

Toothpaste lava: Characteristics and origin of a lava structural type transitional between pahoehoe and aa

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Abstract. Toothpaste lava, an important basalt structural type which illustrates the transition from pahoehoe to aa, is particularly well displayed on the 1960 Kapoho lava of Kilauea Volcano. Its transitional features stem from a viscosity higher than that of pahoehoe and a rate of flow slower than that of aa. Viscosity can be quantified by the limited settling of olivine phenocrysts and rate of flow by field observations related to the low-angle slope on which the lava flowed. Much can be learned about the viscosity, rheologic condition, and flow velocity of lavas long after solidification by analyses of their structural characteristics, and it is possible to make at least a semiquantitative assessment of the numerical values of these parameters.

Toothpaste lava forms either primary lava lobes or is extruded from rootless openings or boccas (see for example, Pinkerton and Sparks 1976) on pahoehoe flows usually late in an eruption. About 30% of the lava flow of Kapoho (Figs. 1, 2), the main study area of this paper, consists of primary toothpaste lava and innumerable secondary toothpaste-lava tongues which occur between, around, and on the primary lobes. Much of the rest of the flow consists of "slab pahoehoe" (Peterson and Tilling 1980) derived from mobilization and breakup of toothpaste-lava tongues.

The Kapoho eruption took place low on the east rift zone of Kilauea Volcano (Fig. 1), three weeks after the end of a month-long summit eruption. Macdonald (1962) and Richter et al. (1970) give excellent eye-witness accounts.

Introduction

Three types of surfaces are generally recognized on basaltic lavas, i.e., pahoehoe, aa, and block lava (e.g., Macdonald 1972, p. 68). In this paper we consider a fourth type, i.e., "toothpaste lava" (Bullard 1947; Einarsson 1949; Macdonald 1967). Such a type has also been called "drawn-surface pahoehoe" (Foster and Mason 1955), "spiny pahoehoe" (Peterson and Tilling 1980), "semi-hoe" (Malin 1980), and "fine aa" (Jones 1943). The name toothpaste lava directs attention to the outstanding feature of this type of flow, i.e., the surface grooves and drawn-out spines imparted at the orifice where the lava encounters the air. We find that toothpaste lava is common on many lava flow fields on Hawaii and many basaltic volcanoes elsewhere (e.g., Mount Etna).

Differences from and relationships to pahoehoe

Toothpaste lava differs from pahoehoe in seven important respects:

1. The surface is characterized by longitudinal grooves and ridges (Fig. 3), lacking on pahoehoe, oriented parallel to the direction of lava movement and caused by scraping against irregularities in the orifice roof. These grooves and ridges characteristically maintain the same separation from each other along the entire length of a toothpaste lava stream, good evidence for a lack of spreading or deformation of the crust.
2. The surface is spinose on a centimeter scale (Fig. 3), whereas pahoehoe is smooth. The spines are typically 1–5 cm long and up to 1 cm wide; they were drawn out of the fluid lava as it issued from the orifice and generally point in the up-flow direction. Vesicles in the upper part of the

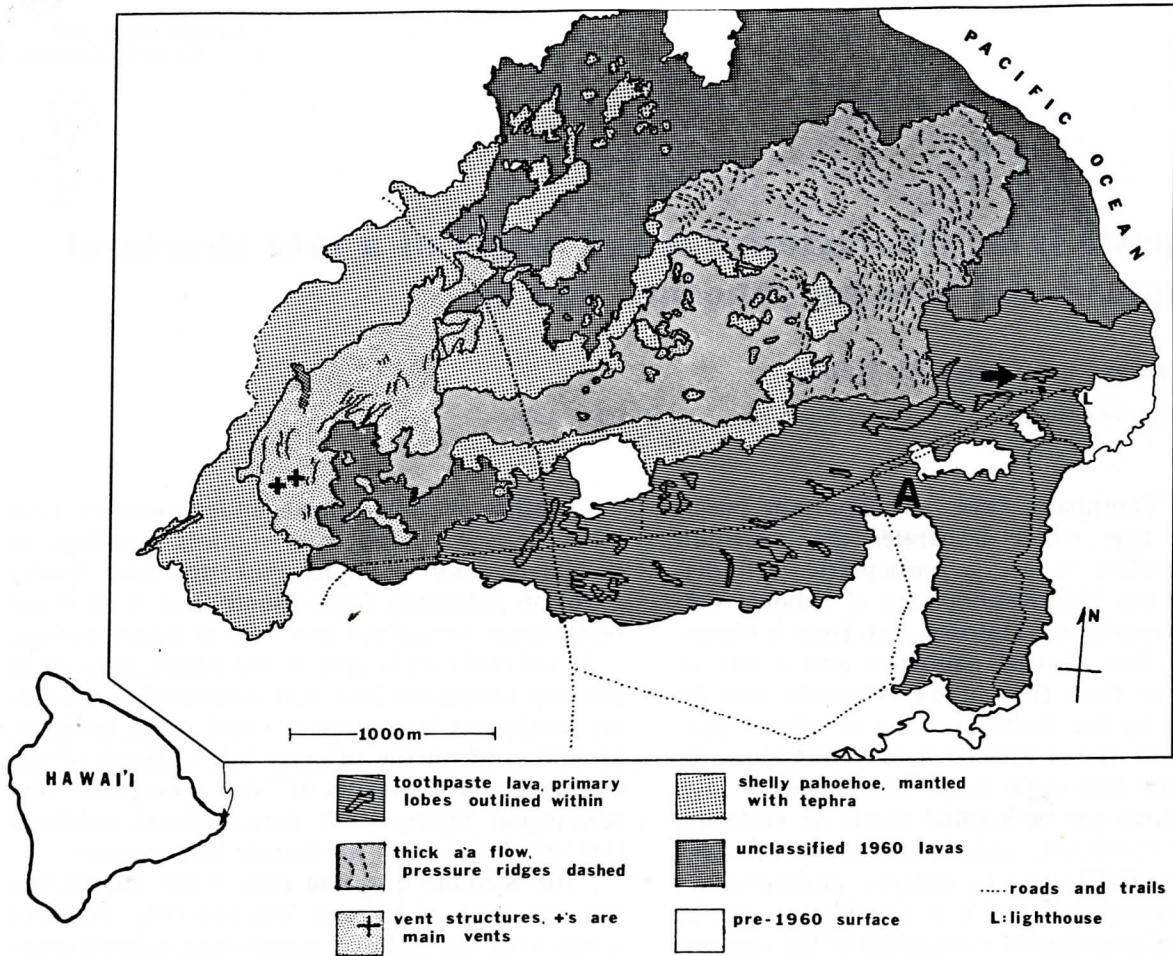


Fig. 1. Location of 1960 Kapoho lava flow, and map of part of flow showing distribution of structural types. Primary toothpaste lava lobe (see text) in Figs. 2 and 9 indicated by *arrow pointing* in flow direction

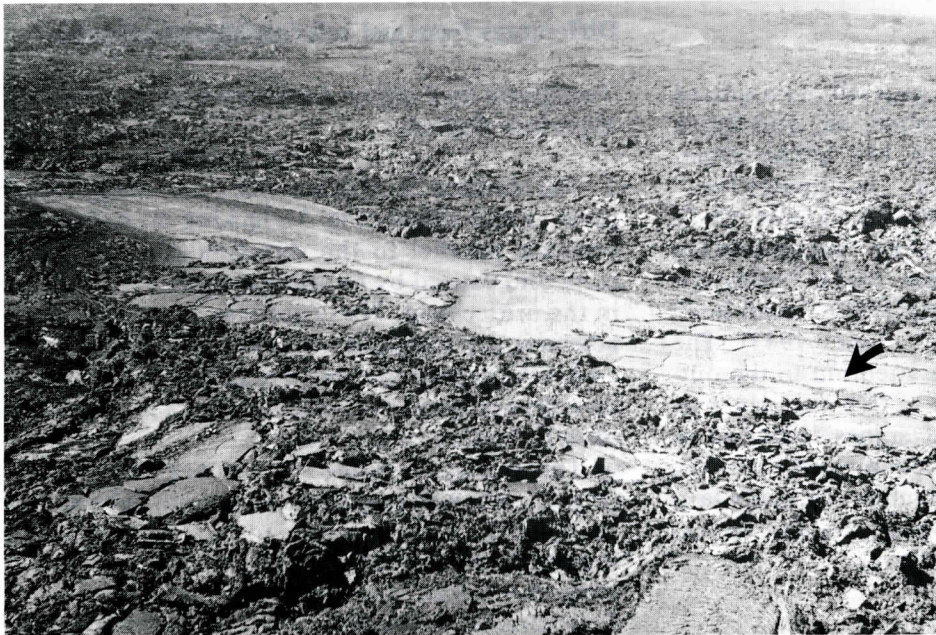


Fig. 2. Large primary toothpaste lava lobe, looking NW from Kapoho lighthouse. Note person (*arrow*) for scale. Flow direction is left to right. Large plate of crust in right center rotated clockwise relative to rest of primary lobe. Foreground composed of broken and jumbled crustal plates of primary lobes as well as smaller toothpaste-lava tongues (see text) from scattered boccas

lava also show structures caused by drag of the surface (Fig. 3).

3. The surface has transverse undulations (Fig. 3) on a much broader scale (tens of cm) than that of the wrinkles (ropy structure) of pahoehoe. The

transverse undulations on toothpaste lava consist of convex-upward waves interpreted to form by nonuniform, pulsing (surging) flow out of the orifice ("discontinuous extrusion" of Macdonald 1972, p. 96) that buckled the surface. When these

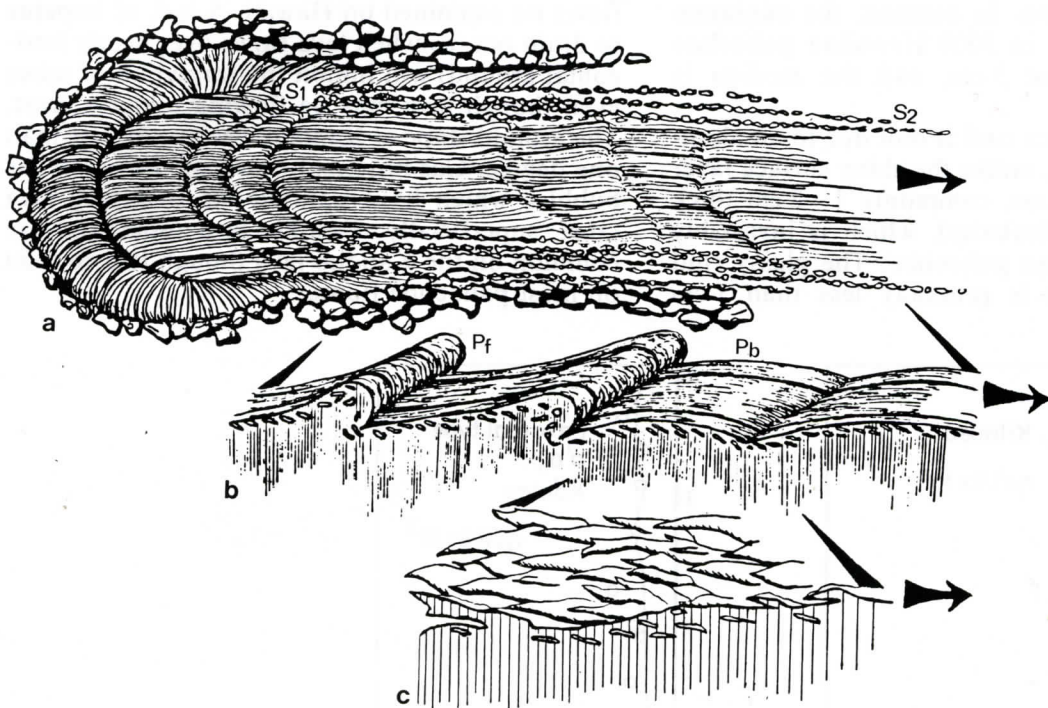


Fig. 3 a—d. Characteristic features of toothpaste lava. Direction of flow is left to right. *Arrows* approximately 1, 0.5, and 0.01 m long in a, b, and c, respectively. **a** Toothpaste tongue issuing from curved bocca. S1—S2, lateral shear zone evidenced by imbricate shearing and clinker. Note how longitudinal lineations maintain same spacing along length of tongue. **b** Cut-away view showing pulse buckles (*Pb*) and pulse flaps (*Pf*), features of discontinuous extrusion. Note how vesicles deformed because crust was retarded relative to underlying lava. **c** Close up showing spines pointing back toward bocca. **d** Photograph of small toothpaste-lava tongue. Flow direction is toward the left

“pulse buckles” became detached and were forced to override the underlying lava, “pulse flaps” were generated (Fig. 3B).

4. Flow units are significantly thicker than those of pahoehoe. The minimum thickness we observed in 20 or more measured toothpaste-lava flow units is about 60 cm, and the median thickness is about 150 cm. In contrast, the minimum thickness observed in 3000 Hawaiian pahoehoe flow units is about 3 cm, and the median is 40 cm.

5. The glassy surface rind is dull due to an abundance of microlites, unlike the shiny surface layer of sideromelane glass, commonly 1–2 cm thick (depending on vesicularity), which is invariably present on Hawaiian pahoehoe. The glassy rind of toothpaste lava is generally less than 1 cm

thick, and crystallization of the lava was well under way when it formed.

6. Lava tubes are scarce. Many pahoehoe flows on Hawaii contain abundant lava tubes from less than 20 cm to 20 m high or wide, where lava flowed beneath a surface crust and then drained out. We found only one in the toothpaste lava flows we examined on Hawaii. A lack of impetus to drain out (as when lava flows over nearly horizontal ground) will inhibit the formation of tubes even though lava may be flowing under a crust. The ground slope at Kapoho was mostly less than one degree. Gas blisters, formed of coalesced gas bubbles which have uplifted the overlying lava crust, superficially resemble lava tubes and are common on the Kapoho lava though less so than on most pahoehoe flows.

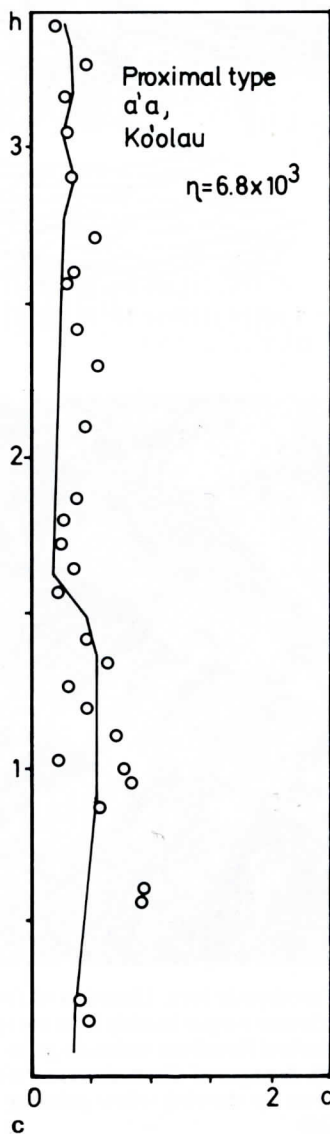
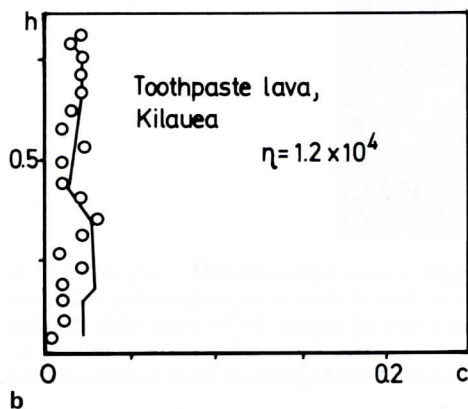
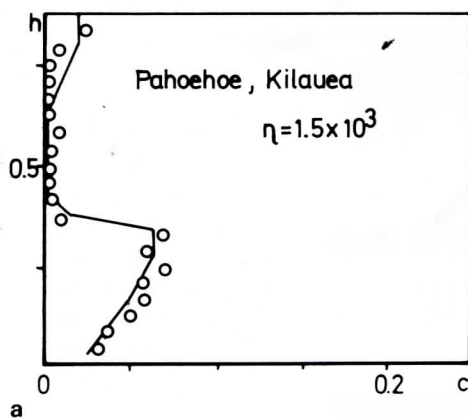


Fig. 4a–c. Graphs of number of olivine crystals (c , crystals per 1 cm^2 of exposure) vs height (h in meters) for (a) pahoehoe exposed in wall of Kapoho graben, (b) toothpaste lava in 1960 flow at Kapoho, and (c) proximal-type aa exposed in gulch eroded in Ko'olau volcano, 4 km SE of Haleiwa. Points are field data. Lines are distributions generated by numerical modeling from which viscosities (η in Pa s) are calculated

7. Mafic phenocrysts show a slight but measurable downward concentration, whereas pahoehoe units show a very pronounced concentration in the lower halves of their flow units (Fig. 4).

These features characterize toothpaste lava as a type distinct from typical pahoehoe. In the time available before solidification, relaxation by flowage did not flatten surface perturbations, i.e., longitudinal grooves and spines, in toothpaste lava which would have been flattened in pahoehoe, nor did olivine crystals settle to any appreciable extent. The toothpaste lava had a higher viscosity than pahoehoe and had crystallized to a greater extent at the time when it erupted.

The olivine crystal distribution is important in quantifying the difference between pahoehoe and toothpaste lava. The Kapoho toothpaste lava carries olivine crystals up to 12 mm across. We found that the content of crystals 4 mm or more across is relatively uniform in the upper 10 to 30 cm of all flow units, regardless of distance from vents. Apparently very little settling took place while the lava was flowing and the surface crust forming. The olivine content is 2–4 times greater in the lower interior part than in the upper interior part of units a meter or more thick; we attribute this to settling of olivine *in situ* in the static lava.

Numerical modeling allows us to generate olivine concentration profiles across lava flows of given thicknesses using different crystal settling rates (Fig. 4). We matched our field profiles with the modeled profiles and obtained a best fit for a settling rate of 1 cm per 5.5 h. For crystals 4 mm in size, the corresponding viscosity from Stokes' law is 10^4 Pa s. For the porphyritic pahoehoe flows that we examined elsewhere in Hawaii, the settling rates are about 1 cm per 40 min for olivine crystals of the same size, indicating a viscosity of about 10^3 Pa s. The content of crystals in the crust of these flows is moreover not uniform, indicating that some crystal settling took place while the flows were moving. A fuller discussion of these relationships is in preparation.

The fact that olivine crystals settled to a small yet measurable degree through the toothpaste lava indicates a low yield strength for the lava. A yield strength of about 4 N/m^2 is required to prevent a spherical olivine 4 mm in diameter from sinking (Sparks et al. 1977).

Differences between and relationships to proximal-type aa

Aa is a lava type whose surface consists of jumbled and loose rubble overlying coherent lava. We

distinguish here between proximal-type aa and distal-type aa (Fig. 5). Proximal-type aa advances with a rolling caterpillar-track motion commonly at a rate of greater than 1 m/min on low-angle slopes and tends to occur relatively near its vent. The surface rubble consists of scoriaceous fragments (clinkers) with spinose surfaces.

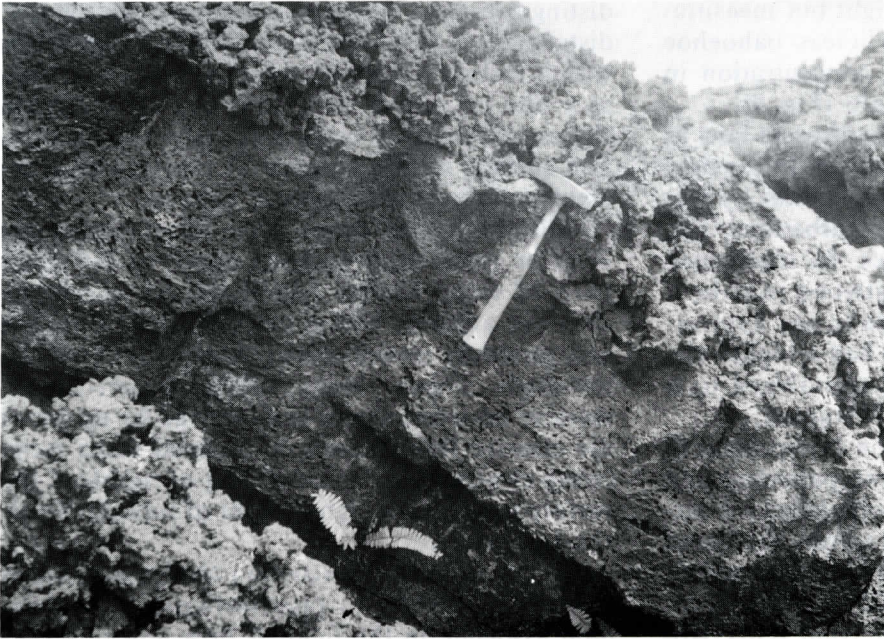
Distal-type aa forms lava lobes commonly 10 m or more thick such as occur in the distal parts of many Mauna Loa flows. Distal-type aa does not advance with a caterpillar-track motion and generally moves slower than 1 m/10 min on low-angle slopes. Many rubble fragments are massive nonscoriaceous lava derived by uprise of the massive flow interior on inclined shear zones (ramp structures). The crumbling of rubble at the surface generates a high content of submillimeter-sized particles.

In the following discussion toothpaste lava is related specifically to proximal-type aa, a common associate in the field. A flow unit of toothpaste lava typically has shear planes along either side (Fig. 3), and rubble litters the surface along or near these planes. The rubble fragments are spinose, and many have a spiral form like the "lava coils" described by Temperly (1966), Peck (1966), and Peterson and Tilling (1980). The shapes and positions of the coils show that they formed by the rotation and tearing of spongy surface lava where it was subjected to a shear torque due to the lateral velocity gradient in the underlying lava.

Such shear zones are a key to how aa lavas form. We envisage that emerging lava rapidly develops a surface skin which, being cooler, is more viscous than the underlying lava (Fig. 6). Skin above a lateral velocity gradient is subjected to a torque because of variable drag exerted on its undersurface. The torque rotates the skin counterclockwise left of the lava median line and clockwise right of the line. Such rotation is possible only if the skin can tear away from adjacent skin. An aa lava is one in which the skin has been torn into fragments due to this torque. The spines of aa clinker are stretched and torn fragments of spongy lava that is unable to coil. An additional factor in the formation of aa is that the underlying lava must be too viscous to rise between the torn-apart fragments and so heal the tears.

The distribution of olivine crystals in proximal-type aa flows at Kapoho and elsewhere in Hawaii is similar to that in toothpaste lava. We interpret that the crystal settling rate and the lava viscosities were about the same.

We also interpret that toothpaste lava emerges



a



b

Fig. 5 a—b. Photographs of sections of proximal-type aa at Kapoho (a) and distal-type aa on coastal plain below Hilina pali, Kilauea (b). Note thinness of clinker cover and lack of internal shear structure within proximal-type aa. In distal-type aa, surface and flow front are covered with large blocks. In b, *arrow* indicates hammer

more slowly from its bocca than does proximal-type aa. A surface skin forms within a short distance of the point of emergence and a small rotation occurs, twisting and coiling some strands of lava. However, the torque is insufficient to tear apart the skin. The rigid crust that characterizes toothpaste lava can thus develop.

Our field observations on toothpaste lava tongues with a crust broken into slabs show that a crust about 5 cm thick had commonly formed

within about 5 m of the bocca. Our measurements on active lava flows of Kilauea show that a crust of this thickness forms in about 30 min. The flow velocity of the toothpaste lava was thus 1 m per 6 min. One of us (G.P.L.W.) measured a flow rate of 1 m per 30 min on toothpaste lava in Heimaey (Iceland) in 1973. One of us (S.K.R.) measured flow rates of 1 m per 25–30 min on a toothpaste lava flow in August 1986 in Kilauea.

We consider toothpaste lava and proximal-

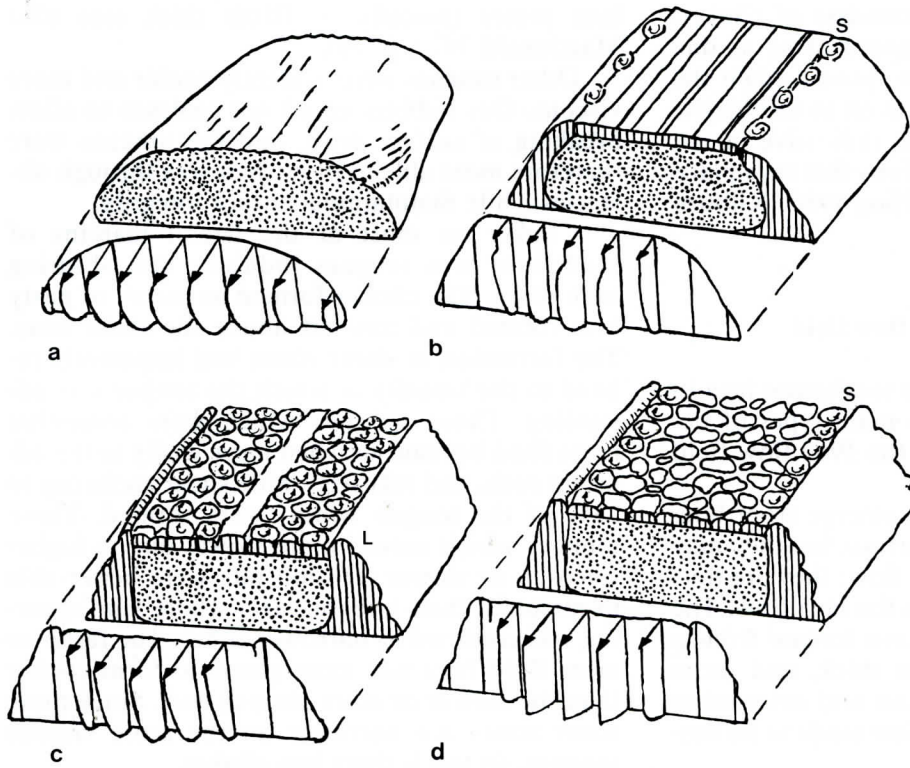


Fig. 6a—d. Schematic block diagrams (not to same scale) of lobes of the four basaltic structural types in Hawaii, showing velocity profiles (arrows proportional in length to flow velocity). **a** pahoehoe, differential flow accommodated by wrinkling or stretching and rapid healing of skin; **b** toothpaste lava, differential flow of rigid crust accommodated by shearing (S) at margins; **c** proximal-type aa, differential flow causes tearing and rotation of portions of skin and also gradual outward movement, eventually to become attached to the levees (L); **d** distal-type aa, plug flow of lava having a yield strength, with loose rubble conveyed on surface, and marginal zones of shearing (S), and rotated rubble

type aa as alternative types that develop from lavas with similar viscosities, since at Kapoho olivines have sunk to similar degrees in both types. The surface of lava emerging rapidly from a bocca tears and generates aa; the surface of lava emerging slowly resists tearing and forms toothpaste lava (Fig. 7).

The relation between lava structure and slope angle is easily observed at Kapoho where an increase in slope occurs (A in Fig. 1). Upslope, the flow field is 90% toothpaste lava and broken crusts of primary lobes. From the top of the 30-m-long steep section, through a second break in slope back to subhorizontal, and all the way to the

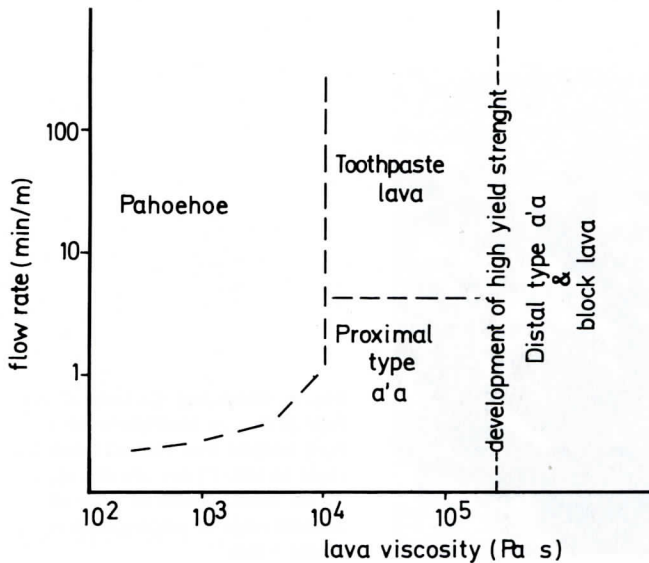


Fig. 7. Semiquantitative diagram showing relation between lava viscosity, flow velocity, and flow type. The reciprocal of flow velocity plotted on vertical axis; velocity therefore decreases upward

sea, 50% of the lava surface consists of clinker. We interpret this increased amount of aa as due to more rapid shearing as lava flowed down the steep slope. The lava did not revert to toothpaste lava where the slope flattened, indicative of the nonreversible structural transitions that take place in lava flows (Peterson and Tilling 1980; Kilburn 1981).

Toothpaste lava in the Kapoho flow field

The above discussion relates to toothpaste lava in general; here we describe two main types of occurrence of toothpaste lava in the 1960 flow field at Kapoho.

Most toothpaste-lava units emerge from boccas on top of an earlier flow surface, but they may also form at the front of a lava flow; they are thus able to both thicken and widen the lava flow. The typical secondary toothpaste-lava tongue from a bocca is 1–3 m wide, 1–2 m thick, and more than 10 m long. The distribution and orientation of these tongues on the main flow tends to be random.

The surface of some toothpaste-lava tongues is broken into imbricately stacked plates (Fig. 8). These plates apparently separated from the underlying lava because of the coalescence of gas bubbles beneath them and became stacked when the tongues encountered an obstacle. The stacks often stand nearly vertical and consist of spiny

lava plates typically 5–10 cm thick (see also Macdonald 1972, p. 79).

Other tongues were evidently cooler and more viscous. Gas bubbles could not coalesce to allow breaking of surface crust, and the tongues were therefore more able to plow their way through obstacles while maintaining surface integrity.

Clinker on most of the lateral margins of toothpaste lava tongues indicates that shearing took place. The clinker formed as pieces of pasty lava rotated and tore off above the shear zone. The formation of shear zones was apparently related to the velocity at which the tongue was advancing. Those tongues which were somewhat more fluid became attached more easily to the adjacent rock, and relatively wide shear zones (up to 25% of the tongue width) were formed. Those tongues which moved more slowly due to higher viscosity or slower effusion rate were better able to maintain their integrity as a whole, and shearing was confined to narrower zones. The faster or more fluid lava was more prone to form clinker than the slower or more viscous lava. Since these shear zones are narrower on the more viscous tongues, so too is there less clinker.

Boccas usually occur tens to thousands of meters away from the vent, and lava issuing from them may have cooled slightly and lost gas. This cooling and gas loss causes a rise in viscosity so that lava from boccas on pahoehoe lava fields is sometimes toothpaste lava. The distal ends of pahoehoe flows are also sometimes toothpaste lava.



Fig. 8. Imbricate stacking of surface plates on toothpaste-lava flow tongue that moved from right to left. Plates are about 10 cm thick. Width of view at bottom edge of photograph is about 5 mm

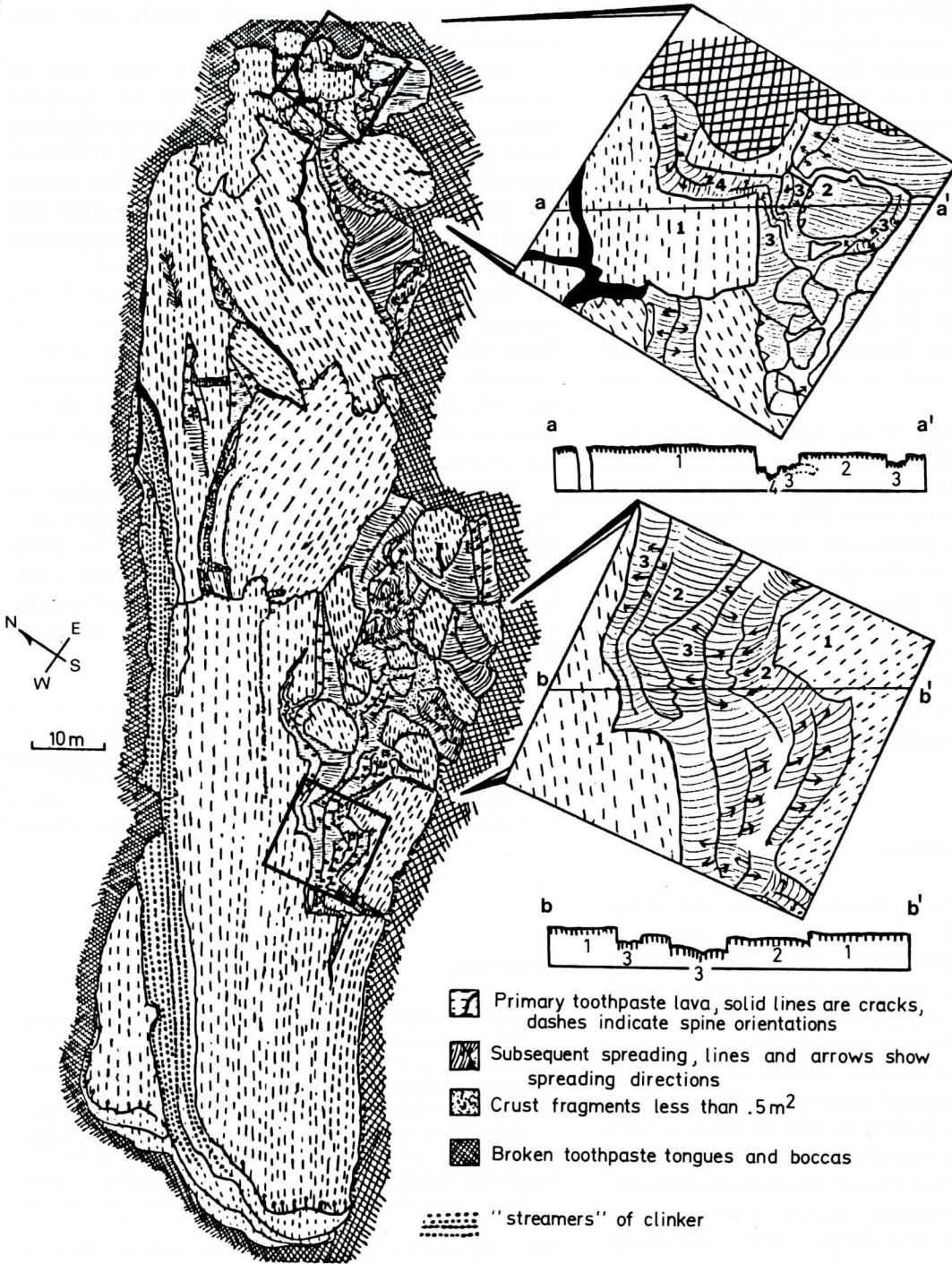


Fig. 9. Map of large primary toothpaste-lava lobe at Kapoho (arrow in Fig. 1). Flow direction is bottom to top. Breakup and spreading of surface crustal plates occurred at many places, as did significant rotation of some plates. *Insets* show spreading in greater detail. *Numbers* on insets and *cross sections* show relative ages of lava surfaces with one being the oldest

This is generally manifested by small flow units that bud from the main body of the flow.

In places at Kapoho the primary flow lobes (as opposed to lava from boccas) consist of toothpaste lava. These lobes are similar in form to the secondary lobes, but are much larger. Figure 9 illustrates characteristics of a primary lobe. A solid crust 10–20 cm thick formed within 10 m of the bocca, preserving on its surface longitudinal grooves and upflow-pointing spines. This crust was relatively rigid and broke into separate plates where movement in the underlying fluid lava diverged, converged, or changed velocity. The plates then diverged, rotated, or became thrust on one another.

New crust formed in the spreading zones between diverging plates. In places this new crust was broken by further spreading, forming third or even fourth generation crust (Fig. 9). By matching outlines of surface plates and noting orientations of surface spines on the new crust, the detailed spreading history of the toothpaste lava can be reconstructed. These histories can be quite complex, and the analogy to plate tectonics is close (Duffield 1972). Neither did the surface plates sink once they fractured, nor did lava ever well up to heal the fractures completely.

Summary and conclusions

Pahoehoe characterizes the most fluid, and aa (or occasionally, block lava) characterizes the most viscous of Hawaiian basaltic lavas. It is tempting therefore simply to correlate flow character with lava viscosity and identify the transition from pahoehoe to aa as the passage of the cooling flow across a viscosity threshold. Toothpaste lava is a recognizable transitional lava type; all gradations are found between pahoehoe and toothpaste lava as well as between toothpaste lava and proximal-type aa. The incorrectness of ignoring flow movement during the viscosity transition was demonstrated by Peterson and Tilling (1980). The recognition of toothpaste lava and study of its characteristics provide further evidence that the lava flow rate was an additional important factor. Slow flowage of moderate to high viscosity lava at one meter per minute to several tens of minutes caused the formation of toothpaste lava which in faster-flowing conditions would have formed aa. We attribute the extensive development of toothpaste lava instead of aa in the 1960 Kapoho flow field to the very low-angle ground slopes (mostly

less than one degree) onto which this flow erupted (Macdonald 1962).

The rheologic condition and slow rate of movement of toothpaste lava can be deduced from a number of features distinctive of this lava type; these features reflect the slow rate of relaxation of the lava when it was deformed. The viscosity correspondence between toothpaste lava and proximal aa is demonstrated by the comparable degree of crystal settling that they exhibit.

The passage from pahoehoe to proximal-type aa might be correlated with the crossing of a rheologic threshold and the acquisition of a yield strength. However, *in situ* crystal settling occurred in both pahoehoe and proximal-type aa at Kapoho so that the yield strength of both types must have been less than 4 N/m².

Our studies demonstrate the feasibility of learning much about the viscosity, rheologic condition, and flow velocity of basaltic lava flows after solidification by an analysis of their structural characteristics and of making at least a semi-quantitative estimate of the numerical values of those parameters.

Acknowledgements. The authors thank Donald Swanson for very helpful reviews of this manuscript, and Michael Sheridan and Michael Malin for reviews of an earlier draft. Research funded by NASA grant no. NAGW-541. Visit by helicopter to the August 1986 eruptive vent of Kilauea made possible by NSF grant no. EAR-8601183. This is Hawaii Institute of Geophysics contribution number 1872.

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Received June 9, 1986/Accepted December 4, 1986