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RESEARCH ARTICLE

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An analogue experimental model of depth fluctuations in lava lakes

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Abstract Lava lakes, consisting of molten degassing lava in summit craters of active basaltic volcanoes, sometimes exhibit complex cycles of filling and emptying on time-scales of hours to weeks such as recorded at Pu'u'O'o in Hawaii and Oldoinyo Lengai in Tanzania. Here we report on a new series of analogue laboratory experiments of two-phase flow in a reservoir-conduit-lava lake system which spontaneously generates oscillations in the depth of liquid within the lake. During the recharge phase, gas supplied from a subsurface reservoir of degassing magma drives liquid magma up the conduit, causing the lake to fill. As the magmastatic pressure in the lake increases, the upward supply of magma, driven by the gas bubbles, falls. Eventually the upflow becomes unstable, and liquid drains downwards from the lake, driven by the magmastatic pressure of the overlying lake, suppressing the ascent of any more bubbles from the chamber. At a later stage, once the lake has drained sufficiently, the descent speed of liquid through the conduit decreases below the ascent speed of the bubbles, and the recharge cycle resumes. Application of a quantitative model of the experiments to the natural system is broadly consistent with field data.

Introduction

Basaltic volcanic eruptions are characterised by relatively low viscosity magma, in which the separation of gas from liquid magma deep in the system can lead to surface degassing activity and gas rich lava eruptions (Wolfe et al. 1987; Wilson and Head 1981). Eruption styles include vigorous fire-fountaining activity, periodic Strombolian explosions associated with bursting gas bubbles, and the more passive maintained eruption of vesicular lava (removed Pyle ref; Jaupart and Vergniolle 1988). However, in many systems, active lava lakes form above the volcanic conduit. These lakes sometimes exhibit complex eruption cycles in which filling of the lake is followed by a quasi-steady phase of degassing from the surface, until backflow develops within the conduit. This leads to rapid draining of the lake. For example, during the 1983-4 Pu'u 'O'o eruption of Kilauea, Hawaii, the lake depth varied in an oscillatory cycle with a period of 4–20 min (Wolfe et al. 1987). Pauses in fountaining from the lake surface typically lasted several tens of seconds, after which the lava rapidly drained back down the conduit. Barker et al. (2003) observed similar behaviour at Pu'u 'O'o in 1999. In another example, Pyle et al. (1995) reported continual fluctuations in the lava level at 'Hornito 5', during the degassing eruption of the carbonatite volcano Oldoinyo Lengai, in Tanzania.

A number of theoretical and experimental models have been developed to explore basaltic eruptions (Wilson and Head 1981; Vergniolle and Jaupart 1986; Jaupart and Vergniolle 1988; Head and Wilson 1987; Wilson et al. 1994; Seyfried and Fruendt 2000). Using a simplified, steady-state homogeneous flow model, Wilson and Head (1981) illustrated the importance of magma gas content and viscosity and also of conduit radius and chamber pressure on eruption rate. Later, in a series of key laboratory experiments, Jaupart and Vergniolle (1988) identified that, depending on the gas flux from deep in the system, either Strombolian or continual fire-fountaining behaviour may develop, owing to bubble-liquid separation (Vergniolle and Jaupart 1986) and the accumulation of a foam layer in the magma reservoir beneath the volcanic conduit. Seyfried and Fruendt (2000) provided further experimental support for these models using an analogue experimental system involving water-air flow up a model conduit. However, these models do not address the complex cycles of magma recharge and draining which are sometimes seen at active lava lakes. The purpose of the present contribution is to describe a very simplified analogue experimental system of

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the lake-conduit-reservoir system, which spontaneously generates oscillations.

Experimental model

Our analogue experimental system (Fig. 1), builds from the experiments of Seyfried and Fruendt (2000), but is now focused on the impact of a lava lake atop the conduit. We have an open reservoir, of dimension 28.5×28.5×39.6 cm connected by a short horizontal pipe from its base to a vertical conduit of square cross-section with dimension 1×1×18 cm, above which there is a small tank, of dimension 14.1×14.1×15 cm as an analogue of a lava lake. A steady flux of air is supplied at the base of the conduit from a compressed air source, with a prescribed supply rate in the range 1–48 cc/s. This picture is somewhat analogous to the system envisaged by Jaupart and Vergniolle (1988) in which bubbles nucleate and grow within a subsurface magma reservoir, and then separate gravitationally from the melt to form a foam layer at the top of the chamber. Their experiments identified that bubble merger within this foam can lead to the periodic release of a series of large gas bubbles or slugs into the conduit. The flux of air supplied at the base of our experimental conduit represents, in a simplified way, the gas flux supplied to the conduit from this foam layer.

Using water as the experimental fluid, we achieved flows with liquid Reynolds numbers as large as 10^2–10^3, corresponding, for example, to the flow of basaltic magma of viscosity 100 Pas, rising with a velocity of order 1–10 m/s in a 1–4-m-wide conduit (Wilson and Head 1981).

In the experiments, we set the level of water in the reservoir to be equal to or lower than the base of the lava lake, so that without the gas flux, there is no flow. At the start of the experiment, gas is supplied at the base of the conduit, and the density of the two-phase mixture in the conduit decreases below that of the water in the reservoir. As a result, a net upward flux of water begins to fill the lake, as shown in the sequence of photographs from a typical experiment (Fig. 2a–d). While the lake is filling, the pressure at the base of the lake increases and the net upward water flux decreases. As a result, bubbles tend to grow to a larger size before detaching from the source, and bubble merging occurs within the conduit (Fig. 2c). Both of these effects lead to progressively less frequent release of larger bubbles from the conduit into the lake (Fig. 2d).

Eventually, we observed that the upflow becomes unstable and there is a transition to a net liquid downflow (Fig. 2e,f). This downflow suppresses the ascent of bubbles from the gas source at the base of the conduit, and the continuing supply of gas leads to a train of bubbles, which are swept back into the reservoir (Fig. 2f). As the water in the lake drains back through the conduit, the down-flow speed decreases. Eventually, it falls below the bubble ascent speed, and bubbles are again able to rise through the conduit. This lowers the density of the water-air mix in the conduit, and we observed that the lake-filling phase of the cycle resumes (cf. Fig. 2a).

Figure 3 illustrates some experimental measurements of the variation of the depth of the lake surface with time. The cycle is highly asymmetric, with a slow filling phase and a rapid draining phase. For sufficiently deep lakes (>4 cm) the amplitude of the oscillation is greater with a larger gas flux, and hence, for a given gas flux, the recharge phase has a longer period. In the present experimental system, the main exception to this general principle occurs when the maximum lake depth is very shallow (<2–3 cm), in which case the oscillation does not fully develop and the lake depth appears to be more stable. We note also that, in the absence of the lake, the flow in the conduit attains an equilibrium depth about which there are rapid fluctuations associated with individual bubble bursting, but no long period oscillation develops.

Criterion for maximum lake depth

In the experiments, once the gas flux is sufficient to create a lake 3–4 cm deep, then the maximum lake depth appears to increase nearly linearly with the gas flux—up to gas fluxes

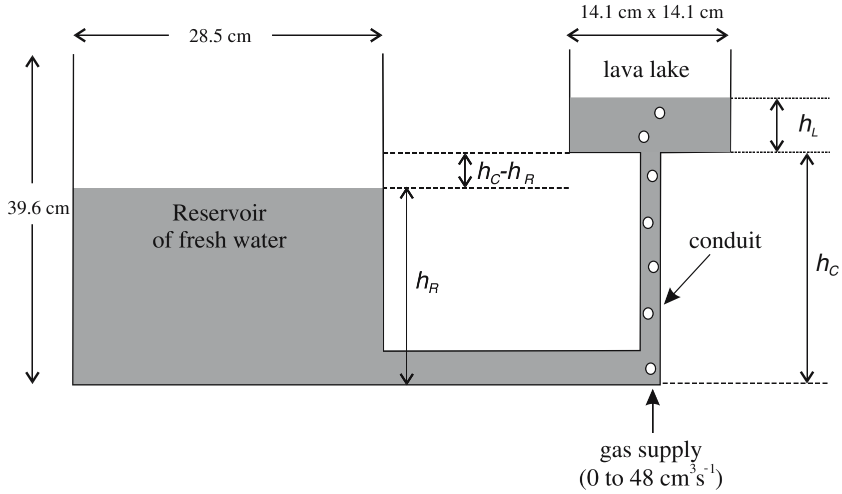


Fig. 1 The experimental apparatus, in which the reservoir vessel is connected from its base to the conduit and the source of gas. The lava lake is modelled with a vessel of square cross-section placed above the conduit

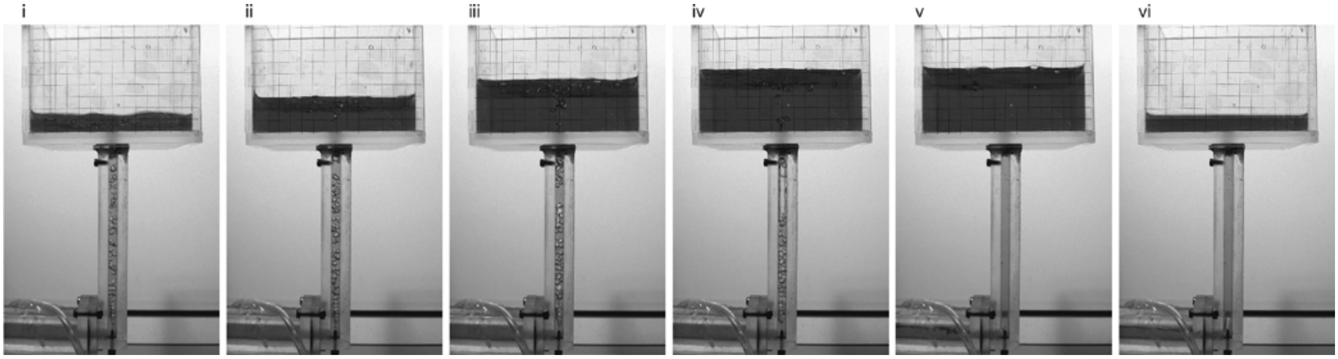


Fig. 2 A series of photographs of the different phases during a lake filling and draining event, including (**a-d**) gradual lake deepening; (**e**) end of the filling phase and onset of back-flow; (**f**) the main draining phase before the lake recharge phase commences again

of about 35 cc/s, the limit of the present experimental study (Fig. 4a)—and also with the initial depth of the reservoir and hence the chamber overpressure. (Note, at much higher gas fluxes, the liquid flow eventually saturates, as the flow in the conduit becomes annular, with gas streaming through the centre, and a liquid film being driven up the walls.) To interpret these observations, it is useful to consider the pressure at the base of the conduit, p_c, relative to the pressure at the base of the reservoir, p_r, as given by

$$p_r = \rho g h_r. \tag{1}$$

Liquid flow up the conduit from the reservoir occurs if

$$p_c < p_r. \tag{2}$$

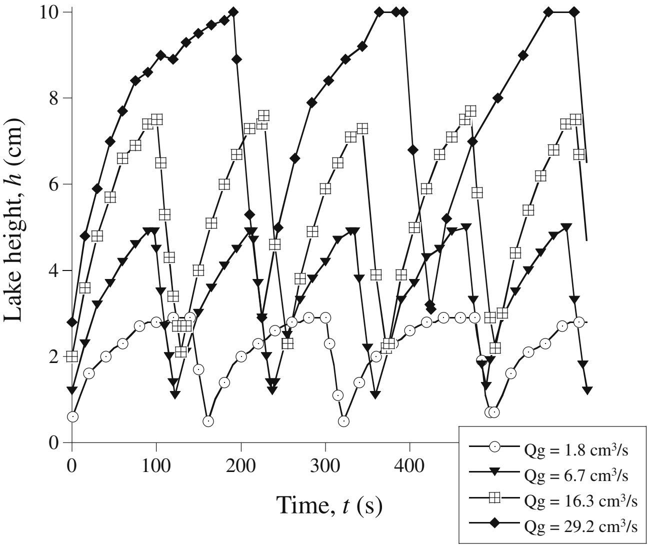


Fig. 3 Variation of the depth of the experimental lava lake in mm as a function of time, for four different values of the gas flux, 1.8, 6.7, 16.3 and 29.2 cm^3/s. In each experiment, the fluid in the reservoir is filled to the same depth as the base of the lake. In all cases the cycle is aperiodic, with a fast draining phase and a more gradual filling phase which is arrested when the pressure of the lake and bubble conduit matches the pressure of the source reservoir

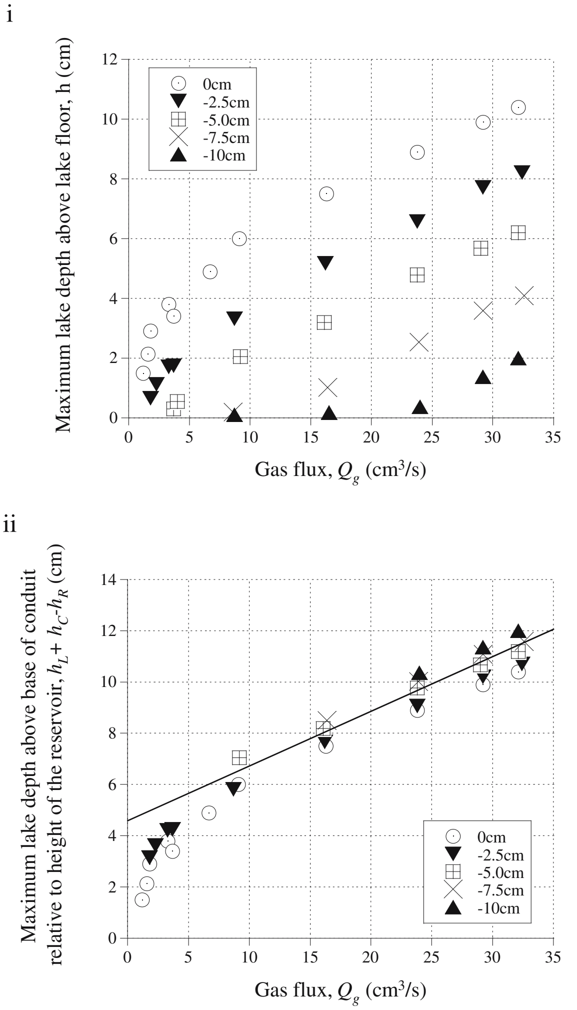


Fig. 4 Maximum depth of water in the experimental lava lake as a function of the gas flux. **a** Experimental data of lake depth above base of lake, corresponding to reservoirs of different depth relative to the base of the lake, 0, −2, −5, −7.5, −10 cm; **b** experimental data of the sum of the lake depth plus the difference between the elevation of the top surface of the reservoir and the lake bottom, as a function of the gas flux. In **a**, once the lake has filled beyond a depth of 3 cm or so, the model provides a very good description of the maximum filling depth in terms of the source gas flux, the chamber pressure and the bubble rise speed

As the lake fills towards its maximum depth, the net upflow in the conduit decreases and so we expect the pressure in the conduit to approach hydrostatic (i.e. equal to the weight of the bubble-water mixture). If we denote the gas volume fraction in the conduit by ϕ, the lake depth byh_l, and the conduit depth byh_c, then this implies that the hydrostatic pressure at the base of the conduit is given by

$$p_c = \rho g((1-\phi)h_c + h_l). \tag{3}$$

Combining this with the condition for liquid upflow, $p_c < p_r$, implies that the lake may continue to fill while the depth of liquid in the lake satisfies

$$h_l < h_r - h_c(1-\phi). \tag{4}$$

It remains to estimate a value for ϕ at the limiting condition of zero liquid net flow. If the conduit is long, and the individual slug-bubbles are small compared to the length of the conduit, then the value of ϕ is given approximately by the volume flux of gas,Q, divided by the mean bubble rise speed,v_s, and the cross-sectional area of the conduit, A.

$$\phi = Q/v_s\,A \tag{5}$$

Note that as the individual slugs become larger, then there will be fluctuations about this mean value of ϕ, because each time a slug issues from the conduit, there will be a finite decrease in gas content, which will then build up again owing to the continuing source of gas at the base of the conduit. However, as a simple approximation, if we combine Eq. (5) with the maximum lake depth, as given by Eq. (4), we find an expression for the maximum lake depth.

$$h_l = Qh_c/(v_s A) - (h_c - h_r) \tag{6}$$

Note that in practice, if the bubbles are large, the lake instability may be triggered before this depth is attained, as individual bubbles vent from the conduit into the lake and lead to a sudden drop in void fraction, and hence increase in hydrostatic pressure at the base of the conduit.

The experimental data show that once the lake becomes established, with a depth in excess of 3–4 cm, the prediction of a linear increase in the maximum height of the lava lake as a function of the gas flux (Eq. 6) is in accord with the measurements in the experiments (Fig. 4a). In Fig. 4b, we have replotted this data to show $h_l + h_c - h_r$ as a function of the gas flux (cf. Eq. 6). In comparison with the large scatter of data shown in (Fig. 4a), the data converge, and using the measured bubble rise speed at the limit of the filling cycle, $v_s = 1+/-0.3\ m/s$, the slope of the curve is consistent with Eq. 6 (Fig. 4b). However, the best-fit line to the data implies lake depths about 4.5 cm in excess of the prediction of Eq. 6. The origin of this offset may be that the bubbly jet, which rises from the conduit up through the lake, may travel some distance before it has adjusted to the lake pressure, especially with large slugs present. As a result, the effective pressure at the top of the conduit may be smaller than the lake hydrostatic pressure, leading to the greater lake depth.

Mechanism for instability

Once the lake has filled to a critical depth during the lake filling phase of the cycle, our experimental observations suggest that the conduit-lake system becomes unstable. The instability develops as the lake depth increases towards the value at which the steady-state hydrostatic pressure at the base of the conduit, associated with the bubble-water mixture in the conduit and the water in the lake, matches the pressure of the source reservoir. This instability appears to be triggered before the lake reaches the equilibrium depth, as a result of the venting of slugs at the top of the conduit. Since the lake area is much greater than that of the conduit, the lake depth does not change substantially when a slug is released. Therefore, a slug release causes fluctuations in the pressure at the base of the conduit relative to the mean hydrostatic pressure, and once the mean pressure is sufficiently close to the equilibrium value, the release of a sufficiently large slug can then cause the pressure at the base of the conduit to exceed that in the reservoir, triggering the downflow (Fig. 2). The ensuing downflow into the conduit impedes any further ascent of bubbles from the gas source at the base of the conduit. The pressure at the base of the conduit then remains elevated relative to the reservoir, and the draining cycle commences as water continues to flow down from the lake, through the conduit. During this descent phase, the continuing gas flux supplied by the source is swept back into the chamber (Figs. 2 and 3). As the lake level falls, the flow gradually decreases, and eventually the waning downward speed of the liquid is no longer able to suppress the ascent of the bubbles from the source into the conduit. At this point, the density of the bubbly-water mix in the conduit decreases, and a net upward flux of water leads to a resumption of the recharge phase of the lake.

Discussion

In a geological context, lava lake dynamics are considerably more complex than the simplified, isothermal system developed in our experiments. However, the mechanism for generating fluctuations in the lake depth associated with separation of the liquid and gas slugs within the conduit may be relevant. For example, if a large slug, 1–5 m in length, explodes at the surface, this will allow a depth of 1–5 m of the conduit to be filled with liquid magma from the lake. Assuming the lake has much larger area than the conduit, this will increase the overpressure in the conduit by ΔP=0.03–0.15 MPa relative to the reservoir. With magma of viscosity μ=10–100 Pas, and a conduit of length H=1–5 km, this may cause a downflow with speed given by

$$u = d^2 \Delta P \big/ 12\mu H \qquad (7)$$

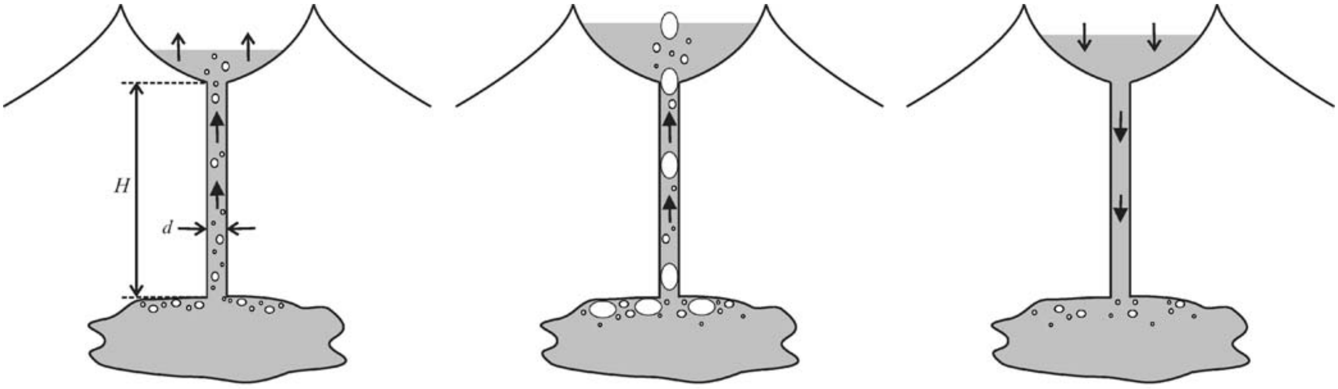
which has values in the range 0.1–5.0 m/s in a conduit of width 1–2 m. At a depth of 5 km, the pressure is 100 times that at the surface, and so bubbles of size 1 m^3 at the surface have a size 0.01 m^3 with rise speeds of order 1–3 m/s. The mean liquid downflow, which could follow the bursting of a large gas slug at the surface may, therefore, be sufficient to suppress the ascent of new bubbles, released from a foam layer at the top of the chamber, up into the conduit. As in our experiments, this could then lead to a maintained downflow and draining of the lake (Fig. 5).

As the draining continues, the flow rate eventually decreases sufficiently so that bubbles, supplied from the top of the magma chamber, can once again rise up into the conduit. The rising gas bubbles then increase the mean void fraction of the gas-magma mixture in the conduit and thereby decrease its bulk density. As a result, the magmastatic pressure at the base of the conduit decreases, and a net liquid upflow develops, leading to a resumption of the lake-filling phase (Fig. 5). This filling phase persists as long as the increase in hydrostatic head associated with the increase in the depth of the lake is balanced by the decrease in the hydrostatic head associated with the larger bubble content in the conduit. As the equilibrium is approached, instability may be triggered by the bursting of a slug at the top of the conduit, which may lead to the hydrostatic pressure at the base of the conduit exceeding that in the reservoir, causing resumption of the draining phase (Fig. 5). Field observations of the initiation of the draining phase indicates it is coincident with vigorous bubbling activity (Swanson et al. 1979) and this is in part consistent with the present picture in which progressively larger slugs reach the top of the conduit prior to the onset of the draining.

Field observations suggest that the amplitude of the oscillations in crater lakes is of order 10–100 m, implying that the hydrostatic head may vary by a comparable amount during the cycle (Wolfe et al. 1987; Pyle et al. 1995). If the mean void fraction of the magma-gas mix in the conduit increased by 0.2–2% owing to the upward flux of gas, then the depth of the lake could increase by 10–100 m before the pressures balance and the draining phase resumes. With flow rates of 1–10 m^3/s, then, if the lake has an area of 10^3–10^4 m^2, it would require a time in the range of 10^3–10^5 s to drain the upper 10–100 m of magma.

Conclusion

Although rather simplified, the present experimental model has exposed a simple mechanism by which oscillations may develop in a lava lake-conduit system. The key element of the model is that when the magma in the conduit is bubble-rich, it has a low density, and can therefore drive an upflow of liquid to the lake, whereas, when the magma is bubble poor, it is dense and hence leads to a downflow. The transition from upflow to downflow occurs as the lake approaches a maximum depth at which the liquid upflow is arrested by the excess hydrostatic pressure of the lake. Bubbles rising up the conduit then coalesce, leading to release of slugs at the surface which may trigger the instability: immediately following the release of a slug, the conduit gas content falls, causing a transient increase in the pressure at the base of the conduit. If the system is close to equilibrium, then the release of a slug may produce a sufficiently large transient downflow that the continuing flux of bubbles from the chamber into the conduit is arrested, and the draining phase commences. The cycle resumes once the lake is drained and bubbles can rise back up into the conduit. Recognition of such instabilities and fluctuations is also important for the broader interpretation of basaltic eruptions, since it identifies how two-phase flow processes in the shallow sub-surface can lead to highly unsteady surface phenomena (cf. Wallis 1969).



i Initial rapid filling phase

ii Conditions just prior to instability

ii Draining

Fig. 5 Cartoon of the periodic **a** recharge, **b** slug-driven instability and **v** draining of a lava lake owing to the relative motion of the slugs and liquid phase

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