CONSTRAINING THE AGE AND DURATION OF GEOTHERMAL ACTIVITY AT THE EXTINCT OHAKURI HYDROTHERMAL SYSTEM, TAUPO VOLCANIC ZONE, NEW ZEALAND

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ABSTRACT

The Ohakuri fossil hydrothermal system is located near the western margin of the Taupo Volcanic Zone (TVZ), and at the southwestern boundary of the Ngakuru Graben, Taupo Fault Belt, New Zealand. Valley erosion along the Waikato River has exposed extensive zones of hydrothermal alteration within Ohakuri Ignimbrite including mineralised quartz-pyrite-adularia bearing vein breccias that formed in response to episodic hydraulic fracturing. The exposed alteration zones have mineral assemblages that formed from chloride waters (quartz, adularia, illite, mordenite, clinoptilolite, smectite), which are overprinted by acid condensate minerals (kaolinite, alunite). Scattered silica sinter float blocks in the area prove that the geothermal system had surface hot springs. Until recently, the timing of these different alteration zones have relied upon maximum and minimum ages of altered lithologies and overlying units. A date of ca. 244 ka for the Ohakuri Ignimbrite places a maximum age on the alkaline chloride alteration. Acid steam altered rocks underlie the Rotoehu Ash, implying a minimum age of ca. 45 ka. Our paper reports the K-Ar radiometric ages of hydrothermal adularia from altered Ohakuri Ignimbrite, as well as radiocarbon ages of organic material entombed in silica sinter. The results show that the adularia formed ca. 190 ± 3 ka and the sinters between 20.1 ± 0.3 ka and 22.5 ± 0.2 ka. These dates imply that the Ohakuri geothermal system was active for at least 170 ka, between 190 and 20 ka, at a period after the Maroa eruption of the Pukeahua Formation pyroclastics (ca. 196 ka). Activity persisted through deposition of the Rotoehu fall deposit (Rotoiti Formation: ca. 45 ka) and the Oruanui Formation (25.4 ± 0.2 ka). Our results provide some valuable constraints on the duration of geothermal activity in the TVZ, which previously could only be estimated using stratigraphic relationships.

1. INTRODUCTION

Ohakuri is situated in the Taupo Volcanic Zone (TVZ), approximately 30 km north of Taupo township on the Waikato River, which bisects the area east-west and where it is dammed for hydro-electric power generation. Over the past 30-years the study area has received irregular attention from several mineral exploration companies (BP Minerals, Amoco Minerals, Cyprus Gold, Delta Gold, Coeur Gold, GCO Minerals and Glass Earth) that have been attracted by the areas of epithermal-style hydrothermal alteration affecting surface rocks. These areas of fossil hydrothermal alteration indicate that a geothermal system was once active in the area.

Early studies by previous workers, which included surface mapping and petrography, established the occurrence of a fossil hydrothermal system at Ohakuri (Henneberger, 1983; Henneberger and Browne, 1988). Subsequent work (Grieve et al., 2006) over the last thirty years involved significant investment by exploration companies in surface mapping and drilling to establish whether the areas of epithermal-style hydrothermal alteration included zones of ore-grade precious metal mineralisation. This work included additional surface mapping, geochemical assays (soil, rock chips, wacker and drill core samples), geophysical surveys (ground magnetic and gravity, DC resistivity, induced polarisation, and both airborne magnetic and gravity), and more than forty-five exploration drill holes, to no more than 500 m depth. This detailed and focused work has resulted in development of a fairly well understood geohydrological conceptual model of the Ohakuri hydrothermal system to ~500 m depth.

Despite having a reasonably well understood geohydrological model for the extinct Ohakuri hydrothermal system, the age and duration of geothermal activity in the area is poorly constrained. Previous estimates are based on stratigraphic relationships, being the maximum and minimum ages of hydrothermally altered geologic units and overlying stratigraphy. Based on such inferences, the Ohakuri geothermal activity is thought to have for 90 ka, between 160 ka and 70 ka (Grieve et al., 2006).

Overall, the ages and longevities of geothermal activity for the TVZ geothermal systems are poorly constrained and not well understood. Attempts to date hydrothermal minerals using radiometric techniques are thwarted by these minerals commonly residing in geothermal reservoirs above radiometric closure temperatures. The best estimates are based on stratigraphic relationships, for example identification of hydrothermal eruption breccia deposits at particular known stratigraphic positions. These estimates have generally resulted in ages of TVZ geothermal systems in the hundreds of thousands of years (Table 1). Whether geothermal activity has been continuous for protracted periods or waxed and waned with episodes of magmatic intrusion (e.g., Ngatamariki; Chambefort et al., 2014) remains at best speculative.

The hydrothermal system at Ohakuri provides an opportunity to use radiometric techniques/methods to date fossil hydrothermal alteration mineral products that are below their radiometric closure temperatures. The resulting ages will constrain the cooling ages of the dated minerals, the time at which the geothermal reservoir cooled below the mineral's closure temperature. The constrained duration of hydrothermal activity at Ohakuri will provide insights into the expected duration of active geothermal systems in the TVZ.

Table 1. Inferred ages for hydrothermal activity at several TVZ geothermal sites.

Geothermal System	Inferred Age	Reference
Kawerau	<0.3 Ma	Milicich et al. (2013)
Ngatamariki	<0.7 Ma	Chambefort et al. (2014)
Wairakei	>0.5 Ma	Grindley (1965)
Te Kopia	~0.12 Ma	Bignall and Browne (1994)
Ohaaki	<0.2 Ma	Lonker et al. (1990); Rosenberg et al. (2009)
Rotokawa	<0.1? Ma	Rae (2007)
Reporoa	<0.24 Ma	Wood (1994)

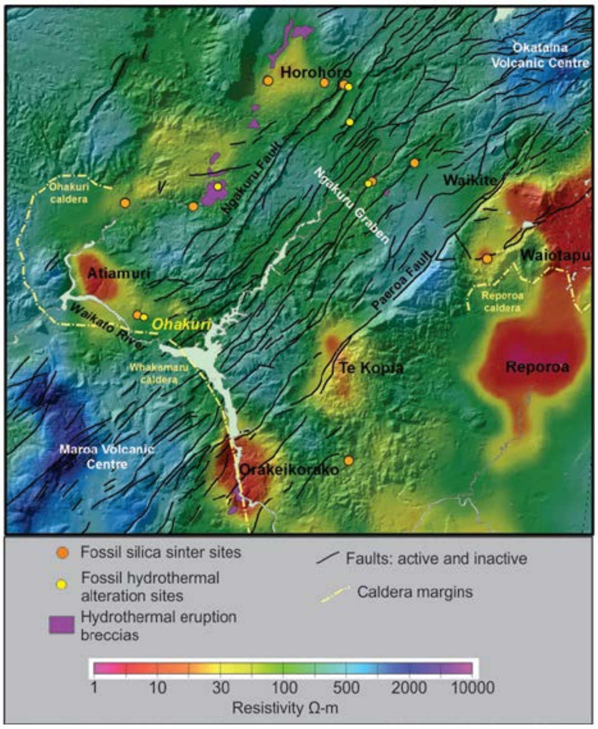

Figure 1. Electrical DC resistivity map (detail from Stagpoole and Bibby, 1998; nominal spacing array of 500 m) showing the location of Ohakuri, at the southwestern termination of the Ngakuru Graben. Also shown are the areas of fossil silica sinter and surface hydrothermal alteration (ie., silicification and zeolitisation), and hydrothermal eruption breccias (the latter from the Rotorua area QMAP; Leonard et al., 2010). Caldera margins are from Leonard et al. (2010). Geothermal systems are defined by areas of conductive rock (<20 Ω-m), with areas of high resistivity (>1000 Ω-m) representing unaltered rhyolite lavas and domes of the Maroa and Okataina volcanic centres.

2. OHAKURI HYDROTHERMAL SYSTEM

2.1 Geology and Structure

Ohakuri is located on the northern margin of the Maroa Volcanic Centre, close to where the inferred boundaries of the Whakamaru and Ohakuri calderas merge (Figure 1; Wilson et al., 1986; Gravley et al., 2007). It lies ~3-5 km southeast of the Atiamuri geothermal system. Electrical DC resistivity maps indicate that shallow crustal rocks (ie., <300 m depths) at Ohakuri have moderate conductivity (ie., >30 Ω-m; Figure 1) and hence absence of a hot, saline geothermal reservoir in the area.

Ohakuri Ignimbrite (244 ± 10 ka; Gravley et al., 2007) dominates the surface geology north and south of the Waikato River. The ignimbrite is considered to be more than 250 m thick and is mainly comprised of non-welded vitric pumice lapilli tuff that is friable and likely to have high porosity (Henneberger and Browne, 1988). Above the Ohakuri Ignimbrite, mainly north of the Waikato River, are small areas of Oruanui Formation (25.4 ka; Vandergoes et al., 2013) and Taupo Pumice Formation (ca. 1718 BP; Hogg et al., 2012) (Leonard et al., 2010). To the east, along the Waikato River, are alluvial deposits of the Hinuera Formation that consist of reworked deposits of the Oruanui Formation.

Structurally, the Ohakuri area is located in the western Taupo Fault Belt at the southwestern termination of the Ngakuru Graben, which occurs between the Maroa and Okataina Volcanic Centres (Figure 1). Northeast of Ohakuri is the main splay of Ngakuru Fault, the most westerly active fault that defines the western boundary of the graben. Closer to the Ohakuri area the fault is a zone of multiple splays with more easterly strikes (Figure 1; GNS active fault database).

2.2 Hydrothermal Alteration

Valley erosion along the Waikato River has incised through areas of surface alteration into zones representative of deeper parts of the hydrothermal system. Hydrothermal alteration zones across the Ohakuri area were first mapped and described by Henneberger (1983) and published by Henneberger and Browne (1988; Figure 2). Subsequent surface studies by exploration companies have added some minor details in areal extent, but otherwise they are consistent with Henneberger and Browne (1988). Exploration drill holes that are mainly located north of the Waikato River have defined the extent and additional detail of hydrothermal alteration zones with depth (Arunsrisanchai, 1991).

Quartz-adularia-chlorite alteration represents the deepest alteration type encountered by drilling (up to 120 – 200 m deep), and is exposed along the deeper flanks of the Waikato River valley (Figure 2 and Figure 3). This alteration largely affects the Ohakuri Ignimbrite and represents wallrock replacement and veining by alkaline chloride waters. These fluids affectively completely replaced the host igneous constituents, with plagioclase phenocrysts pseudomorphed by adularia and ferromagnesian minerals replaced by chlorite-leucoxene (Arunsrisanchai, 1991). The host groundmass has been pervasively silicified, but with relatively minor amounts of adularia, chlorite, pyrite and leucoxene (Arunsrisanchai, 1991). A characteristic of this alteration is the veining and intense hydraulic brecciation of the silicified ignimbrite. These are exposed at surface close to the Ohakuri Dam abutments. The breccia zones and veins are flooded with colloform banded to massive, anhedral, mosaic quartz cement, with accessory adularia and pyrite, that supports clasts of altered (silicified) wallrock and vein material. Fluid inclusion microthermometry from vein quartz indicates temperatures up to 220°C (Arunsrisanchai, 1991).

Quartz-adularia-illite alteration is known to occur north of the river between the quartz-adularia-chlorite and kaolinite-alunite zones (Figure 3). The hydrothermal mineral association is the same for quartz-adularia-chlorite, but with illite that generally occurs at greater abundances than chlorite, which it replaces (Arunsrisanchai, 1991).

Calcite-albite-laumontite alteration is of apparent limited extent at depth north of the Waikato River between the chlorite- and illite-bearing quartz-adularia zones (Figure 3), which it both replaces. The host rocks are typically silicified, with incomplete replacement of the primary igneous minerals. Albite occurs as minor replacement of pumice and can fill fine voids with quartz. This alteration zone includes strong veining that are filled by calcite, but with some laumontite, quartz and adularia predating calcite (Arunsrisanchai, 1991). Bladed calcite is a feature of this zone, and fluid inclusion microthermometry indicates calcite formation at ~180°C (Arunsrisanchai, 1991).

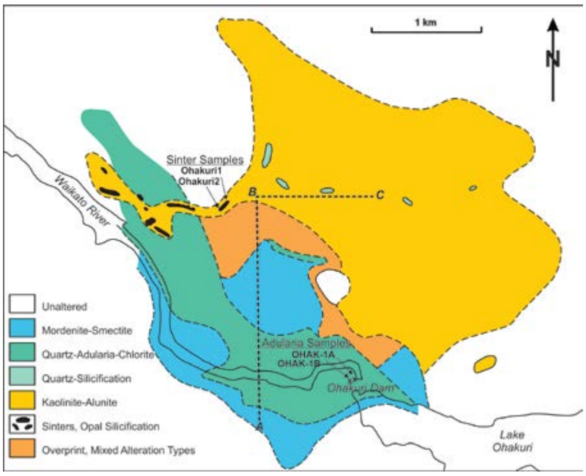

Figure 2. Hydrothermal alteration map of Ohakuri (Hennberger and Browne, 1988), showing location of fossil sinter and adularia samples, and the line of cross-section (Figure 3).

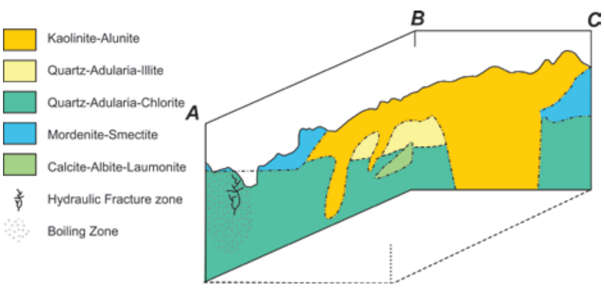

Figure 3. Schematic fence diagram through the Ohakuri hydrothermal system (viewed to the northwest, along line A-B-C in Figure 2) showing the spatial relationships of hydrothermal alteration zones with depth to ~500 m (Arunsrisanchai, 1991).

Mordenite-smectite alteration occurs at surface, at higher elevations than both quartz-adularia types, on northern and southern flanks of the valley (Figures 2). Volcanic glass in host rocks is replaced by mordenite and clinoptilolite, smectite, opal or quartz. Primary plagioclase crystals are weakly replaced by smectite and mordenite, and ferromagnesian minerals are altered to smectite (Arunsrisanchai, 1991; Henneberger and Browne, 1988).

Kaolinite-alunite alteration is the most widespread surface alteration, but restricted to an area north of the Waikato River (Figure 2). It is known to extend to ~150 m depth. This type of alteration is typical of shallow acid-sulphate condensate waters. Host rocks are commonly pervasively altered to kaolinite-quartz-pyrite, with primary crystals leached and cavities filled with quartz-kaolinite-alunite. This alteration type overprints both quartz-adularia types.

Silica sinter and silicified surface formations occurs at a few outcrops and as scattered float material along a creek bed north of the Waikato River (Figure 2), and have been encountered at a few metres depth in some northern drill holes (Arunsrisanchai, 1991).

2.3 Hydrothermal Model of Ohakuri

Generally there is broad agreement between previous workers at Ohakuri (Henneberger and Browne, 1988; Arunsrisanchai, 1991; Grieve et al., 2006) for a relatively simple conceptual model of the hydrothermal reservoir. Documentation by these workers of the distribution and areal extent of hydrothermal alteration zones, along with their description of the various mineral textures within these zones, indicate a simplicity to the geohydrology of the reservoir and its eventual demise. To date, there is no hydrothermal mineralogical evidence for multiple heating events or episodic thermal pulses. Hence, it appears that at Ohakuri there was a single geothermal reservoir with temperatures at least 220°C and a fluid chemistry that was typical for any modern TVZ geothermal system, which eventually cooled and became inactive.

Upwelling hot (~220°C) neutral-alkaline chloride fluids occurred across the area, but are known to have been focussed north of the Waikato River and also towards the south near the present-day Ohakuri dam. At depth beneath the Ohakuri Ignimbrite, reservoir permeability is assumed to have been fracture controlled. However, formation permeability prevailed as fluids reached shallow levels, utilising aquifers in the unwelded and largely permeable Ohakuri Ignimbrite. These fluids produced the pervasive quartz-adularia-chlorite alteration type, resulting in silicification and hydraulic fracturing. Upon reaching the surface these fluids deposited silica sinter aprons at neutral chloride springs and pools. Remnants of these deposits are only preserved in the northwestern parts of the area. On the system margins, mixing between shallow meteoric groundwater and neutral-alkaline chloride water produced the mordenite-smectite alteration zone. Shallow subsurface boiling of the neutral-alkaline chloride fluids resulted in gas-separation and the development of acidic steam-heated groundwaters and the kaolinite-alunite alteration zone.

As the hydrothermal system waned and cooled, acid condensates descended, overprinting quartz-adularia-chlorite alteration to produce the quartz-adularia-illite mineral association. Influxes of cooler (~180°C), CO_2-rich fluids resulted in deposition of calcite and development of calcite-laumontite-albite alteration.

The occurrence of silica sinter in the north indicates that since cessation of the hydrothermal system at Ohakuri there essentially has been no erosion in that area. However, towards the south, elevation differences in the Waikato River valley, indicate that approximately 100-130 m of erosion has occurred in this area (Grieve et al., 2006).

3. METHODS AND RESULTS

3.1 Radiometric ^{14}C Dating of Silica Sinter

Two blocks of fossil silica sinter float were collected along a creek bed in northern Ohakuri (Figure 2) for AMS ^{14}C dating. This was done at Rafter Radiocarbon Laboratory, GNS Science.

For each sample, the exterior surfaces of the block were washed with distilled water, then soaked in hydrogen peroxide to oxidise and remove possible organic contamination from the exterior. After washing again with distilled water, the block was crushed to <10 mm and weighed. Hot hydrochloric acid was added to the crushed sinter to remove any carbonates before the silica was dissolved in hydrofluoric acid. After the silica removal was complete, the residue was washed in hot hydrochloric acid, then in hot distilled water, then in room temperature distilled water. Because of the extreme toxicity of HF, numerous washes were required to remove all traces of the acid.

From several hundred grams of sinter, only a few millilitres of material suspended in distilled water was left. This residue was sieved at 150 µm to remove any large mineral fragments remaining. The material <150 µm was sieved again at 6 µm. Plant fragments were then separated from any remaining mineral in the >6 µm fraction by density separation using Sodium Polytungstate (SPT) at a specific gravity of ~1.9 g/mL. Floating material of < 1.9 g/mL was examined under magnification to verify the presence of plant fragments and pollen. Once a plant microfossil fraction has been obtained, it was photographed and dried for combustion and conversion to graphite.

Plant microfossil fractions from the sinters were combusted to CO_2 in evacuated quartz tubes with copper oxide and silver wire. The carbon content of the combusted fractions from each of these sinters was >40%, confirming that the primary component in the fractions was cellulose. The CO_2 was reduced with H_2 over an iron catalyst and the resulting graphite was analysed in the EN tandem accelerator at GNS Science's National Isotope Centre.

The results (Table 2) are reported as conventional ^{14}C ages as well as 93% and 95% probability calendar age ranges based on the IntCal04 calibration curve (Reimer et al., 2004).

Table 2. Results of radiocarbon carbon dating of Ohakuri silica sinter samples, Ohakuri1 and Ohakuri2. Sample locations shown Figure 2.

Sample	Conventional ^{14}C age yr. BP (±1σ)	Calibrated age range cal. yr. BP
Ohakuri1	16,920 ± 160	20,412 – 19,790 (93%)
Ohakuri2	19,013 ± 80	22,703 – 22,315 (95%)

3.2 Radiometric K-Ar Dating of Hydrothermal Adularia

Radiometric K-Ar dating of adularia pseudomorphs of plagioclase crystals from the Ohakuri Ignimbrite was carried out on two samples (OHAK-1A, OHAK-1B) collected from outcrops of the quartz-adularia-chlorite alteration zone close to the Ohakuri Dam southern abutment (Figure 2).

Adularia separates were ultrasonically washed in acetic acid (1N) for 45 mins. at 60°C. Pure splits of adularia were filtered out using magnetic, gravimetric, and visual hand picking separation. The isotopic composition and abundance of Argon were determined using an unspiked technique described by Charbit et al. (1998). Determination of potassium was carried out at Centre of Petrographic and Geochemical Research (CRPG; Nancy, France) by atomic absorption (flame photometry) with a relative precision of 1%.

In principle, the most critical uncertainty in the K-Ar method is that it is not possible to verify the isotopic composition of the initial argon in the sample. That is, we cannot check the assumption that, at the time of its formation, the $^{40}Ar/^{36}Ar$ ratio was the same as modern atmospheric ratio (295.5). As a result, the analytical errors given in Table 1 may in principle be smaller than the true error.

Unspiked K-Ar analysis of each sample involved three independent determinations of potassium and two (for OHAK-1B) or three (for OHAK-1A) independent determinations of argon (Table 1). Based on replicate analysis of material references the potassium concentrations were determined with an uncertainty of 1% (1σ). The potassium concentrations were combined to yield a mean value. Age determinations of each sample were made using this value and the weighted mean of the two or three independent measurements of $^{40}Ar^*$ (radiogenic Ar). Uncertainties for the Ar data are 1σ analytical only, and consist of propagated and quadratically averaged experimental uncertainties arising from the ^{40}Ar (total), and $^{40}Ar^*$ determinations. Uncertainties on the ages are given at 2σ.

Samples OHAK-1A and OHAK-1B have distinct compositions as illustrated by their different K contents (Table 3), and can therefore be considered as two different samples. Nevertheless, the results demonstrate that they are of the same age. Sample OHAK-1A is dated at 190 ± 4 ka, sample OHAK-1B at 189 ± 4 ka (Table 3). This similarity of age between two different samples implies analytical robustness. Combining the age of OHAK-1A and OHAK-1B, we calculate a weighted mean age of 190 ± 3 ka for the Ohakuri adularia.

Table 3. Results of K-Ar ages of Ohakuri adularia samples, OHAK-1A and OHAK-2A. Sample locations shown Figure 2.

Sample	Split K (wt.%) ± 2σ	Age (ka) ± 2σ
OHAK-1A	6.766 ± 0.068	190 ± 4
OHAK-2A	7.438 ± 0.075	189 ± 4

3. DISCUSSION AND CONCLUSIONS

The results of the radiometric dating (^{14}C and K-Ar) of hydrothermal alteration products from Ohakuri carried out for this study indicate that the system was active at least from 190 ka to 22 – 20 ka, a ~170 ka period of hydrothermal activity. As opposed to some other TVZ geothermal systems (e.g., Ngatamariki, Chambefort et al., 2014), evidence from previous work on the hydrothermal alteration at Ohakuri indicates that this period of activity was not episodic: product of a hydrothermal reservoir heated during a single thermal input that declined over time. A duration of hydrothermal activity for $>10^5$ yrs is of the same order of magnitude as the estimated inferred periods of duration for some TVZ geothermal systems (Table 1; Kissling and Weir, 2005). Our result provides a degree of confidence that periods of activity at TVZ geothermal systems can be expected to be on the order of 10^5 yrs.

The period of activity at the Ohakuri hydrothermal system persisted through three rhyolitic eruptions at the Okataina and Taupo volcanic centres, these being respectively Rotoiti and Earthquake Flat (both ca. 45 ka; Danišík et al., 2012), and Oruanui (ca. 25.4 ka; Vandergoes et al., 2013). The latter eruption is known to have resulted in dramatic geomorphological changes to the landscape through post-eruptive processes of erosion and resedimentation. One such change affected river drainages from pre-Oruanui Lake Huka and post-Oruanui Lake Taupo (Manville and Wilson, 2004). Such changes, although dramatic to surface hydrology and shallow groundwater aquifers, are unlikely to have strongly affected or influenced a deep geothermal reservoir.

The duration of Ohakuri activity is bracketed by eruptions from the neighbouring Maroa volcanic centre, with the eruption of the Pukeahua Formation pyroclastics at ca. 196 ka (Leonard et al., 2010) through to the youngest Maroa eruption: pyroclastics and lava domes of the Puketarata Formation, ca. 16.5 ka (Leonard et al., 2010).

The Ohakuri hydrothermal system is one of at least six extinct systems located in the TVZ that are not spatially associated with any active geothermal systems (Figure 1). Most of these fossil systems are located in the Ngakuru Graben, but along the western boundary and across its northern termination.

Henneberger and Browne (1988) proposed that the collapse and demise of the Ohakuri hydrothermal system was a result of either cooling of a heat source or changes to the permeabilities of the deep fluid conduits. Recent numerical modelling of hydrothermal flow in a structurally-controlled basin by Kissling et al. (2013; 2015) and Ellis et al. (2015) favours the latter. Their work highlights the sensitivities of both basin fault architecture and assigned fault permeabilities to the location of geothermal surface discharges across the basin. Changes to fault permeabilities in an interconnected fault system, via rupture or mineral sealing, will complicate flow path directions and result in transient behaviour of geothermal activity within the basin. Additionally, transiency can be successfully modelled where fault permeabilities are insufficient to pass high fluid volumes to the surface, resulting in movement of flow paths away from faults. Thus we have mechanisms for transient geothermal activity without the requirement for changes to a deep heat source.

Due to their proximal locations (i.e., 3-5 km apart), a genetic relationship between the Atiamuri and Ohakuri systems has been suggested (Henneberger and Browne, 1988). It was thought possible that Atiamuri represents an upflowing reservoir that shifted to its present position from the southeast, or possibly a vestige of a once extensive area of geothermal activity that has since waned and diminished in areal extent. However within the TVZ, proximity between geothermal systems should not be considered evidence for a shared genetic relationship. There are many TVZ geothermal systems that have DC resistivity-defined reservoir boundaries within 5 km of a neighbouring system. These include: Ngatamariki – Orakei korako, Orakei korako – Te Kopia, Ngatamariki – Rotokawa, Wairakei – Rotokawa, Tauhara – Rotokawa; and at Wairakei-Tauhara two reservoir upflow zones effectively define two independent geothermal reservoirs that share shallow aquifers.

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