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Spatial and temporal variations in magma-assisted rifting, Taupo Volcanic Zone, New Zealand

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ABSTRACT

Taupo Volcanic Zone (TVZ), New Zealand, is a NNE-trending rifting arc, active for ~2 Myr, with a 125-km-long central segment characterized by exceptionally voluminous rhyolite volcanism. The volcanic segmentation reflects along-axis variations in magmatism with implications for the thermal state of the crust and consequent rifting dynamics. Along the zone to the north and south of Central TVZ, the limbs of broad monoclines, disrupted to various degrees by normal faults, dip SE against major NW-facing fault zones. In these northern and southern segments, the loci of magmatism (shown by the position of volcanoes) and rifting (manifested by the distribution of seismicity and modern (<61 ka) faulting in the Taupo Fault Belt (TFB)) coincide. Mantle-derived magmas are localized within the crust in a plexus of small bodies, dikes and sills, and dike-assisted rifting operates at times (but not always) as shown by the historic record. In contrast, throughout most of Central TVZ the loci of magmatism and tectonism (shown by the distribution of high-temperature geothermal systems and inferred from geophysical models and surface fault studies) are offset laterally and extensional strain appears to be partitioned accordingly. Geological, geophysical and geodetic studies indicate the following magma-assisted mechanisms of extension in Central TVZ: 1) mafic dike intrusion of length scale >20 km and width >1 m oriented perpendicular to the extension direction; 2) fault slips of <2 m on structures along-strike from and coeval with silicic eruptions, some of which were triggered by mafic dike intrusion; 3) rifting episodes associated with regional-scale uplift, multi-fault rupture (slips <2 m) and transient subsidence, arguably driven by changes in state at shallow depths. Volcanic studies of <340 ka deposits demonstrate that an additional, but less frequent, mechanism involves temporally higher rates of fault slip with regional-scale collapse of rift basins in association with large-scale silicic eruptions. TVZ rifting mechanisms thus vary in space and time according to magmatic style and result in unpredictable fault behaviour over millennial time scales.

1. Introduction

Regions of the Earth's lithosphere that are undergoing active extension are very commonly associated with magmatism, whether at divergent margins (e.g., Dabbahu Rift: Wright et al., 2006; Ayele et al., 2007), in intra-plate settings (e.g., Yellowstone: Puskas et al., 2007), or at convergent margins (e.g., Taupo Volcanic Zone: Wilson et al., 1995; Rowland and Sibson, 2001). The range and styles of magmatism vary greatly between and within these settings, with implications for the spatial and temporal response of the lithosphere to stretching. Over the last 30 years there has been great interest in how continental lithosphere accommodates extensional strain and much effort has focused on characterizing rifts and rifted margins at the regional scale, and understanding the processes that affect their evolution (see Buck, 2004, and references therein). Some rifts, like the Basin and Range Province, USA, extend across widths far greater than their lithospheric thickness and accommodate large strains. In contrast, rifts such as those of East Africa are localized along narrow belts and may form deep basins with only small amounts of extension (e.g., Ebinger et al., 1999). Other narrow zones of apparently localized extension, metamorphic core complexes, accommodate stretching with little local subsidence. This diversity in large-scale rift architecture is thought to depend on the initial thermal structure and thickness of the lithosphere, and its subsequent modification through mantle melting (Buck, 2004).

Mantle melting exerts a fundamental control on rift architecture because upward movement of mafic magma is a very effective means by which extensional strain can be accommodated. Thus, in any rift setting there arise two end-member mechanisms that may accommodate stretching. In non-magmatic settings, extensional strain is accommodated by faulting with its timing governed by the reactivation and elastic

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interaction of arrays of normal faults (e.g., Cowie et al., 2000; Colgan et al., 2004). However, in rifts with plentiful magma, extension may be accommodated by diking, which activates at much lower differential stresses than are required for faulting (e.g., eastern Snake River Plain: Parsons et al., 1998; Holmes et al., 2008). Whereas the former process thins the crust and creates significant topography, dike intrusion preserves crustal thickness and is generally thought to inhibit the development of large-offset (≫10 m) normal faults. Along-strike variations in rift architecture occur in concert with along-strike variations in magma supply.

Narrow continental rifts which are transitional towards seafloor spreading similarly capture in their rift architecture the switch from tectonic- to magma-assisted rifting. For example, the Main Ethiopian Rift displays a transition from extension via crustal or lithospheric-scale detachment faults to magma intrusion and minor faulting in the upper crust above mafic magma injection zones, in concert with the evolving state of the asthenosphere (Ebinger and Casey, 2001; Keranen et al., 2004; Bastow et al., 2005). Evolved rifts, such as those within the Afar Depression and Iceland, appear to accommodate strain in transient episodes, whereby a geologically instantaneous and localized extension accompanies dike intrusion (e.g., Sigmundsson, 2006; Wright et al., 2006). These dike events may occur singly or as a succession of discrete intrusions over several years, followed by a decadal-scale relaxation transient that is larger than the time-averaged plate divergence (e.g., Heki et al., 1993). The periodic repetition of this process is recorded in the morphology as individual tectono–magmatic segments and over time leads to opening rates consistent with far-field plate motions.

Investigations targeting the interplay between magmatism and rifting have focused mostly on provinces in which basalt is the dominant volcanic product (see references in the examples above). In contrast, some active continental rifts are dominated by silicic volcanism and presumably are characterized by far more complex magmatic systems (e.g., Yellowstone: Hildreth et al., 1991; Christiansen, 2001). Three-way coupling between deep mafic magmatism, mid-to-upper crustal silicic magmatism and rifting undoubtedly occurs in these settings, but the additional crustal thicknesses and processes of caldera volcanism, sedimentation and subsidence often obscure the details of how these processes interact. Here we consider an arc setting, the Taupo Volcanic Zone (TVZ), New Zealand (Fig. 1), where the high frequency of volcanism and rapid rifting (by arc standards) allow us to address the processes of magma-assisted rifting in a silicic volcanic province. The TVZ is a young arc which represents the southern ~10% of the 2800-km-long Tonga-Kermadec arc where it intersects, and terminates in, the continental crust of the greater New Zealand microcontinent (Fig. 1 inset). Although atypical in an arc context, the TVZ provides a window into the complex relationships that exist between volcanism, tectonism and magmatism in continental crust (e.g., Wilson et al., 2009). Our review of existing data and concepts related to these processes leads to a new framework for understanding rifting in the TVZ. In particular, we demonstrate that the mechanism of extension varies in time and space according to the availability of magma and the style of magmatism.

2. Regional and local geology of TVZ

The present-day TVZ represents the latest stage in a long and complex history of subduction zones and arc volcanism in the New Zealand region that began at about 23 Ma with a NW–SE arc in Northland, then changed around 16 Ma to the present-day NNE–SSW configuration aligned with the extinct Colville and active Kermadec arcs (Fig. 1) (Herzer, 1995; Herzer and Mascle, 1996; Mortimer et al., 2007). The present TVZ began around 2 Ma with early andesitic volcanism being joined and swamped around 1.6 Ma by voluminous rhyolitic volcanism (Houghton et al., 1995; Briggs et al., 2005). At least 10,000 km^3 of overwhelmingly rhyolitic magma has been erupted in the last 1.6 Myr, but the eruption records from terrestrial and marine records suggest that this volume is a minimum and correlations are presently incomplete (Carter et al., 2003, 2004; Allan et al., 2008). Andesite is an order of magnitude less abundant than rhyolite, and basalt and dacite are minor in volume (<100 km^3 each), with few eruptions exceeding 1 km^3 (Wilson et al., 1995).

The history of TVZ is divisible into Old TVZ from 2.0–0.34 Ma, and Young TVZ from 0.34 Ma to the present (Fig. 1: Wilson et al., 1995). In turn we use 'Modern TVZ' to reflect the present-day situation from ~61 ka for which the silicic eruptive history is well established (Wilson et al., 2009), patterns of geothermal fluid flow (Bibby et al., 1995) can be inferred to have remained more-or-less uniform in distribution, and fault behavior on studied across-rift profiles is somewhat predictable (Nicol et al., 2006). TVZ shows a pronounced segmentation into the Northern and Southern extremities with andesite composite cones and no calderas, and a 125-km-long rhyolite-dominant Central segment (Fig. 1). Eruption styles, volumes and rates are distinctly different in Northern and Southern TVZ compared to those of Central TVZ. These variations reflect fundamentally different magmatic plumbing networks within the crust (cf. Price et al., 2005; Charlier et al., 2005). Within Central TVZ, non-rhyolitic compositions occur apparently irregularly in time and space and there is no evidence for a geographic separation of basalts from andesites, or of either from rhyolites. The world's most active rhyolitic volcanoes, Taupo and Okataina, are located at the southern and northern ends of Central TVZ, respectively. Over the past 61 ka in Central TVZ alone, about 780 km^3 of magma has been erupted, of which 82% was released in three moderate to large caldera-forming eruptions at 61, 26.5 and 1.8 ka (Wilson et al., 2009). However, about four times as much magma is trapped at depth (mostly below the intervening region within Central TVZ) than is erupted at the active caldera volcanoes, feeding heat, volatiles and chemicals through 23 geothermal fields with a total of 4.5 GW thermal energy release (Figs. 1 and 2: Bibby et al., 1995; Hochstein, 1995). In comparison, heat flow is an order of magnitude less and average magma eruption rates amount to no more than ~2 km^3/kyr in total for the Northern and Southern TVZ sectors (cf. Cole et al., 2000; Hobden et al., 2002; Gamble et al., 2003).

The semi-regular 10–15 km spacing of geothermal fields within Central TVZ, together with rheological arguments, indicate that hot (>250 °C) fluid advects across the full depth of the seismogenic zone (6–8 km) (Bibby et al., 1995). Discharge to the surface is mostly localized within two parallel NE-striking belts of broadly conductive character, separated by a more resistive region notable for its arrays of similarly oriented normal faults (Fig. 2). In addition, several geothermal fields are aligned along NW-trending zones of lower resistivity, which appear to correlate with cross-strike discontinuities between the arrays of normal faults (Rowland and Sibson, 2004). Most of the heat flux through Central TVZ is localized along its eastern margin (inset Fig. 2) (Bibby et al., 1995).

Studies on Taupo and Okataina volcanoes demonstrate that the melt-dominant rhyolite magma bodies disgorged during eruptions are lodged at shallow levels (~4 to <10 km deep: Dunbar et al., 1989; Liu et al., 2006; Shane et al., 2008a). Petrological and zircon model-age data imply that these rhyolite bodies may accumulate over exceedingly short time frames (hundreds to thousands of years), and are relatively short-lived when compared with mafic magmatic activity in the lower crust (Sutton et al., 2000; Charlier et al., 2005; Shane et al., 2008a; Wilson and Charlier, 2009). Major caldera-forming eruptions collectively encompassing almost all parts of Central TVZ appear to cluster in time on a range of scales (e.g., Houghton et al., 1995; Gravley and Wilson, 2006), and may even erupt coevally (e.g., Gravley et al., 2007). The rhyolite bodies are part of a complex magmatic system that is distributed across the entire Central TVZ from the base of the seismogenic zone (~6 km) to depths of ~16 km, below which extends the mafic magmatic system. Unlike the mush model for rhyolite