Journal of Volcanology and Geothermal Research 295 (2015) 43–54

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

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

Terrestrial laser scanning observations of geomorphic changes and varying lava lake levels at Erebus volcano, Antarctica

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ARTICLE INFO

Article history:
Received 13 October 2014
Accepted 25 February 2015
Available online 6 March 2015

Keywords:
Erebus
TLS
Lidar
Geomorphology
Lava lake

ABSTRACT

A Terrestrial Laser Scanning (TLS) instrument was used to image the topography of the Main Crater at Erebus volcano each December in 2008, 2009, and 2010. Our high-spatial resolution TLS scans provide unique insights into annual and decadal scale geomorphic evolution of the summit area when integrated with comparable data collected by an airborne instrument in 2001. We observe both a pattern of subsidence within the Inner Crater of the volcano and an ~3 m per-year drop in the lava lake level over the same time period that are suggestive of decreasing overpressure in an underlying magma reservoir. We also scanned the active phonolite lava lake hosted within the Inner Crater, and recorded rapid cyclic fluctuations in the level of the lake. These were sporadically interrupted by minor explosions by bursting gas bubbles at the lake surface. The TLS data permit calculation of lake level rise and fall speeds and associated rates of volumetric change within the lake. These new observations, when considered with prior determinations of rates of lake surface motion and gas output, are indicative of unsteady magma flow in the conduit and its associated variability in gas volume fraction.

1. Introduction

Terrestrial Laser Scanning (TLS), based on time-of-flight light detection and ranging (lidar) technology, is finding widespread application in the geosciences including volcanology (e.g., Tarolli, 2014). Current TLS systems are capable of imaging meter to kilometer-scale areas with centimeter to sub-centimeter precision. TLS mapping and repeat surveys have been applied to geomorphic studies of volcanoes and volcanic terrains (Pesci et al., 2007; Tarquini et al., 2012; Pesci et al., 2013), mapping and characterization of both ancient and active lava flows (James et al., 2009; Nelson et al., 2011; Cashman et al., 2013); in geotechnical studies of slope stability (Nguyen et al., 2011; Norini and Acocella, 2011); and glaciological impacts of tephra fallout (Nield et al., 2013).

Here, we use TLS to study the timescales of both rapid (seconds) and prolonged (years) changes at Erebus volcano, Antarctica each December in 2008, 2009 and 2010. To extend the time interval of the study, we integrate the TLS data with Airborne Laser Scanner (ALS) observations acquired in 2001 (Csatho et al., 2008). Our primary objective was to determine if short-term changes in lava lake level might correlate with ~10 min cycles seen in surface motion of the lake (Oppenheimer et al., 2009; Peters et al., 2014b) and in gas chemistry and fluxes (Boichu et al., 2010; Peters et al., 2014a). A secondary objective was to map the topography of the Inner Crater in order to identify geomorphic changes, such as ground deformation and talus accumulation, which occur between field seasons. While Erebus has been visited annually since the 1970s, few coherent observations have been made to assess the style and rates of geomorphic change within the crater. This study presents a detailed assessment of the processes shaping the dynamic topography of the Erebus crater, and reports on the applications of TLS to monitor the activity of an active lava lake.

2. Erebus summit area and lava lake

Erebus is a large (~2000 km^3) alkaline stratovolcano located on Ross Island, Antarctica (77°32′ S, 167°10′ E), with a summit elevation of 3794 m (Esser et al., 2004). The summit region of Erebus volcano above 3200 m, is a plateau nearly 4 km in diameter, representing the remnants of two episodes of caldera collapse dated between 80–24 ka and 25–11 ka ago (Harpel et al., 2004; Kelly et al., 2008), and subsequent infilling with younger lava flows. Currently, this summit plateau also contains two craters: the Main Crater (600 m × 470 m), which hosts the phonolite lava lake, and the Side Crater (250 m across), which contains areas of hot ground (Csatho et al., 2008; Fig. 1). The lava lake resides in the Inner Crater, which is a pit within the Main

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http://dx.doi.org/10.1016/j.jvolgeores.2015.02.011
0377-0273/

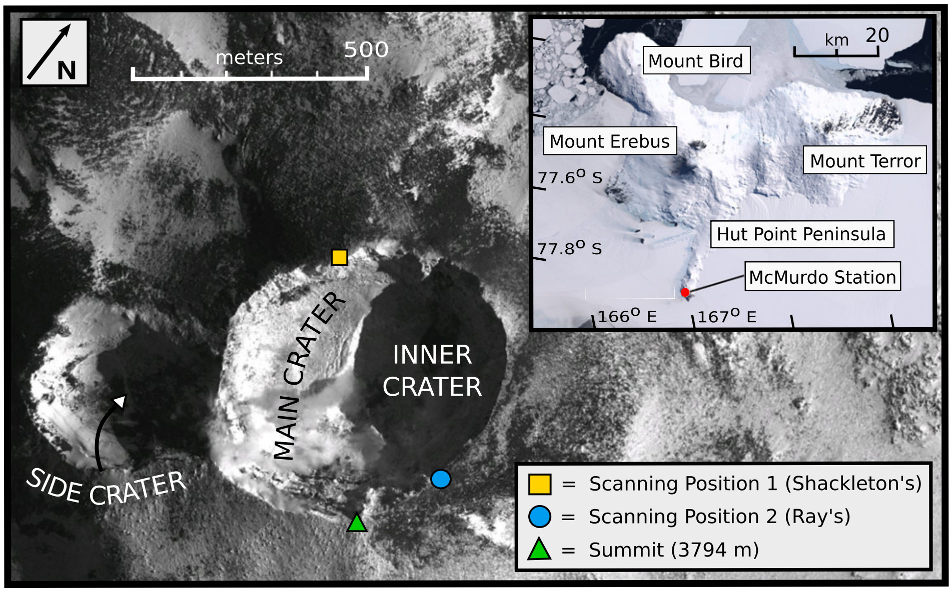

Fig. 1. View of the Erebus summit area showing the locations of the Main, Inner and Side Craters and the positions from which the terrestrial laser scans were acquired. Inset shows Ross Island, Mount Erebus, and other key features of the island not discussed in the text.

Crater (Fig. 1). The Main Crater also contains fumaroles and areas of steaming ground. In contrast to other lava lakes around the world, the Erebus lava lake is composed of evolved anorthoclase-bearing phonolite magma produced by 75% fractional crystallization of a mantle-derived parental basanite magma (Kyle et al., 1992). As a consequence of its phonolitic composition the magma is more viscous than typical basalts (Le Losq et al., 2015), and has a distinctive rheology. Most notably, the Erebus lava lake is the site of sporadic explosions associated with the rupture of large gas bubbles (Dibble et al., 2008). The gas composition in the bubbles is significantly more CO_2-rich than the passively emitted gases from the lake (Oppenheimer et al., 2011; Burgisser et al., 2012).

A number of works have reported on quasi-periodic behavior of the Erebus lava lake. Cycles and variations in SO_2 emission rates were reported by Kyle et al. (1994) and further quantified by Sweeney et al. (2008). Oppenheimer et al. (2009) made observations of corresponding lake surface velocity and gas geochemical cycles. Peters et al. (2014a,b) demonstrated the persistence of the cycles and correlations of lake surface speed, lake level, gas flux, radiative output, and gas composition. More detailed analyses of the variations in gas compositions measured by Fourier transform infrared spectroscopy during the cycles are described by Ilanko et al. (2015).

Several pertinent observations can be drawn from these observations of gas and thermal studies: (1) the cyclic behavior is a prevalent and persistent mode of the lava lake, and is only ephemerally perturbed (for a few minutes) by the rupture of bubbles (even large decametric ones) at the lake surface; (2) the period of cycles varies by over a factor of two but is approximately 10 min; (3) change in lake level slightly precedes (by 1–3 min; Peters et al., 2014b) change in the mean speed of the lake surface (in the horizontal plane) and in gas ratios; (4) the quantity of gas released during a cycle (Boichu et al., 2010; Peters et al, 2014a) represents a volume an order of magnitude greater than the volumetric change associated with half a cycle (the net volume change during a whole cycle is zero); (5) the variations in gas composition appear to reflect subtle variations in redox conditions (Aletti et al., 2014; Peters et al., 2014a; Ilanko et al., 2015) that may be associated with degassing of sulfur from the magma (Moussallam et al., 2014); and (6) the timing of the arrival of gas bubbles with diameters of a few m at the surface appears independent of the phase of the cycles (Peters et al., 2014b). It is with this background that we examine high precise TLS observations of lava lake levels.

3. TLS data collection and processing

3.1. Instrumentation and data collection

We acquired TLS surveys of the Main Crater on Erebus volcano using an Optech ILRIS-3D ER (Extended Range) lidar. This instrument uses a 1535 nm wavelength (near infrared) laser and has a sampling frequency of 2.5–3.5 kHz (Optech, 2009). The instrument has a 40° field of view in both the horizontal and vertical plane with a scanning range of 3 to 1700 m. For this survey, the ILRIS-3D was equipped with a pan-tilt base, providing a scanning field of 360° in the horizontal and 90° in the vertical. Each recorded point contains 5 items: Cartesian x, y, and z coordinate relative to the scanner's bolt hole reference point, normalized (0–255) backscatter intensity, and time (in s) since the scanner was powered on. In order to achieve an accurate time series of the lava lake, a pulse generator was used to time stamp each laser shot. The TLS was programmed to collect the last reflected pulse to minimize the number of returns recorded from the persistent gas and aerosol plume emitted from the lava lake.

The nominal one standard deviation range accuracy of the ILRIS-3D ER is 7 mm at 100 m (Optech, 2009). One significant contribution to error arises from the laser beam width, which increases as follows:

$$D_f = l \cdot \tan\theta + D_i \quad (1)$$

where D_i is the initial beam diameter (1.9 cm at 100 m), D_f is the final beam diameters, l is the scanning distance, and θ is the beam divergence angle (0.00974°; Petrie and Toth, 2008; Abellán et al., 2011). The actual position of the measured reflection can exist anywhere within the beam, meaning that the actual angular position of the measurement may be biased by up to half of the beam diameter (Pesci et al., 2011). This error is taken into account when reporting the spatial resolution of the instrument and depends on both the chosen sampling step and the laser beam width (Lichti and Jamtsho, 2006; Zhu et al., 2008; Pesci et al., 2011). This resolution measurement can aid in selecting the most appropriate sampling step (one that is at least two-thirds the size of the beam) while avoiding oversampling.

At Erebus, the rapidly varying quantity of volcanic gases within the optical path can have a significant effect on the range measurement. Other factors that may also contribute to the uncertainty of the TLS