Journal of Applied Geophysics 73 (2011) 243–250

Contents lists available at ScienceDirect

Journal of Applied Geophysics

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

# Resistivity monitoring of the tephra barrier at Crater Lake, Mount Ruapehu, New Zealand

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ARTICLE INFO

*Article history:*
Received 29 May 2009
Accepted 18 January 2011
Available online 25 January 2011

*Keywords:*
Dc resistivity
Natural dams
Mount Ruapehu

ABSTRACT

The eruptions of Mt Ruapehu in the North Island of New Zealand in 1995 and 1996 caused a tephra barrier to be formed across the outlet of Crater Lake. By 2005 seepage from the refilled lake into the barrier raised the possibility of an eventual collapse of the barrier, releasing a catastrophic lahar down the mountain.

As part of an extensive monitoring programme of the tephra barrier, direct current (dc) resistivity surveys were carried out on a number of lines along and across it in order to test whether the extent of the seepage could be measured (and monitored) by geophysical means. Two dimensional inversion of measured apparent resistivity data showed that between the initial measurements, made in January 2005, and February 2006, there was a gradual decrease in resistivity above the old outlet from ~50–60 Ωm to ~30 Ωm. This gave the first indication that lake water was seeping into the barrier. Between October and December 2006 there was a rapid rise in lake level to only 2 m below the top of the barrier, and a further resistivity survey in January 2007 showed that there had been a further decrease in resistivity throughout the entire barrier with values dropping to <10 Ωm. The extent of this low resistivity indicated that the barrier was now saturated. At this stage lake water was penetrating the barrier and starting to cause erosion on its downstream side. Catastrophic collapse occurred on 18 March 2007, accompanied by a lahar in the Whangaehu river valley.

Subsequent forward 3D numerical modelling of the resistivity structure of the barrier has confirmed that the observed changes in measured resistivity were directly related to the progress of seepage of lake water into the barrier.



## 1. Introduction

Mount Ruapehu, in the central North Island of New Zealand (Fig. 1(a)), is the most southerly andesite volcano of the Kermadec volcanic arc. Crater Lake, the principal surface manifestation of the volcano–hydrothermal system, lies 500 m to the south of the summit plateau of the mountain and has a surface area of approximately 0.25 km$^2$. The present vent of the volcano lies beneath the lake. During the series of major eruptions of Ruapehu in 1995–96 approximately 0.1 km$^3$ of magma was erupted and the lake was completely emptied. Prior to the 1995–1996 eruptions the outlet of Crater Lake was via a narrow channel into a hard ridge of lava on the south side of the lake. The eruptions, which were the largest for 50 years (Ruapehu Surveillance Group, 1996), eroded 0.7 m of lava and boulders from the outlet ridge and deposited a minimum thickness of 7.6 m of tephra in alternating unconsolidated layers comprised of mainly sand and silt sized material to lapilli and some blocks up to 2 m long. This tephra formed a barrier 8 m above the original lake level, blocking the outlet.

Following the formation of the tephra barrier, the refilling of Crater Lake, which by early 2005 had again reached the level of the original outlet and turned the barrier into a dam, raised the fear that catastrophic collapse would release a major lahar into the Whangaehu River Fig. 1(a)). Such a lahar had occurred in December 1953, following the sudden collapse of an ice cave which at that time formed part of the outlet of Crater Lake, causing the loss of 151 lives in one of New Zealand's worst natural disasters (Conly and Stewart, 1986). As a result the New Zealand Department of Conservation investigated the size, character and likely failure modes of the barrier (Gillon et al., 2006), instigated regular monitoring, installed an early warning system and, along with the local and regional councils, the NZ Police and Ministry of Civil Defence and Emergency Management, developed an emergency plan in anticipation of such an eventuality. Collapse of the tephra barrier ultimately occurred on 18 March 2007.

Part of the investigation and monitoring programme involved repeat measurements of a number of 2D multi-electrode resistivity surveys along and across the tephra barrier to detect any changes in bulk resistivity that might result from seepage of acidic, and therefore

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doi:10.1016/j.jappgeo.2011.01.006

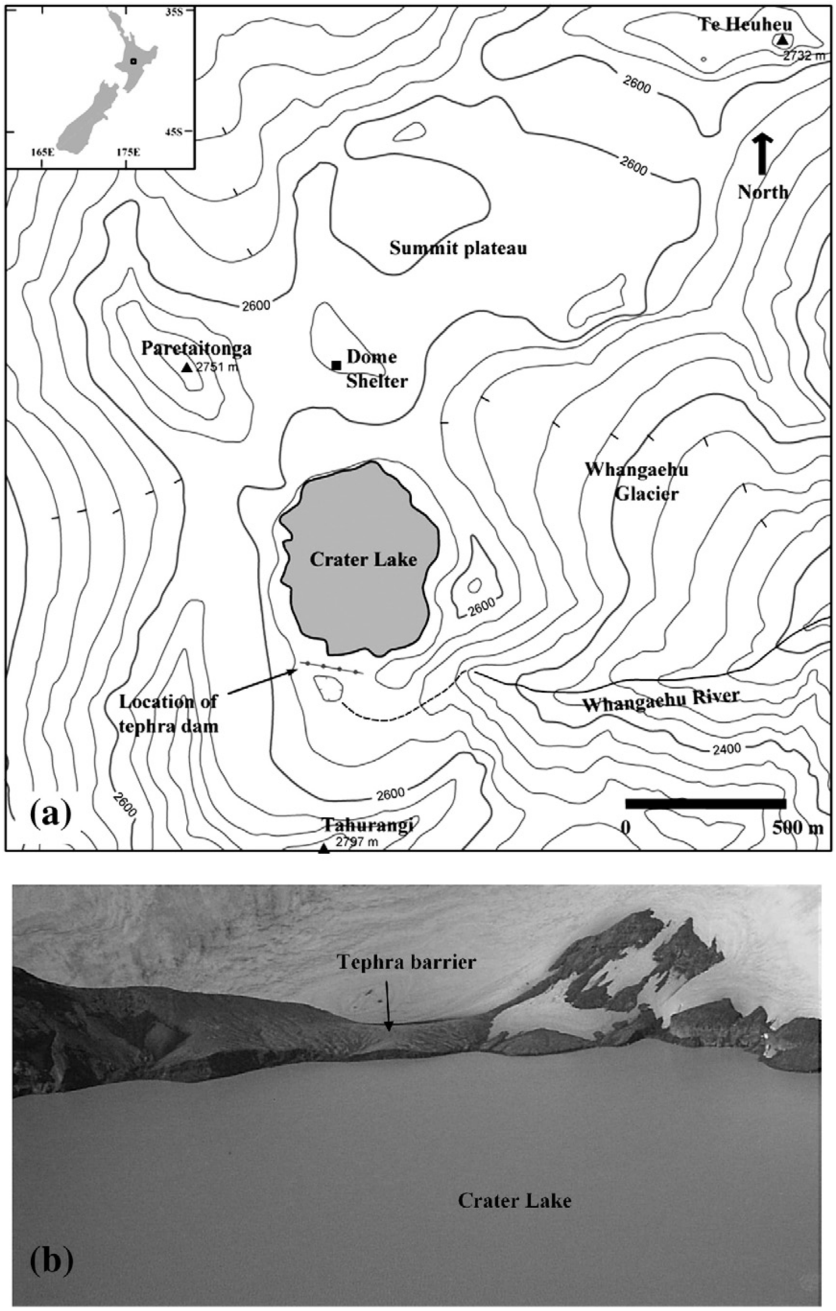


**Fig. 1.** (a) Map showing the location of Crater Lake, the tephra barrier, and the head of the Whangaehu River valley in relation to the summit plateau of Mount Ruapehu. The contour interval is 40 m. (b) Aerial photograph, looking south across Crater Lake, showing the tephra barrier as at January 2005. (Photo: Gillian Turner).

conductive, lake water into it. Such measurements have the potential to detect seepage since the bulk resistivity of a geological unit is highly dependent upon both the quantity and resistivity of any pore fluid within it (Archie, 1942). Thus, in the absence of other variables, any detected changes with time in the derived resistivity structure can give immediate qualitative information about seepage. There has been considerable interest for many years in the stability and possible failure of naturally formed dams (e.g. Clague and Evans, 1994; Costa and Schuster, 1988, 1991; Glicken et al., 1989; Lockwood et al., 1988; Meyer et al., 1985; Walder and O'Connor, 1997; Waythomas, 2001). However, although Haeberli et al. (2001) and Oberholzer et al. (2003) reported on the use of shallow geophysical techniques in the assessment of moraine dams in the Swiss Alps, there have been few other examples of the application of such methods to assessing the stability of natural dams. In contrast, electrical resistivity methods have frequently been used in the investigation of leakage through man-made dams (e.g. Cho and Yeom, 2007; Panthulu et al., 2001; Sjödahl et al., 2008; Song et al., 2005; Titov et al., 2000), as well as in hydrological studies (e.g. Batayneh, 2006; Koukadaki et al., 2007; Wilson et al., 2006). Generally such studies have involved resistivity traversing using multi-electrode lines laid out along the crest of the dam, though Cho and Yeom (2007) reported the development of a tomographic technique analogous to cross-borehole resistivity methods. The use of self-potential measurements has also been reported by Panthulu et al. (2001) and Rozycki et al. (2006).

In this paper we present the results of our resistivity monitoring programme at Crater Lake, Mount Ruapehu. As well as presenting time-lapse images of the resistivity structure of the tephra barrier, we also present the results of forward 3D numerical modelling to quantitatively