WHANGAIROROHEA THERMAL AREA AND THE DEMISE OF A HIGH TEMPERATURE TVZ GEOTHERMAL SYSTEM

A.J. RAE[1], J. BARRETTO[2], L. CARSON[1]

[1] GNS Science, Private Bag 2000, Taupo 3352, New Zealand

[2]GNS Science, PO Box 30-368, Lower Hutt 5040, New Zealand

a.rae@gns.cri.nz

Keywords: *Whangairorohea, Te Kopia, Paeroa Fault, fossil sinter, extinct geothermal*

ABSTRACT

Whangairorohea, Taupo Volcanic Zone (TVZ), New Zealand, occurs on the Waikato River approximately 7 km directly west of Ohaaki and 5.5 km east-northeast of Ngatamariki geothermal fields. Several warm seeps occur along a 1.2 km stretch of the northern bank of the river. There are also extinct silica sinters and silicified surface deposits, as well as a few small circular warm and cold pools (20-50 m diameter). These surface features are evidence that the area once hosted a high temperature (>210°C) geothermal reservoir, with vigorous surface activity, that has since waned. The area is situated on the southern Paeroa block, an asymmetric horst feature that has been displaced by the Paeroa Fault, the most active fault in the TVZ and one that defines the eastern edge of the Taupo Fault Belt. Recently published geological mapping in the area north of Whangairorohea shows additional sinter and hydrothermal eruption deposits that demonstrate geothermal activity was once more widespread (an area approximately 10 x 5 km). Aeromagnetic data suggests a subsurface, shallow rhyolite body has been locally demagnetised by hydrothermal alteration. This work proposes that Whangairorohea geothermal area was once part of a high temperature geothermal reservoir with vigorous and widespread surface manifestations. Its demise resulted from vertical displacement of the Paeroa block, which affected reservoir fluid pathways and deepened aquifers, and demonstrates how high temperature TVZ geothermal systems are prone to irreversible change from active faulting.

1. INTRODUCTION

Whangairorohea, Taupo Volcanic Zone (TVZ), New Zealand, is an area of weak geothermal activity adjacent to the Waikato River where a few warm springs and seeps occur along an approximately 600 m stretch of the northern riverbank. The area is centrally located between several nearby geothermal fields (Figure 1): approximately 4 km west of Ohaaki; 5 km east of Ngatamariki; 10 km southwest of Reporoa; 10 km east-southeast of Orakeikorako; 11 km southeast of Te Kopia.

The few geothermal surface features at Whangairorohea (Figure 1) have been described previously by Youngman (1996). These include thermal springs and seeps along the Waikato River and a warm pond (Whangairorohea Pool) about 500 m from the northern riverbank. In addition to these thermal features, fossil geothermal manifestations in areas with no currently active features have been identified. These include silicified pumice tuff and silica sinters.

The geothermal activity at Whangairorohea represents an anomaly with respect to the other TVZ geothermal systems, as the basis for its existence is not understood. It is possible it represents a separate, independent geothermal system with surface manifestations that are either distal emanations of a deep and otherwise blind high temperature geothermal system, or more proximal emanations from an unrecognised shallow low temperature geothermal system. Alternatively, the Whangairorohea geothermal area might be a distal part of one of the neighbouring known high temperature geothermal systems, such as Ohaaki or Ngatamariki. Youngman (1996) discusses these possibilities and proposes that the parallel alignment of active and fossil geothermal features with regional NE-SW structural trends suggests that the Whangairorohea geothermal system represents a separate geothermal field, located on the margins of the Reporoa caldera.

This paper revisits the anomalous existence of the Whangairorohea geothermal area by summarising the descriptions of Youngman (1996) and reviewing the local surface geology in light of recent field mapping (Downs, 2014; Downs et al., 2020). Aeromagnetic signatures that might be attributed to past geothermal activity are described and integrated with the new geological insights. It reconsiders whether the geothermal activity at Whangairorohea is an extension of one of the neighbouring geothermal systems, or a separate system altogether.

2. GEOLOGY OF THE PAEROA BLOCK

The Paeroa block is a tilted horst that forms the main topographic divide between the western Taupo Fault Belt and the eastern Taupo Reporoa Basin. The horst is tilted eastwards, but with vertical displacement along its western-side where the Paeroa Fault defines the eastern margin of the Taupo Fault Belt. The fault strikes northeast (040-050°) for some 30 km, from the Waikato River in the south to the Okataina Volcanic Centre in the north (Villamor and Berryman 2001). It is a purely normal fault, with a west-facing scarp and an elevated footwall forming the Paeroa Range, reaching approximately 500 m above the valley floor (Berryman et al., 2008). Both eastwards and southwards, the topography of the Paeroa Range slopes down to the Reporoa Basin and the Waikato River, respectively, with an approximately 400 m elevation difference between the Paeroa Range ridge and the Waikato River at Whangairorohea (Figure 1). From paleoseismological studies of the northern Paeroa Fault splays (Berryman et al 2008), the central portion of the Paeroa Fault has an estimated displacement rate 1.5 ± 0.2 mm/yr. The block is transected by two east-west-striking fault zones, the southerly one separating the geology into northern and southern blocks (Downs et al., 2014a) (Figure 1).

ISSN 2703-4275

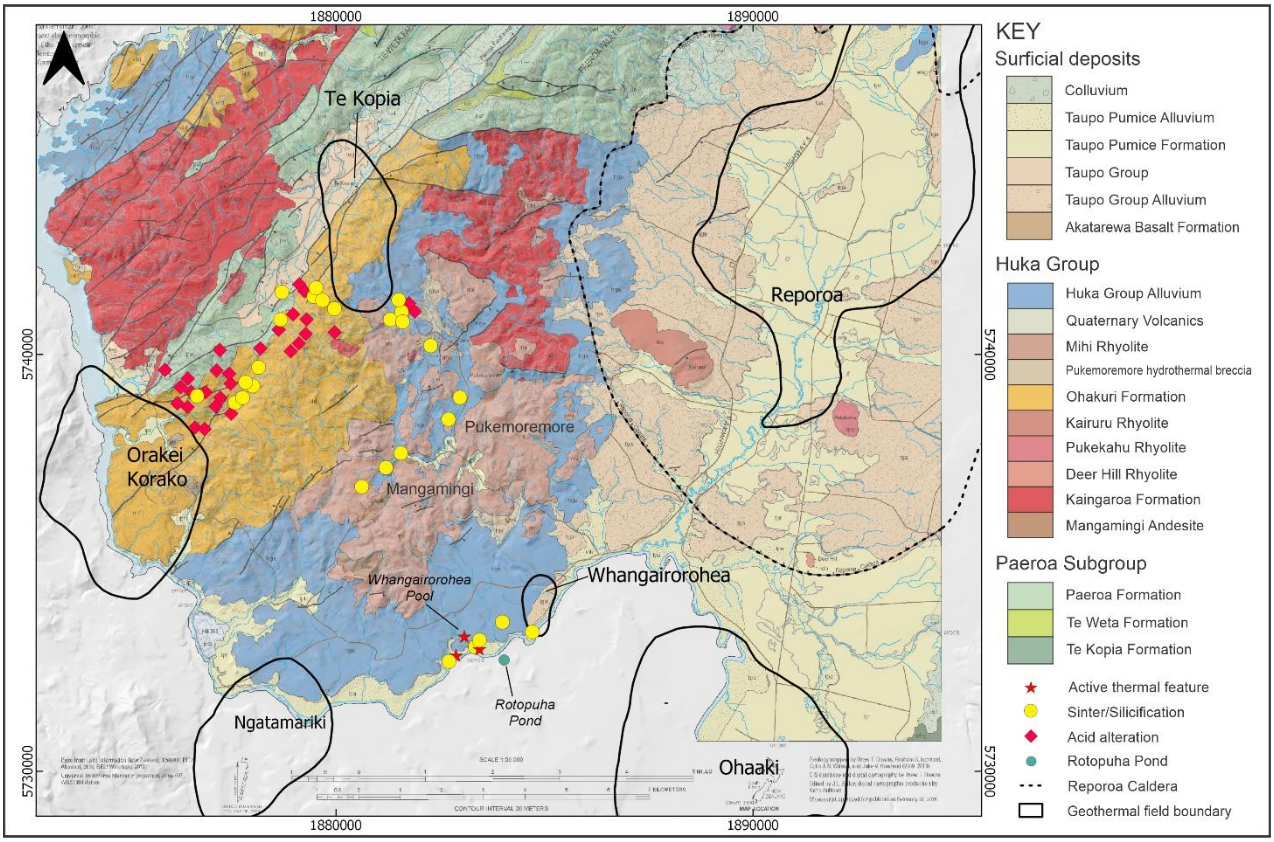

Figure 1. Geological map of the southern Paeroa block, from Downs et al (2020), showing the neighbouring geothermal fields (defined by the 30 Ωm DC resistivity contour from Stagpoole and Bibby, 1998). Also highlighted are the thermal springs/seeps of Whangairorohea, and locations of known extinct geothermal surface features in the form of sinter/silicification and acid alteration (Youngman, 1996; Rowland and Simmons, 2012; Downs, 2014).

The geology of the northern Paeroa block is dominated by ignimbrite formations belonging to the Paeroa Subgroup (339 ± 5 ka; Downs et al. 2014b) of the Whakamaru Group. From oldest to youngest, the subgroup consists of the Te Kopia, Te Weta and Paeroa Ignimbrites, with the latter ignimbrite occurring at surface across the northern block (Figure 1).

The southern Paeroa block has a more complex surface geology but is dominated by Huka Group formations, with older formations from the Whakamaru and Reporoa Groups absent (Figure 1). The Kaingaroa Formation ignimbrite occurs mainly in the central part of the southern block and is interbedded with older units of the Huka Group Alluvium. To the east, in the western part of the Reporoa Caldera, is a small dome belonging to the Kairuru Rhyolite (247 ± 2 ka; Downs et al. 2014b). Ohakuri Formation ignimbrite, sourced from the Ohakuri Caldera, occurs extensively along the western edge of the southern block, at higher elevations along the top of the Paeroa Fault scarp. The surface geology of the remainder of the southern block is dominated by Huka Group Alluvium and the Rhyolitic Mihi Breccia. The Huka Group Alluvium consists of fine to coarse fluvial deposits that grade into finely laminated lacustrine sediments. Their deposition spans a large time interval, post-dating the Paeroa Subgroup ignimbrites (339 ± 5 ka; Downs et al. 2014b) extending through to the beginning of the late Pleistocene (ca. 129 ka; Downs et al. 2014a). The Mihi Breccia (281 ± 9 ka and 239 ± 3 ka; Downs et al. 2014a) represents rhyolitic breccias belonging to intra-caldera rhyolite domes that erupted subaqueously in a lacustrine setting (Downs 2016).

Small areas of Pukemoremore hydrothermal breccia occur in the central parts of the southern Paeroa block (Figure 1; Downs et al., 2020). The deposit is <10 m thick, clast-supported, poorly-sorted with boulder- and cobble-sized clasts (≤2 m) in a clay to sand matrix. Clast types include lacustrine sedimentary rock, rhyolitic ignimbrites and silica sinter. These characteristics, and the lack of any juvenile magmatic clasts, support a phreatic, hydrothermal eruption origin. It is of small volume (<1 km^3) with an unspecified vent location within the southern Paeroa block. Downs et al (2020) notes the deposit underlies the Mihi Breccia, indicating a stratigraphic age older than 239±3 ka, and possibly older than 281±9 ka.

Other indications of early geothermal activity in the southern Paeroa block come from several areas of fossil silica sinter (Downs 2014), south of the Te Kopia geothermal area, at Mangamingi and near Pukemoremore (Figure 1).

3. WHANGAIROROHEA GEOTHERMAL AREA

3.1 Active Surface Features

Short descriptions of the Whangairorohea geothermal surface features are provided by Youngman (1996). They occur at three areas (Figure 1), mostly at water level along the northern Waikato riverbank. No active features occur on the southern bank of the Waikato River. Warm springs (40-45°C) occur at the mouth of the Whangairorohea Stream, discharging from pumice beds over a ~10 m^2 area

(Youngman 1996). Several warm seeps (up to 50°C) occur along a 10-20 m stretch of the riverbank, about 600 m downstream of the Whangairorohea Stream. Thermal seeps and springs are not actively depositing amorphous silica sinter.

Away from the riverbank, about 500 m to the north, adjacent to the Whangairorohea Stream, is a warm pond (Whangairorohea Pool) that occupies an approximately 30 m diameter depression. Its circular shape hints that it represents a phreatic eruption crater (Youngman, 1996). When visited in October 2019, the pool had occasional bubbling at its centre, with water outflowing at approximately 1 l/s along a small channel to the Whangairorohea Stream (Brakenrig et al. 2020). The measured water temperature was 37°C, with a near neutral pH (7.5). Chemical analysis of the water shows it to be a heated bicarbonate-rich meteoric water (Table 1), and its unmineralised dilute nature precludes making any interpretation regarding any primary geothermal origin.

3.2 Extinct Surface Features

In addition to the active geothermal manifestations Youngman (1996) describes several areas affected by hydrothermal alteration, some located well away from active geothermal features (Figure 1). Most are located on the northern side of the Waikato River. These extinct surface manifestations are zones of silicification, namely silica sinters and silicified pumice tuffs. The largest zone mapped by Youngman (1996) is a sinter terrace platform measuring ~150 m across at a bend in the Waikato River approximately 1 km upstream of the Whangairorohea Stream mouth.

Rotopuha Pond, about 200 m south of the Waikato River and approximately 600 m upstream of the Whangairorohea Stream mouth, has an elongate, double circular shape, approximately 75 m long and 40 m wide (Youngman 1996). Its double circular shape might imply two connected phreatic eruption craters (Youngman, 1996). It is the only recognised likely extinct feature on the southern side of the Waikato River. When visited in October 2019, the pool showed no signs of bubbling and there was no visible outflow (Brakenrig et al. 2020). The measured water temperature was 16°C, with a near neutral (slightly acidic) pH (6.1). Chemical analysis of the water shows it to be unmineralised meteoric water, with no thermal input (Table 1).

Table 1. Chemical compositions of Rotopuha Pond and Whangairorohea Pool, in mg/kg unless otherwise specified.

	Collection Temp. (°C)	Field pH	Field Cond. (µS/cm)	Na	K	Ca	Mg	Cl	HCO_3 (total)	SO_4	B	Rb	Li	Cs	SiO_2	H_2S (total)	NH_3	δD (‰)	$\delta^{18}O$ (‰)
Rotopuha Pond	16.1	6.1	118	10.5	2.6	5.1	3.3	6.5	47	4.9	<0.40	0.03	0.01	<0.02	52	<0.01	0.04	-41.9	-7.5
Whangairorohea Pool	37.0	7.5	1556	364	16.9	10.5	8.4	46	937	<0.03	0.45	0.060	1.2	0.002	104	<0.01	<0.003	-34.7	-5.46

Fossil sinter sites and areas of extinct geothermal activity also occur to the north of the Whangairorohea thermal area. Many are associated with the Te Kopia and Orakeikorako, and areas between along the Paeroa Fault scarp. This led Clark and Browne (2000) to propose that the two fields were once part of a single system. However, there are other sinter sites within the southern Paeroa block, south of Te Kopia, that are not clearly associated with either the Te Kopia or Orakeikorako systems. These sites include one at Mangamingi mapped by Clark and Browne (2000), approximately 5 km north-northwest of the Whangairorohea geothermal area, and others mapped by Downs et al (2014b) between Mangamingi and Te Kopia, close to Pukemoremore (Figure 1). A conventional ^{14}C age of Mangamingi sinter has been reported previously as 15.7±0.1 kyr BP (Brathwaite and Rae 2021). Alignment of these sinter locations in the southern Paeroa block was used by Downs (2014) to propose that NE-SW structural controls were focusing hydrothermal fluid flows to the surface, at least at shallow depths.

The other extinct hydrothermal feature of the southern Paeroa block is the Pukemoremore hydrothermal breccia (Downs et al 2020; Figure 1), a hydrothermal eruption breccia with an unknown vent source location. Phreatic, hydrothermal eruptions typically eject material no more than tens or hundreds of metres from the source vent (rarely a few kilometres; Browne and Lawless, 2001). Given the distance from the deposit exposure to Whangairorohea is ~7 km, it is unlikely the inferred Whangairorohea eruption craters (i.e., Whangairorohea Pool and Rotopuha Pond) are the source of the Pukemoremore hydrothermal breccia.

4. GEOPHYSICAL SIGNATURES OF THE SOUTHERN PAEROA BLOCK

4.1 DC Resistivity Signatures

The southern Paeroa block is situated above a broad zone of relatively moderate resistivity (<~70 Ωm), as seen in the DC electrical resistivity map (Figure 2; Stagpoole and Bibby, 1998) with a nominal array spacing of 500 m. This zone extends between the low resistivity areas (<30 Ωm) represented at Te Kopia and Ohaaki geothermal systems, but also connects with Ngatamariki and Orakeikorako systems to the west. Within the broad 70 Ωm zone beneath the Whangairorohea thermal area, the <50 Ωm electrical resistivity signature connects with Ohaaki and there is a weak <30 Ωm area east of the thermal features (Figure 2).

4.2 Aeromagnetic Signatures

Aeromagnetic surveys (Soengkono and Hochstein 1996; Soengkono 2013) across the local district have defined a broad, anomalously high magnetic feature beneath the southern Paeroa block that extends eastwards, beneath the Reporoa caldera (Figure 3). Parts of this anomaly occur beneath the Kairuru rhyolite dome that outcrops on the western side of the Reporoa caldera. Using 3D modelling Soengkono and Hochstein (1996) proposed this feature to be a buried extension of the Kairuru rhyolite beneath the southern Paeroa block. This proposed buried rhyolite occurs beneath the Mihi Rhyolite breccia at surface, and Downs (2016) showed that the juvenile clasts from this breccia share geochemical and petrographic similarities with the Kairuru Rhyolite, implying that the Mihi Rhyolite breccia is a pyroclastic product of a subsurface rhyolitic dome building episode that included the Kairuru Rhyolite.

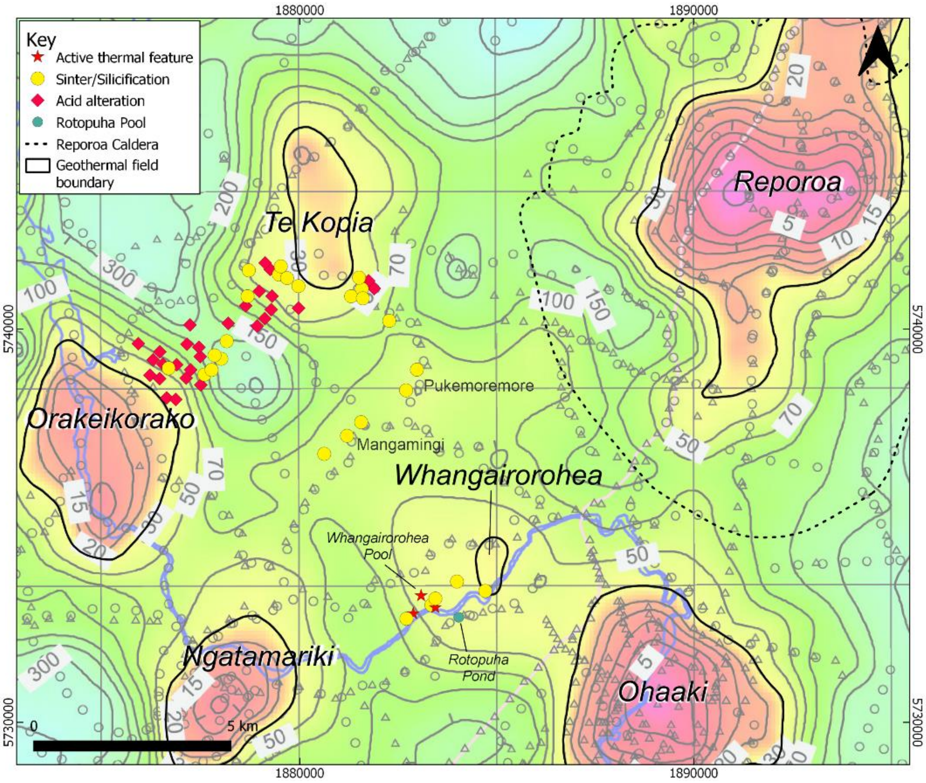

Figure 2. Direct current resistivity map (nominal array spacing 500 m; Stagpoole and Bibby, 1998), highlighting the electrical resistivity lows (yellow to red) geothermal fields neighbouring the Whangairorohea thermal area.

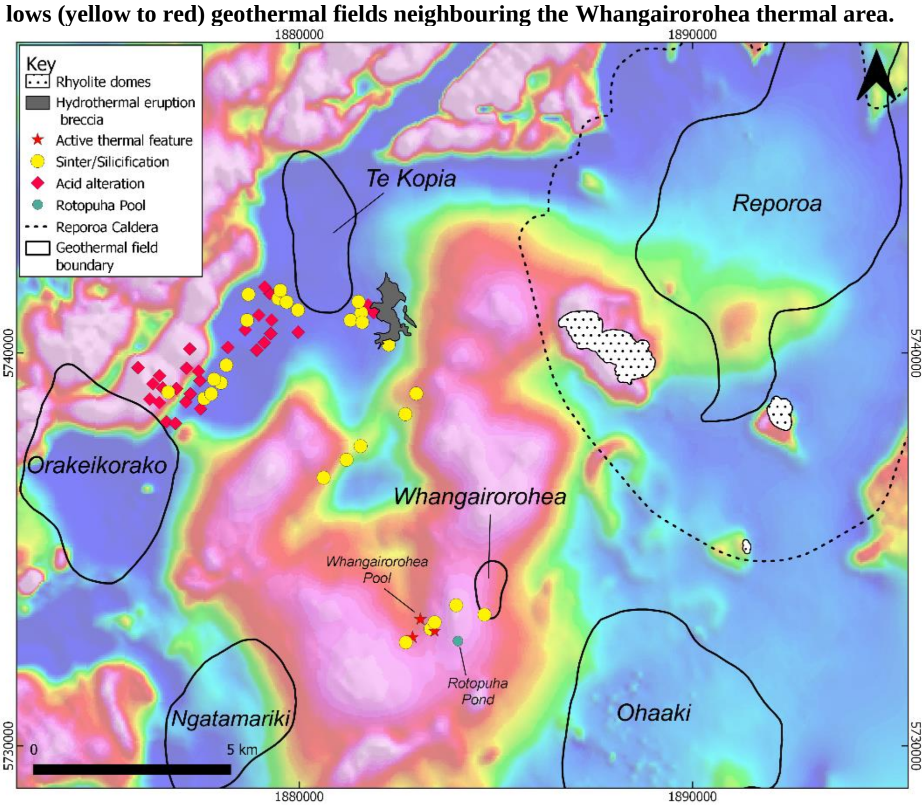

Figure 3 High resolution RTP aeromagnetic map (Soengkono 2013). Blue to yellow colours ≤0 nT; yellow to pink colours ≥0 nT. Map overlaid by the 30 Ωm direct current resistivity contours (Stagpoole and Bibby, 1998) of the neighbouring geothermal fields. Also highlighted are the thermal springs/seeps of Whangairorohea, the extinct geothermal surface features (Youngman, 1996; Rowland and Simmons, 2012; Downs, 2014) and the surface exposures of hydrothermal eruption breccia and the rhyolite domes (Downs et al. 2020).

Another feature of the southern Paeroa magnetic-high is a large, NS-trending linear embayment of demagnetisation (≤0 nT) on its northern side. This demagnetised embayment (Figure 3) was interpreted to be parts of the buried rhyolite that has been demagnetised by the effects of hydrothermal alteration (Downs 2014). The Mangamingi and Pukemoremore sinter deposits occur above the margins of this embayment (Figure 3). The southern projection of the demagnetised embayment into the magnetic-high shows a lineation of relatively weak magnetisation that aligns with the Whangairorohea thermal springs (Figure 3).

5. DISCUSSION AND CONCLUSIONS

Whangairorohea thermal area is characterised by weak geothermal surface activity where a few springs and seeps discharge warm waters along the northern bank of the Waikato River. These are heated meteoric waters with negligible geothermal chemical signature, and their dilute compositions obscure any identification of a geothermal parental fluid. These springs and seeps are located distally to any known primary geothermal reservoir and their origin, and the mechanisms for their heating, remain unresolved. They are possibly a manifestation of a low temperature geothermal system, or a distal manifestation to either a neighbouring high temperature geothermal system or a previously unrecognised (blind) geothermal system.

Despite the lack of understanding for its genesis, a significant observation regarding the Whangairorohea thermal area is that the geothermal activity in the area has changed over time. The extinct geothermal surface features preserved along the northern bank of the Waikato River are testament to surface activity at Whangairorohea being more widespread and dynamic than it is presently. The absence of any actively precipitating amorphous silica at any of the warm springs or seeps implies that water compositions have also changed, becoming more dilute with respect to their silica concentrations. The inferred hydrothermal eruption craters imply the Whangairorohea subsurface was once host to a water-dominated reservoir at close to boiling temperatures (Browne and Lawless, 2001), with the preserved silica sinter terraces implying a hot deep reservoir temperature (i.e., >210°C; Fournier 1985) that discharged neutral to slightly alkaline, silica-saturated thermal water at hot springs. These extinct features are indicators of a once vigorous and dynamic geothermal area with active surface features extending along a ~2 km stretch of the Waikato River, in a similar setting to the presently active Orakeikorako geothermal area. The inferences made from the preserved Whangairorohea surface features, of a once dynamic high temperature geothermal system, contrasts with the present thermal area of a low temperature system with weak geothermal surface activity. The contrast implies geothermal change and decline, where heat is the only geothermal input.

Considering Whangairorohea geothermal system is a waning high temperature geothermal system, the question remains whether it is a separate and unique geothermal system, or a marginal part of a neighbouring system (e.g. Ohaaki, Ngatamariki). To distinguish the former, one needs to consider the aeromagnetic information. A high temperature geothermal reservoir imprints a deep (<1 km) footprint of hydrothermally altered rock, that results in demagnetisation of the host volcanic rocks. Such demagnetised footprints are present beneath all other neighbouring geothermal systems (Figure 3), but not beneath Whangairorohea. This absence leads to the conclusion that a deep high temperature geothermal reservoir is not present, and has never been present, beneath Whangairorohea.

The lack of a demagnetised footprint leads to the conclusion that Whangairorohea is marginal to one of its neighbouring geothermal systems, the closest being Ngatamariki and Ohaaki (Figure 2). With respect to Ngatamariki, the DC resistivity map indicates no conductive link with Whangairorohea, as would be expected if a thermal hydrological connection existed between the two. Also, Whangairorohea is located upstream of Ngatamariki and any shallow groundwater flow is most likely to be downstream along the Waikato River towards Orakeikorako (Figure 2). There is an apparent conductive connection however between Whangairorohea and Ohaaki (Figure 2), where the 50 Ωm contour extends from the northwestern margin of Ohaaki westwards to enclose Whangairorohea. However despite this apparent connection, evidence from several shallow monitoring wells located on the northwestern perimeter of the Ohaaki steamfield indicates an absence of geothermal conditions northwest of the inferred reservoir boundary (<30 Ωm; personal communication, F. Sepulveda, Contact Energy).

Any explanation for the existence of the Whangairorohea geothermal area needs to consider all available field and geophysical evidence, including distribution of inactive or fossil geothermal features and aeromagnetic signatures. Historical geothermal activity has occurred between the Te Kopia and Orakeikorako geothermal areas, where sites of fossil acid (kaolinite) and near-neutral pH (silicification) alteration occur along the Paeroa Fault scarp (Figure 1). Their occurrence above a demagnetised zone is convincing evidence that the two geothermal areas were once part of system that extended between the two areas (Clarke and Browne 1998; Rowland and Simmons 2012). Silica sinters are not actively forming at Te Kopia, but their presence as fossil deposits within the Te Kopia thermal area (Bignall and Browne, 1994), along the Paeroa Fault scarp, and within the Paeroa block footwall outside 30 Ωm boundary are evidence that Te Kopia once hosted neutral to slightly alkaline, silica-saturated chloride springs that discharged from a high temperature (>210°C; Fournier 1985) water-dominated geothermal system.

The lack of actively discharging neutral chloride springs at Te Kopia is testament to the changing dynamics of this geothermal system, which have been in response to vertical displacement of the Paeroa Fault footwall (Bignall and Browne, 1994). We propose that the occurrence of fossil sinters within the footwall, outside the 30 Ωm boundary (Figure 3) and above a demagnetised zone, is evidence that prior to (or at the earliest stages of) vertical displacement, the Te Kopia geothermal system had neutral chloride springs discharging in the area south of present geothermal area. As vertical displacement along the Paeroa Fault proceeded, south- and eastwards facing topographic gradients were established. With progression the top of the neutral chloride reservoir deepened and neutral chloride geothermal aquifers were unable to reach the surface. Instead steam-heated aquifers developed in the vadose zone, and deeper neutral chloride waters were directed southwards in the shallow subsurface along an outflow zone that resulted in demagnetisation of the host rhyolite. With increasing displacement, neutral chloride waters were forced to discharge with increasing distance south of Te Kopia, eventually reaching Whangairorohea, and resulting in southwards extension of a tongue of demagnetisation (or weakened magnetisation) within the rhyolite. With prolonged and ongoing displacement, the source of neutral chloride waters was eventually turned-off. The fossil geothermal features at Whangairorohea represent the southern extent of the outflow, and the active warm springs are meteoric groundwaters that have been heated by a deep geothermal source located close to

Te Kopia. Whangairorohea thermal area is a distal manifestation of geothermal activity located beneath Te Kopia. It is an example of how high temperature TVZ geothermal systems are prone to irreversible change from active faulting.

ACKNOWLEDGEMENTS

Funded by a 2017 Ministry of Business, Innovation and Employment Endeavour Fund: the GNS-led research programme "Empowering Geothermal Energy: Increased Utilisation of Geothermal Energy Through New Integrated Geoscience Methods". Thank you to Agnes Reyes (GNS Science) for providing an informal assessment of the Whangairorohea geochemistry data.

REFERENCES

Berryman, K., Villamor, P., Nairn, I., van Dissen, R., Begg, J., Lee, J.: Late Pleistocene surface rupture history of the Paeroa Fault, Taupo Rift, New Zealand. *New Zealand Journal of Geology and Geophysics*, 51, 135–158. https://doi.org/10.1080/00288300809509855 (2008).

Bignall G., Browne, P.R.L.: Surface hydrothermal alteration and evolution of the Te Kopia thermal area, New Zealand. *Geothermics*, 23, 645-658, (1994).

Brakenrig, T., Graham, D.J., MacDonald, N., Sanders, F.: Sampling of features in the Ohaaki-Broadlands, Whangairorohea and Reporoa geothermal systems. GNS Science Miscellaneous Series 135 31p. Lower Hutt (NZ). https://doi.org/10.21420/3S70-1J88 (2020).

Brathwaite, R.L., Rae, A.J.: Epithermal zeolite alteration associated with siliceous sinters, hydrothermal eruption breccias, and gold-silver mineralization, central Taupo Volcanic Zone, New Zealand. *Economic Geology*, 116, 1093-1114, https://doi.org/10.5382/econgeo.4820 (2021).

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

Clark, J.P., Browne, P.R.L.: Past and present-day thermal activity between the Orakeikorako and Te Kopia geothermal areas, New Zealand. *Proc. 25th Workshop Reservoir Engineering Stanford University*, Stanford, California (2000).

Downs, D.T.: Deciphering the 4-D geological framework of the Taupo-Reporoa Basin: implications for hydrothermal fluid flow and volcanism. PhD thesis. University of Auckland. 216p. (2014)

Downs, D.T., Wilson, C.J.N., Cole, J.W., Rowland, J.V., Calvert, A.T., Leonard, G.S., Keall, J.M.: Age and eruptive center of the Paeroa Subgroup ignimbrites (Whakamaru Group) within the Taupo Volcanic Zone of New Zealand. *Geological Society of America Bulletin*, v. 126, p. 1131–1144, https://doi.org/10.1130/B30891.1 (2014a).

Downs, D.T., Rowland, J.V., Wilson, C.J.N., Rosenberg, M.D., Leonard, G.S., Calvert, A.T.: Evolution of the intra-arc Taupo-Reporoa Basin within the Taupo Volcanic Zone of New Zealand. *Geosphere*, 10, 185–206, https://doi.org/10.1130/GES00965.1 (2014b).

Downs, D.T.: Mihi Breccia—A stack of lacustrine sediments and subaqueous pyroclastic flows within the Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research*, 327, 180–191, https://doi.org/10.1016/j.jvolgeores.2016.08.004 (2016).

Downs, D.T., Leonard, G.S., Wilson, C.J.N., Rowland, J.V.: Geologic map of the Paeroa Fault block and surrounding area, Taupo Volcanic Zone, New Zealand. *U.S. Geological Survey Open-File Report 2020-1021*, scale 1:50,000. https://doi.org/10.3133/ofr20201021 (2020).

Fournier, R.O.: The behavior of silica in hydrothermal solutions. *Reviews in Economic Geology*, 2, 45-61 (1985).

Rowland J.V., Simmons, S.F.: Hydrologic, magmatic, and tectonic controls on hydrothermal flow, Taupo Volcanic Zone, New Zealand: implications for the formation of epithermal vein deposits. *Economic Geology*, 107, 427-457, (2012).

Soengkono S.: Distribution, age and hydrothermal alteration of Quaternary volcanic rocks in the Taupo Volcanic Zone (North Island, New Zealand) seen from high resolution airborne magnetic data. *Proc. 35th New Zealand Geothermal Workshop*, Rotorua, New Zealand. (2013)

Soengkono, S., Hochstein, M.P.: Interpretation of magnetic anomalies over the Reporoa geothermal field, Taupo Volcanic Zone. *Proc. 18th New Zealand Geothermal Workshop*: Auckland, New Zealand, 243–248. (1996).

Stagpoole, V.M., Bibby, H.M.: Electrical resistivity map of the Taupo Volcanic Zone, New Zealand: nominal array spacing 500 m, 1:250 000: Institute of Geological and Nuclear Sciences Geophysical Map 11. (1998).

Villamor, P., Berryman, K.: 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, 243–269, https://doi.org/10.1080/00288306.2001.9514937 (2001).

Youngman, K.J.: Whangairorohea geothermal field. *Proc. 18th New Zealand Geothermal Workshop*, Auckland, New Zealand. 151-156 (1996)