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Pahoehoe and aa in Hawaii: volumetric flow rate controls the lava structure

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Abstract. The historical records of Kilauea and Mauna Loa volcanoes reveal that the rough-surfaced variety of basalt lava called aa forms when lava flows at a high volumetric rate (>5-$10\ m^3/s$), and the smooth-surfaced variety called pahoehoe forms at a low volumetric rate (<5-$10\ m^3/s$). This relationship is well illustrated by the 1983-1990 and 1969-1974 eruptions of Kilauea and the recent eruptions of Mauna Loa. It is also illustrated by the eruptions that produced the remarkable paired flows of Mauna Loa, in which aa formed during an initial short period of high discharge rate (associated with high fountaining) and was followed by the eruption of pahoehoe over a sustained period at a low discharge rate (with little or no fountaining). The finest examples of paired lava flows are those of 1859 and 1880-1881. We attribute aa formation to rapid and concentrated flow in open channels. There, rapid heat loss causes an increase in viscosity to a threshold value (that varies depending on the actual flow velocity) at which, when surface crust is torn by differential flow, the underlying lava is unable to move sufficiently fast to heal the tear. We attribute pahoehoe formation to the flowage of lava at a low volumetric rate, commonly in tubes that minimize heat loss. Flow units of pahoehoe are small (usually <1 m thick), move slowly, develop a chilled skin, and become virtually static before the viscosity has risen to the threshold value. We infer that the high-discharge-rate eruptions that generate aa flows result from the rapid emptying of major or subsidiary magma chambers. Rapid near-surface vesiculation of gas-rich magma leads to eruptions with high discharge rates, high lava fountains, and fast-moving channelized flows. We also infer that long periods of sustained flow at a low discharge rate, which favor pahoehoe, result from the development of a free and unimpeded pathway from the deep plumbing system of the volcano and the separation of gases from the magma before eruption. Achievement of this condition requires one or more episodes of rapid magma excursion through the rift zone to establish a stable magma pathway.

Introduction

Hawaiian basalt flows form two main and very distinctive morphologic types, namely aa and pahoehoe. Dutton (1884) and Emerson (1926) were among the first to describe their characteristics (see also Macdonald 1953). Although transitional forms exist (Macdonald 1953; Peterson and Tilling 1980; Rowland and Walker 1987) and some flows consist of block lava, probably 90% of Hawaiian basaltic lava flows fit into either the aa or pahoehoe categories. Both morphologic types are also widely recognized on basaltic volcanoes outside Hawaii.

Aa and pahoehoe are distinguished by their different surface structures: aa has a very rough surface composed of often loose clinkers and rubble, whereas pahoehoe has a smooth surface. The two types have equally distinct internal structures, chief among which are the strong subdivision of pahoehoe into many small flow units (Nichols 1936; Walker 1971), and in pahoehoe the abundance of lava tubes.

The striking structural differences between aa and pahoehoe are not the result of systematic differences in the chemistry of the rocks (Macdonald 1972; Macdonald et al. 1983) or in eruptive temperatures, but are related to surface processes of flow dynamics. More than one explanation has been given for why some lava flows, or parts of some lava flows, are aa and others pahoehoe (e.g., Emerson 1926; Macdonald 1953; Pinkerton and Sparks 1976; Sparks and Pinkerton 1978; Peterson and Tilling 1980). The proposed main controls are lava viscosity, shear rate, volumetric flow rate, and changes accompanying degassing.

In this paper we demonstrate from the historical records of Kilauea and Mauna Loa (Fig. 1) that the type of flow is closely correlated with the volumetric flow rate (usually determined by - though not necessarily the same as - the volumetric discharge rate from the vent) in any given lava flow. We are particularly impressed by the clarity of the evidence from the ongoing 1983-1990 eruption of Kilauea and from the less well documented but very striking paired lava flows (such as

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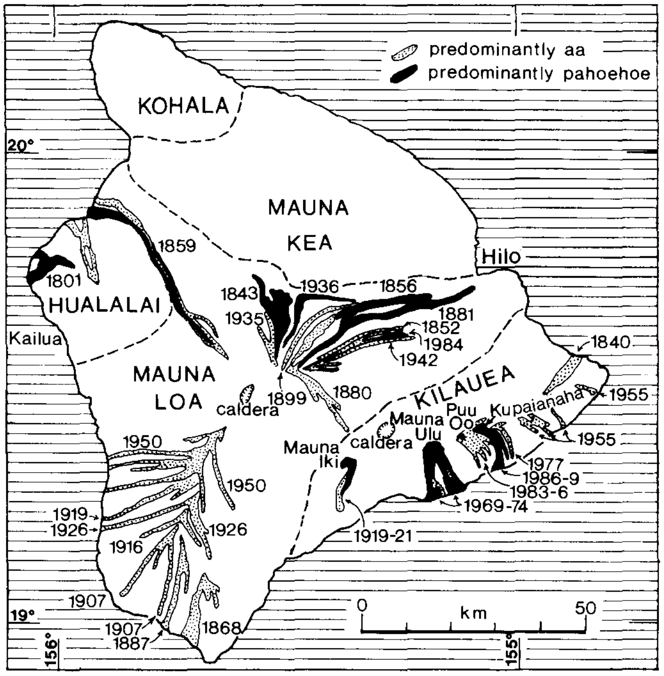

Fig. 1. Map of the island of Hawaii showing flows and locations mentioned in text. *Dashed lines* are volcano boundaries

those erupted from Mauna Loa in 1859 and 1880–1881) that consist of an earlier aa member and a later pahoehoe member. We propose a dynamic explanation in which, at a given volumetric flow rate, the significance of flow conditions and viscosity in generating the distinct structural types can be assessed.

A number of clarifications should be made: (1) Unless otherwise stated, flow velocity refers to flow-front velocity. (2) In most cases, instantaneous flow velocities were not measured, and average velocities (flow length divided by eruption duration) are used and identified as such. (3) All volumetric flow rates are average values (flow volume divided by eruption duration). (4) This study was concerned with lava flows that travelled considerable distances, therefore those flows confined to calderas and pit craters are not discussed.

Correlation of structural type with volumetric flow rate

Here we collate and discuss the data, drawn from the records of historical eruptions (Table 1), from which we correlate the lava structural type with volumetric flow rate. First we discuss the well-documented data from Kilauea and Mauna Loa volcanoes, and then we describe the several remarkable paired lava flows of Mauna Loa which, although less well documented, clearly show the correlation of lava type with flow rate.

Kilauea

The Puu Oo and Kupaianaha eruptions of Kilauea. The eruption of Kilauea volcano that began in January 1983 was initially from an 8-km-long, discontinuous fissure on the east rift zone (Wolfe et al. 1987). By June 1983 the episodic eruption became concentrated at one vent where, in the 37 months until mid-July 1986, the scoria/spatter cone of Puu Oo (Fig. 2) grew to a height of ~250 m. The 37-month period was marked by 44 eruptive episodes at Puu Oo; each episode consisted of vigorous fountaining (heights approached 500 m; Wolfe et al. 1987; Heliker et al. 1987) and the outpouring of fast-moving lava flows. Most of the episodes lasted less than 24 hours and were separated by repose periods lasting ~3 weeks during which Kilauea's summit inflated (Wolfe et al. 1987), the east rift near Puu Oo widened (Hoffmann et al., in press), and the column of magma in the Puu Oo conduit slowly rose to the surface (Wolfe 1988, p. 39). The timing of these episodes and the average discharge rate during each are plotted in Fig. 3. Average discharges ranged from 20 to 380 m^3/s; in most episodes one or two main lava flows were generated, and average volumetric flow rates of these flows were therefore probably not less than 10–150 m^3/s. Rates of advance of the flows ranged from 50 to 500 m/h. Practically the entire lava output was aa; the flow of episode 35B was, however, pahoehoe. Episode 35B was anomalous in that shortly after a typical high-fountaining episode (35A), lava flowed out quietly and continuously from a fissure near Puu Oo for 16 days at an average discharge of 3.4 m^3/s (Heliker et al. 1985). A small lava shield formed against the base of Puu Oo during this activity.

In mid-July 1986, eruption of lava from Puu Oo ceased, and effusion began from Kupaianaha (originally referred to as the C-vent; Ulrich et al. 1987), 3 km downrift from Puu Oo and just south of one of the vents on the original fissure of January 1983. Since mid-July 1986, effusion has been continuous from Kupaianaha at an estimated discharge of about 5 m^3/s (U. S. Geological Survey monthly report for December 1986, courtesy of George Ulrich).

This sustained activity has lacked significant fountaining and has built an extensive lava shield and flow field that we estimate to be about 90% pahoehoe. Pahoehoe flows have reached the ocean several times as of this writing (April 1990), and their flow fronts advanced 11 km from the vent to the coast at an average velocity of 4–8 m/h.

In summary, each of the 44 high-fountaining episodes from 1983 to 1986 produced predominantly aa lavas at high volumetric flow rates of >10 m^3/s. In contrast, the two prolonged periods of steady and quiet effusion at a low discharge of 3.4–5 m^3/s generated predominantly pahoehoe lava. A threshold volumetric flow rate between 5 and 10 m^3/s separated aa formation form pahoehoe formation.

The Mauna Ulu eruptions of Kilauea. The Mauna Ulu eruptions of Kilauea lasted from May 1969 until July 1974, including a hiatus between October 1971 and February 1972. All data in the following section are from Swanson et al. (1979, part 1, prior to the hiatus) and Tilling et al. (1987, part 2, after the hiatus).

Table 1. Flow data for major historical Mauna Loa and Kilauea flank eruptions. Flows that are confined mainly to calderas or pit craters have not been included

Mauna Loa

Year (named flows)	Average flow velocity (m/h)	Measured flow velocity (m/h)	Volumetric flow rate[a] (m^3/s)	Flow type	References and notes
1843	33	n.r.	39	aa	Brigham (1909); data poorly constrained
	17	n.r.	19	pahoehoe	
1852	46	n.r.	105	aa	
1855-1856	n.r.	n.r.	n.r.	varied	data poorly constrained
1859	133	267	208	aa[b]	Brigham (1909); this study
	7	8	5	pahoehoe	
1868	1.1	n.r.	95	aa[b]	
1880-1881 (Ka'u)	25	n.r.	19	aa	Baldwin (1953); this study
(NE)	33	n.r.	19	aa	
	8	8	4	pahoehoe	
1887	133	n.r.	212	aa[b]	
1899	n.r.	n.r.	n.r.	varied	data poorly constrained
1907	58	n.r.	47	aa	data poorly constrained
	50	n.r.	47	aa	
1916	42	n.r.	30	aa	
1919 (Alika)	28	917	56	aa[b]	Finch (1925)
1926 (Honomalino)	83	87	100	aa[b]	Jaggar (1926a); Jaggar (1926b)
	25	67	100	aa	
	37	n.r.	100	aa	
1935-1936	33	267	101	aa	Jaggar (1935a); Jaggar (1935b)
	33	25	14	pahoehoe	
1942	92	1750	157	aa	Finch (1942)
1950 (W flank)	1750	667	97	aa	Finch & Macdonald (1950)
(Ho'okena)	2167	9292	1044	aa[b]	Macdonald & Finch (1950)
(Magoon Ranch)	562	3667	325	aa[b]	
(Ohi'a Lodge)	250	1167	213	aa[b]	
(Kahuku)	229	n.r.	32	aa	
(Punalu'u)	1917	n.r.	133	aa	
1984	54	42-750	110[c]	aa	Lockwood et al. (1987)

Kilauea

Year (named flows)	Average flow velocity (m/h)	Measured flow velocity (m/h)	Volumetric flow rate[a] (m^3/s)	Flow type	References and notes
1840	12	146	94	aa[b]	Macdonald (1941)
1919-1920	2	n.r.	2	pahoehoe	Jaggar (1930)
1955 (Ki'i)	83	100	28	aa	Macdonald (1959)
(Kaueleau)	125	1600	33	aa[b]	
(Ke'eke'e)	150	250	33	aa[b]	
(Kehena)	54	n.r.	28	aa[b]	
1969-1971 (phase 1)	58	417	140-400	aa[b]	Swanson et al. (1979)
(phase 3)	1	12	4	pahoehoe[b]	
1972-1974 (phase 1)	1	4-21	3.4[c]	pahoehoe[b]	Tilling et al. (1987)
(phase 5)	75	n.r.	7	aa	
1977	79	283	29-56	aa	Moore et al. (1980)
1983-1990 (Puu Oo)	150	50-500	20-300[c]	aa	Wolfe et al. (1987); G Ulrich, personal communication
(Puu Oo 35B)	5	5	3.4[c]	pahoehoe	Heliker et al. (1985)
(Kupaianaha)	5	8	5[c]	pahoehoe[b]	Heliker, personal cummunication

[a] Flow volume divided by eruption duration
[b] entered ocean
[c] measured volumetric flow rate
n.r. not recorded or poorly constrained
Flow lengths from Stearns & Macdonald (1946); Mauna Loa volumes from Lockwood & Lipman (1987); Kilauea volumes from Macdonald et al. (1983)

Part 1 (May 1969-May 1971) was subdivided into 4 stages: an episodic high-fountaining stage, a shield-building overflow stage, a tube-fed pahoehoe stage, and a waning stage. The first and third stages generated significant lava flows that reached the ocean.

The first stage lasted seven months, during which

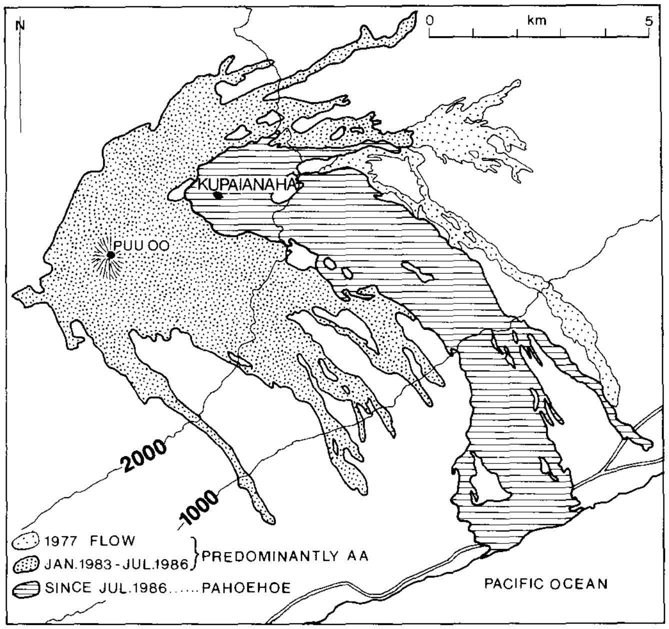

Fig. 2. Map of Puu Oo/Kupaianaha area, east rift zone of Kilauea, showing distribution of predominantly aa and predominantly pahoehoe flows of the ongoing eruption that began in 1983 contour interval 1000 feet (map from U.S. Geological Survey's Hawaiian Volcano Observatory monthly Report for Dec. 1987, courtesy of Christina Heliker; note figure added in proof)

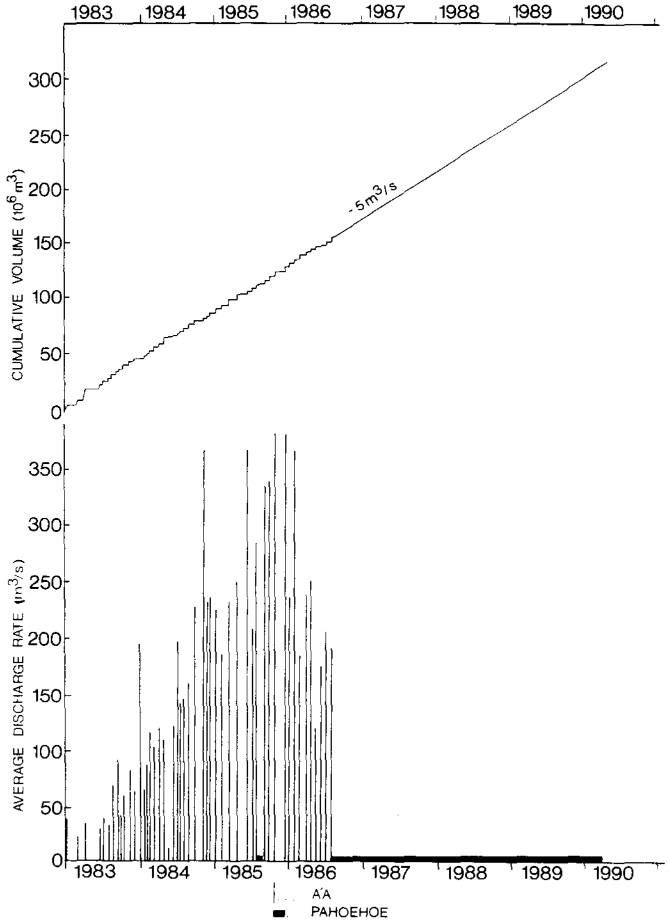

Fig. 3. Chart of average discharge rates, cumulative volume, and lava types produced during the ongoing Puu Oo/Kupaianaha eruption (data from U.S. Geological Survey's Hawaiian Volcano Observatory monthly Report for Dec. 1986, courtesy of George Ulrich)

there were 12 episodes of high fountaining (up to 540 m high) at discharge rates of 140-400 m^3/s. Flows were predominantly aa, and the one flow that reached the ocean traveled the 12 km from the vent at an average velocity of 400 m/h. Between episodes of high fountaining only minor activity (small dome fountains and short flows) occurred at the vent area.

The second stage built the bulk of the Mauna Ulu shield, and flows of the third stage issued from tubes within this shield. The first of these pahoehoe flows to reach the sea advanced at an average velocity of 12 m/h. The average discharge rate during this period was 4 m^3/s.

Part 2 (February 1972-July 1974) was divided into 5 stages, depending on the type of activity and the location of eruptive vents. The first, third, and fifth of these stages produced significant volumes of lava. The first stage was similar to the tube-fed stages in part 1 of the eruption (before the hiatus); the average discharge was 3.4 m^3/s, and two pahoehoe flows reached the ocean after advancing at average velocities of 6 and 20 m/h. This stage of the eruption ended soon after the $M = 6.2$ Honomu earthquake, and Tilling et al. (1987) attribute cessation of activity to disruptions caused by the earthquake in both the conduit that fed the eruptive vents and the lava tubes that carried lava to the sea.

The third stage produced no significant lava flows; all activity was confined to the lava lake at the summit of Mauna Ulu. The fifth stage involved a return to episodic activity. Discharge data are not divided into separate episodes, so exact correlation with specific flows is difficult. The longest flow generated by one of these episodes was produced during a period of five days and reached a length of 9 km (average rate of advance of 75 m/h). The change in summit tilt during this 5-day episode amounted to 10 microradians, approximately equivalent to 3×10^6 m^3 (Dzurisin et al. 1984) which corresponds to a discharge rate of 7 m^3/s. A photograph of this flow (Fig. 16.35 of Tilling et al. 1987) shows it to be channelized aa.

In summary, although the activity during the 5-year eruption of Mauna Ulu was more complex than that of the Puu Oo/Kupaianaha eruption, the correlation of discharge with lava type is well displayed.

Other major eruptions of Kilauea. The 1977 eruption on Kilauea's middle east rift zone lasted for a week, but the main part of the eruption occurred from 25 to 28 September. Lava fountains ranged from 60 to 120 m high (Moore et al. 1980), and a prominent 35-m-high cinder and spatter cone, Kai'i, was formed. The discharge was sustained at 28-56 m^3/s, and most of the lava formed a single aa flow 7.5 km long that advanced at an average velocity of 80 m/h.

The 1955 eruption took place from a discontinuous system of fissure vents that stretched 15 km along the lower east rift zone (Macdonald 1959). Four main lava flows were generated: (1) the Ki'i flow (average volumetric flow rate of 28 m^3/s, average velocity of 80 m/h), (2) the Kaueleau flow (33 m^3/s, 125 m/h), (3) the Ke'eke'e flow (33 m^3/s, 150 m/h on a 3.5° slope through dense forest), and (4) the Kehena flow (28 m^3/s, 50 m/h). All four flows are aa (Macdonald 1959).

The Mauna Iki southwest rift eruption began in December 1919 and lasted for 221 days (Macdonald et al. 1983). Jaggar (1930) described the eruption, including the surface manifestation of the propagating dike and concurrent activity in the Halemaumau lava lake. The eruption formed a satellite shield (see photo in Greeley 1987, p. 1592) and a tube-fed pahoehoe flow field extending ~ 10 km to the south. A large volume of lava stored within the satellite shield broke out and flowed along the west margin of the pahoehoe. This partially cooled lava formed aa (see section on qualifications and complications). The average discharge and flow-front velocities for the Mauna Iki eruption were 2 m^3/s and 20 m/h, respectively.

Mauna Loa

Well-documented aa-forming eruptions. The 1984 eruption began from a fissure that cut the summit caldera and extended a short distance down both the southwest and northeast rift zones (Lockwood et al. 1987). The activity then shifted down the northeast rift zone, and 90% of the lava during the 3-week eruption issued from a vent system between 2800 and 2900 m elevations (Lockwood et al. 1987). Three large channelized aa flows were successively generated from these vents (Lipman and Banks 1987) and traveled alongside one another (Lockwood et al. 1987); flow rate thus equaled discharge, which averaged 110 m^3/s. Flow-front velocity decreased exponentially with time from 750 to 20 m/h (Lockwood et al. 1987).

The 1950 eruption on the southwest rift zone was the largest historic flank eruption of Mauna Loa. It lasted 23 days, during which 440×10^6 m^3 of fast-moving (flow-front velocities of up to 10000 m/h; Finch and Macdonald 1950) aa was erupted at an average discharge of 250 m^3/s. The lava formed six main aa flows, but no more than three flowed simultaneously and occasionally only one was flowing. The volumetric flow rates ranged from 32 to 1044 m^3/s, and the flows traveled at velocities that ranged from 230 to 10000 m/h (data calculated from accounts in Finch and Macdonald 1950; Macdonald and Finch 1950).

The 1942 eruption lasted 13 days and originated from a fissure on the northeast rift zone between the 2850- and 2760-m elevations (Macdonald et al. 1983). A fast-moving aa flow advanced toward Hilo at an average velocity of 1900 m/h (data from Finch 1942). About 75×10^6 m^3 of lava was erupted, giving an average discharge of 72 m^3/s.

Paired lava flows. Certain lava-flow fields on Mauna Loa consist of two parts that cover comparable areas and extend comparable distances from the vent. One part is aa and the other pahoehoe; both of these formed successively in the same eruption. We refer to these lava-flow fields as "paired lava flows", and regard the one produced by the 1859 eruption as the type example.

The 1859 flow is the longest historic flow (51 km) in Hawaii and provides a remarkable example of a paired flow (Figs. 1, 4). Following a small summit outbreak, the main eruption began on 23 January (Brigham 1909) from a radial vent (Lockwood and Lipman 1987) high on the north side of Mauna Loa. The first lava flow was aa and reached the sea on 31 January, advancing at an average of 270 m/h. Haskell (in Brigham 1909) reported high lava fountains at the vent on 5 February that had ceased by 7 February; pahoehoe formation had begun when the area was visited on 9 February. Haskell made a second visit to the vent area and in a letter dated 22 June noted that the lava was flowing "under a cover" (i.e., in tubes). The pahoehoe flow also reached the coast, although the date of arrival was not recorded, and continued to flow into the sea for several months (Green 1887).

The 1859 aa flow is channelized along much of its 51-km length, varies from 0.1 to 2.5 km wide, and has an estimated volume of 270×10^6 m^3. The pahoehoe flow came from a lower point on the same fissure and flowed mostly alongside or overlapping the aa flow; it is 47 km long and varies from 0.3 to 2.5 km wide. Its estimated volume is 113×10^6 m^3 (based on combined volume of aa and pahoehoe given by Lockwood and Lipman 1987). Assuming that the change from aa to pahoehoe production occurred relatively quickly around 7 February, aa would have erupted for 16 days at an average discharge of about 200 m^3/s, and pahoehoe would have erupted for 285 days at about 5 m^3/s. Since single flows were generated during each phase, volumetric flow rates are the same as discharge from the vent.

Another fine example of a paired lava flow was erupted from the northeast rift zone in 1880–1881. The pahoehoe portion entered what is now a suburb of Hilo (Figs. 1, 5). The eruption began on either 1 November (Baldwin 1953) or 5 November 1880 (Macdonald et al. 1983) with high fountaining at the 3200-m elevation. A fast-moving aa flow traveled NNE into the saddle between Mauna Loa and Mauna Kea and then turned east. Another aa flow began a few days later and traveled southeast (Baldwin); these flows were 14 and 19 km long, respectively. According to Baldwin, a change to eruption of pahoehoe took place soon after 29 November; here we assume that the aa-forming part of the eruption lasted 25 days. Much of the NNE flow is now concealed by flows erupted in 1899. The exposed volume is about 22×10^6 m^3, but the actual volume is much larger according to recent mapping by JP Lockwood (personal communication 1987). The SE flow is well preserved and has a volume of about 20×10^6 m^3. Assuming that the flows formed simultaneously, their volumes yield average volumetric flow rates of at least 10 m^3/s for each, and average rates of advance of 23 and 32 m/h for the NNE and SE flows, respectively.

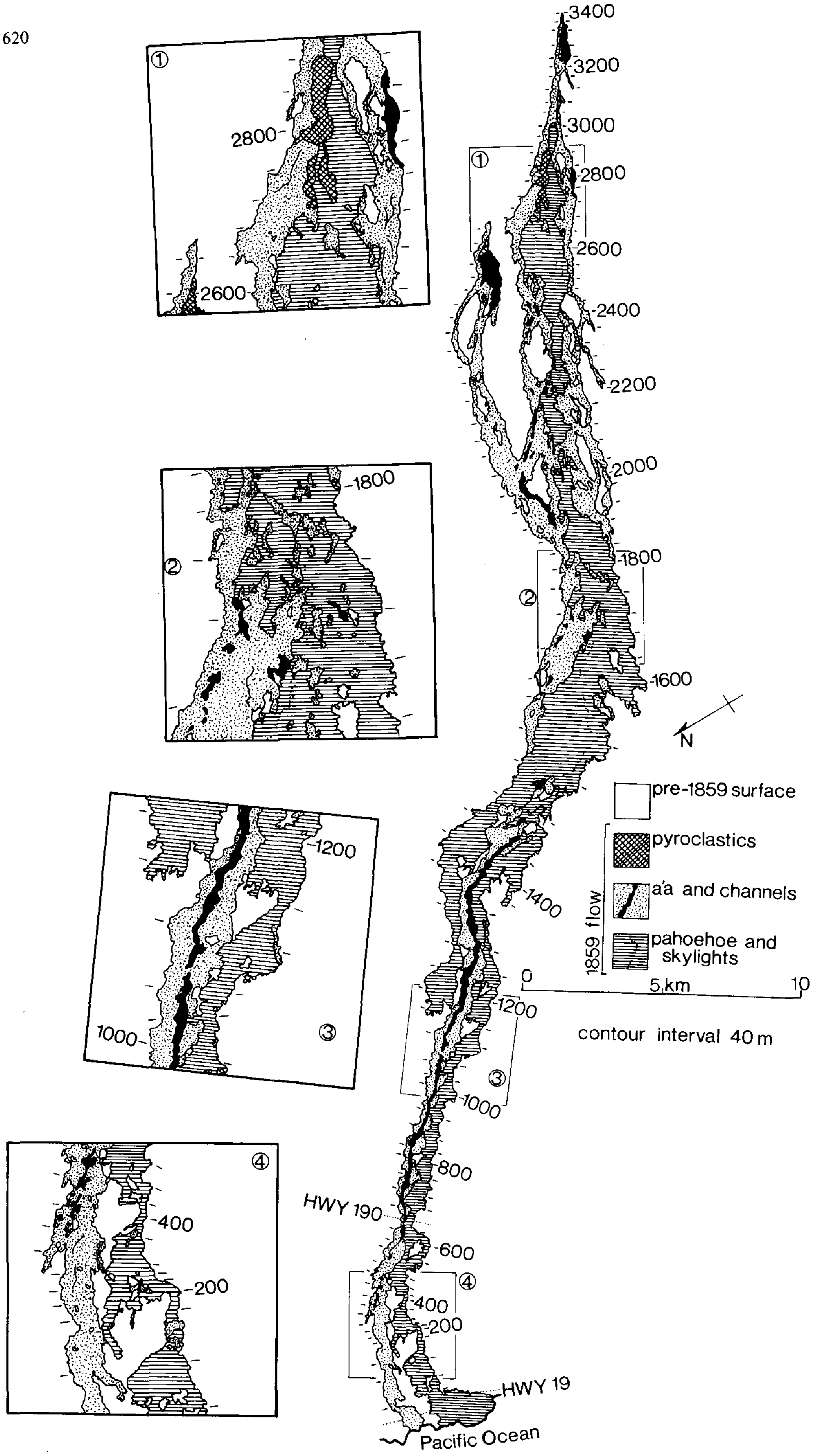

Fig. 4. Map of Mauna Loa's 1859 paired lava flow. Enlarged insets showing more detail are just over 4 km on a side

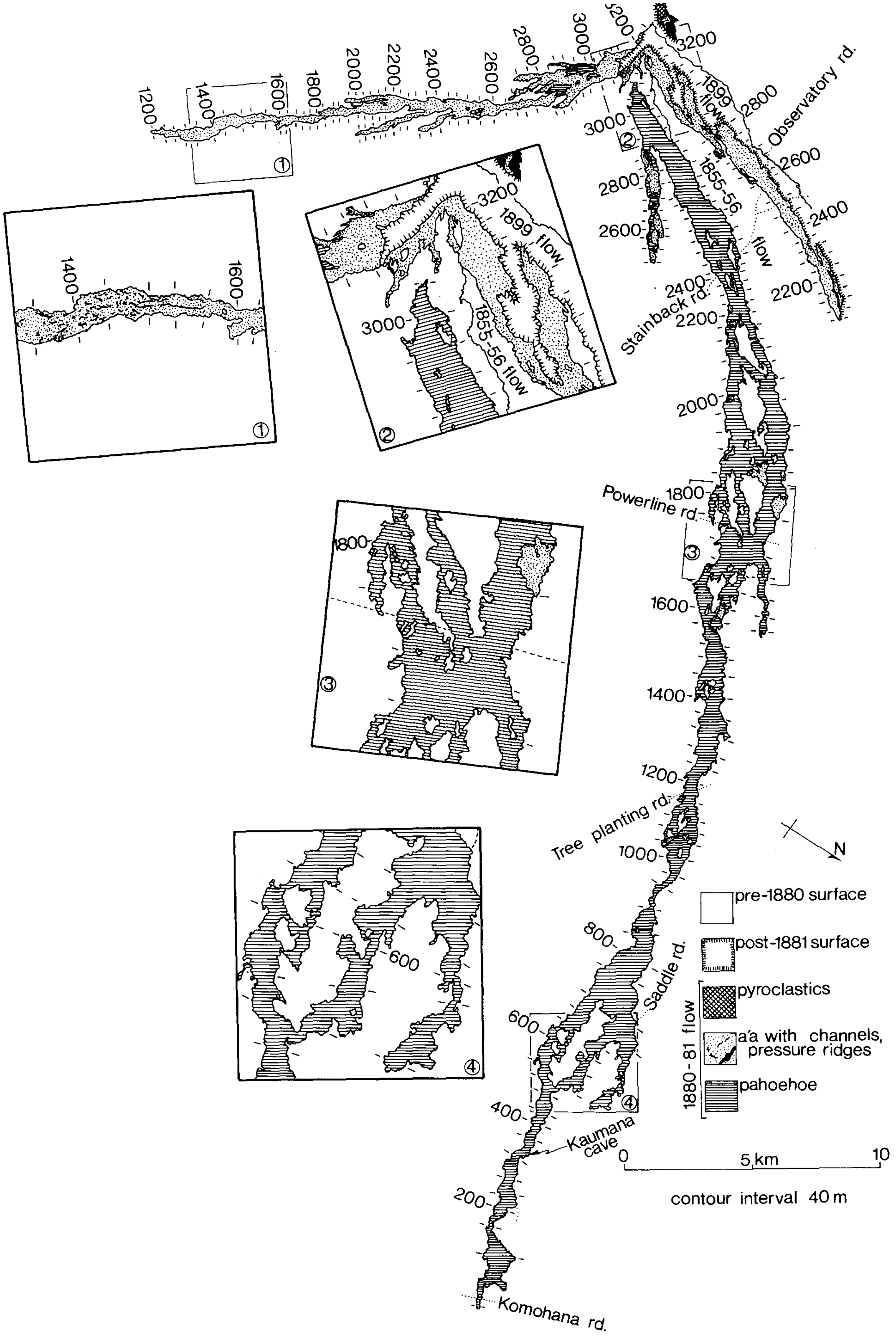

Fig. 5. Map of Mauna Loa's 1880–1881 paired lava flow. Enlarged insets showing more detail are just over 4 km on a side

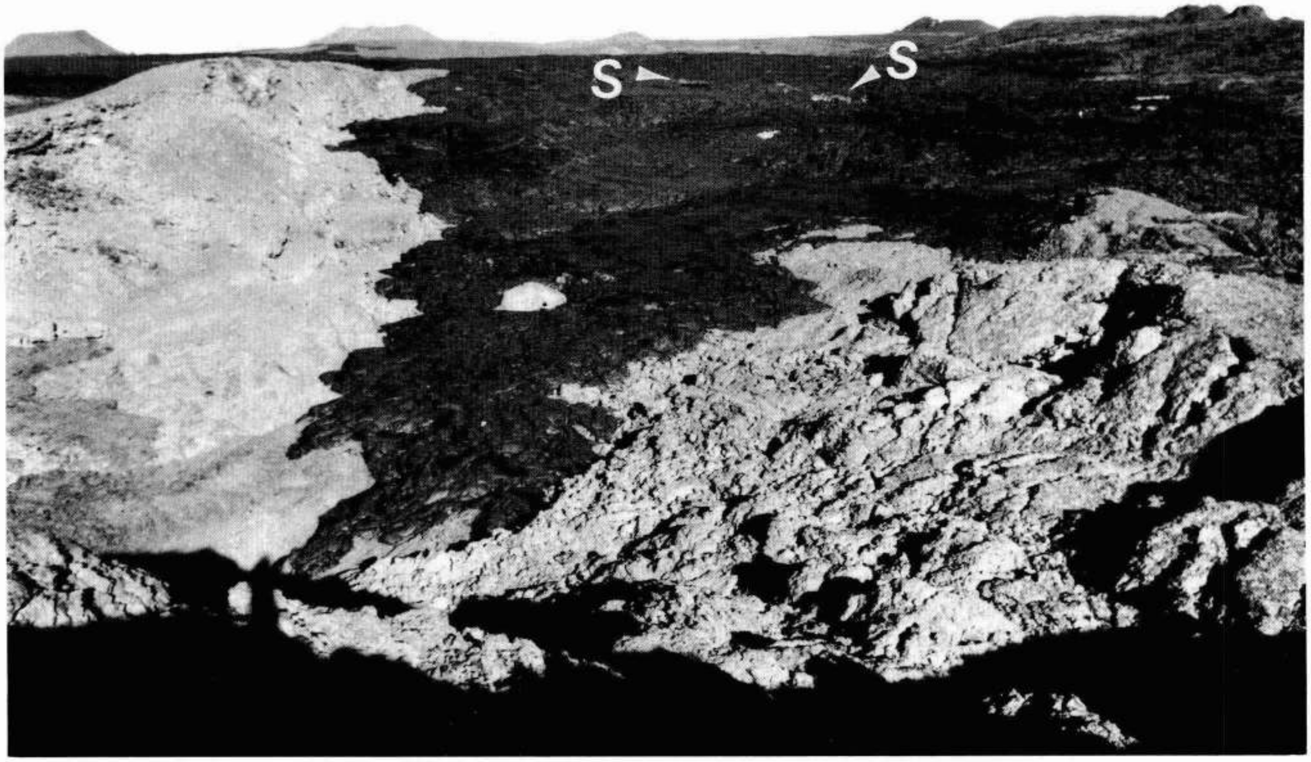

Fig. 6. Vent area of 1880–81 pahoehoe flow (dark lava widening away from viewer). Note lack of associated pyroclastic material and presence of skylights into master tubes (*S*). Light-colored surrounding rocks are prehistoric. View is downflow to the north

Baldwin (1953) stated that the succeeding pahoehoe flow came out of the same vent as the aa, whereas Jaggar (1939) identified spatter cones 2.5 km downrift from the aa vents as the 1880–1881 pahoehoe vents. We agree with Macdonald (1945), however, that the pahoehoe vents are a little more than 1 km downrift from the aa vents. We found no trace of pyroclastic deposit there, indicating a lack of fountaining (Fig. 6). The pahoehoe flow is 47 km long and varies in width from 0.1 to 1.8 km. It is remarkably uniform in structure and appearance along its entire length. Large lava tubes occur, though there are few skylights; the best-known tube is Kaumana Cave, entered from a skylight at the 340-m elevation (Fig. 5).

Eruption of pahoehoe continued until 7 July 1881 and generated a volume of about 88×10^6 m^3. An assumed eruption duration of 255 days yields an average volumetric flow rate of 4 m^3/s. The average advance rate was 8 m/h.

Other paired eruptions. The Mauna Loa eruptions of 1840 and 1935–1936 also produced aa flows followed by pahoehoe, but time constraints are significantly poorer than for the two examples discussed above. The 1855–1856 and 1899 eruptions consisted of both high-fountaining, aa-producing periods and low-fountaining, pahoehoe-producing periods, but the sequences were complex and unrecorded. The Huehue lava flow from the lower 1801 vent system on Hualalai volcano is also distinctly paired, and the vent system itself consists of a large pyroclastic complex (Puhi o Pele) in addition to a low, elongate shield. No chronologic data are available for this eruption.

Summary of historical eruption data

The data discussed above, as well as additional (less well constrained) data, are presented in Table 1 and Fig. 7. Figure 7 plots volumetric flow rate versus flow velocity. The strong correlation between volumetric flow rate, flow velocity, and flow type is illustrated; the critical minimum discharge for aa formation is around 5–10 m^3/s. The average flow-front velocity of pahoehoe ranges between 1 and 10 m/h, compared to a range of 20–2000 m/h for aa flows.

Mechanism of production of aa and pahoehoe

We have reviewed the evidence that volumetric flow rate operates on lava flows (here considered to have the same composition and initial viscosity) to determine whether the lava is aa or pahoehoe. We now examine how volumetric flow rate operates to produce this result.

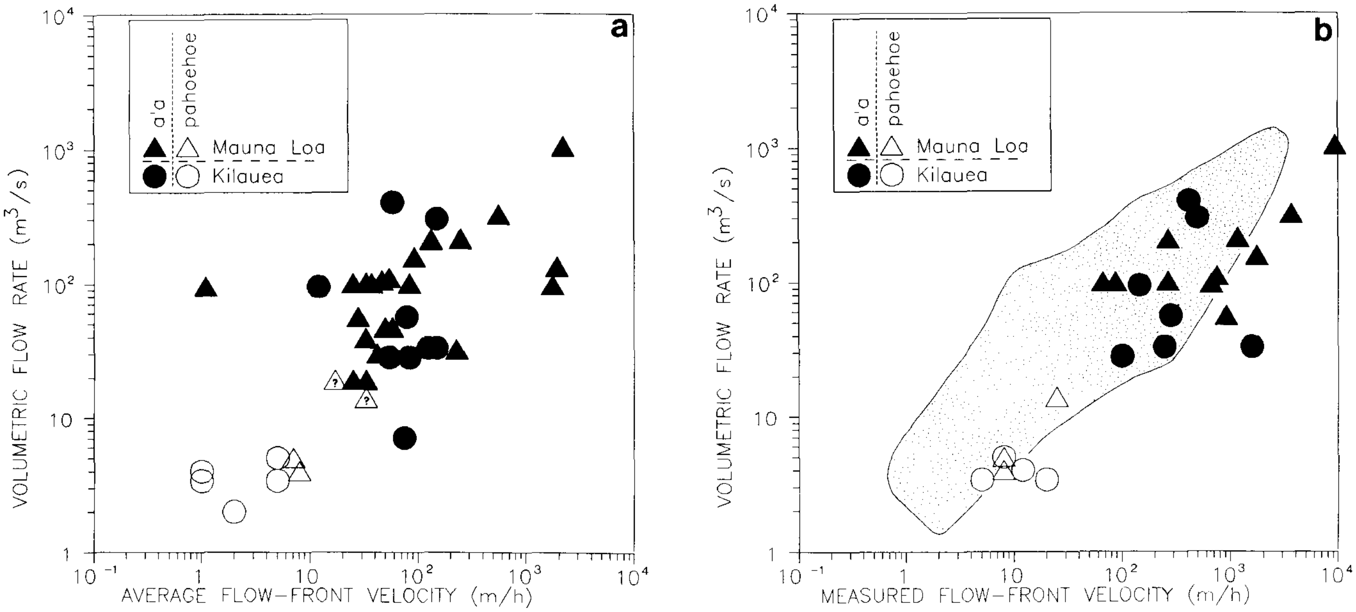

Fig. 7. a Plot of volumetric flow rate vs average flow-front velocity (flow length divided by eruption duration). Except for the uncertain data (question marks), note the distinct division of flow types at a critical volumetric flow rate of between 5 and 10 m^3/s and at a flow-front velocity of about 20 m/h. **b** Plot of volumetric flow rate vs measured flow-front velocity (where such data are available or calculable from historic accounts). Note that measured velocities are commonly greater than average velocities (*stippled*, from a)

Aa

Lava leaving the vent at a high volumetric rate, destined to become aa, flows rapidly in an open channel. Initially the entire body of a newly formed lava lobe flows downslope, but a channel begins to form a short distance upflow of the advancing flow front, as the margins of the flow stagnate and flow becomes concentrated between these margins (Hulme 1974). Channelized flow tends to become more concentrated as levees are constructed by accretion on either side (cf. Sparks et al. 1976). By advancing on narrow, rather than wide flow fronts, high-discharge lava flows rapidly. Flow in an open channel is strongly favored over flow in tubes because at a high volumetric flow rate, the channel is unlikely to become roofed over, and any roof that does form is likely to be torn away. The flow rapidly lengthens and the channel likewise lengthens, lagging behind the flow front (by approximately 1 km in the 1984 Mauna Loa example; Lipman and Banks 1987). Actual flow velocities in channels have approached 60 km/h (e.g., Macdonald 1959), but the flow front advances more slowly at 80–10000 m/h.

A large proportion of the lava surface in the channel is incandescent; clumps of slightly cooler lava (Peterson and Tilling 1980) and any solid crusts that form tend soon to be disrupted so as to expose incandescent lava. Heat loss from the lava in the channel, mainly by radiation but also by air cooling, is very high. The channelized lava thus cools significantly, and the lava viscosity increases correspondingly.

The lateral velocity gradient in a moving lava channel causes torque to be applied to adjacent pasty clumps or small portions of lava crust (Fig. 8); clockwise torque is applied if the lava lies to the right of the median line (looking downflow), and counter-clockwise torque is applied if the lava lies to the left of the median line (see Moore 1987). Two adjacent portions of lava (such as A and B in Fig. 8) tend, therefore, to be torn apart due to the applied torques.

The critical stage for aa formation is reached when the viscosity or yield strength of the lava beneath the crust is too high for it to flow fast enough between the torn-apart portions of lava to heal the tear. This critical viscosity will vary because the velocity gradient determines the amount of tearing, in turn the amount of

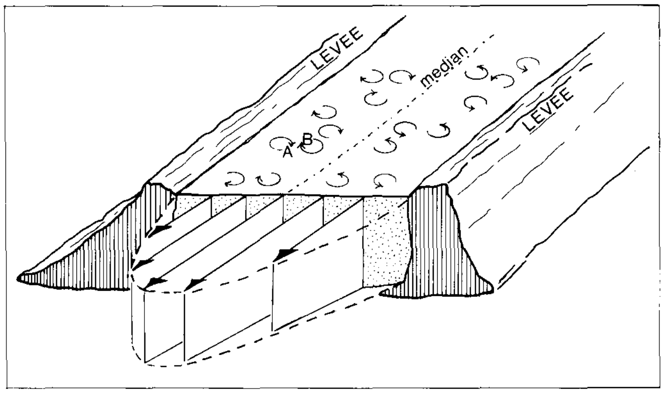

Fig. 8. Schematic diagram of flow in a lava channel. *Curved arrows* indicate sense of torque applied to the undersides of surface-crust fragments. Torques tend to tear apart adjacent portions of crust (i.e., *A* and *B*; see text)

cooling, and in turn finally the viscosity of lava attempting to heal the tear. The combination of these processes may eventually lead to aa formation. We consider from our study of mafic-phenocryst distribution profiles (Rowland and Walker 1988) that the critical viscosity is typically of the order of 10^4 Pa s. Once portions of the crust are torn apart and the underlying lava fails to heal the tears, the lava has become aa; the spinose torn-apart portions of lava crust are clinkers. Additional descriptins of aa formation are given by Peterson and Tilling (1980) and Finch (in Macdonald 1953).

The higher viscosity (or yield strength; cf. Hulme 1974) also favors preservation of the ragged and spinose form of the clinker fragments (as in proximal-type aa; Rowland and Walker 1987). Abrasion later smooths some of these irregularities. Farther downflow, where the lava has a still higher viscosity, riding of lava up over slower-moving lava in front brings massive flow interior to the flow top (observed by the authors on the 1984 Mauna Loa flow). Breakage of this massive lava along cooling joints then contributes planar-surfaced and nonvesicular debris to the flow top (as in distal-type aa; Rowland and Walker 1987).

Pahoehoe

In pahoehoe-producing eruptions that we have observed, tens or hundreds of pahoehoe flow units (Nichols 1936; Walker 1971) are simultaneously in motion. Some of these become single-flow-unit tubes when flowage continues after their outer skins have become static. These tubes are commonly less than 1 m^2 in cross section. Thus, an advancing pahoehoe flow contains passageways within the solid and static carapace of flow units through which lava flows continuously or intermittently to sustain other units. Large master tubes may form locally as several single-flow-unit tubes coalesce, or as open channels roof over (Peterson and Swanson 1974; Greeley 1987). Lava in the distal parts of the pahoehoe flow field has traveled from the vent in these master tubes, but it generally emerges from them through a system of small distributary tubes (Swanson 1973) of the single-flow-unit type (Fig. 9). Because of efficient heat conservation, lava that emerges from tubes has nearly the same temperature at all distances from the vent (Swanson 1973).

Because the effusion rate of 5–10 m^3/s is divided among many lobes, pahoehoe lobes are mostly very small. Flow velocities of simultaneously active lobes that we have observed are generally under 120 m/h (as compared to ~ 10 m/h for the flow front as a whole), and the lengths of distal or surface lava streams that are in motion at any one time (as distinct from the parts that flow inside master lava tubes) are generally less than several tens of meters.

Controls as envisaged by Moore (1975) for pillows operate to limit the size of pahoehoe lava lobes. Lobe growth is accomplished by extension of the chilled skin, but at the same time the skin is thickening due to cooling. Lobe growth (expansion as well as lengthening) at any given point continues as long as skin stretching (due to hydrostatic pressure) exceeds skin thickening (due to cooling). That part of the lobe where skin thickening prevails soon becomes static, although the lava may still be flowing under the static carapace.

Growth of a pahoehoe flow field thus takes place by the formation of a chilled carapace over a succession of innumerable lava flow units. Movement of the carapace has essentially ceased before the viscosity of the lava has reached the threshold appropriate to aa formation, and so the smooth pahoehoe surface is preserved intact (Peterson and Tilling 1980). Renewed supply of lava may fracture this solidified surface (usually at the seams between flow units), and new pahoehoe lobes emerge and advance. By this mechanism, the flow front advances.

Summary of aa and pahoehoe mechanisms

Whether aa or pahoehoe forms depends on whether flowage continues after a certain viscosity threshold (the value of which varies with flow velocity) is crossed, or ceases before that threshold is reached (Peterson and Tilling 1980): If flowage still continues rapidly, the surface crust is torn apart and aa results; if the lava is static or nearly so, then smooth-surfaced pahoehoe results instead. The important predetermining factor is whether flowage is at a high volumetric rate in an open

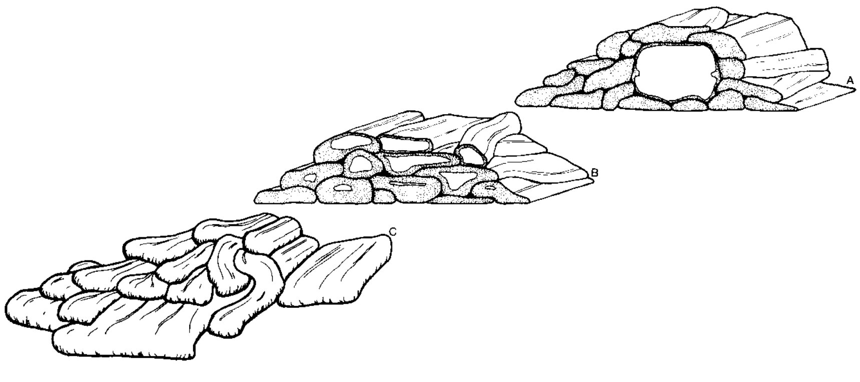

Fig. 9. Cutaway views of a tube-fed pahoehoe flow. *A* master tube formed in pile of flow units; *B*, distributary tube system near flow front. Continued flow in one or more of these flow units can allow for the extension of the master tube downflow. *C*, flow front; low discharge rate is divided among many flow units resulting in very low volumetric flow rates for each

channel (from which heat loss is rapid) or is at a low volumetric rate in tubes (from which heat loss is slow).

Pinkerton and Sparks (1976) observed a highly phyric hawaiite flow of Etna. They determined that a critical volumetric flow rate of 2×10^{-3} m^3/s separated aa formation from pahoehoe formation. This large difference between the critical Hawaiian and Etnaen volumetric flow-rate values is probably due to a number of factors: (1) the difference in lava temperatures, i.e., 1070–1090° C for Etna vs 1130–1150° C for Hawaii; (2) the presence of a significant yield strength in the Etna lava, i.e., 370 N/m^2 (Pinkerton and Sparks 1978), vs <5 N/m^2 for Hawaii (Rowland and Walker 1988); and (3) the high crystallinity of the Etna lava, i.e., 50–60% phenocrysts (Pinkerton and Sparks 1976). Furthermore, Etna "pahoehoe" does not possess the smooth surface characteristic of Hawaiian pahoehoe and would be considered by us to be rough pahoehoe (Rowland and Walker 1988) or toothpaste lava (Rowland and Walker 1987; spiny pahoehoe of Peterson and Tilling 1980).

Qualifications and complications

Several qualifications and complications are now considered: (1) Lava that flows strongly in a channel but then escapes from that channel before cooling significantly may form pahoehoe. Such channel overflows are smooth-surfaced pahoehoe, because their generally small size and low volumetric flow rate are sustained for only a short time, they soon develop a chilled crust and become static. In distal areas, however, the viscosity of lava in the channel has already increased beyond its threshold value (an irreversible change; Peterson and Tilling 1980; Kilburn 1981) so that even small overflows form aa. (2) The lava that congeals in the channel after supply from the vent has been cut off may form pahoehoe. (3) When lava that is forming pahoehoe begins to flow down a steeper slope it accelerates, and the resulting increase in flow velocity may then cause aa to form if the viscosity threshold for that increased velocity has already been crossed (cf. Peterson and Tilling 1980). We prefer this explanation for the pahoehoe/aa change to that of Wentworth and Macdonald (1953), who attributed the change to accelerated gas loss by stirring. (4) Increases in viscosity and/or yield strength to critical values may not take place until the lava has flowed a few kilometers from the vent. For this reason, flows consisting mostly of aa may be pahoehoe close to the vent, even though fountaining and discharge rate were both high (fountain-fed pahoehoe of Swanson 1973). (5) Lava that has acquired a viscosity appropriate for forming aa but flows at a low volumetric rate may form toothpaste lava (Rowland and Walker 1987) instead. (6) Lava may collect within, and/or be injected into the flanks of satellitic shields during pahoehoe eruptions, which causes perceptible bulges in the shields (Hon et al. 1987; Peterson and Tilling 1980), and the lava can eventually break through and drain out. This lava has cooled during its residence in the shields, and the flows resulting from the drain-out are often aa (Peterson and Tilling). (7) The option of whether to form pahoehoe or aa does not apply to lava that, when emerging from the vent, already has a viscosity higher than the threshold; if, however, it travels at a low volumetric rate, it may instead form toothpaste lava that superficially resembles pahoehoe.

In this account we have considered examples where aa and pahoehoe have formed successively from the same vent system. The two structural types may also form simultaneously if several lava streams leave the vent flowing at different volumetric rates. We observed a good example of this at the flank vent of the 1984 Mauna Loa eruption. Most of the lava output from the breached SE side of the spatter cone was flowing very fast in a major channel and was destined to form aa, but lava was also leaking from a number of points around the NE foot of the cone and forming a small pahoehoe flow.

Eruptive mechanisms

In this section we consider how the internal plumbing system of a Hawaiian volcano may determine the discharge. We rely particularly on the Kilauea events of 1983–1990 because they are so well documented (Wolfe 1988; Wolfe et al. 1987; Heliker et al. 1985; Ulrich et al. 1987) and because we observed many of these events ourselves. In this as in several other eruptions, the initial high discharge that formed aa later changed to slow but long-sustained discharge that formed pahoehoe.

We here define "magma excursion" as a general term meaning any movement of magma that culminates in an intrusion, eruption, or both. The 1983 lateral magma excursion (which culminated in episode 1 of the ongoing eruption) was aseismic along its first 10 km of travel (Klein et al. 1987), indicating that previous intrusive events had established a pathway extending this distance from the summit magma chamber. The magma excursion extended an additional 18 km downrift; this was marked by an earthquake swarm with a propagation rate that varied from 0.6 to 0.025 km/h (Klein et al. 1987). The seismicity was accompanied by deflation at the summit (Fig. 10), a combination that was interpreted to mark the lateral propagation of a dike beyond the existing pathway. The seismicity indicated that the magma had to create a pathway through the country rock on its way downrift and to the surface, even though residual bodies of 1980, 1977, or earlier magma evidently still resided locally in this part of the rift zone (Garcia et al. 1985; Wolfe et al. 1987).

Each of the subsequent 44 high-fountaining episodes of Puu Oo was preceded by a small inflation of the summit magma chamber (average of 13 microradians; Wolfe et al. 1987) whereas the fountaining episodes themselves were accompanied by a correspondingly small but rapid deflation. This has been interpreted to mean that the pathway from the summit magma chamber to the vent became blocked at the end of each fountaining episode by either a rheological or

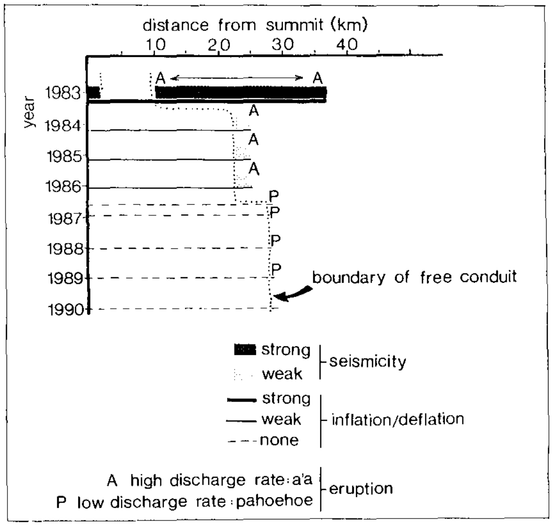

Fig. 10. Time-distance plot for activity along Kilauea's east rift zone. Activity is indicated by both seismicity and deformation symbols. Symbols for 1983 and July 1986 indicate specific events, whereas those for other years indicate representative activity (episodic or continuous) during that year as a whole

mechanical barrier (Hoffmann 1988; Wilson and Head, in prep.), and that only a small pressure buildup was required to break the blockage. The accompanying seismicity was confined to the section of the east rift zone near Puu Oo, indicating that the blockages were in that section. The possibility of a subsidiary magma chamber located just uprift from Puu Oo has also been suggested (Wolfe et al. 1987; Hoffmann et al., in press); associated degassing, rheologic changes, and/or physical blockages in this near-surface plumbing were responsible for the distinct episodicity of the Puu Oo eruption. Since mid-July 1986 lava has flowed out almost continuously from Kupaianaha (Ulrich et al. 1987) without systematic summit inflation or seismicity. We consider that this period has been one of unimpeded magma flow from deep beneath the summit magma chamber (from the mantle?) to Kupaianaha. In effect, a stable extension from the summit magma chamber has been established into the east rift zone as far as Kupaianaha (Fig. 10). The continuously discharged lava is chemically identical to that erupted episodically (MO Garcia, personal communication), and the overall discharge has been constant during the entire eruption (Fig. 3).

The high discharge and associated high fountaining of the 44 (Numbers 4–47) episodes of Puu Oo can be attributed to the rapid expansion of accumulated gas; indeed, it may have been the accumulation of gases that enabled the blockages in the plumbing system to be cleared for each of the fountaining episodes, all of which formed aa flows. The activity since mid-July 1986 has been placid, without high fountaining, and pahoehoe flows have formed. Our explanation is that the magma conduit from Puu Oo to Kupaianaha is very shallow and that the large amount of gas that has been continuously emitted from Puu Oo throughout this period comes from magma moving through the conduit. By the time the magma reaches Kupaianaha it has already lost most of its exsolved gas. The rapid expansion of a large volume of gas that is needed to drive high fountains is therefore not available.

A similar situation existed during the 1984 Mauna Loa eruption (Lockwood et al. 1987). In this case, however, the high fountaining (producing aa up rift) and low fountaining (producing pahoehoe and forming a shield down rift) occurred simultaneously. Additionally, in 1859, extensive degassing was reported from the uprift, aa-producing vents (after they had shut off) during the pahoehoe-producing phase of the eruption (Brigham 1909).

Correlation of lava flow-type with eruption scenarios

The observations above can be combined to form a scenario of activity for Mauna Loa and Kilauea. Initially, gas-rich magma is stored in a magma chamber until pressure buildup allows it to fracture the chamber walls or blockages in preexisting conduits, and a magma excursion that may lead to an eruption occurs. Much (possibly all) of the stored magma is quickly erupted and the rapid expansion of gas bubbles at the vent drives high fountains. Most aa flows are evidence of such eruptions.

Sometimes the repetition of magma excursions leads to the establishment of an open, hot pathway extending from at least as deep as the summit magma chamber all the way to the vent. The last few kilometers of this pathway are shallow and locally may be open to the surface. If the magma moves slowly, exsolved gas can escape before the magma reaches the vent, and the eruption lacks fountaining. A tube-fed pahoehoe flow is evidence of such an eruption.

The details of this scenario differ slightly on Kilauea and Mauna Loa. On Kilauea, the aa portion of the eruption is usually episodic and lasts for months to years, whereas the pahoehoe portion results (over a span of a few years) in the formation of a satellitic shield, lava pond, and tube system. On Mauna Loa, however, the aa portion of an eruption is confined to a single 1 to 3-week episode, followed closely by the pahoehoe portion, lasting a few months to slightly over a year. The steeper slopes of Mauna Loa's rift zones seem to prevent significant buildup of pahoehoe lava, and thus satellite shields are rare and small.

Summary and conclusions

The striking differences that exist between aa and pahoehoe are attributable to differences in the volumetric flow rate, which in turn is closely related to the eruptive discharge. We have found that when the volumetric flow rate is greater than about 5–10 m^3/s, aa lava is formed, whereas at lower values pahoehoe is produced.

When a large volume of lava is moving at one time, it flows in open channels from which heat loss is rapid.

Because of the high volumetric flow rate, the lava continues to move even after its viscosity and yield strength have increased greatly, eventually reaching the point at which surface disruptions can no longer be healed by flowing of the underlying lava. The lava then forms a rubbly surface and becomes aa.

When only a small volume of lava is moving, the chilled surface skin becomes static very early in the cooling history of the lava, and the flowing lava can rapidly heal disruptions of its surface. The smooth pahoehoe surface is therefore preserved intact (Peterson and Tilling 1980).

In most cases, the volumetric flow rate is determined directly by the discharge at the vent, which in turn is controlled by processes within the volcano. Thus, internal volcanic processes are manifested by flow morphology at the surface; aa flows result from vigorous eruptions at high discharge, and pahoehoe flows result from placid eruptions at low discharge from stable conduits out of the magma chamber. The implications have only been partially explored to date (Rowland and Walker 1986; Rowland 1987a, b).

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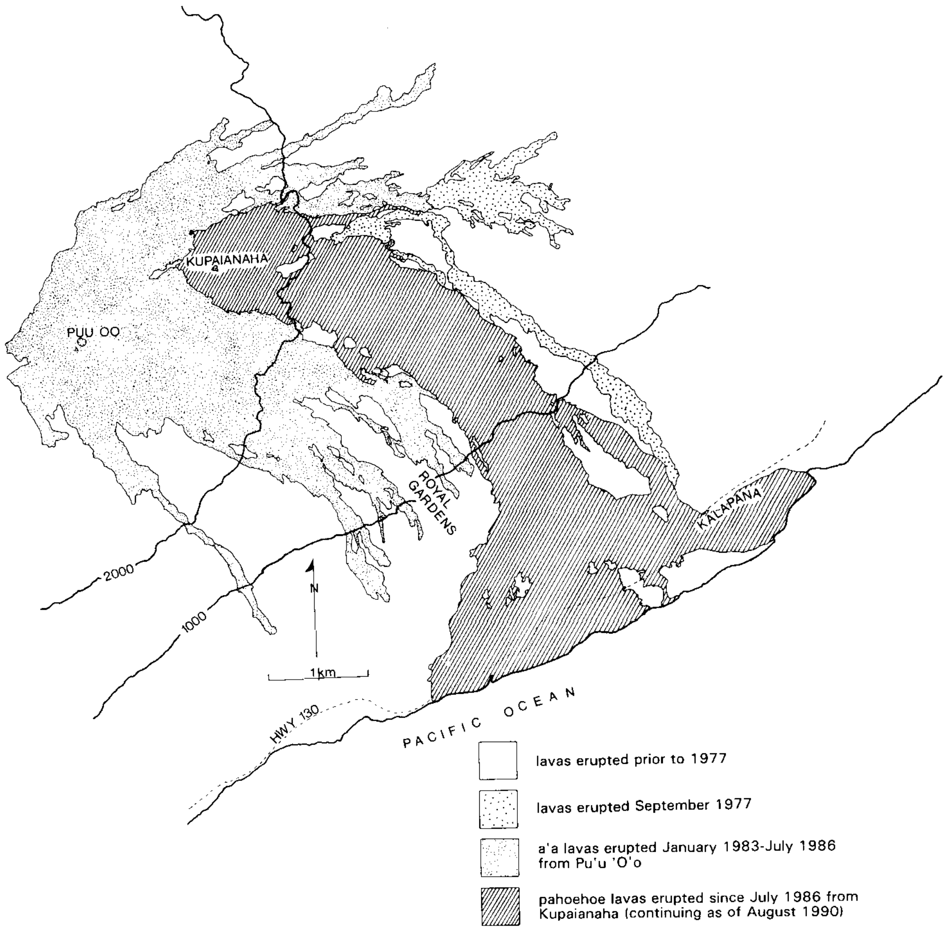

Figure added in proof: map of current eruption site as of mid-August, 1990 (contours at 1000 feet). Unpublished data courtesy of Christina Heliker and Ken Hon, U.S. Geological Survey Hawaiian Volcano Observatory