Journal of Volcanology and Geothermal Research 314 (2016) 57–83

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

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

Reconstruction of the geology and structure of Lake Rotomahana and its hydrothermal systems from high-resolution multibeam mapping and seismic surveys: Effects of the 1886 Tarawera Rift eruption

C.E.J. de Ronde [a], S.L. Walker [b], C. LeBlanc [a], B.W. Davy [a], D.J. Fornari [c], F. Caratori Tontini [a], B.J. Scott [d], H. Seebeck [a], T.J. Stewart [a], A. Mazot [d], A. Nicol [e], M.A. Tivey [b]

[a] GNS Science, 1 Fairway Drive, Lower Hutt 5010, New Zealand
[b] Pacific Marine Environmental Laboratory, NOAA, 7600 Sand Point Way NE, Seattle, WA 98115-6349, USA
[c] Woods Hole Oceanographic Institution, 266 Woods Hole Road, Woods Hole, MA 02543, USA
[d] GNS Science, 114 Karetoto Road, RD4, Taupo 3384, New Zealand
[e] Geological Sciences, University of Canterbury, Private Bag, 4800, Christchurch, New Zealand

ARTICLE INFO

Article history:
Received 11 August 2015
Accepted 4 February 2016
Available online 13 February 2016

Keywords:
Lake Rotomahana
Rotomahana West
Rotomahana East
Hochstetter
Waingongongongo and Rotomakariri craters
Pink Terraces and Patiti hydrothermal systems

ABSTRACT

Present-day Lake Rotomahana is one of the two focal points of the most destructive eruption in New Zealand's historical record, i.e., that of Mt. Tarawera on 10 June 1886, with devastating loss of life and presumed destruction of the iconic Pink and White Terraces that adorned the margins of the lake. Basaltic dikes are considered to have ascended near surface in the area, intruding into hydrothermally altered and water-saturated ground beneath the existing lake. The consequential hydrothermal and phreatomagmatic eruptions ejected 0.5325 km^3 of material from the lakefloor and below, plastering the nearby landscape for several kilometers with mud and other debris. The eruption buried the natural outlet of the lake, with the bottom of the craters becoming filled by water within months and completely concealed from view within years; today Lake Rotomahana has depths up to 118 m.
High-resolution (0.5 m) bathymetric mapping, when combined with a 2-D seismic reflection survey, enables us to 'see' details of the maar craters on the lakefloor, including those parts subsequently buried by sediment. The large Rotomahana Crater described by workers immediately after the eruption measures ~2.5 km in diameter near its southwestern end, and excavated ground to 155 m below present-day lake level. The vent system, as revealed by the present study, forms an array of right-stepping (dextral) craters, with the main crater being host to two sub-craters Rotomahana West Crater and Rotomahana East Crater today buried beneath the lakefloor, and which are in-filled by 36 and 37 m of sediment, respectively. Subordinate craters along the same 057° Tarawera Rift trace include Hochstetter Crater (11 m of infill), Waingongongongo Crater (14 m) and Rotomakariri Crater (26 m). These craters host a total 0.0268 km^3 of sediment. Other features highlighted by the bathymetric data include; craters not filled by sediment, sediment fan deltas, volcanic ridges and dikes, submerged wave-cut terraces formed during times of lower lake levels and gas pockmarks, all either related to the 1886 eruptive episode or post-eruption hydrothermal and erosional processes.
Application of results from bubble plume, CO_2 flux, magnetic and heat flux surveys of Lake Rotomahana to this study, when combined with regional earthquake relocation analysis and broadband magnetotelluric data, suggest an explanation in terms of a magmatic heat source located south of Waimangu and a corresponding convective water/heat transport system extending thence to beneath the western end of the lake. A holistic approach has provided a coherent context for the eruption and its effect on the historical Pink and White Terraces hydrothermal system that appears to have been the eastern-most extension of a larger system that lay beneath the Waimangu area before the eruption. The newly named Pink Terraces hydrothermal system (~1.5 km^2) is a continuation of the historical hydrothermal activity that was concentrated on the western shores of the old lake, and together with the formation of the new, post-1886 Patiti hydrothermal system (~1 km^2) located SW of Patiti Island, mark the two distinct areas of hydrothermal activity in the lake today.

1. Introduction

On 10 June 1886, Mt. Tarawera erupted, forever changing the landscape in the near vicinity of this volcano and ensuring a place in New Zealand history, taking the lives of about 120 inhabitants and presumably destroying the iconic Pink and White Terraces, considered at the time to be one of the natural wonders of the world. Fortunately, practical photography as a commercially available interest was invented in

http://dx.doi.org/10.1016/j.jvolgeores.2016.02.002
0377-0273/

1839, ensuring that the Terraces were captured for perpetuity in all their glorious detail prior to the eruption. In addition, the advent of photography meant that the effects of the 1886 eruption in the general Lake Rotomahana area were precisely (accurately) recorded, in concert with surveys and expeditions made by various groups immediately post-eruption (see Keam, 2016).

The eruption of Mt. Tarawera began around 2:00 AM on June 10 1886, with the explosions at 3:30 AM considered to be the outbreak at Rotomahana. The violent magmatic stage of the eruption ended around 6:00 AM (Keam, 2016, and references therein). In the days that followed the eruption, various groups visited the region, including one journalist (T.W. Leys) who described how the original lake was gone with no remnant of the famed Terraces that could be discerned. Instead, he described a "… great crater over a mile [>1600 m] long and half a mile [800 m] wide…" with "… dense volumes of steam and smoke, with a din and a roar and rattle baffling description…". At least 11 separate orifices, or small craters, were seen to be ejecting rock fragments high into the air along the western end of the crater (T.W. Leys, 1886).

Today's Lake Rotomahana began forming within the largest of the craters shaped by the eruption soon after they were established. Historical records show that the lake level rose most rapidly in the first few decades after the eruption, and that within the last 90 years having fluctuated between 332 and 342 m above sea level (asl) (Keam, and references therein, 2016). Thus, no person has laid eyes on the volcanic structures and associated geothermal manifestations concealed beneath Rotomahana and attributed to the 1886 eruption for over 100 years. Today, the application of state-of-the-art techniques, such as high-resolution multibeam mapping of the lakefloor, when combined with two dimensional (2-D) seismic reflection profiles, not only affords us the opportunity to both 'see' the lakefloor as if there were no lake present, but also below the lakefloor and the ground surface at the time of the 1886 eruption. This relatively rare use of modern investigative techniques in a lake, commonly reserved for marine surveys, means we can for the first time since 1886 reconstruct the volcanological aftermath of the 1886 eruption as it displaced the original Lake Rotomahana, and document both the evolution of pre-existing geothermal systems and the birth of any new ones following the eruption. Moreover, relatively few volcanic lakes deeper than 30 m have been studied for their hydrothermal emissions. The limited number that have, so far, include: Crater Lake, Oregon (Dymond et al., 1989) and Yellowstone Lake, Wyoming (Remsen et al., 1990) in the USA; Lake Baikal in Siberia (Crane et al., 1991); Lake Tanganyika in East Africa (Tiercelin et al., 1993); Lake Taupo in New Zealand (de Ronde et al., 2002). Thus, this study, which includes sublacustrine venting of Lake Rotomahana, adds significantly to our inventory of those hydrothermal processes occurring within volcanic lakes.

2. Okataina Volcanic Centre

The Okataina Volcanic Centre (OVC) comprises an area of ~700 km^2 within the Taupo Volcanic Zone of New Zealand east of Lake Rotorua (Fig. 1). It is comprised largely of the Okataina Caldera, a large, multiple collapse structure within the OVC with two definite, one probable, and one possible periods of collapse (Cole et al., 2010; de Ronde et al., 2016-a), with one of the major collapses around ~280,000 to 322,000 years ago, as given by Ar/Ar dating of the Matahina Ignimbrite (Houghton et al., 1995; de Ronde et al., 2016-a), the first really widespread volcanic formation originating within the OVC (Nairn, 2002). The present-day margins of the southern half of the Okataina Caldera are considered to have formed by 220,000 years ago. The northern part of the Okataina Caldera is thought to have collapsed around 65,000 years ago with the eruption of the Rotoiti Pyroclastics (Nairn, 1979, 2002). In all, it is thought that the OVC has erupted ~2000 km^3 of magma over the past 65,000 years, making it one of the most productive rhyolite volcanic centers ever documented (Wilson et al., 2009). A series of intra-caldera lava and pyroclastic eruptions has occurred in the OVC during the past 22,000 years, including the progressive building of the rhyolite domes of the large Haroharo Volcanic Complex to the north and the large Tarawera Volcanic Complex to the southeast (see Fig. 1). For additional details concerning the OVC and the Okataina Caldera, see de Ronde et al. (2016-a, b).

2.1. Lake Rotomahana structural and tectonic setting

Lake Rotomahana is located within the Tarawera Linear Vent Zone (TLVZ) as part of the OVC (Fig. 1). The TLVZ occurs along the southeastern margin of the Taupo Volcanic Zone and the intra-arc Taupo Rift. Rift faults formed over the past 1.6 million years (Wilson et al., 1995) in response to steepening and/or rollback of the subducting Pacific Plate and clockwise rotation of the eastern North Island (Wallace et al., 2009; Seebeck et al., 2014). At ground surface, the Taupo Rift comprises a dense network of active NE–SW striking and steeply dipping normal faults (>60°), with vertical displacements of up to 550 m (Villamor and Berryman, 2001; Nicol et al., 2010; see Fig. 1). Some active normal faults extend into the OVC where they become buried by volcanic deposits (Seebeck et al., 2010). Outside the OVC, extension and crustal thinning is considered largely due to rift faulting (Nicol et al., 2006, 2010; Villamor et al., 2011), while within the OVC crustal extension is thought to be a combination of dike intrusion and normal faulting (Rowland and Sibson, 2001; Seebeck and Nicol, 2009). The TLVZ is 28 km long and 5 km wide and is inferred to overlie a basic intrusion associated with the basaltic eruptives at Waimangu, Rotomahana and Tarawera (Cole 1973; Keam, 2016). The two most recent eruptions from the TLVZ (i.e., 1315 AD and 1886 AD) were accompanied by intrusion of basaltic dikes ≤5 m wide in the near surface, along the axis of the system (Smith, 1886; Nairn and Cole, 1981; Rogan and Hochstein, 1984; Nairn et al., 2005). The 17 km long 1886 Tarawera Rift lies within the TLVZ (Nairn and Cole 1981, Nairn 2002). During the 1886 AD eruption of Mt. Tarawera the dike(s) and associated phreatic eruptions extended along the vent system, terminating within 1 km of active faults in the Taupo Rift (Fig. 1).

2.2. Lake Rotomahana geology

Volcanic units outcrop around the margins of Lake Rotomahana. The very western end of the lake has outcropping <65 ka rhyolite domes and flows and undifferentiated pyroclastic fall, flow and surge deposits of the Okataina Rhyolite and Haparangi Rhyolite Pyroclastics, respectively (Nairn, 2002). The northeastern shoreline, parts of the southeastern shoreline and Patiti Island reveal various units ascribed to volcanic events ranging in age between ~22 ka and 15 ka (Nairn, 2002), including pyroclastic surge deposits (Fig. 2A) and rhyolite lava (Fig. 2B). Other prominent outcrops include the 0.7 ka 'Green Lake Plug' (Fig. 2C), or more correctly referred to as 'Poupoutunoa' by Keam (1988), which is an ~30 m high rhyolite domelet extruded southwest of Mt. Tarawera in the northeastern reaches of the lake, formed during the penultimate Kaharoa eruption (Fig. 4B). Rotomahana 'mud' that was expelled during the June 10 1886 eruption can be seen in northwestern and southern parts of the lakeshore, including a recently exposed example in a road cut (Fig. 2D), as part of the Rotomahana Pyroclastics Member (Nairn, 2002).

2.3. Lake Rotomahana hydrothermal activity

Geothermal manifestations seen along the margins of Lake Rotomahana largely occur on the western shoreline of the lake; minor hot springs also occur along parts of the southern shoreline southwest of Patiti Island and directly south of Awarua Cliffs, and