Journal of Volcanology and Geothermal Research 314 (2016) 39–48

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Imaging the deep source of the Rotorua and Waimangu geothermal fields, Taupo Volcanic Zone, New Zealand

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ARTICLE INFO

Article history:
Received 27 February 2015
Accepted 12 October 2015
Available online 27 October 2015

Keywords:
Magnetotellurics
Rotorua geothermal system
Waimangu geothermal system
Taupo Volcanic Zone

ABSTRACT

Magnetotelluric data were recorded in a 45 × 10 km band crossing the Rotorua and Waimangu geothermal fields in the northern part of the Taupo Volcanic Zone in the central North Island of New Zealand. 3-D inverse modelling of these data show that beneath the low resistivity areas marking the near surface geothermal fields, localised electrically conductive zones are present in the crust below about 2.5 and 3.5 km depth at Rotorua and Waimangu, respectively. At increasing depth these conductive zones broaden and appear to merge with a larger conductive zone at 8 km depth situated between the geothermal systems. At Rotorua the top of the conductive zone is situated directly beneath the area of greatest surface heat and gas discharge. At Waimangu the uppermost part of the deeper conductive zone is situated beneath the western part of Lake Rotomahana, also an area of intense surface thermal activity and high heat flux. The localised conductive zones are interpreted to be high temperature (quasi-magmatic) fluids rising from a broader zone of partial melt at deeper levels.

1. Introduction

The Taupo Volcanic Zone (TVZ) is a rifted arc characterised by its voluminous rhyolitic volcanism, rapid crustal extension and large (~4.5 GW) convective heat flux (Bibby et al., 1995; Wilson et al., 1995), which is ultimately driven by the subduction of the Pacific Plate beneath the North Island of New Zealand. The heat source for the geothermal systems in the TVZ is thought to be a zone of partial melt or 'silicic-mush' as described for example by Bachmann and Bergantz (2008). This zone is thought to lie below the brittle–ductile transition at ~8 km depth in the TVZ (Bibby et al., 1995). This model of large scale heat transport in the TVZ is supported by analysis of regional (widely spaced) magnetotelluric (MT) measurements (Ogawa et al., 1999; Heise et al., 2007, 2010). More recently Bertrand et al. (2012, 2013) have shown that the link between the deep magmatic sources and the geothermal systems is closer than envisaged by Bibby et al. (1995).

The Rotorua and Waimangu geothermal systems (marked by areas of low apparent resistivity in Fig. 1, see Bibby et al. (1994)) lie in the northern part of the TVZ; at the southern margin of the Rotorua Caldera and at the western tip of the present day Lake Rotomahana, respectively (Figs. 1 and 2). Waimangu is part of a larger region of surface thermal activity referred to as Waimangu–Rotomahana–Mt Tarawera Geothermal Field. South of the Rotorua Caldera, there is a change in the strike of the active faulting (Fig. 2) marking the axes of the present day extension from N37°E to N69°E in the Okataina Volcanic Centre (Acocella et al., 2003). The cause for the change in strike is not well understood but may be linked (Ellis et al., 2014) to the presence and location of large crustal volumes of partial melt beneath the region suggested by Heise et al. (2010).

The MT survey discussed in this paper covers the south-western part of Rotorua caldera and the western margin of the Okataina Volcanic Centre (Fig. 2). The Okataina Volcanic Centre has erupted ~80 km^3 of rhyolitic magma in the last 21 kyrs (Nairn, 1989); the most recent rhyolitic eruption being the 5 km^3 Kaharoa event which was triggered by basaltic intrusion about 700 y ago (Leonard et al., 2002; Hogg et al., 2003). In 1886 a ~15 km long fissure eruption of basaltic magma ruptured the cluster of rhyolite domes that form the Tarawera Volcanic Complex (Fig. 2) destroying the famous 'Pink and White Terraces' and creating the modern day lake at Rotomahana (Keam, 1988). The south-western-most part of the eruption fissure is the focus of the present day hydrothermal activity at Waimangu and Rotomahana (Walker et al., 2016; de Ronde et al., 2016). Caratori Tontini et al. (2016) also note a magnetic anomaly associated with the hydrothermal activity on the north-western shore of Lake Rotomahana near Waimangu.

Evidence for volcanism, post-dating caldera formation at Rotorua which formed ~240 ka ago during the eruption of the Mamaku ignimbrite (Gravley et al., 2007) consists of rhyolitic domes (total volume of ~4.3 km^3) that occur within the caldera. The largest, at Ngongotaha is dated at 200 ka but much younger domes (60 ka and 36 ka) are present at Mokoia Island (in Lake Rotorua) and at the southern end of Lake Rotorua (Fig. 2) (Ashwell et al., 2013).

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http://dx.doi.org/10.1016/j.jvolgeores.2015.10.017
0377-0273/

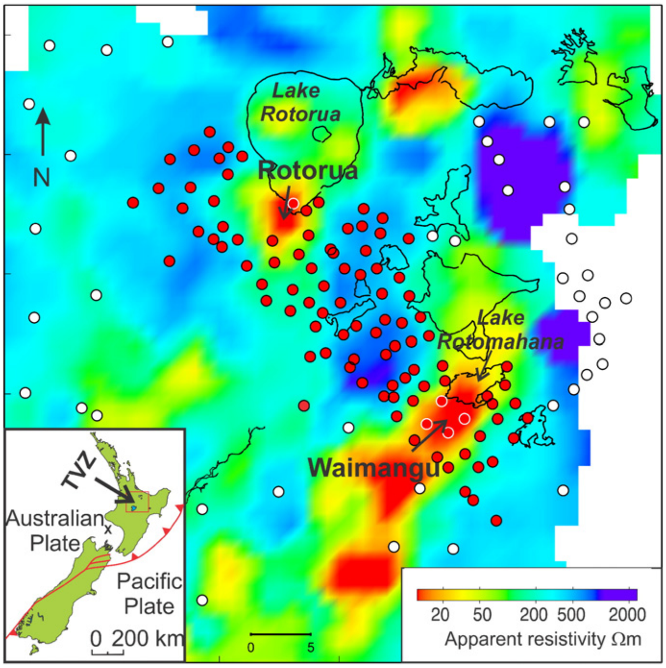

Fig. 1. Locations of MT measurement sites in the Rotorua and Waimangu region superimposed on a DC apparent resistivity map (Bibby et al., 1994; Stagpoole and Bibby, 1998). The shallow extent of geothermal fluid and hydrothermal alteration are shown by areas of low (<20 Ωm) apparent resistivity. The locations of MT measurements included in the 3-D inversion are shown by red dots. Other MT measurement locations in the wider region (Heise et al., 2010) are shown by white dots.

The geothermal field at Rotorua has one of the highest heat fluxes (470 MW, Glover, 1992) in the TVZ. Gas discharge at Rotorua (mainly CO_2) is similar to the rate (~1000 t/d) found at active volcanoes, with the highest gas flux in the Ngapuna-Sulphur Bay area at the south western corner of the lake (Werner and Cardellini, 2006). The largest concentrations of H_2S, a feature of the Rotorua geothermal system, are also found in this area. The Ngapuna-Sulphur Bay area is interpreted to be the main up-flow zone of the geothermal field (Horwell et al., 2005).

Studies of CO_2 flux at Lake Rotomahana showed that the CO_2 discharge into the lake is about half the amount at Rotorua (Mazot et al., 2014). This study and the high concentration of helium, from a recent water chemistry study at Lake Rotomahana (Stucker et al., 2016) infer that the Waimangu geothermal system is driven by magmatic degassing of an underlying magma body. The estimated heat output for Waimangu is 325 ± 80 MW, based on the chloride flux (Nairn and Findlayson, 1981), is also smaller than at Rotorua.

In this paper we analyse MT data from 94 new broadband MT soundings spaced about 2 km apart (Figs. 1 and 2) to help determine the heat source and underlying magmatic system supplying the geothermal fields at Rotorua and Waimangu–Rotomahana. The MT measurements reported here are too widely spaced to adequately image the near surface resistivity structure. The shallow resistivity structure is better defined by the extensive DC apparent resistivity measurements (including near-shore measurements in Lake Rotomahana Bibby et al., 1994) used to construct the apparent resistivity map shown in Fig. 1. The new MT data also address the question raised by Heise et al. (2010) about the nature of the resistivity structure in this part of the TVZ.

2. Magnetotelluric data

The MT method measures the natural variation of the Earth's magnetic field and the electric fields induced in the Earth by these variations. The depth to which the MT signal penetrates into the earth depends on both the conductivity of the rocks and the frequency of the variation; with low-frequency (or long-period) variations sensing more deeply. The relationship or transfer function, between horizontal electric (**E**) and magnetic (**H**) field vectors in the frequency domain form one part of the data used in our analysis. These data are expressed mathematically by the 'impedance tensor' **Z** defined by the equation $\mathbf{E} = \mathbf{ZH}$ where **Z** is a complex 2×2 matrix. Because of the dependence on the electric field, the magnitudes of the impedance tensor components are susceptible to distortion by localised, near-surface conductivity-heterogeneities. Near-surface distortion makes impedance tensor data poorly suited for data visualization. However, the phase relationships in the impedance tensor, represented by a real 2-D tensor defined by the ratio of real and imaginary parts of the impedance tensor (Caldwell et al., 2004), are not distorted in this way. By representing the phase tensor by its tensor ellipse we can visualise conductivity gradients in the underlying resistivity structure directly.

An additional component of the MT data is the transfer function (also complex) between horizontal (H_x, H_y) and vertical (H_z) magnetic field components defined by the equation $H_z = -\mathbf{KH}$ where **K** is the 'induction vector'. The sign of the induction vector is chosen so that the induction vectors will in simple situations point towards a region of greater electrical conductance (Parkinson, 1962).

3. Phase tensor and induction vector maps

Fig. 3 shows the phase tensor ellipses and induction vectors at three different periods chosen so that the effective detection depth doubles between periods. The MT data shown in Fig. 3 includes both results used for the 3-D inversion discussed later and from more widely spaced measurements used by Heise et al. (2010) in their discussion of the regional resistivity structure.

In a 2-D case, the induction vectors should point perpendicular to the strike direction of the 2-D resistivity structure, and parallel to one of the phase tensor ellipse axes. At 1.3 and 5.3 s period (Fig. 3a, b) the induction vectors point perpendicular to the strike of the axis of active faulting and towards the near surface areas of DC low apparent resistivity (Fig. 1) that mark the locations of Rotorua and Waimangu geothermal fields.

The geometric mean of the phase tensor principal values or ellipse axes Φ_2 provides a (coordinate independent) measure of the amplitude of the overall phase response. Values of $\Phi_2 > 1$, or equivalently $\tan^{-1}\Phi_2 > 45°$, shown by warm colours in Fig. 3 indicate increasing conductivity (or lower resistivity) at deeper levels. A remarkable feature of the data is the region of high phase (i.e. >45°) in the central part of the survey area shown for 5.3 s period in Fig. 3(b). This feature indicates that a conductive zone is present in the mid-crust between the geothermal fields at Rotorua and Waimangu. The small magnitude of the induction vectors observed between the geothermal fields is consistent with this indication. Note however, that at the margins of this feature, the induction vectors at periods of 1.3 and 5.3 s point away from area of high phase, in what at first sight seems to be a contradiction of their expected the behaviour (i.e. pointing towards the high phase area). However, as we will show later, this behaviour of the induction vectors indicates that narrow conductive zones are present beneath the geothermal fields. This can be seen most clearly south-east of Waimangu, where the induction vectors on either side of the geothermal field point towards each other at 5.3 s. Where there is data coverage to the south of Rotorua City, the induction vectors point northwards towards the geothermal field.

On the south-eastern and north-western margins of the data coverage at 21.3 s period (Fig. 3c), the induction vectors point inwards towards the axis of extension (about N45°E) consistent with their location at margins of the TVZ and a deep seated conductive region beneath the TVZ (Heise et al., 2007, 2010).

The variation of both ellipse orientation and induction vector directions with location and period in Fig. 3 show that large 3-D effects are present in the MT response. This is consistent with the large (>10°)