Journal of Volcanology and Geothermal Research, 55 (1993) 129–142
Elsevier Science Publishers B.V., Amsterdam

P-type and S-type pahoehoe: a study of vesicle distribution patterns in Hawaiian lava flows

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(Received June 3, 1992; revised version accepted June 18, 1992)

ABSTRACT

Wilmoth, R.A. and Walker, G.P.L., 1993. P-type and S-type pahoehoe: a study of vesicle distribution patterns in Hawaiian lava flows. *J. Volcanol. Geotherm. Res.*, 55: 129–142.

Two main types of Hawaiian pahoehoe lava, P-type (pipe vesicle-bearing) and S-type (spongy), are characterized. Their origin is inferred from features of the vesicle sizes and abundances, particularly in their chilled margins which record, frozen in, the vesicle population at the time and place of solidification. S-type margins are distinctly more vesicular than P-type. Porosity and vesicle size and range in S-type margins are highest at the vent. Vesicle size reaches a minimum in medial areas, and then increases while porosity decreases onto the flatter ground of the coastal terrace. The vesicles are inferred to be part of the complement of bubbles that was present at the vent, modified by loss and coalescence during travel in lava tubes. The minimum porosity occurs on the coastal terrace and is the result of degassing during a longer residence time in lava tubes there. The systematically lower porosity of P-type margins than S-type is attributed to a still longer residence, allowing more time for bubble coalescence and loss. P-type pahoehoe is common only on flatter ground, such as the coastal terrace. It is found where tumuli and lava rises are widespread and where extensive networks of lava-expansion clefts occur through which lava moving below the surface crust can lose gas without significant cooling. Additionally, P-type pahoehoe shows clear evidence that a strong inward movement and growth of bubbles took place from the outermost selvage into an inner selvage concentration zone. A mechanism that might cause this inward movement is surface tension, operating against deforming forces in the steep viscosity gradient of flow margins, causing down-gradient bubble translation. Inward movement does not usually occur in the upper crust of thick (>2 m) flow-units because of the absence of strong deforming forces in the shallow velocity gradient there. Many of the larger bubbles that entered the inner selvage rose buoyantly to form pipe vesicles.

P-type pahoehoe is characterized by sampled profiles across 20 flow-units. Continued gas loss through surface clefts caused a general overall reduction in vesicle content within each flow-unit to less than that in the upper crust, and the pronounced depletion of vesicles from its lower half is attributed to scavenging by ascending pipe bubbles. In a small proportion of flow-units, overall gas loss was small and a median gas blister fed by pipe bubbles developed instead.

Introduction

Lava flows erupted on land almost invariably contain vesicles, representing bubbles of gas trapped in the solidified lava. The importance of gases in volcanism has long been acknowledged, and the roles that exsolving gases may play in lava flows has been discussed, for example, by Lipman et al. (1985) in their study on the degassing-induced crystallization of a Hawaiian pahoehoe lava, and by Sparks and Pinkerton (1978) on the effect on lava rheology. Swanson (1973) describes pahoehoe showing variable degrees of vesicularity from the Mauna Ulu eruption.

Very few studies have, however, concentrated attention on the details of vesicle distribution patterns or employed vesicles as tools

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0377-0273/93/$06.00

to understand lava flows better. Those by Aubele et al. (1988) on vesicle distributions in basalt, by McMillan et al. (1987, 1989) on vesiculation in lava flows of the Columbia River Plateau, by Walker (1989) on spongy pahoehoe, by Walker (1987), Philpotts and Lewis (1987), and Godinot (1988) on the origin of pipe vesicles, and by Sahagian (1985) and Sahagian et al. (1989) on bubble coalescence mark a beginning in the quantitative study of vesicle populations in lava flows.

Here we distinguish two distinct pahoehoe types in Hawaii which we term P-type (pipe vesicle-bearing) and S-type (spongy; following Walker, 1989) that have contrasting vesicle populations in their chilled margins. We describe and document the vesicle distributions of the two types and describe measured profiles across a number of P-type flow-units to characterize the type.

This paper describes two separate, yet complementary, vesicle studies of pahoehoe lava flow-fields on Hawaii. One, we studied downflow variations in vesicle populations in flow-top selvages from several pahoehoe flow-fields to establish the setting in which P-type pahoehoe occurs. Two, we studied profiles across 20 P-type flow-units and investigated the processes that have affected their vesicle populations.

The two pahoehoe types: P and S

Pahoehoe lava flows in Hawaii, as elsewhere, are divisible into flow-units (Nichols, 1936). Each flow-unit is bounded by a chilled margin in which the vesicles are the smallest, inside which there is a general inward increase in vesicle size. Each flow-unit is, therefore, also a vesiculation unit. Hawaiian pahoehoe flows are typically 1 to 20 m thick (average thickness 4.5 m; Walker, unpub. data), and their flow-units are commonly 0.1 to 5 m thick (average thickness 0.45 m). Near the top and bottom of each pahoehoe lava flow, the outermost 1 cm or so of the chilled margins are glassy; elsewhere the margins are finely crystalline.

In the following, we adopt the convention of using "bubble" to denote rounded voids in molten lava (generally they are >0.2 mm in size), and "vesicle" to denote the same voids in the solidified lava. The lavas that we studied also contain diktytaxitic voids (Dickinson and Vigrass, 1965), these being irregular intercrystalline voids that are generally <0.2 mm in size.

This study first concentrates attention on vesicles in the outermost roughly 6 cm, the selvage, of each flow-unit. The most common type of pahoehoe in Hawaii is spongy or S-type (Walker, 1989), in which the selvages contain very abundant, small and approximately

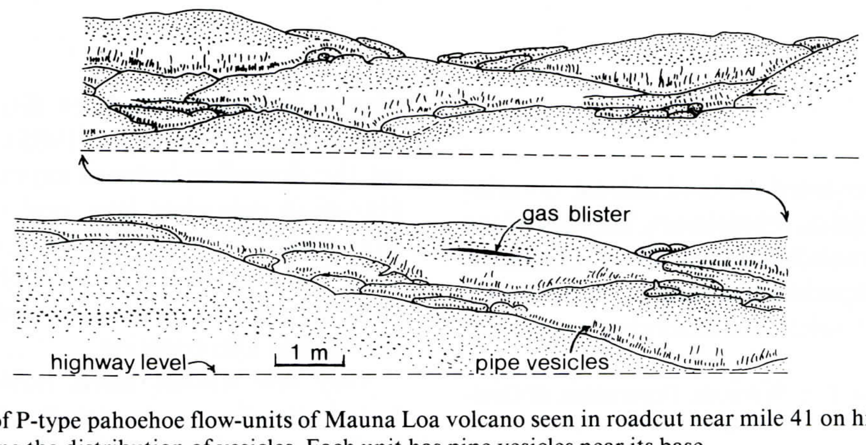
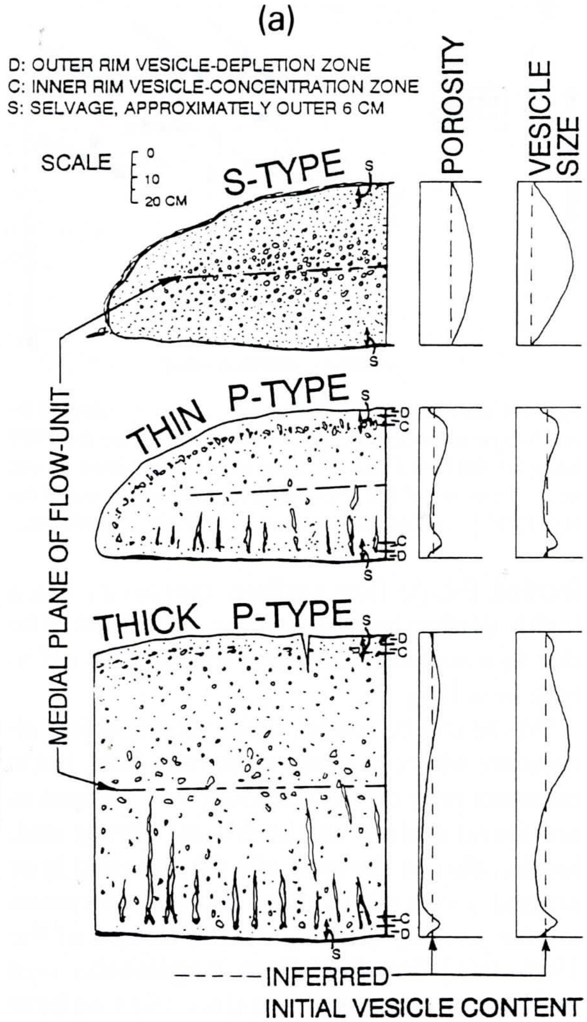


Fig. 1. Drawing of P-type pahoehoe flow-units of Mauna Loa volcano seen in roadcut near mile 41 on highway 11, Island of Hawaii, showing the distribution of vesicles. Each unit has pipe vesicles near its base.



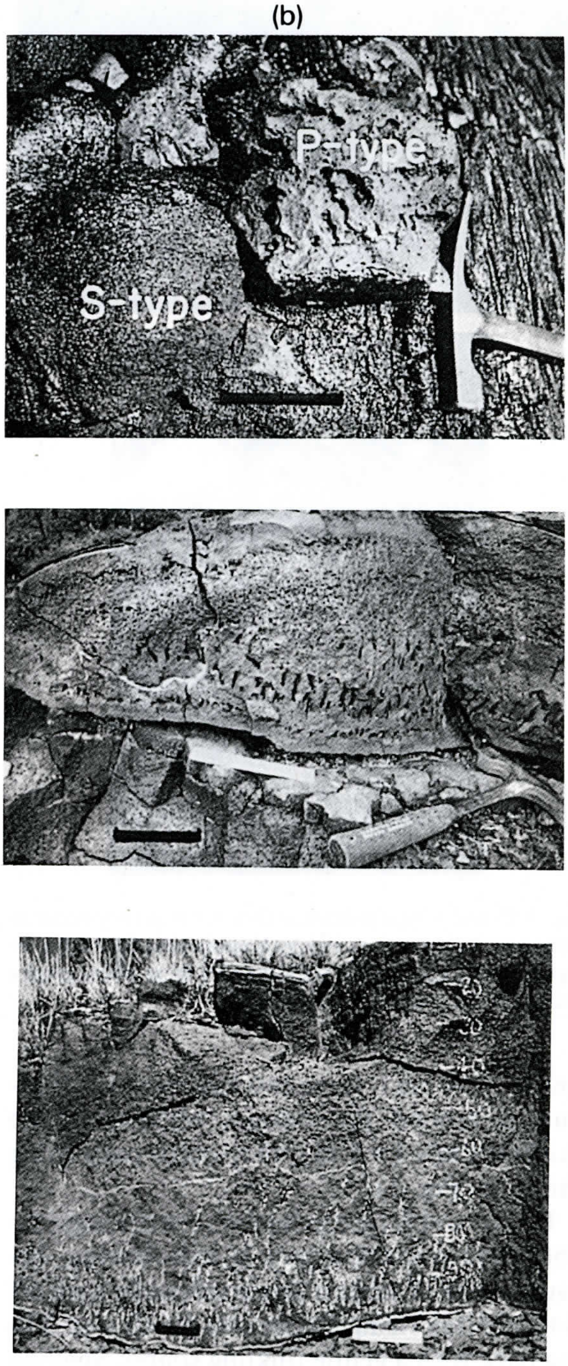
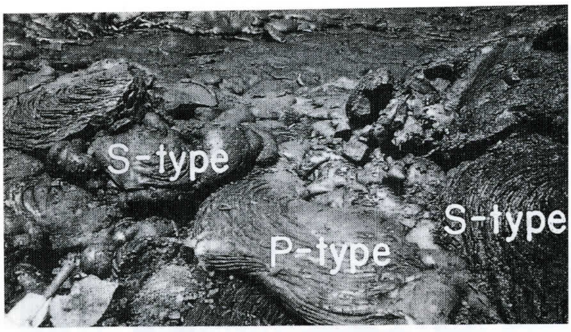


Fig. 2. Cross-sections of S- and P-type pahoehoe.
(a) Generalized drawings showing selvages and outer and inner rim zones, and porosity and vesicle-size profiles.
(b) Photographs. Upper: S- and P-type toes, Kupaianaha flow-field of Kilauea volcano. Middle: thin P-type pahoehoe, south coast of Kilauea. Lower: P-type, roadcut at mile 41 on highway 11. Scale bars are 15 cm.

spherical vesicles. Vesicles commonly comprise >40 vol.% of the rock and most of them are <4 mm in diameter. The somewhat less common P-type is much less vesicular (exhibits a lower porosity), has generally larger vesicle sizes, and has pipe vesicles near the base of each flow-unit (Fig. 1). Pipe vesicles are part of and stem from an inner-selvage vesicle-concentration zone - commonly 2–3 cm thick, rich in large vesicles - around which there is an outer-selvage vesicle-depletion zone, commonly 1–3 cm thick which has a low content of vesicles. A thin (outermost) part of this outer zone may be glassy. In the thinnest P-type flow-



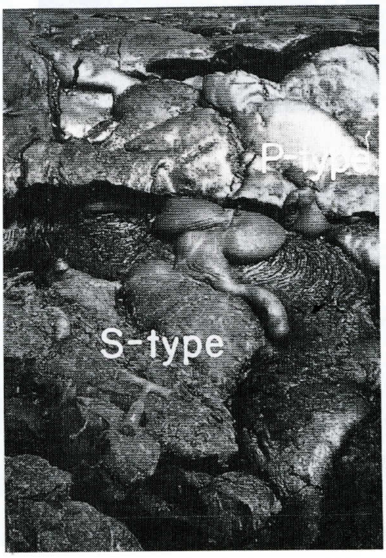


Fig. 3. P- and S-type pahoehoe flow-units as they occur in close proximity on the 1989-90 Kupaianaha flow-field. P-type appears lighter and smoother on these photographs because it lacks spalled-off material.

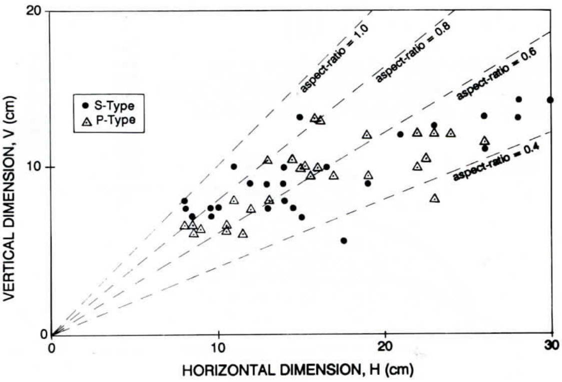


Fig. 4. Cross-section dimensions of randomly selected P- and S-type units occurring in close proximity on the 1989 Kupaianaha flow-field. All were measured at least 25 cm from the point of the toes. Dashed lines are of equal aspect ratio V/H. No systematic size difference is evident.

units (< 50 cm), these two zones are continuous all around the margin, whereas in the thickest units (> 2 m), they occur only along the base (Fig. 2).

P-type and S-type pahoehoe are distinguishable even when the lava is still flowing, because flakes of surface skin continually spall off S-type, often rising 50 cm into the air and falling back with a gentle tinkling sound. Spalling of S-type lava may continue for half an hour after visible flow has ceased. It presumably results from stresses set up by contraction of the cooling lava, easily relieved by spalling off the highly vesicular and mechanically weak skin. Spalling is negligible on P-type lava. The freshly formed P-type flow surface, moreover, has a highly distinctive bluish color, presumed to be due to a surface oxide film that spalled off S-type lava (Fig. 3).

P-type can be found, when searched for, almost anywhere in a pahoehoe flow-field, but is common only on the shallow (< 4°) slopes as are found mainly on the coastal terrace and, locally, also on the crest of a rift zone and in or around a summit caldera. P-type is common on the actively forming coastal terrace of the 1986–1992 flow-field from Kupaianaha vent on Kilauea volcano, where since 1989 we have often seen small flow-units of both types forming simultaneously, sometimes within ten meters of each other.

The smallest flow-units (toes) of P-type pahoehoe flow at the same velocity as, and are practically identical in size to, toes of S-type. The size relationship is shown by Figure 4.

Methods of study

Our study of down-flow variations in vesicle populations in flow-top selvages was conducted on Kilauea volcano along the eastern edge of the Mauna Ulu flow-field (mostly from the lava of 1972) and from the 1986–1992 Kupaianaha flow-field. Samples were collected from sites about 1 km apart down the length of each flow-field, and at each site an average of 5 random hand-samples of flow-top were taken. In addition, hot and freshly formed flows on the Kupaianaha coastal terrace were sampled on five separate occasions from 1987 to 1989.

The hand-samples were sawn into rectilinear blocks mostly between 10 and 100 cm^3 in size. On each sawn block, an average of 100 vesicle diameters 0.3 mm or larger were measured parallel with the flow top on a surface cut normal to the flow top and about 1 cm deep (attempting to measure all vesicles), from which the median diameter was derived. Bulk-rock densities of the rectilinear blocks were calculated after weighing the blocks in air and obtaining the volume of each block from its linear dimensions. Completely non-vesicular pahoehoe is rare in Hawaii, but samples with the lowest porosity give density values mostly in the range 2.93 to 3.05 Mg/m^3. A standard non-vesicular basalt density of 3.0 Mg/m^3 was therefore assumed from which to estimate the porosity. This estimate is considered good for lava that is crystalline and not picritic. Note that diktytaxitic voids as well as vesicles contribute to the porosity.

In our study of P-type flow-units, we sampled profiles across 20 P-type flow-units (mostly from road cuts on Kilauea and Mauna Loa), covering the thickness range of 8 to >290 cm. We cut rectilinear blocks from which we constructed porosity and vesicle-size profiles across each unit.

Results, part 1: Down-flow vesicle variations in pahoehoe flow-fields

Figure 5 plots down-flow variations in bulk-rock density and vesicle size in selvages of S-type pahoehoe. Vesicle size and porosity are greatest in proximal collecting sites where many of the flow-units are of the shelly type (Swanson, 1973) and have a crust 3–6 cm thick that is up-arched over a big gas blister. Voids, including blisters, may constitute 90% or more of the total volume of the flow-unit.

From proximal to medial sites, the porosity and median vesicle-size decrease and the vesi-

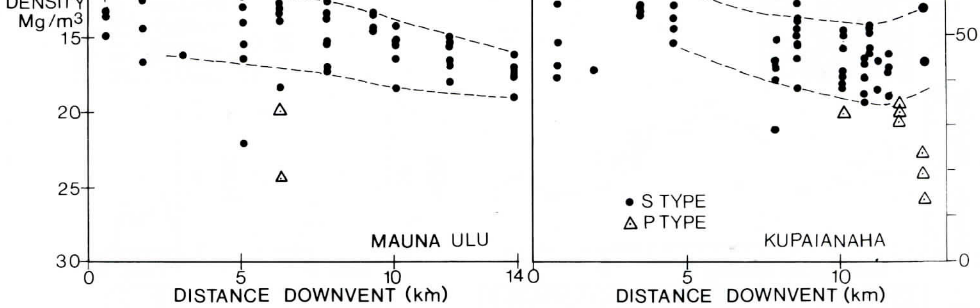


Fig. 5. Down-flow variations in median vesicle size and porosity in the upper 5 cm of crust in Mauna Ulu and Kupaianaha pahoehoe flow fields. Inferred porosity based on a density of 3.0 Mg/m^3 for non-vesicular basalt. Note the relative uniformity through each flow field, the small but consistent downflow variations, and the fact that P-type samples (i.e. outside the S-type trend).

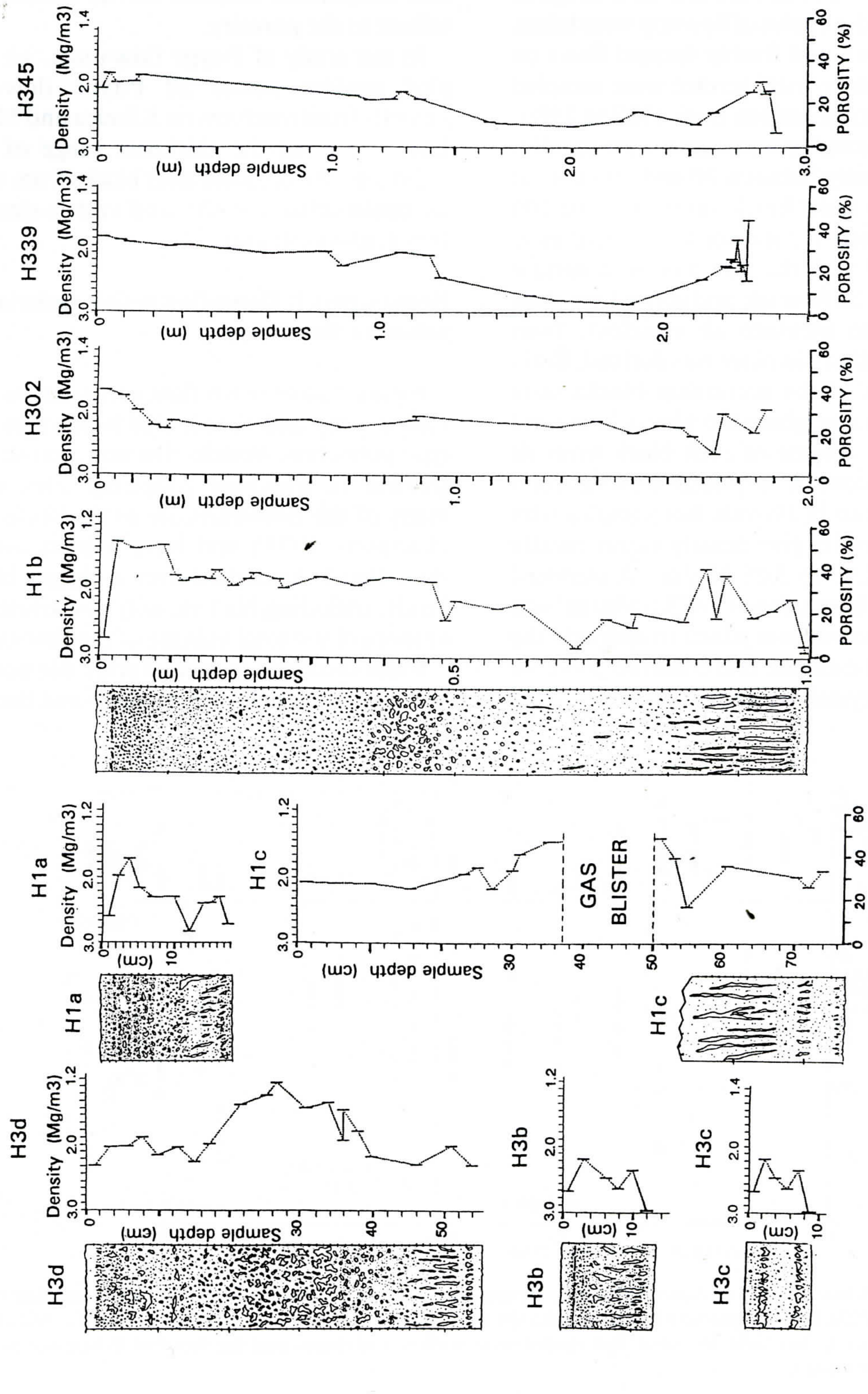


Fig. 6. Profiles across typical P-type pahoehoe flow-units, showing schematically the distribution, size, and shape of vesicles. The density profiles were determined on cut blocks; the inferred porosity is based on a density of 3.0 Mg/m^3 for non-vesicular basalt. Note varying vertical scales.

cle-size range also decreases. From medial to distal sites, the porosity decreases by a further 10% while the vesicle size begins to increase. In both the Mauna Ulu and Kupaianaha flow-fields, the distal sites occur on the shallowly inclined coastal terrace, and these changes are regarded as reflecting the decreased slope angle there. The lack of dependence on the absolute distance is illustrated by the fact that nearly identical vesicle populations are found on the coastal terrace in the 1859 Mauna Loa and 1801 Hualalai (Keahole) lavas, 45 km and 6 km respectively from their sources.

The more shallow slope of the coastal terrace is an environment where lava-rises and tumuli are best developed (Walker, 1991). Lava-rises, previously called pressure plateaus (Macdonald, 1967), are areas where the pahoehoe crust has been elevated by the injection of lava below. Tumuli (Daly, 1914) are whaleback hillocks, formed where subcrustal injection was concentrated, causing localized uplift with significant tilting of crustal slabs.

The systematic changes in the same flow-field (Fig. 6) are readily attributable to the slower flow of lava through, and longer residence time in, tubes on the more shallow slope, permitting significant bubble growth and loss. P-type pahoehoe becomes common on the more shallow slope of the coastal terrace, and this type simply continues the same development trends.

Interpretation

A basic element in our interpretation is that the upper crust or selvage of each pahoehoe flow-unit faithfully records, frozen in, the complement of bubbles present, when that particular lava emerged from the tube system and flowed to the surface. The lava contains a population of bubbles inherited at the vent, modified to a lesser or greater extent by bubble loss and bubble coalescence during travel in tubes.

Our evidence for these relationships is that the porosities and vesicle sizes: (1) are almost identical in upper and basal selvages; (2) are relatively uniform throughout most of the same flow-field (Fig. 6); and (3) in general increase inward in each flow-unit, attributable to vesicle growth by coalescence accompanied by some in-situ gas exsolution (Walker, 1989).

We consider that P-type lava acquires its characteristics during a relatively long residence beneath the surface crust in lava tubes, lava-rises, and tumuli. Growth of bubbles by coalescence and considerable bubble loss occur there without significant changes in temperature or viscosity.

We watched P-type pahoehoe emerging from many actively growing lava-rises and tumuli on the Kupaianaha flow-field. We also noted many examples of tumuli from which higher-level flow-outs of S-type occurred at an early stage of tumulus growth, followed by lower-level squeeze-ups of P-type which tended to become progressively more vesicle-poor as tumulus growth proceeded.

The similarity in size of S-type and P-type toes (Fig. 4) implies that the two types have the same viscosity. The S-type lacks the slightly higher aspect ratio that might be expected from the "stiffness" or foam effect imposed by the abundant vesicles. In part, this is due to the observed inflation of P-type toes which may be only 5 cm high when flowing, but expand by several centimeters as lava continues to be injected below the chilled skin.

Other types of pahoehoe exist in Hawaii having a distinctly larger minimum flow-unit size, implying a higher viscosity; they include toothpaste pahoehoe (Rowland and Walker, 1987) and rough pahoehoe (Rowland and Walker, 1988). They represent lava that did cool significantly during residence beneath the surface crust. The spinose or rough surface texture of these types also results from their higher viscosity.

Results, part 2: Characteristics of profiled P-type units

Figure 6 illustrates and Figure 7 summarizes the vesicle distribution patterns shown by the profiled P-type flows. All profiles show a peak in porosity where pipe vesicles are most abundant, 3 to 10 cm up from the base, and all have a significantly lower porosity (less than the average for the whole profile) between this peak and the flow base. We refer to these zones of high and low porosity as the inner and outer selvages, respectively.

An important difference exists between thin and thick P-type flow-units. In the thin units the inner high-porosity and outer low-porosity selvages occur right around the unit; vesicles in the inner selvage along the flow-unit top are relatively large (commonly 1 cm) but are not pipe-like. Commonly, the concentration of vesicles in the top inner selvage is sufficiently high that vesicles are joined laterally to produce a parting, and the outer selvage then easily lifts off the top of the flow-unit. In the thick units the inner and outer selvage zones are not distinguishable over the flow-unit top and the entire upper selvage has a uniform porosity of 15–35 vol.%.

Thin-walled gas blisters up to 30 cm high by 50 cm wide occasionally occur on the P-type lava surface where the glassy crust, typically 1–10 mm thick, is strongly distended.

The interior of thicker P-type flow-units (the part inside the top and bottom selvages) is consistently much more vesicular in its upper half than in its lower half (Fig. 7). Typically, the lower half has an average porosity of only 5–20%, compared with 20–35% in the upper half. The boundary between upper vesicular and lower, almost nonvesicular zones generally occurs nearly midway between flow-unit selvages.

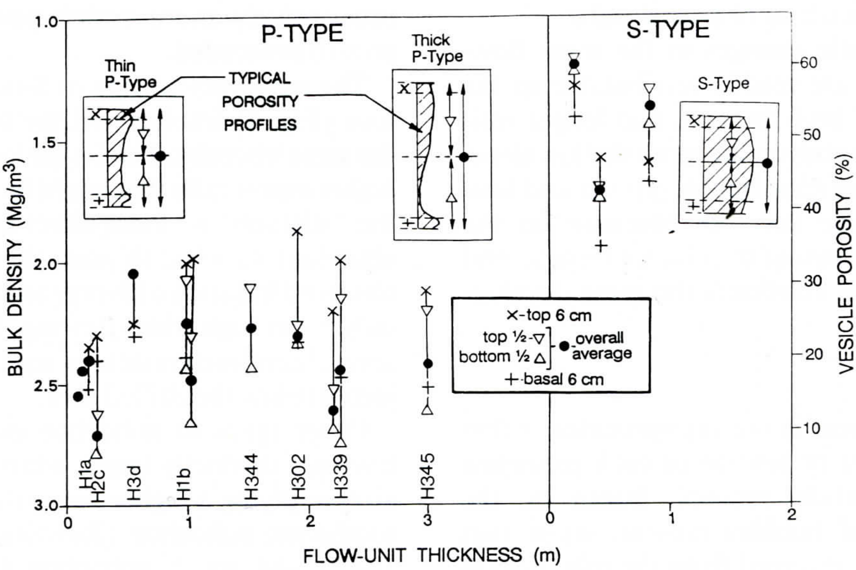


Fig. 7. Summary of porosity values, derived from bulk-rock density measurements, in profiled pahoehoe flow-units, plotted against flow-unit thickness. The top 6 cm selvage of the P-type units generally has a higher porosity than the average. Insets explain symbols used in the plots to illustrate typical porosity profiles that are characteristic of the various flow types (thin P-type, thick P-type, and S-type). The solid dot is the average density obtained by integrating the density profile for the whole flow-unit, and is consistently lower for P-type than for S-type pahoehoe. The open triangles give the average density for the half of each flow-unit above and below the median level; they tend to diverge as flow-thickness increases, due to upward migration of vesicles, and are more closely spaced in S-type pahoehoe. The lower selvage is consistently denser than the upper, attributable to upward forcing of gas bubbles out of the selvage.

Interpretation

Selvages of P-type flow-units include an outer-selvage in which the vesicle content is low and an inner-selvage in which the vesicle content is high. We interpret the outer selvage to be a depletion zone caused by a physical forcing of bubbles into, and their concentration in, the inner-selvage where pipe vesicles initiate. An alternative view (Philpotts and Lewis, 1987) that most of the vesicles in the lava represent gas exsolved in situ during crystallization and that the outer-selvage is less vesicular because it is glassy fails to explain the thin concentration zone of the inner selvage, the fact that the glassy selvage is only a minor part of the outer selvage zone, or why, in the top crust of thick P-type units and also in S-type pahoehoe, the vesicularity of the glassy rim is the same as that of the crystalline rock farther in.

In P-type pahoehoe, the inner-selvage concentration zone along the base contains pipe vesicles which project up toward the flow center. In thicker P-type flow-units, the average porosity of the two basal selvage zones is generally slightly less than that of the top selvage, suggesting that an overall gas loss has occurred from the basal selvage. We infer that pipe vesicles mark the avenues along which this gas loss occurred.

We have identified a physical mechanism that may be capable of causing such an inward migration of bubbles from the outer selvage: surface tension opposing deforming forces in the steep viscosity gradient of the cooling flow margins. Bubbles deformed by flowage tend to become elongate approximately parallel to equal-viscosity surfaces of the cooling flow-unit in the flow direction. Surface tension acts to oppose the deformation forces and tends to reinstate the smaller surface area of a spherical bubble shape. It is most capable of doing this in the direction of least viscosity, and the side of the bubble exposed to the least viscous lava moves in this direction of least resistance. The net result is that the center of mass of a deformed bubble is displaced down the viscosity gradient toward the center of the flow-unit.

The flow-top inner-selvage concentration zone containing large vesicles is best developed in thin P-type flow-units (<0.3 m thick), becomes increasingly diffuse as the flow-unit thickness increases, and is normally not recognizable in flow-units thicker than 2 m (Fig. 8). It is inferred that the mechanism causing the inward migration of bubbles operates only where vesicles are being deformed, which is in a velocity gradient. Pahoehoe toes have a sufficiently steep velocity gradient all around their periphery, whereas thick pahoehoe flow-units have a steep velocity gradient only along their base (Fig. 8).

In support of their formation in a velocity gradient, we note that pipe vesicles are almost invariably non-vertical, and commonly have a curved form.

We consider that pipes are initiated when an ascending bubble rises at the same velocity as the rheology front between lava having a yield strength and lava lacking a yield strength. The front of a bubble is then rising into lava that lacks a yield strength, while the back of the bubble is in lava having a yield strength sufficient to prevent closure. The rheology front is inferred to be a short distance in advance of the solidification front.

A simple calculation shows that at the level where pipes are initiated the bubble rises at the same velocity as the solidification front. At a crustal thickness of about 4 cm, our measurements show that the top crust of cooling P-type toes thickens at about 0.08 cm/min. The basal crust should thicken slightly more slowly, at perhaps 0.06 cm/min. Consider bubbles 4 mm in diameter (the typical width of pipe vesicles at their lower end). Assuming an effective viscosity (based on mafic-crystal settling relationships, Rowland and Walker, 1988) of 1500 Pa and a density of 1700 kg/m^3, such bubbles have a Stokes' Law ascent velocity of 0.06 cm/min.

With time, the pipe bubble accelerates as it

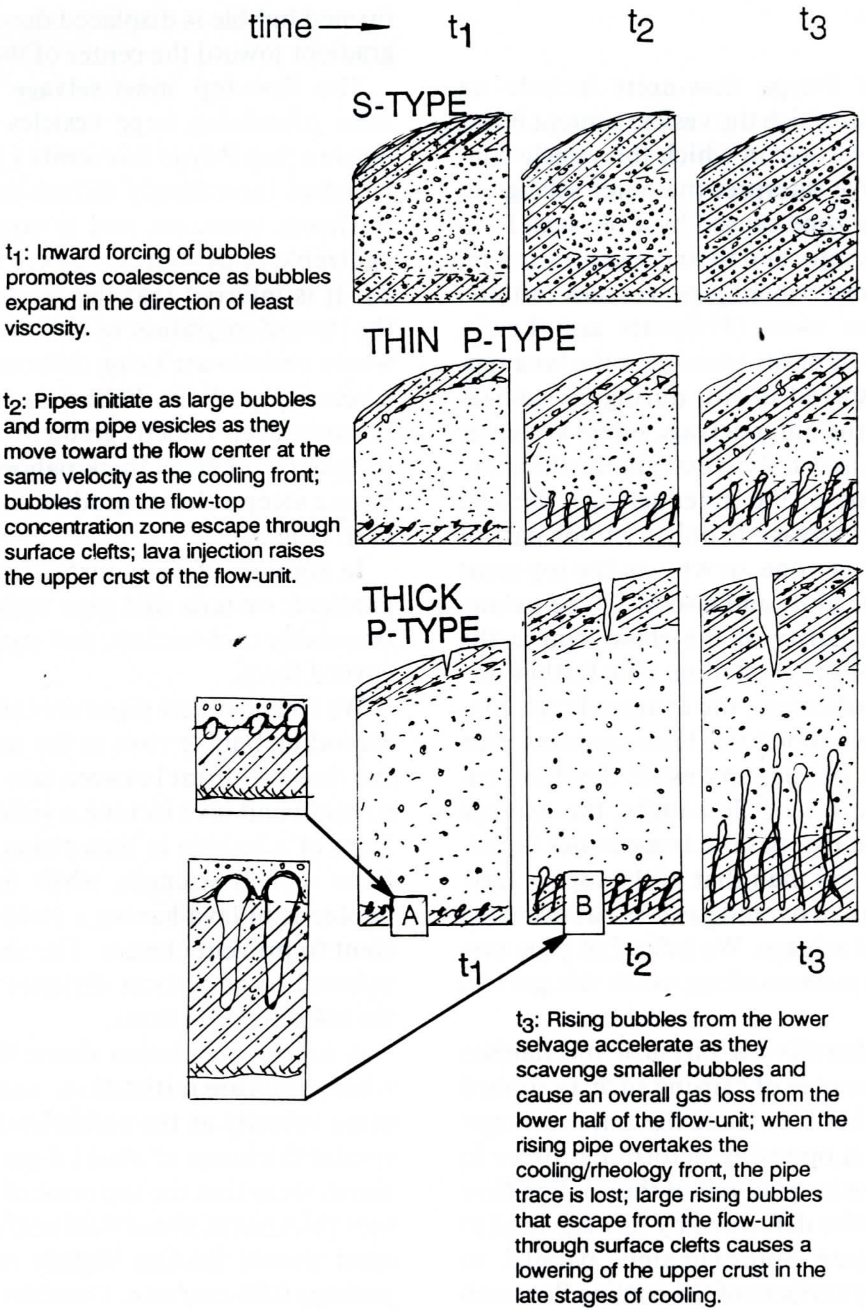


Fig. 8. Schematic diagrams showing inferred evolution of vesicle distributions. Solidified portion of basalt is shaded.

grows (by scavenging other bubbles; also by expansion due to decompression) but the solidification-front and rheology-front velocities decrease. The bubble, therefore, tends to become detached from the rheology front. Here, we think, another effect operates, namely cooling of pipe-bubble walls in their upper part by radiation into lower parts of the pipe (Philpotts and Lewis, 1987). This creates a thin cooler layer (like a glove) around the upper part that tends to inhibit bubble rise.

Although most pipe vesicles are short and usually extend only 10–20 cm above the base, a few pipe vesicles extend to about the medial level. A clear distinction should be made between the course taken by ascending pipe bubbles and the part of that course that is traced by a pipe vesicle. We suggest that most pipe bubbles record their passage (in the form of a vesicle) over only the lower part of their course, and the extension of occasional pipe vesicles up to the medial level suggests the possibility that all reached this level, but most of them failed to produce a pipe there.

Several of the flow-units studied (H1a, H1c, H3d) have two zones of pipe vesicles (Fig. 9). A zone of smaller pipes close to the base in the lower selvage is separated from a broader zone of larger pipes by a centimeter-thick zone of nonvesicular basalt. We infer that pipe growth was rejuvenated by lava injection within the cooled outer margins of the flow-unit; the lower pipes were formed as the solidification front rose about 2 cm, followed by injection of new lava, and the upper pipes formed as the new batch of lava cooled. One of the studied flow-units (H1c) has three zones of pipe vesicles (Fig. 6), suggesting that a second injection of new lava occurred. Flow-units with multiple zones of pipe vesicles often developed gas blisters in the medial planes, apparently because lava injection brought additional bubbles into the flow center and the top selvage, already cooled and lacking deep clefts, inhibited bubble loss.

Inward movement of bubbles apparently does not occur in S-type pahoehoe. Two possible causes are considered: (1) the high concentration of bubbles constitutes a foam that has a sufficient yield strength to resist deformation; and (2) the bubbles are smaller, and hence there is a smaller viscosity contrast across their width than in P-type.

To assess these, median vesicle size is plotted against porosity for upper selvage samples of P and S types (Fig. 10). A boundary between the two types based on porosity is much clearer than one depending on vesicle size, suggesting that the strength of foam prevented inward movement of bubbles in S-type, with a threshold porosity of about 30%.

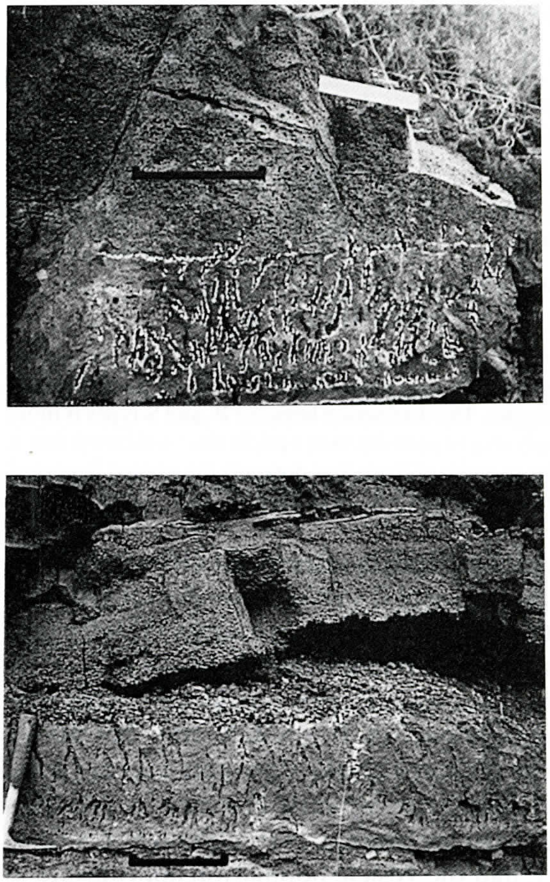


Fig. 9. Photographs of P-type units that show more than one zone of pipe vesicles, regarded as evidence of multiple lava injections within the cooled outer crust. Pipe vesicles in the upper photograph (mile 41 on highway 11) enhanced by chalk. The pipe vesicles in the lower photograph (Mauna Ulu lava on Chain of Craters Road) terminate upwards at the medial gas blister, and in this flow-unit the pipe bubbles collected to form the blister instead of losing gas through surface clefts. Scale bars are 20 cm.

Bubble ascent in flow-units

Following Walker (1987), we consider that the bubbles that rose had a larger diameter than the pipe vesicles that represent their traces and

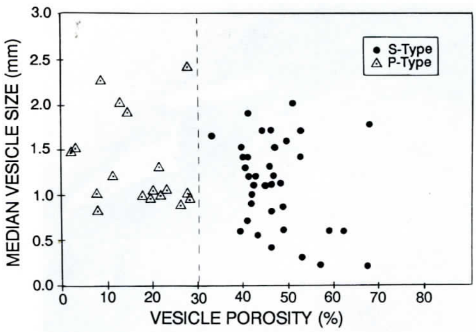


Fig. 10. Plot of median vesicle size against porosity in samples of the top several cm of selvage of the two pahoehoe types. The distinction between P- and S-types is more clearly one of porosity than vesicle size, indicating that it is the strength of foam that prevents the inward forcing of bubbles in S-type.

were consequently capable of efficiently scavenging vesicles from the lower flow-interior.

One of our profiled flow-units (H302) possesses the characteristics of, and is intimately associated with, P-type, but does not itself contain pipe vesicles. It is noteworthy that the interior of this particular flow-unit does not show any significant upward increase in porosity. Our interpretation is that, although this flow-unit had the vesicle population appropriate to P-type pahoehoe, the flow rate was sufficiently low that no significant inward forcing of bubbles occurred in the basal rim, so the bubbles did not grow sufficiently for pipe bubbles to form.

Bubble redistribution and loss

The fact that thicker P-type flow-units have a more vesicular interior in their upper half than in their lower half is, we think, best explained by large pipe bubbles scavenging other bubbles as they rose through the lower half. The inward forcing of bubbles from the basal outer selvage into the inner selvage is important because it actively promotes bubble growth at an early stage in the life of a lava flow-unit.

A critical element in our interpretation is that the upper crust of each pahoehoe flow-unit records, frozen in, the complement of bubbles present when that particular lava emerged from the tube system and flowed to the surface (except in thin P-type units in which concentration and depletion zones occur). Thicker P-type flow-units most often have an overall averaged porosity less than that in the selvages (Fig. 7) and we interpret this as due to a significant loss of bubbles from the flow-unit interior. Lava-inflation clefts such as are developed in lava-rises and tumuli are favorable avenues for bubble loss and allow degassing to occur without necessarily changing the temperature or viscosity of the lava.

A small proportion of P-type flow-units have gas blisters occupying a position at or above the medial plane, and several (H344, H1b, and H1c) were sampled in this study. In each, the averaged porosity is quite similar to the porosity of the upper crust. Vesicles clearly ascended in these flow-units but bubble-escape did not occur. Gas blisters developed instead when the concentration of vesicles exceeded about 40–45%.

Cooling rates of some P-type and S-type units

We determined the cooling rate of several 1986–1990 Kupaianaha pahoehoe toes by breaking them open at various time intervals after they became static and measuring the thickness of solid crust. We did this separately for S-type and P-type lobes, and our measurements (Fig. 11) demonstrate that the former has a cooling rate nearly twice that of the latter.

Heat transfer occurs by a combination of conduction through the basalt and radiant transfer across vesicles. Transfer of heat by radiation is much more efficient than conduction, and satisfactorily accounts for the difference between S-type and P-type (cf. Robertson and Peck, 1974).

The S-type crust thicknesses lie on a line extending that derived from drillholes through the crusts of Hawaiian lava lakes (Fig. 11), and conform well with the relationship that crust thickness is proportional to the square root of

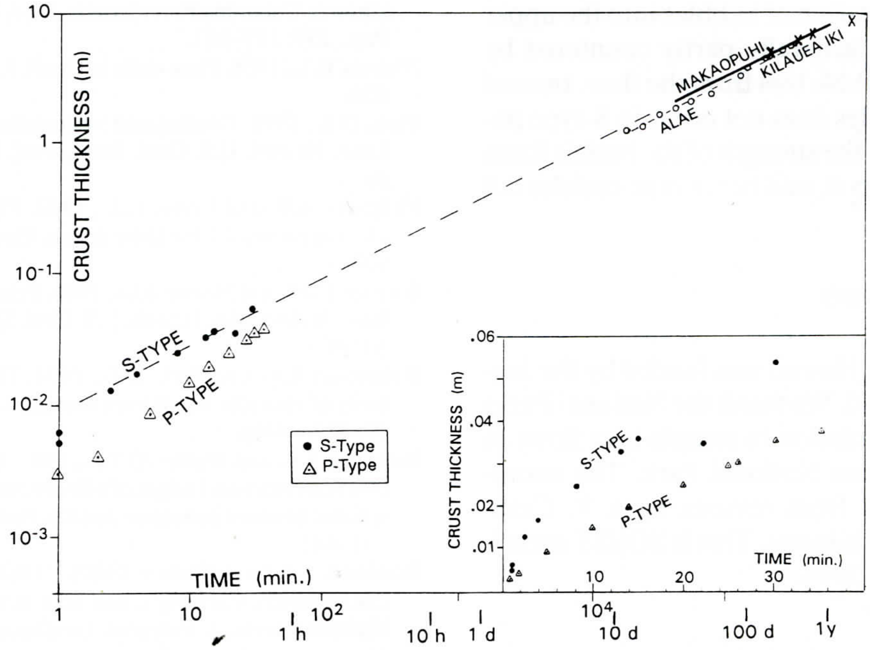


Fig. 11. Plot of crust against time, measured on active pahoehoe toes on the Kupaianaha flow-field on May 20 and May 26, 1989, plotted on an expanded, logarithmic scale to include drillhole data from Hawaiian lava lakes (Alae - Peck, 1978; Makaopuhi - Wright and Okamura, 1977; Kilauea Iki - Richter and Moore, 1966). Inset shows linear plot of time against depth below surface to the crust/melt interface of the Kupaianaha toes.

the time. The P-type crustal thicknesses do not fit so well, which may reflect the nonhomogeneous vesicle distribution in it. Cooling by conduction dominated the outer several centimeters and cooling by radiation dominated the inner-selvage.

Conclusions

The two pahoehoe types, P and S, characterized in this paper, differ considerably from one another in their internal structures. These differences record a subtle interplay of several processes.

We infer that at the time when the lava emerges from its tube system and flows on the surface, it contains a population of bubbles inherited at the vent, and modified to a greater or lesser extent by bubble loss and coalescence during travel and residence in tubes. That which emerges least-modified from the tubes contains >30% vesicles and becomes S-type pahoehoe; that which emerges most-modified contains <30% vesicles (having suffered vesicle loss during longer sub-surface residence) and if it has not cooled significantly becomes P-type pahoehoe. That which suffers vesicle loss and has cooled significantly may emerge as the more viscous toothpaste lava or rough pahoehoe.

In an average-length pahoehoe flow of S-type lava, the time spent in tube travel may be of the order of 1 hour or less; we consider that P-type may commonly reside for a day or longer in tubes before emerging at the surface. P-type squeeze-ups commonly develop on tumuli after the crust exceeds 1 m thick, implying more than a week of cooling. Considerable inward forcing of bubbles into an inner-selvage concentration zone occurs in the less-vesicular P-type pahoehoe. This forcing causes rapid vesicle growth by coalescence. The resulting bubbles then rise as pipe bubbles and effectively scavenge bubbles from the lower flow interior, while the resulting concentration of bubbles into the upper flow-interior is generally partly countered by considerable bubble loss from the flow. Inward forcing of bubbles does not occur in S-type pahoehoe because the strength of the bubble foam effectively resists it, and hence pipe vesicles fail to form.

Acknowledgements

Field work in Hawaii was funded by the Jaggar Bequest Fund. We thank the National Parks Service for permission to sample lava flows in Hawaii Volcanoes National Park. The manuscript benefited from reviews by K.V. Cashman and A.R. Philpotts. This is SOEST contribution number 3094.

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