GEOLOGICAL EVOLUTION OF THE ROTOKAWA GEOTHERMAL SYSTEM, NEW ZEALAND

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ABSTRACT

New data from the Rotokawa geothermal system (central Taupō Volcanic Zone), has constrained the magmatic, structural and hydrothermal evolution of the hottest utilised geothermal system in New Zealand. U-Pb zircon geochronology data on buried lithologies at Rotokawa provide constraints on the 3-km-thick sequence of volcanic products. The oldest volcanic rock dated is a Tahorakuri Formation ignimbrite, with an eruption age estimate of 1.84 ± 0.04 Ma. This and other old ignimbrites onlap the Rotokawa Andesite lava pile, up to 1.2 km thick, that rests on Mesozoic basement greywacke. Between ~1.8 and 0.7 Ma, there is a magmatic hiatus, with the next oldest being a rhyolite lava dated at 720 ± 90 Ma. At 350 ka, the area was buried by ignimbrites of the Whakamaru Group. Ignimbrites and sediments of the Waiora Formation were then emplaced over a 150 kyr period. Extensive rhyolitic lava bodies of the 90 ± 10 ka Oruahineawe Formation show evidence suggesting both extrusive dome and shallow intrusive emplacement. Mostly lacustrine sediments of the Huka Falls Formation and pyroclastic deposits of the 25.4 ka Oruanui eruption then cap the system. Rotokawa is typical of high gas and high 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, to abundant quartz, chlorite and calcite, with common but variable adularia, epidote, calcite and illite at depth.

1. INTRODUCTION

The central Taupō Volcanic Zone (TVZ: New Zealand; Fig. 1) is one of the world's most active regions of Quaternary silicic magmatism, with associated volcanism and geothermal activity. The rifting arc 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 that 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, with a maximum measured temperature of 337 °C (Sewell et al., 2015). The system's stratigraphic succession is characterised by the Mesozoic greywacke basement overlain by a magmatic sequence transitioning from earlier andesitic to later rhyolitic volcanism (Browne et al., 1992). The onset of the latter is linked with regional extensional tectonics and

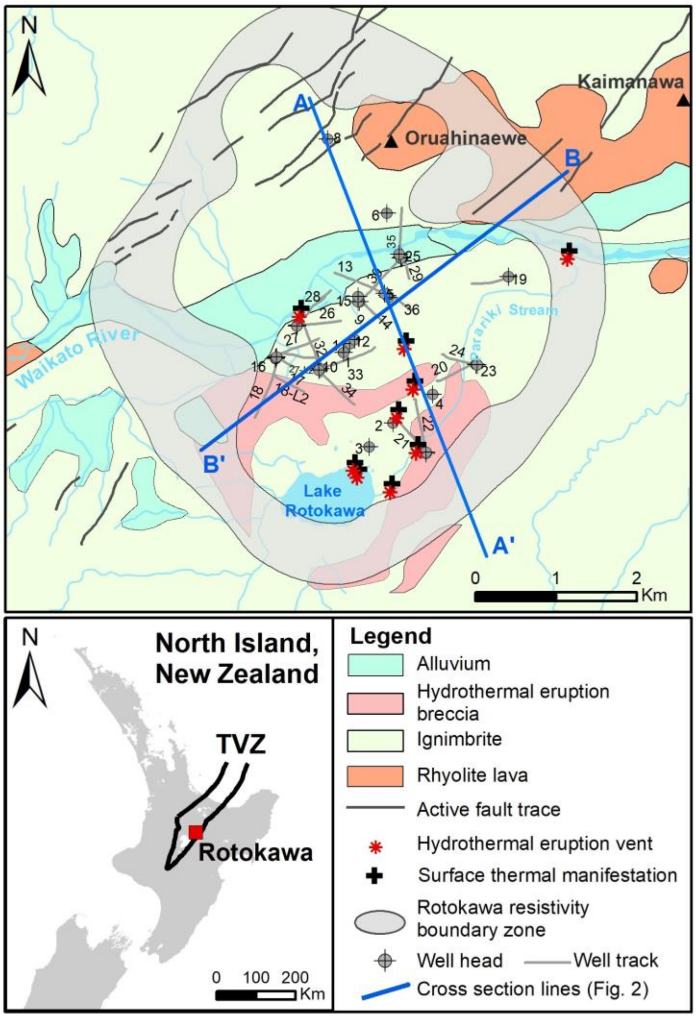

Figure 1: Detail of the Rotokawa area, with well heads (prefixed by RK in text), simplified surface geology (Leonard et al., 2010), resistivity boundary zone (Risk, 2000), and active faults (GNS Science Active Fault Database, 2020). Blue lines labelled A-A' and B-B' are for cross sections in Figure 2.

caldera formation within the central TVZ (Cole, 1990; Wilson et al., 1995; Rowland et al., 2010; Deering et al., 2011), 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 with 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 is 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).

2. ROTOKAWA GEOTHERMAL SYSTEM: LOCATION, CHARACTERISTICS 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 (Fig. 1: 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., 2009; 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 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 (Sewell et al., 2015). 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 712 ± 27 ka Ma Rolles Peak andesite (Tanaka et al.,1996), 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 on a SHRIMP-RG instrument at the Research School of Earth Sciences, Australian National University. A comprehensive data set is presented in Milicich et al. (2019), with a summary of the dated samples and revised geological units presented in Table 1 and Figure 2.

3. DISCUSSION

3.1. Geological history of the Rotokawa area

A review of the drill 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.

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, present in all wells at Rotokawa, and matches in age characteristics (i.e., older than 1.8-1.9 Ma) the 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.

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., 2019, 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	-	-

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, 2017) and >1000 m at Waiotapu (Wilson et al., 2010). Based on these differences in thickness, and the ages of the earliest post-andesite pyroclastic deposits being the same within error at Ngatamariki and Rotokawa (Eastwood et al., 2013; Chambefort et al., 2014), we infer these differences cannot simply reflect thinning of Tahorakuri Formation deposits over a high-standing edifice of Rotokawa Andesite. 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. In contrast, the silicic deposits at Ngatamariki include at least 800 m thickness of rocks with ages from 700 to 900 ka (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 may lie 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 masl at Rotokawa and ~0 masl at Ngatamariki.

The lacustrine-dominated Huka Falls Formation is less well developed at Rotokawa than at Wairakei or Ngatamariki.

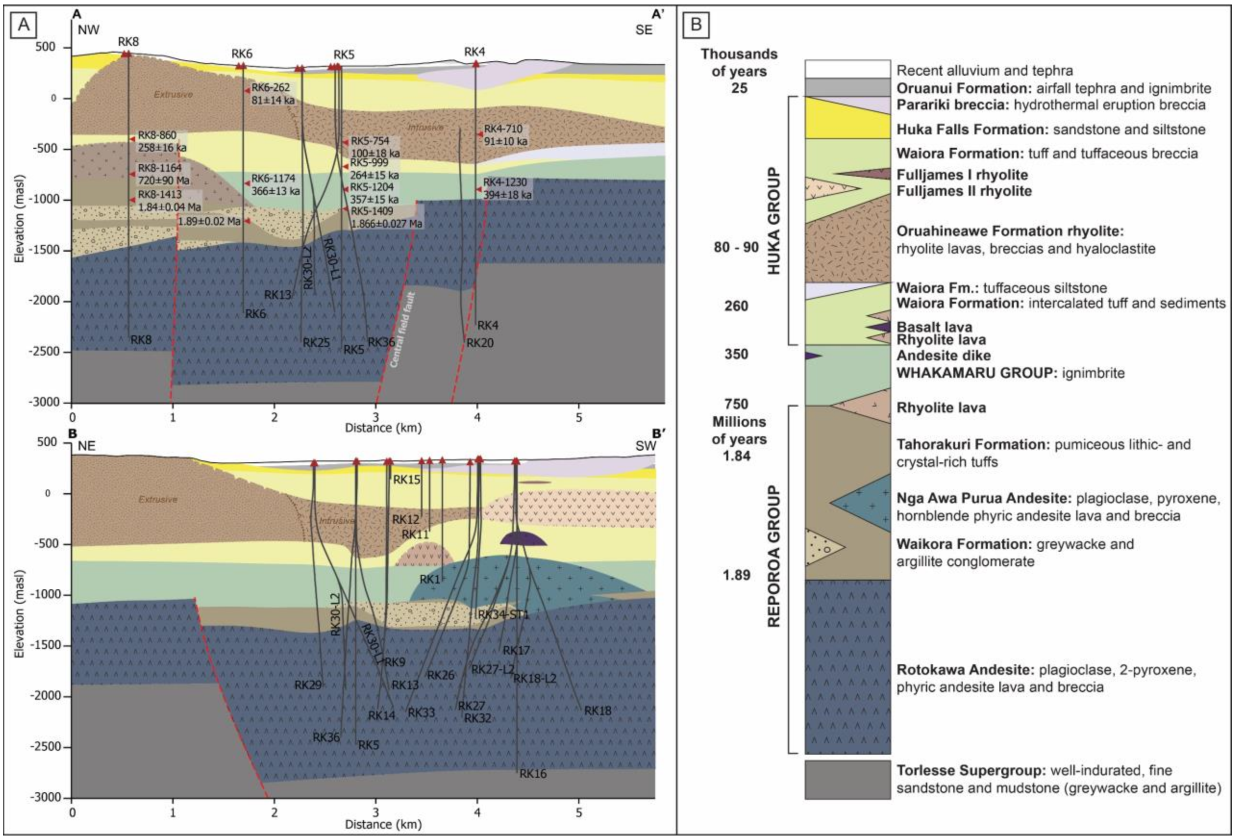

Figure 2: (A) Cross sections of the geological formations of the Rotokawa geothermal system, along lines shown in Figure 1. (B) Summary of the chronostratigraphy derived from this study.

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 it 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 (Fig. 3). 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.

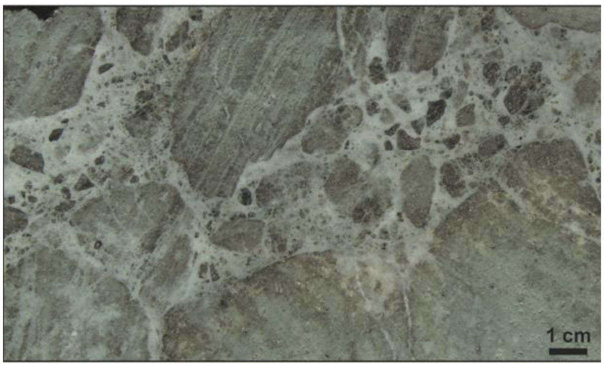

Figure 3: RK34; -150 masl. Autobrecciated interval of Oruahineawe Formation rhyolite.

3.2. Evolution of the Rotokawa geothermal system

Similar to nearby Ngatamariki and Wairakei geothermal areas (Chambefort et al., 2014; Rosenberg, 2017), rhyolite lavas provide evidence of local magmatism at Rotokawa at 700-750 ka, ~ 250 ka and ~ 90 ka. These magmatic episodes 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 itself.

Unlike at Ngatamariki and Kawerau (Milicich et al., 2018; Chambefort et al., 2014, 2017), we do not see evidence of thermal overprint from previous magmatic events. The onset of hydrothermal alteration is poorly constrained at Rotokawa. Hydrothermal eruption breccias (the Parariki breccia), emplaced since the 25.4 ka Oruanui ignimbrite provide limited constraints on the timing of the modern system (Collar and Browne, 1985; Krupp and Seward, 1987). 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 identical within error to the age of onset of a sequence of rhyolitic eruptions from Lake Taupo, following >3 kyr of dormancy (subgroup 2 rhyolites: Barker et al., 2015).

4. SUMMARY

A study of the Rotokawa geothermal system using zircon U-Pb age determinations, stratigraphy, petrography, and 3D modelling has been used to reconstruct the geological history of the Rotokawa area.

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 in the TVZ. These ignimbrites overlie an andesite unit which extends at least to the nearby Ngatamariki geothermal system. Locally erupted rhyolite lavas 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) from the Oruahineawe Formation show stratigraphic and petrographic relationships implying 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 high enthalpy geothermal systems of the central North Island with a deep chloride water reservoir and an excess steam phase.

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