CHARACTERISATION AND STRATIGRAPHIC CORRELATION OF THE ANDESITES ENCOUNTERED IN THE WAIRAKEI GEOTHERMAL FIELD

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ABSTRACT

Active volcanism in the central Taupo Volcanic Zone (TVZ) during the past ~1.8 Ma has changed from predominantly andesitic to silicic composition, with widespread rhyolitic volcanism dominating the central TVZ by ~0.34 Ma. There are few surficial outcrops of andesite in the central TVZ, although buried andesites have been encountered by drillholes at several TVZ geothermal fields, including 30 geothermal wells in the Wairakei Geothermal Field. Extrusive lavas of the Waiora Valley Andesite (WVA) occur at relatively shallow depth (i.e., <1 km depth) in the Western Borefield (WBF) at Wairakei, with deeper andesites (i.e., >1.5 mRL) in drillholes to the northwest and southeast of the WBF. In thin section, the WVA is distinguished from the deep andesites by its dual plagioclase populations (dominated by large, resorbed plagioclase), and large plagioclase-pyroxene-amphibole glomerocrysts. In contrast, the deep andesites include rare amphibole, and plagioclase-only glomerocrysts within their mineral assemblage. New geochemical analyses revealed that WVA lavas are distinct from at least two of the deep andesites, and likely had separate magmatic sources. This has important implications for the timing and source of geothermal heat input to the Wairakei-Tauhara geothermal system and evolution of the central TVZ. Further work is required to constrain the emplacement mechanism(s) and timing of the deep Wairakei andesites, and their relationship both to each other, and to the nearby Spa Andesite and Tauhara dacite.

1. INTRODUCTION

Andesite has been encountered in multiple drillholes in the Wairakei Geothermal Field. Most of the andesites occur at relatively shallow depths (<1 km depth) and represent a series of extrusive lavas collectively known as the Waiora Valley Andesite (WVA; Grindley, 1965). Deep (generally >1 km) andesites have been encountered in six drillholes at Wairakei; however, they are poorly defined spatially and their textural and petrological characteristics and relationship with the WVA have not been established.

The Taupo Volcanic Zone (TVZ) has been the dominant region of active volcanism in New Zealand since the late Pliocene, producing over 90% of the known late Pliocene and Quaternary volcanic products in New Zealand (Wilson et al., 1995). The central TVZ has been the focus of rhyolitic volcanism since ~1.8 Ma (age of the oldest silicic ignimbrite interpreted to be part of the TVZ; Eastwood et al., 2013; Chambefort et al., under review), and young andesites exposed in surface outcrop in the region are rare (Browne et al., 1992; Arehart et al., 2002).

Subsurface andesite lavas and breccias encountered in geothermal drillholes in the region can provide important insights on both the timing of andesitic volcanism, and the relationship between intermediate and silicic composition magmas in the central TVZ. On a local scale, understanding the source, nature and relationships of the andesites at Wairakei will enhance our current understanding of the evolution and structure of the Wairakei Geothermal Field.

Thin section and whole rock major and trace element (including rare earth elements) analyses using X-ray fluorescence (XRF) was undertaken on selected samples of WVA and deep andesites (Table 1) to quantify mineralogical, textural and geochemical characteristics of the andesites. Where available, drill core samples were preferentially selected over drill cuttings to enable a more detailed examination of rock textures; however, in more recently drilled wells only drill cuttings were available for analyses.

2. SPATIAL AND TEMPORAL DISTRIBUTION OF ANDESITES IN THE CENTRAL TVZ

Although young andesites are rarely exposed in the central TVZ (e.g. Rolles Peak; Browne et al., 1992), subsurface andesite lavas and breccias have been encountered in geothermal drillholes in the Ngatamariki, Rotokawa, Ohaaki, and Wairakei-Tauhara Geothermal Fields (Grindley, 1965; Browne et al., 1992; Wood, 1996; Prasetyo et al., 2012 Chambefort et al., under review). The andesites encountered at Ngatamariki, Rotokawa and Ohaaki typically occur at depths ≥1000 mRL (metres relative to sea level). At Rotokawa, andesites of an inferred age >1.89 Ma (based on recent U-Pb dating of the overlying Tahorakouri Formation; Eastwood et al., 2013) directly overlie the Mesozoic basement greywacke and represent early volcanism in the central TVZ (Arehart et al., 2002). Similarly, andesite lava within the Tahorakouri Formation at Ngatamariki has recently been dated at 1.8 Ma– 0.9 Ma (Chambefort et al., under review). Deep andesites also occur in several Ohaaki drillholes, either within the lower sections of the Tahorakouri Formation, or directly overlying the Mesozoic greywacke basement, while shallow andesites were also encountered directly overlying the Rangitaiki (Whakamaru-group) Ignimbrite (Rae et al., 2007). At Tauhara, a shallow (15 to -186 mRL), ~200 m thick andesite lava, referred to as the Spa Andesite, was encountered in one drillhole, between the Huka Falls Formation and the underlying Waiora Formation (Rosenberg, et al. 2010; Prasetyo et al., 2012).

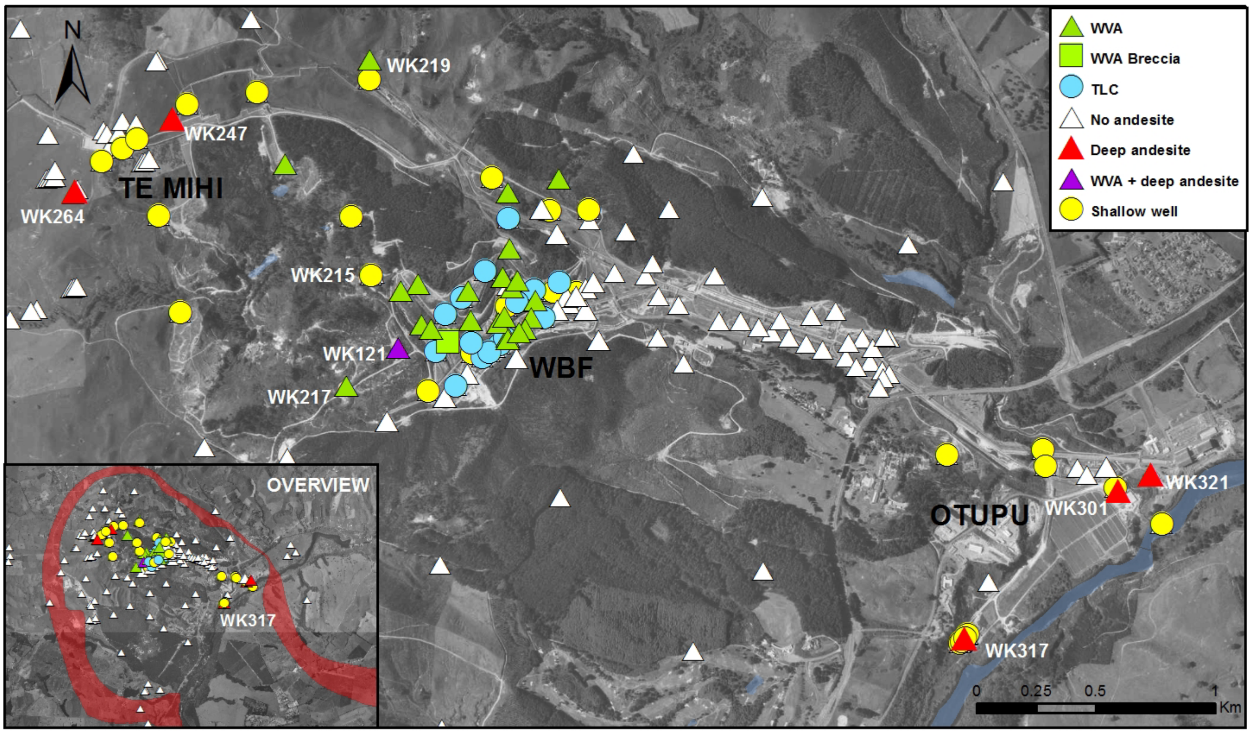

Figure 1: Distribution of the Waiora Valley Andesite (WVA) and deep andesites encountered in the Wairakei Geothermal Field. Inset: location of drillholes shown in main figure, relative to the resistivity-defined boundary zone for the Wairakei-Tauhara Geothermal Field (red shaded area) defined by Risk et al. (1984). Abbreviations: WVA-Waiora Valley Andesite; TLC-total loss of circulation while drilling; shallow well refers to any wells that were drilled to shallower depths than the WVA, or in the case of drillholes proximal to deep Wairakei andesites, too shallow to penetrate deep andesites at similar depths.

2.1 Distribution of andesites at Wairakei Geothermal Field

Thirty drillholes have encountered andesites in the Wairakei Geothermal field, of which 23 are located in the Western Borefield (WBF; Figure 1). The WBF andesites all occur at relatively shallow depths (i.e., top boundary -100 m to -300 mRL), either within the Waiora Formation or between the Waiora Formation and the Wairakei Ignimbrite (Table 1). Shallow andesite (-172 m and -195 mRL) was also encountered by two drillholes outside the WBF, (WK215 and WK219; Figure 1; Table 1). The shallow andesites encountered in the WBF and in drillholes WK215 and WK219 are inferred to represent a series of extrusive lavas, collectively known as the Waiora Valley Andesite (WVA; Grindley, 1965). These lavas are ≥14 m – 164 m thick (Table 1), although true thickness is poorly constrained due to blind drilling in many of the drillholes. Several drillholes in the WBF incurred a loss of returns at comparable depths to the WVA (Figure 1), which may reflect the presence of WVA in these drillholes.

With the exception of the WK264 andesite, deep Wairakei andesites are generally encountered in the Tahorakouri Formation below -1100 mRL. These are intersected by one Te Mihi area drillhole (WK247), three Otupu drillholes (WK301, WK317 and WK321), and in one WBF drillhole (WK121; Figure 1; Table 1). At Te Mihi, WK247 encountered a 135 m thick andesite, whereas a shallower (< -900 mRL), 20 m thick andesite was intersected by WK264 within the Poihipi Rhyolite (Table 1). At Otupu, a 675 m thick andesite lava was intersected by WK321, and WK301 and WK317 each encountered two separate andesite / dacite units ranging from 60 – 330 m thick (Table 1). In WK121, three deep, 30 m to ≥92 m thick andesite units were encountered, between within the Tahorakuri Formation (Table 1). The remaining drillholes in the WBF are too shallow to encounter deep andesites.

3. PETROLOGICAL CHARACTERISTICS

The following describes the petrography of the Wairakei andesites. Where multiple andesite units occur in the same drillhole they are numbered 1 to 4, in parentheses after the well ID number, representing shallowest to deepest units.

The Wairakei andesites display variably moderate to intense hydrothermal alteration, generally increasing in intensity and rank with depth, hindering accurate identification of the primary mineralogy and texture of the rocks. The hydrothermal alteration mineral assemblage for each of the andesites examined is summarised in Table 1, and includes variable abundances of illite, chlorite, quartz, calcite, actinolite, adularia, epidote, clinozoisite, biotite, leucoxene, rutile, hematite and pyrite.

3.1 Waiora Valley Andesites

In general, the Waiora Valley Andesites are weakly porphyritic (~10 – 15 vol.%), consisting predominantly of plagioclase, with rare pyroxene (<1 vol.%), accessory magnetite and apatite, and rare to minor plagioclase-pyroxene-amphibole glomerocrysts (<1 – 2 vol.%). Typically, the WVA includes two distinct plagioclase populations: 1. Common (~60 – 70 vol.% of plagioclase) coarse (~1 – 3 mm) anhedral, subhedral, moderately to strongly sieve-textured, commonly oscillatory zoned megacrysts, and, 2. small (~0.2 – 1 mm), euhedral phenocrysts that do not display resorption features or oscillatory zoning (Figure 2A). The WVA groundmass is generally microlitic and commonly includes fine (~0.1 – 0.2 mm) swallow-tail plagioclase crystals. Weakly to strongly-developed flow-banding textures are present in some andesites (e.g., WK26, WK29, WK71, WK80 and WK122).

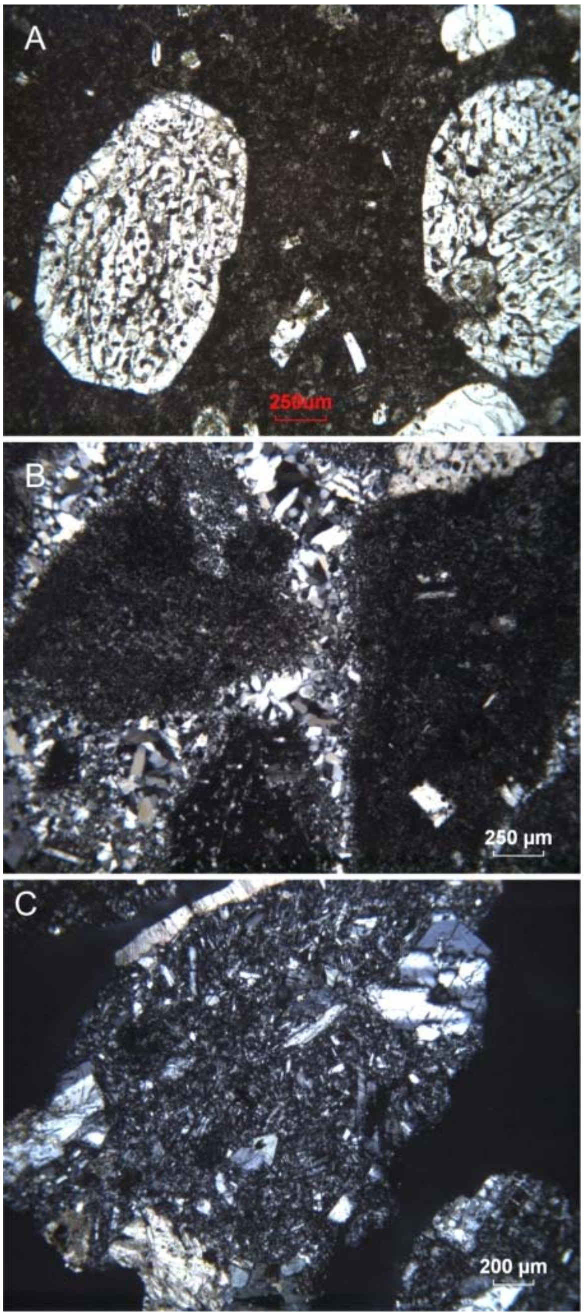

Figure 2: Representative mineralogy and textures of the Wairakei andesites in thin section under crossed polarized light. A, Resorbed, strongly sieve-textured plagioclase megacrysts, and smaller plagioclase phenocrysts typically seen in the WVA (WK215, 2300', 701 m); B, Angular, clast-supported andesite breccia with a hydrothermal quartz cement (WK44, 1952', 595 m); C, Coarse-grained, microlitic groundmass with fragmented plagioclase phenocrysts (WK121(4), 7300', 2225 m).

The WVA in WK44 is a hydrothermally altered, clast-supported, andesite-bearing breccia. The breccia is dominated by angular andesite fragments that appear mineralogically and texturally comparable to the WVA. It also includes rare fragments of strongly altered ignimbrite with pumice fiamme, and dark streaks of apparent organic material. The breccia matrix appears fine-grained and has been almost entirely replaced by hydrothermal quartz cement (Figure 2B).

3.2 Deep Wairakei andesites

The deep Wairakei andesites are all variably porphyritic and generally comprise ~15 – 20 vol.% phenocrysts, although the two Te Mihi andesites (WK247 and WK264) are weakly porphyritic (~7 – 10 vol.% phenocrysts). The phenocryst population in all of the deep andesites is dominated by plagioclase but includes rare pyroxene. Plagioclase phenocrysts are typically euhedral to subhedral, 0.5 – 1 mm size, and rarely display resorption or oscillatory zoning textures. Rare small fragments of strongly sieved plagioclase are present in WK247 and WK264 drill cuttings. Rare plagioclase glomerocrysts (~1 – 2 mm) are present in all the deep andesites except WK121(4) and WK301(2). Larger plagioclase glomerocrysts (~2 – 4 mm) are common in the WK121(2) andesite, accounting for more than half of the total plagioclase population. Both orthopyroxene and clinopyroxene are only observed in the WK264 andesite; however, due to the intensity of hydrothermal alteration it is not possible to confirm if they are a consistent component of the phenocryst assemblage in all the deep Wairakei andesites. Rare amphibole phenocrysts are also present in most of the deep andesites, although this is not confirmed in the Otupu samples (WK301 and WK317) due to the intense nature of their hydrothermal alteration. A minor abundance of magmatic quartz phenocrysts are present in the WK317(1) dacite (Table 1), with possible small magmatic quartz grains also present in the Te Mihi andesites (WK247, WK264).

The deep Wairakei andesites display a relatively coarse-grained microlitic groundmass (Figure 2C), with the WK247 and WK301(1) andesites also displaying a pseudotrachytic texture. The exception is the WK264 andesite groundmass which is predominantly fine-grained. Rare swallow-tail plagioclase laths are present in all but the WK301(1) and WK317(1) andesites / dacites, although their presence elsewhere may be obscured by intense hydrothermal alteration.

4. GEOCHEMICAL CHARACTERISTICS

Geochemical analyses were undertaken on selected samples of WVA and two of the deep andesites / dacites from Otupu drillholes (WK301(2) and WK317(1); Table 1). Due to the intense hydrothermal alteration, major and most trace element geochemistry is not a suitable tool for characterising the andesites at Wairakei. For example, Waiora Valley Andesites commonly display quartz replacement / veining, and in whole-rock composition appear to be intermediate to silica-rich, with 65.6 – 73.4 wt.% SiO_2. Similarly, the two deep Otupu andesites (WK301(2), WK317(1)) comprise 66.6 and 65.5 wt.% SiO_2, respectively.

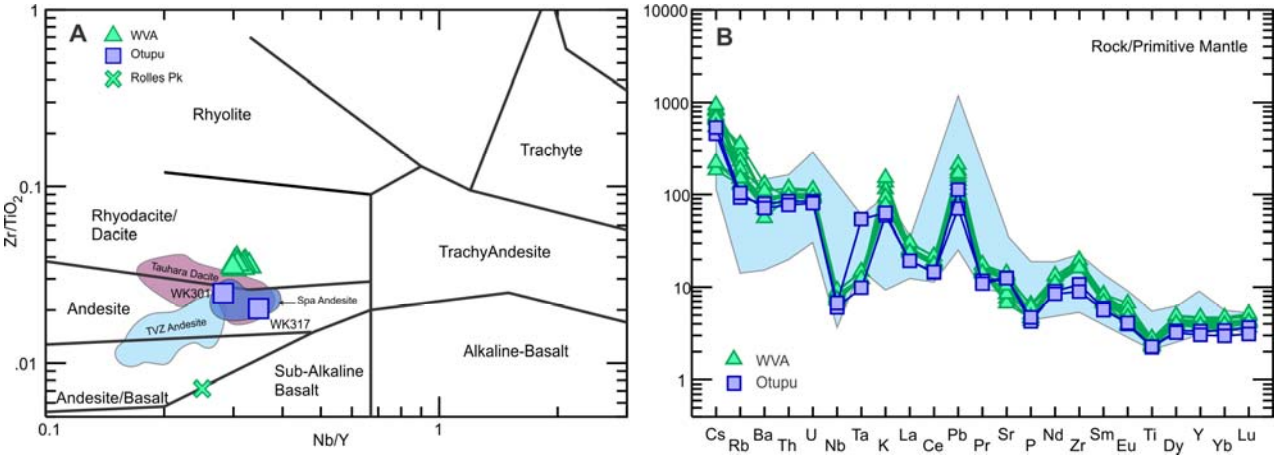

Figure 3: Geochemical composition of the WVA and deep Wairakei andesites. A, Immobile element ratio diagram (after Winchester and Floyd, 1977); B, Trace element spider diagram normalised to primitive mantle (after Sun and McDonough, 1989). Key: WVA-Wairakei Valley Andesite; Otupu-Otupu area andesites (WK301(2), WK317(1)); Rolles Pk-Rolles Peak Andesite (data from Graham and Worthington, 1988). Shaded fields represent composition of known TVZ rocks, where red-Tauhara dacite (data from Graham and Worthington, 1988), light blue-other TVZ andesites, including southern TVZ (data from Cole et al., 1983; Browne et al., 1992; Price et al., 1992; Gamble et al., 1999; Price et al., 2010), dark blue-Spa Andesite (data from Prasetyo et al., 2012).

Trace elements commonly regarded as being immobile in geothermal environments are most appropriate to use in igneous classification of hydrothermally altered rocks. Using the immobile element classification diagram of Winchester and Floyd (1977; Figure 3A), data from the WVA samples plot within the normal range of dacitic compositions, whereas the two deep Otupu andesites / dacites analysed fall within the intermediate andesite range.

A plot of trace element compositions for the Wairakei andesites normalised against the primitive mantle (Figure 3B; Sun and McDonough, 1989) shows that both the WVA and deep Otupu andesites generally fall within the range of other known TVZ andesites (Cole et al., 1983; Browne et al., 1992; Price et al., 1992; Gamble et al., 1999; Price et al., 2010). These are consistent with subduction-derived arc magmas, in that they display a pronounced negative anomaly in high field strength elements Nb and Ta. Some of the WVA andesites appear to be slightly more enriched in Rb, K and Zr than is typically seen in TVZ andesites, although this can probably be attributed to hydrothermal alteration intensity. The Otupu area andesites / dacites are slightly depleted in all trace elements relative to the WVA andesites (Figure 3B).

5. DISCUSSION

With the exception of WK44 (confirmed in this study as an andesite-bearing breccia), all samples of WVA examined appear mineralogically and texturally consistent with extrusive, plagioclase-phyric andesite lava. The deep Wairakei andesites also display mineralogical and textural characteristics somewhat consistent with a porphyritic andesite, although, with the exception of the WK264 andesite, the groundmass is generally dominated by relatively coarse-grained microlites, suggesting instead that these andesites might be intrusive in nature. The occurrence of andesite within the Poihipi Rhyolite (i.e., in WK264) may also support intrusive emplacement of the WK264 andesite, but supporting mineralogical and textural evidence is equivocal.

There is a weak mineralogical distinction between the WVA and the deep andesites, primarily based on the absence of amphibole phenocrysts in the WVA. However, the WVA is also characterised by the presence of coarse, sieve-textured plagioclase megacrysts dominating the overall plagioclase population, and these appear to be absent in the deep Wairakei andesites.

The andesite / dacite in WK317(1) is mineralogically distinct from the WVA and other deep Wairakei andesites in that it contains magmatic quartz phenocrysts.

The geochemical composition of the WVA samples analysed show close correlation, and tightly cluster within the dacite / rhyo-dacite field of Winchester and Floyd (1977) confirming that they have petrogenetic affinity. The two deep Otupu area andesites / dacites analysed are geochemically distinct from the WVA, plotting in the andesite field of Winchester and Floyd (1977).

In comparison with other known TVZ andesites (Cole et al., 1983; Browne et al., 1992; Price et al., 1992; Gamble et al., 1999; Price et al., 2010), and dacites (Graham and Worthington, 1988), the WVA has higher Zr / TiO_2 ratios; whereas, the two Otupu andesites / dacites overlap the Spa Andesite and Tauhara dacite fields. In terms of the immobile element ratios plotted in Figure 3A, both the WVA and deep Otupu andesites are geochemically distinct from the Rolles Peak Andesite, located ~15 km northeast of Taupo.

6. CONCLUSIONS

This study has helped refine the stratigraphic framework in the Western Borefield sector of the Wairakei Geothermal Field.

The Waiora Valley Andesite is shown to be extrusive, plagioclase-phyric lava that extends through much of the Western Borefield. Its extrusive origin implies that emplacement of the WVA post-dates the Whakamaru-group Ignimbrite (<0.34 Ma; Wilson et al., 2009).

The emplacement mechanism for the deep andesites remains unclear, but the occurrence of andesite within Poihipi Rhyolite in WK264 could indicate that some other deep andesites are possibly of intrusive origin.

The deep Wairakei andesites occur at a range of stratigraphic levels within the Tahorakuri Formation and are of variable thickness. Their relationship to the shallow extrusive WVA remains under investigation; however, based on the two Otupu andesites analysed, they appear to be chemically distinct.

The immobile element ratios of the WVA are also distinct from the Tauhara dacite, Spa Andesite, Rolles Peak Andesite and other TVZ andesites; whereas, the deep andesites display similar immobile element ratios to the Spa Andesite and Tauhara dacite.

Mineralogical variation amongst the deep Wairakei andesites is indistinct, with the exception of the quartz-phyric andesite /dacite in WK317(1).

Further geochemistry is necessary from other deep Wairakei andesites, especially those in the Te Mihi area. This will elucidate any chemical variation between the andesites. This geochemical work may include mineral geochemistry. U-Pb dating (in progress) of zircons entrained within the andesites will constrain age relationships among Wairakei-Tauhara magmas.

The presence of at least two separate andesite magma types at Wairakei has important implications in understanding the geological and structural framework of the geothermal field.

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Table 1: Summary data for the andesites encountered in the Wairakei Geothermal Field. Abbreviations: WBF-Western Borefield; WVA-Waiora Valley Andesite; AND-andesite; DAC-dacite; mRL-metres relative to sea level; Dc-drillcore; C-cuttings; Pl-plagioclase; px-pyroxene; opyx-orthopyroxene; cpx-clinopyroxene; op-opaques; qtz-quartz; am-amphibole; Fe-Mg-ferromagnesian minerals (not identified due to hydrothermal alteration); Chl-chlorite; Ill-illite; leuc-leucoxene; act-actinolite; ep-epidote; py-pyrite; czo-clinozoisite; hem-hematite; adul-adularia; cc-calcite; rt-rutile. Numbers in parenthesis next to Well ID are given where more than one andesite unit occurs in a drillhole; numbers from 1 onwards refer to shallowest to deepest andesite units. Refer to Figure 1 for field locations of the wells.

Well ID	Field location	Inferred unit	Top depth (mRL)	Unit thickness (m)	Sample type	Thin Section	XRF	Primary Minerals	Alteration Intensity	Alteration Minerals
WK24	WBF	WVA	-107	99	Dc	•	•	Pl >> px + op	strong	Chl, Ill, leuc, act, ep, py
WK26	WBF	WVA	-100	≥ 31	Dc	•	•	Pl >> px + op	strong	Chl, Ill, leuc, act, cc, epi, czo, qtz, py
WK26B	WBF	WVA	-100	31						
WK29	WBF	WVA	-99	107	Dc	•	•	Pl >> px + op	intense	Chl, Ill, leuc, hem, act, qtz, epi, py
WK30	WBF	WVA	-154	≥ 30						
WK44	WBF	WVA	-170	11	Dc	•	•	Pl >> qtz > pyx + op	strong	Qtz, adul, chl, leuc, py
WK47	WBF	WVA	-128	85	C	•	•	Pl >> px + op	moderate	Chl, leuc, Ill, cc, py
WK48(1)	WBF	WVA	-112	172	Dc/C	•	•	Pl >> px + op	moderate to strong	Chl, Ill, leuc, adul, cc, qtz, act, py
WK50	WBF	WVA	-131	≥ 28						
WK54	WBF	WVA	-164	30	Dc	•	•	Pl >> px + op	moderate to strong	Ill, Chl, cc, act, leuc, hem
WK56	WBF	WVA	-137	≥ 38						
WK57	WBF	WVA	-122	42						
WK70	WBF	WVA	-97	≥ 30						
WK71	WBF	WVA	-117	≥ 105	Dc	•	•	Pl >> px + op	strong	Chl, Ill, adul, leuc, qtz, epi, py
WK76	WBF	WVA	-122	≥ 86	Dc	•	•	Pl >> px + op	strong	Cc, Ill, ep, chl, act, leuc
WK80	WBF	WVA	-133	≥ 136	Dc	•	•	Pl >> px + op	moderate	Chl, Ill, cc, leuc, rt, py
WK116	WBF	WVA	-143	≥ 18						
WK118	WBF	WVA	-143	≥ 23						
WK119	WBF	WVA	-155	≥ 20						
WK121(1)	WBF	WVA	-119	≥ 43						
WK122	WBF	WVA	-132	≥ 43	Dc	•	•	Pl >> px + op	strong	Chl, I-S, leuc, adul ,qtz, cc, act, czo
WK215	NW of WBF	WVA	-172	≥ 61	Dc	•	•	Pl >> px + op	moderate to strong	Chl, cc, Ill, leuc, hem, py
WK217	WBF	WVA	-151	≥ 31	Dc	•	•	Pl >> px + op	strong	Chl, Ill, adul, leuc, qtz, epi
WK219	NW of WBF	WVA	-195	≥ 31	Dc	•	•	Pl >> px + op	strong	Chl, cc, Ill, leuc, hem, py
WK121(2)	WBF	AND	-1368	20	Dc	•		Pl >> px + am	strong	
WK121(3)	WBF	AND	-1562	82						
WK121(4)	WBF	AND	-1741	≥ 92	Dc	•		Pl >> px + amp	moderate to strong	Cc, Ill, chl, qtz, act
WK247	TE MIHI	AND	-1914	135	C	•		Pl >> px + am + qtz?	moderate	Clay, leuc, chl, ep, qtz, adul
WK264	TE MIHI	AND	-872	20	C	•		Pl >>opx + cpx + am + qtz?	moderate	Cc, clay, chl, leuc
WK301(1)	OTUPU	AND/DAC	-1121	140	Dc/C	•		Pl >> Fe-Mg	intense	Qtz, Ill, cc, leuc, py, bt,
WK301(2)	OTUPU	AND	-1306	≥ 330	C	•	•	Pl >> Fe-Mg	intense	Qtz, Ill, cc, leuc, py
WK317(1)	OTUPU	DAC	-1421	305	C	•	•	Pl >> Fe-Mg + qtz	intense	Qtz, chl, bt
WK317(2)	OTUPU	AND	-2206	60						
WK321	OTUPU	AND	-1499	675						