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Decadal persistence of cycles in lava lake motion at Erebus volcano, Antarctica

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ABSTRACT

Studies of Erebus volcano's active lava lake have shown that many of its observable properties (gas composition, surface motion and radiant heat output) exhibit cyclic behaviour with a period of ∼10 min. We investigate the multi-year progression of the cycles in surface motion of the lake using an extended (but intermittent) dataset of thermal infrared images collected by the Mount Erebus Volcano Observatory between 2004 and 2011. Cycles with a period of ∼5–18 min are found to be a persistent feature of the lake's behaviour and no obvious long-term change is observed despite variations in lake level and surface area. The times at which gas bubbles arrive at the lake's surface are found to be random with respect to the phase of the motion cycles, suggesting that the remarkable behaviour of the lake is governed by magma exchange rather than an intermittent flux of gases from the underlying magma reservoir.

1. Introduction

Persistently active lava lakes are a spectacular but rare form of open-vent volcanism found at only a handful of volcanoes around the world. An active lava lake is the exposed top of a volcano's magmatic plumbing system. Longevity of such lakes has been argued to reflect either effective transfer of magma between the lake and the deeper system (e.g. Oppenheimer et al., 2004; Francis et al., 1993), or a supply of gas bubbles from depth (Witham and Llewellin, 2006; Bouche et al., 2010). It can be shown experimentally that processes occurring at depth will manifest themselves at the surface as changes in the lake's behaviour, for example its surface level (Witham et al., 2006) or gas flux (Divoux et al., 2009). It follows therefore, that observations of lake properties can yield valuable insights into the processes occurring at depth in the magmatic system, where direct measurements are not possible. This link with the deeper magmatic system makes the study of active lava lakes (sensu Tilling, 1987) of particular importance.

Erebus is a 3794-m-high stratovolcano located on Ross Island, Antarctica. It is often claimed to be the southernmost active volcano in the world and is known to have hosted an active phonolite lava lake since at least 1972 (Giggenbach et al., 1973). Although other small lakes have appeared intermittently over this period, the main, "Ray" lake, has been a permanent feature of the crater throughout (with the notable exception of 1984–1985 when it was buried following sustained explosive eruptions) (Kyle et al., 1990).

The stable convective behaviour of the Erebus lava lake is punctuated by intermittent (De Lauro et al., 2009) Strombolian eruptions associated with the rupture of large (decametric) gas bubbles at the lake surface (Dibble et al., 2008; Gerst et al., 2013). Phases of increased and more intense Strombolian activity (several explosions per day, with ejecta escaping the main crater) recur, lasting 1–10 months and are followed by more extended intervals during which gas bubble bursts are less frequent and of a smaller size (a few explosions per week, with all ejecta being confined to the crater – see for example Jones et al. (2008)). The chemical and mineralogical composition of erupted lavas has remained constant for approximately 17 ka and the abundance of unusually large anorthoclase crystals is indicative of sustained shallow magma convection throughout this period (Kelly et al., 2008). Indeed, the presence of such large crystals may be a significant influence on the behaviour of the shallow convection at Erebus (Molina et al., 2012). Other properties of the lake also demonstrate remarkably consistent long-term behaviour, for example SO_2 flux (Sweeney et al., 2008) and radiant heat output (Wright and Pilger, 2008).

On shorter time scales, many of the lake's properties exhibit a pronounced pulsatory behaviour. Oppenheimer et al. (2009) observed that the radiative heat loss, surface velocity and certain

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magmatic gas ratios all oscillated with a period of ∼10 min. The cycles appeared to be phase locked with each other, suggesting a common mechanism was responsible for the oscillations in each property. Evidence of similar cyclicity has also been observed in the SO_2 flux (Boichu et al., 2010), and the H_2/SO_2 ratio (Moussallam et al., 2012), but these have yet to be linked definitively to the cycles observed by Oppenheimer et al. (2009).

One possible explanation for the observed behaviour is pulsatory exchange flow of hot, degassing magma into the lake from the subjacent conduit. It has been shown experimentally that given two liquids flowing in opposite directions in a vertical pipe (for example driven by a density difference between them), under certain flow conditions an instability occurs which results in a pulsed flow (Huppert and Hallworth, 2007). Oppenheimer et al. (2009) suggested that such behaviour may explain the cycles at Erebus volcano, with bubbly and degassing, low density magma rising up the conduit into the lake whilst degassed, denser magma sinks back down the conduit again. The resulting pulsatory flow delivers packets of fresh magma into the lake quasi-periodically, giving rise to the observed cycles in lake properties. The period of the cycles would be expected to reflect the rheological properties and velocity of the bubbly flow and geometry of the conduit.

The previous studies at Erebus have analysed only very short time-series of data (circa 1 h), and no investigation of the long-term behaviour of the cycles has yet been conducted. However, thermal infrared (IR) images of the Erebus lava lake have been collected almost every year since 2004 during the Mount Erebus Volcano Observatory's annual austral summer field campaigns. Using a similar technique to that of Oppenheimer et al. (2009), we have extracted mean surface speed estimates from the usable portions of the now substantial IR dataset. Using the mean surface speed as a proxy to assess the cyclicity of the lake motion, we present an overview of its behaviour between 2004 and 2011 and compare this to visible changes in the lake's appearance. Using a dataset recorded at higher time resolution in 2010, we identify times when bubbles arrive at the surface of the lake and compare this to the phase of the cycles.

Our specific aims are to identify the persistence (or otherwise) of the cyclic behaviour within and between field seasons; to search for any variability in cycle length that might point to changes in lake/conduit configuration or rheological characteristics of the magma; and to probe further the origins of the remarkable cyclic behaviour of the lava lake. We also compare observations at Erebus with those for other active lava lakes.

2. Summary of activity

In the following analyses, data from field campaigns between 2004 and 2011 have been used. Although the general behaviour of the lava lake at Erebus is fairly consistent from year to year, there are some observable variations. It is therefore important to set the results presented here within the context of the state of activity of the lake during each of the respective field campaigns.

During the 2004 field season, there were two separate lava lakes present in the crater (Calkins et al., 2008). By the 2005 field season, only the "Ray" lake remained (Davies et al., 2008), and no additional lakes have since been observed. All data presented here are from the "Ray" lake, and henceforth, we refer to it simply as the lava lake.

Fig. 1 shows how the visible surface area of the lava lake has changed throughout the period of study. Possible reasons for this change are discussed in detail in Section 4. Despite the reduction in visible surface area from 2004 onwards, there have been no other apparent changes in the behaviour of the lava lake. Stable convective behaviour has been maintained throughout. This is characterised by the lateral migration of cracks in the lake's crust

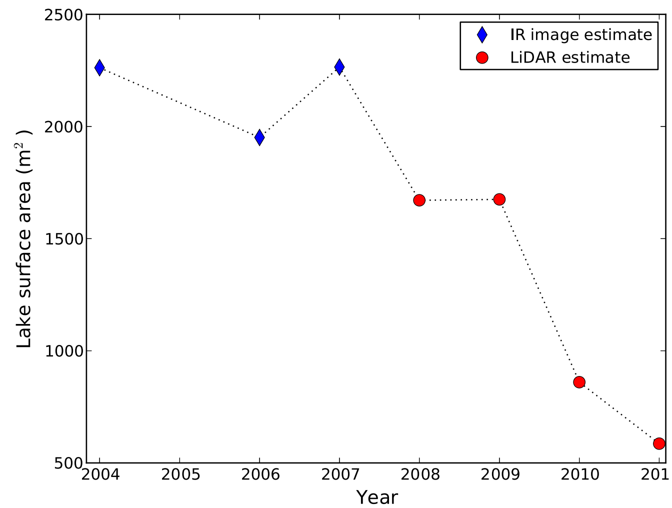

Fig. 1. Surface area of the Erebus lava lake by field season (i.e. December of the year shown). The areas have been estimated from a combination of terrestrial laser scan data (Jones, 2013, Frechette and Killingsworth, pers. comm.) and rectified IR images.

across the surface. These typically move radially outwards from the approximate centre of the lake, but more complex flow patterns with several "convection cells" and abrupt reversals of flow direction are also common. Lobes of fresh lava are occasionally observed to spread across the surface of the lake from upwelling regions, and there is visible subduction of the surface crust at the downwelling regions. These behaviours are all evident in the animation provided in the supplementary material for the electronic version of this manuscript.

Bubbles of a variety of sizes are observed to surface in the lake. We describe bubbles as "large" if they result in significant ejection of material from the lake. Such bubbles (e.g. Fig. 8) are typically 10–30 m in diameter and cause a visible emptying of the lake. We classify such events as being distinct from the far more frequently occurring "small", metre and sub-metre scale bubbles (e.g. panel (d) in Fig. 5) which arrive at the surface of the lake, but do not rupture violently.

A study of explosive events (due to large bubbles) between 2003–2011 using seismic data (Knox, 2012) shows that, with the notable exception of the period from late 2005 to early 2007, their frequency has remained fairly constant at a few per week, with ejecta being entirely confined to the crater. During 2005–2007 however, there were several explosions per day, often of sufficient magnitude to propel ejecta out of the crater, the frequency of these events then gradually declined and by the 2007 field season the lake had returned to its more typical level of activity.

3. Methodology

Fieldwork on Erebus volcano is limited to the austral summer, and typically takes place from late-November to early January. Where we refer to a field season by year, we are referring to the year in which it began. The logistics involved in reaching the crater rim, combined with frequent bad weather conspire to limit the interval of IR image data acquisition to a few weeks each year. The intervals of useful data are further reduced due to fluctuations in the IR transmission between camera and lava lake. When the gas/aerosol plume is highly condensed (high relative humidity) the IR transmission in the camera waveband is poor and the images of the lake are of unusable quality. The latest IR camera system, which was deployed in December 2012, is capable of year-round operation (dependent on power) (Peters et al., 2014). The data from this fully automated system will be analysed in future work.