# RELICT MAGMATIC-HYDROTHERMAL ALTERATION AT NGATAMARIKI: IMPLICATIONS FOR THE DEEP ROOTS OF TVZ GEOTHERMAL SYSTEMS

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***Keywords:*** *Ngatamariki geothermal field, Taupo Volcanic Zone, potassic alteration, phyllic alteration, advanced argillic alteration, SWIR spectrometry*

## ABSTRACT

Zones of hypogene potassic and advanced argillic alteration have been encountered for the first time in the central Taupo Volcanic Zone (TVZ). Geothermal drilling at Ngatamariki in 2012 for Mighty River Power intercepted the diorite pluton and phyllic alteration halo first encountered by NM4 in 1985. Wells NM8 and NM9 encountered not only the diorite and phyllic alteration halo, but also a tonalite body, mafic dykes, and high-temperature magmatic-hydrothermal alteration minerals not previously recognised at Ngatamariki or in any TVZ geothermal fields. The phyllic alteration halo is a vertically extensive (~1.5 km thick) zone characterised by texturally destructive quartz-muscovite-pyrite alteration. Detailed study of alteration mineralogy and textures in wells from the northern part of the field using short-wave infrared spectroscopy, XRD, and thin section microscopy indicate that high-temperature potassic and advanced argillic alteration minerals are also present. Biotite-magnetite ± K-feldspar alteration is present within and immediately above the intrusive complex, constituting a potassic alteration halo formed by high-temperature magmatic-hydrothermal fluids exsolved during magma degassing. Above this potassic core and cross-cutting the phyllic zone is a zone of pyrophyllite-andalusite-topaz (± anhydrite and vuggy silica) advanced argillic alteration formed by upward migration of acidic magmatic-hydrothermal fluids as far as 1.4 km above the pluton. These zones of hypogene potassic and advanced argillic alteration are the first to be recognised in a TVZ geothermal field, and are analogous to those found in porphyry copper systems, high-sulfidation epithermal gold systems, and andesite-arc setting geothermal systems (e.g. Indonesia, Philippines). Furthermore, the record of magmatic-hydrothermal fluid-rock interactions preserved at Ngatamariki may be analogous to processes occurring at depth currently beneath other TVZ geothermal systems.

## 1. INTRODUCTION

The Ngatamariki Geothermal Field is one of 21 geothermal fields in the Taupo Volcanic Zone (TVZ), and one of seven that is developed for geothermal power generation. It is the first TVZ geothermal field in which drilling has encountered plutonic rocks at depth. The Ngatamariki diorite and associated phyllic alteration halo were intersected by NM4, the last of four early Crown exploration wells drilled in 1985 (Wood, 1986). Development-stage injection wells NM8 and NM9, drilled in 2012-13 and located near NM4 in the northern part of the field, encountered the diorite and a tonalite at greater depth (Lewis et al, 2012, 2013; Chambefort et al, submitted), as well as alteration minerals not documented before in TVZ geothermal systems.

In TVZ geothermal systems, hydrothermal alteration is generally the product of near-neutral to moderately acidic, meteoric-dominated fluids that are heated and circulated by a deep magmatic heat source. Typical alteration minerals in this environment include quartz, clay minerals (smectite, illite-smectite, illite), pyrite, calcite, chlorite, epidote, and at higher temperatures actinolite (Browne, 1978).

Alteration haloes proximal to and genetically associated with shallow intrusions generally contain hydrothermal minerals that form at temperatures higher than those typical of TVZ geothermal systems. Additionally, the chemistry of the fluids in this magmatic-hydrothermal environment is influenced by contributions of brines and volatiles exsolved from the magma that have mixed with meteoric-derived fluids. The effects of higher temperatures and the influence of a magmatic fluid therefore generates alteration mineral assemblages not typically formed in a purely hydrothermal environment. Drilling at Ngatamariki has encountered magmatic-hydrothermal minerals for the first time in the TVZ, and as such enables inferences to be made about fluid-rock interactions above the magmatic heat sources associated with TVZ geothermal systems.

## 2. GEOLOGICAL BACKGROUND

The geology of the northern part of the Ngatamariki geothermal field consists of four main elements (Figure 1): 1) silicic tuffs with minor andesite flows and associated coarse sediments of the lower Tahorakuri Formation; 2) interbedded lacustrine sediments and minor rhyolite and basalt lava flows of the upper Tahorakuri Formation; 3) Whakamaru group ignimbrite and post-Whakamaru pyroclastic and sedimentary cover; 4) dioritic to tonalitic plutonic rocks of the Ngatamariki Intrusive Complex (Chambefort et al, submitted). Two faults are mapped at the surface in this area of the field (Leonard et al., 2010), one south of NM4 and another between NM9 and NM2. Their depth extents, orientations, and offsets are not known.

The Ngatamariki Intrusive Complex is a texturally and compositionally diverse composite pluton, containing microdiorite, diorite, and tonalite intrusive phases, and possibly associated mafic dykes. The microdiorite is white to pink, equigranular, aplitic to microporphyritic, and contains quartz and pseudomorphs of ferromagnesian minerals and plagioclase (Chambefort et al, submitted). The diorite is greenish-grey, fine-grained, equigranular, and contains mostly plagioclase, amphibole, magnetite, and quartz, with rare pyroxene (Christenson et al, 1998; Lewis et al, 2012, 2013; Chambefort et al, submitted). The tonalite is greyish-white, porphyritic, and contains distinctive rounded quartz phenocrysts, plagioclase, rare ferromagnesian minerals, and magnetite in a granophyric to myrmekitic groundmass (Lewis et al, 2012, 2013; Chambefort et al, submitted). The mafic dykes consist of plagioclase microlaths that define a pseudo-trachytic texture within a completely hydrothermally altered fine-grained groundmass.

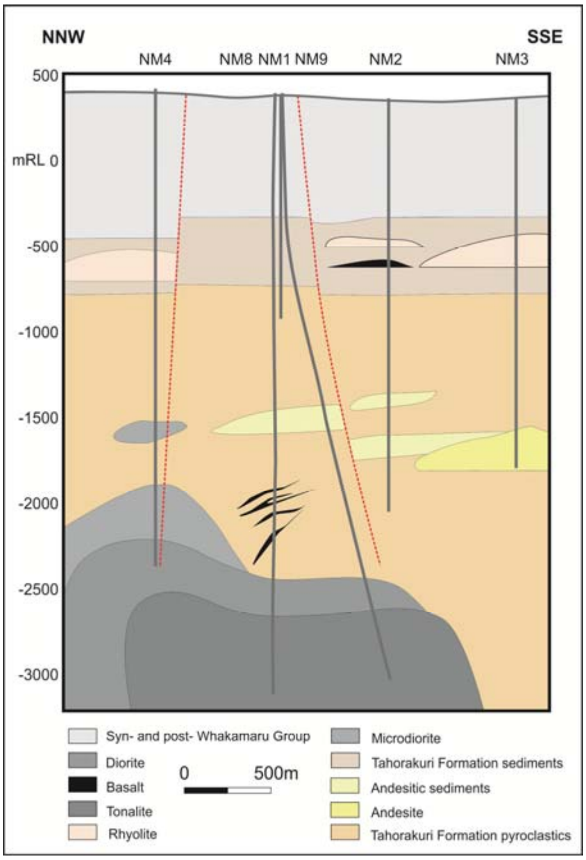


**Figure 1: Simplified geological cross-section through the northern part of the Ngatamariki geothermal field. Wells = solid grey lines. Inferred faults = dotted red lines.**

Microdiorite and tonalite in the intrusive complex have been dated using zircon U-Pb geochronology at 716 ka and 644 ka, respectively (Chambefort et al, submitted). Based on the stratigraphic relationships, the microdiorite and tonalite are inferred to represent the oldest and youngest intrusions, respectively, and therefore the ages obtained by Chambefort et al (submitted) bracket the emplacement time of the intrusive complex. Hydrothermal amphibole in altered diorite, the intrusive lithology occurring stratigraphically between the microdiorite and tonalite, was dated at 550 ka using Ar-Ar geochronology by Arehart et al (2002), who inferred this to represent the cooling age for the intrusive complex.

At the time of emplacement, country rock above the pluton consisted of 800 – 1700 m of mostly Tahorakuri Formation silicic pyroclastics that can be broadly grouped in order of deposition into non-welded crystal-poor tuffs, local andesite lavas and associated proximal coarse volcaniclastic breccias, pumiceous crystal-lithic tuffs, and lenticular vitriclastic crystal-rich welded ignimbrite (Lewis et al, 2012, 2013; Chambefort et al, submitted). Precise definition of the internal stratigraphy of the Tahorakuri Formation at Ngatamariki is severely hampered by intense and pervasive hydrothermal alteration. Above the pyroclastic succession are 200 – 400 m of interbedded lacustrine sediments, tuffs, and small rhyolitic lava flows and basaltic breccias (Chambefort et al, submitted). The uppermost 700 – 800 m of the Ngatamariki stratigraphic sequence postdates the emplacement of the intrusive complex (Arehart et al, 2002; Chambefort et al, submitted), and consists of the 330 ka Whakamaru Group ignimbrites, and younger overlying sediments, tuffs, and rhyolite lavas and/or domes.

The magmatic-hydrothermal alteration halo above the Ngatamariki Intrusive Complex was first recognised when NM4 was drilled and the diorite was intersected at ~-2290 mRL. In this well, Wood (1986) described the pervasive and texturally destructive quartz-white mica-pyrite “phyllic” alteration above the pluton and characterised the entire stratigraphic sequence between ~-810 and -2290 mRL simply as “phyllic zone (intensely altered volcanic rocks).” Christenson et al (1997) presented unequivocal evidence implicating magmatic fluids in formation of the phyllic alteration, citing fluid inclusions in vein quartz that contain >30 wt % NaCl equiv. brines and homogenise at temperatures >500°C, as well as mineral stable isotope evidence using quartz-water and anhydrite-water equilibria that indicates a magmatic fluid contribution (see also Chambefort et al, 2011).

## 3. METHODS

In order to understand the spatial relationships of the magmatic-hydrothermal alteration types at Ngatamariki, drill cores and cuttings were analysed from five wells located in the northern part of the field. From north to south they are NM4, NM8, NM1, NM9, and NM2 (Figure 1). A total of 23 drill cores (and any corresponding thin sections) were examined. Drill cuttings, collected as 5 m composite samples, are available from a combined drilled interval of ~8.4 km.

Samples were analysed for mineralogy by short-wave infrared spectrometry (SWIR) and X-ray diffraction (XRD), and for textural relationships by hand sample examination and thin section microscopy. SWIR spectrometry was conducted on 23 cores and 226 cuttings samples using the TerraSpec 4 portable field spectrometer housed at GNS Science. The Terraspec 4 measures the absorption of wavelengths of visible (350 – 700 nm), near infrared (700 – 1300 nm), and short-wave infrared (1300 – 2500 nm) light by certain molecular bonds (including Al-OH, Fe-OH, Mg-OH, $CO_3^{2-}$, $OH^-$, $H_2O$, and $NH_4^+$) within the crystal lattice of a mineral.

The result is an absorption spectrum indicating the presence of certain minerals within a sample. Generally, micas and clays are detectable down to as little as 3 vol. % of a sample, whereas carbonates and chlorite may require up to 20 vol. % to be detected (Lipske and Dilles, 2000). Samples are dried prior to analysis, analysed at least twice with 10 second scan intervals, and interpreted with the aid of The Spectral Geologist (TSG) software suite. Representative absorption spectra from Ngatamariki are presented in Figure 2, and discussed in the following section.

XRD analyses were conducted at GNS Science using a PANalytical Phillips X’Pert Pro X-ray diffractometer with Cobalt K-alpha (CoKα) radiation (40 kV, 45 mA). Clay separate (≤ 2 μm) samples were run at a step size of 0.05° between 2θ = 2° and 80°, and the resultant diffraction patterns were interpreted using Jade 3.1 software.

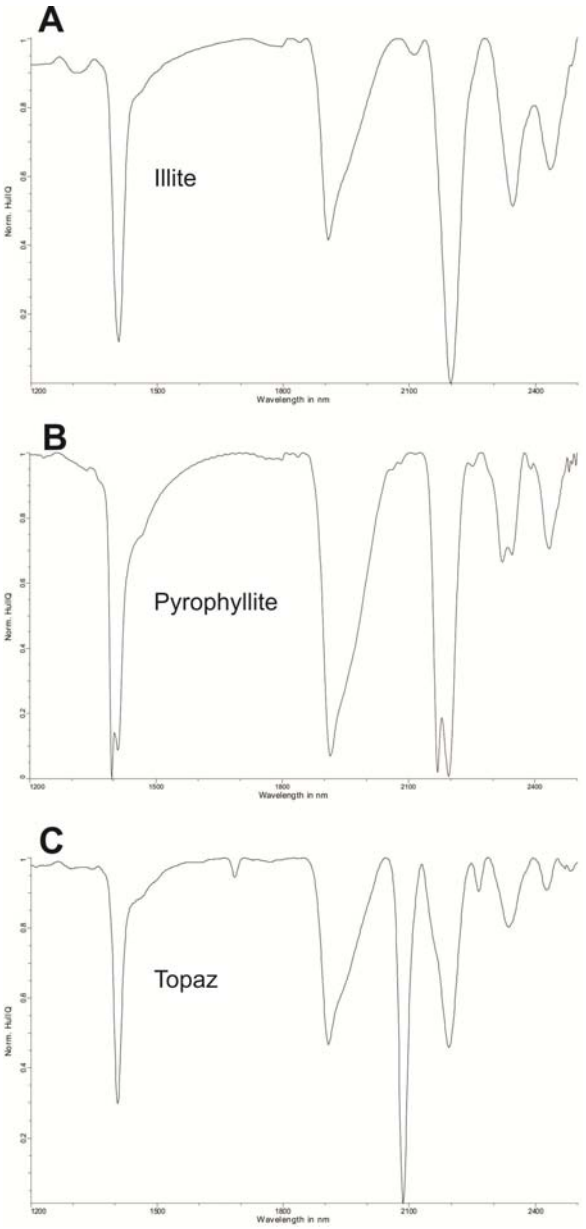


**Figure 2. Representative SWIR spectra plotted as the normalised hull quotient of reflectance. A) Illite, NM4, -1500 mRL. B) Pyrophyllite; note the similarity to the illite profile, except that most absorption features are doublets; NM9, -1910 mRL. C) Topaz; note the distinctive absorption feature at 2085 nm; NM4, -1450 mRL.**

## 4. ALTERATION TYPES

Examination and analysis of cores and cuttings from the northern part of the Ngatamariki field helped to further define the extent of the phyllic alteration reported by Wood (1986) and Christenson et al. (1997), but also revealed the presence of other, previously un-documented relict magmatic-hydrothermal alteration types. For the purposes of discussion, the standard hydrothermal alteration nomenclature from the porphyry and epithermal mineral deposit literature (Meyer and Hemley, 1967; Sillitoe, 2010) is used here. The magmatic-hydrothermal alteration types recognised at Ngatamariki are: potassic, phyllic, and advanced argillic.

### 4.1 Potassic Alteration

In porphyry systems, potassic alteration usually consists of K-feldspar, biotite, and magnetite ± anhydrite (Meyer and Hemley, 1967; Sillitoe, 2010). Additionally, in ore-bearing environments the low-sulfidation state sulphide minerals (i.e., high metal cation to sulphur ratio) such as chalcopyrite, pyrrhotite, or bornite are common (Sillitoe, 2010). At Ngatamariki, potassic alteration, encountered at deep levels in NM8 and NM9, is characterised by biotite, magnetite, and K-feldspar ± anhydrite in a zone extending to ~500 m above the pluton.

In NM8, flecks of secondary magnetite and dark brown biotite are observed above the intrusive complex in drill cuttings to levels as shallow as -1940 mRL, and K-feldspar is detected by XRD below -2390 mRL. In NM9, secondary magnetite is present in trace amounts up to -1900 mRL and is consistently present in cuttings beneath -2000 mRL, and secondary biotite is present in cuttings beneath -2290 mRL.

Biotite, magnetite, K-feldspar, and chalcopyrite are present within a mafic dyke irregularly cross-cutting intensely altered Tahorakuri Formation pyroclastic wall rock in drill core at -2160 mRL in NM8. In thin section, interstitial space surrounding weakly altered trachytic plagioclase laths (≤ 2 mm) is completely replaced by fine euhedral crystals (≤ 75 μm) of dark brown biotite. The dyke margins contain irregular zones (≤ 2 mm wide) with mosaics of quartz and euhedral K-feldspar, and chlorite pseudomorphs of biotite (Figure 3A, B). Hairline veinlets of biotite and magnetite ± chalcopyrite cross-cut the dyke (Figure 3C). These are cut by late quartz veins having diffuse haloes of chlorite and epidote that replace the biotite.

### 4.2 Phyllic Alteration

Phyllic, or sericitic, alteration is generally dominated by white mica ("sericite," i.e. muscovite, illite-smectite, and/or illite), quartz, and pyrite (Meyer and Hemley, 1967; Sillitoe, 2010). At Ngatamariki, the phyllic alteration is pervasive and widespread in NM8, NM9, NM1, and especially NM4. In NM4, the zone is dominated by quartz, interstratified illite-smectite, and pyrite between -400 and -1350 mRL, and from -1350 to -1850 mRL nearly all primary igneous textures are destroyed by pervasive alteration to quartz, illite (Figure 2A), pyrite, and chlorite ± sphalerite and galena (Wood, 1986; Christenson et al, 1997; Arehart et al, 2002). In NM8 and NM9, the Tahorakuri Formation tuffs are similarly altered, bleached, brecciated, and cross-cut by dense networks of veins containing quartz, pyrite, illite, and calcite. In NM8, drill cuttings between -1310 and -1440 mRL (and similarly in NM9 between -1400 and -1460 mRL) are dominated by quartz-pyrite stockworks and cement-dominated jigsaw and crackle breccias containing clay-altered tuff clasts (Lewis et al, 2012, 2013). The phyllic zone is the most widespread and extensive of the magmatic-hydrothermal alteration types at Ngatamariki, grading downward into the potassic zone near the intrusive complex and upward into zones of advanced argillic alteration near the paleosurface.

### 4.3 Advanced Argillic Alteration

Hypogene advanced argillic alteration is usually characterised by the presence of one or more of dickite, pyrophyllite, alunite, and pyrite; other minerals that may be present include vuggy quartz, tourmaline, andalusite, topaz, and zunyite (Meyer and Hemley, 1967; Sillitoe, 2010).

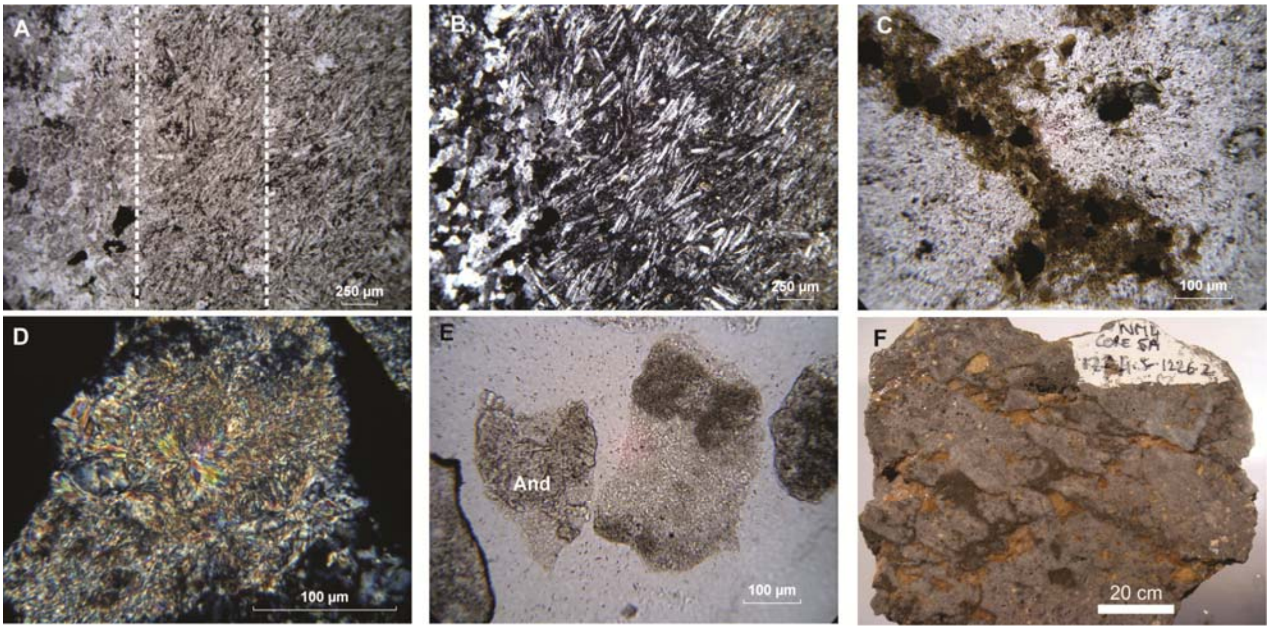


**Figure 3. Photomicrographs of alteration mineralogy and textures (PP = plane-polarised light; XP = cross-polarised light; HS = hand specimen). A (PP) and B (XP): Predominantly K-feldspar (left third) and biotite (right third) progressively replacing trachytic plagioclase in mafic dyke. Biotite in middle third is replaced by chlorite; NM8, -2160 mRL. C (PP): Biotite-magnetite vein cross-cutting pyroclastic rock of the Tahorakuri Formation; NM8, -2160 mRL. D (XP): Pervasive white mica alteration; XRD indicates presence of pyrophyllite and muscovite; NM9, -1910 mRL. E (PP): High-relief andalusite (And) being replaced by fine white mica; NM9, -2200 mRL. F (HS): Longitudinal slice through core showing vuggy silica cross-cut by pyrite veinlets and lenses, and containing illite patches; NM4, -870 mRL.**

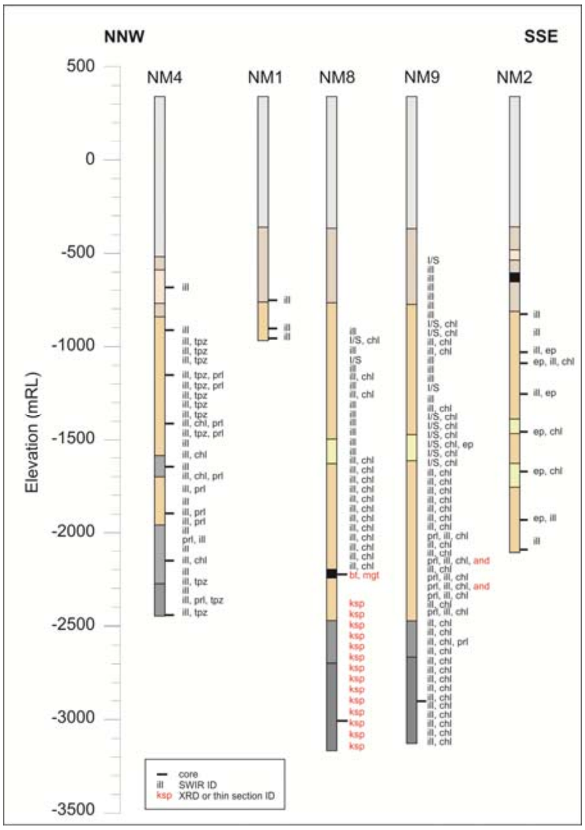


**Figure 4. Well logs showing alteration minerals identified by SWIR, and additional key magmatic-hydrothermal alteration minerals identified by XRD and/or thin section. Colours within well traces represent stratigraphy and are the same as those in Figure 2. SWIR results are presented as composite mineralogy over ~50 m intervals. Distance between wells is arbitrary. Mineral abbreviations: ill = illite, I/S = illite-smectite, chl = chlorite, ep = epidote, bt = biotite, mgt = magnetite, ksp = K-feldspar, prl = pyrophyllite, tpz = topaz, and = andalusite.**

At Ngatamariki, advanced argillic alteration is dominated by pyrophyllite, with local andalusite and/or topaz. Pyrophyllite is detected by SWIR spectrometry in NM4 sporadically, generally between -1100 and -1200, -1375 and -1425, -1650 and -1750, -1850 and -1900, and at -2000 and -2350 mRL. In NM9, pyrophyllite is present at -1910 (Figure 2B), consistently between -2050 and -2280, and at -2470 and -2560 mRL (Figure 4).

Thin sections of drill cuttings from NM9 at -1910 mRL show intensely altered, fragmental crystal-poor tuff (Tahorakuri Formation) with highly crystalline radial growths (≤ 50 µm) of white mica (Figure 3D; XRD analyses and SWIR spectrometry indicate mostly pyrophyllite with some illite), as well as quartz, chlorite, and rare epidote. Pyrophyllite has not been detected in NM8 or NM1. Wood (1985b) noted pyrophyllite in a mudstone cored at -380 mRL in NM2.

Andalusite, identified in thin sections and confirmed by whole rock XRD analysis, is an alteration product of the intensely altered Tahorakuri Formation pyroclastics in NM9 at -2100, -2200, and -2410 mRL. Thin sections show silicified matrix containing high-relief prismatic pinkish-brown grains (≤ 300 µm) of andalusite, whose morphology suggests that they are pseudomorphs after feldspar (Figure 3E). The andalusite shows incipient alteration to clays or white micas.

Topaz is identified by its strong SWIR absorption spectrum, which is dominated by a sharp, deep absorption feature at 2085 nm (Figure 2C). SWIR spectrometry indicates that topaz is present in appreciable amounts in NM4 between -950 and -1450 mRL, and sporadically beneath this at -2225 and -2395 mRL (Figure 4).

Vuggy quartz (± abundant pyrite ± chalcedony) is recognised in core from NM4 at -870 mRL (Figure 3F), in drill cuttings from NM8 between -440 and -1040 mRL, and in drill cuttings from NM9 between -440 and -820 mRL. These depths, which are within and immediately below the interbedded lacustrine sediment and tuff sequence at the top of the Tahorakuri Formation, approximately coincide with the Ngatamariki paleosurface (inferred to be ~950 m below the present surface, or -600 mRL) during the time of intrusion emplacement (Chambefort et al, submitted).

## 5. DISCUSSION AND CONCLUSIONS

Progressing upward and outward from the composite intrusive complex, the relict magmatic-hydrothermal alteration types at Ngatamariki include zones of potassic, phyllic, and advanced argillic alteration. These alteration zones, representing the old Ngatamariki magmatic-hydrothermal system, have been overprinted by propylitic type alteration consisting of chlorite, epidote, calcite, and some wairakite. The propylitic alteration is the product of near-neutral hydrothermal fluids that are associated with the modern geothermal system and are commonly found in the TVZ. Figure 5 presents a reconstructed interpretive cross-section depicting the relict Ngatamariki magmatic-hydrothermal system at the time of intrusion emplacement. Alteration zones and the processes contributing to their formation are presented schematically, and discussed below.

Potassic alteration is not observed in NM4. However, the intrusive complex is shallowest beneath this well, and the country rocks above the intrusion exhibit the most intense phyllic and advanced argillic alteration. It is therefore likely that any potassic alteration in this area has been overprinted. Phyllic alteration is most intense in NM4 but is also intense and pervasive in NM8 and NM9. It is the most widespread and easily recognised of the magmatic-hydrothermal alteration types at Ngatamariki.

Advanced argillic alteration is apparently lacking in NM8, restricted mostly to high-temperature pyrophyllite- and andalusite-bearing assemblages at deeper levels (below -1860 mRL) in NM9, and to topaz- and pyrophyllite-bearing assemblages at shallower levels (above -1450 mRL) in NM4. While it is possible that advanced argillic alteration was present in NM8 but has been overprinted, this is unlikely because advanced argillic alteration, in which mobile elements have been stripped from the rock, is difficult to overprint. Zones of advanced argillic alteration in NM4 and NM9, although exposed to fluids in the modern geothermal system, are not overprinted. It is therefore possible that advanced argillic alteration never formed in the rocks encountered by NM8. However, because advanced argillic alteration often forms as late-stage fluids travel along structural conduits (Lipske and Dilles, 2000; Khashgerel et al, 2009; Sillitoe, 2010), it is also possible that advanced argillic alteration is present in the vicinity of NM8 but was not encountered by it due to the alteration not being laterally extensive.

The magmatic-hydrothermal alteration types at Ngatamariki and their spatial relationships bear strong genetic similarities to those found in porphyry copper and high sulfidation epithermal gold deposits (porphyry-epithermal systems). Genetic models for the formation of these types of mineral deposits (Meyer and Hemley, 1967; Arribas, 1995; Corbett and Leach, 1998; Robb, 2005; Seedorf et al, 2005; Sillitoe, 2010) provide insights into how the relict Ngatamariki magmatic-hydrothermal system probably developed.

As a magma rises upward through the crust to depths of ~4 km, depressurisation causes it to exsolve a hypersaline (35-70 wt. % NaCl equiv.) liquid (containing Na, K, and Fe-chlorides) and low-salinity vapour phase (containing $H_2S$, $SO_2$, $CO_2$, HCl, and HF; Hedenquist and Lowenstern, 1994; Sillitoe, 2010). As the magma cools, the fluid and vapour phases ascend, interacting with wall rock at high temperatures (> 500°C). Potassium and iron are added to the host rocks, resulting in biotite, K-feldspar, and magnetite alteration. Sinuous quartz veins form under high temperature ductile conditions (Sillitoe, 2010). Peripherally, conductive heat from the pluton drives circulation of meteoric water, which causes hydration of wall rocks, resulting in the typical propylitic assemblage containing predominantly chlorite, epidote, and calcite.

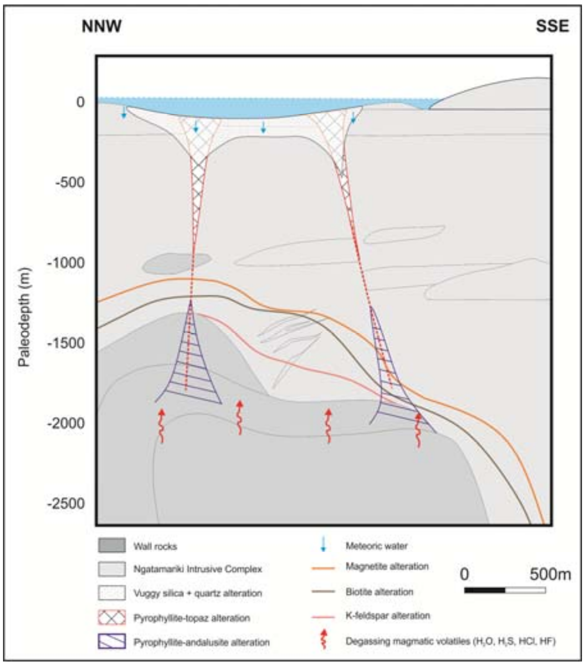


**Figure 5. Reconstructed interpretive cross-section through the relict Ngatamariki system at the time of intrusion and alteration, based on known paleosurface depth ~950 m below present surface, contemporaneous with rhyolite flow (top right) and tonalite intrusion. Lithologic units are outlined and are the same as those in Figure 1. Some alteration has been overprinted by the current system.**

Dilution of the magmatic-derived hypersaline liquid by meteoric waters and, if pressures are low enough, the condensed vapour phase, produces slightly acidic fluids that leach cations from the wall rock, and results in a phyllic assemblage of K-Al silicates (muscovite), quartz, and pyrite (Hedenquist and Lowenstern, 1994; Arribas, 1995; Sillitoe, 2010). In-situ crystallisation through hydrothermal mineral deposition generates net volume increases, resulting in brittle fracturing and the formation of stockwork veins and breccias (Sillitoe, 2010), a phenomenon which Christenson et al (1997) suggested may have occurred at Ngatamariki. Continued evolution of the volatile-rich vapour phase from the magma (via cooling or depressurisation) and interaction with meteoric-derived water results in condensation of the dissolved gases to form strongly acidic fluids that leach the wall rock of all minerals except aluminosilicates (e.g., kaolinite, dickite, pyrophyllite; Arribas, 1995; Sillitoe, 2010). At deep levels, andalusite may be produced at temperatures between ~350-390°C (Corbett and Leach, 1998; Seedorf et al, 2005). Pyrophyllite indicates temperatures between ~280-360°C (Seedorf et al, 2005). Topaz, although not a significant indicator of temperature (it forms at a variety of temperatures, ranging from ≤ 280°C to ≥ 550°C; Reyes, 1990; Seedorf et al, 2005; Sillitoe, 2010), indicates the presence of HF amongst the volatiles. In the most extreme cases of leaching (e.g. pH 2), only vuggy silica will remain (Arribas, 1995).

The similarity of the relict Ngatamariki magmatic-hydrothermal system with porphyry-epithermal systems is striking, and includes all the main factors: the composite intermediate to felsic intrusion, a zoned alteration halo, and hypersaline magmatic fluids and magmatic volatiles that interacted with the wall rock. As such, it also bears striking similarities to modern Philippine geothermal systems, which commonly contain not only the neutral-pH suite of hydrothermal alteration minerals characteristic of New Zealand geothermal systems, but also contain extensive acid alteration. Whereas typical New Zealand geothermal fluids contain 3-4% magmatic fluid and have salinities of 1-2000 ppm Cl, typical Philippine geothermal fluids contain up to 50% magmatic fluid and have salinities on the order of 10,000-15,000 ppm (Browne, 1978; Reyes, 1990; Corbett and Leach, 1998).

The record of fluid-rock interactions preserved within the magmatic-hydrothermal alteration zones of the relict Ngatamariki system represent a likely analogue for the conditions and processes happening currently beneath TVZ geothermal systems, with the exception that the intrusion at Ngatamariki reached shallower levels than those reached by intrusions at the moment. For example, magnetotelluric evidence (Bertrand et al., 2012) and recent sulphur isotopes from anhydrite (Chambefort et al, 2011) suggest the presence of a shallow degassing intrusion at ≤ 4km depth beneath the Rotokawa geothermal system. The record of deep magmatic-hydrothermal conditions at Ngatamariki could represent a snapshot of fluid-rock interactions currently occurring beneath Rotokawa, as well as in other TVZ geothermal systems.

## 6. ACKNOWLEDGEMENTS

The authors thank Mighty River Power for their input, as well permission to utilise rock samples from NM8 and NM9, and to publish this data. Te Arawa Group Holdings is thanked for allowing use of samples from NM1, NM2, and NM4. We acknowledge funding support for this project from GNS Science CSA (Core Science Area) Geothermal Research Programme, and the Royal Society of New Zealand Marsden Fund to IC, “Fingerprinting of Geothermal Fluids: Tracking the Magmatic Signature.”

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