Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

New (Zealand) Perspectives on Continental Arc Geothermal Systems – Overview and Future Prospects

Isabelle Chambefort[1], Colin JN Wilson[2] and Julie V Rowland[3]

[1]GNS Science, Wairakei Research Centre, Taupō 3377, New Zealand

[2] SGEES, Victoria University, Wellington 6140, New Zealand

[3] School of Environment, University of Auckland, Auckland 1142, New Zealand

i.chambefort@gns.cri.nz

Keywords: Geothermal system roots, caldera, brittle-ductile transition, basement, accommodation zones

ABSTRACT

An enduring question in geothermal exploration and development is: what controls the longevities and positions of geothermal systems in areas of active volcanism and rifting? Can deep-seated crustal discontinuities focus the upwards transport of subduction-related volatiles and influence the compositional variability in magmatic and geothermal fluids? Rifting arc models of the Taupō Volcanic Zone (TVZ, North Island, New Zealand) are still challenged to link disparate observations, including deep seismicity, magnetotelluric (MT) models, the location and evolution of geothermal systems, magmatic and aqueous fluid compositions, caldera locations and the North Island tectonic environment. We here synthesise published geophysical, geological and geochemical studies to propose an integrated model and suggest future research avenues. The TVZ represents the on-land continuation of the Tonga-Kermadecs arc/back-arc system, marked in its central part by intense silicic volcanism and associated magmatism expressed as 23 high temperature (>250 °C) geothermal systems. To accommodate the slightly oblique extension in the TVZ, the brittle crust is segmented, with accommodation zones orientated oblique to the arc. These accommodation zones may also be the expression of cross-arc magmatic migration as seen in the northern, offshore continuation of the arc structure in the Havre Trough. Published 3D magnetotelluric inversion models of several TVZ geothermal fields propose deep feeder zones (>3-5 km depth) with a NW-SE cross-arc orientation. These magnetotelluric anomalies are interpreted as resulting from fluids (magma or aqueous) in the crust. We hypothesise that deep, long-lasting, NW-SE crustal discontinuities favour permeability in the proposed ductile crust. These discontinuities enable vertical mass transport from the mantle wedge, enhancing crustal melting and creating ridges on the sub-surface plane of the isotherm that is widely interpreted as the brittle–ductile transition. These ridges create loci for groundwater convective cells and explain the spatial persistence of many of the geothermal systems (despite interruption in some cases by caldera collapse) and the variability of geothermal fluid chemistry.

1. INTRODUCTION

There have been global efforts in the last ~10 years to better understand deep geothermal resources. In New Zealand, these efforts have resulted in state-of-the-art geophysical studies, the acquisition of field-scale fluid and rock geochemistry, and regional structural and magmatic investigations in order to characterise the deep-seated controls on New Zealand geothermal systems. A particular emphasis has been on extending the knowledge base available from present drilling depths (maximum ~3 km) to infer the sources and pathways of deep-seated feeder zones for high-temperature geothermal fluids and their potential for utilisation. Independent studies in various disciplines have generated a large amount of data that can now start to be integrated to test new model hypotheses.

The central portion of the Taupō Volcanic Zone (TVZ) in New Zealand is the locus of intense silicic volcanism and magmatism associated with 23 high-enthalpy geothermal systems, representing in total a heat flux about an order of magnitude higher than in conventional arcs (Bibby et al., 1995; Wilson and Rowland, 2016) and comparable to Yellowstone (Hurwitz and Lowenstern, 2014). The locations and chemistries of the geothermal systems are a by-product of the tectonic rifting in the arc setting, and clear links between the magmatism and geothermal activity have been invoked in multiple studies. An enduring challenge that the New Zealand geothermal community has faced for the last ~50 years is to constrain the volcanic-hosted versus volcanic-influenced nature of the fluid chemistries in the geothermal systems. Giggenbach (1995) proposed that up to 20% (e.g. for Rotokawa and Waiotapu geothermal fields) of the water was magmatic in origin based on O and H isotopes, using as a basis the water compositions defined on active andesitic volcanoes world-wide.

Although the chemical characteristics and behaviour during utilisation of a given geothermal reservoir may be relatively well understood, in order to achieve a sustainable utilisation of the resource and consider the targeting of future deep resources, five fundamental uncertainties need to be addressed:

1) What is the nature of the deep upflow/plume?
2) What are the magmatic contributions?
3) How do geothermal systems evolve?
4) Why are they located where they are?
5) Where is the best potential for utilisation?

When considered in isolation, geophysical, structural, and igneous petrology studies are challenged to explain the variations in fluid compositions observed in the TVZ and their deep controls. By combining recent geophysical, geological and geochemical studies we can revise and refine our views on the external controls for the well-known Henley and Ellis (1983) geochemical model (Fig. 1A) and revisit the Giggenbach (1995) andesite arc ('arc type') versus bimodal (basalt-rhyolite) back-arc ('rift-type') model (Fig. 1B). In the following sections, we summarise the characteristics of TVZ geothermal systems and refine, on the basis of recent and ongoing research, their magmatic, geological, structural and geophysical constraints and problems. We then discuss new perspectives on the deep roots of these systems and their future exploration.

2. CHARACTERISTIC OF TVZ GEOTHERMAL SYSTEMS

2.1 Geochemistry

In this paper, we use the term 'geothermal system' to define an active hydrothermal system characterised by high-enthalpy (T > 250 °C in the reservoir) and near neutral-pH chloride reservoir fluid compositions in a volcanic-hosted environment (Fig. 1).

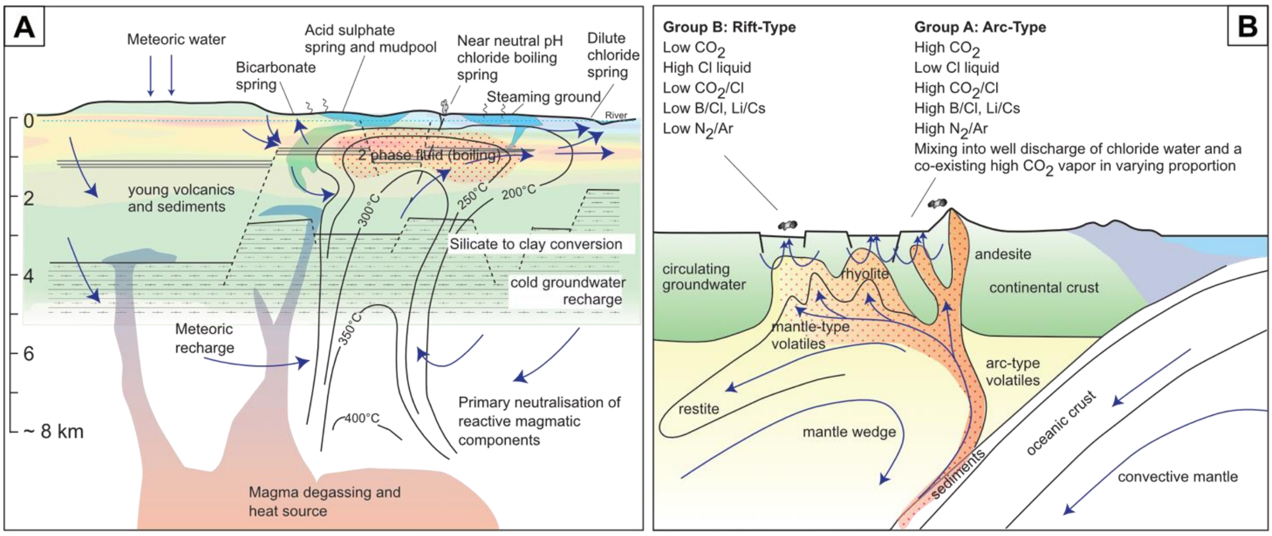

Figure 1: (A) Conceptual model of continental arc geothermal systems based on fluid chemistry and geological records. From Henley and Ellis (1983), as modified by Hedenquist (1986). (B) Schematic model compatible with fluid geochemical evidence illustrating the potential processes forming variations in the chemical composition of fluid discharges from TVZ geothermal systems (from Giggenbach, 1995).

In the central TVZ, the combination of a rifting arc and high volumes of (dominantly rhyolitic where erupted) magma accompanies a thinned quartzo-feldspathic mid- to upper crust (above 15-16 km depth), a denser lower crust of mafic underplated intrusions (i.e., with higher seismic velocities than appropriate for quartz, feldspar-dominated rocks), and a high heat flow (Bibby et al., 1995; Harrison and White, 2004; Stern et al., 2010). This unique setting and the associated thick faulted sequences of pyroclastic deposits from the intense volcanic activity favour the deep circulation of groundwaters in convection cells. The meteoric water is then heated and convects toward the surface, along with some magmatic fluids, underneath focussed (5-25 km^2) hydrothermal surface expressions (Fig. 1A). The regional active faults, defining the Taupō Rift (Villamor et al., 2017), cutting through the volcanic sequence and underlying metasedimentary greywacke are generally considered to control deep penetration of the meteoric water in the crust (White and Reeves, 2017; Pearson-Grant et al., 2017).

Meteoric water dominates the hydrothermal fluid chemistry, but is mingled with a magmatic contribution, the proportions of which are widely debated (Giggenbach, 1992, 1993; Blattner, 1993; Giggenbach, 1995; Christenson et al., 2002). The circulation of meteoric waters, with the formation of deep, hot slightly acidic fluids, leads to intense hydrothermal alteration characterised by primary neutralisation (to yield near-neutral chloride reservoir fluids), silicate to clay conversion and shallow acid assemblages in steam-heated environments (Henley and Ellis, 1983; Hedenquist, 1986; Giggenbach, 1992: Fig. 1A).

Variations in gas and liquid chemistries from surficial and borehole fluids led Giggenbach (1995) to delineated gas-rich 'group A' systems (e.g. Kawerau, Ohaaki, Rotokawa: Fig. 1B) versus gas-poor 'group B' systems (e.g. Wairakei, Mokai, Rotorua), with Waiotapu geothermal fluid composition in between. Giggenbach (1995) proposed that group A discharge compositions were consistent with the addition of volatiles from subducted sediments (e.g. high N_2/Ar), whereas group B compositions were closer to mantle-derived fluids (via leaching or shallow degassing of "…rhyolite magma…", although note that the rhyolites themselves are not direct products of mantle melts). The variations in CO_2 and Cl abundances between groups cannot be explained solely by phase separation: an extra source of CO_2 as a separate gas phase is necessary in group A reservoirs, hence the term "gas-rich systems" (Giggenbach, 1995). He proposed that the excess gas is associated with a more arc-type andesitic magmatism, despite the fact that andesite is in itself a crustally controlled magma composition (e.g. Price et al., 2012).

2.2 Longevity - Geological Records

The age of an individual geothermal system is generally poorly constrained as the system is still hot, usually altered and therefore radiometric techniques such as $^{40}Ar/^{39}Ar$ are restricted in applicability. It is impossible mineralogically to make any distinction in the equilibrium alteration mineralogy in the host rock between that which formed last year or many thousands of years previously. The hydrothermal mineralogy is also strongly dependent on the water-rock equilibrium, and any temporal variations in the fluid (natural or anthropogenic) will induce hydrothermal overprinting in the system.

A close linkage between geological knowledge from geothermal drilling and high-precision dating of the volcanic stratigraphy is the key to assessing the minimum ages and lifetimes of geothermal systems. There is evidence that ancient hydrothermal events (represented by hydrothermal breccias and/or overprinted mineral assemblages) affected volcanic and sedimentary deposits at Kawerau, Tauhara, Wairakei, Orakeikorako, Te Kopia, and Ngatamariki (e.g. Chambefort et al., 2014, 2017). These fossil hydrothermal features are unrelated to the current geothermal activity and instead represent repeated hydrothermal activities in the same location.

Recent studies (Milicich et al., 2013a, 2020 this volume; Chambefort et al. 2014; Rosenberg, 2017) utilise U-Pb dating on zircon to demonstrate the superimposition on older hydrothermal events of the present-day systems at Kawerau, Ngatamariki and Wairakei, respectively. Evidence of buried phreatic eruption breccia older than the 360 ka Caxton rhyolite show that Kawerau system has been active (potentially episodically) in the same location at least since that time. The older hydrothermal system was likely fed by the rhyolitic magma source that produced the Caxton unit (Browne, 1979; Milicich et al., 2018). The current system is interpreted to reflect magmatism of the andesitic Putauaki volcano, with an onset of associated magmatism around ~16,000 years ago (Milicich et al., 2013b, 2018).

Similarly, a >5 km^3 buried intrusive complex, emplaced between 710 and 650 ka, at Ngatamariki produced a large hydrothermal alteration halo that likely was active for ~100 kyr (Chambefort et al., 2014). The relict acid and high temperature alteration patterns are in disequilibrium with the present-day geothermal fluid conditions (Chambefort et al., 2017). The deep source of the current system is poorly constrained, but the current model proposes a deep input from the SSE direction (Chambefort et al., 2016).

In the Wairakei-Tauhara geothermal system, several buried hydrothermal breccias represent past hydrothermal events in the same location, including the 100-150 ka Rautehuia Breccia (Rosenberg, 2017). Similarly, altered lithics are also common in some Whakamaru Group ignimbrite and young (post-30 ka) Taupō deposits. The hydrothermally altered clasts, in the young Taupō deposits come from systems that are separate and distinct from Wairakei-Tauhara, and were destroyed by the caldera eruptions.

2.3 Influence of Volcanic Events

At one extreme, the most catastrophic modification of a hydrothermal system is to be engulfed in a caldera collapse event. Hydrothermally altered clasts in the 25.4 ka Oruanui ignimbrite associated with the formation of the Taupō caldera are evidence that a hydrothermal system was active beneath the area consumed by caldera formation. The system at present may be considered to be recovering, as shown by localised zones of enhanced heat and fluid flow on the floor of the modern lake (Whiteford, 1996; de Ronde et al., 2002). Caldera-forming events may also induce extreme stress changes and modification of the hydrology and fault structure of any nearby hydrothermal systems. Indeed, such events have implications for the entire central TVZ, with permeabilities in the upper few kilometres of crust likely to change drastically, thus affecting heat and mass flow. Despite these impacts, it is apparent that many geothermal systems have been rejuvenated in the same location, with minimal long-term consequences from caldera-forming volcanic events (especially Wairakei-Tauhara: Rosenberg, 2017). While fluid chemistry, fracture/lithology-controlled permeability, and reservoir hydrogeological characteristics (fluid flow, feed zones, outflow) may have changed, the location of the deep fluid and/or heat source appears to remain relatively fixed. The Wairakei-Tauhara geothermal system appears to have been active through the period of the Taupō 232 AD eruption and, more recently, the Waimangu-Rotomahana geothermal system remained after the 1886 Tarawera eruption (Keam, 1988; Simmons et al., 1993; de Ronde et al., 2016), although with some changes in the patterns of surface activity.

Every drilled geothermal system in the TVZ is hosted not only by large volumes of silicic pyroclastic products but also by buried lava domes and flows. An important point is that the lava domes and flows represent directly past magmatic activity beneath the geothermal systems and thus their magmatic source can be inferred to have been a potential contributor for heat and fluids during the life history of the geothermal systems (Wilson et al., 2008; Milicich et al., 2013b; Rosenberg, 2017). Shallow intrusions are not an infinite heat source, however, as cooling happens quite rapidly (typically of the order of ~ 20 kyr), mainly due to meteoric water circulation (Cathles, 1977; Norton & Knight, 1977; Schöpa et al., 2017). The timing and longevity of the TVZ geothermal systems require a long-lasting magmatic heat supply that is repeatedly focussed in the same geographical area. It is often uncertain whether systems wane or die in between episodes of vigorous activity, but the important point is that the location of some hydrothermal systems has been the same for over half a million years (e.g. Chambefort et al., 2017).

What controls the location and the deep heat source of the geothermal systems is thus likely to be linked to structures or pathways beneath the brittle crust. This inference is in agreement with recent structural investigations (Villamor et al., 2017), which show that many active systems are located at fault intersections. However, not all intersections are favoured by hot plumes, implying that deep permeable structures are also necessary. We hypothesise that deep, long-lasting, crustal cross-arc discontinuities (occurring to accommodate the rifting and facilitate caldera volcano dynamics), favour permeability in the ductile crust.

Several features might control these deep discontinuities: 1) the position and orientation of deeply buried caldera margins or magmatic systems; 2) inherited basement structures; 3) magmatism – deep-seated mush versus shallow melt-rich intrusions; and 4) arc-scale processes. In the following sections, we discuss petrological and geophysical evidence on the structure of the ductile crust in the TVZ that can influence the locations and variations in chemistry of the geothermal systems.

3. CRUSTAL INFLUENCES ON THE TVZ GEOTHERMAL SYSTEMS

3.1 Caldera Collapse

The locations of TVZ calderas have been studied for many years (Modriniak and Studt, 1959; Wilson et al., 1995, 2009; Davy and Caldwell, 1998; Milner et al., 2002; Cole et al., 2005, 2010; Davy and Bibby, 2005; Spinks et al., 2005; Gravley et al., 2007; Seebeck et al., 2010). Recent work has proposed that some of the TVZ calderas, such as Okataina and Taupo, are influenced by the present-day NE-SW extensional tectonic regime and NW-SE or NNW-SSE-oriented inherited structures or basement structural trends aligned with the North Island Fault System (Milner et al., 2002; Cole et al., 2005; Spinks et al., 2005; Seebeck et al., 2010: Fig. 2).

The geometry of a caldera collapse structure is dependent on the depth, size, and shape of the magma volume that is syn-eruptively emptied (Roche et al., 2000; Acocella, 2007). As suggested by Cole et al. (2005), it is thus important to know what controls the location and geometry of the parental magma body. It can be inferred that magma distribution below a volcano may itself depend on the intersection between basement fault systems, and thus be oriented perpendicular to the rift axis, as at Okataina or Taupō calderas (Rowland et al., 2010: Fig. 2).

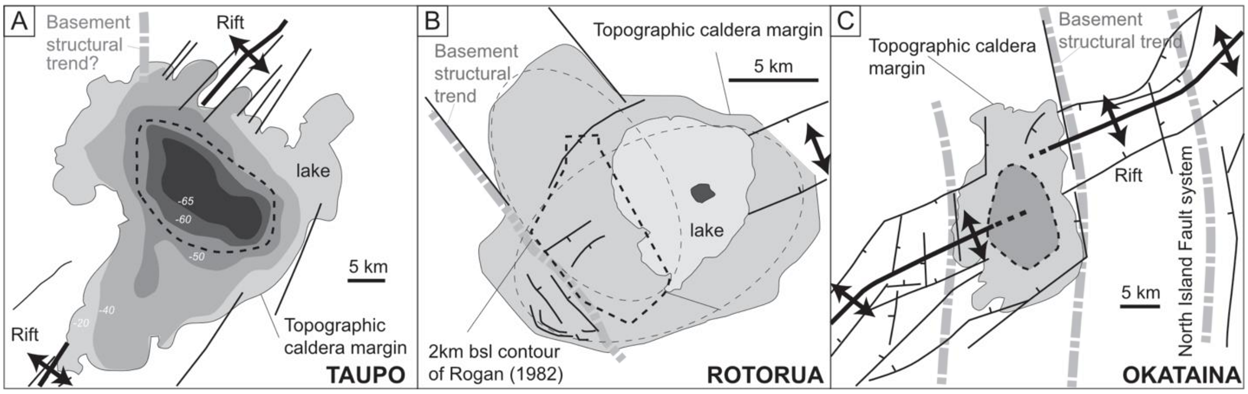

Figure 2: Schematic diagram of the main structural elements of A. Taupo, B. Rotorua and C. Okataina calderas (after Davy and Caldwell, 1998; Wilson, 2001; Milner et al., 2002; Cole et al., 2005, 2010; Davy and Bibby, 2005; Spinks et al., 2005; Gravley et al., 2007; Seebeck et al., 2010). Contours in panel A are residual Bouguer gravity anomalies from Davy and Caldwell (1998).

Caldera collapse can reach quite deep into the crust and has been interpreted to 'stop' at the brittle-ductile transition (Cole et al., 2005). Although the collapse itself may be contained within 3-4 km depth, the underlying source mush will extend deeper and be strongly decompressed, degassed and partially evacuated in some case following the caldera-forming event (e.g. Barker et al., 2015).

3.2 Basement Lithologies

The basement beneath the central TVZ consists of volcaniclastic sandstones and argillites of the Waipapa and Torlesse composite terranes. These rocks occur at the surface to the west and east of the TVZ, respectively (Edbrooke, 2005; Charlier et al., 2010; Leonard et al., 2010; Price et al., 2015). Wood et al. (2001) reported that the basement at Ohaaki differs compositionally from the basement at Kawerau geothermal system, with the latter likely to sustain brittle failure to greater depth due to its mineral content. The basement at Ohaaki contains a greater abundance of quartz and illitic/chloritic matrix (5 to 20 times more) when compared to the basement of the Kawerau geothermal field, which has a far greater abundance of lithic volcanic clasts. Clastic plagioclase occurs in similar amounts, but the total feldspar content in Kawerau greywacke is much higher because the andesitic volcanic clasts contain common microcrystals of plagioclase.

Similarly, Calibugan and Chambefort (2020, this volume) investigated the mineralogy of the basement for the Rotokawa geothermal field which proved to be relatively similar to Ohaaki basement terrane. It is thus inferred that the northern geothermal system(s?) sit on the andesitic-derived Waipapa terranes, while the southern systems of Ohaaki and Rotokawa sit on Torlesse metasandstone. The suture between the two terranes is buried beneath the Quaternary volcanic sequence and may not be a simple sub-vertical structure (cf. Charlier et al., 2010; Ring et al., 2019).

From a hydrological perspective, both terranes have insufficient primary permeability to sustain production: flow through basement requires connected fracture networks (e.g. Kawerau: Milicich et al., 2016).

3.3 Central Taupō Volcanic Zone Magmatic Setting

In the last decade, many petrological studies have refined our understanding of central TVZ crustal magmatic systems and how they evolved before and after caldera-forming events (e.g. Fig. 3: Wilson et al., 2006; Deering et al., 2008, 2011; Bégué et al., 2014; Barker et al., 2015, 2016; Gravley et al., 2016; Allan et al., 2017; Gualda et al., 2019). The evolution and differentiation of magmas beneath the central TVZ is debated: however, it is generally agreed that the voluminous crystal-poor rhyolites appear to be stored in the crust at shallow levels (Figs. 3, 4, Gualda et al., 2019), and accumulate rapidly before any given volcanic event (e.g. Barker et al., 2015, 2016; Allan et al., 2017). Based on volatile contents in quartz-hosted melt inclusions, and pyroxene and amphibole geobarometry, Liu et al. (2006), Shane et al. (2007, 2008), Deering et al. (2011), Barker et al. (2015) and Allan et al. (2012) have proposed that most of the crystal-poor silica-rich magma accumulates between 90 and 140 MPa pressure (~3.5-to-6 km depth: Fig. 3), whereas the source mush zones for the rhyolites extend deeper in the crust, down to 300 MPa (~ 12 km) or more. The mush zone is likely dominated by andesitic to dacitic overall compositions and can contain multiple pockets of variably differentiated bodies of melt (Bégué et al., 2014; Barker et al., 2015; Allan et al., 2017). The building of the Oruanui magma body (530 km^3) occurred over only a few hundred years at most and peaked within decades of the eruption (Allan et al., 2017). Other, smaller, examples also show comparable rates of accumulation of eruptible magma (e.g. Barker et al., 2016).

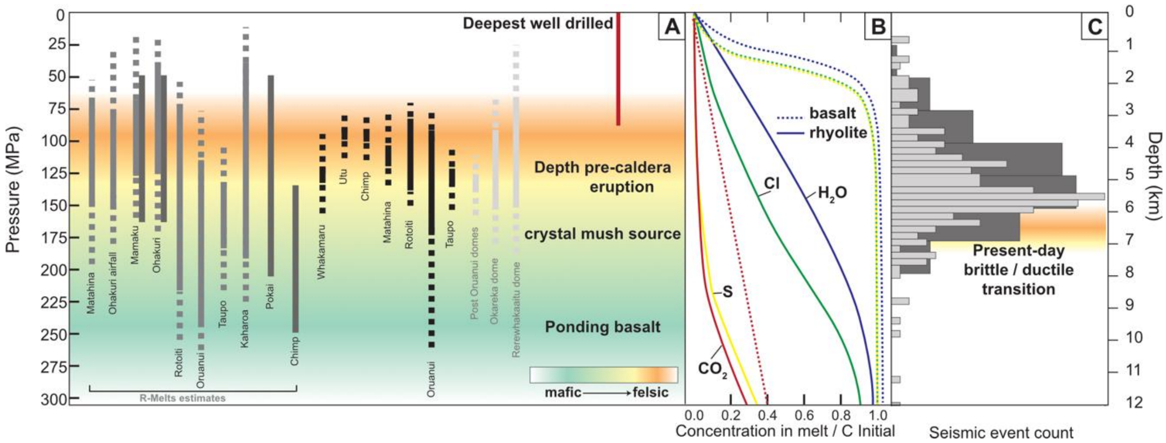

Figure 3: A. Petrological estimates of the pressures and storage depths of the high-Si rhyolites sampled in caldera-related (black) and dome (light grey) eruptions, from Liu et al. (2006); Shane et al. (2007, 2008); Deering et al. (2011); Allan et al. (2012, 2017); Barker et al. (2015, 2016); Rhyolite melts estimates are from Bégué et al. (2014) (pale grey) and Gualda et al. (2019; Qz-Pl storage; darkest grey); B. exsolution behaviour of various volatile components in rhyolite (full lines) and basalt (dashed lines), from Wallace and Edmonds (2011), C. Present-day seismic events as a function of depth, from Sherburn et al. (2003; Taupō area, dark grey) and Bannister et al. (2016; Okataina area, pale grey).

There have been proposed to be spatially distinct rhyolite end-member types (Deering et al., 2008, 2011; Bégué et al., 2014), although these often occur within single eruptions (e.g. Brown et al., 1998) or occur within the evolution of a single volcanic centre (e.g. Barker et al., 2015). The spectrum of rhyolite compositions presents variable volatile compositions, as based on analysis of quartz-hosted melt inclusions. Sulfur and CO_2 are generally low or below detection limits in quartz-hosted melt inclusions, while Cl and H_2O vary from 0.2 to 0.3 wt% and 4 to 6 wt%, respectively (Dunbar et al., 1989; Liu et al., 2006; Johnson et al., 2011; Bégué et al., 2015). Volatile melt inclusion data are also consistent with shallow depths as reported in Figures 3 and 4. Relatively low CO_2 contents in quartz-hosted and rare plagioclase hosted melt inclusions are showing similar depths, in particular for the later-erupted Oruanui magmas (~150 ppm CO_2, ~140 MPa: Liu et al., 2006). Johnson et al. (2011) and Bégué et al. (2015) also report very low CO_2 contents, mostly below detection limit, all associated with gas-saturated pressures of <150 MPa, and no detectable sulfur. These variations in bulk volatile concentrations can control variations in relative timing of exsolution of volatile phase(s) prior to melt inclusion entrapment, which are relevant to the magmatic contributions to geothermal fluids (Bégué et al., 2017) during genesis of the high silica rhyolites. Quartz, which hosts most of the studied melt inclusions, is only stable in the uppermost, cooler parts of the mush body prior to melt segregation (Liu et al., 2006; Bégué et al., 2015; Allan et al., 2017). Thus, the use of quartz-hosted melt inclusions to track volatile content and infer a chemical link with present day-geothermal fluid compositions may not be optimal.

Large shallow bodies of crystal-poor magma are, however, not seen in the available present-day seismic profiles of the central TVZ (Fig. 3). Geophysical studies show that the aseismic zone in the central TVZ is likely below 6 km depth where the brittle-ductile transition is located (Fig. 3; Sherburn et al., 2003; Stern et al., 2010; Bannister et al., 2016). During extraction of rhyolite melt from a mush zone and its storage at shallow depths this transition would be significantly shallower (3-4 km depths).

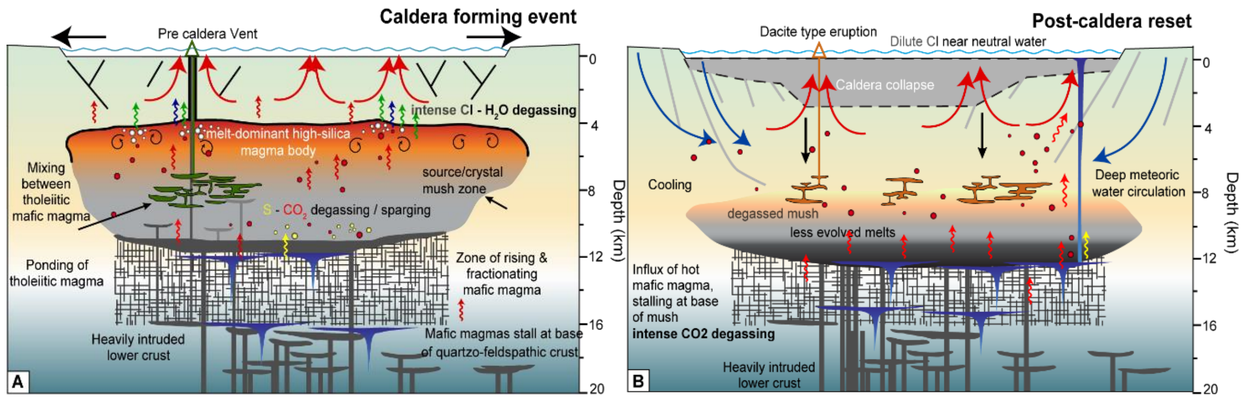

Figure 4: Scaled cross-sections through Taupō volcano, to show the evolution of the A. the Oruanui magma body before eruption and B. a post-caldera mush in replenishment (modified after Barker et al., 2015; Allan et al., 2017).

3.4 Influences on Crustal Fluid Flow

Geophysical and modelling studies of TVZ have previously discussed the notion of fixed positions for the geothermal plumes (Bibby et al., 1995; Kissling and Weir, 2005). Here we consider the evidence for fluid and heat transport beneath the brittle crust.

Three-D inversion magnetotelluric (MT) models of several TVZ geothermal fields show lower resistivity, deep feeder zones below 5 km depth that are oriented perpendicular or oblique to the overall arc alignment (Fig. 5A). Somewhat surprising is the orientation of the modelled MT anomaly below the Waimangu geothermal system (Heise et al., 2016; Fig. 5A), which is perpendicular to the orientation of the Tarawera Rift and the dike feeder of the 1886 eruption. Although the MT models image a potential mush zone below 8 km depth that is consistent with generalised petrological inferences about the location of central TVZ mush systems, the conductive pathway toward the geothermal expression is likely to be guided by oblique discontinuities that may be poorly expressed or absent at the surface.

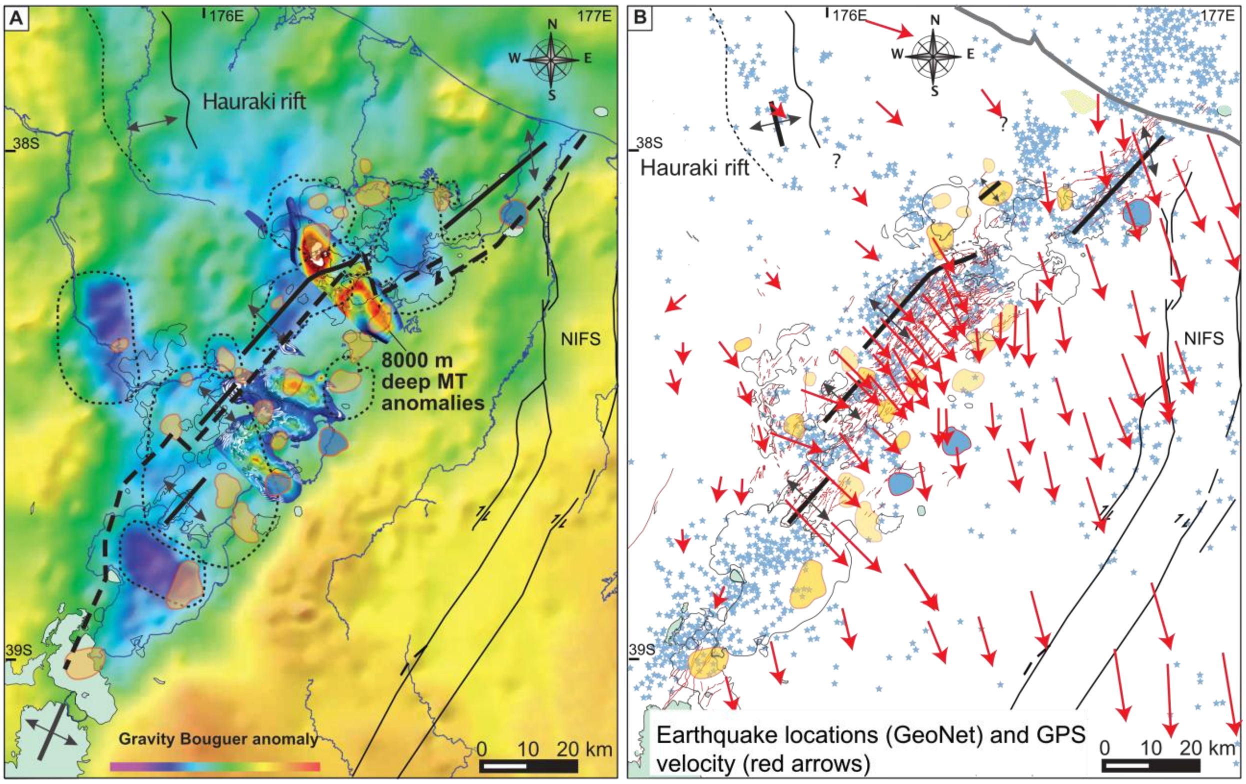

Figure 5. Compiled geophysical data for the central TVZ. A. Bouguer anomaly (and projection of the deep MT model at 8 km depth) from Bertrand et al. (2015) and Heise et al. (2016). Yellow and blue areas represent high gas and low gas geothermal systems, respectively. NIFS: North Island Fault System (strike slip). B. GeoNet earthquakes and GPS velocities in an Australian Plate fixed reference frame (Beavan et al., 2016), presented as reference.

In the Rotokawa-Ohaaki-Ngatamariki area, although the MT models suggest the presence of partial melts at shallow depth (5-4.5 km) with interstitial highly conductive hypersaline brine, no evidence of magmatic input is observed in terms of metal zoning (e.g., Zn) from the hypothetical intrusion to the surface (Chambefort, unpublished data). Normally, Cl-bearing brines are rich in metals, which results in a zonation in precipitates formed while the host fluids are rising toward the surface, as has been observed in the Ngatamariki fossil hydrothermal system (Chambefort et al., 2017). Gas-rich systems such Rotokawa have no chemical signs (e.g. elevated levels of Sn, Pb, Cu or Zn) indicative of an actively degassing shallow intrusion, despite the enrichment in gas.

The previous observations suggest that discontinuities or conductive zones in the ductile zone are likely pathways for CO_2 and subduction-related gases such as N_2. CO_2 will reach saturation at greater depths than any other volatiles in magmatic systems, possibly as deep as 15 to 20 km, depending on the magma composition. CO_2 will then behave independently from the other volatiles whilst rising through the crust following favourable pathways.

4. A DEEP-SEATED CONCEPTUAL IDEA

With the present state of knowledge, any attempts at combining all of these observations to propose a unique model for the overall suite of TVZ geothermal systems is clearly speculative. However, we propose here a conceptual idea explaining the how, why and where of the high-enthalpy geothermal systems that is summarised in Fig. 6.

Deep-seated, long-lasting, crustal cross-arc discontinuities, seen reflected at the surface in cross-linkages between rifting segments (e.g. Rowland and Sibson, 2001) or as biaxial extension (Villamor et al., 2017; McNamara et al., 2019) favour permeability in the crust and may ultimately be related to mantle processes (e.g. Illsley-Kemp et al., 2019). These discontinuities enable vertical mass transport of melts and volatiles, locally enhancing crustal melting and creating ridges on the brittle–ductile transition. These ridges create loci for the roots of groundwater convective cells. The presence of these ridges could explain the apparent persistence of the geothermal systems, despite interruption in some cases by caldera collapse or active faulting, and the variability of geothermal fluid chemistry and magma compositions.

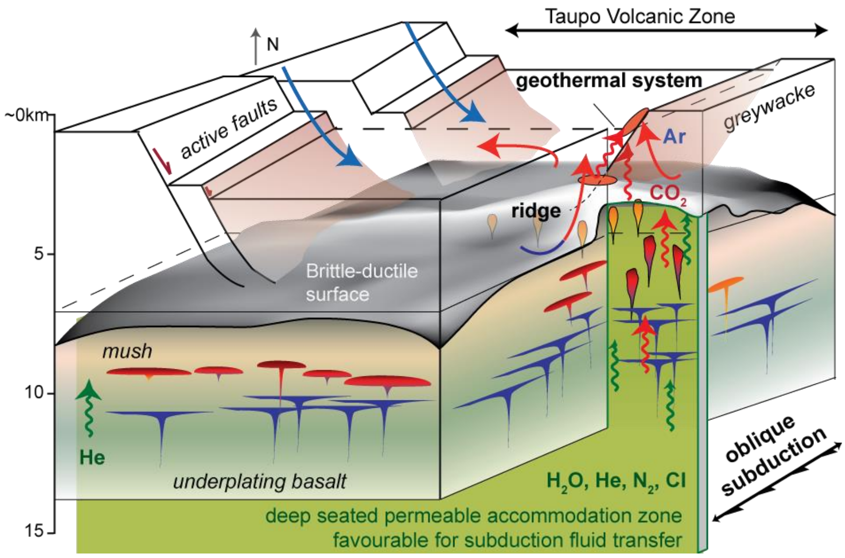

Figure 6. Conceptual model of the deep controls on high enthalpy New Zealand geothermal systems.

Downward recharge of cool meteoric water is enhanced by the abundant faulting of the Taupō Rift as suggested by Villamor et al. (2017). These waters, once heated, react with the volcanic sequence and greywacke basement rocks resulting in an enrichment in sulfur and chlorine (as suggested by Mountain et al., 2017). Simultaneously, deep-derived CO_2 and unreactive gases migrate upwards from the subducting slab and the deep crust via long lasting discontinuities. Passage of these gases in association with melts may influence the volume and composition of crustal magmatism. Rising hot CO_2 from the deep mush zone will encounter circulating groundwater at or above the brittle ductile transition creating a hot plume of two-phase upflow dilute fluid. The nature and role of the suture between the two greywacke basement terranes is uncertain. However, the change in GPS velocities and directions at the western margin of the TVZ (Fig. 5B) is likely to reflect a change in tectonic environment. Once in the upper brittle crust the fluid circulation is affected by the active faulting, and intersections with recent caldera margins and the North Island Fault System.

5. FUTURE PERSPECTIVES

Our model proposes a potential new avenue for exploration of deep high-temperature geothermal resources in New Zealand. If deep discontinuities are facilitating the escape of fluids and /or melt from the mush, we need to better understand their precise roles and location.

The increased knowledge acquired world-wide from geophysical exploration in particular from magnetotelluric modelling needs now to be coupled with geochemistry and structural understanding. We need to resolve the true chemical nature of the deep conductive anomalies in the crust. Refining this understanding is crucial for future geothermal exploration in particular for deep-seated potential future resources. Increase interest in supercritical resources in magmatic provinces (Iceland, Japan. Italy) requires a better grasp on magma versus fluids (brine) in the crust. A key for future deep geothermal drilling in volcanic domain particularly for those targeting supercritical fluid resources is to identify what is the true nature of geophysical models. Only by merging disciplines and innovating will we succeed to extract fluids at greater depths.

ACKNOWLEDGEMENTS

This research is currently supported by the Government of New Zealand through the GNS Science Strategic Science Investment Fund Programme "*New Zealand's Geothermal Future*". It also reflects generous funding for over a decade from the Foundation for Research, Science and Technology, Ministry for Business, Innovation and Employment, Marsden Fund and the geothermal industry, notably Contact Energy and Mercury NZ Limited. We also thank our colleagues in the geothermal industry for their contributions to many of the studies on which this summary paper is based. This work benefitted from numerous discussions with Sarah Milicich, Pilar Villamor, Ed Mrozcek, Ted Bertrand, Wiebke Heise, Simon Barker, Greg Bignall, Stephen Bannister, Susan Ellis, Darren Gravley, Florence Bégué, and Jim Faulds.

REFERENCES

Acocella, V.: Understanding caldera structure and development: an overview of analogue models compared to natural calderas, *Earth-Sci. Rev.*, **85**, (2007), 125–160.

Allan, A.S.R., Wilson, C.J.N., Millet, M.-A., and Wysoczanski, R.J.: The invisible hand: tectonic triggering and modulation of a rhyolitic supereruption, *Geology*, **40**, (2012), 563–566.

Allan, A.S.R., Barker, S.J., Millet, M.-A., Morgan, D.J., Rooyakkers, S.J., Schipper, C.I. and Wilson, C.J.N.: A cascade of magmatic events during the assembly and eruption of a super-sized magma body, *Contrib. Mineral. Petrol.*, **172,** (2017), article 49.

Bannister, S., Sherburn, S. and Bourguignon, S.: Earthquake swarm activity highlights crustal faulting associated with the Waimangu–Rotomahana–Mt Tarawera geothermal field, Taupo Volcanic Zone, *J. Volcanol. Geotherm. Res.*, **314**, (2016), 49–56.

Barker, S.J., Wilson, C.J.N., Allan, A.S.R. and Schipper, C.I.: Fine-scale temporal recovery, reconstruction and evolution of a post-supereruption magmatic system, *Contrib. Mineral. Petrol.*, **170**, (2015), article 5.

Barker, S.J., Wilson, C.J.N., Morgan, D.J. and Rowland, J.V.: Rapid priming, accumulation and recharge of magma driving recent eruptions at a hyperactive caldera volcano, *Geology*, **44**, (2016), 323–326.

Beavan, J., Wallace, L.M., Palmer, N., Denys, P., Ellis, S., Fournier, N., Hreinsdottir, S., Pearson, C. and Denham, M.: New Zealand GPS velocity field: 1995–2013, *N.Z. J. Geol. Geophys.*, **59**, (2016), 5–14.

Bégué, F., Gualda, G.A.R., Ghiorso, M.S., Pamukcu, A.S., Kennedy, B.M., Gravley, D.M., Deering, C.D. and Chambefort, I.: Phase-equilibrium geobarometers for silicic rocks based on rhyolite-MELTS. Part 2: application to Taupo Volcanic Zone rhyolites, *Contrib. Mineral. Petrol.*, **168**, (2014), article 1082.

Bégué, F., Gravley, D.M., Chambefort, I., Deering, C.D. and Kennedy, B.M.: Magmatic volatile distribution as recorded by rhyolitic melt inclusions in the Taupo Volcanic Zone, New Zealand. In: Zellmer, G.F., Edmonds, M. and Straub, S.M. (Editors), The role of volatiles in the genesis, evolution and eruption of arc magmas, *Geol. Soc. Lond. Spec. Publ.*, **410**, (2015), 71–94.

Bégué, F., Deering, C.D., Gravley, D.M., Chambefort, I. and Kennedy, B.M.: From source to surface: Tracking magmatic boron and chlorine input into the geothermal systems of the Taupo Volcanic Zone, New Zealand, *J. Volcanol. Geotherm. Res.*, **346**, (2017), 141-150.

Bertrand, E.A., Caldwell, T.G., Bannister, S., Soengkono, S., Bennie, S.L., Hill, G.J. and Heise, W.: Using array MT data to image the crustal resistivity structure of the southeastern Taupo Volcanic Zone, New Zealand, *J. Volcanol. Geotherm. Res.*, **305**, (2015), 63–75.

Bibby, H.M., Caldwell, T.G., Davey, F.J. and Webb, T.H.: Geophysical evidence on the structure of the Taupo Volcanic Zone and its hydrothermal circulation, *J. Volcanol. Geotherm. Res.*, **68**, (1995), 29–58.

Blattner, P.: "Andesitic water": a phantom of the isotopic evolution of water-silicate systems. Comment on "Isotopic shifts in waters from geothermal and volcanic systems along convergent plate boundaries and their origin" by W.F. Giggenbach, *Earth Planet. Sci. Lett.*, **120**, (1993), 511-518.

Brown, S.J.A., Wilson, C.J.N., Cole, J.W. and Wooden, J.: The Whakamaru group ignimbrites, Taupo Volcanic Zone, New Zealand: evidence for reverse tapping of a zoned silicic magma system, *J. Volcanol. Geotherm. Res*., **84**, (1998), 1–37.

Browne, P.R.L.: Minimum age of the Kawerau geothermal field, North Island, New Zealand, *J. Volcanol. Geotherm. Res*., **6**, (1979), 213–215.

Calibugan, A. and Chambefort, I.: A comparison of the greywacke basement in Kawerau and Rotokawa geothermal fields in Taupo Volcanic Zone, New Zealand, *Proceedings* World Geothermal Congress 2020, Reykjavik, Iceland (2020).

Cathles, L.M.: An analysis of the cooling of intrusives by ground water convection which includes boiling, *Econ. Geol*., **72**, (1977), 804–826.

Chambefort, I., Lewis, B., Wilson, C.J.N., Rae, A.J., Coutts, C., Bignall, G. and Ireland, T.R.: Stratigraphy and structure of the Ngatamariki geothermal system from new zircon U-Pb geochronology: implications for Taupo Volcanic Zone evolution, *J. Volcanol. Geotherm. Res*., **274**, (2014), 51–70.

Chambefort, I., Buscarlet, E., Wallis, I.C., Sewell, S. and Wilmarth, M.: Ngatamariki geothermal field, New Zealand: geology, geophysics, chemistry and conceptual model, *Geothermics*, **59**, (2016), 266–280.

Chambefort, I., Lewis, B., Simpson, M.P., Bignall, G., Rae, A.J. and Ganefianto, N.: Ngatamariki geothermal system: magmatic to epithermal transition in the Taupo Volcanic Zone, New Zealand, *Econ. Geol.*, **112**, (2017), 319–346.

Charlier, B.L.A., Wilson, C.J.N. and Mortimer, N.: Evidence from zircon U-Pb age spectra for crustal structure and felsic magma genesis at Taupo volcano, New Zealand, *Geology*, **38**, (2010), 915–918.

Christenson, B.W., Mroczek, E.K., Kennedy, B.M., van Soest, M.C., Stewart, M.K and Lyon, G.: Ohaaki reservoir chemistry: characteristics of an arc-type hydrothermal system in the Taupo Volcanic Zone, New Zealand, *J. Volcanol. Geotherm. Res*., **115**, (2002), 53-82.

Cole, J.W., Milner, D.M. and Spinks, K.D.: Calderas and caldera structures: a review, *Earth-Sci. Rev.*, **69**, (2005), 1–26.

Cole, J.W., Spinks, K.D., Deering, C.D., Nairn, I.A. and Leonard, G.S.: Volcanic and structural evolution of the Okataina Volcanic Centre: dominantly silicic volcanism associated with the Taupo Rift, New Zealand, *J. Volcanol. Geotherm. Res*., **190**, (2010), 123–135.

Davy, B.W. and Bibby, H.: Seismic reflection imaging of the Haroharo Caldera boundary beneath Lake Tarawera, Okataina Volcanic Centre, New Zealand, *N.Z. J. Geol. Geophys.*, **48**, (2005), 153–166.

Davy, B.W. and Caldwell, T.G.: Gravity, magnetic and seismic surveys of the caldera complex, Lake Taupo, North Island, New Zealand, *J. Volcanol. Geotherm. Res*., **81**, (1998), 69–89.

Deering, C.D., Cole, J.W. and Vogel, T.A.: A rhyolite compositional continuum governed by lower crustal source conditions in the Taupo Volcanic Zone, New Zealand, *J. Petrol*., **49**, (2008), 2245–2276.

Deering, C.D., Cole, J.W. and Vogel, T.A.: Extraction of crystal-poor rhyolite from a hornblende-bearing intermediate mush: a case study of the caldera-forming Matahina eruption, Okataina volcanic complex, *Contrib. Mineral. Petrol.*, **161**, (2011), 129–151.

de Ronde, C.E.J., Stoffers, P., Garbe-Schonberg, D., Christenson, B.W., Jones, B., Manconi, R., Browne, P.R.L., Hissmann, K., Botz, R., Davy, B.W., Schmitt, M. and Battershill, C.N.: Discovery of active hydrothermal venting in Lake Taupo, New Zealand, *J. Volcanol. Geotherm. Res*., **115**, (2002), 257–275.

de Ronde, C.E.J., Fornari, D.J., Ferrini, V.L., Walker, S.L., Davy, B.W., LeBlanc, C., Caratori Tontini, F., Kukulya, A.L. and Littlefield, R.H.: The Pink and White Terraces of Lake Rotomahana: what was their fate after the 1886 Tarawera Rift eruption?, *J. Volcanol. Geotherm. Res*., **314**, (2016), 126–141.

Dunbar, N.W., Hervig, R.L. and Kyle, P.R.: Determination of pre-eruptive H_2O, F and Cl contents of silicic magmas using melt inclusions: examples from Taupo volcanic centre, New Zealand, *Bull. Volcanol*., **51**, (1989), 177-184.

Edbrooke, S.W. (compiler): Geology of the Waikato area. 1:250,000 geological map 4. Institute of Geological & Nuclear Sciences Limited, Lower Hutt, New Zealand (2005).

Giggenbach, W.F.: Isotopic shifts in waters from geothermal and volcanic systems along convergent plate boundaries and their origin. *Earth Planet. Sci. Lett.*, **113**, (1992), 495–510.

Giggenbach, W.F.: Reply to comment by P. Blattner: "Andesitic water": a phantom of the isotopic evolution of water-silicate systems. *Earth Planet. Sci. Lett.*, **120**, (1993), 519-522.

Giggenbach, W.F.: Variations in the chemical and isotopic compositions of fluids discharged from the Taupo Volcanic Zone, New Zealand, *J. Volcanol. Geotherm. Res.*, **68**, (1995), 89–116.

Gravley, D.M., Wilson, C.J.N., Leonard, G.S. and Cole, J.W.: Double trouble: paired ignimbrite eruptions and collateral subsidence in the Taupo Volcanic Zone, New Zealand, *Geol. Soc. Am. Bull*., **119**, (2007), 18–30.

Gravley, D.M., Deering, C.D., Leonard, G.S. and Rowland, J.V.: Ignimbrite flare-ups and their drivers: a New Zealand perspective, *Earth-Sci. Rev.*, **162**, (2016), 65–82.

Gualda, G.A.R., Gravley, D.M., Deering, C.D., Ghiorso, M.: Magma extraction pressures and the architecture of volcanic plumbing systems, *Earth Planet. Sci. Lett.*, **522**, (2019), 118-124.

Harrison, A.J. and White, R.S.: Crustal structure of the Taupo Volcanic Zone, New Zealand: stretching and igneous intrusion, *Geophys. Res. Lett.*, **31**, (2004), L13615.

Hedenquist, J.W.: Geothermal systems in the Taupo Volcanic Zone: their characteristics and relation to volcanism and mineralisation. In I.E.M. Smith (Editor) Late Cenozoic Volcanism in New Zealand, *Roy. Soc. N.Z. Bull.*, **23**, (1986), 134–168.

Heise, W., Caldwell, T.G., Bertrand, E.A., Hill, G.J., Bennie, S.L. and Palmer, N.G.: Imaging the deep source of the Rotorua and Waimangu geothermal fields, Taupo Volcanic Zone, New Zealand, *J. Volcanol. Geotherm. Res.,* **314**, (2016), 39–48.

Henley, R.W. and Ellis, A.J.: Geothermal systems ancient and modern: a geochemical review, *Earth-Sci. Rev.*, **19**, (1983), 1–50.

Hurwitz, S. and Lowenstern, J.B.: Dynamics of the Yellowstone hydrothermal system, *Rev. Geophy.*, **51**, (2014), 375–411.

Illsley-Kemp, F., Savage, M.K., Wilson, C.J.N., Bannister, S.: Mapping stress and structure from subducting slab to magmatic rift: crustal seismic anisotropy of the North Island, New Zealand, *Geochem.*, *Geophys*., *Geosyst.,* (submitted).

Johnson, E.R., Kamenetsky, V.S., McPhie, J. and Wallace, P.J.: Degassing of the H_2O-rich rhyolites of the Okataina Volcanic Center, Taupo Volcanic Zone, New Zealand, *Geology*, **39**, (2011), 311–314.

Keam, R.F.: Tarawera: the volcanic eruption of 10 June 1886. Published by the author, Auckland, New Zealand (1988).

Kissling, W.M. and Weir, G.J.: The spatial distribution of the geothermal fields in the Taupo Volcanic Zone, New Zealand, *J. Volcanol. Geotherm. Res.*, **145**, (2005), 136–150.

Leonard, G.S., Begg, J.G. and Wilson, C.J.N. (compilers): Geology of the Rotorua area. 1:250,000 geological map 5. Institute of Geological & Nuclear Sciences Limited, Lower Hutt, New Zealand (2010).

Liu, Y., Anderson, A.T., Wilson, C.J.N., Davis, A.M. and Steele, I.M.: Mixing and differentiation in the Oruanui rhyolitic magma, Taupo, New Zealand: evidence from volatiles and trace elements in melt inclusions, *Contrib. Mineral. Petrol.*, **151**, (2006), 71–87.

McNamara, D.D., Milicich, S.D., Massiot, C., Villamor, P., McLean, K., Sépulveda, F. and Ries, W.F.: Tectonic controls on Taupo Volcanic Zone geothermal expression: Insights from Te Mihi, Wairakei Geothermal Field, *Tectonics*, (2019), in press.

Milicich, S.D., Wilson, C.J.N., Bignall, G., Pezaro, B., Charlier, B.L.A., Wooden, J.L. and Ireland, T.R.: U-Pb dating of zircon in hydrothermally altered rocks of the Kawerau Geothermal Field, Taupo Volcanic Zone, New Zealand, *J. Volcanol. Geotherm. Res*., **253**, (2013a), 97–113.

Milicich, S.D., Wilson, C.J.N., Bignall, G., Pezaro, B. and Bardsley, C.: Reconstructing the geological and structural history of an active geothermal field: a case study from New Zealand, *J. Volcanol. Geotherm. Res.*, **262**, (2013b), 7–24.

Milicich, S.D., Chambefort, I., Wilson, C.J.N., Charlier, B.L.A. and Tepley, F.J.: The hydrothermal evolution of the Kawerau geothermal system, New Zealand, *J. Volcanol. Geotherm. Res.*, **353**, (2018), 114–131.

Milicich, S.D., Chambefort, I., Simpson, M., Wilson, C.J.N., Alcaraz, S., Calibugan, A., Bardsley, C., Morales, A.: Geology, geochronology, alteration and geochemistry of the Rotokawa geothermal system, Taupō Volcanic Zone, New Zealand, *Proceedings* World Geothermal Congress 2020, Reykjavik, Iceland (2020).

Milner, D.M., Cole, J.W. and Wood, C.P.: Asymmetric, multiple-block collapse at Rotorua Caldera, Taupo Volcanic Zone, New Zealand, *Bull. Volcanol.*, **64**, (2002), 134–149.

Modriniak, N. and Studt, F.E.: Geological structure and volcanism of the Taupo-Tarawera district, *N.Z. J. Geol. Geophys.*, **2**, (1959), 654–684.

Mountain, B.W., Chambefort, I. and Sajkowski, L.: Progressive devolatilisation of New Zealand reservoir rocks from sub-critical to supercritical conditions, *Proceedings*, New Zealand Geothermal Workshop, Rotorua, New Zealand (2017).

Norton, D. and Knight, J.: Transport phenomena in hydrothermal systems: cooling plutons. *Am. J. Sci.*, **277**, (1977), 937–981.

Pearson-Grant, S.C., Milicich, S.D., White, P.A., Kissling, W.M.: Numerical modelling of the influence of geology and groundwater recharge on geothermal systems in the central TVZ, *Proceedings*, New Zealand Geothermal Workshop, Rotorua, New Zealand (2017).

Price, R.C., Gamble, J.A., Smith, I.E.M., Maas, R., Waight, T., Stewart, R.B. and Woodhead, J.: The anatomy of an andesite volcano: a time–stratigraphic study of andesite petrogenesis and crustal evolution at Ruapehu volcano, New Zealand, *J. Petrol.*, **53**, (2012), 2139–2189.

Price, R.C., Mortimer, N., Smith, I.E.M. and Maas, R.: Whole-rock geochemical reference data for Torlesse and Waipapa terranes, North Island, New Zealand, *N.Z. J. Geol. Geophys*., **58**, (2015), 213–228.

Ring, U., Mortimer, N. and Deckert, H.: Critical-wedge theory and the Mesozoic accretionary wedge of New Zealand. *J. Struct. Geol*., **122**, (2019), 1–10

Roche, O., Druitt, T.H. and Merle, O.: Experimental study of caldera formation, *J. Geophys. Res.*, **105**, (2000), 395–416.

Rosenberg, M.D.: Volcanic and tectonic perspectives on the age and evolution of the Wairakei-Tauhara geothermal system. Ph.D. thesis, Victoria University of Wellington (2017).

Rowland, J.V. and Sibson, R.H.: Extensional fault kinematics within the Taupo Volcanic Zone, New Zealand: soft-linked segmentation of a continental rift system, *N.Z. J. Geol. Geophys*., **44**, (2001), 271–283.

Rowland, J.V., Wilson, C.J.N. and Gravley, D.M.: Spatial and temporal variations in magma-assisted rifting, Taupo Volcanic Zone, New Zealand, *J. Volcanol. Geotherm. Res.*, **190**, (2010), 89–108.

Schöpa, A., Annen, C., Dilles, J.H., Sparks, R.S.J. and Blundy, J.D.: Magma emplacement rates and porphyry copper deposits: thermal modeling of the Yerington Batholith, *Econ. Geol.*, **112**, (2017), 1653–1672.

Seebeck, H., Nicol, A., Stern, T.A., Bibby, H.M. and Stagpoole, V.: Fault controls on the geometry and location of the Okataina caldera, Taupo Volcanic Zone, New Zealand, *J. Volcanol. Geotherm. Res.*, **190**, (2010), 136–151.

Shane, P., Martin, S.B., Smith, V.C., Beggs, K.F., Darragh, M.B., Cole, J.W. and Nairn, I.A.: Multiple rhyolite magmas and basalt injection in the 17.7 ka Rerewhakaaitu eruption episode from Tarawera volcanic complex, New Zealand, *J. Volcanol. Geotherm. Res.*, **164**, (2007), 1–26.

Shane, P., Nairn, I.A., Smith, V.C., Darragh, M., Beggs, K.F. and Cole, J.W.: Silicic recharge of multiple rhyolite magmas by basaltic intrusion during the 22.6 ka Okareka eruption episode, New Zealand, *Lithos*, **103**, (2008), 527–549.

Sherburn, S., Bannister, S. and Bibby, H.: Seismic velocity structure of the central Taupo Volcanic Zone, New Zealand, from local earthquake tomography, *J. Volcanol. Geotherm. Res.*, **122**, (2003), 69–88.

Simmons, S.F., Keywood, M., Scott, B.J. and Keam, R.F.: Irreversible change of the Rotomahana-Waimangu hydrothermal system (New Zealand) as a consequence of a volcanic eruption, *Geology*, **21**, (1993), 643–646.

Spinks, K.D., Acocella, V., Cole, J.W. and Bassett, K.N.: Structural control of volcanism and caldera development in the transtensional Taupo Volcanic Zone, New Zealand, *J. Volcanol. Geotherm. Res.*, **144**, (2005), 7–22.

Stern, T., Stratford, W., Seward, A., Henderson, M., Savage, M., Smith, E., Benson, A., Greve, S. and Salmon, M.: Crust-mantle structure of the central North Island, New Zealand, based on seismological observations, *J. Volcanol. Geotherm. Res.*, **190**, (2010), 58–74.

Villamor, P., Nicol, A., Seebeck, H, Rowland, J., Towsend, D., Massiot, C., McNamara, D.D., Milicich, S.D., Ries, W. and Alcaraz, S.: Tectonic structure and permeability in the Taupo Rift: new insights from analysis of lidar derived DEMs. New Zealand Geothermal Workshop 2017 *Proceedings*. Rotorua, New Zealand (2017).

Wallace, P.J. and Edmonds, M.: The sulfur budget in magmas: evidence from melt inclusions, submarine glasses, and volcanic gas emissions, *Rev. Mineral. Geochem.*, **73**, (2011), 215–246.

White, P.A. and Reeves, R.R.: Groundwater circulation systems of high-temperature geothermal fields in the upper Waikato catchment, Taupo Volcanic Zone, New Zealand, *Proceedings*, New Zealand Geothermal Workshop, Rotorua, New Zealand (2017).

Whiteford, P.C.: Heat flow in the sediments of Lake Taupo, New Zealand, *Tectonophysics*, **257**, (1996), 81–92.

Wilson, C.J.N.: The 26.5 ka Oruanui eruption, New Zealand: an introduction and overview, *J. Volcanol. Geotherm. Res*., **112**, (2001), 133–174.

Wilson, C.J.N. and Rowland, J.V.: The volcanic, magmatic and tectonic setting of the Taupo Volcanic Zone, New Zealand, reviewed from a geothermal perspective, *Geothermics,* **59**, (2016), 167–186.

Wilson, C.J.N., Houghton, B.F., McWilliams, M.O., Lanphere, M.A., Weaver, S.D. and Briggs, R.M.: Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review, *J. Volcanol. Geotherm. Res*., **68**, (1995), 1–28.

Wilson, C.J.N., Blake, S., Charlier, B.L.A., Sutton, A.N.: The 26.5 ka Oruanui eruption, Taupo volcano, New Zealand: development, characteristics and evacuation of a large rhyolitic magma body, *J. Petrol*, **47**, (2006), 35–69.

Wilson, C.J.N., Charlier, B.L.A., Fagan, C.J., Spinks, K.D., Gravley, D.M., Simmons, S.F. and Browne, P.R.L.: U-Pb dating of zircon in hydrothermally altered rocks as a correlation tool: application to the Mangakino geothermal field, New Zealand, *J. Volcanol. Geotherm. Res*., **176**, (2008), 191–198.

Wilson, C.J.N., Gravley, D.M., Leonard, G.S. and Rowland, J.V.: Volcanism in the central Taupo Volcanic Zone, New Zealand: tempo, styles and controls. In: Thordarson, T., Self, S., Larsen, G., Rowland, S.K. and Hoskuldsson, A. (Editors), Studies in Volcanology: The Legacy of George Walker, *Spec. Publ. IAVCEI*, **2**, (2009), 225-247.

Wood, C.P., Braithwaite, R.L. and Rosenberg, M.D.: Basement structure, lithology and permeability at Kawerau and Ohaaki geothermal fields, New Zealand, *Geothermics*, **30**, (2001), 461–481.