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Channel overflows of the Pōhue Bay flow, Mauna Loa, Hawai'i: examples of the contrast between surface and interior lava

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Abstract A number of overflows from a large lava channel and tube system on the southwest rift zone of Mauna Loa were studied. Initial overflows were very low viscosity gas-rich pāhoehoe evidenced by flow-unit aspect ratios and vesicle sizes and contents. Calculated volumetric flow-rates in the channel range between 80 and 890 m^3/s, and those of the overflows between 35 and 110 m^3/s. After traveling tens to hundreds of meters the tops of these sheet-like overflows were disrupted into a surface composed of clinker and pāhoehoe fragments. After these 'a'ā overflows came to rest, lava from the interiors was able to break out on to the surface as pāhoehoe. The surface structure of a lava flow records the interaction between the differential shear rate (usually correlated with the volumetric flow-rate) and viscosity-induced resistance to flow. However, the interior of a flow, being better insulated, may react differently or record a later set of emplacement conditions. Clefts of toothpaste lava occurring within fields of clinker on proximal-type 'a'ā flows also record different shear rates during different times of flow emplacement. The interplay between viscosity and shear rate determines the final morphological lava type, and although no specific portion of lava ever makes a transition from 'a'ā back to pāhoehoe, parts of a flow can appear to do so.

Key words Channel overflows · Shear rates · Viscosity · Lava types · 'a'ā · pāhoehoe

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Introduction

Channels form in lava flow units of all sizes, including pāhoehoe toes <20 cm wide and 'a'ā lavas a few hundred meters across. Sparks et al. (1976) described the formation mechanism of a number of channel morphologies on Mt Etna; the main requirement for a channel to form is that the margins of a flow or flow unit must lag sufficiently behind the center so that well-defined shear zones are established. Levees are thus mostly cut off from the supply of fresh lava and can start to cool, further accentuating the differences between them and the centrally flowing lava. Overflows due to surges upstream or blockages downstream can build channel levees higher than the thickness of the original flowing lava (Sparks et al. 1976; Wolfe et al. 1988). Across a flow front there is generally little difference in the advance rate, and distinct shear zones are rare or poorly developed. Channels develop behind the flow front. During the 1984 Mauna Loa eruption the initial development of distinct shear zones lagged behind the flow front by about 1 km (Lipman and Banks 1987). The longer lava flows past a point where a channel has formed, the more distinct the channel becomes.

Lava in a well-developed channel is able to flow in a smooth and relatively insulated (except for the top) pathway. It is thus little disturbed until it reaches the distal regions of the flow where the channel is poorly (or not) developed. The commonly observed incandescent surface does indicate that enough disruption exists to prevent the maintenance of a continuous insulating skin. This allows for significant radiative cooling and, in turn, increased viscosity. Near the flow front, rapid shearing of the viscous lava often produces an 'a'ā surface. Many flows therefore have smooth-surfaced channels feeding 'a'ā flow fronts. The smooth-surfaced lava within a channel is neither pāhoehoe nor 'a'ā, and channel overflows illustrate this. When an overflow is slow moving and/or stops shortly after leaving the channel the lava surface is usually pāhoehoe. When an overflow is more rapid (and usually larger) and flows farther from the channel, it often makes the transition to 'a'ā.

The pāhoehoe to 'a'ā transition is non-reversible because the increase in viscosity and loss of gas and heat are (in nature) unidirectional processes (e.g. Wentworth and Macdonald 1953; Peterson and Tilling 1980; Kilburn 1981). Occurrences of isolated patches of pāhoehoe within 'a'ā flows were noted by Macdonald (1953) but not discussed in detail. Greeley (1971) suggested that pāhoehoe lava could occupy pre-existing tubes, flow underground for a while and re-emerge downslope, perhaps within an 'a'ā flow. During an eruption, pāhoehoe and 'a'ā flows may be simultaneously active within a flow field, and can form complicated patterns of kīpukas within each other (e.g. Holcomb 1976; Swanson 1973). We became particularly interested in locations within the Pōhue Bay flow where we could identify relatively low-viscosity lava (pāhoehoe or toothpaste lava) that had issued directly from within 'a'ā flows; they were not merely kīpukas. Additionally, at the flow front of the nearby Halepōhāhā flow (which is mostly 'a'ā), pāhoehoe flow units have issued out of the flow front. Very similar occurrences have been described on Mt Etna (Pinkerton and Sparks 1976; Chester et al. 1985). Indeed, Pinkerton and Sparks (1976) suggest that on Mt Etna the breaking out of fluid lava from the front of a stagnated or nearly stagnated flow is a common mechanism of flow advancement. The occurrences in Hawai'i described here are a result of the strong contrast between the interior and surface of a flow. We will attempt to describe these examples in the context of previous explanations of the pāhoehoe to 'a'ā transition (e.g. Peterson and Tilling 1980; Kilburn 1981).

This paper first describes high volumetric flow-rate channel overflows as a source of lava that can undergo and record numerous flow processes. We present the histories of some hypothetical lava elements as they are emplaced to form a complex flow of both 'a'ā and pāhoehoe. Elsewhere in Hawai'i, occurrences of toothpaste lava within 'a'ā flows record low volumetric flow-rates in otherwise high volumetric flow-rate 'a'ā flows, and also highlight the differences between the surfaces and interiors of flows.

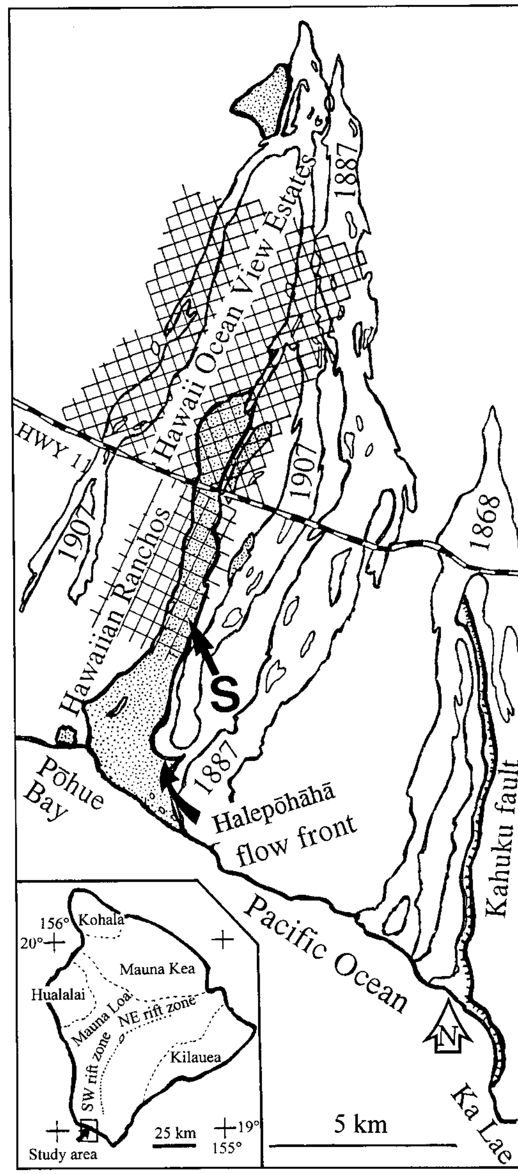


Fig. 1 Location map showing the Pōhue Bay flow (stippled) and its relationship with the lower south-western rift zone of Mauna Loa (traced from Lipman and Swenson 1984). Arrow (S) shows study area illustrated in Fig. 2. On the inset map Mauna Loa rift zones are dotted, and volcano boundaries are dashed

Channel overflows

The Pōhue Bay flow, on the western flank of Mauna Loa's south-west rift zone (Fig. 1), has an estimated age of 740–910 years (based on surface weathering characteristics; Lipman and Swenson 1984). Paleomagnetic work using a comparison with the paleosecular variation curve of Holcomb et al. (1986), however, indicates an age closer to 1300 years (Jurado-Chichay et al. 1995). The Pōhue Bay flow can be followed from the coastline up to an elevation of 920 m; between there and its vent area (located further upslope) it has been buried by younger lavas. The Pōhue Bay flow consists of both 'a'ā and pāhoehoe. We have focused most of our study on overflows of 'a'ā and pāhoehoe from a very large channel/tube system located along the south-eastern margin of the flow (Figs. 1 and 2).

Channel and tube system

The channel/tube system can be traced between the elevations of 100 and 400 m. Skylights into the tube range from 30 by 30 to 75 by 600 m, with the long dimension always parallel to the flow direction. The largest sky-

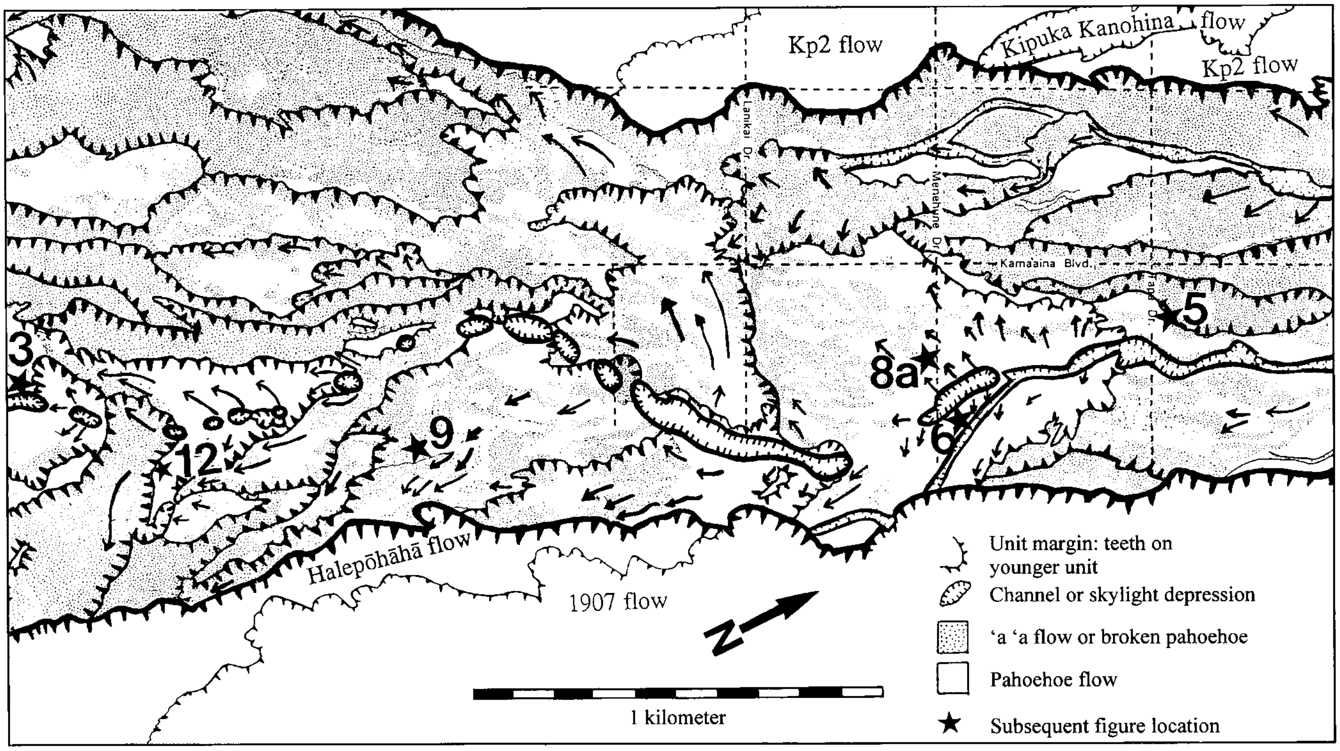


Fig. 2 Detailed map (drawn from aerial photographs) of the 100–400 m elevation section of the Pōhue Bay flow. Arrows indicate flow directions, and those that lead directly from the channel or skylights (hatchured) comprise the overflows discussed in the text. The 1907, Halepōhāhā, and Kīpuka Kanohina flows are all 'a'ā, and the Kp2 flow is pāhoehoe. Numbered stars indicate locations of subsequent figures

lights (Figs. 2 and 3) are up to 25 m deep, although the tube diameter is usually <10 m. In the upper part of the study area the structure is a simple channel without roofed segments. The inner walls of the channel/tube system consist of numerous flows, most of which are vesicular pāhoehoe less than a meter thick. In many locations the walls have a veneer of lava that was deposited during drainback following overflow events. Much of the floor of this channel/tube system is occupied by an olivine-rich 'a'ā flow that obscures the true channel depth. The paleomagnetic data of Jurado-Chichay et al. (1995) suggest that this 'a'ā flow is perhaps 1000 years younger than the Pōhue Bay flow, and that it utilized the pre-existing pathway provided by the large channel/tube system.

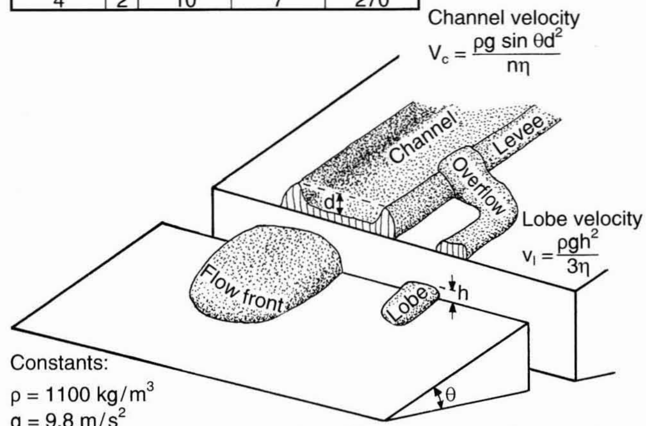
We have used Jeffrey's formula (e.g. Johnson 1970; Fink and Zimbelman 1990) to calculate first-order approximations of flow velocities, both in the channel and of the overflows (Fig. 4). The values input to the formula are considered approximate and conservative (i.e. the channel flowing at three-quarters of its present depth) and because channel dimensions vary along the flow, we present calculations for more than one location. The tubed sections place a limit on the cross-sectional area of lava that could have been flowing within the channel/tube system. Assuming a 5 m tube radius, the maximum flowing cross-section will be about 80 m^2. Combined with channel widths (w) measured from aerial photos, the flow depth (d) is thus limited so that $wd \leq 80$ m^2. The calculations yield velocities in the channel between 1 and 12 m/s, with corresponding volumetric flow-rates between 80 and 890 m^3/s. A different form of Jeffrey's formula allows the calculation of flow velocities for non-channelized lavas (i.e. the overflows). If the overflows were 1 m thick initially, they overflowed at 3.6 m/s, with volumetric flow-rates between 36 and 108 m^3/s, again with conservative values (i.e. the overflow width was about two-thirds of its present width when it first left the channel). The average volumetric flow-rate for all Mauna Loa lava flows is around 100 m^3/s, and for those that were channelized it is around 150 m^3/s (data of Rowland and Walker 1990), meaning that the volumetric flow-rates of both the main Pōhue Bay flow channel and its overflows were high compared with historical eruptions.

The overflows

The flow field consists almost entirely of overflows from the channel/tube system and many can be traced back to specific skylights or sections of channel (Fig. 2). The overflows are up to 50 m wide and 750 m long, and formed when surges or blockages caused the level of lava flowing in the channel/tube system to overtop the levees. At their origins (the channel edge) most of these overflows consist of thin (10–20 cm) sheet-like flow units of very smooth and highly vesicular pāhoe-

Fig. 3 Photograph looking across a large skylight of the channel/tube system (view is upflow). Note the strand line approximately halfway between the bottom and the rim. Below this strand line the channel/tube is veneered by a thin layer of lava indicating a late flow level; above this line are drain-back structures. Note also that the cross-sectional area of the tubed portion is much smaller than that of the open portion (see text). Arrow indicates authors for scale (photo by G. P. L. Walker)

Depth (m)	n	Width (m)	V_c (m/s)	Q (m^3/s)
4	2	20	7	540
3	2	20	4	230
1.8	2	45	1	110
7.5	4	10	12	890
4	4	6	3	80
6	4	8	8	365
4	2	10	7	270



Constants:
$\rho = 1100$ kg/m^3
$g = 9.8$ m/s^2
$\theta = 4.5°$
$\eta = 1000$ Pa-s
n = 4 for near-equant channels, 2 for wide channels

h (m)	Width (m)	v_l (m/s)	Q (m^3/s)
1	30	3.6	108
1	20	3.6	72
1	10	3.6	36

Fig. 4 Diagram to illustrate variables and dimensions (not to scale) used to calculate velocities and volumetric flow-rates (after Wadge and Lopes 1991). Density used is that calculated for the solidified overflows (see text) and viscosity is a general value for Hawaiian pāhoehoe (Rowland and Walker 1988). Results presented in boxes

hoe (Fig. 5). Much of the surface has today broken along numerous cooling joints to form 'prisms' 5–10 cm^2 in area and 5–10 cm deep (Fig. 6). Vesicles in the top and bottom few centimeters of the near-channel parts of the overflows are spherical and have a uniform diameter of around 0.5–1 mm. The average vesicle diameter increases inward; these flows are spongy pāhoehoe (Walker 1989), meaning that the vesicles are primary. Measurements of 55 samples of the top few centimeters of these lavas (collected along a 2 km length of channel) yield an average density of 1.1 g/cm^3 (Fig. 7). A non-vesicular Pōhue Bay flow sample (collected near the coast) has a density of 3.4 g/cm^3, giving the overflows a vesicularity of 68%.

In Hawai'i, the aspect ratios (thickness:width) of pāhoehoe flow units typically vary between 1:3 and 1:10 and decrease with flow unit cross-sectional area (G. P. L. Walker, personal communications). Measured aspect ratios of the Pōhue Bay overflows are as small as 1:45 (Fig. 8A). The overflows described here differ in an additional way from most tube-fed pāhoehoe flow fields in that they are generally not subdivided into numerous flow units (Fig. 8B; Nichols 1936; Walker 1972).

One pāhoehoe overflow was examined in detail where it is exposed in a road-cut (Fig. 8A). This overflow is 22 m wide and has an average thickness of about 50 cm. The outcrop is approximately perpendicular to the flow direction and is located about 50 m from the edge of the channel from which the overflow issued. This lava has a flat upper surface and an irregular bottom (where it flowed into pre-existing cracks and depressions). Both of these surfaces indicate a low viscosity at the time of emplacement; upper surface irregularities that may have formed could not be maintained or supported, and the lava showed a strong tendency to fill in even narrow depressions over which it flowed.

Transitions to 'a'ā and later pāhoehoe outbreaks

At various distances from their source at the channel, many of the overflows lost their pāhoehoe character. They formed 'a'ā flows 1–3 m thick, some with surfaces consisting almost entirely of broken and jumbled pāhoehoe fragments and others with surfaces of true clinker. The transition occurred because the lava con-

Fig. 5 Numerous sheet-like overflows from the channel/tube system exposed in a road-cut perpendicular to the direction of flow

Fig. 6 Closely spaced cooling joints in the surface of a sheet-like overflow. Note the absence of ropy structures. In the dark area at the lower right, the top 1–2 cm have spalled off

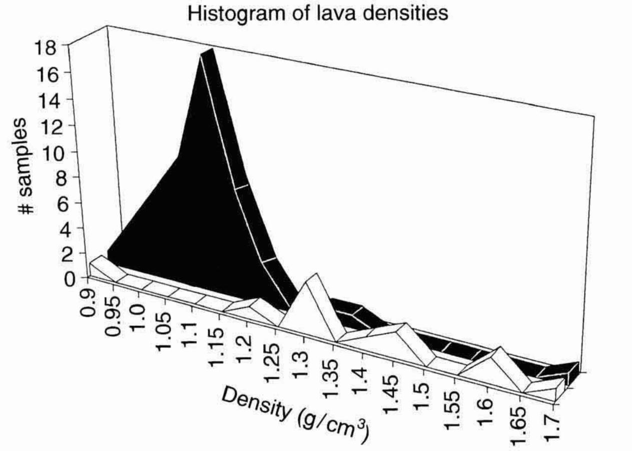


Fig. 7 Density histograms of initial pāhoehoe overflows (filled) and secondary pāhoehoe toes (unfilled). Densities were determined by sawing rectilinear blocks, measuring their dimensions and weighing them on a laboratory balance

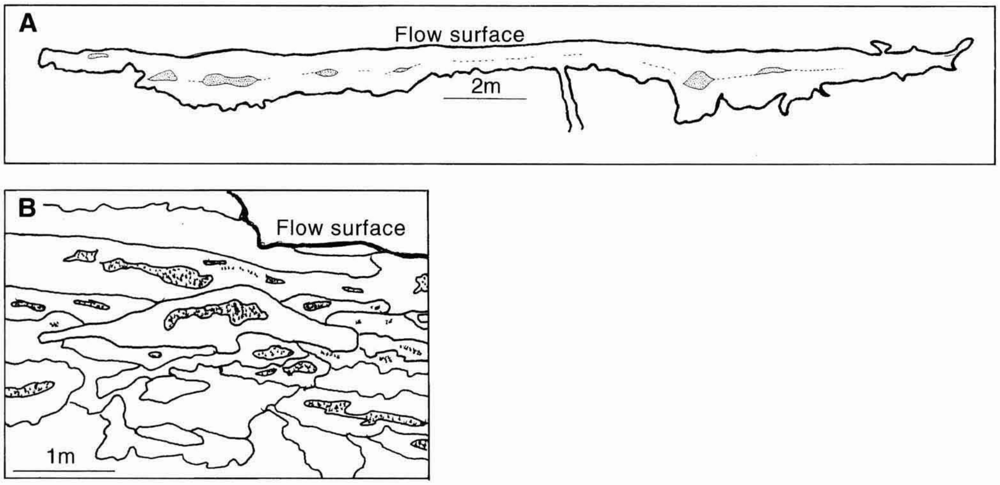


Fig. 8A Road-cut perpendicular to a Pōhue Bay flow pāhoehoe overflow (viewed up-flow) 200 m from the eastern end of Menehune Dr. (see Fig. 2). **B** Road-cut through a tube-fed pāhoehoe on Kīlauea. Note the differences in the sizes and number of flow units in these road-cuts (scale in **B** is twice that in **A**). Stipple indicates void space. In **A** voids are gas blisters; in **B** they are drained single flow-unit tubes

Fig. 9 Photograph of pāhoehoe that issued out of an 'a'ā overflow. Note hammer (arrow) for scale

tinued to be strongly sheared after its outer skin could no longer deform plastically (Peterson and Tilling 1980). The formation of clinker is also an indication that the lava immediately under the surface cooled to the point that its viscosity did not allow it to well up and heal ruptures in the surface skin. These unhealed ruptures allowed further heat loss and the transition to 'a'ā was inevitable.

The carapace of broken pāhoehoe fragments and clinkers would be classified as 'a'ā. However, this did not necessarily express the nature of the interior lava because after some of the overflows came to rest, the lava in the interiors welled out as pāhoehoe (Figs. 9 and 10). This 'second generation' pāhoehoe is characterized by much larger and less uniform-sized vesicles than the original overflows as well as a tendency to subdivide into toes, which is more common for pāhoehoe lava (e.g. Nichols 1936; Walker 1972; Macdonald et al. 1983). Twelve samples of these toes yield a mean density of 1.3 g/cm^3 (Fig. 7), 18% higher than that of the original overflow samples, and corresponding to a vesicularity of 61%. The subdivision into numerous flow units suggests that the interior lava broke out onto the surface at a much lower volumetric flow-rate than the initial overflow.

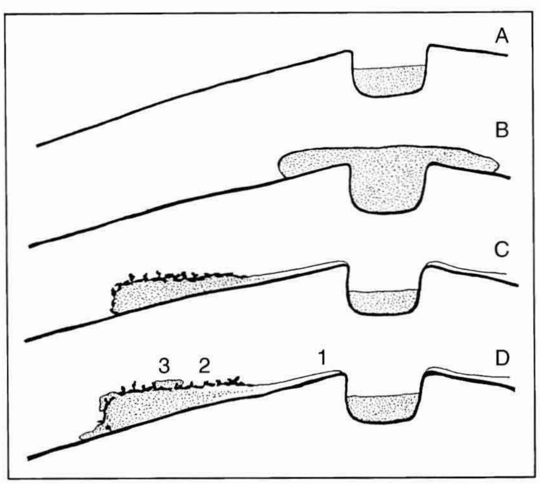


Fig. 10 Diagrams to show a channel overflow making the transition from pāhoehoe to 'a'ā and then producing pāhoehoe from its interior. Stipple indicates fluid lava, and numbers show the final positions of hypothetical elements 1, 2 and 3 (see text and Fig. 11)

At the Pōhue Bay flow there are many of these overflows that started out as pāhoehoe, made the transition to 'a'ā and then produced pāhoehoe from their interiors. We consider that if a flow has a clinker carapace it is 'a'ā, even though it possesses an interior capable of producing pāhoehoe. This is because the clinker surface usually records rapid and vigorous flow, activity that in Hawai'i is characteristic of 'a'ā (Rowland and Walker 1990).

A similar occurrence of pāhoehoe issuing from an 'a'ā surface can be found at the front of the Halepōhāhā flow (Fig. 1). This flow front is 1–2 m thick and consists of both clinkers and broken pāhoehoe fragments. Pāhoehoe flow units have issued from the flow front and are 2–5 m long. The pāhoehoe outbreaks from the interior were not overrun by the main flow of 'a'ā and therefore took place after the flow as a whole had come to rest. This is a similar situation to the development of boccas at the fronts of stagnated flows described by Pinkerton and Sparks (1976). Rather than a mechanism of flow advancement, however, the Halepōhāhā example appears to have been a late-stage event.

In the examples above, no single volume of lava makes the transition from pāhoehoe to 'a'ā and then back to pāhoehoe; however, an occasional overflow as a whole might (mistakenly) give the appearance that it has. To illustrate this we next follow the histories of

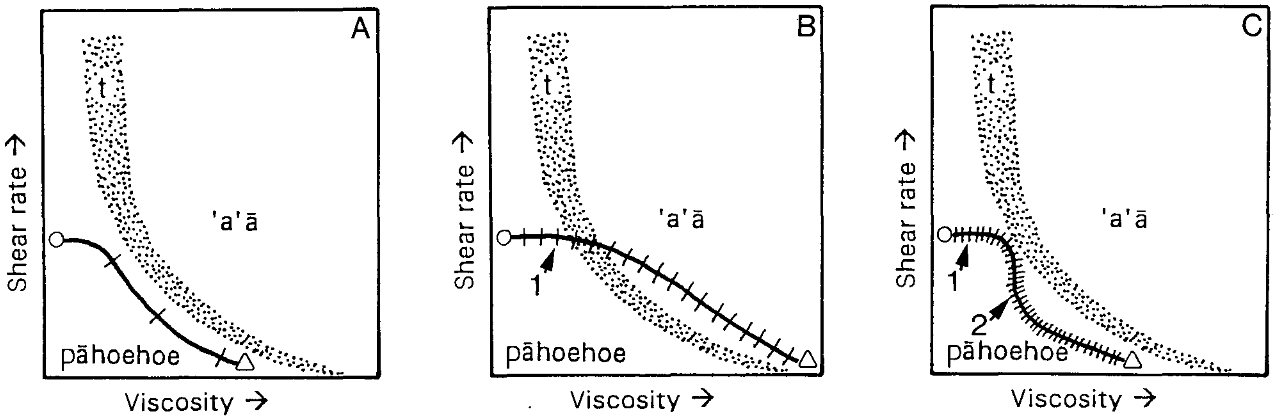


Fig. 11A–C Qualitative graphs (after Peterson and Tilling 1980; Kilburn 1981) to show the viscosity and shear rate paths of different elements of an overflow. Fields of pāhoehoe and 'a'ā are shown, as well as the irreversible transitional boundary between them (stippled, t). Each lava element leaves the channel (simultaneously) at the circle and solidifies at a triangle. The hatchmarks represent arbitrary units of time and have equal values in **A**, **B** and **C**. **A** Element 1 flows for only a short time and comes to rest before it gains a high viscosity. **B** Element 2 flows at a high shear rate beyond the point at which it has cooled to a high viscosity, and becomes 'a'ā. It then slows to a stop and cools as 'a'ā. Arrow indicates 'time' at which element 1 stopped flowing. **C** Element 3 flows for an even longer period of time, but by being in the flow interior it maintains a low viscosity. When the shear rate eventually drops and element 3 oozes to the surface it forms pāhoehoe. Arrows indicate 'times' at which elements 1 and 2 stopped flowing

three separate elements of lava within an overflow (Figs. 10 and 11). Figure 11 (after Peterson and Tilling 1980; Kilburn 1981) shows qualitatively the co-variation in viscosity and shear rate of these elements and helps to illustrate their separate evolutions. The first element represents lava that formed the smooth-surfaced overflow near the edge of the channel. It was initially moving rapidly, but soon stopped. It cooled through high viscosities while stagnant and thus retained its pāhoehoe character as it solidified (e.g. Peterson and Tilling 1980).

The second element of lava is one that became part of the skin of the overflow after the lava had traveled a few tens of meters away from the channel. This lava element cooled rapidly during this movement, especially once it became part of the surface. Because the overflow continued to advance after the second element had lost the ability to deform easily, the element broke apart to form an 'a'ā surface of pāhoehoe fragments and clinkers; unlike the first element it was disturbed after it had cooled through higher viscosities.

The third element of lava is one that remained in the interior of the overflow until the initial movement away from the channel stopped. It underwent some gas loss, but only minimal cooling during the trip. Once the overflow lost its initial momentum, the still-fluid interior allowed it to spread under its own weight. Any lava that broke to the surface during this slower movement (such as the third example element) still had a relatively low viscosity and formed pāhoehoe. When element 3 finally began cooling through higher viscosities it was either flowing slowly or stationary. This scenario attempts to portray the significant differences (at different times) between the conditions on the surface and in the interior of an active lava flow. It retains the irreversible nature of the pāhoehoe to 'a'ā transition for any particular element of lava (e.g. Kilburn 1981). It allows, however, for pāhoehoe lava to emerge from a flow with an 'a'ā carapace.

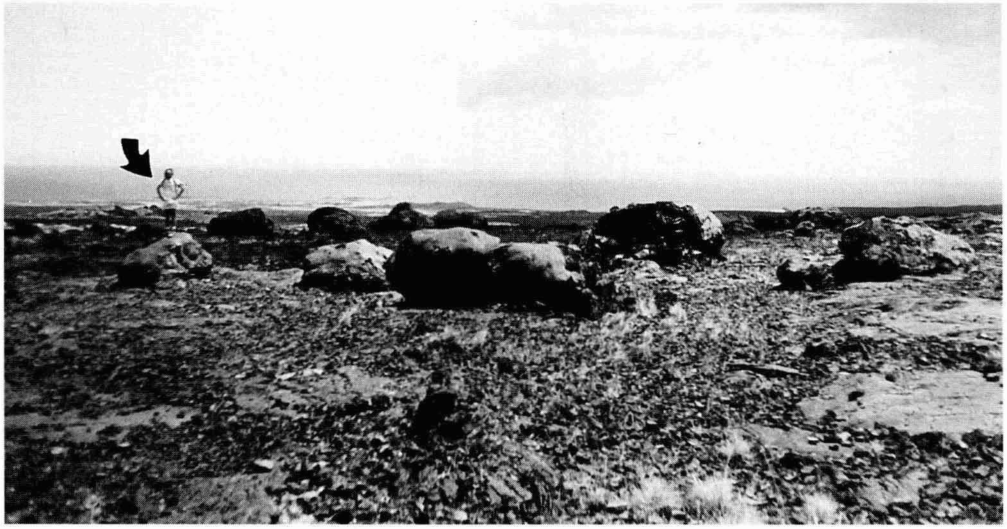
Layered lava balls

Another aspect of the Pōhue Bay flow channel/tube system is the large number of layered lava balls that the overflows were capable of carrying. Some of the layered lava balls are up to 2.5 m in diameter (Fig. 12). Such layered lava balls are commonly found on channel levees in Hawai'i. They form when large fragments of vent structure, channel wall or tube roof fall into the flowing lava (Fig. 13). As they are carried along the fragments roll and tumble in the lava stream and accrete layers of lava about 10 cm in thickness. Their mode of travel down a channel ranges from being rolled along in shallow lava to being floated by deeper flows (D. Peterson personal communication 1993). They are able to (barely) float because the internal cavities and spaces between layers provide enough void space for a slight positive buoyancy. Overflows may then wash these lava balls out of the channel or tube. The resulting structures are rounded, concentrically layered lava balls draped with a layer of the overflow lava. Most of them are deposited within 100 m of the channel edge.

Toothpaste lava and cleft structures

Clefts and patches of toothpaste lava (similar to crease structures; Anderson and Fink 1992) can often be found within large 'a'ā flows and are additional evidence of a strong contrast between the natures of, and

Fig. 12 Layered lava balls about 50 m from their source channel. Note figure (arrow) for scale



the processes that affect, surface and interior lava. Toothpaste lava is considered to be lava with the viscosity of proximal type 'a'ā, but which has not undergone the sufficient disruption and cooling necessary to form clinkers (Rowland and Walker 1987). Cleft-like structures of toothpaste lava provide a glimpse of the lava that makes up the interior of a proximal type 'a'ā flow. These structures can be either sequeeze-ups with axial clefts or pull-apart features, and they form in a flow after its initial emplacement (Nichols 1938). The clefts can be 1–2 m deep with surfaces that are either steeply or gently dipping into their axes. The spines that occur on the surface of the toothpaste lava in a cleft are always perpendicular to the long axis of the cleft, are formed as pasty lava is pulled apart during spreading, and are thus indicators of the direction of opening. Relative to the overall flow direction, this spreading direction varies depending on where the cleft develops within the flow. Those near flow margins tend to be parallel to the margins because secondary flowage here is dominated by lateral spreading. In more medial positions, secondary flowage is usually in the downhill direction so that the clefts develop with their long axes perpendicular to the main flow axis (Fig. 14).

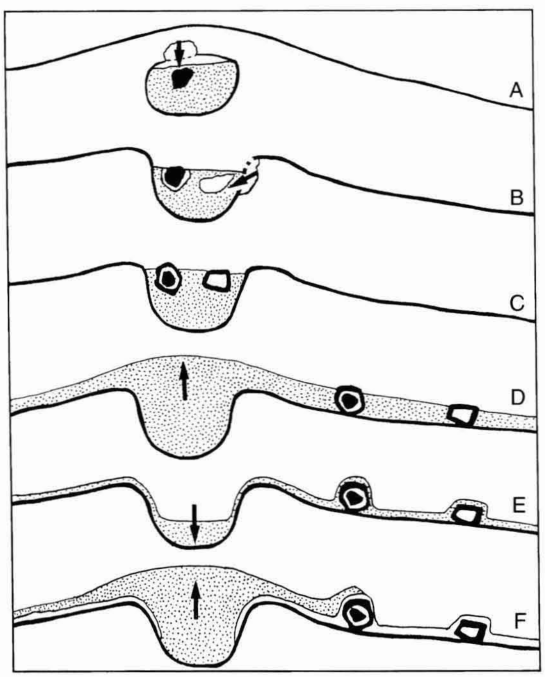


Fig. 13 Formation of a layered lava ball. Stipple indicates flowing lava. In **A,** a piece of tube roof falls in, and in **B,** a part of a levee falls in. Both fragments accrete layers of lava as they are carried downstream (step **C**), and washed out (step **D**). In step **E**, most of the overflow has drained away leaving a thin coating of lava on the now stranded lava balls. In **F**, a second overflow laps against the uphill side

Conclusions

The Pōhue Bay flow illustrates a number of interesting characteristics that provide insight to some of the processes taking place within flowing lava. In Hawai'i, pāhoehoe lava can in general be found in three locations: (1) near vents; (2) forming tube-fed flows; and (3) forming channel levees in flows that are otherwise mostly 'a'ā. Near-vent pāhoehoe contains a large proportion of gas bubbles which separate out to form shelly pāhoehoe (e.g. Swanson 1973). Tube-fed pāhoehoe is usually erupted at low volumetric flow-rates (Rowland and Walker 1990), and only sometimes, for example when encountering a steeper slope or after storage in a pocket within the flow field (Peterson and Tilling 1980), does it make the transition to 'a'ā.

Pāhoehoe overflows associated with lava channels are common on the Pōhue Bay flow. We have described some overflows from a large channel/tube system in the Pōhue Bay flow, and by measuring channel dimensions determined that the lava may have been flowing at relatively high volumetric flow-rates. The channel overflows left a smooth vesicle-rich surface at their point of origin where they over-topped the levee. Many of them continued to move far enough and fast enough so that they developed 'a'ā surfaces. Some

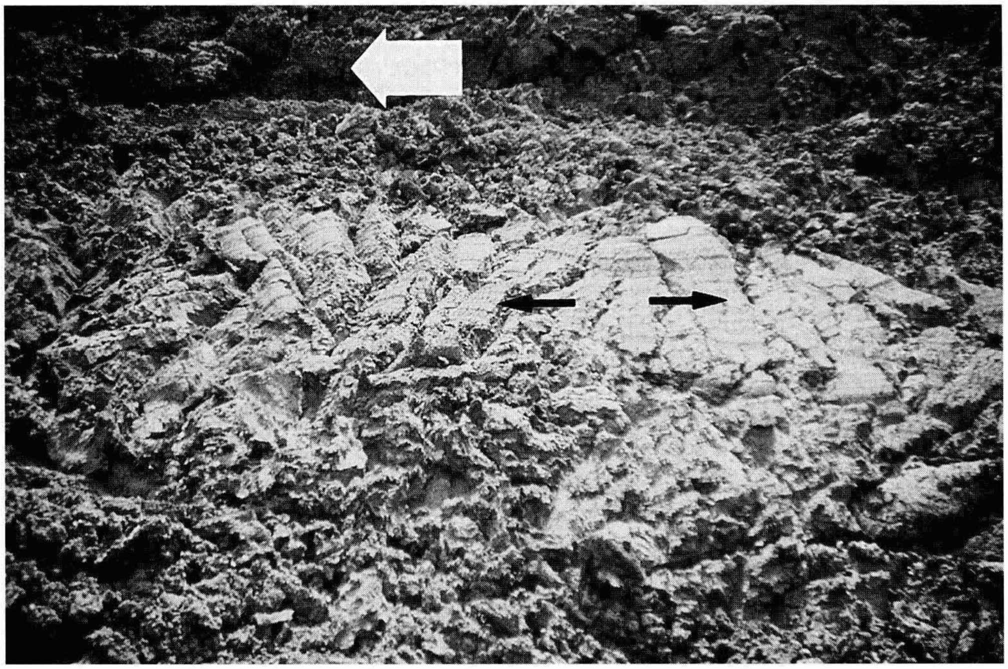


Fig. 14 Photograph of a tothpaste lava cleft within the 1984 Mauna Loa 'a'ā flow. The small arrows show the opening direction of the clefts and the large arrow indicates the overall flow direction. Width of base of photo ~2 m

overflows retained a fluid interior that could escape to the surface as pāhoehoe after the overflow lost its initial momentum.

By reconstructing the histories of overflows from this channel/tube system, we have been able to illustrate the strong contrast between the nature of surface and interior lava within a moving flow. These overflows also provide excellent examples of how the interplay between viscosity and differential shear rate determines lava surface structure: when an overflow that has developed an 'a'ā surface slows and its shear rate drops, the interior lava can escape as pāhoehoe if it has not yet gained a high viscosity. Toothpaste clefts within 'a'ā flows also illustrate the interior/exterior contrast and the shear rate/viscosity interplay. Although examples such as these are not particularly common in Hawai'i, their importance lies in their ability to have previous pāhoehoe to 'a'ā transition models applied to them to semi-quantitatively illustrate the interplay between viscosity and shear rate within a single flow lobe. Although it is useful to classify flows as pāhoehoe or 'a'ā because in most cases this provides information about the volumetric flow-rate and nature of the eruption, it is important to keep in mind that the nature of the surface does not necessarily indicate the nature of the interior lava.

The Pōhue Bay flow and its channel overflows are examples of a very high volumetric flow-rate lava. The highest recorded volumetric flow-rate of a Mauna Loa flow was the 1950 Ho'okena 'a'ā flow (1044 m^3/s), and it had a measured flow-front velocity of about 2.5 m/s (almost 10 km/hour; Rowland and Walker 1990). Calculations based on the dimensions of the Pōhue Bay flow yield volumetric flow-rates in the channel similar to that of the Ho'okena flow, however, much of the coastal part of the Pōhue Bay flow is pāhoehoe. Thus merely mapping 'a'ā versus pāhoehoe may not always give an accurate assessment of volcanic hazard.

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