrothermal evolution of the Wairakei-Tauhara geothermal system are anticipated.

6. ACKNOWLEDGEMENTS

7. REFERENCES

Arehart, G.B., Wood, C.P., Christenson, B.W., Browne, P.R.L. and Foland, K.A.: Timing of volcanism and geothermal activity at Ngatamariki and Rotokawa, New Zealand. *Proceedings 19th New Zealand Geothermal Workshop*, University of Auckland, Auckland, New Zealand (1997), 117-122.

Bibby, H.M., Risk, G.F., Caldwell, T.G. and Heise, W.: Investigations of deep resistivity structures at the Wairakei geothermal field. *Geothermics*, 38, (2009), 98-107.

Bignall, G., Rosenberg, M.D., Kilgour, G.N., Milicich, S.D. and Rae, A.J.: Stratigraphy of the western Wairakei Geothermal Field : insights from recent drilling in the greater Te Mihi area. *Proceedings 29th New Zealand Geothermal Workshop*, Auckland, New Zealand, (2007), 6 pp.

Bixley, P.B., Clotworthy A.W. and Mannington, W.I.: Evolution of the Wairakei geothermal reservoir during 50 years of production. *Geothermics*, 38, (2009), 145-154.

Browne, P.R.L.: Hydrothermal alteration in active geothermal fields. *Annual Review of Earth and Planetary Sciences*, 6, (1978), 229-250.

Browne, P.R.L. and Ellis, A. J.: The Ohaki-Broadlands hydrothermal area, New Zealand; mineralogy and related geochemistry. *American Journal of Science*, 269, (1970), 97-131.

Browne, P.R.L. and Lawless, J.V.: Characteristics of hydrothermal eruptions, with examples from New Zealand and elsewhere. *Earth Science Reviews*, 52, (2001), 299-331.

Charlier, B.L.A., Wilson, C.J.N., Lowenstern, J.B., Blake, S., van Calsteren, P.W. and Davidson, J.P.: Magma generation at a large, hyperactive silicic volcano (Taupo, New Zealand) revealed by U-Th and U-Pb systematics in zircons. *Journal of Petrology*, 46, (2005), 3-32.

ECNZ: Water right applications and impact assessment, Wairakei Geothermal Power Station. Electricity Corporation of New Zealand Limited, Wellington, New Zealand Unpublished report July, 1990. 232 pp.

Graham, I.J. and Worthington, T.J.: Petrogenesis of Tauhara dacite (Taupo Volcanic Zone, New Zealand): evidence for magma mixing between high-alumina andesite and rhyolite. *Journal of Volcanology and Geothermal Research*, 35, (1988), 279-294.

Gravley, D.M., Wilson, C.J.N., Rosenberg, M.D., Leonard G.S.: The nature and age of Ohakuri Formation and Ohakuri Group rocks in surface exposures and geothermal drillhole sequences in the central Taupo Volcanic Zone, New Zealand. *New Zealand Journal of Geology and Geophysics*, 49, (2006), 305–308.

Grindley, G.W.: Sheet N85 – Waiotapu "Geological Map of New Zealand 1:63,360", New Zealand Department of Scientific and Industrial Research, Wellington, New Zealand (1959).

Grindley, G.W.: The geology, structure and exploitation of the Wairakei Geothermal Field, Taupo, New Zealand. Bulletin No.75, New Zealand Geological Survey, Wellington, New Zealand, (1965), 131 pp.

Grindley, G.W. and Hull, A.G.: Historical Taupo Earthquakes and deformation. *Royal Society of New Zealand Bulletin*, 24, (1986), 174-186.

Healy, J.: Wairakei Geothermal Field in review. New Zealand Geological Survey, unpublished Geothermal Circular JH/10, New Zealand, (1984), 34 pp.

Houghton, B.F., Wilson, C.J.N., McWilliams, M., Lanphere, M.A., Weaver, S.D., Briggs, R.M. and Pringle, M.S.: Chronology and dynamics of a large silicic magmatic system: central Taupo Volcanic Zone, New Zealand. *Geology*, 23, (1995), 13–16.

Hunt, T.M., Bromley, C.J., Risk, G.F. and Sherburn, S., Soengkono, S.: Geophysical investigations of the Wairakei field. *Geothermics*, 38, (2009), 85-97.

Milicich, S.D., Rosenberg, M.D., Ramirez, L.E. and Kilgour, G.N.: Geology of Exploration Well TH9 Tauhara Geothermal Field, GNS Science Consultancy Report 2008/56, (2009). Confidential to Contact Energy Ltd.

Rae, A.J., Rosenberg, M.D., Bignall, G., Kilgour, G.N. and Milicich, S.D.: Geological Results of Production Well Drilling in the Western steamfield, Ohaaki Geothermal system: 2005–2007. *Proceedings 29th New Zealand Geothermal Workshop*. Auckland, New Zealand, (2007), 6 pp.

Ramirez, L.E., McCoy-West, A.J., Alcaraz, S.A., Rosenberg, M.D. and Rae, A.J. Geology of Exploration Well TH18 Tauhara Geothermal Field. GNS Science Consultancy Report 2009/277, (2009). Confidential to Contact Energy Ltd.

Ramirez, L.E., Rae, A.E. and Bignall, G.: Geochemistry of buried rhyolite lavas, western steamfield, Wairakei Geothermal Field, Taupo Volcanic Zone, New Zealand. *Transactions, Geothermal Resources Council*, 33 (2009, in press).

Rosenberg, M.D. and Kilgour, G.N.: Explosive volcanism at Tauhara Volcanic Complex: implications for the emplacement of Hipaua dome. Programme and Abstracts, Geological Society of New Zealand 2003 Annual Conference, Dunedin, New Zealand, (2003), 125 pp.

Rosenberg, M.D., Bignall, G., and Rae, A.J.: The geological framework of the Wairakei-Tauhara Geothermal System, New Zealand. *Geothermics*, 38, (2009), 72-84.

Rowland, J.V. and Sibson, R.H.: Extensional fault kinematics within the Taupo Volcanic Zone, New Zealand: soft-linked segmentation of a continental rift system. *New Zealand Journal of Geology and Geophysics*, 44, (2001), 271-84.

Rowland, J.V. and Sibson, R.H.: Structural controls on hydrothermal flow in a segmented rift system, Taupo Volcanic Zone, New Zealand. *Geofluids*, 4, (2004), 259-283.

Sandiford, A., Alloway, B. and Shane, P.: A 28,000–6600 cal. yr record of local and distal volcanism preserved in a paleolake, Auckland, New Zealand. *New Zealand Journal of Geology and Geophysics*, 44, (2001), 323-336.

Self, S. and Healy, J.: The Wairakei Formation, New Zealand: stratigraphy and correlation. *New Zealand Journal of Geology and Geophysics*, 30, (1987), 73-86.

Spinks, K.D., Acocella, V., Cole, J.W. and Bassett, K.N.: Structural control of volcanism and caldera development in the transtensional Taupo volcanic zone, New Zealand. *Journal of Volcanology and Geothermal Research*, 144, no.1-4, (2005), 7-22.

Stagpoole, V.M. and Bibby, H.M.; Residual gravity anomaly map of the Taupo Volcanic Zone, New Zealand, 1:250:000. Geophysical map 13. Institute of Geological and Nuclear Sciences, New Zealand (1999)

Steiner, A.: The Wairakei Geothermal Area, North Island, New Zealand: its subsurface geology and hydrothermal rock alteration. *New Zealand Geological Survey, Bulletin*, 90, (1977), 134 pp.

Sutton, A., Blake, S. and Wilson, C.J.N.: An outline geochemistry of rhyolite eruptives from Taupo volcanic centre, New Zealand. *Journal of Volcanology and Geothermal Research*, 68, (1995), 153-175.

Villamor, P. and Berryman, K.R.: A Late Quaternary extension rate in the Taupo Volcanic Zone, New Zealand, derived from fault slip data. New Zealand *Journal of Geology and Geophysics*, 44, (2001), 243-269.

White, N.C. and Hedenquist, J.W.: Epithermal environments and styles of mineralization: variations and their causes, and guidelines for exploration. *Journal of Geochemical Exploration* 35, (1990), 445-474.

Wilson, C.J.N.: Stratigraphy, chronology, styles and dynamics of late Quaternary eruptions from Taupo volcano. *Philosophical Transactions of the Royal Society*, London A343, (1993), 205-306.

Wilson, C.J.N.: The 26.5 ka Oruanui eruption, New Zealand: an introduction and overview. *Journal of Volcanology and Geothermal Research*, 112, (2001), 133-174.

Wilson, C.J.N., Charlier, B.L.A., Fagan, C.J., Spinks, K.D., Gravley, D.M., Simmons, S.F. and Browne, P.R.L.: U-Pb dating of zircon in hydrothermally altered rocks as a correlation tool: application to the Mangakino geothermal field, New Zealand. *Journal of Volcanology and Geothermal Research*, 176, (2008), 191-198.

Wilson, C.J.N., Houghton, B.F. and Lloyd, E.F.: Volcanic history and evolution of the Maroa-Taupo area, central North Island. In: Smith, I.E.M. (Ed.), Late Cenozoic Volcanism in New Zealand. Royal Society of New Zealand, Bulletin 23, Wellington, New Zealand, (1986), 194-223.

Wilson, C.J.N., Houghton, B.F., McWilliams, M.O., Lanphere, M.A., Weaver, S.D., Briggs, R.M.: Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review. *Journal of Volcanology and Geothermal Research,* 68, (1995), 1-28.

Wood, C.P.: The Waiora Formation geothermal aquifer, Taupo Volcanic Zone, New Zealand. *Proceedings, 16th New Zealand Geothermal Workshop*, Auckland, New Zealand, (1994), 121-126.

Wood, C.P., Mroczek, E.K. and Carey, B.S.: The boundary of Wairakei geothermal field: geology and chemistry. *Proceedings, 19th New Zealand Geothermal Workshop*, Auckland, New Zealand, (1997), 25-30.