THE DEEP CONTROLS ON HIGH ENTHALPY GEOTHERMAL SYSTEMS: A MULTI-DISCIPLINARY OVERVIEW FROM NEW ZEALAND

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ABSTRACT

An enduring question is: what controls the longevity and position of geothermal systems in areas of active volcanism and rifting? Can deep-seated crustal discontinuities focus the upwards transport of subduction-related melts and volatiles and influence the compositional variability in magmatic and geothermal fluids? Rifting arc models of the Taupo Volcanic Zone (TVZ, New Zealand) still are challenged to link diverse observations, including deep seismic anisotropy and tomography, 3D magnetotelluric inversions, the location and evolution of geothermal systems, magmatic and aqueous fluid compositions, locations of caldera development and the North Island tectonic environment. By reviewing and combining recent geophysical, geological, geochemical and structural studies we here consider an integrated model to suggest future research avenues.

The TVZ is an extensional arc, representing the on-land continuation of the Tonga-Kermadec arc/back-arc system, marked in its central part by intense magmatism associated with 23 high-enthalpy geothermal systems. To accommodate the slightly oblique extension, the brittle crust is segmented, expressed in the form of accommodation zones. These zones may be the expression of cross-arc magmatic migration as seen just north of the TVZ in the Havre Trough.

Three-D inversion magnetotelluric (MT) models of several TVZ geothermal fields show deep feeder zones perpendicular or oblique to the overall arc alignment below ~5 km depth. These MT anomalies have been interpreted as reflecting concentrations of fluids (magma or aqueous) in the crust. We hypothesise that deep, long-lasting, crustal cross-arc discontinuities (occurring in response to the oblique extension and caldera forming processes), favour permeability in the deeper, ductile crust. These discontinuities enable vertical mass transport, enhancing crustal melting and creating upwarped ridges on the surface representing the brittle–ductile transition. These ridges in turn create pinning loci for groundwater convective cells, and explain the persistence of many of the geothermal systems, despite interruption in some cases by caldera collapse and/or active faulting, and the variability of geothermal fluid chemistry and magma compositions.

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 geochemistries, and regional structural and magmatic investigations in order to characterise the deep-seated controls on New Zealand geothermal systems. Independent studies in various disciplines have generated a large amount of data that can now start to be integrated into a single multidisciplinary model.

The central Taupo Volcanic Zone (TVZ) in New Zealand is the locus of intense magmatism associated with 23 high-enthalpy geothermal systems. These geothermal systems are a by-product of the tectonic rifting-arc setting, and the clear link between the magmatism and the geothermal systems has been invoked in multiple studies over the years. One of the interesting challenges that the New Zealand scientific community has been facing for the last ~50 years is to constrain the volcanic-hosted versus volcanic-influenced nature of the geothermal systems' fluid chemistries. Giggenbach (1995) quantified that up to 20% (e.g. for Rotokawa and Waiotapu geothermal fields) of the water is 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 behaviour of a geothermal reservoir may be relatively well understood, in order to achieve the sustainable utilisation of the resource, 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 individually, geophysical, structural, and igneous petrology studies fail to explain the variations in fluid compositions observed in the TVZ and their deep controls (Giggenbach, 1995). By combining recent geophysical, geological, geochemical and structural studies we can revise and refine the external controls for the well-known Henley and Ellis (1983) geochemical model and revised Giggenbach (1995) arc- versus rift-systems model. This study aims to develop an integrated model to build future research avenues.

In the following sections, we summarise the characteristics of TVZ geothermal systems and refine their magmatic, geological, structural and geophysical constraints and problems, before discussing our new perspectives on the deep roots of these systems.

2. CHARACTERISTICS OF TVZ GEOTHERMAL SYSTEMS

2.1 Geochemistry

In this paper, the term geothermal system defines an active hydrothermal system characterised by a high-enthalpy (T > 250 °C in the reservoir) and near neutral-pH chloride water reservoir compositions in a volcanic-hosted environment (Fig. 1). We use the definition of Rowland and Simmons (2012): "[a] geothermal system is a hydropressured system involving circulation of water to >5 km depth driven by magmatic heat and centered on a rising column of hydrothermal fluid".

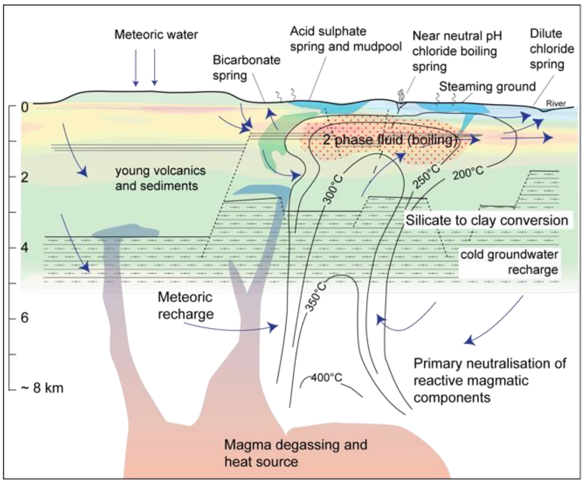

Figure 1: Conceptual model of continental arc geothermal systems based on fluid chemistry and geological record from Henley and Ellis (1983), as modified by Hedenquist (1986).

In the central TVZ, the combination of a rifting arc and high volumes of (dominantly rhyolitic) magma accompany an anomalously thin continental (quartzo-feldspathic) crust and/or heavily intruded lower crust and a high heat flow (Bibby et al., 1995; Harrison and White, 2004; Stern et al., 2010). This unique setting and the resulting thick sequences of pyroclastic deposits from the intense volcanic activity favours the convection of descending cold groundwater. The regional active faults, defining the Taupo rift, cutting through the volcanic sequence and underlying metasedimentary greywacke are inferred to favour deep penetration of the meteoric water in the crust close to the partial melt area (Villamor et al., 2017). 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. 1).

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

Variations in gas and liquid chemistries led Giggenbach (1995) to delineated gas-rich group A systems (e.g. Kawerau, Ohaaki, Rotokawa: Fig. 2) versus gas-poor group B systems (e.g. Wairakei, Mokai, Rotorua, Waiotapu). 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). 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 (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 influenced magma composition (e.g. Price et al., 2012).

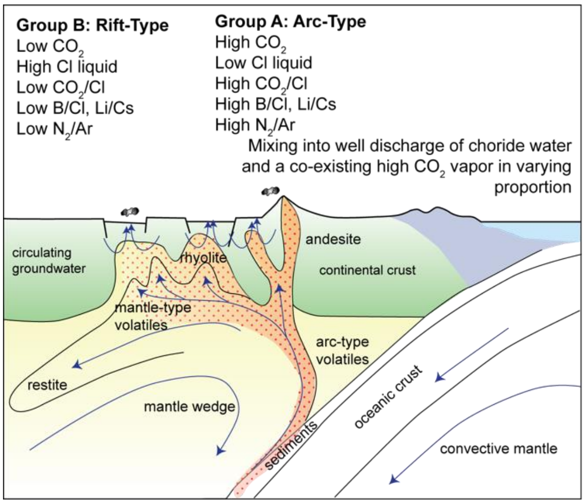

Figure 2: Schematic model compatible with fluid geochemical evidence illustrating the potential processes forming variations in the chemical composition of fluid discharges from TVZ geothermal systems (from Giggenbach, 1995).

2.2 Longevity - Geological records

The age of an individual geothermal system is generally poorly constrained as the system is still hot, generally altered and therefore radiometric techniques such as $^{40}Ar/^{39}Ar$ are restricted in application. 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 thousand 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 geology from geothermal drilling and high-precision dating of the volcanic stratigraphy provides the best tool to assess minimum ages and lifetimes of geothermal systems. There is evidence that ancient hydrothermal events (revealed by hydrothermal breccias and/or overprinted mineral assemblages) affected volcanic and sedimentary deposits at Kawerau, Tauhara, Wairakei, Orakeikorako, Te Kopia, and Ngatamariki (Wilson and Rowland, 2016, and references therein). 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; Chambefort et al. 2014, 2017) utilise U-Pb dating on zircon to demonstrate the superimposition on older hydrothermal events of the present-day systems at Kawerau and Ngatamariki. Evidence of buried phreatic eruption breccia material older than the 0.36 Ma 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., 2013b). The current system is interpreted to reflect magmatism of the andesitic Putauaki volcano, with an onset around ~16,000 years ago (Milicich et al., 2013b).

Similarly, a >5 km^3 buried intrusive complex emplaced between 0.71 and 0.65 Ma 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 prior to the Oruanui caldera collapse (Rosenberg, 2017). Hydrothermally altered clasts in the Oruanui volcanic deposit associated with the formation of the Taupo Caldera are evidence that a hydrothermal system was active beneath the area engulfed by the Oruanui caldera. Similarly altered lithics are also common in some Whakamaru-group ignimbrite and young (post-25 ka) Taupo deposits.

2.3 Influence of the volcanic events

Catastrophic caldera-forming events, such as the 25.4 ka Oruanui eruption at Taupo, are expected to produce 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 (Wairakei-Tauhara, Rotokawa, Ngatamariki, Ohaaki, Kawerau). While fluid chemistry, fracture/lithology-controlled permeability, and reservoir characteristics (fluid flow, feed zones, outflow) may have changed, the location of the deep fluid and/or heat source is relatively stationary. The Wairakei-Tauhara geothermal system appears to have been active through the period of the Taupo 232 AD eruption and, more recently, the Waimangu geothermal system was rejuvenated after the 1886 Tarawera eruption (Keam, 1988; Simmons et al., 1993), although with some irreversible changes in 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. These latter volcanic products are the direct witnesses of past magmatic activity beneath the geothermal systems and thus their deep magmatic source can be inferred as a potential contributor for heat and fluids during the life history of the geothermal systems (Wilson et al., 2008; Milicich et al., 2013b). 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; 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 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., 2014).

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 while many active systems are located at fault intersections, not all intersections are favoured by hot plumes, implying that deep permeable structures are necessary. We hypothesise that deep, long-lasting, crustal cross-arc discontinuities (occurring to accommodate the oblique extension and caldera volcano processes), 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 structure; 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. TVZ CRUSTAL CHARACTERISTICS

3.1 Calderas

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 controlled 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. 3).

The geometry of a caldera collapse structure is dependent on the depth, size, and shape of the magma volume that is emptied in an eruption (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 a 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 Taupo calderas (Rowland et al., 2010: Fig. 3).

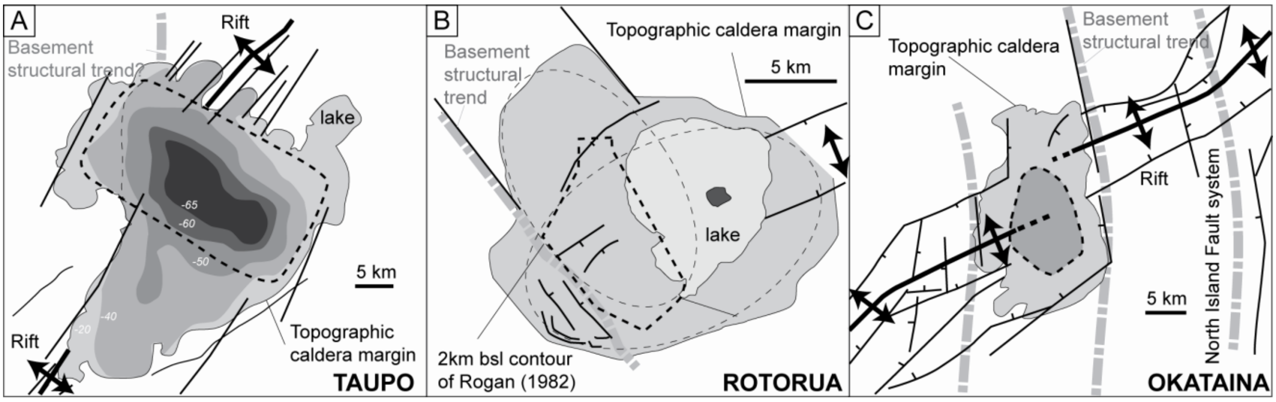

Figure 3: Schematic diagram of the main structural elements of A. Taupo, B. Rotorua and C. Okataina calderas (after Davy and Caldwell, 1998; Wilson, 2001; Milner et al., 2002; Cole et al., 2005, 2010; Davy and Bibby, 2005; Spinks et al., 2005; Gravley et al, 2007; Seebeck et al., 2010). Contours in panel A are residual Bouguer gravity anomalies from Davy and Caldwell (1998).

Caldera collapse can reach quite deep into the crust and is 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 and degassed following the eruptions (e.g. Barker et al., 2015).

One aspect that is generally neglected in the literature is the impacts that a caldera collapse has on the regional stress states, the depth to the brittle-ductile transition, the pressure and temperature gradients of the crust, and the regional hydrogeology. Intense disruptions to all of these physical factors are, however, expected to happen not only during caldera formation but also for some time afterwards. As discussed above, caldera structures are likely to be genetically linked to basement or crustal discontinuities.

3.2 TVZ basement

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; Leonard et al., 2010; Price et al., 2015). The suture between the two terranes is buried beneath the Quaternary volcanic sequence but drillcore petrographic analysis and recent U-Pb dating show that both terranes are present beneath the TVZ geothermal system (Wood et al., 2001; Milicich et al., in preparation; see also Charlier et al., 2010).

3.3 TVZ mush and magmas

In the last decade, many petrological studies have refined our understanding of what the crustal magmatic systems of the central TVZ may be at the present day and how they evolve before and after caldera-forming events (e.g. Fig. 4: (Graham et al., 1995; Wilson et al., 1995; Deering et al. 2008, 2011; Rowland et al., 2010; Bégué et al., 2014; Barker et al., 2015, 2016; Gravley et al., 2016; Allan et al., 2017).

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. 4, 5), and accumulate rapidly before a volcanic event (e.g. Barker et al., 2015, 2016; Allan et al., 2017). The building of the Oruanui magma body (530 km^3, erupted at 25.4 ka from Taupo) occurred over only a few hundred years at most and peaked within decades before the eruption (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. (2013) proposed that most of the crystal-poor silica-rich magma accumulates between 90 and 140 MPa pressure (~3.5-6 km depth: Fig. 4). 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 dacite overall composition and can contain multiple pockets of variably differentiated bodies of melt (Bégué et al., 2014; Barker et al., 2015; Allan et al., 2017).

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 limit 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). These disparities in bulk volatile concentrations can lead to variations in relative timing of exsolution of volatile phase(s) prior to melt inclusion entrapment, which are relevant to the magmatic contribution 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).

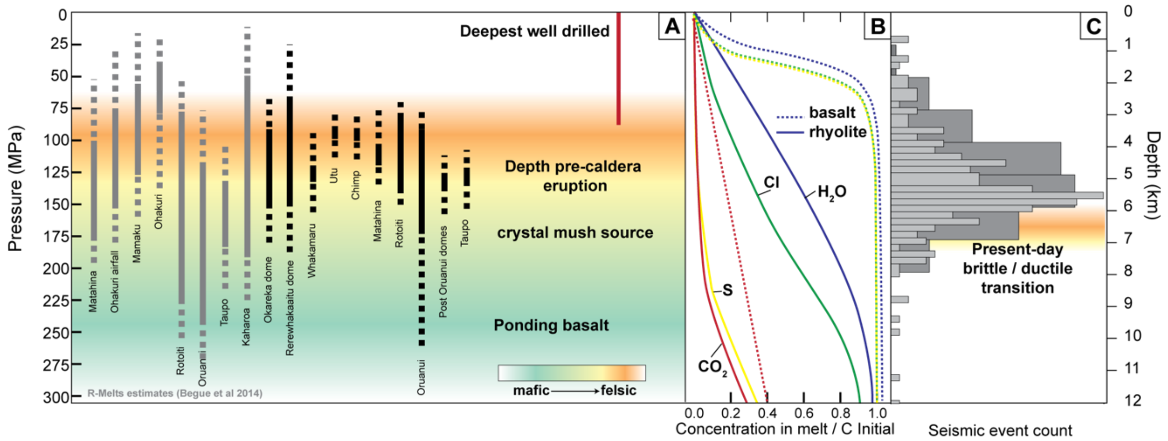

Figure 4: A. Petrological pressure estimates of the storage depths of the high-Si rhyolite sampled in caldera forming eruptions, from Liu et al. (2006); Shane et al. (2007, 2008); Deering et al. (2011); Allan et al. (2012, 2017); Bégué et al. (2014); Barker et al. (2015, 2016); B. exsolution behaviour of various volatile components in rhyolite (full lines) and basalt (dashed lines) from Wallace and Edmonds (2011), and present-day seismic events in function of depth from Sherburn et al. (2003) and Bannister et al. (2016).

The source of the fluids in the TVZ has been debated since the industrial development of the region but the scientific community agrees that the dominant source of water in these systems is meteoric in origin with 6 to 20% magmatic-derived waters (Giggenbach, 1995).

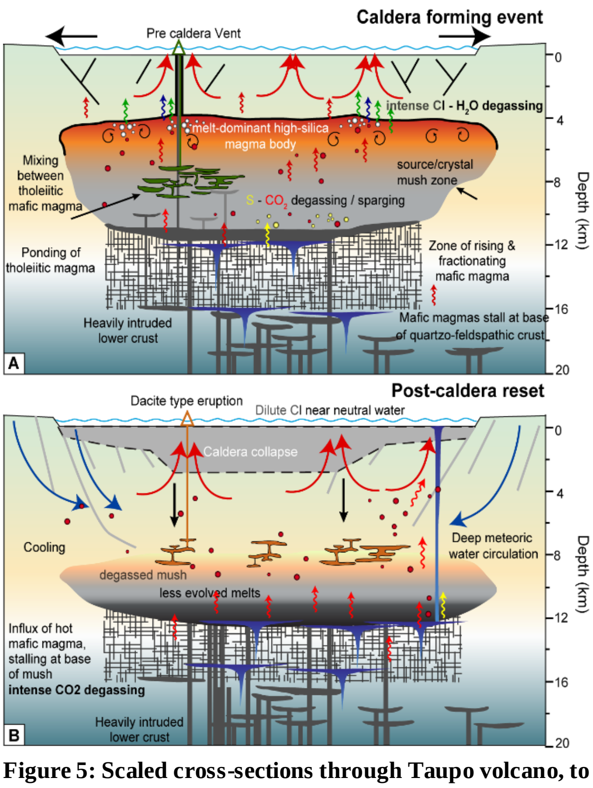

Figure 5: Scaled cross-sections through Taupo volcano, to show the evolution of the A, the Oruanui magma body before eruption and B, a post-caldera mush in replenishment (modified after Barker et al., 2015; Allan et al., 2017).

Volatile melt inclusion data are also consistent with shallow depths as reported in Figures 4 and 5. 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.

Large shallow bodies of crystal-poor magma are, however, inconsistent with the present-day seismic profile of the central TVZ (Fig. 4). 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. 4; 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).

3.4 Geophysical evidence

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 deep feeder zones below 5 km depth that are oriented perpendicular or oblique to the overall arc alignment (Fig. 6A). Somewhat surprising is the orientation of the MT anomaly below the Waimangu geothermal system (Heise et al., 2016; Fig. 6A) which is clearly 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 that is consistent with petrological investigations, the conductive pathway toward the geothermal expression is likely to be guided by oblique discontinuities that are not or poorly expressed at the surface.

Although these 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 term of metal zoning (eg. Zn) from the intrusion to the surface (Chambefort and Dilles, in preparation). Normally, Cl-bearing brines are rich in metals which form a zonation in precipitates while the host fluids are rising toward the surface, as has been observed in the Ngatamariki fossil hydrothermal system (Chambefort et al., 2017). High gas systems such Rotokawa have no chemical sign of actively degassing shallow intrusions, despite the enrichment in gas (Fig. 6B).

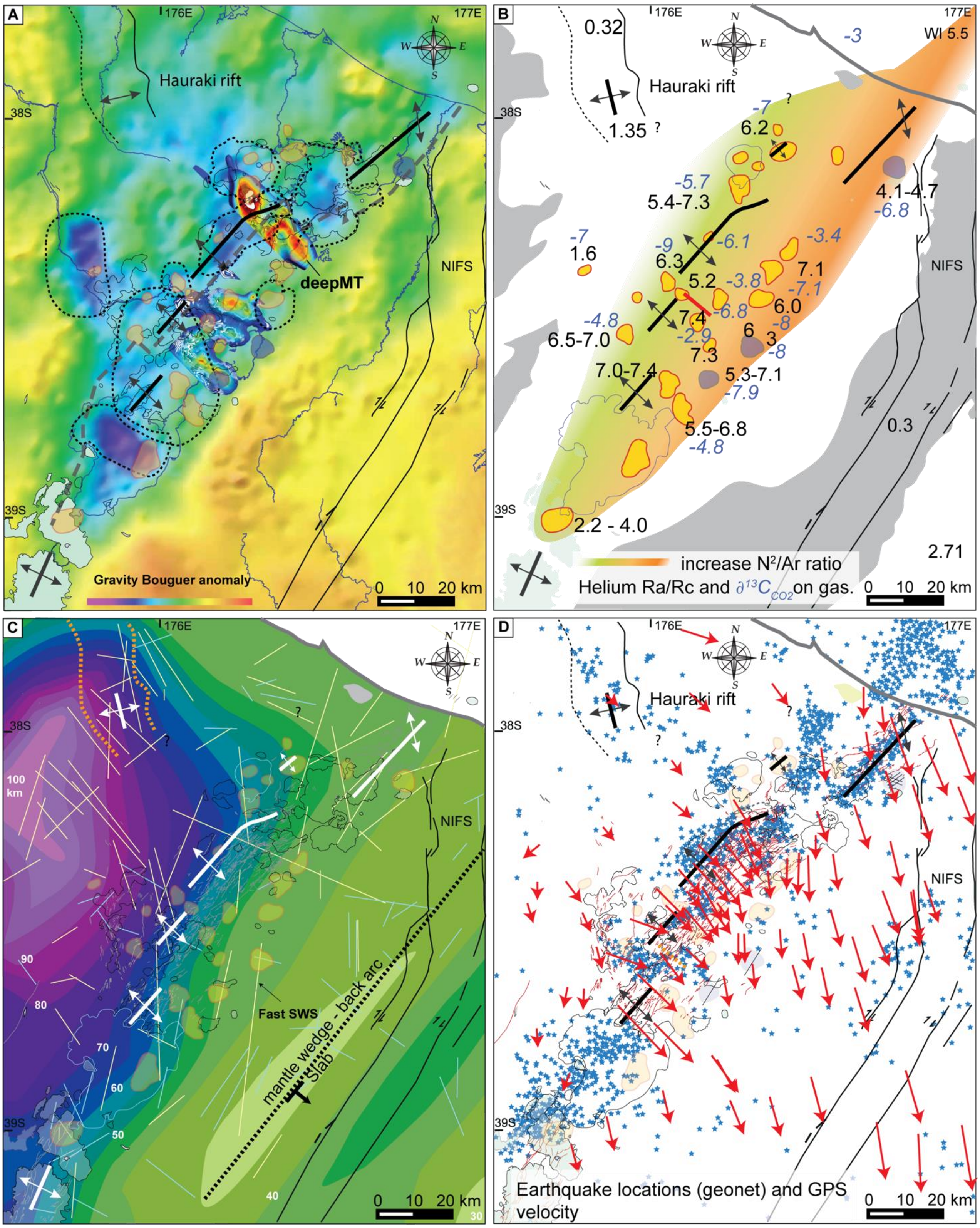

Figure 6. Compiled geophysical, structural and geochemical data for the central TVZ. A. Bouguer anomaly (and projection of the deep MT model at 8000 m depth) from Bertrand et al. (2015) and Heise et al. (2016). B. Helium and carbon isotopes in gas, and zoning in non-reactive gases (Ar, N). C. Depth variation of the isovelocity surfaces for V_P = 7.9 km s^{-1} from Reyners et al. (2006) and spatially averaged fast shear wave splitting directions determined by Audoine et al. (2004). D. GEONET earthquakes and GPS velocities in an Australian Plate fixed reference frame (Beavan et al., 2016). Yellow and blue areas represents high gas and low gas geothermal systems, respectively. NIFS: North Island Fault System (strike slip).

The previous observations suggest that the discontinuities or conductive zones in the ductile zone are likely pathways for CO_2 and subduction-related gas 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.

The unreactive gases N_2 and He are directly linked to the dehydration of subducted sediments and mantle conditions, respectively. This is the reason why arc volcanic gases are typically enriched in N_2 with respect to mid-ocean ridge or oceanic island basalt systems that are more enriched in He (Hilton et al., 2002). Transport of these gases towards the surface is thus directly linked to fluid transfer in the mantle wedge and crust. Fluid percolation in the mantle has been inferred to be linked with mineral creeping and can be expressed by seismic anisotropy (Hirth et al., 2003; Nakajima et al., 2009). Lattice preferred-orientations generated by corner flow-induced strain of olivine within the mantle wedge are the most likely cause for the fast polarization directions in the western TVZ (Fig. 6C; Audoine et al., 2004; Reyners et al., 2006). A combination of the oblique subduction, corner flow in the mantle wedge and dislocation-creep rheology favour fluid transfer in the mantle wedge and may ultimately be linked to magmatism. The same processes have been proposed to occur in oth er extensional arc such as Japan (e.g. Wada et al., 2015).

4. A DEEP SEATED CONCEPTUAL IDEA

Combining all of these observations to propose a unique model for the TVZ geothermal system is clearly speculative. We proposed here a conceptual idea explaining the how, why and where of the high-enthalpy geothermal systems that is summarised in Fig. 7.

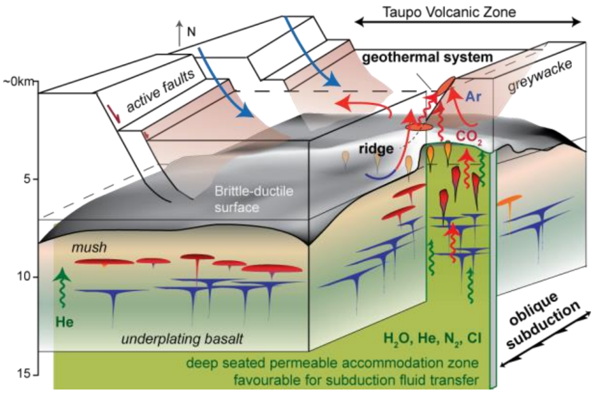

Figure 7. Conceptual model of the deep controls on high enthalpy New Zealand geothermal systems.

Deep, long-lasting, crustal cross-arc discontinuities favour permeability in the ductile crust and may be related to mantle processes. These discontinuities enable vertical mass transport of melts and volatiles, locally enhancing crustal melting and creating ridges on the surface representing 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.

Downward recharge of cool meteoric water is enhanced by the abundant faulting of the Taupo 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 subduction 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 intersection of the oblique discontinuities with the eastern edge of the TVZ and less permeable Torlesse greywacke (Wood et al., 2001) may force the fluid upwards, thus explaining the persistent location of the geothermal systems. The 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. 6D) 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.

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