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PAHOEHOE, AA, AND BLOCK LAVA*

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ABSTRACT. Pahoehoe is characterized by a smooth, billowy, or ropy surface, and spheroidal vesicles. Aa is characterized by a fragmental and spinose surface, and irregularly shaped vesicles. Block lava differs from aa in greater regularity of the shapes of the fragments in the breccia phase, and less spinose surfaces. Beneath the fragmental tops of aa and block lava flows is a nearly continuous nonfragmental layer. Pahoehoe is a more primitive form, richer in gas, than aa. The three types of flows form a continuous intergradational series.

The formation of aa instead of pahoehoe is largely the result of greater viscosity resulting from lower temperature, smaller gas content, and more advanced crystallization. The typical spinosity of aa results from continued flow after loss of gas and crystallization have imparted a definite granularity to the lava. Fragmentation of the surface of the flow occurs at a stage determined by both viscosity and rate of flow. In more salic lavas the higher viscosity results in fragmentation at a lesser degree of crystallinity than in basaltic lavas, and the fragments of a block lava flow are therefore less granular and spinose than those of typical aa.

INTRODUCTION

THE purpose of this paper is threefold: to describe the structural features of recent lava flows as an aid to the recognition of similar flows in old geologic terranes; to point out certain fundamental relationships between pahoehoe, aa, and block lava, and set forth in so far as possible the apparent reasons for the formation of one type or another; and to attempt to correct certain persistent errors concerning the genetic relationships and structure of aa and pahoehoe.

Pahoehoe may be defined as the type of lava that in solidified form is characterized by a smooth, billowy, or ropy surface, and *aa* as the type characterized by a rough, jagged, spinose, and generally clinkery surface. To the ancient Hawaiians the terms had no further connotation, and the original definitions (Dutton, 1884, p. 95) implied nothing as to either internal

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structure or mode of origin. It is now recognized, however, that not only the surfaces but also in general the internal structures of the two types of lava are distinctly different. The internal structures, as revealed in cross section, usually are much more useful than the surface characteristics in the recognition of the different types of flow in old terranes. In this paper the terms aa and pahoehoe are used to designate the entire flow, and not only the flow surface. Primarily, the terms refer to the partly or completely solidified flows, though commonly the surfaces of the molten feeding rivers also are sufficiently distinct in appearance to make possible their recognition as one type or the other.

Although pahoehoe and aa are very distinct in their characteristic development, there is complete intergradation between the two forms. Examples occasionally are found in which the characteristics are intermediate, or in which some characteristics belong typically to one form and others to the other form. This fact of intergradation between the two forms is important in considering their origin.

Block lava resembles aa in its general appearance, but is less spinose and the fragments are less irregular in form.

Since their introduction to geologic literature by Dutton (1884), the Hawaiian terms pahoehoe and aa have come into common use the world over. Basic volcanoes everywhere produce lavas which are closely similar in forms to the aa and pahoehoe of Hawaii. In general the recognition of the two types in other regions is quite accurate and consistent. However, there appear to be some confusion and misunderstanding as to their genetic relationships and structure, not only among geologists, but among volcanologists as well. During conversations with geologists interested in volcanic rocks it has become apparent to the writer that many of them are unaware of the general presence beneath the fragmental tops and margins of aa and block lava flows of a nearly continuous layer of nonfragmental material. Also, several leading volcanologists have expressed the belief that live aa lava contains more gas than does pahoehoe, and the statement is gradually finding its way into geologic literature as fact. Actually, the observed relationships and internal features appear to indicate conclusively that the opposite is true. Admittedly the evidence is largely from Hawaii, but the flow types are so closely similar, if not identical, all over the earth that there is no reason to suppose the relationships are different in other regions.

Block lava is commoner than either aa or pahoehoe in the tectonic belts of the continents, but it appears to be only poorly understood by many geologists. Few geologists have had the experience of working with flows in regions of recent or present volcanism. Furthermore, workers in regions of fresh flows commonly either have not investigated the internal structures of the flows, or have not described them carefully in their published reports. Better knowledge of these structures will aid greatly in the interpretation of ancient volcanic rocks. It appears very probable that some of the breccias in old terranes which have been interpreted as pyroclastic are actually the fragmental portions of lava flows.

Recent pahoehoe and aa flows exhibit a great many structures. especially minor ones, which are seldom seen in ancient flows and which are not particularly germane to any of the purposes of this paper. These are touched upon herein only very briefly or not at all. Readers interested in greater detail of this sort are referred to a longer paper now in preparation (Wentworth and Macdonald).

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DESCRIPTION OF LAVA TYPES

Pahoehoe.—The surface of large pahoehoe flows is relatively smooth, with broad billows or hummocks, and locally rolls (plate 1, fig. 1). Small areas of ropy or corded surface are common, although not nearly as general as one would be led to understand from some textbooks.

The two principal characteristics of the internal structure of pahoehoe are the presence of lava tubes, either open or filled, and the smooth spheroidal shapes of the vesicles. After the initial burst of liquid lava the top of the flow becomes crusted over and the advance of the lava is almost entirely internal, through the resulting lava tubes. Major rivers may remain open near the vents, but even they become roofed over, with the exception of occasional small openings or "windows," within a mile or two of the vents. In mature flows the major feeding rivers commonly are enclosed in tubes almost continuously from the vent to the actively advancing flow margin.

There are two principal modes of advance of pahoehoe flows. One is exhibited by pahoehoe flows of high mobility and generally relatively small size. In it the entire front advances essentially as a unit, with a rolling motion. The upper part of the sheet of liquid moves forward more rapidly than the lower part, and at the front of the flow is rolled under and buried by the lava coming after it. The other and commoner mode of advance is observed in flows of moderate to low mobility. In these each large tube divides into many smaller ones, each of which feeds a lobe of lava at the moving flow front. The entire front advances by successive protrusion of one small bulbous toe after another (plate 1, fig. 1). Most toes advance only a few feet before they chill to immobility, after which the skin of the flow front ruptures at some other point and another toe is sent out. Many toes advance in essentially the same manner as the highly mobile pahoehoe flow-front described above. Others extend themselves by a process of inflation, the skin remaining unbroken, or if broken, quickly sealed again by lava squeezed from within. The front is gradually built up by the accumulation of a heap of these toes, generally 1 to 3 feet in diameter, lying alongside and on top of each other and closely molded to each other. A few of the central tubes which fed the toes are more persistent, continue to function as feeding tubes, and even become enlarged by melting and stoping away of their walls and roofs to form the major supply channels as the flow advances down the mountainside.

Some very hot pahoehoe streams close to the vents during Mauna Loa eruptions are almost wholly uncrusted. Commonly, however, ropy crusts form on them momentarily, only to be torn apart and floated downstream as dark rafts on an incandescent bubbling liquid surface. Thus the river pouring along the erupting fissure during the 1950 eruption had a bright orange surface agitated by lava fountains exploding through the river and with only scattered flecks of darker crust. Yet the crusts which were present showed the characteristic features of pahoehoe surfaces, and where overflows of liquid rolled over the banks typical ropy pahoehoe was formed. The surface of the lava river at the highway, 11 miles from the vents, appeared much like that at the vents except for a darker color resulting from lower temperature. But at the highway overflows formed aa, not pahoehoe, and fragments of crust on the river were aa.

Thin pahoehoe flows, and the upper part of thick flows, are characterized by very abundant vesicles. As was early noted by S. E. Bishop (cited by Hitchcock, 1909, p. 282), the vesicles typically are spherical or spheroidal, or composed of clusters of slightly to moderately distorted spheroids. The outlines of the vesicles are smooth regular curves. Many pahoehoe flows contain more than 20 per cent of these spheroidal vesicles, and it is not uncommon to find pahoehoe containing more than 50 per cent vesicles (Daly, 1911, p. 77). Some flows, especially in the summit region of Mauna Loa, are so rich in gas that they develop a surficial layer of exceedingly vesicular pumice (Finch, Powers, and Macdonald, 1948).

A heap of pahoehoe toes belonging to several successive flow units may appear in transverse cross section somewhat like pillow lava (plate 1, fig. 2), using the term "pillow lava" in the more useful restricted sense employed by Stearns (1938) and McKinstry (1939). It does not, however, have the same genetical interpretation as pillow lava, and its misinterpretation as such may lead to erroneous deductions regarding the geologic structure or history of an area. If they are well exposed, true pillow lavas can generally be distinguished without difficulty from pahoehoe toes. In general, in cross section each pillow gives an impression of radial structure, whereas each toe gives an impression of concentric structure (plate 1, fig. 2, and plate 2, fig. 1). When the forms are exposed in three dimensions it can be seen that the toes are commonly much more elongate than the pillows. The major axis of a pillow is seldom more than three or four times as long as the shorter axes, whereas a pahoehoe toe may exhibit a length along the principal axis of flowage several times greater than its cross-sectional dimensions. Three-dimensional exposures are comparatively rare, however. The following table lists some of the features useful in distinguishing two-dimensional cross sections of pahoehoe toes from those of pillows.

As pointed out by Stark (1939), the usage of the term "pillow lava" has in the past been exceedingly vague. It appears to the writer that the usefulness of the term can be much increased by restricting it to the forms herein termed pillows, as advocated by Stearns and McKinstry, the forms being distinct morphologically from pahoehoe tube structures as well as commonly having different environmental significance. The general term "ellipsoidal lavas" may then be used for any forms showing ellipsoidal cross sections, including both true pillows and pahoehoe toes.

Pahoehoe toes	*Pillow lavas*
Glassy shell commonly poorly developed.	Glassy shell generally well developed.
Commonly moderately to highly vesicular or amygdaloidal.	Commonly only moderately vesicular to poorly vesicular or amygdaloidal.
Vesicles commonly elongated tangentially or not at all.	Vesicles commonly elongated radially, especially near the edge.
Tube structures very common, resulting in axial cavities or forms resulting from the partial or complete filling of axial cavities.	Tube structures rare.
Radial joints generally poorly developed or absent.	Radial joints commonly well developed and conspicuous in cross section.
Interstitial spaces absent, or where present, open or filled with secondary minerals deposited by circulating water.	Interstitial spaces commonly filled with fine glassy debris or its alteration products, or with sedimentary material squeezed up from underlying bed or settled in from above.

Most pahoehoe flows are covered with a thin glassy skin (Powers, Ripperton, and Goto, 1932, p. 6). The skin commonly is a mere film, but in places it attains a thickness of an inch or even more. At least in some instances it appears probable that such exceptionally thick glassy skins have resulted from unusually rapid surface quenching, as by heavy rains (Finch, R. H., personal communication). While a pahoehoe toe is active the skin remains tough and flexible. It is so resistant to rupture that one can jump on the top of a small toe and cause the internal liquid to squirt out the end without breaking the skin on the top.

The skin commonly confines just below it a layer of gas bubbles risen from the underlying fluid. Most commonly the skin overlying the vesicle layer is less than a millimeter thick, and with weathering it soon flakes off. Occasionally the skin is puffed up as a distinct blister, as much as 3 or 4 feet across and a foot or two high, by the pressure of the accumulated gas. Close to some vents, especially on the upper slopes of Mauna Loa, there is an abundant development of so-called shelly pahoehoe. This consists of a mass of hollow toes and tubes covered by vesicular crust from 1 to 3 or 4 inches thick. The central cavities range from a foot to 3 feet or more in diameter. A few of the hollow tubes may have formed by draining away of the interior liquid, but many of the tubes and most of the toes along the edge of the flow could not have been formed in that manner, since there is no place for the liquid to have gone. These must have been blown up like balloons by the liberated gas.

Commonly the crust of an active pahoehoe flow remains sufficiently plastic to be dragged into twisted ropy forms and festooned folds by the movement of the fluid lava beneath. In most instances the curved ropes and festoons are convex in a downstream direction. However, local irregularities of flow may result in the festoon being convex upstream, and consequently this feature must be used with caution in an attempt to determine the direction of flowage from limited exposures in an old terrane.

During the brief interval before the flow crusts over, gas is liberated abundantly all over its surface. Many of the myriads of escaping gas bubbles drag behind them filaments of the viscous liquid lava. The filaments quickly solidify. In some instances they form sharp upright spines a millimeter or two high, but more commonly they bend largely or completely over before they become immobile and form an intricate lacy mass of threads on the flow surface. All these features, like the high vesicularity, point to high gas content in the typical liquid pahoehoe.

On some pahoehoe flows the crust has been fractured and broken up, and the surface of the flow consists of innumerable slabs tilted on edge, sometimes arranged in a fairly regular imbricated fashion, but more commonly lacking any regular arrangement (plate 2, fig. 2). This type of flow has been called slab lava by Jones (1943). The slabs are generally 2 to 6 inches thick and 1 to 4 or 5 feet across. Each shows one smooth or ropy surface, which once comprised the upper surface of the flow, and one rougher, more spinose surface which was formerly the under surface of the crust. Although the general aspect of the fragmental top resembles aa, each fragment is clearly pahoehoe. It is not uncommon, however, to find in this type of flow some development of spinosity and granularity indicating gradation toward aa, and in some slab lava a small amount of true aa clinker can be found associated with the slabs of pahoehoe crust. In some examples the fragmentation of the pahoehoe surface appears clearly to have been the result of increase of viscosity, accompanied by a transformation to aa, in the moving fluid beneath the crust.

Aa.—Aa lava is characterized by an exceedingly rough, jagged, or spinose surface (plate 3, fig. 1). Most of the surface is covered with loose fragmental material known as "clinker" or "flow breccia." The surficial clinker layer ranges in thickness from a few inches to several feet. Each of the fragments of clinker is exceedingly rough, irregular, and spiny. The general character defies verbal description, and an adequate idea of it is best conveyed by photograph (plate 3, fig. 1). Not all of the jagged surface material of the flow is loose clinker. Jaggar (1930, p. 3) has pointed out that many of the spinose boulder-like masses are rigidly connected with the solid central mass of the flow (plate 3, fig. 2). These apparently develop by a process of "sprouting" as the flow congeals. It appears probable that many of the loose fragments of clinker are formed by detachment of these spinose sprouts during movement of the flow, and somewhat modified in shape by attrition.

The clinker phase of the flow consists of fragments of all sizes from the maximum to fine dust. In many flows the maximum size of the clinker fragments is about 5 or 6 inches, but in some it is as much as 2 or 3 feet. In all flows there are a few scattered fragments larger than the general maximum. Commonly, however, there is a fairly definite upper limit of size with a large proportion of the fragments approaching it, and as noted by Krauskopf (1948, p. 1278) individual flows may be characterized more or less throughout their extent by coarse clinker or fine clinker. This has made it possible for Jones (1943) to classify flows as fine aa, medium aa, or coarse aa. Many of the fragments show evidence of some rounding by

Fig. 1. Pahoehoe of the 1919 lava flow on the floor of Kilauea Caldera. Note the smooth billowy surface, and the congealed toes along the edge of the upper flow unit. The latter is 12 to 18 inches thick.

Fig. 2. Ellipsoidal cross sections of pahoehoe toes, in the sea cliff near Waialua, island of Molokai, Hawaii. Note the distinct concentric arrangement of flow banding and vesicles, and the absence of radial structure. The toe in the center is 2 feet across.

PLATE 2

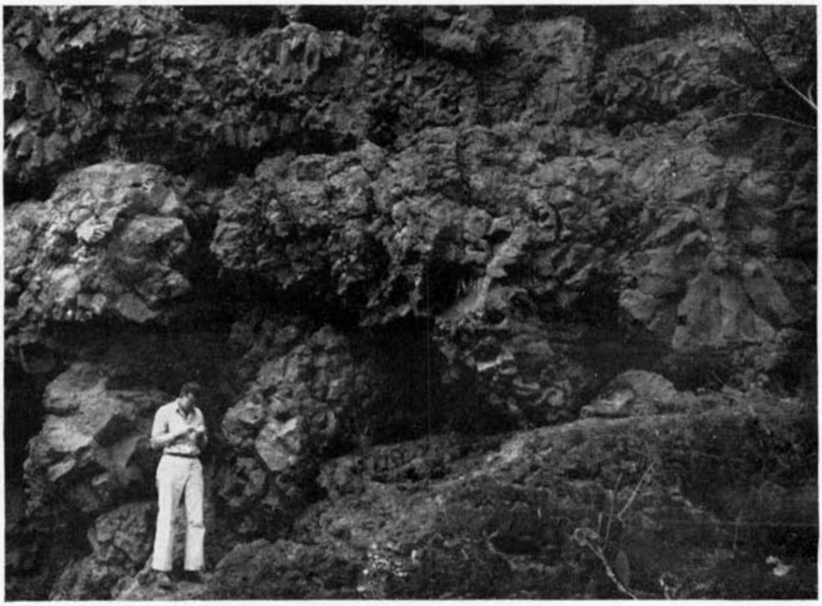

Fig. 1. Pillow lavas at the Menehune Ditch, Waimea River, island of Kauai, Hawaii. Note the radial structure. Photo by D. A. Davis.

Fig. 2. Slab pahoehoe, on floor of Kilauea Caldera, Hawaii. Each of the fragments is a sheet of pahoehoe crust. The camera case is 6 inches across.

mutual abrasion during movement of the flow. This same abrasion creates fine sand and dust which lie in the interstices between the larger fragments. Dust generally comprises only a very small proportion of the material, not nearly enough to form a continuous matrix for the larger fragments. In new flows the clinker phase is open-structured and very permeable to ground water, although in older flows, especially where they have been deeply buried, there is a great reduction in pore space owing to compaction and deposition of secondary materials. Commonly, even in new flows, below the surface the clinker fragments are stuck firmly together, apparently by adherence of still slightly plastic surfaces soon after movement of the flow stopped. This may be termed *welded clinker*, or *welded flow breccia.*

The fragmental phase of an aa flow does not closely resemble a pyroclastic breccia. The clinker fragments are quite distinctive in form, although difficult to describe, and differ in appearance from fragments of cinder or scoria. The principal differences are the denseness of the fragments and their spinosity. The breccia phase of some block lava flows (discussed later) rather closely resemble certain pyroclastic breccias, particularly in small exposures. In either aa or block lava flows gradation of the breccia into the massive phase serves to distinguish the breccia from a pyroclastic deposit. Also, the flow breccias are essentially monolithologic, fragments of rock types other than that which constitutes the flow being exceedingly rare. Pyroclastic breccias may also be essentially monolithologic, but admixture of other rock types is very much commoner than in flow breccias. Sorting, and bedding other than the general arrangement of phases in the flow and the succession of one flow on another are practically absent in flow breccias, and the presence of sorting or small-scale bedding may be taken as a criterion of pyroclastic origin.

Besides the clinker, there are present in the fragmental tops of many aa flows *accretionary lava balls*, formed by the rolling up of viscous lava around some solid fragment as a core (Macdonald, 1943, pp. 253-254). These balls range from a few inches to 15 or 20 feet in diameter. Their surfaces are for the most part rough and spiny, or even clinkery, although portions of the surface may be fairly smooth. On some flows they are abundant, but on others they are rare.

Typically, the upper clinker layer of an aa flow is underlain by, and grades into, a central massive layer (Macdonald, 1945). Only rarely and very locally is the massive layer lacking. Many flows also have a layer of clinker at the bottom, but that is commonly thinner and less persistent than the upper clinker layer (plate 4, fig. 1). The percentage of clinker in the flow commonly ranges from about 15 to 65 per cent, and averages less than 50 per cent.

In connection with the later discussion of origin of aa, it is important to note that the "sprouts" sometimes develop on extensive aa surfaces on which the crust is essentially continuous and loose clinker is nearly or entirely absent. At places of this sort the sprouts range in height from a quarter of an inch or less to 6 or 8 inches. It is possible that a few of them form by squeezing up through a dielike aperture in the flow crust, like the larger spines which are known to form in that way on the summits of many viscous domes (tholoids) and some thick viscous flows. Most, however, are so exceedingly irregular in form in all directions that they could hardly have formed in that way. Finch (personal communication) observed the formation of these spinose sprouts on a clinker-free aa surface during the 1920 eruption of Kilauea. He states that they seemed to grow almost like plants, and that there was no pulling apart of the crust involved.

Tongues of highly viscous lava of the sort termed "toothpaste lava" by some investigators (Bullard, 1947, p. 444; Einarsson, 1949, p. 31) may be squeezed out through openings in the flow crust, especially at and near the lower end of the flow. They generally show grooving and chatter-marks owing to friction against the sides of the opening. Commonly their surfaces are covered with characteristic small aa sprouts. Occasionally these "toothpaste" tongues are squeezed up through fractures in the flow top. They may be isolated or in groups, and rarely they may cover a fairly large area. Thus in the central part of a prehistoric aa flow near the southern coast of the island of Hawaii, between Punaluu and Kawaa, a series of slightly recurved grooved "toothpaste" squeeze-ups (Nichols, 1939), appearing almost like a series of breaking waves 2 to 4 feet high, occupies an area about 100 feet wide and 200 feet long.

The massive phase of aa is on the average distinctly less vesicular than pahoehoe, although there is great variation in the vesicularity of both types and it is possible to find many specimens of aa which are more vesicular than many specimens of pahoehoe. The vesicularity of aa may reach as much as 50 per cent, but it is generally less than 30 per cent. Typically the vesicles of aa (and block lava) are markedly irregular and distorted, and commonly they are much stretched in the direction of flowage. The contrast in vesicle shape between typical aa and typical pahoehoe is shown in plate 4, figure 2. Some exceptions exist, and gradational samples difficult to assign with certainty to either type are fairly common, but the general distinction between the shapes of aa and pahoehoe vesicles is quite marked and is a useful criterion for distinguishing the two types of lava in hand specimen or in cross sections of old flows in the field.

A typical active flow of aa consists of a main lava river, which flows in an open channel seldom more than 20 to 30 feet wide, bordered on each side by fields of clinkery aa as much as half a mile in width. The fluid lava of the river spreads out at the end of the flow to form the active front, and it also retains a close relationship with the central pasty layer which underlies the clinkery top in the marginal portions of the flow. On either side of the lava river, and particularly at the advancing front of the flow, the pasty central layer of the flow pushes outward. The marginal fields may continue to move slowly throughout the life of the flow, fed by the pasty central layer which in turn is fed from the main river. Surges of liquid lava in the main river may be accompanied by a slight swelling up of the marginal clinker fields, which may otherwise appear motionless (Finch and Macdonald, 1950, p. 8).

Generally aa flows are more viscous than pahoehoe flows, and advance much less rapidly than pahoehoe flows on the same slope. Commonly the most active part of the front advances only a few hundreds of feet to a mile or two a day. There are some exceptions, however. Thus the aa flows of the 1950 eruption on the western slope of Mauna Loa advanced at a rate of 1 to 2 miles an hour in the lower part of their courses (Finch and Macdonald, 1950, pp. 3-6). This high speed resulted largely from the steepness of the terrane, but partly also from lower than normal viscosity for an aa flow. The speed of advance of the flow front is to be distinguished from the speed of flow of the lava in the upper portion of the main feeding river, which may locally reach as much as 30 miles an hour.

The advance of a typical aa flow front takes place in the following manner: The black or dark reddish brown clinkery front of the flow may appear temporarily as a steep, relatively immobile bank. Its liveness is shown only by moderate fume liberation, the typical hot iron odor, incessant grating and cracking of surficial rock resulting from cooling and slight shifting, an occasional boulder tumbling down the flow front, and especially at night by innumerable glaring red spots showing through the clinker cover from the deeper parts of the flow. During such times radiant heat may be so low that it is possible to walk directly up to the flow front.

Gradually the flow front steepens and bulges, sometimes imperceptibly but at other times at an easily observable rate. Movement is greater near the top, resulting in a tendency for the top to overhang the lower portion of the front. Eventually the bulging results in instability at some point on the flow front, and a slab of dark clinkery rock peels off, breaks into fragments, and tumbles to the foot of the bank with a sound like the clinking of breaking crockery (plate 5, fig. 1). A talus bank of fragmental material forms against the base of the flow front. Attrition of the rolling fragments often results in a rising cloud of dust. At the point where the slab of rock broke away there is revealed a glowing hot face of the pasty lava in the interior of the flow, and radiant heat is suddenly greatly increased, making it decidedly uncomfortable to remain close to the flow margin. The falling and fracturing block also is generally incandescent inside. The exposed glowing paste is quickly chilled to a dark clinkery flow front, which again remains relatively immobile until bulging makes it unstable. In the meantime, the same process is going on at other points on the flow front.

In detail, the separation of the large fragment commonly is preceded and accompanied by granulation of the immediately adjacent material, producing streamlets of incandescent sand and pebbles down the flow front. In its final separation, the large fragment commonly tilts forward as the fracture behind it opens downward, until it finally breaks free and tumbles down the embankment. More rarely the block separates by gliding forward apparently on a forward-sloping fracture beneath.

The flow tends to advance over a layer of its own debris, formed by collapse of the repeatedly bulging front. The spasms of bulging may occur every few seconds, or at intervals of several minutes, depending on the activity of the flow. In very rapidly advancing flows it is essentially continuous, and the rolling of blocks down the flow front to its base, to be overridden by the advancing flow, gives somewhat the same impression as the forward rolling motion of tractor or tank treads.

Occasionally, particularly in thin flows, the pasty layer may move forward with little or no collapse of the front, chilling to form a spinose clinkery top, but developing little or no basal clinker. The gliding forward of the flow over an irregular surface may cause grooving of the lower side of the pasty layer.

The difference between aa and pahoehoe is sometimes not apparent in the appearance of the molten lava of the main feeding channel. The surface of the main river of an active aa flow may appear very much like that of an uncrusted river near the vents which is making pahoehoe along its edges, or even that of a large pahoehoe river viewed through a window in the roof of a tube. However, less active rivers commonly show evanescent skins of the type of material being formed at their margins. Thus a pahoehoe river commonly develops thin skins of ropy pahoehoe, and an aa river shows a tendency for the development of a clinkery and spinose surface.

There are some instances in Hawaii of aa being erupted directly from the vent. Dikes, many of them probably the feeders of surface flows, occasionally show the vesicle forms of typical aa, and rarely even the fragmental structure of aa (Stearns, 1940, pp. 39-40). Generally, however, the lava issues from the vent as pahoehoe. There are some examples, like the Mauna Loa flow of 1881, in which the lava remained pahoehoe flowing in tubes all the way to the terminus of the flow, many miles downslope. More commonly, however, the lava changes from pahoehoe to aa within a few miles of the vent. It is very common, in fact it is the normal sequence of events for a flow to change from pahoehoe to aa during its course. Often the last lava to move through a large pahoehoe tube is aa, which consolidates to form a typical spinose aa surface on the floor of the tube.

In contrast, the reverse change, from aa to pahoehoe, is unknown. A few examples which on first sight appeared to represent changes of aa into pahoehoe on further examination appear almost certainly to have resulted from a pahoehoe flow burrowing under a slightly older flow of aa and emerging at its snout. The statement has been made in some older literature on Hawaiian volcanoes that early flows of aa changed to pahoehoe as the eruption progressed. Apparently, however, what actually happened was that later pahoehoe flows advanced over and beyond earlier aa flows. Although that is not the most common sequence, it has been observed during several eruptions. It is not at all the same as a change of the same flow from aa to pahoehoe. The latter has never been substantiated.

Block lava.—True aa appears to be confined in its occurrence to basaltic lavas (including basaltic andesites and the ultramafic feldspathoidal lavas). The more salic lavas characteristically exhibit a form much like aa, but distinct from it in the absence of the spinose character typical of aa. Finch (1933) has proposed that this type be termed *block lava,* thus restricting a term used by many German and Dutch writers for partly fragmental lavas in general, including aa. Block lava is distinguished from true aa by the fact that the individual fragments are relatively smooth polyhedral blocks bounded by dihedral angles, lacking the exceedingly rough and spinose character of typical aa (plate 5, fig. 2). In other words, in block lava the fragments are more regular in shape and tend to have somewhat smoother faces than do those in aa.

It is common to find much variation in the smoothness of the faces of the blocks. On a single block some faces may be smooth, but others spinose. In typical block lava, however, the spinosity seldom even locally equals that characteristic of aa. To be sure, some flows are difficult to classify as one form or the other. I have never observed a gradation from aa to block lava within a single flow, but in separate flows every gradation in form of fragments and spinosity from typical aa to typical block lava can be found.

The overall structure of block lava is essentially identical to that of aa. Commonly the flows are thicker and slower moving than those of aa. Typical aa seldom attains a thickness as great as 50 feet except where it is ponded, and most flows are less than 30 feet thick. In contrast, block lava flows quite commonly exceed 50 feet in thickness. Both the fragmental and massive parts of block lava flows generally contain a larger proportion of glass than do the corresponding portions of aa flows. Also, the fragmental material typically makes up a greater proportion of the flow, and more commonly than in aa constitutes the whole thickness of the flow. However, even in block lava the absence of the central massive layer is a purely local condition. In most places the massive phase is present, overlain and generally underlain by breccia. In exposures that are continuous for several hundred feet the massive phase generally can be seen near the base of the flow, as a continuous bed or a series of lenses grading upward and laterally into the breccia.

I have not had the opportunity to observe directly the movement of an active block lava flow. However, a photograph by Einarsson (1949, plate 3, fig. 1) demonstrates clearly that the dense lava of the 1947-48 eruption of Hekla is typical block lava. Einarsson's excellent description of the movement of this type of flow (1949, pp. 26-30) during the Hekla eruption indicates a close similarity to the movement of aa, except possibly for a greater degree of separation into discrete plastic layers within the flow and more abundant formation of "toothpaste" type tongues.

Examination of old flows suggests that block lava flows more commonly advance by sliding or gliding over the surface of the underlying material than do aa flows. In some instances they act as plows, in much the same manner as some glaciers. Advancing over soft material they may push some of it up ahead of them, and they may locally groove and striate the underlying surface. Probably the sliding motion is restricted to the portion of the flow close to the advancing front, and movement farther back in the flow takes place by true viscous flowage.

REASONS FOR THE DIFFERENCE BETWEEN AA AND PAHOEHOE

The reasons for the formation of pahoehoe and aa have long been a subject of debate. The facts bearing on the problem are as follows:

1. Both pahoehoe and aa commonly form in the same flow.

2. There is no appreciable difference in chemical composition between the solidified pahoehoe and aa of the same flow, although there may be a slightly higher degree of oxidation of the iron in the aa (Washington, 1923).

3. A flow of pahoehoe may change downslope to aa, but the change of aa to pahoehoe has never been observed.

4. Floods of highly gas-charged lava near the vents in early stages of Hawaiian eruptions are always pahoehoe, which commonly changes to aa only a short distance downslope.

5. In contrast, during long eruptions, after the initial lava fountaining dies down, flows of pahoehoe may develop which continue for great distances down the mountainside before changing to aa. Some, such as the 1881 flow of Mauna Loa, may remain pahoehoe to their ends.

6. Pahoehoe commonly changes to aa where it pours over a cliff or steep slope, and the flow remains aa for the remainder of its course below the escarpment.

7. Both pahoehoe and aa, on remelting in the laboratory, yield aa when stirred (Emerson, 1926).

8. Pahoehoe tends to be more vesicular than aa.

9. The vesicle shapes of pahoehoe typically are regular spheroids and clusters of spheroids; those of aa are exceedingly irregular and much deformed.

10. An active pahoehoe flow appears to give off more gas than aa. Thus during the 1950 eruption of Mauna Loa it was impossible to approach close to the lee side of the pahoehoe river near the vents, because of the large amounts of choking gas being liberated. In contrast, although the intense radiant heat and the oxygen-deficient hot air made it decidedly uncomfortable, it was possible to cross the slow-moving marginal fields of the aa flows farther downslope and approach the edge of the main river without detecting more than slight traces of gas.

11. An active pahoehoe flow is in general more mobile and freely flowing, and therefore less viscous, than aa.

12. The groundmass of the central part of a pahoehoe flow is more commonly partly glassy than that of the corresponding part of an aa flow, in flows of the same composition and of comparable thickness.

13. Commonly, although not always, active pahoehoe flows have a tough flexible skin capable of undergoing much stretching and distortion without fracturing.

14. In general, the temperature of liquid pahoehoe appears to be higher than that of aa. During the 1950 eruption of Mauna Loa the temperature of the pahoehoe river near the vents was close to 1050° C., whereas that of the aa river on the lower slopes of the mountain ranged from about 900° to 920°. Crusts

Fig. 1. Clinkery top of the southernmost aa lava flow of 1950 near the highway on the western slope of Mauna Loa. The jagged crag (or "sprout") in the center is about 5 feet high, and is continuous with the massive central phase of the flow.

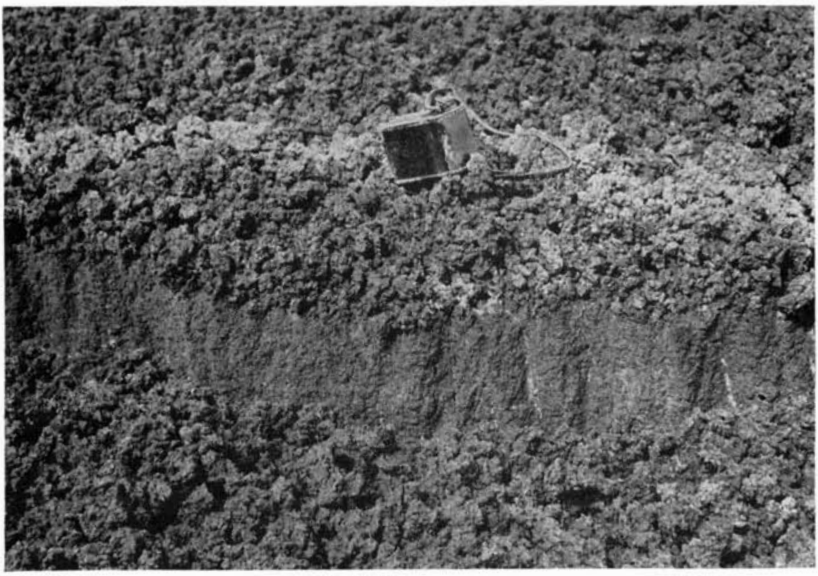

Fig. 2. Cross section of the upper part of an aa flow formed in 1920 on the southwest rift of Kilauea, exposed in a crack. The massive central phase of the flow grades upward into a clinkery layer only about 4 inches thick. Most of the fragments of clinker were never detached, but remain firmly anchored to the massive phase. The camera case, about 6 inches long, is lying on top of the flow.

PLATE 4

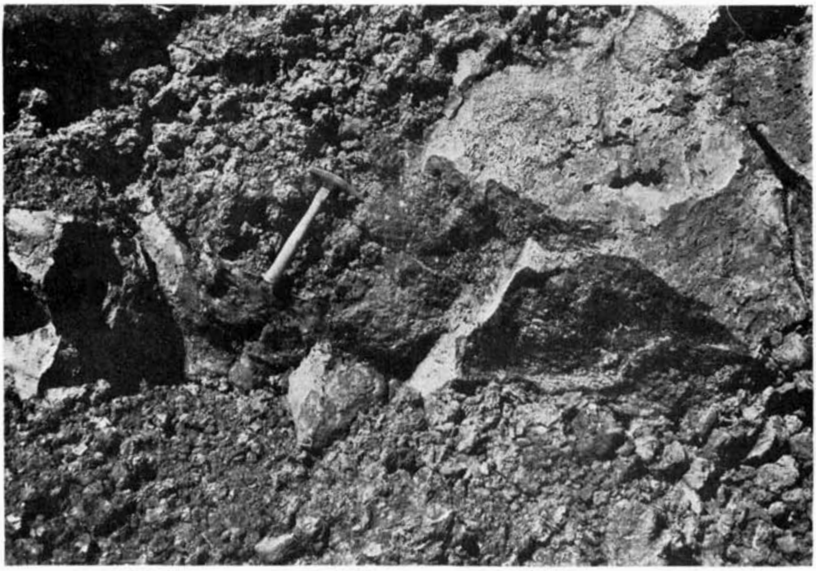

Fig. 1. Massive central phase of an aa flow grading upward and downward into clinkery fragmental material, on Hawaii National Park truck trail on the southeastern slope of Mauna Loa. Note the irregular shapes of the vesicles in the massive phase.

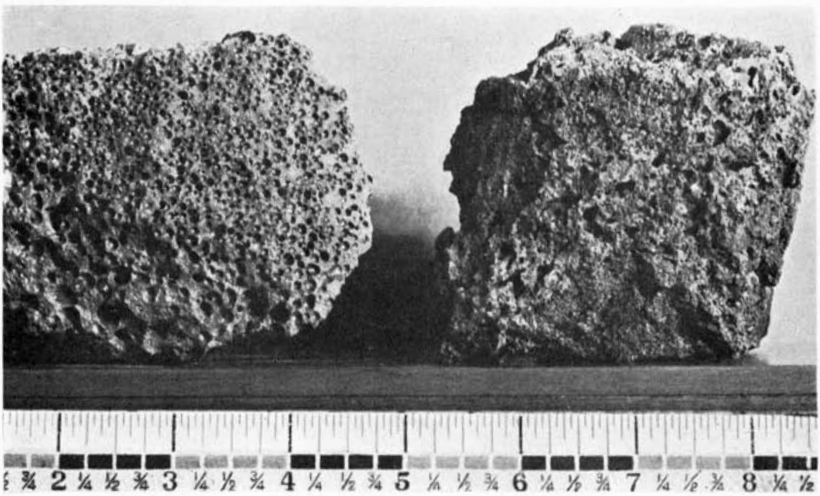

Fig. 2. Hand specimens of pahoehoe (left) and aa (right) showing the marked contrast in typical vesicle shapes. The scale at the bottom is in inches.

Fig. 1. Advancing front of an aa flow about 50 feet thick, during the 1950 eruption of Mauna Loa. The surface and front of the flow are largely loose clinker. In the center of the front a fragment has just broken loose, revealing hot glowing pasty material. At the left a cloud of dust is rising where fragments are rolling down the front.

Fig. 2. Fragmental phase of a block lava flow near Cinder Cone, Lassen National Park, California. Note the regularity and smoothness of the blocks. The fragments average about 6 inches across. Photo by R. H. Finch.

were forming on both rivers, but more abundantly on the pahoehoe.

Dutton (1884) called attention to the greater viscosity of liquid aa as compared to pahoehoe, and attributed its formation to the fragmentation of the upper part of the flow by movement of the viscous fluid beneath. He says (p. 96): "The fields of aa are formed by the flowing of large masses of lava while in a condition approaching that of solidification. . . . A mass so large but still plastic undergoes, for a considerable time, a slow movement amounting to perhaps a few hundred feet in a single day. . . . During this slow glacier-like motion crushing strains of great intensity are set up throughout the entire mass, and its behavior conforms strictly to that of viscous bodies. The superficial portions in part yield plastically to the strains, in part yield by crushing, splintering, and fissuring. The result is a chaos of angular fragments." So far as it goes, Dutton's deduction is correct, and the process he pictures is an important part of the total process of formation of aa. The fact that the movement of the flow need not be slow (some aa flows during the 1950 eruption of Mauna Loa advanced at a rate of more than 2 miles an hour) is not important. Dutton's picture does not, however, explain and correlate many minor features of the flows, nor explain in more than a very general way the reason for the greater viscosity of aa. Furthermore, it appears probable that absolute viscosity is not an adequate explanation. Although actual measurements of their viscosity are lacking, it appears quite certain that liquid lava of approximately the same viscosity may under different conditions form either pahoehoe or aa.

It appears definitely established that there is no significant difference in chemical composition between aa and pahoehoe, so far as the fixed constituents are concerned. The slightly greater oxidation of the iron in the aa, commonly evidenced in the field by the brownish hue of the clinker, does not appear to be important and results largely from the easier access of air to interior parts of the aa flow. There may, however, have been a difference in the fugitive constituents while the lavas were still mobile. There is no way of measuring the gas content directly, but several of the features listed above indicate with a considerable degree of certainty that mobile pahoehoe is richer in gas than is mobile aa. This is just the opposite of the statement by some volcanologists that pahoehoe is poor and aa rich in gas (Washington, 1923, p. 419; Escher, 1929, p. 136; Rittmann, 1936, p. 56; Perret, 1950, p. 50). Inasmuch as pahoehoe is frequently observed to change downslope to aa, but the reverse change is unknown, it appears obvious that pahoehoe is the more primitive form.

It has been suggested that the essential feature in the formation of pahoehoe may be the presence on the flow of a tough, flexible glassy skin. The importance of the flexible skin in determining the formation of pahoehoe rather than aa is difficult to evaluate. Certainly a flexible skin is a common feature of pahoehoe, and undoubtedly some of the surface forms characteristic of pahoehoe, such as the ropy surfaces, depend for their formation on a flexible crust which can be deformed without fracture by the movement of liquid beneath. On the other hand, aa surfaces also sometimes show ropy structure, obviously resulting from plastic deformation of the crust. The writer has observed typical pahoehoe toes swelling up as they roll forward, the dark crust rifting and pulling apart, revealing the underlying material as a network of glowing orange-red lines. Obviously, in these the outer crust was not sufficiently flexible to stretch without fracturing. It may, however, have been underlain by a flexible layer between the relatively cool fracturing surface and the molten core. Possibly, instead of being essential to the formation of pahoehoe, the flexible crust is merely a typical characteristic of liquid lava in the physical state appropriate to form pahoehoe.

The greater degree of crystallinity in the central massive phase of aa flows, as compared to pahoehoe, is certainly very general. It may be partly the result of stirring, which promotes crystallization. The expansion of the gas in the pahoehoe vesicles results in some cooling, which undoubtedly contributes to the chilling which causes the formation of large amounts of glass in some pahoehoe flows. In some flows a thin layer of glass directly surrounding the vesicles appears with little question to be the result of this expansion cooling. However, the expansion of the gases to form the vesicles in aa must also have caused cooling of the surrounding liquid. Cooling caused by gas expansion probably is not the cause of the systematically greater proportion of glass in the pahoehoe.

One of the essential differences between pahoehoe and aa appears to be that the gases in the pahoehoe were still expanding when the lava stiffened to immobility, whereas in the aa the gases had accomplished most of their expansion while the lava was still flowing. This was clearly recognized by Jaggar (1920, pp. 167-168), who termed pahoehoe "live lava" and aa "dead lava." The vesicles in the pahoehoe are smooth and regular. They may be somewhat stretched by flowage, but the forms are still essentially those determined by the expanding gas bubbles (plate 4, fig. 2). In contrast, the vesicles of the aa are very irregular, and must have been twisted out of shape by the movement of the lava after the gas bubbles had stopped expanding sufficiently actively to maintain a spheroidal shape in spite of distortion by the enclosing liquid.

As shown in the experiments by Emerson (1926), the loss of gas while the lava is still flowing, resulting in the change from pahoehoe to aa, may be at least partly caused by mechanical stirring. This effect is evident at many places in the change of a flow from pahoehoe to aa where it descends an abrupt slope. Thus during the 1942 eruption of Mauna Loa highly gas-charged pahoehoe which cascaded into a small pit crater at 12,700 feet altitude formed heaps of aa at the foot of the cliff. Once changed, the flow remains aa to its terminus. Similarly, violent stirring by the lava fountains during the early part of an eruption may result in sufficient loss of gas to account for the early flows commonly changing to aa near the vent, whereas later flows, retaining more of their gas, may remain pahoehoe for great distances down the mountainside. Likewise, at least some examples of aa issuing directly from the vent may be the result of stirring by gas liberation in the vent before extrusion.

The characteristic spinose top of an aa flow probably also is the result in part of continued agitation of the lava after the gases have ceased active expansion and crystallization has advanced to the point of imparting a definite granularity to the material. A close analogy exists in the making of fudge, wherein if the candy is poured or otherwise agitated after crystallization has advanced beyond a certain stage there results a rough, spinose, somewhat granular surface akin to the surface of aa. The commonly fragmental character of the aa surface results from the mechanical fragmentation of the upper part of the flow caused by stresses induced by the moving fluid beneath. Various workers in Hawaii, as well as elsewhere (Krauskopf, 1948, p. 1275), have observed the breaking up of the moving flow surface. Undoubtedly the rough, spinose surfaces of individual fragments of clinker result in part from the pulling apart of blocks of still plastic flow crust. Wood (1917, p. 334) states: "The rough, pointed, and edged texture of the natural aa surface was *seen* [the italics are Wood's] in some cases to be due to the drawing out of points and the shaping of rough edges as the blocks were tilted and rotated away from each other and from the plastic matrix within, while the forward bulging motion was taking place." That this cannot be the sole cause is evident, however, when it is remembered that the characteristic spinose and granular surface is present also in those places on aa flows where the fragmental layer is absent, and the formation of the spinose surface has been observed where no pulling apart of crustal fragments was involved.

CONCLUSION

It is concluded that the formation of aa instead of pahoehoe is at least largely the result of greater viscosity resulting from cooling, loss of dissolved gas, and greater degree of crystallization. The last two factors are promoted by turbulence and internal shearing, and may result from violent stirring by fountain action at the vents or by turbulence in pouring over a steep slope, or merely from prolonged flowage to great distance from the vent. If the lava is erupted quietly and the flow descends no escarpments, the crusting over and the formation of tubes may so retard the loss of heat and gases that the lava will remain pahoehoe to great distances from the vent. The greater amount of glass in pahoehoe undoubtedly contributes to the toughness and flexibibility of the confining skin which is evident in the formation of the typical pahoehoe toes. When active flowage continues after loss of gas and cooling have brought about sufficient crystallization to impart a definite granularity to the magma, the typical spinosity of aa results, both on unfragmented surfaces and on the surfaces of the clinker fragments.

The factor determining whether pahoehoe or aa is formed appears to be a critical relationship involving both viscosity and the amount of internal disturbance owing to flowage. With rapid flow on a steep slope the fragmentation may take place in lava of such a viscosity that it would remain pahoehoe on a gentler slope. When the critical relationship between viscosity and flowage is reached the continuous confining surface of the flow is broken up and the upper part of the flow is fractured into fragments. The spinose character of the surface of the fragments results partly from the pulling apart of still plastic surfaces and partly from the same granularity which produces the spinose character on the unbroken aa surfaces. The fragments continue to be modified in shape by slight plastic deformation and by attrition against each other in the moving flow top.

The subject of viscosity relationships within the flow, and the relationship of viscosity to the degree of turbulence causing fragmentation must at present be left rather vague and wholly qualitative. As yet we have very little quantitative information on the viscosity of lava flows, even in general (Wentworth, Carson, and Finch, 1945, p. 103), and none at all on the variations of viscosity within flows, either aa or pahoehoe. Furthermore the mathematical treatment is greatly complicated, or rendered impossible, by the nonhomogeneity of the liquid involved. Especially in the more advanced stages of consolidation the large proportion of solid crystalline material in the magma may make totally invalid its theoretical treatment as a true liquid.

Pahoehoe is much less common at central volcanoes on the continents, even those erupting basaltic lavas, than it is at the Hawaiian volcanoes. This, no doubt, is related to greater viscosity of the lavas at continental volcanoes, and the greater viscosity may in turn be related to more explosive eruption with a greater degree of stirring out of the dissolved gas at the vent. Because the explosiveness of the eruption probably also increases with increase of viscosity of the lava reaching the surface, the effect is self-multiplying, a small increase in the viscosity of the lava rising from depth producing a great decrease in the proportion of pahoehoe formed. However, as recently pointed out by Verhoogen (1951), viscosity is only one of several factors determining the explosivity of a volcanic eruption. It is probable that an increase in explosivity, for whatever cause, would tend to decrease the proportion of pahoehoe formed.

The granulation point and the fragmentation point are generally close together in basaltic rocks, so that fragmentation of the flow top and development of the exceedingly rough spinose character commonly take place essentially simultaneously, although granulation may occur a little in advance of fragmentation and give rise to the unbroken spinose aa surfaces. In more salic lavas the greater viscosity results in fragmentation at a lower degree of crystallization. The fragments are glassier, do not develop the spinose character resulting from granularity, and because of the lesser plasticity do not develop any appreciable spinose character by pulling apart of the blocks. The more salic the lava, the less spinose and more regular in outline the individual blocks become, until the typical block lava is reached. The mode of formation of block lava thus is one of mechanical fragmentation during flowage similar to that which produces the fragmental tops of aa flows. Owing to the greater viscosity, the fragmentation is commonly more extreme, and produces a greater proportion of fragmental material. The critical relationship of viscosity and flowage thus produces a series of forms which, as pointed out by Jones (1943), is continuous from pahoehoe through aa to block lava.

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