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Geology, Geochronology, Alteration and Geochemistry of the Rotokawa Geothermal System, Taupō Volcanic Zone, New Zealand

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ABSTRACT

A more detailed understanding of the Rotokawa geothermal system, central Taupō Volcanic Zone (New Zealand), has been realised in order to constrain the magmatic, volcanic, structural and hydrothermal evolution of the hottest utilised geothermal system of New Zealand. Geochronology undertaken on buried hydrothermally altered lithologies at Rotokawa has provided constraints on the stratigraphy and volcanic evolution of the region. A 3-km-thick sequence of volcanic products is present at Rotokawa. This sequence is comprised of rhyolitic ignimbrites from large, caldera-forming events at volcanoes outside the field area, and locally sourced andesite and rhyolite lava bodies. The oldest volcanic rock from U-Pb dating of zircon is an ignimbrite, which yields an eruption age estimate of 1.84 ± 0.04 Ma. This ignimbrite, part of the Tahorakuri Formation, is among the oldest silicic volcanic deposits from the Taupō Volcanic Zone and can be linked to comparably-aged counterparts at three other nearby geothermal systems (Ngatamariki, Ohaaki and Kawerau). These ignimbrites onlap a basal andesite lava pile, up to 1.2 km thick, that rests on Mesozoic basement greywacke. Between ~1.8 and 0.7 Ma, there are no eruptives represented at Rotokawa, with the next oldest lithology being a rhyolite lava dated at 0.72 ± 0.09 Ma. At 350 ka, the Rotokawa area was buried by regionally extensive ignimbrites of the Whakamaru Group. Ignimbrites and sediments of the Waiora Formation were then emplaced over a 150 kyr period, coeval with dome-building activity forming the Maroa dome complex to the west, with this same rhyolite buried at the nearby Ngatamariki and Wairakei geothermal systems. Extensive rhyolitic lava bodies of the 90 ± 10 ka Oruahineawe Formation show stratigraphic and petrographic relationships suggesting both extrusive dome and shallow intrusive emplacement. Dominantly lacustrine sedimentary rocks of the Huka Falls Formation and pyroclastic deposits of the 25.4 ± 0.2 ka Oruanui eruption then cap and seal the system. The geothermal system is typical of the high gas and enthalpy New Zealand geothermal systems with a deep chloride water reservoir and an excess steam phase. As a result, the volcanic and sedimentary succession has been variably altered by hydrothermal minerals with alteration to abundant quartz, chlorite and calcite with common but variable amount of adularia, epidote, calcite and illite at depth. Zones of acid alteration characterised by kaolinite occur at shallow depths and can occur up to 1,000 m below the ground surface. Arsenic, Sb, and S abundances increase toward the surface, likely associated with sulfur complexing and deposition upon boiling and cooling.

1. INTRODUCTION

The central segment of the Taupō Volcanic Zone (TVZ:North Island, New Zealand) is one of the world's most vigorously active regions of Quaternary silicic magmatism, with associated volcanism and geothermal activity (Fig. 1). The rifting arc, associated with subduction of the Pacific Plate beneath the Australian Plate (Cole and Lewis, 1981; Seebeck et al., 2014), has an overall magmatic flux and associated geothermal heat flow about an order of magnitude greater than in a typical arc (Wilson and Rowland, 2016, for overview). The central TVZ in areal extent, heat flux (4.2 ± 0.5 GW: Bibby et al., 1995), and volume of rhyolitic magma erupted in the last ~2 Myr, closely parallels the Yellowstone system (Christiansen, 2001; Hurwitz and Lowenstern, 2014). Drilling of geothermal systems for energy has revealed the predominantly silicic rocks have accumulated to >3 km thicknesses over much of the central TVZ in areas down-dropped by caldera collapse and/or rifting.

Rotokawa is the hottest utilised geothermal system in the TVZ (Fig. 1), with a maximum measured temperature of 337 °C (Sewell et al., 2015). The system contains a stratigraphic succession including Mesozoic basement greywacke and documents a transition from earlier andesitic to later rhyolitic volcanism (Browne et al., 1992). The onset of the latter is linked with the development of regional extensional tectonics and caldera development within the central TVZ (Cole, 1990; Wilson et al., 1995; Rowland et al., 2010; Deering et al., 2012) likely around 1.8 Ma (Eastwood et al., 2013; Chambefort et al., 2014).

In geothermal systems drilled for geothermal energy, the correlation and reconstruction of stratigraphy plus the spatial and temporal determination of alteration minerals is vital to unravelling the complex volcanic, structural, and hydrothermal history of the host rocks. This information can then be directly fed into the development of more robust reservoir models to aid management and development of the geothermal resource. Stratigraphic correlation is often challenging due to strong hydrothermal alteration that often destroys the primary textures and mineralogy of the rocks, and often-severe mixing of cuttings during drilling, frequently hindering accurate correlations (Milicich et al., 2013a). U-Pb dating of zircon, which is highly resistant to hydrothermal alteration processes, has proved invaluable at reconstructing field histories and correlating major regional ignimbrite units throughout the central TVZ (Wilson et al., 2008, 2010; Milicich et al., 2013a; Eastwood et al., 2013; Chambefort et al., 2014; Rosenberg, 2017).

Here we present preliminary results from a multidisciplinary study of the Rotokawa geothermal system using zircon U-Pb age estimates from altered subsurface rocks, coupled with stratigraphic correlations, petrography, X-ray diffraction (XRD) and hyperspectral short-wave infrared (SWIR) reflectance spectroscopy analyses, lithogeochemistry, combined in a 3D visualisation.

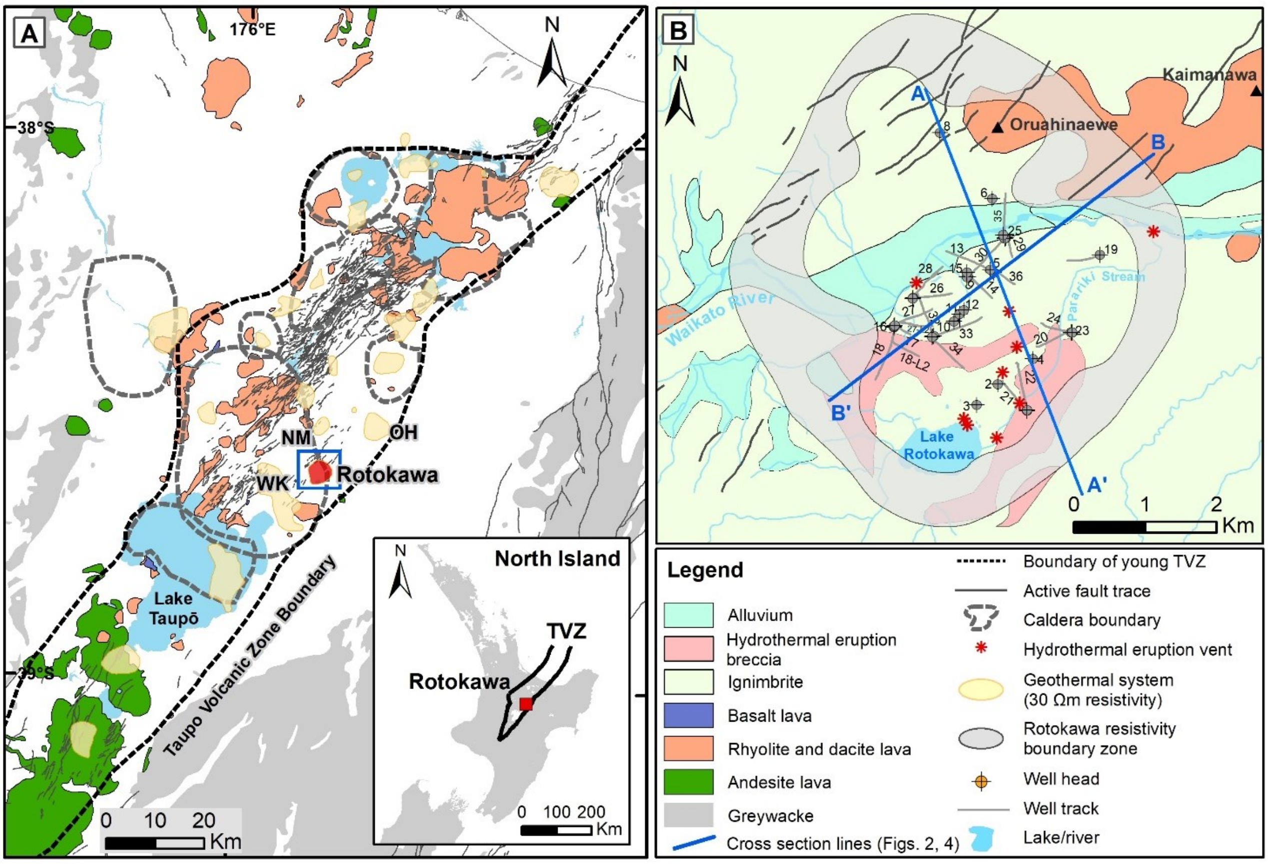

Figure 1: (A) Simplified map of the Taupō Volcanic Zone (TVZ) showing the locations of the geothermal systems as defined by anomalously low electrical resistivity (<25 Ωm: Bibby et al., 1995), WK: Wairakei, NM: Ngatamariki, OH, Ohaaki. The boundary of the young (350 ka-present) TVZ and caldera locations are from Wilson et al. (1986, 2009). Active faults are from the GNS active fault database (GNS Science Active Fault Database, 2020). Blue box indicates the extent of (B). (B) Detail of the Rotokawa area, with well heads (prefixed by RK in text), simplified surface geology from Leonard et al. (2010) and the resistivity boundary zone of Risk (2000). Blue lines labelled A-A' and B-B' are for cross sections shown in Figure 2 and 4.

2. ROTOKAWA GEOTHERMAL SYSTEM: METHODS AND KEY RESULTS

The Rotokawa geothermal system is located in the southern part of the central TVZ, about 10 km NE of Lake Taupō (Fig. 1). Drilling and geophysical investigations since the 1960s have identified a large high-temperature (>300 °C) resource of c. 28 km^2, as delineated by the 30 Ωm resistivity contour (Cole and Legmann, 1998; Risk, 2000; Sewell et al., 2015). Numerous surficial thermal manifestations in the Rotokawa geothermal system are mostly concentrated in two areas (Krupp and Seward, 1987; Milicich and Hunt, 2007; Price et al., 2011). In the southern area, the acid–sulfate (pH ~2) Lake Rotokawa occupies a hydrothermal eruption crater (Collar and Browne, 1985; Browne and Lawless, 2001). This area also includes springs in a steam heated altered lagoon on the NE shore of Lake Rotokawa, a fumarole, acid-sulfate-chloride springs along the Parariki Stream, and a silica rich, acid fluid discharge actively depositing sinter on the flood plain of the Parariki Stream (Schinteie et al., 2007). The northern area contains a group of chloride–bicarbonate springs on the banks of the Waikato River, and a small area of steaming ground north of the river near well RK8.

Rotokawa is a gas-rich high-temperature geothermal system (Giggenbach, 1995) with three different aquifers: shallow meteoric groundwater, a complex intermediate aquifer and a chloride geothermal reservoir of >300 °C below 1000 m depth (Winick et al., 2011; Addison et al., 2015). The intermediate aquifer is a mixture of gas-rich steam condensates, groundwater, boiled reservoir fluids, and mixed acid-sulfate - chloride fluids from a shallow, steam-heated aquifer in the vicinity of Lake Rotokawa.

Rotokawa hosts the highest content of H_2S and CO_2 amongst the central TVZ geothermal systems, with estimated H_2S emission of 441 t d^{-1} and up to 31 t d^{-1} of CO_2 (Bloomberg et al., 2014). The high H_2S and CO_2 contents of the reservoir coupled with boiling at shallow levels, create the common acid-sulfate and bicarbonate fluids. The main upflow zone of the field is inferred to be south of the field beneath Lake Rotokawa, with deep reservoir water rising and outflowing towards the north. Dilution by cooler marginal fluids is interpreted to be responsible for the observed chemical gradients (Sewell et al., 2015).

2.1. Surface and subsurface geology

The surface geology of the Rotokawa area to the north, is dominated by Oruahineawe and Kaimanawa rhyolite domes (Fig. 1; Leonard et al., 2010; Anderson, 2011; Downs et al., 2014). To the east, there is the deeply eroded cone of the 0.71 Ma Rolles Peak andesite (Wilson et al.,1995), and to the west there is rhyolite lava exposed at the Aratiatia dam on the Waikato River. Elsewhere, the surface geology is composed of young pyroclastic and sedimentary rocks. The area around Lake Rotokawa is blanketed by hydrothermal eruption breccias and Holocene tephras (Collar and Browne, 1985; Browne and Lawless, 2001). Lake Rotokawa, together with at least twelve other hydrothermal eruption craters, and associated deposits, across the field indicate hydrothermal eruptive activity since emplacement of the 25.4 ka Oruanui ignimbrite (Collar and Browne, 1985; Krupp and Seward, 1987; Browne and Lawless, 2001; Vandergoes et al., 2013).

The stratigraphy subsurface consists of a sequence of volcanic and volcaniclastic units above Torlesse greywacke basement. These units are summarised in Figure 2. As in all of the drilled geothermal systems within the TVZ, correlating individual eruptive and sedimentary units within the sub-surface silicic volcanic sequence at Rotokawa is challenging. For this study, zircons were extracted from eleven drill core samples from different Rotokawa formations for single-crystal zircon U-Pb dating by Secondary Ion Mass Spectrometry (SIMS) on a SHRIMP-RG instrument at the Research School of Earth Sciences (RSES), Australian National University. A summary of the dated samples is presented in Table 1, with the ages used to guide a reconsideration of the geological succession. The revised geological units are presented in Fig. 2.

Table 1: Samples analysed for U-Pb analyses (well locations in Fig. 1). Depths are in metres below the well head (mRF), while depths masl are relative to sea level. The total number of analyses is all those obtained (see Milicich et al. (in press) for full details). *From Eastwood et al. (2013). **Indicative age only from 4 ages with coherent values.

Sample	Well	Depth (mRF)	Depth (masl)	Lithology	Formation	Age	95% cond. interval	Number of analyses	
								total	ages used
RK4-710	RK4	710	-360	Rhyolite	Oruahineawe Formation	91 ka	10 ka	36	19
RK4-1230	RK4	1230	-878	Ignimbrite	Whakamaru Group ignimbrite	333 ka	13 ka	29	25
RK5-754	RK5	754	-431	Rhyolite	Oruahineawe Formation	100 ka	18 ka	17	6
RK5-999	RK5	999	-676	Tuff	Waiora Formation	264 ka	15 ka	28	17
RK5-1204	RK5	1204	-881	Ignimbrite	Whakamaru Group ignimbrite	357 ka	15 ka	30	25
RK5-1409	RK5	1409	-1086	Tuff	Tahorakuri Formation	1.866 Ma	0.027 Ma	52	49
RK6-262	RK6	262	68	Rhyolite	Oruahineawe Formation	81 ka	14 ka	26	9
RK6-1174	RK6	1174	-844	Ignimbrite	Whakamaru Group ignimbrite	362 ka	17 ka	35	33
RK8-860	RK8	860	-427	Tuff	Waiora Formation	258 ka	16 ka	30	13
RK8-1164**	RK8	1164	-730	Rhyolite	Old rhyolite lava	720 ka	90 ka	6	4
RK8-1413	RK8	1413	-979	Tuff	Tahorakuri Formation	1.84 Ma	0.04 Ma	35	35
RK06-01*	RK6	1612	-1275	Tuff	Tahorakuri Formation	1.89 Ma	0.02 Ma	-	-

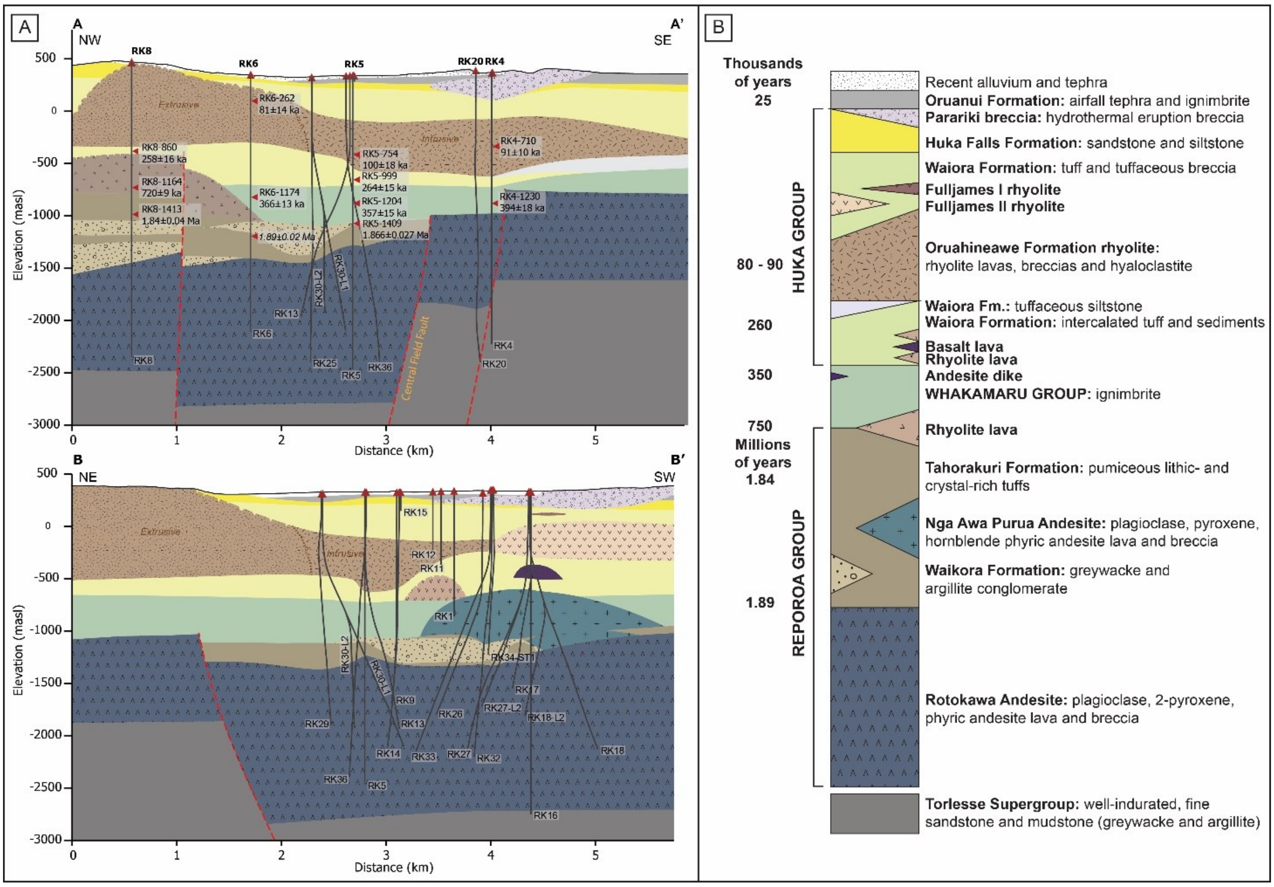

Figure 2: (A) Cross sections of the geological formations of the Rotokawa geothermal system, along lines shown in Figure 1. (B) Summary of revised stratigraphy from this study.

2.2. Hydrothermal alteration

Interaction of the geothermal fluids with the host rocks has resulted in the formation of hydrothermal alteration minerals. Hydrothermally altered samples examined are mainly of rock cuttings and limited core from 15 geothermal wells, from the near surface (≥30 m) to a depth of 3070 m. The mineralogy of 339 rock cutting samples was determined by clay-separate XRD and for 3243 samples by hyperspectral SWIR analyses. Due to spectral overlap, the identification of illite, mixed-layered illite-smectite, and smectite is broadly based on the calculated H_2O/Al-OH depth ratio (Simpson and Rae, 2018). There is excellent agreement between the identification of illite by clay separate XRD and hyperspectral reflectance spectroscopy.

2.2.1. Alteration and associated minerals

Hydrothermal alteration of the host rock at Rotokawa is variable and ranges from weak (<25% of rocks original mineralogy) to moderate (25-75% of rocks original mineralogy) to strong (>75% of rocks original mineralogy). In general, widespread andesite and rhyolite flows are moderately altered. Alteration in the greywacke is less obvious, as the original metamorphic minerals can be the same as those formed via hydrothermal alteration (e.g., chlorite, illite, epidote).

A wide range of hydrothermal alteration minerals have been identified from XRD, SWIR and petrographic analyses. These include quartz, chlorite, pyrite, calcite, illite, smectite and pyrite. Less common are mixed layered illite-smectite, epidote, mordenite, and kaolinite. Rare minerals include anhydrite, actinolite-tremolite, wairakite, buddingtonite (ammonium-feldspar) and alunite. Adularia and albite are important alteration minerals, but because they have primarily been identified from limited petrography (Fig. 3) the spatial distribution of these hydrothermal feldspars is poorly constrained. Figure 4 shows the distribution of selected alteration minerals (chlorite, illite, illite-smectite, calcite, kaolinite) and igneous magnetite; the latter in volcanic rocks is indicative of the degree of alteration (moderate to weak). Figure 5 shows the occurrence and distribution of alteration minerals compared against geology and measured well temperature for well RK19.

Chlorite is a common and widespread alteration mineral (Fig. 4A). It is essentially ubiquitous at depths greater than ~1000 m below the ground surface, but can also occur at shallower depths (≥150 m) in some wells. Smectite is widespread and occurs at shallow levels forming a cap to the system, and can extend to a depth of ~1000 m below surface (Fig. 4A). Associated locally with smectite is minor mordenite. Below the smectite carapace is an extensive zone of illite. The amount of illite replacing the rocks is highly variable, but is typically present in low to trace amounts. Based on XRD data, in some wells, between the smectite and illite zones are narrow intervening intervals of mixed layered illite-smectite that typically extend over a less than 100 m vertical depth (Fig. 4B).. Calcite is a common and widespread alteration mineral and is most abundant and essentially ubiquitous from 700 to 1350 m below surface. In some wells, weaker (trace to minor; <3%) calcite alteration can extend to near surface (e.g., 90 m in RK5), but in other wells (e.g., RK8) calcite is mostly absent at such shallow levels.

Kaolinite is a less common alteration mineral and in the geothermal wells examined can occur near the surface, but also to a depth of 1,000 m in zones individually up to 200 m thick (Figs. 4D, 5). A deep zone of kaolinite (790 to 1010 mRF) is seen in well RK19

(Fig. 5) located towards the eastern margin of the geothermal system and in RK25 (Fig. 4D). Kaolinite also occurs at depth in well RK14 (520 to 650 mRF) in association with rare alunite; calcite alteration occurs above and below this kaolinite-alunite zone. Alunite in the samples studied is rare and spectrally identified infrequently in kaolinite altered rocks.

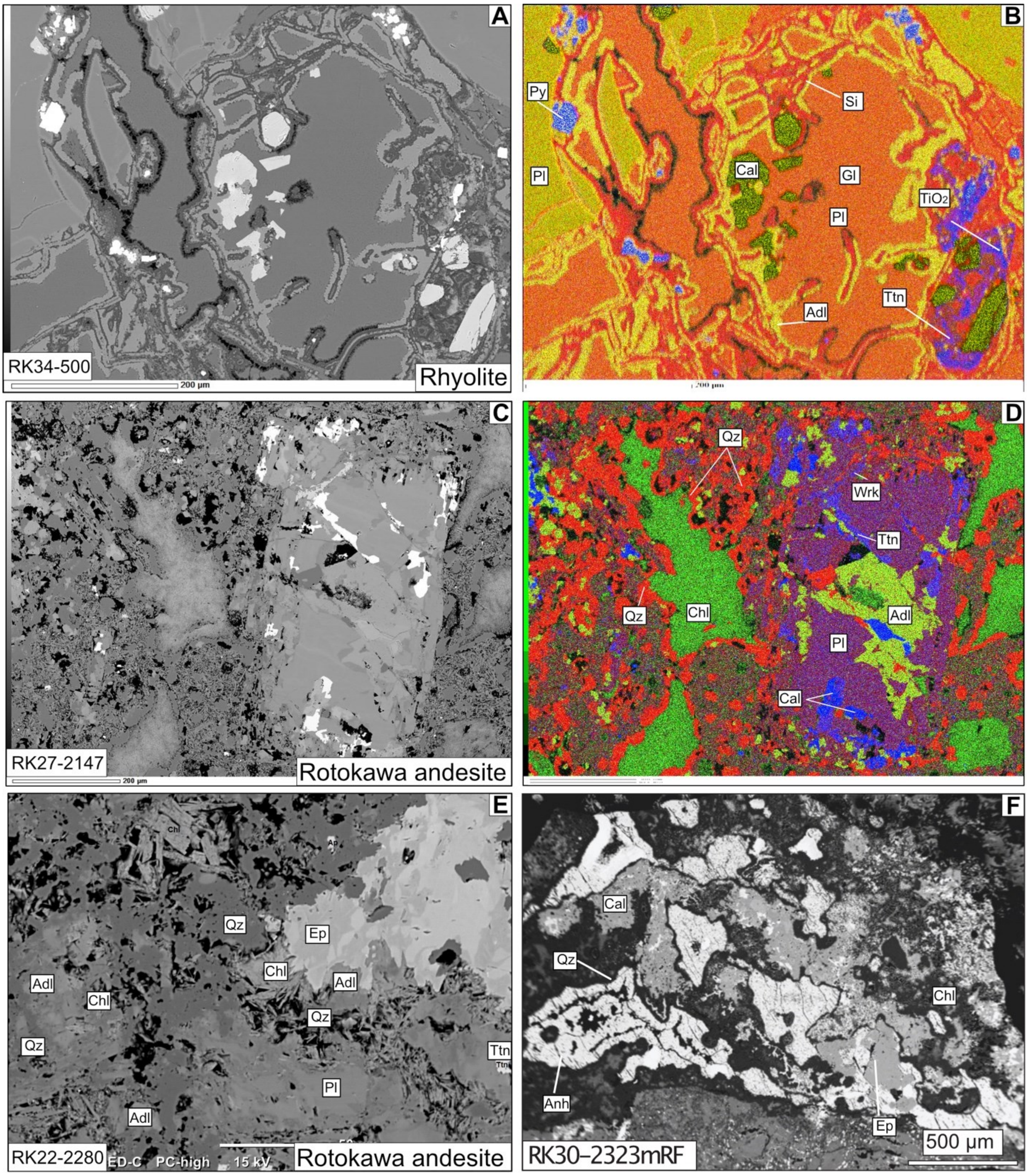

Figure 3: Examples of hydrothermal alteration. Abbreviations: Adl: adularia, Anh: anhydrite, Cal: calcite, Chl: chlorite, Ep: epidote, Gl: glass, Pl: plagioclase, Py: pyrite, Qz: quartz, Si: silica, Ttn: titanite, TiO_2: titanium oxide and Wrk: wairakite. (A, B): BSE-EDS RK34-500 mRF, Oruahineawe Formation rhyolite. Hyaloclastite texture with glass fragments overprinted by hydrothermal alteration, resulting in a partial replacement of the glass by adularia and quartz. (C, D) BSE-EDS RK27-2147 mRF, porphyritic amygdaloidal Rotokawa Andesite. The rock is partially replaced by hydrothermal minerals. Plagioclase is partly altered to adularia and calcite. Vesicles and/or amygdales are filled/replaced by mainly by chlorite and thinly rimmed by quartz. (E) BSE RK22-2280 mRF, quartz, epidote dominant replacement vein texture, overprinting the lava texture. Plagioclase is partially altered to albite, adularia, and the groundmass by chlorite and quartz. (F) BSE RK30-2323 mRF, anhydrite and epidote vein overprinted by calcite and quartz, which are themselves overprinted by illite and chlorite.

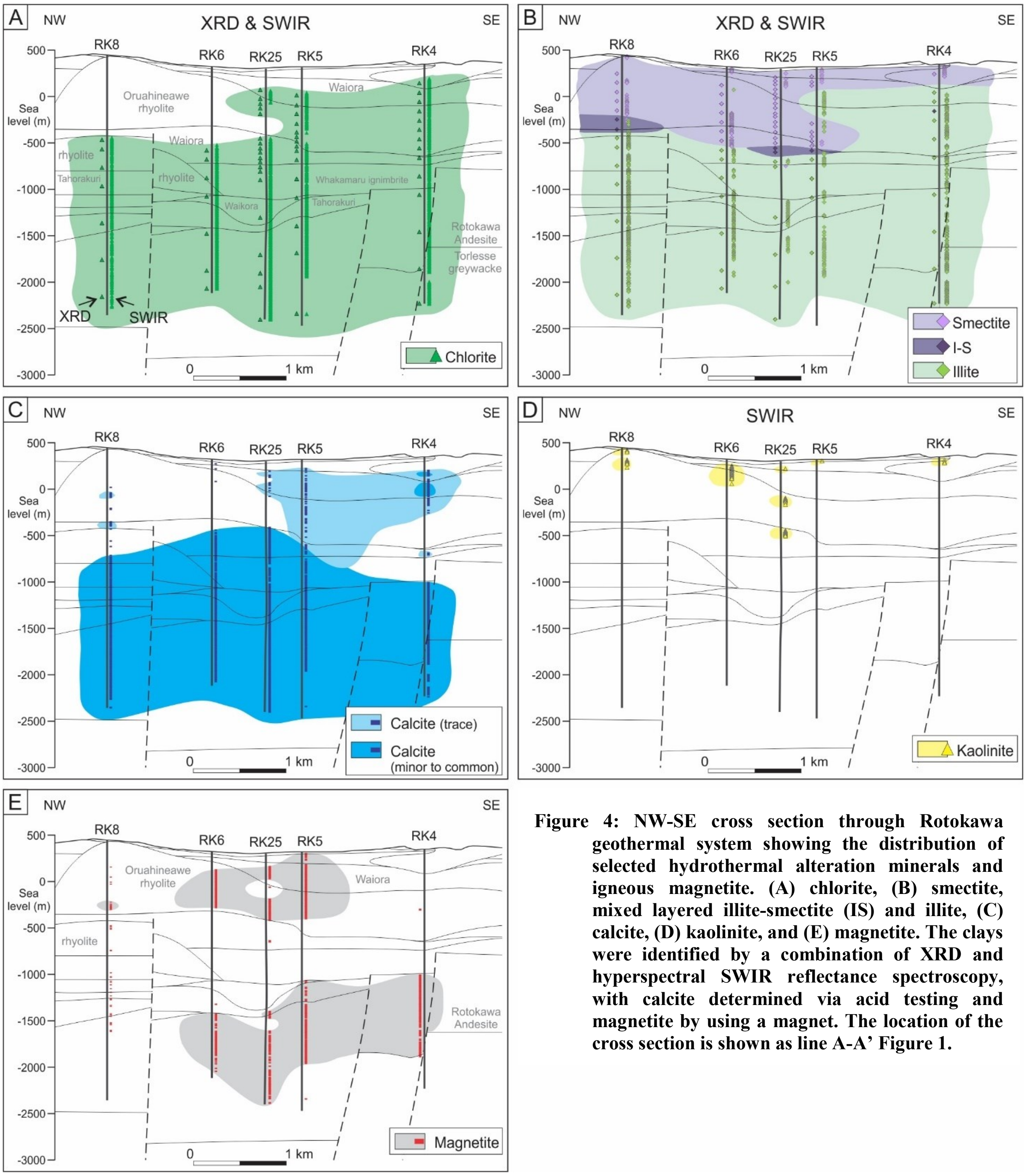

Figure 4: NW-SE cross section through Rotokawa geothermal system showing the distribution of selected hydrothermal alteration minerals and igneous magnetite. (A) chlorite, (B) smectite, mixed layered illite-smectite (IS) and illite, (C) calcite, (D) kaolinite, and (E) magnetite. The clays were identified by a combination of XRD and hyperspectral SWIR reflectance spectroscopy, with calcite determined via acid testing and magnetite by using a magnet. The location of the cross section is shown as line A-A' Figure 1.

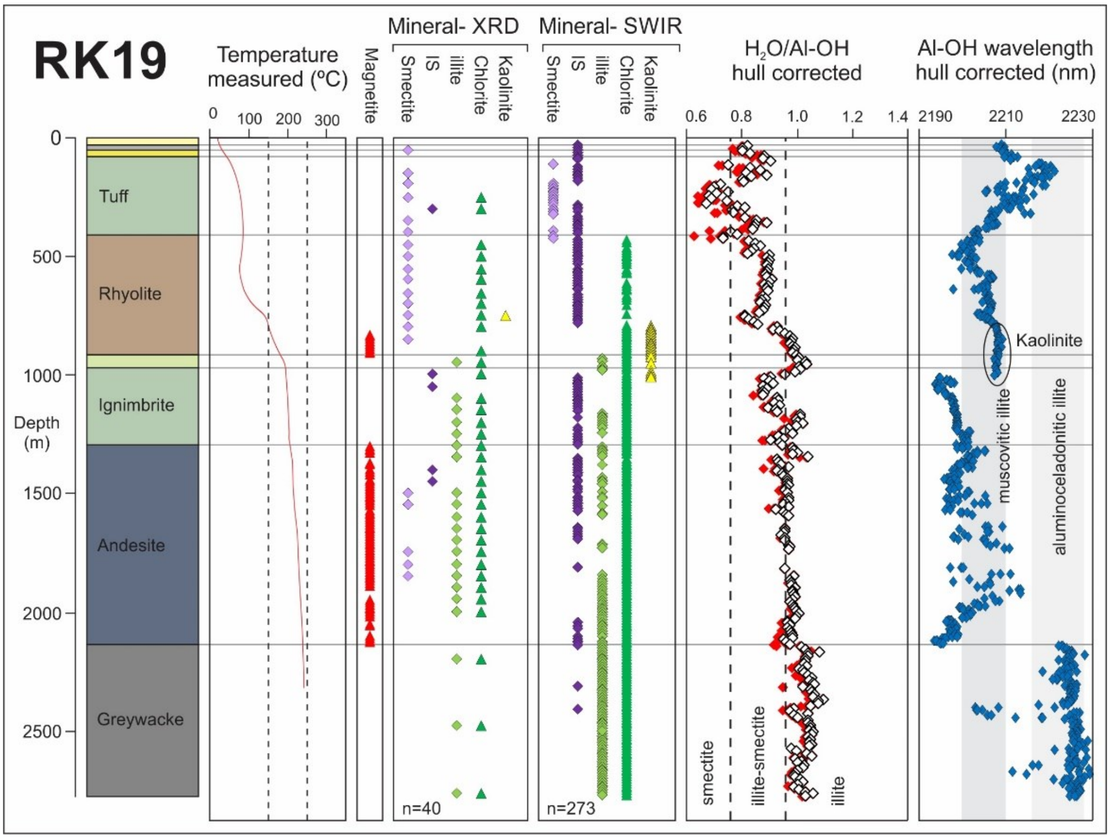

Figure 5: Hyperspectral SWIR mineral identifications and spectral parameter plots compared against stratigraphy, measured well temperature, and clay-separate XRD mineralogy for well RK19, Rotokawa geothermal system. The H_2O/Al-OH show all 3 values for each sample with the highest value highlighted (open diamonds). Temperature data supplied by Mercury NZ Ltd. Due to spectral overlap the distinction of smectite, illite-smectite, and illite is based on the H_2O/Al-OH depth ratio. Spectrally, there appears some illite-smectite in the illite zone, but the former has been mis-identified due to the spectral dominance of other minerals (chlorite ± calcite) that perturb the ratio by contributing H_2O. Despite this complication, the broad zone of illite from SWIR is identical to that identified from XRD. Note the composition of illite in the greywacke is different from that of volcanic rocks.

2.3. Trace metal zoning

Most of the samples from Rotokawa sent for full lithogeochemistry were selected from the zone of maximum upflow of geothermal fluids and elevated temperature anomalies. A few samples were selected from outside the upflow zone on the resistivity boundary of the geothermal system and are associated with cooler temperatures and lower temperature gradients with depth.

Rotokawa rocks show little variation in major element whole rock and pumice composition when compared to the overall range of TVZ volcanic rock composition and other geothermal systems (Deering et al., 2008 and references therein), reflecting the relatively low fluid/rock ratio and the rock-dominated nature of the hydrothermal alteration. Despite the pervasive propylitic alteration of the majority of the samples, no major chemical variation is observed except for gains and losses in Na and K for 10-20% of samples, which likely reflects alkali exchange to form hydrothermal albite or K-feldspar. Compared to rhyolite, andesites at Rotokawa have higher Al_2O_3 and lower SiO_2 contents that vary little as function of alteration. More than 50 trace elements were analysed and include ore metals, alkalis and light elements, such as S, Li, Cs, Au, Ag, Sb and As that are generally enriched in geothermal systems.

Rotokawa samples are less enriched in metals (Au, As, Sb) at depth than other geothermal systems such as Ohaaki (Simmons and Browne, 2000; arsenic in Fig. 6 as an example). As previously observed by Simmons and Browne (2000), rock samples from the active geothermal systems are all enriched in As and Sb towards the surface (Fig. 6), and there is a relatively good positive correlation between Au, As and Sb. No clear correlation exists between S and Au, As and Sb, even though S is enriched in the top kilometre of the system. The subsurface rock samples, even the shallowest, have several orders of magnitude lower abundances of Au, Ag, Hg, Sb, As and Cs than the immediately overlying surface samples from mud pools and sinters (Krupp and Seward, 1987).

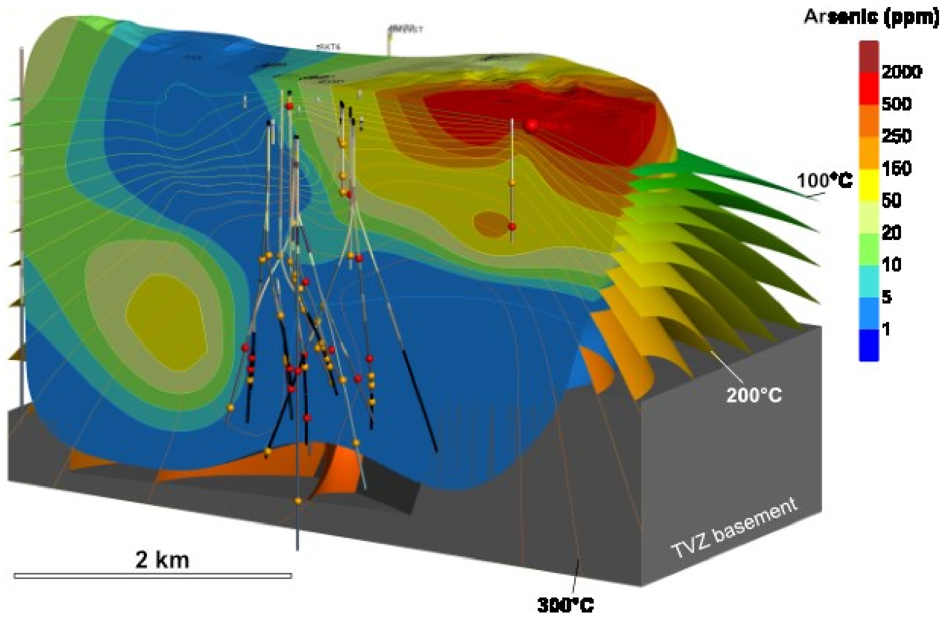

Figure 6: Section through 3D Leapfrog® visualisation (based on linear interpolation) of the arsenic (As in ppm, colour coded) zoning of the Rotokawa geothermal system. The red and orange spheres on the well traces are the locations of the major (red) and minor (orange) feed zones in the wells.

3. DISCUSSION

3.1. Geological history of the Rotokawa area

A review of the dill cuttings from geothermal drilling at Rotokawa, combined with U-Pb dating of key stratigraphic units, provides new constraints on the volcanic and hydrothermal evolution of the Rotokawa area. A comprehensive review of the data is presented in Milicich et al. (in prep), with a selection of the key findings summarised here.

3.1.1. Early Andesites

There are two episodes of andesitic volcanism in the Rotokawa area. The older voluminous Rotokawa Andesite is up to 2 km thick, and present in all wells at Rotokawa, matches in age characteristics (i.e., older than 1.8-1.9 Ma) andesite lavas at Ngatamariki and Ohaaki (Eastwood et al., 2013; Chambefort et al., 2014). The Rotokawa Andesite sits directly on the Mesozoic greywacke basement, which is inferred to have had some topographic relief (hundreds of metres, in particular along the Central Field Fault (Fig. 2), developed prior to or during emplacement of the andesite.

A second period of younger andesitic volcanism is represented by the Nga Awa Purua Andesite that is undated, but was erupted prior to the 350 ka Whakamaru Group ignimbrites. This supports the notion presented elsewhere (Milicich et al., 2013b: Kawerau; Chambefort et al., 2014: Ngatamariki, Sanders et al., 2013: Wairakei) that andesitic and rhyolitic volcanism occurred concurrently in the central TVZ throughout its history.

3.1.2. Tahorakuri Formation

Rocks of the Tahorakuri Formation represent the oldest silicic deposits in the TVZ, and at Rotokawa show less textural and lithological diversity than their equivalents nearby at Ngatamariki (Chambefort et al., 2014). They are also thinner (50-300 m thick) relative to the 0.8-1.7 km thickness at Ngatamariki (Chambefort et al., 2014), >700 m at Wairakei (Rosenberg et al., in prep.) and >1000 m at Waiotapu (Wilson et al., 2010). These differences cannot simply reflect thinning of Tahorakuri Formation deposits over a high-standing edifice of Rotokawa Andesite, as the available ages of the earliest post-andesite pyroclastic deposits are the same within error at Ngatamariki and Rotokawa (Eastwood et al., 2013; Chambefort et al., 2014). We suggest that the Ngatamariki geothermal system was at that time located in a graben structure relative to the Rotokawa area.

The volcaniclastic sequence at Rotokawa is condensed with respect to Ngatamariki, with the youngest Tahorakuri Formation rocks dated 1.87 ± 0.03 and 1.84 ± 0.04 Ma sitting directly beneath the Whakamaru Group ignimbrite. Only the rhyolite lava (dated here at 720 ± 90 ka) and the undated Nga Awa Purua Andesite formed high-standing features around which the Whakamaru Group ignimbrite accumulated, but did not bury. In contrast, the silicic deposits at Ngatamariki include at least 800 m thickness of rocks with ages from 0.7 Ma to 0.9 Ma (Chambefort et al., 2014). These data suggest that the Rotokawa area was likely higher ground prior to eruption of the Whakamaru Group, and subsequently subsided.

3.1.3. Whakamaru Group

After an eruptive hiatus of at least 350 kyr, the Rotokawa area was engulfed by ignimbrite units of the Whakamaru Group. These ignimbrites collectively are extensive, absent only where the 720 ± 90 ka rhyolite and Nga Awa Purua Andesite represented local topographic high features around which the ignimbrite was deposited (Fig. 2). The surface of the Whakamaru Group ignimbrite shows little evidence for subsequent faulting. The Whakamaru Group at nearby geothermal fields (Ngatamariki, Ohaaki, Mokai) is comparable in thickness to that found at Rotokawa (50 to 400 m), but the top is at deeper levels at Rotokawa, Ohaaki and Mokai (approx. -600 masl) than at Ngatamariki (-300 masl; Chambefort et al., 2014). The ignimbrite thins to <100 m thickness to the north at Waiotapu and is at shallow depths (>200 masl; Wilson et al., 2010). To the southwest of Rotokawa, there is a marked contrast, with the Whakamaru Group in the Wairakei geothermal system being up to ~1 km thick and intensively block-faulted (Rosenberg et al., 2009; Rosenberg, 2017). The overall variations in thickness of the Whakamaru Group ignimbrite and lack of syn-eruptive faulting at Rotokawa suggest that the boundary of the Whakamaru caldera as originally mapped in Wilson et al. (1986) is inaccurate and that the boundary of caldera collapse lies between Rotokawa and Wairakei. Such a structural feature, orientated roughly north-south would help explain the independent behaviour of fluid flow patterns between the Wairakei and Rotokawa fields (O'Sullivan et al., 2009).

3.1.4. Huka Group

Within rocks considered together as the Huka Group, there are a number of complexities. At Rotokawa the Huka Group is comprised of the earlier Waiora Formation and the later Huka Falls Formation. The Waiora Formation at Rotokawa is fine-grained suggesting that Rotokawa is farther from the source of the Waiora pyroclastic material that is so dominant at Wairakei (Rosenberg, 2017), with lacustrine conditions locally persisting through much of the depositional interval. We infer that the resulting lacustrine record at Rotokawa was overprinted by an influx of volcaniclastic material from these areas. Rhyolite domes and basalt lava, inferred to be of similar age, are also present within the Waiora Formation at Rotokawa which, as at Ngatamariki, have now subsided to ~ -500 mrsl at Rotokawa and ~0 msrl at Ngatamariki.

The lacustrine-dominated Huka Falls Formation is less well developed at Rotokawa than at Wairakei or Ngatamariki. Overall, we suggest that the contrast between the Waiora and Huka Falls formations be regarded as a broad lithological distinction with a change upwards from volcaniclastic-dominated to lacustrine-dominated deposition, respectively, and that the contact between them is not isochronous within the areas encompassed by those geothermal systems.

The extensive Oruahineawe Formation rhyolite has coherent ages and petrographic characteristics that link them to the subaerial dome of Oruahineawe. However, the shallow subsurface rhyolite shows contact textures that are anomalous for a subaerial lava (cf., Richnow, 1999), with intervals of hyaloclastite, autobreccia and perlitic textures, along with flow banding and spherulites that collectively indicate that the top surface is intrusive. The elevation differences between the subaerial dome and subsurface materials is at least 300 m (Fig. 2) and there is demonstrably no evidence for pre-existing topographic relief or fault displacement of this magnitude between the two rhyolite bodies.

3.2. Hydrothermal alteration

The intensity of hydrothermal alteration of host rocks at the Rotokawa geothermal system is highly variable: it ranges from weak to strong with significant intervals of andesite and some rhyolite lava flows often only moderately altered. The rocks are altered by a diversity of hydrothermal alteration minerals dominated by quartz, chlorite, calcite and widespread, but volumetrically minor illite.

Many of the minerals, including quartz, chlorite, calcite, illite, pyrite, adularia, albite and epidote, are inferred to have formed from near-neutral chloride waters. Marginal smectite with local mordenite have formed from chloride waters mixed with groundwater. By contrast, kaolinite with rare alunite has formed from steam-heated acid-sulfate waters formed by the condensation of H_2S into groundwater. Deep kaolinite with minor alunite in the central part of the field is considered to have formed from acidic condensates in a localised rock-controlled steam zone within the Oruahineawe rhyolite below its brecciated carapace.

3.2.1. Temperatures- mineral inferred and measured

Previous studies of alteration minerals in geothermal fields have determined that certain hydrothermal minerals correlate with measured temperatures (Browne, 1978). Temperature-sensitive minerals at Rotokawa include smectite (<130 °C), mixed-layered illite-smectite (130 °C to 230 °C), and illite (>230 °C), in addition to mordenite (<150 ºC), epidote (>240 ºC), and actinolite (>300 ºC) (Steiner, 1968; Browne and Ellis, 1970; Reyes, 1990). In general, there is broad overlap between the temperatures inferred from hydrothermal minerals and those measured from geothermal wells. For example, in RK6 smectite, which is inferred to have formed at <150 ºC, coincides in occurrence with measured temperatures of ~100 to 150 ºC, and illite at depth inferred to have formed at >230 ºC coincides with measured temperatures of 230 to 320 ºC. In RK19 illite is present below 950 m depth, however the corresponding measured temperature is only ~195 ºC and temperatures of ≥230 ºC are reached at a greater depth of 1900 m (Fig. 5). This well is located towards the eastern margin of the field and the difference between inferred and measured temperatures could suggest that there has been cooling in this area since the illite formed.

3.2.2. Elemental zoning

Similar to observations by Simmons and Browne (2000) for Ohaaki geothermal system, As, Sb and Au, in addition to Li and Cs abundances increase toward the surface. Surface samples from mud pools and sinters are the most enriched in precious metals and we conclude that these metals are largely transported directly to the surface with less deposition at reservoir depths. Because mud pools and sinters are largely chemical precipitates that result from extreme fluid changes such as boiling, cooling and mixing, these are not readily comparable to the deeper rock samples that largely reflect fluid-rock reactions.

3.3. Evolution of the Rotokawa geothermal system

Similarly to what has been observed in nearby Ngatamariki and Wairakei geothermal areas (Chambefort et al., 2014; Rosenberg et al. in press), rhyolite lavas provide evidence of local magmatism at between 700 and 750 ka, around 250 ka and at Rotokawa around 90 ka. These episodes of magmatism provide evidence of potential heat sources prior to the onset of the modern hydrothermal systems. The eruption of the Oruahineawe subaerial and intrusive rhyolites around 90 ka is the first evidence for a substantive magma system (i.e., large enough to generate several cubic kilometres of crystal-poor rhyolite) underlying the Rotokawa area.

Unlike at Ngatamariki and Kawerau (Milicich et al., 2018; Chambefort et al., 2014, 2017), we do not see any evidence of thermal overprint linked to previous magmatic events. The date of onset of hydrothermal alteration is very poorly constrained at Rotokawa. Hydrothermal eruptions breccia that make up the Parariki breccia, emplaced since the 25.4 ka Oruanui ignimbrite provide limited constraint on the timing of the modern system (Collar and Browne, 1985; Krupp and Seward, 1987; Vandergoes et al., 2013). Breccias from the largest hydrothermal eruption (6,060 ± 60 years ago, uncalibrated Libby ^{14}C age), inferred to have originated from the Lake Rotokawa area, cover an area of ~12 km^2 with a maximum thickness of ~11 m (Collar and Browne, 1985; Browne and Lawless, 2001). This age estimate is interestingly coincident within error to the age of onset of the subgroup 2 sequence of rhyolitic eruptions from Lake Taupo, following a >3 kyr period of quiescence (Wilson, 1993, Barker et al., 2015).

4. SUMMARY

A multidisciplinary study of the Rotokawa geothermal system using zircon U-Pb age determinations, stratigraphic correlation, petrography, XRD, hyperspectral analyses, lithogeochemistry and 3D modelling has been used to reconstruct the geological history of the Rotokawa area and investigate the overprinting of the hydrothermal activity on the host rocks.

A thick sequence of silicic volcanic products is present at Rotokawa and includes ignimbrites of the Tahorakuri Formation that are among the oldest silicic volcanic deposits from the TVZ. These ignimbrites overly an andesite unit which extends at least to the nearby Ngatamariki geothermal system. Locally erupted rhyolite lava units provide evidence of periods where magmatic activity could provide a local heat source for hydrothermal activity, the earliest of these being present between 700 and 750 ka.

Following burial of the area at 350 ka by ignimbrite of the Whakamaru Group, ignimbrites and sediments of the Waiora Formation were deposited over a 150 kyr period, coeval with dome-building activity still represented at the surface in the Maroa dome complex west of Rotokawa, but buried at the nearby Ngatamariki and Wairakei geothermal systems. Extensive rhyolitic lava bodies of the 90±10 ka (combined age of 3 samples; Table 1) from Oruahineawe Formation show stratigraphic and petrographic relationships suggesting both extrusive dome and shallow intrusive emplacement. Dominantly lacustrine sediments of the Huka Falls Formation and pyroclastic deposits of the 25.4 ± 0.2 ka Oruanui eruption then cap and seal the system.

The Rotokawa geothermal system is characteristic of the high gas and enthalpy central North Island geothermal systems with a deep chloride water reservoir and an excess steam phase. As a result, the volcanic succession has been variably hydrothermally altered, with the geothermal reservoir coinciding with quartz, chlorite, and calcite, together with variable amounts illite, adularia, and epidote. Zones of acid alteration characterised by kaolinite occur at surface and locally at depths of up to 1000 m below surface. Arsenic, Sb, and S contents increase toward the surface, likely associated with sulfur complexing and deposition upon boiling, cooling and/or mixing.

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