Emplacement of pahoehoe lobes: a simplified two-component model and field measurements by ground penetrating radar.
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Introduction: Observations of active pahoehoe flow advance [e.g., 1,2] reveal that, typically, a series of small lobes and toes continually appear from breakouts in a surface crust, and perhaps these are interconnected to each other to form a broad pahoehoe field. Although the formation of a lobe itself seems chaotic [3,4], the gross shapes of lobes seem to be more deterministic, because (1) the width of a pahoehoe lobe is relatively constant, and (2) a lobe often shows a transverse profile that has a central ridge, a crude bilateral symmetry, and decay in the thickness of the deposit toward the margin. These observations strongly suggest the existence of a lateral self-confinement mechanism at the scale of a lobe. Baloga and Glaze [4] took a stochastic approach and proposed the random walk model to describe the emplacement of toes and lobes. In this work, we take a more deterministic approach and present a simple two-component model as a possible theoretical explanation of the self-confinement mechanism of the lateral spreading of an isolated lobe. Our model requires an estimation of the thickness of chilled crust at the surface of a pahoehoe flow; however, its direct measurement is usually quite difficult. Here, we also present a preliminary result of the ground penetrating radar (GPR) measurement at the Aokigahara pahoehoe flow field, which indicates that the GPR method is a useful technique to understand the subsurface structure of a pahoehoe lava flow.

The aim of this work: A key factor, which controls pahoehoe flow emplacement, is the behavior of a chilled crust developed at the surface of the flow. Scaling analyses of a fluid in the presence of surface cooling have been successfully performed to discuss its gross behavior [e.g., 5-8]; however, direct application to localized features might not be possible [2]. In addition, since the spreading of a toe or a lobe is likely controlled by a continuous brecciation of the surface crust rather than by viscous resistance, a dynamic link between the liquid core and the surface crust should be carefully considered. If the flow front does not move while the flow material is still continuously supplied, the flow would form a swelled part, possibly near the vent. In this case, the excess pressure due to the swell may play a more important role than the downslope gravitational force (at least for a several-meters scale of a lobe). In this work, we focus on the force from the push of the inflated core rather than "core pull" [9] to explain the brecciation of the crust and the lateral spreading of a pahoehoe lobe.

Two-component model: Here we present a simple two-component model to explain a gross behavior of pahoehoe lobe emplacement. If a flow front does not move while the flow material is still continuously supplied, a part of the flow near the vent would swell because of the incompressibility of the flow and potential visco-elastic behavior of the crust. Assuming that the elastic force related to the deformation of the surface crust is negligible, we consider that the pressure inside the flow increases due to the thickness difference (Δh) resulting from the swell. If the width of the flow does not change, the pressure difference before and after the swell (the over pressure, Δp), may roughly be expressed as $\Delta p \sim \rho g \Delta h$. If we assume that the apparent strength of the crust is mainly controlled by the tensile strength of the crust (σ), the overpressure at the very moment of the breakout may be balanced by the apparent tensile strength. In this case, we obtain a first order estimate of the increased thickness required to form a breakout as

$$\Delta h \sim \frac{\sigma\delta}{D\rho g}. \qquad (1)$$

Once the breakout occurs, the fresh new flow lobe would appear from the breakout point and migrate into the side of the original flow. The lateral flow from the original channel feels the gravitational driving force due to the difference in thickness. This can then be laterally and longitudinally integrated to obtain the order of magnitude integrated force for the lateral movement of the flow, which may be balanced with the viscous resistance force ~ηεL, where η is the viscosity of the flow and ε is the strain rate:

$$L \sim \frac{\sigma\delta H^2 \Delta h}{\eta q} \sim \frac{(\sigma\delta H)^2}{\eta q D\rho g}. \qquad (2)$$

The above equation may be considered a maximum scale of how far the new flow lobe can extend from the original flow. If we can reasonably estimate the surface tensile strength and thickness of the crust, the effusion rate of a branched flow may be calculated using the above equation.

Application to a Hawaiian pahoehoe flow: Equation (1) gives a possible inflated thickness before a breakout occurs. A typical tensile strength of a basaltic crustal rock is σ~10^6-10^7 Pa. If we use $1\text{x}10^6$ Pa for a typical pahoehoe flow, the Δh becomes ~3cm for a flow, whose crustal thickness and flow width are 1 cm and 10 m, respectively. This is consistent with thickness measurements of pahoehoe toes in the field [3]. Equation (2) suggests that the distance between the original channel and the new lobe cannot be infinitely large. To the contrary, it is strongly controlled by the thickness of the original flow. A pile of several toes may behave as a larger toe when the pile has a new breakout. Since a lobe is composed of a group of small toes, the width of a lobe may be controlled by the thickness of the lobe. In this sense, equation (2) may apply, at least qualitatively, to the broader shape of a pahoehoe lobe. This can explain why the cross section of a flow has a parabolic shape. Figure 1 shows a plot of the width v.s. thickness of the lobes measured by Crown and Baloga [3]. A general trend (can be fitted by L~H^2) may be aptly explained by equation (2), which has the same trend as L~H^2.

Field measurement: The above model requires an estimate of the thickness of a chilled crust, which is quite difficult to estimate/measure. We are testing the feasibility of the GPR method to map vertical structures of pahoehoe lava flows. At Kajima corporation, we have newly developed a GPR system (Kawasaki Geological Engineering Co. Ltd. in charge), which has a couple of antennae for a common mid-point (CMP) measurement (the length of the antenna is 40cm). The GPR is a step-frequency radar that is operated in the frequency range of 50~500MHz. We performed a preliminary field test at Aokigahara pahoehoe lava flow at Mt. Fuji, Japan, since we have measured the same area by the other pulse radar system [10]. Different from the previous measurement, we perform a CMP measurement (Figure 2), which enables us to estimate the propagation velocity as well as the vertical possible variations in dielectricity (Figure 3). We will further explore the possibility of mapping the lava structure by the GPR method.

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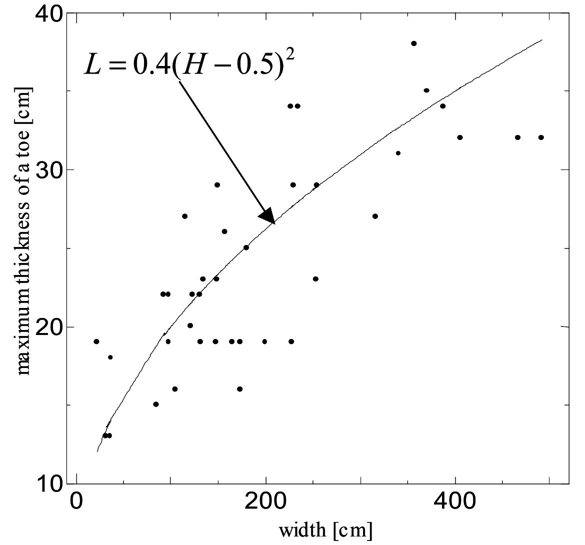

Figure 1. The widths vs thicknesses of lobes (re-sampled from data by [3]), fitted by a curve, which has a trend of L~H^2. We suggest the dependency of the squared power of the thickness is qualitatively explained by the two-component model.

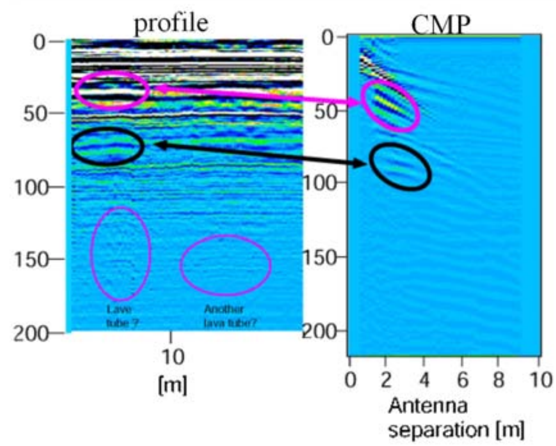

Figure 2. The result of a vertical profile measurement of the Aokigahara pahoehoe lava flow (left) and the plot of a corresponding CMP measurement (right).

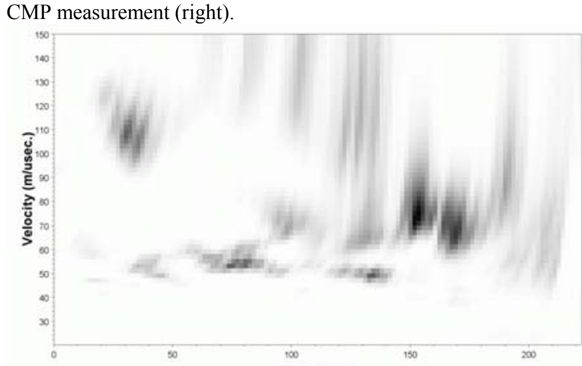

Figure 3. Velocity analysis of the CMP measurement (Fig. 2) on the basis of a constant velocity stack.