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The role of large bubbles detected from acoustic measurements on the dynamics of Erta 'Ale lava lake (Ethiopia)

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ABSTRACT

The activity at the surface of the lava lake on Erta 'Ale volcano (Ethiopia) shows that large bubbles are regularly breaking at a fixed position on the lava lake. This is also where the small lava fountains are sometimes produced. Since this location is likely to be directly above the volcanic conduit feeding the lava lake, we have done continuous measurements between March 22 and 26, 2003 to understand the degassing of a volcano in permanent activity. The bubble size has been first estimated from videos, which once combined with the acoustic pressure, can constrain the source of the sound. The gas volume and overpressure stayed roughly constant, between 36–700 m^3 and 4×10^3–1.8×10^4 Pa, respectively. Simultaneous thermal measurements showed regular peaks, which occurred when the crust was broken by a large bubble, hence gave a direct indication on the typical return time between the bubbles (1 h). These spherical cap bubbles had a high Reynolds number, 4600–20000, therefore a wake, periodically unstable, formed and detached from the bubble bottom. The bubbly wake, if the detachment occurs close to the surface, can explain the duration of lava fountains, measured on the videos. The periodic arrival of bubbly wakes, which mostly detach from the driving spherical cap within the lava lake, could explain the absence of cooling at Erta 'Ale, Erebus (Antartica), Villarica (Chile) and Nyiragongo (Democratic Republic of Congo) without invoking a convective downflow of magma in the conduit, as previously done.

1. Introduction

Long-lived active lava lakes, which are connected to an underlying conduit, are extremely rare. Examples include Erta 'Ale, known since 1967 (Tazieff, 1968; Le Guern et al., 1979; Tazieff, 1994), Erebus observed since 1972 (Giggenbach et al., 1973) and Nyiragongo seen since 1928 (Komorowski et al., 2003; Sawyer et al., 2008a).

The surface of a lava lake can either display a mosaic composed of several cold plates separated by incandescent zones, such as at Nyiragongo (Komorowski et al., 2003; Sawyer et al., 2008a) and Erta 'Ale (Harris et al., 2005), or be quasi-solidified with a few small permanent openings that let the gas escape, as frequently seen at Villarica (Calder et al., 2000; Palma et al., 2008) but rarely at Erta 'Ale (Smith. Inst., 2005a,b). When the surface of the lava lake is not solidified, the mosaic of cold plates can be stagnant or slowly drifting towards the crater rim at velocities varying between 0.08 and 0.1 m s^{-1} at Erta 'Ale (Harris et al., 2005), 0.1 and 0.8 m s^{-1} at Erebus (Calkins et al., 2008), and ≥0.1 m s^{-1} at Nyiragongo (Sawyer et al., 2008a).

Degassing at the surface of a lava lake mostly occurs at fixed positions, likely to be directly above the conduits, or at the boundaries between cold plates (Burgi et al., 2002; Harris et al., 2005; Palma et al., 2008; Sawyer et al., 2008a). The degassing occurring above volcanic conduits is often made by bursting large bubbles of radius ≤10 m at Villarica (Gurioli et al., 2008) and 8–23 m at Erebus (Johnson et al., 2008). Occasionally it can also consist of small lava fountains, 5–10 m high for a duration up to 5 min at Erta 'Ale in February 2002 (Burgi et al., 2002) and up to 40 m high at Villarica with a relatively short duration, 20–120 s (Palma et al., 2008). They have been recently interpreted as a zone locally rich in small bubbles (Palma et al., 2008).

The gas volume expelled by lava lakes has been estimated by continuously measuring the ratio between volatile species using the open-path FTIR spectroscopy and combining it with SO_2 fluxes (Oppenheimer and Kyle, 2008; Sawyer et al., 2008a,b; Sweeney et al., 2008). This technique gives access to the total degassing but cannot distinguish between passive degassing and that resulting from large bubbles rising in the underlying conduit, here called active degassing. These large bubbles, by coming from depth, are still

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overpressurised when bursting at the surface, which makes them perfectly detectable on acoustic records. So far, only one study has used acoustic records to deduce their diameter (Johnson et al., 2008).

A long-lasting lava lake can be relatively small, with a diameter of 34 m at Erta 'Ale in March 2003 (Oppenheimer et al., 2004) and 40 m at Erebus (Johnson et al., 2008), or large, 200 m at Nyiragongo (Komorowski et al., 2003; Sawyer et al., 2008a). Little is known on the depth of a lava lake, which varies from zero to several hundreds of meters at Nyiragongo (Komorowski et al., 2003). In any case, the large exposed area of a lava lake, combined with its high temperature, should lead to its cooling on a decadal time scale (Davaille and Jaupart, 1993; Worster et al., 1993; Jellinek and Kerr, 2001). This paradox is currently explained by a strong convective motion in the volcanic conduit, which brings to the surface the hot, fresh and degassing magma while the cold and degassed magma is simultaneously sinking (Francis et al., 1993; Kazahaya et al., 1994; Stevenson and Blake, 1998; Oppenheimer et al., 2004; Harris et al., 2005; Jones et al., 2006; Huppert and Hallworth, 2007; Harris, 2008). Alternatively an exogeneous supply of bubbles from depth could also explain a persistently degassing stable lava lake (Witham and Llewellin, 2006; Stix, 2007). The role of the gas flux at the base of the conduit has been further explored for a system composed of a magma reservoir, a conduit and a lava lake to explain the variations in the levels of lava lakes (Witham et al., 2006).

One of the key questions remaining to be further answered to understand long-lived active lava lakes is whether the widely used model of a thermally or compositionally-driven convective flow within the underlying volcanic conduit is appropriate or if an alternate model could be proposed. To address this question, we have performed simultaneous acoustic, seismic and thermal measurements at Erta 'Ale to unravel the physical processes taking place in the underlying volcanic conduit. After describing our measurements, we discuss the temporal evolution of the gas volume and pressure during 5 days in March 2003. Here we focus on finding the pattern of degassing within the volcanic conduit, as the only way to provide some of the initial conditions driving the behaviour of a long-lived active lava lake.

2. Behaviour of the Erta 'Ale lava lake

In March 2003, the active lava lake, located within the southern crater, was low, ≃95 m below the crater rim, small, ≃910 m^2, and circular whereas in February 2001 its level was 20 m higher with an elliptic area of 6200 m^2 (Burgi et al., 2002; Oppenheimer et al., 2004). Our infrared and visible videos, recorded from March 22 to 27, 2003, for a few hours each day and at ≃100 m from the lava lake (Fig. 1), hardly showed any variation in the level of the lava lake, ⩽1 m. Once a day, numerous incandescent cracks were formed suddenly on the crust, leading to the massive breaking and sinking of the crust (Fig. 2). This event, discussed in the companion paper (Bouche and Vergniolle, 2010-in revision), never lasted more than 1 h.

The lava lake, although comparatively low and small in March 2003, was degassing significantly, both by bursting bubbles and by producing lava fountains (Fig. 3). Two main types of large bubbles are recognized and associated to a specific location. Bubbles can break either at a fixed place (Fig. 3a) or at any of the boundaries separating the cold plates (Fig. 3b).

Bubbles at a fixed location are roughly hemispherical with a diameter between 3 m and 6 m, deduced by comparing their size to that of the lava lake on the video. The vertical dimension of these bubbles, L_b, apparent after the bursting, is similar to their radial dimension, R_b (Fig. 4f). Their shapes are characteristic of spherical cap bubbles (Wallis, 1969), with a hemispherical head and a bottom marked by an inward protuberance on the vertical axis (Fig. 4h). Their fixed location, independent of the time of observation, is also that of the three small cones, called hornitos, remaining when the lava lake

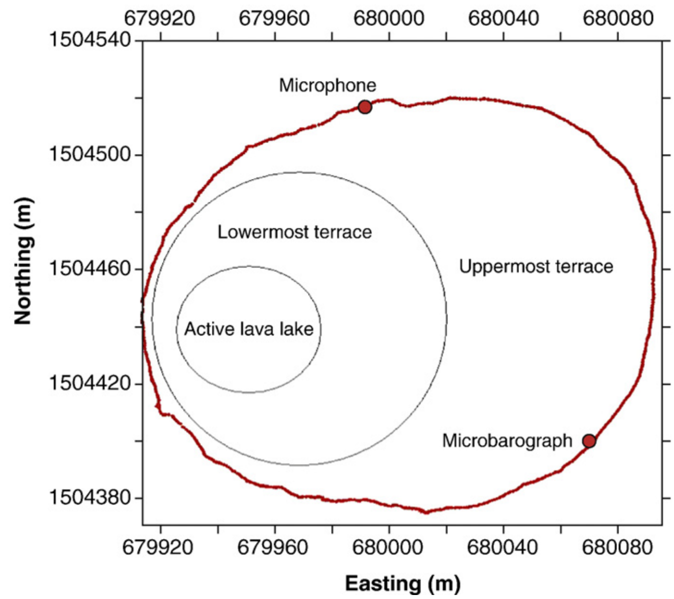

Fig. 1. Map of the south crater at Erta 'Ale with distances in meter towards the east (horizontal) and the north (vertical) and the location of the active lava lake and that of the instruments. Microbarograph indicates where seismic, thermal and infrasound pressure were simultaneously recorded at a frequency of 75 Hz while Microphone marks where the acoustic pressure was measured at a frequency of 4096 Hz. The study of the acoustic pressure recorded at high-frequency is the focus of the companion paper (Bouche and Vergniolle, 2010–in revision).

had a solid cap (Smith. Inst., 2005a). Hence this place is likely to be directly above one of the conduits. These bubbles, also observed in March 2001 and February 2002 (Burgi et al., 2002; Harris et al., 2005), occurred every hour in March 2003 and will be referred to as spherical caps.

Videos from March 2003 show that the surface of the lake is either a single cold plate or made of a mosaic of a few cold plates, occasionally surrounded by a ring of incandescent magma. Bubbles are always observed breaking at the boundary between cold plates (Fig. 3b), regardless of the number of cold plates. These bubbles are interpreted to be flat, less than 2 m in length, burst frequently, with a typical return time of several minutes. Their breaking, only occurring where the magma is hot, suggests that these bubbles, called flat bubbles, are not sufficiently overpressurised to break the crust above them, in contrast to the spherical caps.

Lava fountains, sometimes initiated by the bursting of a spherical cap, were observed in March 2003 at the same location as the spherical caps (Fig. 3c). The lava fountain lasts 2 to 3 min for a maximum height between 1 m and 5 m, which never exceeds the diameter of the spherical caps, from 3 m to 6 m. Sometimes, fountains are observed drifting at the surface of the lava lake probably due to underlying motions.

The phenomena were identical at Erta 'Ale in March 2001. Close-up images, taken from the lowest terrace, show that numerous small bubbles are trapped within the wake of the spherical caps, which can sometimes lead to a lava fountain. Its maximum height varies between a few meters and 20 m for different periods of observations (Table 1).

3. Instrumentation

The ground displacement, the wind velocity, the acoustic pressure and the temperature at the surface of the lava lake have been monitored continuously for 128 h, from March 22, 2003, 00 h00 to March 27, 2003, 10 h00 (all times are UTC), from two locations (Fig. 1). The first site, located on the north-west side of the crater rim at 110 m from the center of the lava lake, is used for the study of the