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Stability of lava lakes

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Abstract

A physical model of a generic lava lake system is developed. We derive the requisite conditions for the existence of an 'equilibrium lava lake' in which magmastatic pressure at the base of the conduit balances the pressure in the underlying magmatic reservoir. The stability of this lava lake system is tested by investigating the response of the system to perturbation. We develop a graphical method, based on the system's pressure–depth profile, to predict the subsequent behaviour of the system. Despite the simplicity of the modelled system, we find a broad behavioural spectrum.

Initially, the rise of bubbles through the magma is ignored. In this case, both stable, long-lived lava lakes, and unstable lakes that are prone to sudden draining, are predicted. The stability of the system is shown to be controlled by lake-conduit geometry, the solubility and gas expansion laws and the magma's volatile content. We show that an unstable lake must collapse to a new, stable equilibrium. Subsequent recharge of the system by, for example, conduit overturn, would promote a return to the original equilibrium, giving rise to cyclic behaviour. Such a mechanism is consistent with lava lake behaviour during the 1983–1984 Pu'u 'O'o eruption of Kilauea.

When the rise of bubbles through the magma is considered, our model predicts that stable lakes must drain over time. We, therefore, deduce that persistently degassing, stable lava lakes, such as those observed at Mt. Erebus, Antarctica, and Mauna Ulu, Kilauea, Hawaii, must have an effective conduit convection mechanism or an exogenous supply of bubbles from depth.

Keywords: lava lakes; lava ponds; cyclic behaviour; magma degassing

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1. Introduction

Lava lakes occur in a variety of volcanic systems, ranging from the basaltic Erta Ale lake in Ethiopia (Carniel et al., 2002), and the basaltic andesite volcano of Villarrica, Chile (Calder et al., 2004), to the unique phonolitic lava lake at Mt. Erebus, Antarctica (Dibble et al., 1984).

Lava lakes have been observed to exhibit a range of behaviours. Swanson et al. (1979) document a "constantly circulating, apparently steady-state" lava lake during the 1969–1971 Mauna Ulu eruption of Kilauea, Hawaii. By contrast, Wolfe et al. (1987) observed a lava lake at the 1983–1984 Pu'u 'O'o eruption of Kilauea, which displayed cyclic behaviour with a period of 4–20 min. Gas "pierced the surface" of the lake, and the lava rapidly drained back down the conduit before the onset of a new phase of lake activity. The time between collapse of the lake and resumption of the eruption was very short compared with the timescale of the cycles

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(Wolfe et al., 1988). Barker et al. (2003) observed similar drainback phenomena at Pu'u 'O'o in 1999.

The behaviour observed is influenced by the combined effects of pressure within the reservoir, exsolution and decompression of gas bubbles within the conduit (Wilson et al., 1994) and, potentially, exsolution of bubbles within the reservoir (Jaupart and Vergniolle, 1989). Superimposed upon this is the effect of bubble rise through the liquid, and coalescence of bubbles within the conduit. Many of these processes are complex and poorly understood. Witham et al. (2006) addressed the problem by undertaking a series of analogue laboratory experiments to model a simple lava lake system. They found that, depending on the gas flux, lake depth was either steady, aperiodic, or oscillated periodically, even though reservoir pressure and gas flux were constant.

In this work, we develop a physical model that captures much of the observed behaviour of natural lava lake systems. 'Behaviour' is characterised by two phenomena that are observable at the surface: changes in the level of the lake with time and the flux of bubbles at the lake's surface. The model, which is based on an analysis of the magmastatic pressure–depth profile, is deliberately simple. We consider only the geometry of the lake-conduit system, equilibrium bubble exsolution and growth (though no specific exsolution or growth law is assumed), and buoyant bubble rise.

Within this framework, we begin by establishing the basic criteria for the presence of a lava lake in pressure equilibrium with its underlying reservoir (Section 2) and investigate the response of this equilibrium lake system to perturbation (Section 3). We do not assume any particular distribution of bubbles with pressure or depth, hence the model is applicable regardless of the source, number or density of bubbles in the system. In Section 4, we derive the rules that govern the evolution of a lava lake system that is out of equilibrium and the criteria that determine lava lake stability. In Section 5, we apply these rules to predict the behaviour of various lava lake systems. The effect of more complicated processes, such as the rise of bubbles through the magma, is discussed in Section 6. A quantitative example of the application of the model, to a lava lake at Pu'u 'O'o, Kilauea, is presented in Section 7. We conclude by synthesizing our analyses to link subsurface processes to observable surface behaviour.

A remarkable richness of behaviour is predicted for even this highly simplified model system. We show that the criteria for the presence of a steady state, degassing lava lake are rather restrictive (Section 6.1). Observation of such a lake indicates that the system must have an effective conduit convection mechanism, or an exogenous supply of bubbles from depth. By contrast, unstable collapse of the lava lake is predicted for a large portion of the relevant parameter space and such behaviour, in a natural system, may be considered 'normal'.

2. The model system

We consider a system comprising a reservoir connected, via a vertical conduit, to a volcanic crater that is open to the atmosphere (Fig. 1). The conduit has length Z and cross-sectional area A_c; the crater has depth h_d and cross-sectional area A_l; the cross-sectional areas of the conduit and crater are constant with depth. The reservoir is filled with magma of uniform density ρ and maintains a constant pressure P_r. Density changes resulting from the compressibility of silicate melt (Ghiorso, 2004) and from variations in the concentration of dissolved volatiles are small compared with density changes resulting from changes in gas volume fraction, hence, we use a single value of ρ throughout the system.

2.1. The bubbly layer

Initially, the magma is assumed to contain dissolved volatiles such that, if the pressure experienced by a packet of undegassed magma drops below a critical pressure P_b, exsolution occurs to produce a bubble

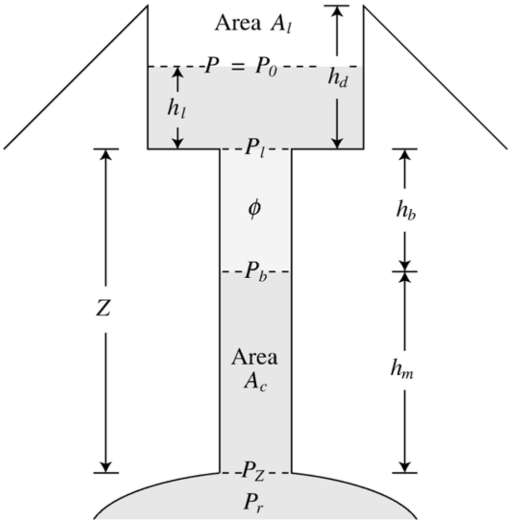

Fig. 1. The model system. A magma reservoir is connected via a vertical conduit to a crater which is open to the atmosphere. A lava lake may form in this crater. See Section 2 in the main text for an explanation of the notation.