Earth and Planetary Science Letters 432 (2015) 115–125

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Structure of the Tongariro Volcanic system: Insights from magnetotelluric imaging

Graham J. Hill[a,b,*], Hugh M. Bibby[c], Yasuo Ogawa[d], Erin L. Wallin[e], Stewart L. Bennie[c], T. Grant Caldwell[c], Harry Keys[f], Edward A. Bertrand[c], Wiebke Heise[c]

[a] Antarctica Scientific Limited, Wellington, New Zealand
[b] Gateway Antarctica, University of Canterbury, Christchurch, New Zealand
[c] GNS Science, Lower Hutt, New Zealand
[d] Tokyo Institute of Technology, Tokyo, Japan
[e] University of Hawaii Manoa, Centre for the Study of Active Volcanoes, Hawaii, USA
[f] Department of Conservation, Turangi, New Zealand

ARTICLE INFO

Article history:
Received 26 June 2015
Received in revised form 30 September 2015
Accepted 1 October 2015
Available online 3 November 2015
Editor: P. Shearer

Keywords:
geophysics
magnetotellurics
Tongariro

ABSTRACT

The dynamics of magma reservoirs (the main repositories for eruptible magma) play a fundamental role in the style and behaviour of volcanic systems. A key first step in understanding these systems is to identify their location and size accurately. We present results from a broadband magnetotelluric study of the Tongariro Volcanic system and discuss how the results fit within current petrological models. The Tongariro Volcanic system is a composite andesitic cone complex, located at the southern end of the Taupo Volcanic Zone in the central North Island of New Zealand. We use data from 136 broadband magnetotelluric soundings within a 25 × 35 km area covering the volcanic system to construct a 3D image of the magmatic system of the Tongariro Volcanic Complex including Mount Ngauruhoe. The structure of the Tongariro magmatic system has been determined from 3D forward and inverse modelling of the magnetotelluric data and allowed for an estimation of the melt fraction present within the system. 3D inverse modelling of the magnetotelluric data shows: a well-developed shallow low resistivity zone outlining the geothermal system; a zone of even lower resistivity representing a shallow crustal magma accumulation zone located at a depth of ∼4–12 km offset to the east of the Tongariro vent system; and a zone with a slightly higher resistivity connecting these two components of the magmatic system providing the path for magmatic fluids from the deeper source region to reach the surface during eruptive events.

1. Introduction

The Tongariro Volcanic Centre is comprised of three separate volcanoes Mount Ruapehu, Mount Ngauruhoe, and Mount Tongariro which together mark the southern extent of the Taupo Volcanic Zone on the North Island of New Zealand (Fig. 1). Here we present a detailed magnetotelluric study of the volcanic structure of the two northern volcanoes of the Tongariro Volcanic Centre, Mounts Tongariro, and Ngauruhoe, while Mount Ruapehu was the subject of previous study (Ingham et al., 2009). Since the data collection for the survey was completed, Mount Tongariro has produced two small eruptions, the first in July 2012 and the second in November 2012, both from a vent located at the Upper Te Maari Craters area (Fig. 1). The eruptions were limited to this vent location and there has been no activity of note at the other vents of the Tongariro Volcanic Centre. Mount Ngauruhoe is the youngest (∼7000 yrs) of the three main vents of the Tongariro Volcanic Centre and has been the most active in recent history with a small eruption on average every three years, although it has not erupted since 1977 (Moebis et al., 2011). Though the northern volcanoes of the Tongariro Volcanic Centre (Mounts Tongariro and Ngauruhoe) have a permanent monitoring network, little is known about the structure of the hydrothermal and magmatic systems.

High electrical conductivity values are typically associated with volcanic–hydrothermal systems and the underlying magmatic systems – making them a good target for electrical geophysical methods which are sensitive to conductivity. The resistivity (the reciprocal of conductivity) of a rock usually depends on the amount and interconnectivity of a conductive fluid contained within the

* Corresponding author.
E-mail address: graham@antarcticascientific.com (G.J. Hill).

http://dx.doi.org/10.1016/j.epsl.2015.10.003

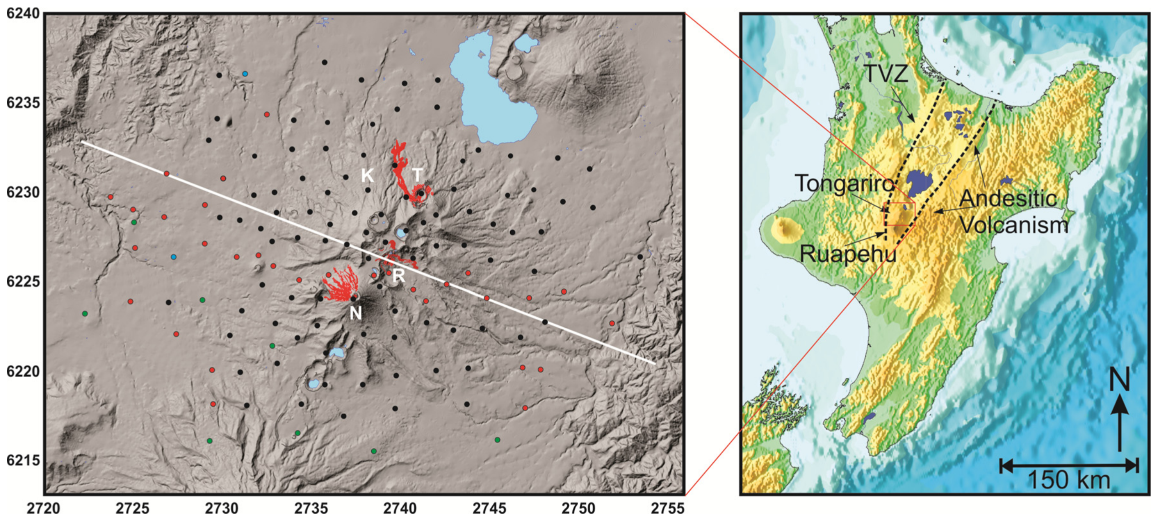

Fig. 1. Location of the Tongariro Volcanic Massif in the central North Island New Zealand, showing the outline of the Taupo Volcanic Zone (black dashed line) and the locations of the two large cone Volcanoes Ruapehu and Tongariro. In set map plotted using NZMG distance labels (km) shows measurement locations and the largest deposits from historic eruptions (N = Ngauruhoe, R = Red Crater, T = Te Maari Crater, K = Ketatahi geothermal springs). Measurement locations were recorded over four field campaigns (green 2004, blue 2008, red 2009, and black 2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

rock matrix. As such rocks containing an interconnected melt fraction will have low resistivity. Resolving the electrical conductivity structure of volcanic systems can thus provide information on the location and properties of melt and hydrothermal structure testing the petrological models. A key step in effectively monitoring volcanic systems is first understanding the structure and dynamics of the magmatic systems and locations of magma storage zones; as such magnetotelluric studies are becoming more commonly used to study volcanoes in Japan (Aizawa et al., 2014; Ogawa et al., 2014), Indonesia (Moore et al., 2008), North and South America (Hill et al., 2009; Diaz et al., 2012; McGary et al., 2014; Wannamaker et al., 2014) and New Zealand (Ingham et al., 2009).

We completed a 136 station magnetotelluric survey of Mounts Tongariro and Ngauruhoe and their surrounding area designed to identify zones of magma storage, the ascent paths taken as the magma migrates from depth to the surface during eruption, and the nature of the change from the caldera forming silicic volcanism which typifies the northern TVZ and that of the cone building Andesite volcanism present at the southern boundary of the TVZ. As Mount Ruapehu had a 3D electrical structure we expected that this would be the case for Mounts Tongariro and Ngauruhoe, and the survey was designed with the intention of completing a 3D analysis and interpretation.

2. Structural and geologic setting

The Tongariro Volcanic Centre consists of three large andesite volcanoes, Mounts Ruapehu, Ngauruhoe, and Tongariro, and marks the southern boundary of the Taupo Volcanic Zone (TVZ). The extension occurring within the TVZ, ∼7 mm/yr (Villamor and Berryman, 2001), occurs through the Taupo Rift which is characterised by an exceptional heat flux (Bibby et al., 1995). The portion of the rift in which the Tongariro Volcanic Complex is located is called the Tongariro domain (Fig. 1) and extends from south of Lake Taupo to south of Mount Ruapehu (Rowland and Sibson, 2001). The basement is comprised of Mesozoic greywacke metasediments which outcrop on both sides of the rift (Rowland and Sibson, 2001).

The Tongariro Volcanic complex can broadly be separated into the Mount Ruapehu system and the Tongariro Massif system which includes Mounts Tongariro and Ngauruhoe (Fig. 1). Mount Ruapehu was the focus of a previous study by Ingham et al. (2009). The Tongariro massif is comprised of multiple cones and craters, and compositionally is predominantly andesitic with lesser amounts of dacite and basaltic-andesite (Hobden et al., 1996). The age of eruptive products, like the volcano itself, is complex, with the oldest deposits 275 Ka exposed in the Tama Lakes in the south (Fig. 1) with younger lavas generally in the southwest, near centre and northeast that is along the whole length of the SW-NE corridor (Hobden et al., 1999).

Eruptive activity within the Tongariro and Ngauruhoe system has been predominantly from single vents or closely located adjacent vents, though a period of increased activity occurred at ∼10 ka at which time multiple vents were active contemporaneously at both Mounts Ruapehu and Tongariro (Nairn et al., 1998). From geochemical studies Hobden et al. (1999) argue that the magmatic ascent paths have been short-lived and of limited extent over the last 1000 years, while Price et al. (2005) have suggested that changes in the magmatic composition on short time scales indicate a complex magmatic plumbing system with a series of small magma reservoirs which may have limited interconnectivity.

Previous geophysical studies have been mainly seismic in nature with the most recent being that of Rowlands et al. (2005) in which they completed a detailed tomography study of the Tongariro Volcanic Complex. The main features identified by the tomographic models include: an aseismic conduit beneath Ruapehu which is considered to remain hot from prior eruptions offering a preferential path to the surface for new magmatic inputs to the system; a shallow (<5 km) series of small interconnected mush zones (magma reservoirs) underlying Ngauruhoe; that the geothermal system at Mount Tongariro, is underlain by a hot body providing the heat source; and a thick sequence of volcanic deposits that form a low velocity package which make up the ring plains around Ruapehu and Tongariro (Rowlands et al., 2005). The crust underlying the region from Ngauruhoe south to Mount Ruapehu is virtually aseismic which may indicate a shallower depth to the Brittle–Ductile transition here (Rowlands et al., 2005). These observations agree with petrological models (Nairn et al., 1998; Nakagawa et al., 1998; Gamble et al., 2003) of these systems which favour an 'open source system' in which andesite and basaltic melt is sourced from depths greater than ∼20 km, and dacite melt from depths greater than ∼8 km (Nakagawa et al., 1998) which rise rapidly through the system prior to being extruded. The cut off