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Internal structure and volcanic hazard potential of Mt Tongariro, New Zealand, from 3D gravity and magnetic models

Craig A. Miller [a,b,*], Glyn Williams-Jones [b]

[a] Department of Earth Sciences, Simon Fraser University, Burnaby, BC V5A 1S6, Canada
[b] GNS Science, Wairakei Research Centre, Private Bag 2000, Taupo 3352, New Zealand

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ABSTRACT

A new 3D geophysical model of the Mt Tongariro Volcanic Massif (TgVM), New Zealand, provides a high resolution view of the volcano's internal structure and hydrothermal system, from which we derive implications for volcanic hazards. Geologically constrained 3D inversions of potential field data provides a greater level of insight into the volcanic structure than is possible from unconstrained models. A complex region of gravity highs and lows (±6 mGal) is set within a broader, ~20 mGal gravity low. A magnetic high (1300 nT) is associated with Mt Ngauruhoe, while a substantial, thick, demagnetised area occurs to the north, coincident with a gravity low and interpreted as representing the hydrothermal system. The hydrothermal system is constrained to the west by major faults, interpreted as an impermeable barrier to fluid migration and extends to basement depth. These faults are considered low probability areas for future eruption sites, as there is little to indicate they have acted as magmatic pathways. Where the hydrothermal system coincides with steep topographic slopes, an increased likelihood of landslides is present and the newly delineated hydrothermal system maps the area most likely to have phreatic eruptions. Such eruptions, while small on a global scale, are important hazards at the TgVM as it is a popular hiking area with hundreds of visitors per day in close proximity to eruption sites. The model shows that the volume of volcanic material erupted over the lifespan of the TgVM is five to six times greater than previous estimates, suggesting a higher rate of magma supply, in line with global rates of andesite production. We suggest that our model of physical property distribution can be used to provide constraints for other models of dynamic geophysical processes occurring at the TgVM.

1. Introduction

Knowledge of a volcano's internal structure is important for many aspects of volcanology and volcanic hazard assessment. This is especially so in complex multi-vent systems where there is no central vent through which most eruptions occur and where multiple vents have been active in historic times. By geophysically imaging the volcano plumbing system and structures in the basement below the volcanic edifice, it is possible to assess the importance of these structures in controlling magma ascent paths and vent locations. In addition, knowledge of the extent of a volcano's hydrothermal system provides important information on the likely style of eruptions. Hydrothermal systems often manifest as scenic surface features, attracting hikers and tourists, but when over-pressurised can produce small, but dangerous phreatic eruptions with very little warning (e.g., Raoul Island, Christenson et al., 2007; Te Maari, Procter et al., 2014; Ontake, Sano et al., 2015) and are often overlooked in volcanic hazard assessments. As such, knowledge of the extent of a hydrothermal system and its interaction with magma pathways provides important information on the likelihood of such eruptions and allows suitable hazard mitigation to be put in place (Potter et al., 2014). Long-lived hydrothermal systems considerably alter and mechanically weaken large volumes of rock, which if coincident with steep slopes presents a considerable landslide, lahar and flank collapse hazard (e.g., López and Williams, 1993, Day, 1996; Finn et al., 2001; Reid et al., 2002; Moon et al., 2005; Tontini et al., 2013).

Geophysical knowledge of a volcano's internal physical property distribution also provides context within which processes that occur during volcanic unrest can be interpreted. Often, geophysical models of volcano unrest are limited by use of an unrealistic uniform halfspace or simple 1D model: the necessary geophysical context required for more detailed modelling is unknown (Cannavò et al., 2015). This results in inaccurate models which impedes scientists' ability to make informed decisions during times of volcanic unrest.

Here we present a new, detailed, 3D geophysical model of the multi-vent Mt Tongariro volcanic massif (TgVM), New Zealand, combining an extensive new gravity dataset with aeromagnetic and geological data. We use a geologically constrained inverse modelling technique not previously applied to complex multi-vent andesite stratovolcanoes (cf. Blaikie et al., 2014), to produce a geologically sound and geophysically accurate model of the TgVM. This model enables examination of

* Corresponding author at: Department of Earth Sciences, Simon Fraser University, Burnaby, BC V5A 1S6, Canada.
E-mail address: c.miller@gns.cri.nz (C.A. Miller).

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1) the basement surface and faulting under the edifice, 2) the bulk internal structure of the volcano and 3) the extent of the hydrothermal system. Furthermore, we assess the volcanic hazard implications of features in our model. For example the distribution of hydrothermally altered rock has an influence on future landslide potential and we consider the likelihood of basement faults acting as future magma pathways.

2. Geologic setting and existing geophysical data

Interest in the TgVM has increased since early 2000 when unusual tornillo-type earthquakes were detected (Hagerty and Benites, 2003) around the Te Maari craters (Fig. 1). In 2005–2009, a long sequence of small volcanic earthquakes occurred close to Mt Ngauruhoe (Jolly et al., 2012), 30 years after its last eruption, and in 2012 two eruptions occurred from the Upper Te Maari Crater, the first confirmed eruptions from this vent in over 100 years (Scott and Potter, 2014).

The TgVM lies at the southern end of the Taupo Volcanic Zone (TVZ), in a back-arc setting resulting from the westward subduction of the Pacific plate beneath the North Island of New Zealand. Within the back-arc setting is an extensional environment known as the Taupo or Ruaumoko Rift (Rowland and Sibson, 2001, Acocella et al., 2003). Extension across this rift is accommodated by segments or domains of sub-parallel north-west and south-east dipping normal faults (Seebeck et al., 2014). The TgVM is located at the northern end of the Ruapehu or Tongariro domain, an area dominated by andesitic volcanism, south of the dominantly rhyolitic Taupo domain. The geologic extension rate across the graben (Mt Ruapehu graben) formed by normal faulting in the Tongariro domain is estimated by Villamor and Berryman, (2006b) to be 2.3 ± 1.2 mm/year. Several sub-parallel faults and fault zones delineate the graben in our study area; from west to east, these are the National Park fault, Waihi fault zone, Poutu fault zone and the inferred location of the northwest dipping Rangipo fault (Fig. 1).

Jurassic age basement rocks of the Torlesse Terrane outcrop in the Kaimanawa Ranges on the east, while Waipapa Terrane rocks outcrop in the far west of the model area. In the centre of the Mt Ruapehu graben, basement rocks are inferred to be overlain by a thin layer (100 m) of Tertiary sediments. Tunnels drilled as part of the Tongariro power scheme in the far north-west of the study area intersected Waipapa Terrane greywacke beneath surface Tertiary sediments at a depth of around 100 m (Beetham and Watters, 1985).

Here we refer to the TgVM as the various eruptive centres that make up Mt Tongariro, including Mt Ngauruhoe (2280 m). The TgVM is constructed of at least 17 overlapping vents built during 6 main cone building episodes and covers an area of 5 by 13 km (Hobden et al., 1999). The massif has been extensively modified by glaciation since the first eruptions around 275 ka, thus surface exposures of early vents are obscured by later eruptions or have been removed by erosion.

Earliest activity began in the area of Lower Tama Lake (Tama 1) (Fig. 1), followed by activity around 200 ka at a nearby centre, Tama 2. A long lived cone north of Oturere Valley (Northeastern Oturere, Mangahouhounui lavas) was built between 105 and 130 ka during which time a vent near Pukekaikiore was also active. Another centre, Tongariro Trig formed between 65 and 110 ka, while contemporaneously a cone formed to the south of Oturere Valley (Southwestern Oturere, Waihohonu lavas) (Hobden et al., 1996). Around 25 ka, activity started at Te Maari, Tama Lakes, Red Crater, North Crater, Blue Lake and Pukekaikiore (Nairn, 2000). Since around 7 ka, activity has been dominated by the growth of Mt Ngauruhoe cone (Moebis et al., 2011) while historic activity has been from Mt Ngauruhoe, Red Crater and Upper Te Maari (Scott and Potter, 2014).

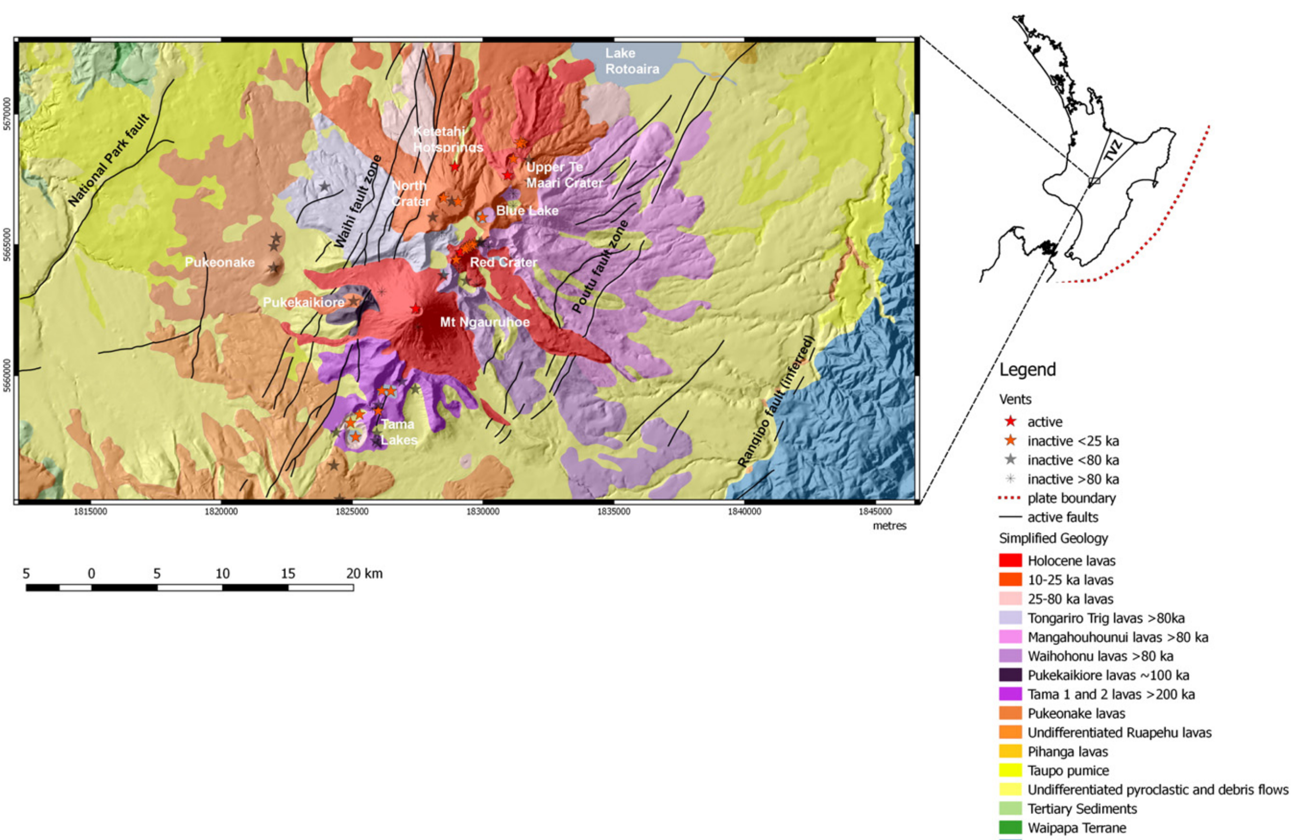

Fig. 1. Simplified geological map of the TgVM. The inset map shows the North Island of New Zealand with the TVZ and model area outlined in black. The dashed red line is the Pacific/Australian plate boundary. Coordinates are easting and northing in m using the NZTM projection.