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MAFIC-CRYSTAL DISTRIBUTIONS, VISCOSITIES, AND LAVA STRUCTURES OF SOME HAWAIIAN LAVA FLOWS

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Abstract

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The distribution patterns of mafic phenocrysts in some Hawaiian basalt flows are consistent with simple *in situ* gravitational settling. We use the patterns to estimate the crystal settling velocity and hence viscosity of the lava, which in turn can be correlated with surface structures. Numerical modeling generates theoretical crystal concentration profiles through lava flow units of different thicknesses for differing settling velocities. By fitting these curves to field data, crystal-settling rates through the lavas can be estimated, from which the viscosities of the flows can be determined using Stokes' Law. Lavas in which the crystal settling velocity was relatively high (on the order of 5×10^{-4} cm/sec) show great variations in phenocryst content, both from top to bottom of the same flow unit, and from one flow unit to another. Such lava is invariably pahoehoe, flow units of which are usually less than 1 m thick. Lavas in which the crystal-settling velocity was low show a small but measurable variation in phenocryst content. These lavas are part of a progression from a rough pahoehoe to toothpaste lava to a'a. Toothpaste lava is characterized by spiny texture as well as the ability to retain surface grooves during solidification, and flow units are usually thicker than 1 m. In the thickest of Hawaiian a'a flows, those of the distal type, no systematic crystal variations are observed, and high viscosity coupled with a finite yield strength prevented crystal settling. The amount of crystal settling in pahoehoe indicates that the viscosity ranged from 600 to 6000 Pa s. The limited amount of settling in toothpaste lava indicates a viscosity greater than this value, approaching 12,000 Pa s. We infer that distal-type a'a had a higher viscosity still and also possessed a yield strength.

Introduction

Viscosity is an important property of lava flows, but few attempts have been made to correlate it with the structures in lavas. It is generally recognized that pahoehoe on the whole forms from a more fluid lava than does a'a. There is however no simple correlation of lava type and viscosity because shear rate during flow is also important (Peterson and Tilling, 1980). Some observations indicate that the more mobile lava exhibits Newtonian behavior, but Hulme (1974) argued that even pahoehoe lava is non-Newtonian and possesses a yield strength, and Pinkerton and Sparks (1978) demonstrated the presence of a yield strength by measurements made on smooth-surfaced Etnean lava. Our study establishes a simple way to estimate the viscosity that a now-solidified lava flow had at the time it was moving.

Some basaltic flows carry phenocrysts of ol-

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ivine and/or augite which are considerably denser than the liquid and therefore tend to sink. We measured the variation of phenocryst content with depth in many flows. The distribution of these crystals through the solid lava should provide an insight into the rheological condition of the lava when it was fluid and yield quantitative estimates of the viscosity. We find that simple gravitational settling after the flow came to rest can quite well account for many of the distributions observed.

Gravitational settling of dense crystals has long been acknowledged as an important petrological process, but comparatively few studies have been made of the settling or sorting of crystals in lava flows and few have exploited crystal distributions as tools for understanding lava flows. Fuller (1939) clearly recognized that crystal-concentration and depletion zones in olivine-bearing pahoehoe lava from Oregon had been generated by settling of olivines, and he likened the process to "the deposition of sediments at the delta of a river". Church et al. (1964) and Yagi (1965) found that olivine content increased downward in pillows of an Icelandic pillow lava and used this to estimate the viscosity of the lava. A similar variation has been noted in basalt flows around the world (McBirney and Aoki, 1968; McBirney and Williams, 1969) and various explanations have involved flow differentiation and eruption from zoned magma chambers. Pinkerton and Sparks (1978) demonstrated that a smooth-surfaced Etnean lava possessed a yield strength which they correlated with a high crystal content; they explained the lack of obvious variations in crystal content through the lava by the presence of this yield strength.

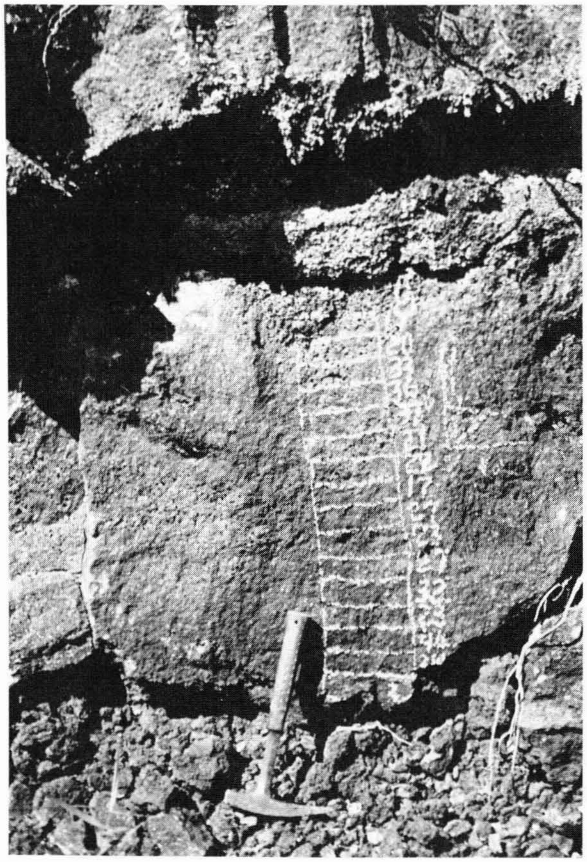


Fig. 1. Photograph of outcrop of 1868 lava flow of Mauna Loa, showing method of determining crystal counts vs. depth. Note numbers along right side of marked areas, indicating number of crystals greater than 4 mm in size counted in each area.

Method of study

We made field studies of mafic-phenocryst distributions in sections through selected Hawaiian lavas by marking off measured areas on rock surfaces, in bands 2 or 4 cm wide parallel to the top and bottom flow surfaces, and counting the number of mafic crystals exceeding a chosen threshold size in each area (Fig. 1). We also collected samples and repeated the crystal counts on sawn slabs in the laboratory; this was particularly necessary where the olivine had oxidized to a dark color and was hence rather difficult to distinguish from the matrix under field conditions.

The crystal counts we obtained (Fig. 2) are given as the number of crystals larger than a threshold size (chosen as 4 mm across) per cm^2 of counted surface; this is termed the 'C-number'. By numerical modeling we generated families of crystal-concentration profiles for different settling rates through flows of different thicknesses. A measured profile that compared well with a model profile for the same flow thickness was assumed to have a similar crystal settling rate. This enabled us to calculate the lava viscosity employing Stokes' Law.

The generation of variations in phenocryst concentrations

In many Hawaiian lavas the concentration of phenocrysts varies with depth. Typically the upper several centimeters has a moderate C-number. Below this zone, the C-number rapidly decreases, often to zero. This depleted zone usually persists to about half way through the flow. Below that, the C-number rises, surpasses the value in the upper zone, reaches a maximum, and drops again to attain a value at the base similar to that in the topmost zone.

We interpret the upper and lower C-numbers to represent the initial phenocryst content of the lava as it flowed from the vent. This value was frozen into the rapidly cooled top and bottom skins of the flow (Fuller, 1939). The flow began cooling as soon as it left the vent, but the middle portion remained hotter and fluid longer than the top and bottom parts. Crystals not frozen into the top crust were hence able to sink through the still molten interior of the flow (Fig. 3).

The lava acquired a yield strength as it cooled. A 'holding isotherm' can be defined as the temperature where the lava yield strength was sufficient to prevent a crystal of olivine bigger than the chosen threshold size from sinking. This temperature is probably about 1130°C (Shaw, 1969), the yield strength required to support a crystal 4 mm in diameter being around 4 N/m^2 (Sparks et al., 1977).

A zone devoid of crystals was generated when the crystal settling rate exceeded the rate at which the holding isotherm moved downward into the flow. Meanwhile, another holding isotherm moved upward from the bottom of the flow. Crystals settled through the middle of the flow only until they encountered this rising isotherm, upon which a relatively high concentration of crystals accumulated. The C-number thereafter decreases downward from the maximum to its initial value at the base of the flow.

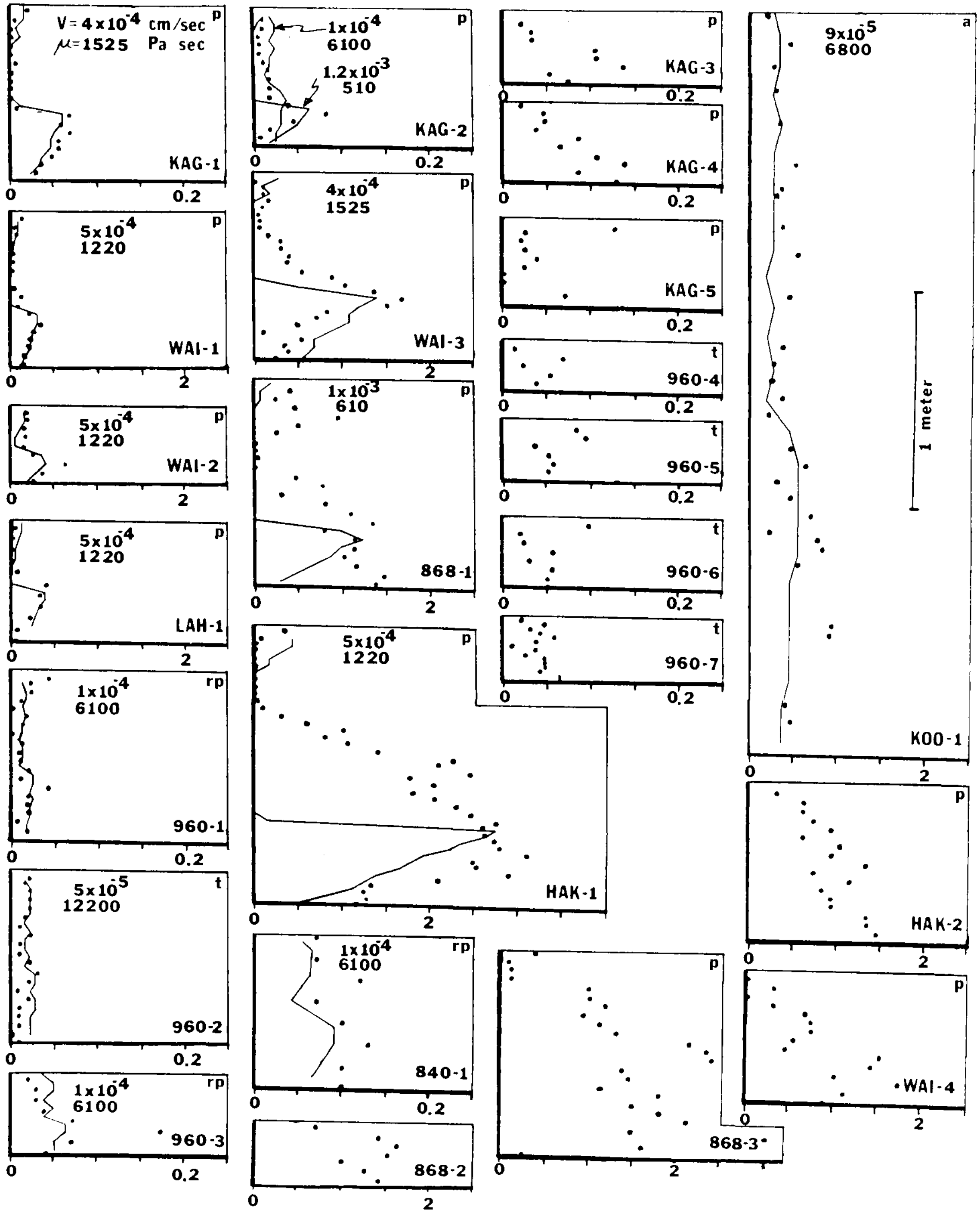
Phenocryst-distribution patterns

We observed a wide spectrum of crystal distribution patterns in Hawaiian flows we studied. At one end of the spectrum, flows show great variations in phenocryst content that occur laterally and vertically in the same flow unit as well as from one flow unit to another of the same flow. Parts of these flows show high phenocryst concentrations and have evidently been strongly enriched, while other parts are totally devoid of phenocrysts. Near the middle of the spectrum, the flows show small systematic vertical variations in phenocryst content, though only careful measurements establish their existence. At the other end of the spectrum, flows show a more or less uniform distribution of phenocrysts and there is no evidence that crystals moved through the liquid under the influence of gravity. In the following we describe specific examples of lava flows that illustrate the viscosity spectrum.

Highly-fluid lavas

An example of a fluid pahoehoe, a prehistoric flow, occurs low on the east rift zone of Kilauea, exposed in the 10 m high Halekamahina fault scarp north of the main vents of the 1960 eruption at Kapoho (KAG in Fig. 2). It has many flow units, most of which contain olivine phenocrysts. Some flow units have a lower concentration zone and a corresponding upper depletion zone, and the measured profile well matches modeled profiles consistent with the *in situ* settling of olivine crystals at 4×10^{-4} cm/sec. The concentration zone has a maximum C-number of 0.07.

Another example is the prehistoric Kapaloa pahoehoe flow, well exposed in cuts alongside the Sheraton Waikoloa Hotel (WAI in Fig. 2).


V = 4x10-4 cm/sec
μ=1525 Pa sec
KAG-1
WAI-1
WAI-2
LAH-1
960-1
960-2
960-3
KAG-2
WAI-3
868-1
HAK-1
840-1
868-2
KAG-3
KAG-4
KAG-5
960-4
960-5
960-6
960-7
868-3
KOO-1
HAK-2
WAI-4
1 meter

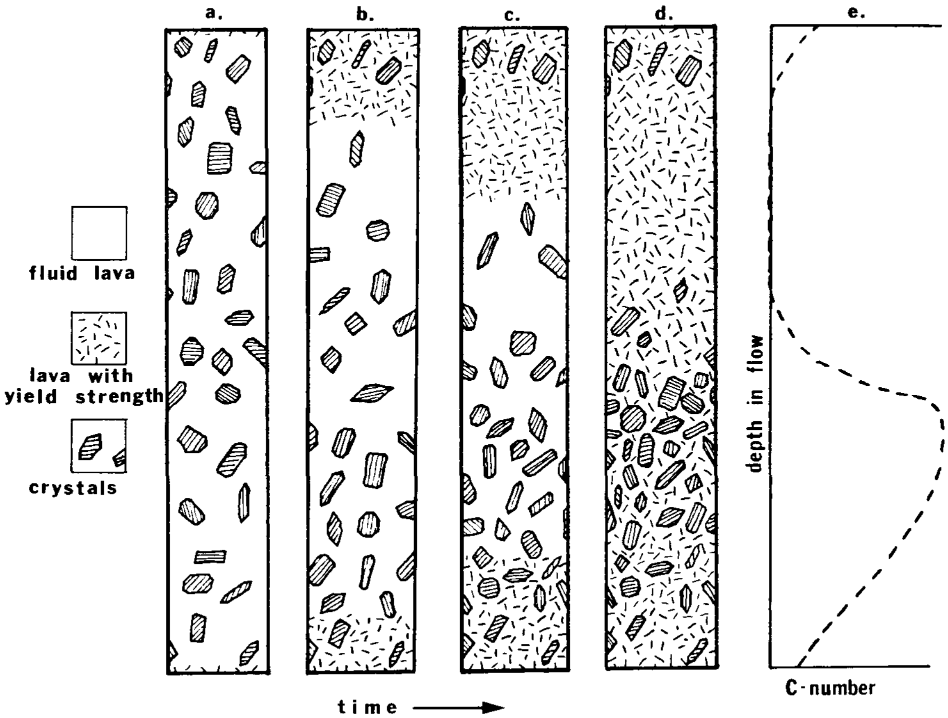


Fig. 3. 'Ideal' sinking process to cause distribution of crystals often observed. Blocks a, b, c, and d are arranged in order of increasing time. Boundary between the two zones is 'holding isotherm'. Note how original concentration of crystals is preserved in both top and bottom of flow. Block e is hypothetical depth vs. C-number graph for final distribution.

Mild explosions occurred where the flow entered the sea, building up a mound of flow units intermixed with scoria and coated with spatter. All of the flow units contain olivine phenocrysts, the largest of which measure 16 mm across. Typical flow units have a concentration zone, in which the C-number reaches about 0.5, and an upper depletion zone. Two measured flow units match modeled profiles for settling rates of 5×10^{-4} cm/sec.

One unit of the Kapaloa flow is connected by a dike-like feeder channel to the underlying flow unit. The margins of this lava dike were fed mostly from the depletion zone, while the middle was fed from the olivine concentration zone. The overall content of olivine in the overlying flow unit is less than in the concentration zone of the source unit. Slight crystal enrichment attributed to *in-situ* settling occurs toward the lower part of the overlying unit, indicating that

Fig. 2. Data collected in this study, presented as plots of C-number (number of crystals greater than 4 mm per cm^2) vs. depth, from various lava flows on Hawaii and O'ahu. Dots represent field data and lines show the results of best-fit numerical modeling for each distribution (some field data were impossible to match). Where a good match was made, settling rate used to generate modeled distribution is presented (top number in cm/sec) along with its corresponding Stokes' Law viscosity for a 4 mm olivine sphere (bottom number in Pa sec). Horizontal (C-number) scales differ to accommodate different absolute crystallinities. Vertical scale for all diagrams given by 1 meter reference at right. Three-letter codes correspond to locations as follows: KAG = Kapoho graben (Halekamahina fault); WAI = Sheraton Waikoloa (Kapaloa lava flow); LAH = Mauna Lahilahi (west coast of O'ahu); 960 = 1960 Kilauea E. Rift lava at Kapoho; 868 = 1868 Mauna Loa flow (in road cut 11 km west of Na'alehu); HAK = ankaramites of Hualalai volcano (exposed in and around Kailua); 840 = 1840 Kilauea E. Rift lava on the Puna coast; KOO = Ko'olau lava flow exposed in gulch 4 km south of Haleiwa, O'ahu. The code for lava type (top right corner of each graph) is as follows: p = pahoehoe; rp = rough pahoehoe; t = toothpaste lava; a = a'a.

lava viscosity was still low, even in a secondary flow unit.

Three other lava flows which we investigated showed crystal distributions indicative of low viscosities. The distributions in these particular flows were modified by extreme absolute crystallinity, however, and are described in a later section discussing modifications to gravitational distribution patterns.

Intermediate-viscosity lavas

Two structural varieties of pahoehoe that we singled out to investigate are rough pahoehoe and toothpaste lava (Rowland and Walker, 1987). Rough pahoehoe exhibits some features common to both pahoehoe and a'a. It represents a stage between them and almost invariably forms as a late ooze-out on pahoehoe flow fields, commonly as flow units 1 m wide and up to 10 m long (Fig. 4). It is ropy but more rough-surfaced than ordinary pahoehoe. Evidence of its intermediate viscosity is the formation of clinker along the margins of flow units. Some such units broke up wholly to clinker at their distal ends. Examples of rough pahoehoe are plots 960-1, 960-3, and 840-1 in Fig. 2.

A volumetrically more important variety of pahoehoe is toothpasta lava, which we interpret to form slowly from intermediate-viscosity lava which, if it moved faster, would form a'a flows. The surface of toothpaste lava is covered with characteristic spines and longitudinal grooves, both indicators of a viscosity greater than that of typical pahoehoe (Fig. 5). Buckles on the surface are analogous to pahoehoe ropes, yet are 20 cm or more across. Clinker occurs on the margins of flow units where shearing was highest.

Toothpaste lava is particularly common on the 1960 Kapoho flow of Kilauea volcano. Olivine phenocrysts occur rather sparingly and range up to 15 mm across. We measured olivine contents of the lava at 7 sites in the flow, some near to the vent and others near the distal end of the flow. These sites include rough pahoehoe, toothpaste lava, and a'a.

One particularly significant relation is that the C-number in the few centimeters of upper and lower crust is about the same in all mea-

Fig. 4. Rough pahoehoe of prehistoric Mauna Loa flow, showing representative combination of ropy structure and clinker on these flows. Proportion of clinker to ropes increases downstream. Flow was toward observer.

Fig. 5. Toothpaste lava on Kapoho 1960 flow, Kilauea. Characteristic pulse structures, grooves, and spiny texture shown. Flow from lower right to upper left.

sured sections (Fig. 2). The thickness of upper crust, within which the C-number is constant, ranges from 5 cm on the typical pahoehoe to more than 20 cm on the toothpaste lava. Our interpretation of this uniformity is that no significant crystal settling took place while the lava flowed from the vent to the measurement locations. Comparison of sinking rates with average flow durations strengthens this interpretation. The erupting lava must also have been homogeneous, with no significant variation in crystal concentration, during at least the later stage of the eruption when these flow units were formed (the earlier lavas were generally aphyric; Macdonald, 1962; Richter et al., 1970).

The C-number varies in a manner consistent with *in situ* crystal settling in the interior of each flow unit. It increases slightly but distinctly downward. The concentration of crystals is neither high (the C-number is less than 2 times that in the crust) nor very low (the C-number exceeds about 1/4 that of the crust). We interpret the measured concentration profiles to *in situ* settling of olivine crystals and infer that the settling rate was low, about 5×10^{-5} to 1×10^{-4} cm/sec, and took place mostly in the static lava during the relatively long time-period of *in situ* cooling (960-2 in Fig. 2).

One anomaly is that the average C-number of the flow-unit interior is generally less than that of the homogeneous crust. If no crystal enrichment occurred in the crust, some crystals were lost from the flow unit, after the crust formed but before flowage ceased. We found no sections in which the resulting crystal concentrations could be identified.

Relatively high viscosity lavas

In Hawaii, flowing lava having a relatively high viscosity forms a'a. Two types of a'a can be distinguished, proximal and distal (Rowland and Walker, 1987), which differ markedly in their characteristics and rheology. Proximal-type a'a has a viscosity similar to that of toothpaste lava and forms relatively fast-moving flows, usually less than 2 m thick, which advance like pahoehoe with a rolling caterpillar-track-like motion. Distal-type a'a flows in contrast, are commonly 10 m or more thick, and move more slowly, apparently by plug flow. Distal-type a'a thickens by shearing on internal sloping planes (ramp structures) and cascades of debris ranging in size from boulders to fine sand fall from the advancing flow-front and are pushed aside or over-ridden by the advancing flow.

Proximal-type a'a flows (KOO-1 in Fig. 2) have crystal concentration profiles closely comparable with those in toothpaste lava. No crystal settling is evident in distal-type a'a, it is thought because the lava had a yield strength too high to permit movement of crystals relative to liquid.

Factors that complicate sinking-generated crystal distributions

A small proportion of the lava flow-units that we investigated have crystal concentration profiles that do not conform in detail with those generated by numerical modeling. Two factors explain most of the anomalous flows. One is that a practical limit to the concentration of crystals exists at which the crystals are so closely spaced that they form a crystal-supported framework with interstitial fluid. The other is that secondary flowage of crystal-rich slurries or crystal-depleted layers can take place after sinking occurs.

A good example of a flow that was locally too crystal rich to allow further sinking forms the surface of Hualalai volcano in and near Kailua, Kona. It is well exposed in numerous shallow cuts up to 6 m deep and also in low coastal cliffs. Phenocrysts in the Kailua flow are mainly olivine and augite, in roughly equal amounts, reaching a maximum size of 16 mm. Small inclusions of gabbroic or diabasic rock with diktytaxitic texture also occur and have a distribution similar to the larger mafic phenocrysts.

In one particular flow unit of the Kailua flow, an aphyric upper layer 10 cm thick is underlain by an extremely porphyritic ankaramitic layer. The contact between the two layers is sharp (less than 1 cm across) and coherent. It is not a flow unit boundary. The extreme depletion and concentration of crystals in this flow unit (HAK-2 in Fig. 2) indicate a very low viscosity. The upper surface of the flow shows a slight ropiness, similar to that of hummocky pahoehoe (Swanson, 1973). The development of an upper layer completely devoid of large phenocrysts and the abrupt top of the concentration layer indicate that crystals sank rapidly. Crystals that sank to the concentration zone were stopped by other crystals, not by a holding isotherm. Probably the eruption concentration of crystals was high, not much less than that of the concentration zone.

The Mauna Loa flow of 1868, exposed in road cuts 11 km west of Na'alehu is also highly porphyritic. Its crystal distribution (868-3 in Fig. 2) shows a wide concentration zone with no well-defined peak, although a depletion zone exists beneath the top. Sinking was relatively rapid but stopped once the concentration reached a certain limiting value (C-number about 2.5).

We modeled the sinking of olivine in some of these crystal-rich lava flows (Fig. 2; WAI-3, 868-1, and HAK-1). Model profiles match the depth of highest concentration rather well, but not the zones of crystal depletion. We attribute this to the inability of crystal concentration to reach a C-number much greater than 2 in the flows, whereas our simple numerical modeling took no such maximum concentration limit into account.

The second major process that can affect the sinking-derived distributions is secondary flowage. At one place, the above-mentioned Kailua ankaramite contains an internal shear zone that juxtaposes contrasting settling-derived layers. Another Hualalai flow, exposed in a road cut near mile post 85 on the Queen Ka'ahumanu Highway north of Kailua, is a more extreme example. This flow has many thin pahoehoe flow units. Phenocrysts are nearly absent except in one flow unit, which has a concentration zone up to 40 cm thick of gabbroic

Fig. 6. Photograph of zone rich in xenoliths and xenocrysts in prehistoric flow of Hualalai volcano, Hawaii. Irregular boundary between this zone and host aphyric part of flow chalked for clarity (hatchures extend into host lava). Nowhere was this boundary wider than 1 cm. Irregularity of boundary suggests plastic deformation within still-fluid flow. Scale (near center of photo) 15 cm long.

or diabasic xenoliths which are up to 10 cm across as well as olivine and augite crystals up to 3.7 cm in size. The xenoliths and megacrysts in this zone have a more or less coarse-grain-supported fabric. The concentration zone is in sharp contact with the containing lava or grades into it over a few centimeters. The contact is very irregular (Fig. 6), suggesting that it did not form by *in situ* settling in its present position. Possibly an extreme crystal and xenolith concentration formed by settling, and then moved like an olistostrome within the flow unit.

Lava structural types and transport mechanisms

The lava flows that we investigated form a spectrum of rather distinct structural types. This spectrum is determined mainly by viscosity during flow and grades from common pahoehoe through rough pahoehoe, toothpaste lava, and proximal-type a'a to distal-type a'a. Increasing viscosity through the spectrum is evidenced by a number of structural features. For instance, the ease with which the surfaces can fold due to shortening (Fink and Fletcher, 1978) decreases as the viscosity increases. Pahoehoe can form 'ropes' less than 1 cm across, toothpaste lava has surface buckles up to about 1 m wide, and distal-type a'a flows have pressure ridges commonly many meters across.

The thickness of flow units increases as the viscosity increases. In pahoehoe, the strength of the surface skin partly controls the eventual thickness that a flow unit will reach. Flow units generally range from 10 to 50 cm (see Swanson, 1973). In distal-type a'a the high yield strength causes the flows to be 10 m or more thick.

Another feature related to viscosity is the nature of the conduits by which lava travels from the vent to the advancing flow front. Tubes and channels are conduits that allow lava to travel great distances from source vents with minimal cooling (Wentworth and Macdonald, 1953; Swanson, 1973). Tubes form almost exclusively in pahoehoe (Swanson, 1973) whereas channels can form in all lava types. Lava tubes require that the roof lava withstand the drag caused by the underlying flowing lava (Peterson and Swanson, 1974), which can happen only when that lava is fluid. On all the lava types less fluid than pahoehoe, any crust that forms cannot withstand the viscous drag and channels cannot roof over; lava tubes are hence scarce in proximal-type a'a flows and virtually nonexistent in distal-type a'a.

The formation of channels requires the margins of lava flows to cease moving while the middle continues (Hulme, 1974). Upstream from flow fronts, channelization occurs as the margins of flows cool and solidify or acquire a yield strength, while the centers continue to be supplied with lava. Channels commonly range from 30 cm to 30 m wide, and from 20 cm to 15 m deep. The channel rapidly supplies a large quantity of fluid lava to the distal part of the flow, feeding the advancing front which in turn becomes channelized. Lava flowing in a large channel is often unidentifiable as either a'a or pahoehoe, and only overflows give a true picture of the viscosity (Macdonald, 1953).

Constraints on numerical modeling

Figure 7 illustrates examples of numerically modeled crystal distributions. To determine the rate at which crystals sink, we need to know the descent rate of the upper holding isotherm. Analysis of data from lava-lake studies (Peck et al., 1964; Hardee, 1980) gives the following relation: $d = 0.14t^{1/2}$, where d is the depth to the holding isotherm (taken to be 1130°C) and t is the time in seconds. We also need to know the ascent rate of the lower holding isotherm. Lovering (1933) calculated the "turnover" depths of isotherms as they vary with cooling. From his work we assume that the height of the lower holding isotherm at any given moment above the flow base is 0.75 times the depth of the upper one below the flow top.

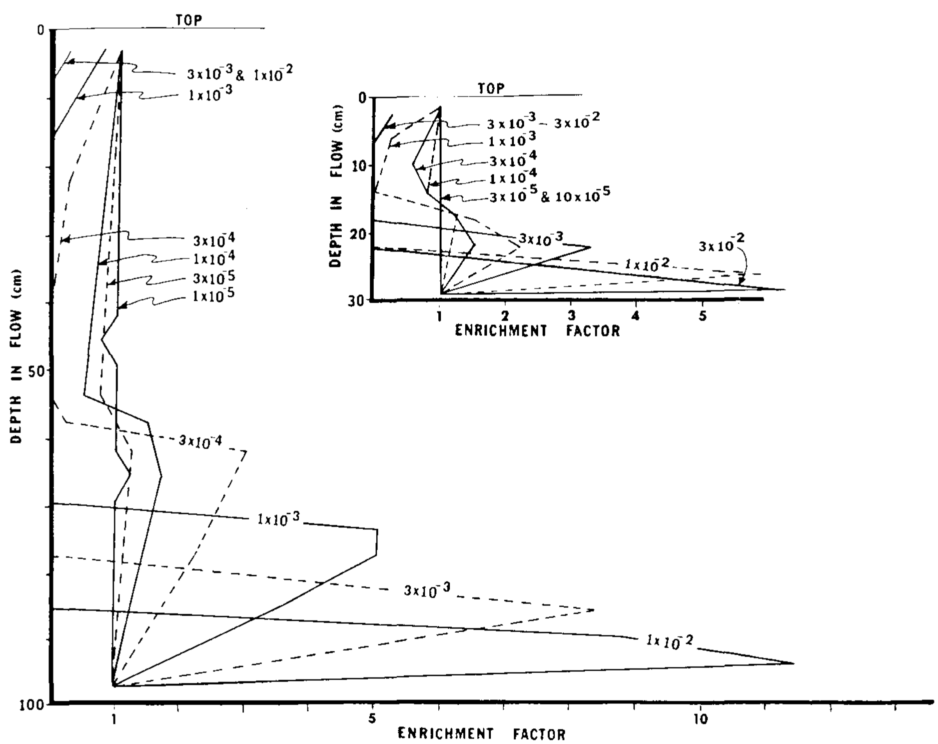


Fig. 7. Plots generated by numerical modeling of enrichment factor (= multiple of original concentration) vs. depth. For two flow thicknesses, seven curves have been plotted. Settling rate used to calculate each is given in cm/sec.

Lava passes through a range of viscosity as it cools, so our crystal sinking rates are average values. The viscosities that we calculate are therefore intermediate between the initial viscosity on eruption and the viscosity at the temperature of the holding isotherm though closer to the former.

Application of Stokes' Law assumes that the crystals are spheres (McNown and Malaika, 1950). Our crystals are not spherical, but they depart little from equant forms and the resulting shape error is small. Stokes' Law applies only to Newtonian fluids. Olivine crystals as small as 2 mm sank in the basaltic fluid, so the yield strength must have been less than 2 N/m^2 (Sparks et al., 1977). This is a very small value, so our assumption of Newtonian flow is good.

Laminar flow must be maintained during the sinking process. We determined the Reynolds number of the fastest-sinking crystals to be 6.5×10^{-11}, well within the range for laminar flow. We used density values for the basalt fluid and olivine crystals of 2600 and 3300 kg/m^3 respectively, but realize the difficulty in making realistic correction for vesicles in the fluid. Vesicles much smaller than the crystals would effectively reduce the density of the fluid. Vesicles comparable in size with the crystals collide with them and might reduce the settling rate. A high concentration of vesicles confers a yield strength to the liquid. Bubbles that nucleate on and remain attached to crystals reduce their settling rate possibly to the extent of conferring to them a positive buoyancy. A high concentration of gas bubbles will also change the shape of the temperature vs. depth profile in a cooling flow. All of these factors complicate the crystal-distribution profiles.

Summary and conclusions

We calculated viscosities for three types of basalt lava: typical pahoehoe, rough pahoehoe, and toothpaste lava. Typical pahoehoe is the least viscous (viscosity equals 600–1500 Pa s), rough pahoehoe is definitely more viscous (6000 Pa s), and toothpaste lava is more viscous still (12,000 Pa s). Distal-type a'a is either more viscous or possesses a yield strength or both. The values that we calculated fall well within the range of those previously published (cf. Macdonald, 1972).

We have been able to correlate numerous macroscopic lava properties (i.e., surface structure, flow thickness, pressure-ridge dimension) with estimated viscosity. By utilizing the distribution patterns of mafic phenocrysts, we have been able to quantify the viscosities of a number of the lavas in the overall lava-viscosity spectrum.

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