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The volcanic, magmatic and tectonic setting of the Taupo Volcanic Zone, New Zealand, reviewed from a geothermal perspective

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ABSTRACT

The Taupo Volcanic Zone (TVZ) in the North Island of New Zealand is one of the world's most spectacular and productive areas of Quaternary silicic volcanism and geothermal manifestations. The TVZ is only the latest manifestation of NNE–SSW-orientated arcs that have migrated in step-wise fashion to the SSE over the past ca. 16 Ma. The TVZ began erupting around 2 Ma, with early andesitic volcanism being joined and rapidly swamped by voluminous rhyolitic volcanism. The zone shows a pronounced segmentation into northern and southern extremities with andesite composite cones, no calderas and only limited vent-hosted geothermal systems, and a 125 km long rhyolite-dominated central segment. About four times as much magma is trapped at depth below the central TVZ than is erupted, feeding heat, volatiles and chemicals into 23 geothermal systems with a total of ca. 4.2 GW thermal energy release. The modern (post-61 ka) TVZ is an actively rifting arc, widening at 7 mm/year at the south end to 15 mm/year at the Bay of Plenty coastline, with an associated zone of young to active faulting (Taupo Fault Belt: TFB, or the Taupo Rift), but the axes of the modern TFB and TVZ are offset by 15–20 km through much of the central TVZ. Although there is a dominant NNE–SSW tectonic grain within the central TVZ, there are also influences of deeper basement structures that sometimes extend outside the limits of the zone, such as NW–SE, arc-perpendicular accommodation zones linking local domains of extension as well as N–S orientated structures related to the Hauraki Rift that may control fluid flow into the roots of the geothermal systems. Models for the geothermal systems favour either a source in a relatively shallow localised magmatic intrusion (e.g., Kawerau, Ngatamariki) or treat the systems as reflecting large-scale fluid dynamical instabilities from an evenly heated 'hot plate' at ~7 km depth. Where controls from dating of host lithologies are available, systems at Kawerau and Ngatamariki are seen to represent renewed activity superimposed on a fossil system fed by past intrusions, and it is unclear what is meant by the lifetime of any single geothermal system. TVZ geothermal systems appear in turn to react too sluggishly to respond to disruptive episodes of volcanism, and recover within geologically short periods of time, as seen at Waimangu and Taupo. In the central TVZ, there are complex inter-relationships between volcanism, magmatism, and tectonism. Magmatism and volcanism are obviously linked, but it is uncertain why intense magmatism at Taupo and Okataina should yield voluminous rhyolite volcanism, whereas more intense magmatism in the Taupo-Reporoa Basin has not yielded significant silicic volcanism but instead feeds multiple large geothermal systems. The central TVZ is unique for an arc segment in the intensity of its magmatic-volcanic-geothermal flux (matching the Yellowstone system), and the cause(s) of this uniqueness are not yet established. Any explanation needs to address the segmented nature of the zone, and why the thermal flux should be so geographically and temporally constrained.

1. Introduction

The Taupo Volcanic Zone (TVZ) represents the southernmost ~300 km-long portion of the ~2800-km-long Tonga-Kermadec arc system where it intersects and terminates in the North Island, within the continental crust of Zealandia (Cole and Lewis, 1981; Luyendyk, 1995; Mortimer, 2004; Smith and Price, 2006: Fig. 1).

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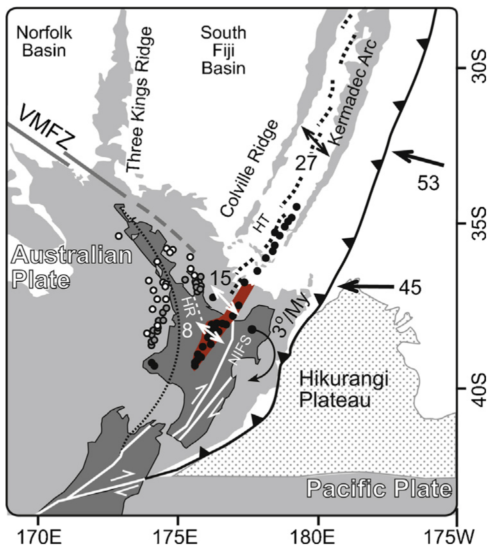

Fig. 1. Current tectonic setting of northern New Zealand, annotated with loci of volcanism for three different time periods ± 0.5 Ma (Circles: black = 0 Ma, grey = 8 Ma, white = 16 Ma) from Seebeck et al. (2014a), geodetic vectors of extension (double arrows: Parson and Wright, 1996; Wallace et al., 2004) and relative plate motion (single arrows: DeMets et al., 1994) in mm/year. Terrane suture in basement rocks as inferred from magnetic anomaly = dotted line. Rotation of eastern North Island shown for the period 3 Ma to present (Wallace et al., 2004). HR = Hauraki Rift; HT = Havre trough; NIFS = North Island Fault System; VMFZ = Vening Meinesz Fracture Zone (see text for context).

Although a small part of the Tonga-Kermadec arc – itself only a fraction of the major subduction zones and arc systems encircling the Pacific Ocean – the TVZ is recognised globally for its intense volcanic and geothermal manifestations. Within a ~120 km × 60 km central segment of the TVZ, rhyolitic volcanism is exceptionally frequent and voluminous, and crustal magmatism and the modern geothermal systems are overwhelmingly concentrated (Wilson et al., 1995). In particular, this central segment is host to an exceptionally vigorous active hydrothermal province which, coupled with its volcanic output, puts it in the same class as the Yellowstone system (Christiansen, 2001; Hurwitz and Lowenstern, 2014). The central TVZ has a present-day average heat flow of 700 mW/m^2 and a total flux of 4.2 GW (Bibby et al., 1995; Hochstein, 1995), together with a volcanic output of large caldera-forming eruptions alone exceeding 6000 km^3 of rhyolitic magma during the Quaternary (Wilson et al., 2009). The geothermal flux of fluids and consequently heat is mostly concentrated at 23 highly active systems in this central area of the TVZ (Fig. 2), and these are the focus of other papers in this volume. Other important geothermal systems occur in association with the andesite–dacite composite cone volcanoes in the TVZ, and there is surficial evidence for recently deceased (late Pleistocene to Holocene) systems in the form of fossil sinter deposits.

Geothermal systems and fields of the central TVZ have played an important role in the worldwide development of many concepts around geothermal exploration and utilisation. In this paper we follow the convention of using the term 'system' to refer to the natural entity, and 'field' to refer to the geothermal resource and the infrastructure associated with its utilisation. The Wairakei Geothermal Field was one of the earliest areas globally to be utilised for geothermal energy on a commercial scale for electricity generation (e.g., Hunt et al., 2009). Studies of TVZ geothermal systems have contributed greatly to understanding of many related important topics, for example, mineralogical alteration patterns (Browne, 1978; Hedenquist and Browne, 1989; Hedenquist, 1990) and numerical modelling of sub-surface fluid flow (e.g. Kissling and Weir, 2005; Dempsey et al., 2012; Kaya et al., 2014), as well as to geophysical exploration and monitoring techniques, especially electrical resistivity (e.g. Bibby et al., 1998, 2008), magnetotellurics (Bertrand et al., 2012) and microseismicity (Sherburn et al., 2015). Other facets of the geothermal systems include their roles as model settings for epithermal (Rowland and Simmons, 2012) and porphyry copper systems of active mineralisation, such as White Island for high-sulfidation epithermal (Hedenquist et al., 1993), Ruapehu for sub-lacustrine vent-hosted systems (Christenson and Wood, 1993), and Broadlands-Ohaaki (Brown, 1986; Simmons and Browne, 2000) and Rotokawa (Krupp and Seward, 1987) for epithermal gold. Geothermal systems in New Zealand, as globally, are currently also the subject of much research on extremophile microorganisms (e.g. McKenzie et al., 2001; Handley et al., 2005, 2008; Stott et al., 2008; Sharp et al., 2014).

In this paper we present a generalised overview of the tectonic, magmatic and volcanic setting to the geothermal systems in the central TVZ in order to provide a background to the other topic- and field-specific papers in this volume. Although we deal with many concepts that are still controversial or poorly understood, we have tried to cite a wide cross-section of the relevant papers for access into the literature. There are several key questions that provide the impetus for this review and are addressed in this paper. These include (but are not limited to) the following.

- The big picture behind the modern picture – why is there a central TVZ with its accompanying extraordinary geothermal and magmatic fluxes?
- Why is there the spatial separation of geothermal systems and volcanism within the central TVZ and how does it reflect igneous and tectonic processes?
- How stable are the geothermal systems in their positions? Once established, are the systems rooted in the same place?
- How steady-state are the geothermal systems? Do they wax and wane, and if so, what are the causes for these fluctuations?

We bring attention back to these four questions in the last section of this paper.

2. Large-scale background to the TVZ

2.1. Tectonic setting in the North Island plate boundary

The genesis and evolution of the modern TVZ represents only the latest stage of a long and complex history of interactions between the Pacific and Australian plates over the past 25–30 Myr (e.g., Schellart et al., 2006; Mortimer et al., 2010; Schellart and Spakman, 2012; Reyners, 2013; Timm et al., 2014). The present-day configuration of the subduction system with westwards-directed oblique subduction of the Pacific plate beneath the Australian plate under the North Island of New Zealand, transitioning south-westwards into the strike-slip zone of the Alpine Fault, dates from ~16 Ma onwards. The relevance of this history from a geothermal perspective is because of its implications for the origins of major features of the mid- to upper crustal structure and present-day tectonics in the TVZ. Such features have fundamental importance in understanding the deep structural controls in the modern TVZ, potentially controlling rifting processes and the location and nature of large-scale faults that may act as either barriers to, or pathways for, deep fluid flow (Rowland and Sibson, 2004; Rowland and Simmons, 2012). The principal tectonic elements that have played a role in the Late Oligocene-to-present evolution of the plate boundary and which likely have impacts on the structure of the TVZ are depicted in Fig. 1 and include: