

# VOLCANOLOGICAL AND TECTONIC INSIGHTS INTO GEOTHERMAL SYSTEMS IN THE CENTRAL TAUPO VOLCANIC ZONE, NEW ZEALAND

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## ABSTRACT

Volcanism, tectonism and geothermal systems in the central Taupo Volcanic Zone (TVZ), New Zealand are intimately linked in time and space. The central TVZ is an exceptionally active 120 x 60 km area of rhyolitic-dominated volcanism, about 1.6 million years old and expressed by 25 large caldera-forming and about 2 orders of magnitude more additional smaller eruptions. Vent sites tend to be clustered, and the greatest volumes of magma have been discharged from 8 so-far delineated caldera volcanoes or volcanic complexes. The central TVZ is actively rifting and subsiding, but the rates of rifting and subsidence may be uneven on the 10<sup>5</sup> year timescale. There are 23 high-temperature geothermal systems across the same area, from Tokaanu in the south to Kawerau in the north, each of which requires a source of heat and permeability. The sources of heat ultimately are magma bodies intruded at depth yet, to a first order, magma and geothermal fields are widespread throughout the central TVZ and not tied to the youngest active volcanic systems at Taupo and Okataina. The most productive geothermal systems are in areas where young (<~65 ka) volcanism has not occurred.

Studies of central TVZ volcanism and tectonism contribute to several aspects of geothermal interest. Volcanic studies indicate where bodies of magma lodge within the crust, with the shallowest being 4±1 km below the surface (only one example, Ngatamariki, has been intersected by a geothermal well). Other examples may be within reach of the next generation of drilling. Lifetimes of large silicic magmatic systems are of the order 10<sup>5</sup> years, and geothermal systems may have waxed and waned in the same geographic location in tune with the heat sources, with permeability pathways being re-exploited. Age dating of subsurface horizons by U-Pb techniques on zircon allow rates of subsidence and throws across fault systems to be assessed, leading to a long-term integrated picture of the TVZ rifting processes. Large and small-scale studies of faulting allow the controls on the positions of fields, as well as the controls on field-specific permeability to be understood.

## 1. GEOLOGICAL SETTING

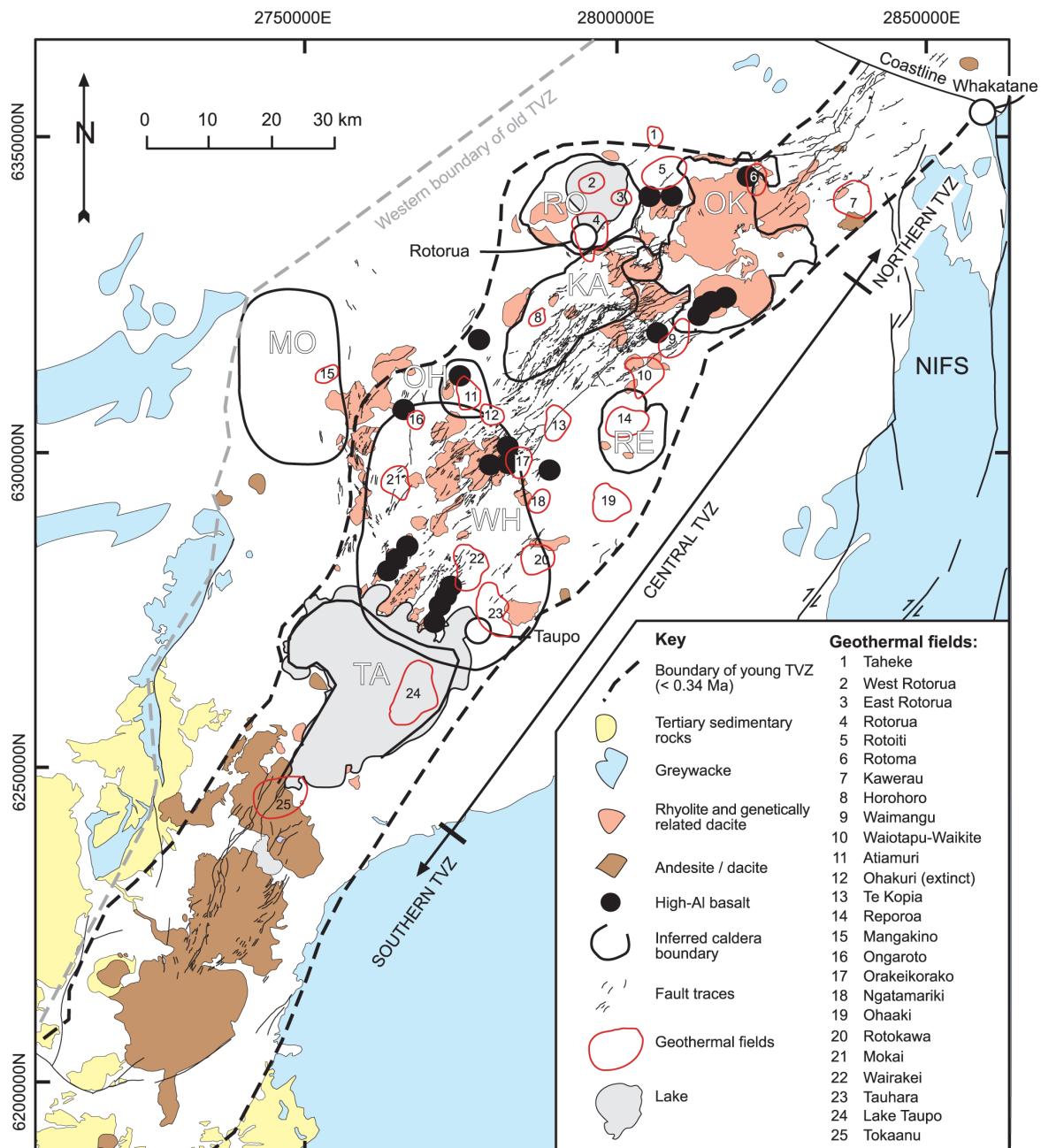
The present-day and future development of New Zealand's geothermal resources requires an understanding of how the geothermal systems are sited geographically and temporally with respect to concurrent processes of magmatism, volcanism and tectonism. A geothermal interest in volcanism, magmatism and tectonism is a consequence of the observation that geothermal systems suitable for exploitation require a source of focused heat at depth

(supplied by magmatism) and pathways for fluids to rise to exploitable depths (supplied by tectonism). The role of volcanism is threefold; first, as a modern source of hazard to geothermal developments and other infrastructure, second as a drain of magma and heat out of magmatic systems, and third as a supplier of widespread marker horizons that can be used to measure subsidence and fault displacements within and beyond geothermal systems. All but one of the high-enthalpy systems onshore in New Zealand are in the central North Island, in the area termed the Taupo Volcanic Zone (TVZ). In this paper we review the TVZ regional-scale inter-relationships between volcanic and tectonic processes and the high-temperature geothermal fields that are of interest economically.

The TVZ began erupting around 2 Ma, with early andesitic volcanism being joined and swamped around 1.6 Ma by voluminous rhyolitic volcanism (Wilson et al., 1995). At least 10,000 km<sup>3</sup> of overwhelmingly rhyolitic magma has been erupted in the past 1.6 Myr, but the eruption records from terrestrial and marine records (both in sedimentary basins and on the ocean floor) suggest that this volume is a minimum and correlations are presently incomplete. Andesite is an order of magnitude less abundant than rhyolite, and basalt and dacite are minor in volume (<100 km<sup>3</sup> each), with few individual eruptions exceeding 1 km<sup>3</sup>.

The history of TVZ can be divided into Old TVZ from 2.0-0.34 Ma, and Young TVZ from 0.34 Ma to the present. The term Modern TVZ reflects the present-day situation, from ~61 ka for which the silicic eruptive history is well established and patterns of geothermal fluid flow can be inferred to have remained more-or-less uniform in distribution. TVZ shows a pronounced segmentation into northern and southern extremities with andesite composite cones and no calderas, and a 125 km long rhyolite-dominated central segment (Figure 1). Within central TVZ, about four times as much magma is trapped at depth than is erupted, feeding heat, volatiles and chemicals into 23 geothermal systems with a total of 4.2 ± 0.5 GW thermal energy release (Bibby et al., 1995). Taken as a whole, the central TVZ is about the same areal size as the Yellowstone system, but has a slightly smaller geothermal heat flux (4.3 vs. 5.3 GW) and somewhat larger volcanic output (>10,000 km<sup>3</sup> in 1.6 Myr, vs. ~6500 km<sup>3</sup> in 2.1 Myr: Houghton et al., 1995; Christiansen, 2001). Over the past 61 ka in central TVZ alone 780 km<sup>3</sup> of magma has been erupted, of which 82 % was released in three large caldera-forming eruptions at 61, 27 and 1.8 ka (Wilson et al., 2009). Average magma eruption rates have been ~13 km<sup>3</sup>/kyr, while the geothermal heat flux represents about another ~50 km<sup>3</sup>/kyr of intrusions into the middle crust, assuming a steady-state situation.

Eruption rates for the northern and southern TVZ sectors amount to no more than ca. 2 km<sup>3</sup>/kyr in total, with another

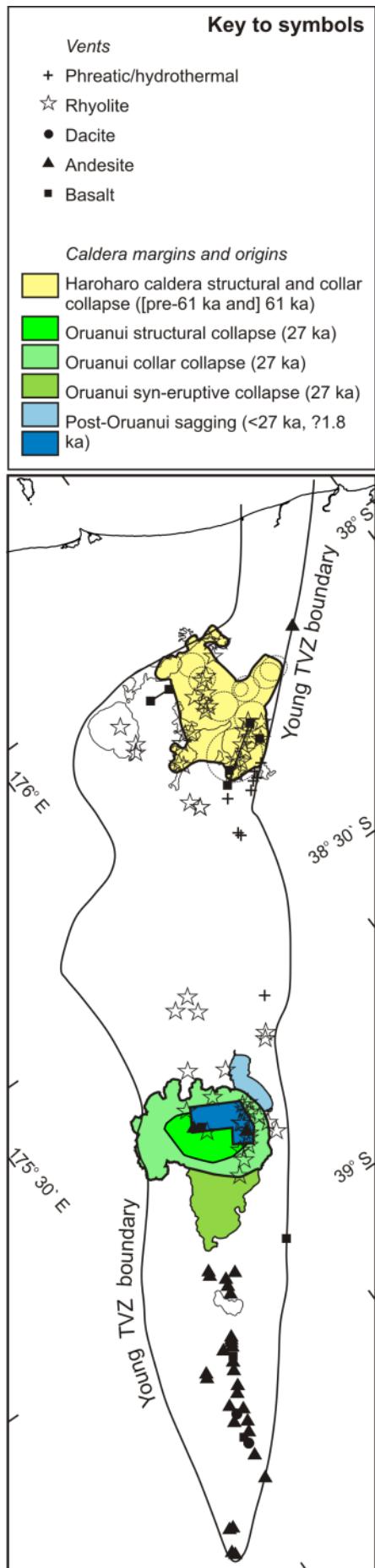


**Figure 1: Simplified map of the TVZ showing the distribution of geothermal systems, defined by the presence of low-resistivity zones (<30  $\Omega$ m), major rock types and caldera boundaries (Rowland & Sibson, 2004).**

<5 km<sup>3</sup> inferred to occur as intrusions, based on modern thermal fluxes. As a result of the lower magma fluxes (though these are typical of many arcs globally), there are only three high-temperature geothermal systems in the northern and southern TVZ sectors. None of these are suitable for exploitation, especially as two of them are associated with historically active vents

The present-day TVZ is an actively rifting arc, with geodetically measured widening rates ranging from 7 mm/yr at the south end to 15 mm/yr at the Bay of Plenty coastline (Wallace et al., 2004). The young TVZ is largely

coincident with a zone of young to active faulting (the Taupo Fault Belt [TFB] of Pillai and Berryman, 2001), but the loci of the surficial fault traces and the main thermal and volcanic fluxes are offset by 15-20 km through much of the central TVZ. Fault slip estimates from the modern TFB in central TVZ only can account for ~3 mm/yr of widening. The remainder is inferred to be taken up by strain along the locus of the arc (especially along the axis of the Taupo-Reporoa Basin) and other areas where weak crustal rocks and frequent re-surfacing by volcanic and sedimentary processes in actively subsiding basinal areas conceal surface rupturing. Although there is a dominant NNE-SSW tectonic grain within the TVZ, there are also influences of NW-SE, arc-perpendicular accommodation zones linking local domains of extension as well as N-S orientated structures related to the Hauraki Rift (Rowland and Sibson, 2004). The brittle-ductile transition (~350 °C), as measured



**Figure 2: Summary figure to show all vent sites, where defined, and caldera collapse areas for eruptions from the Modern TVZ (61 ka onwards). This figure. Vent locations are from Wilson et al. (1995), supplemented by data from Jurado-Chichay and Walker (2000; these are the 'approximate' dashed ovoids at Okataina), Leonard (2003) and C.J.N. Wilson, unpublished data.**

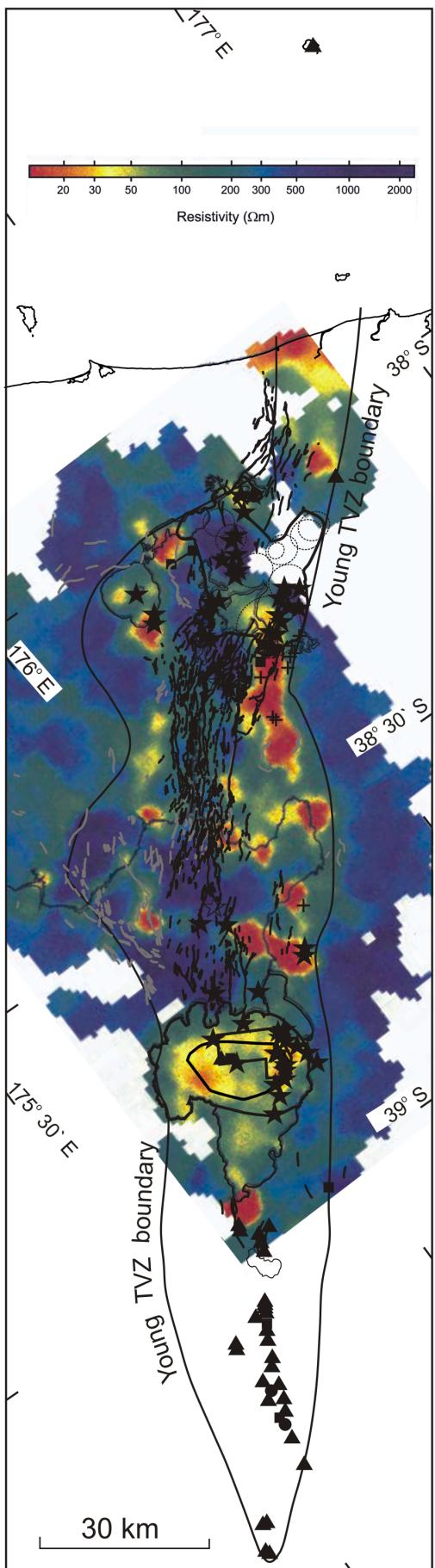
by the seismogenic zone lies no deeper than 7-8 km, and is perturbed upwards in geothermal upflow zones.

Until recently, correlations of subsurface units in geothermal fields to their subaerial dated equivalents has generally been made on the basis of stratigraphic superposition and petrography. Of particular importance in this regard are the coarsely crystal-rich ignimbrites of the  $347 \pm 4$  ka ignimbrites of the Whakamaru Group (Leonard et al., 2010). Newly applied techniques using U-Pb age dating of zircons in suitable lithologies allows the crystallization age of sub-surface rock units (whether extrusive or intrusive) to be estimated to a typical accuracy of  $\pm 50$  kyr. This approach allows the history of rock units in an individual field to be established (and thus allows timing and rates of fault movement to be estimated), enables correlations of surface and subsurface units, and allows the first-order rates of subsidence to be established. At Mangakino, dating established that the deepest 1.8 km of material intersected in wells, despite variations in petrographic properties) had essentially the same age, and could be correlated to a large eruption at  $\sim 1$  Ma (Wilson et al., 2008). At Waiotapu, Te Kopia and Orakei Korako fields, dating of key marker horizons enabled the correlation of deep units with their subaerial equivalents and changed previously proposed correlations of subsurface units (Wilson et al., 2010). A continuing outcome of these studies is estimates of the subsidence rates at many locations across the central TVZ thus allowing identification of the first-order horst and graben structure. For example, the age-depth relationships of dated rock units allow there to be recognized a central locus of material from Waiotapu through to Wairakei that has subsided at rates 2-3 times less than in the TFB area to the NW or the Taupo-Reporoa Basin to the SE.

Taken as a whole, it is not surprising that there is a close overall relationship between geothermal systems, magmatism, tectonism and volcanism in the central TVZ. The interconnections and controls, however, are complex and many aspects remain to be explained. We consider some of these in this paper.

## 2. LARGE-SCALE GEOGRAPHICAL CONTROLS

The first-order insight from volcanological studies is the spatial separation of the areas of young vents and the sites of geothermal systems (Figures 2 and 3). Virtually all of the post-61 ka volcanic eruptives have come from the caldera volcanoes of Okataina at the NNE end, and Taupo at the SSW end of the central TVZ, yet most of the heat flux indicated by low-resistivity areas comes from the intervening area, particularly the Taupo-Reporoa Basin. Despite the long history of caldera volcanism throughout most of the central TVZ, many of the geothermal systems appear to reflect large-scale upflow of fluids that is little affected by volcanism, except when engulfed within a collapsing caldera. Even then, geothermal systems may



**Figure 3:** Summary figure to show vent sites and caldera collapse areas from Fig. 2 superimposed on the resistivity map published by Bibby et al. (1995). Faults active within the past 20 ka (black) and those active recently but prior to 20 ka (grey) are superimposed. Fault positions are from the GNS Active Faults Database (2008), with the age definitions from Villamor and Berryman (2001), and are shown only where overlying or closely adjacent to the resistivity coloured underlay. Note the coaxial locations of vent foci and the locus of greatest geothermal flux in the less volcanically active portion of the Central TVZ between Taupo and Okataina calderas, forming a ~20 km-wide corridor that represents the surface expression of the rifting arc. Note also the contrast between the volcanically active areas, and the volcanically quiet zones where the geothermal heat flux is very high (indicated by warm colours). See text for discussion.

recover quite rapidly on a geological time scale. For example, a substantial volume of hydrothermally altered rock material was ejected in the 27 ka Oruanui eruption at Taupo, suggesting that a substantial geothermal system was destroyed at that time. The patterns of lower resistivity within Lake Taupo at present (Figure 3) suggest that this geothermal system is re-establishing itself at present in the western part of the lake. On a more modest scale, the destruction of the former Rotomahana geothermal system in the 1886 eruption of Tarawera and its recovery in the form of Waimangu (Simmons et al., 1993) is instructive, because it shows that catastrophic destruction of the surface features can have little or no affect on the deep-fluid upflow.

Within the central TVZ, numerous lines of evidence are available to suggest the presence of partial melt in the crust. Studies of rhyolite volcanic deposits imply that their parental melt-dominant magma chambers accumulated at depths of 4-8 km (e.g., Liu et al., 2006; Johnson et al., 2011). In the central TVZ, magnetotelluric soundings show the presence of conductive zones inferred to represent connected melt at depths of 10-20 km (Heise et al., 2010). Note, however that there are two unusual features about the resulting 3-D distribution of partial melt. First, the long axis of the low resistivity zone is offset from the line of the volcanic arc front and the zone of highest surface heat flow, which lies  $15 \pm 5$  km to the east. Second, the zones of greatest accumulation of melt proposed by Heise et al. (2010) lie below areas that have not experienced surface volcanism for at least 200-300 kyr. This contrast between surface volcanic patterns and the presence of intrusions deeper than those inferred to reflect silicic magma bodies, together with the implications for fluid flow into geothermal systems has yet to be explained. There is some factor in the overall tectonic and magmatic evolution of the Modern TVZ that has focused rhyolitic volcanism to the extremities and is confining magmatism to deeper levels in the intervening zone.

With regard to the locations of the geothermal fields themselves, there are two contrasting viewpoints. First, Bibby et al. (1995) suggested that geothermal fields are a part of the large-scale convection system which occupies the entire region, and do not require specific heat sources beneath them; i.e., plutonic bodies as advocated by Henley and Ellis (1983). Although the spatial correlation between

the Ngatamariki geothermal field and a diorite pluton intersected by drilling at a depth of 2200 m is proven (Browne et al., 1992), the age of the diorite is approximately 700 ka (CJNW et al., unpublished data) making it irrelevant as a heat source. Mathematical modeling shows that the spatial distribution of geothermal fields in the TVZ is similar to the convection pattern produced by the heating of a homogenous porous medium from below (Kissling and Weir, 2005, for review). The aspect ratio of convection cells created in such a medium is about 1:1, therefore the mean spacing of TVZ geothermal fields suggests a depth of circulation of 5 to 10 km. Once established, deep circulating fluids can concentrate heat from a wide area without necessarily disrupting established plumes, regardless of the heat source (Bibby et al., 1995). A key point inherent in this model is the lack of structural control on the location of upwelling geothermal plumes.

Second, and in contrast, Rowland and Sibson (2004) observed that the regional distribution of the geothermal systems bears a demonstrable relationship to surface structure. Sixty percent of geothermal systems occur within accommodation zones, and some exhibit NW-SE trending features; e.g. shallow and deep isotherms, gravity contours, geochemical anomalies, and/or shallow hydrology. Overall, 80% of geothermal systems, channelling ~90% of the total natural heat output, correlate spatially with rift architecture in the form of splays or linkage structures at the lateral tips of large normal faults, known buried faults, and accommodation zones and inferred basement structures between rift segments. Such regional-scale correlation of geothermal systems with rift architecture suggests structural control at depth within the convective regime.

### 3. LARGE-SCALE CHRONOLOGICAL CONTROLS

In considering the nature of the TVZ and its geothermal fields at the present day, questions arise as to the longevity of each system, and how that system might have changed over time. Evidence for the duration of individual systems is remarkably hard to gain for several reasons, including the overprinting of evidence for waxing and waning of systems and a lack of age controls on such evidence. For example, widely cited is the proposal by Browne (1979) from the presence of hydrothermally altered fragments in a deposit at depth that the Kawerau geothermal field is older than the Matahina Formation ignimbrite (now dated at ~320 ka: Leonard et al., 2010) New studies suggest, however, that the modern system with an inferred magmatic source under the <5.5 kyr old Putauaki volcano and the older system may be separate entities which share a common geographic location (Milicich et al., 2011).

For magmatic systems the only evidence for their longevity and style is through the volcanic products. Such studies suggest that large shallow magmatic systems, as are inferred to be the sources of the dominant rhyolitic eruptions, can be focussed in single areas for periods of up to the order 100 kyr but on time periods of 100-300 kyr shift in position within the central TVZ. Any geothermal systems reliant on relatively shallow (4-8 km) rhyolitic magmatic sources (e.g. those currently active below Lake Taupo) will thus have a finite lifetime of the order 100 kyr years. Systems fed from deeper magmatism, not necessarily feeding volcanic activity, such as the 10-15 km deep melt-bearing crustal zones imaged by MT (Heise et al., 2010) may have much longer lifetimes, possibly to the order of 1 million years, because of the size of the thermal anomaly,

its immunity to disruption by caldera collapse and the stability of the fluid upflow conduits. Ngatamariki may be an example of such a system, with the presence of the quartz diorite intrusion being purely coincidental, although both the old intrusion and the modern field may share a common structural control. If fluid pathways are critical to the positioning and output of the modern fields, then such systems may have multiple lifetimes as thermal sources within the crust come and go.

### 4. CHALLENGES IN GEOTHERMAL SYSTEMS

There are many aspects of the geothermal systems seen at present in the central TVZ that represent challenges in understanding their history and evolution, and the potential effects of any exploitation beyond that being undertaken at the present day. We identify some of them here.

What does the present-day distribution of geothermal systems actually represent? Electrical resistivity surveys have been highly successful in locating geothermal fields in the central TVZ. However, earlier inferences that the anomalously low resistivities were due to the uprise of alkaline chloride waters have now largely been replaced by the notion that the exceptionally low shallow-level resistivities are controlled by clay-alteration products (e.g. Heise et al., 2008, at Rotokawa), and that the deeper feeder zones that contain the chloride waters are less conductive. For example, horizontal 2-D slices through the top 20 km of crust below the central TVZ show no clear zones of higher conductivity between the shallow highly conductive zones matched to individual geothermal systems and the deep conductors between 15 ± 5 km depth that are reasonable inferred to reflect partially molten rock (Heise et al., 2010). The distribution of surface geothermal systems does not therefore in itself allow us to identify all possible areas where high-temperature geothermal fluids might be present in the upper crust. It is also possible through geochemical studies (particularly of gas species) to identify more ‘magmatic’ versus more ‘crustal’ components in the geothermal fluids, but it is unclear what such components actually represent

How stable are the geothermal systems? By this we mean if geophysical surveys and field mapping have identified all surface areas of active and extinct fluid flow in the Central TVZ, how have the systems survived burial by volcanic products and/or destruction by caldera collapse? Does the lack of relatively shallow geophysical anomalies (say, in the top 2-3 km of crust) mean that there are no undiscovered geothermal systems that became extinct through withdrawal of their heat source or destruction by eruption of their host rocks?

How steady-state are the geothermal systems? Although individual fields are observed to be moribund or extinct, particularly in the line of resistivity anomalies west of the zone of intense modern faulting (Figure 3), such as Ohakuri (Henneberger and Browne, 1988), there is almost nothing known about how much and over what timescales the thermal and mass fluxes of fluids can vary. The positions and intensities of magma fluxes can be inferred from patterns of surface volcanism, yet there is almost no corresponding information on the responses of any associated geothermal system. In addition, although observed rift-related faulting in the TVZ has reached to depths of 8 km or so (Edgcumbe: Anderson and Webb, 1989) there is no information on how rupture to that depth

might influence (or in turn be influenced by) fluid flow in nearby geothermal systems. Knowledge as to whether deep geothermal fluid flow (~10 to ~3 km depth) is steady state, or driven by pulses of flow as fluid pressures influence the fracture permeability under the prevailing local stress regime is important but lacking at present. Application of downhole seismic techniques may allow the microseismic accompaniment to fluid flow to be imaged and these issues to be addressed.

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