PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Lengths of Lava Flows [and Discussion]

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Lengths of lava flows

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The principal factor influencing the length of a lava flow is the rate of effusion. With a high rate the lava flows rapidly from the source and tends to form an extensive and far-reaching flow which is simple in character (i.e. made of a single flow unit). With a low rate the lava tends to pile up layer upon layer to form a local accumulation of limited lateral extent near the source, and this accumulation is strongly compound in character (i.e. divisible into flow units). The initial viscosity affects the length indirectly by controlling the thickness of the extrusion, and this thickness control is capable of accounting for the fact that the median length of low-viscosity basaltic extrusions is 3.2 times that of high-viscosity andesite, trachyte and rhyolite ones. Other factors, such as the local topography, are thought to be relatively unimportant, an exception being when lava is ponded in a topographic depression.

Measurement of the rate of effusion may be critical in any attempt to predict the distance that a lava flow will travel, such as the one which threatened Fornazzo and other towns and villages on Etna in 1971.

Introduction

The mechanism of flow and the factors which govern the dimensions of a lava extrusion have seldom been discussed, although there may be a real social need to predict the behaviour of a lava flow which is advancing into a densely populated district. The lack of any basis, theoretical or empirical, on which the length of a flow can be predicted became particularly apparent to the author during the 1971 eruption of Etna when each of the two main lava flows in turn threatened land and property.

The present paper examines the factors governing the length of a lava extrusion. Perhaps the main reason why they have not hitherto been analysed is the likelihood *a priori* that there are many different factors involved: too many to be analysed. The following at once spring to mind:

(1) The initial viscosity of the lava.

(2) The total volume of lava extruded.

(3) The rate of effusion.

(4) The slope of the underlying surface.

(5) The form of the topography: whether the lava flow is confined to a narrow valley or is able to spread widely outward from the vent.

(6) Special circumstances: whether the lava is ponded in a depression or not, and whether it flows entirely on land or enters a body of standing water that restricts its forward movement.

While it is generally considered that the first is likely to be the most important, and some workers have emphasized the importance of the second and fourth, the author from his observations on Etna and other volcanoes concludes that the third, the rate of effusion of lava, is the most important single factor, and the viscosity has at most an indirect control. This paper gives the evidence on which this conclusion is based. The effect of viscosity is first examined, however, because of the widespread belief that it is the most important factor in determining the length of lava flows.

Viscosity-dependent characters of lavas

The simplest approach is to compare the lengths of low- and high-viscosity lavas using features other than length as a function of their viscosity. Table 1 summarizes the known features which are believed to be viscosity-dependent. In this table, lava types which have similar field characteristics are grouped together. Thus in group B, basalts and mafic feldspathoid-bearing types (such as nephelinites, leucites and tephrites) are brought together because they

Table 1. Summary of known features of lavas which are believed to be viscosity-dependent

	group B low-viscosity lavas	group A high-viscosity lavas
composition	basalt and mafic feldspathoid-bearing types	trachyte andesite/dacite rhyolite
average thickness	about 10 m	about 100 m
normal thickness range	2 to 30 m	20 to 300 m
aspect ratio†	high, typically > 50	low, typically < 50 commonly < 8
surface structure	pahoehoe, passing to aa as the viscosity increases	mostly block lava
internal flow structure	poor or absent	well developed: ramp structure common†
granularity of groundmass	more or less holocrystalline; grain-size generally > 0.1 mm, coarsest in pahoehoe	commonly vitreous; grain-size of andesite/dacite and rhyolite generally < 0.1 mm
in situ sorting of phenocrysts	common in pahoehoe, uncommon in aa	no examples described
spherulites and lithophysae	rare or absent from subaerial flows	very common in rhyolite

† See appendix 1.

form flows which are indistinguishable in external form and internal structure, and the same applies to the trachytes, andesites and rhyolites in group A. It would be sensible to subdivide the lavas in group B further into those which are predominantly pahoehoe, and those which which are aa, and group A could also be subdivided. A further subdivision has however not been made here because the broad groupings are sufficient for present purposes.

The most useful viscosity-dependent characters, and the ones about which most information can be obtained from published accounts and maps, are the lateral extent and thickness, and the aspect ratios which can be derived from them (figure 1). The *aspect ratio* is the ratio of the horizontal extent to the thickness of a lava extrusion, as explained in appendix 1. It can be seen that lavas of groups A and B plot in quite separate fields on figure 1 with little or no overlap, although the intermediate field of group I (basaltic andesites and phonolites) overlaps the fields of the other two groups. It is the occurrence of two distinct fields on figure 1 for groups A and B which justifies making a direct comparison between lavas of these two groups to assess the effect of viscosity on length.

The reason why such an indirect method is used to classify lavas into viscosity groups is that there are remarkably few field or laboratory determinations of the viscosity of lavas. The available data are summarized in appendix 2, from which it is seen that field viscosity measurements have to date been published on fewer than 25 basaltic lavas, and only five lavas of other compositions. The paucity of data on the latter partly reflects the practical difficulties of making measurements on high-viscosity lavas, but mainly the scarcity of opportunities to make them: no phonolite or rhyolite lava extrusions, and probably only one trachyte extrusion, are known to have formed on the world's volcanoes since the scientific observation of them began.

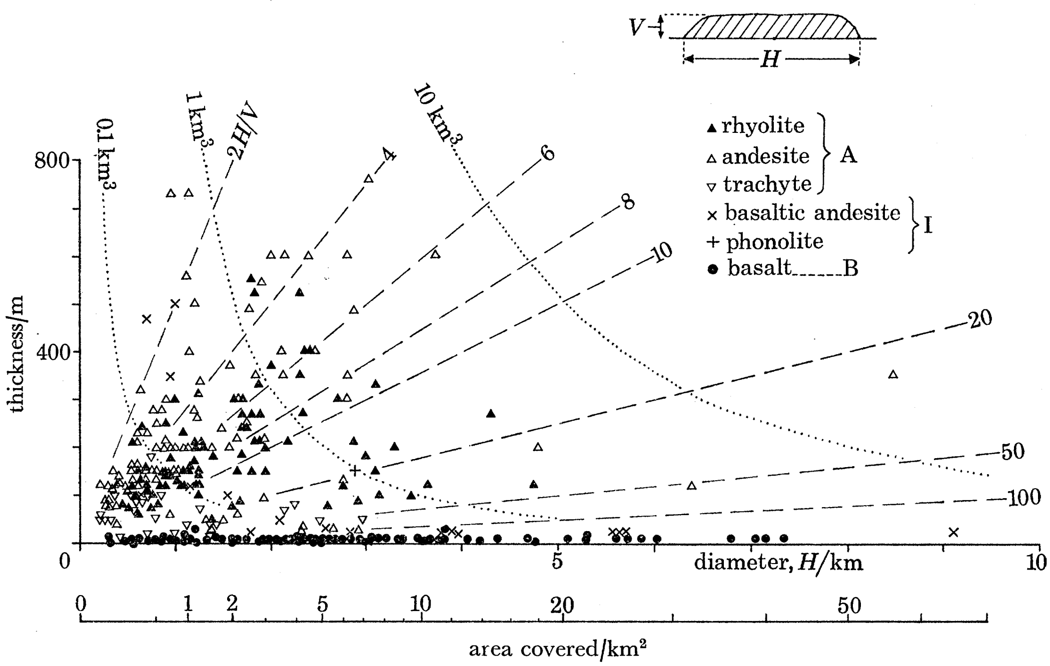

FIGURE 1. The dimensions of lava extrusions of different compositions. The two scales along the base give the area covered by the extrusion, and the diameter of a circle having this area. The dashed lines give the aspect ratio, H/V, as explained in the diagram, top right. The dotted lines give the volumes of circular disk-like bodies of the dimensions shown, as a rough guide to the volumes of lava extrusions. All the extrusions plotted are Quaternary, and most are Recent.

THE EFFECT OF VISCOSITY ON LENGTH

Figure 2 is a histogram of the lengths of 479 separate group B and 417 group A lava extrusions (see appendix 3). As far as it is possible to tell, the sample is a representative one in each case except that extrusive domes are probably over-represented in the second group. These data are more readily compared when plotted on logarithmic probability paper, figure 3, on which each group plots on or near a straight line, indicating a lognormal length distribution. The median lengths of each group, given by the point of intersection of these lines with the 50 % level, are as follows:

479 group B lavas (mostly basalt)	4.1 km
135 group I lavas	3.5 km
36 phonolites	4.1 km
99 basaltic andesites	3.2 km
417 group A lavas	1.3 km
94 trachytes	1.7 km
147 andesites and dacites	1.2 km
176 rhyolites and rhy. obsidians	1.1 km

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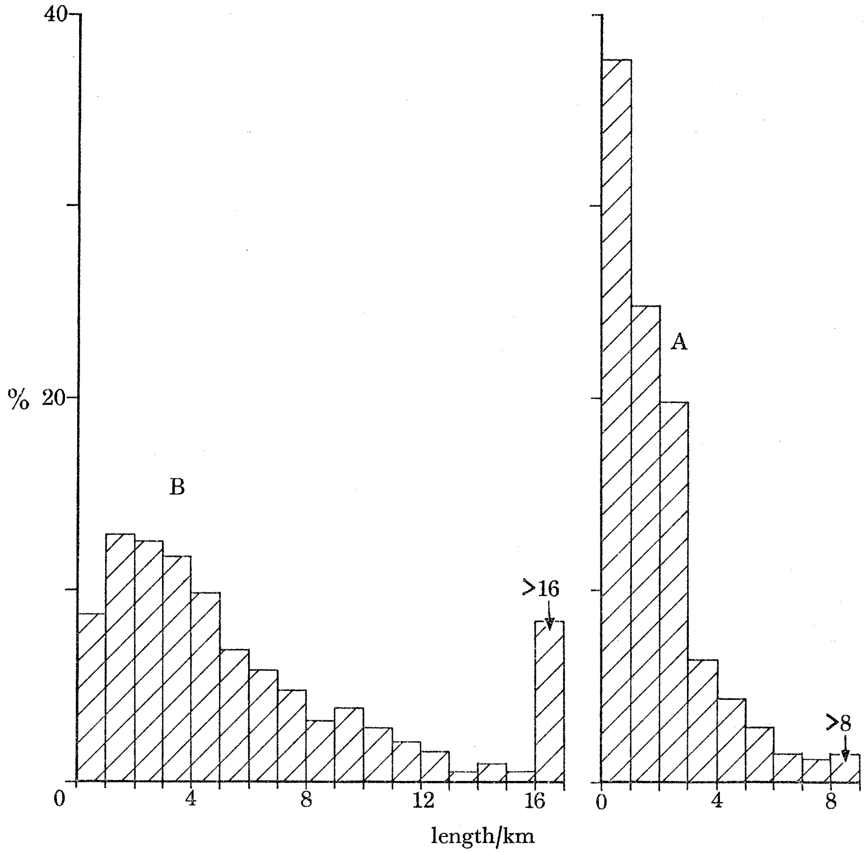

FIGURE 2. Histogram of the length of 479 group B lavas (left) and 417 group A lavas (right).

Table 2 compares the median lengths of groups A and B lavas with estimated average viscosity values, and for lavas which differ in their initial viscosity by a factor of the order of 10^5, a difference in median length by a factor of 3.2 is indeed small and at once suggests that viscosity is of minor importance in determining the length. The difference in median length can be fully accounted for by the difference in thickness of the two groups of lavas.

TABLE 2. COMPARISON OF VISCOSITY AND DIMENSIONS OF LOW- AND HIGH-VISCOSITY LAVAS

	average initial viscosity/P	median length / km	average thickness† / m	diameter of 1 km³ circular extrusion / km
group B	10^4	4.1	10	11.3
group A	10^9	1.3	100	3.5
B/A	10^{-5}	3.2	10	3.2

† See appendix 4.

A realistic value for the average thickness of group B lavas is 10 m, and for group A lavas 100 m (see appendix 4). If lava flows are then treated as being disk-like bodies of circular plan and uniform thickness, a group B lava will have a diameter 3.2 times that of a group A lava of the same volume. The diameter or lateral extent thus differs for the two groups by the same factor as the median length (appendix 4).

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It is therefore concluded that the effect of viscosity is merely to control the thickness of a lava extrusion. Indirectly it affects the length to the extent that, because of its increased thickness, a group A lava will have a proportionately reduced length compared with a group B lava of the same volume.

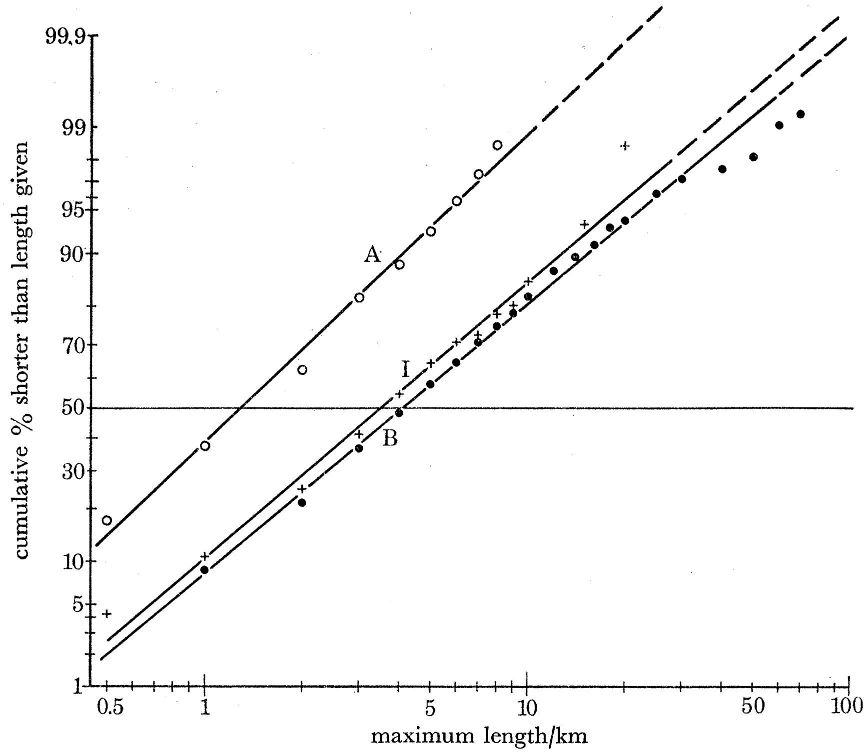

FIGURE 3. Logarithmic probability plot of the lengths of 479 group B (mostly basalt), 135 group I (phonolite and basaltic andesite) and 417 group A (trachyte, andesite/dacite and rhyolite) lava extrusions.

The longest known Quaternary basalt flow is 130 km long (Kjartansson in Askelsson *et al.* 1960) compared with the 18 km longest group A lava known to the author (the Ring Creek dacite, Mathews 1958). Extrapolation of the lines on figure 3 enables predictions to be made about the possible lengths of lava flows of different compositions; for example, roughly one lava in 10000 in group B should be 200 km, in group I 150 km, and in group A 35 km or more long. Much longer flows than these are possible, though their frequency of occurrence should be lower still. Basalt lavas of the order of 200 km long are well known in the Columbia River plateau and inferred in the Deccan Traps, flood phonolites of comparable length are known in Kenya (B. C. King, personal communication), and a rhyolite lava has been described from Texas which appears to extend at least 35 km from its source (the Star Mountain rhyolite, Gibbon 1969).

THE EFFECT OF THE EFFUSION RATE

The importance of the effusion rate became apparent to the author on Etna in 1966 (Walker 1967) when he watched the birth, life and death of many lava streams coming from secondary boccas near the foot of the northeast crater. A lava stream with a cross-sectional area immediately below its bocca of less than about 1 m^2 (giving a flow rate of less than about 0.2 $m^3 s^{-1}$) was found to have a life of minutes or hours and to travel at most only a few tens of metres, whereas one with a cross-section of 2 to 3 m^3 (flow rate about 1 $m^3\,s^{-1}$) could flow for a day or more and reach a distance of the order of 1 km from its bocca. The lava streams in 1971 from the two main Citelli boccas had a much greater cross-sectional area, 5 m^2 or more, giving a flow rate of the order of 10 to 20 $m^3\,s^{-1}$, and combined they produced a lava flow some 7 km long.

To assess the effect of the effusion rate, data on the volume of lava, the duration of effusive activity, and hence the average effusion rate have been collected for a number of historic basalt and basaltic andesite lava eruptions. On figure 4 the length of each lava is plotted against this average rate, omitting eruptions which were either very short (less than about 30 h) or very long (longer than about 9 months). A few andesite/dacite lavas are also included.

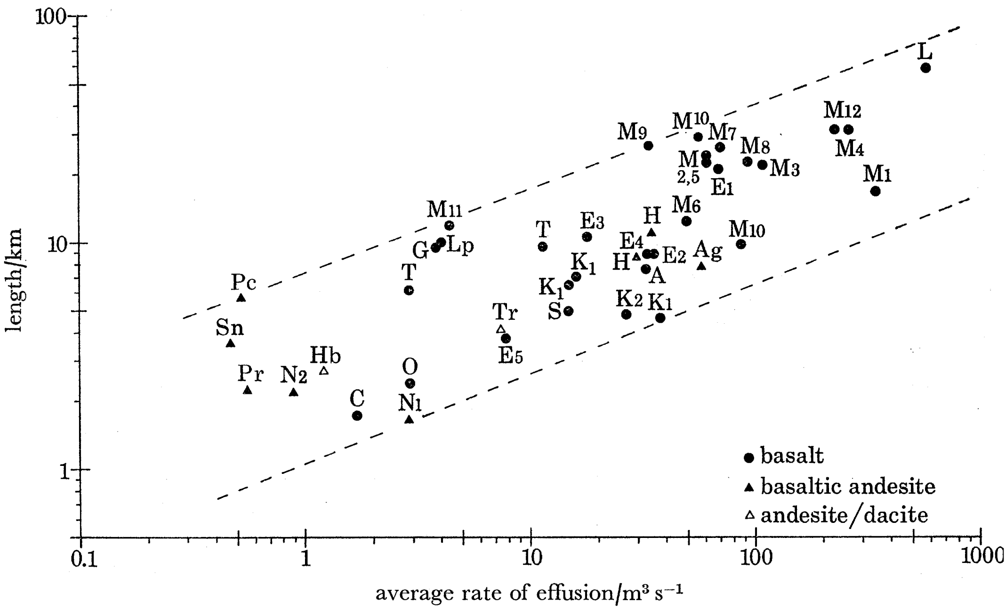

FIGURE 4. Plot of lava length against average effusion rate for lava eruptions (mostly basaltic) on various volcanoes. Basaltic lavas, ●: A, Askja 1961 (Iceland); C, Cerro Negra 1968; E, Etna (1, 1669; 2, 1911; 3, 1923; 4, 1928; 5, 1971); G, Gituro 1948 (Congo); K, Kilauea (1, 1955; 2, 1965); L, Laki, 1783 (Iceland); Lp, La Palma 1585; M, Mauna Loa (1, 1851; 2, 1852; 3, 1868; 4, 1887; 5, 1907; 6, 1916; 7, 1919; 8, 1926; 9, 1935; 10, 1942; 11, 1949; 12, 1950); O, Oosima 1951; T, Tenerife 1705; S, Sakurajima 1946. Basaltic andesite lavas, ▲: Ag, Mt Agung 1963 (Bali); H, Hekla (1, 1845/6; 2, 1947); N, Ngauruhoe (1, 1949; 2, 1954); Pc, Pacaya 1961 (Guatemala); Pr, Paricutin (first 8 months 1945); Sn, Santiaguita (Guatemala). Andesite/dacite lavas, △: Hb, Hibok-Hibok 1948; Tr, Trident 1953.

Although there is a scatter of points on figure 4, it is striking how good is the correlation between length of flow and average effusion rate when one bears in mind that the data are drawn from different volcanoes, involving lavas differing in initial viscosity by a factor of 10^3 or more, which have come down slopes varying from 1 to 30°, and based on volume estimates probable of varying degrees of reliability.

There is, however, another variable which could account for much of the scatter. In many Hawaiian and Icelandic basaltic eruptions it is known that the rate of effusion during the first day or days is much higher than the average rate. Thus the average effusion rate over the first 8 h of the Askja 1961 eruption (Thorarinsson & Sigvaldason 1962) was estimated at 800 $m^3\,s^{-1}$, and thereafter the rate fell to less than 10 % of that value, while the overall average rate was about 33 $m^3\,s^{-1}$. The eruption lasted 5 weeks, but the lava attained nearly its maximum length by the end of the first day.

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The likelihood is therefore that the length of a lava flow is properly a function of the rate of effusion averaged over the first few days of an eruption, and it may be more realistic to plot this value than the overall average rate. Unfortunately currently available data are inadequate to enable this idea to be followed up.

The effect of the angle of slope

The effect of the angle of slope of the underlying land surface on the length of a lava flow, though not negligible, seems to be small in relation to other factors. Some of the particularly long Icelandic lavas, for instance, have succeeded in flowing many tens of kilometres down an average gradient of only $\frac{1}{4}$ to $\frac{1}{2}°$, while in contrast most of the flow units of the 1955 Ngauruhoe lava barely succeeded in reaching the bottom of 30° slopes (Gregg 1956). However, lava can flow as a thinner layer on a steep slope than on a level surface, and may flow somewhat farther in consequence although it will also cool more rapidly. Moreover, viscous lava bodies extruded on or above a steep slope often become mechanically unstable and large portions of them become detached and collapse to generate glowing avalanches. These collapses, which can take place repeatedly during the extrusion of the same lava body, must effectively limit its length. Good examples are known from Merapi, and small-scale examples developing from lava of moderate viscosity have been observed on Ngauruhoe (Gregg 1956), whereas avalanche deposits having this origin are extremely widespread on many of the andesitic volcanoes of northern Chile (Cobbold *et al.* 1972).

Mechanism of the effusion rate control

Finally it remains to examine the way in which the rate of effusion controls the length of a lava extrusion. It has elsewhere been postulated (Walker 1972) that with a high rate the lava tends to flow rapidly away from the vent to form a far-reaching flow of *simple* type, made of a single flow unit. In contrast, a low rate favours the formation of a *compound* lava, one which is composed of many flow units (Nichols 1936), in which the units overlap or are superposed one on another to form a localized accumulation around the vent.

A comparison between the lava of the 1960s from the northeast crater of Etna with that of 1971 from the Citelli boccas is very revealing. During a visit in 1966 the effusion rate of the former was about 1 $m^3\,s^{-1}$, and the resulting lava was strongly compound in character; many tens of units were added to it daily, and the birth, life and death of many flow units was observed. A strongly compound lava probably several tens of metres thick accumulated during the 1960s around and downslope of the northeast crater, probably composed of many thousands of separate flow units ranging in individual volume from less than 1 to more than $10^5\,m^3$. If this compound lava had formed on a level surface it would undoubtedly have formed a lava shield of the type which is so well known in Iceland.

In contrast, the 1971 Citelli lava was simple during the first days of activity and flowed quite rapidly to near Fornazzo, about 6 km from the boccas. Only a small number of lateral offshoots subsequently developed into separate flow units, and these for the most part flowed along the side of the first lava stream. It was only towards the end of the eruption (when, it is supposed, the effusion rate dropped to a low value) that repeated over-riding of the earlier lava near the boccas by thin flow units took place to form a localized compound lava accumulation.

One implication is that the overall shape of a lava volcano may be controlled by the average effusion rate during its eruptions. The gentle slope of Hawaiian volcanoes stands in striking contrast with the steep conical form of Fuji-san (Japan) and Pico (Azores), although all are basaltic volcanoes. Pico rises from sea level to over 2000 m at an average slope of about 30°. Its lavas show evidence of having been at least as fluid as those of Hawaii: pahoehoe is very prevalent, the flow units are very thin, and fine examples of post-extrusion fractionation of phenocrysts are commonly seen. The lava flows of Pico appear to be comparable in volume to those of Hawaii but are more strongly compound in character.

It is now postulated that the Hawaiian volcanoes have a gentle shield-like form not because their lavas have a low viscosity but because their rate of effusion during eruptions is high. Pico has a steeply conical form in spite of the low viscosity of its lavas because the rate of effusion during eruptions is low. Much the same result would presumably be achieved by a variation in the quantity of lava formed in each eruption: a volcano in which the quantity was habitually large might tend to be less steep-sided than one in which the quantity was habitually small.

It is interesting to note that the eruption of Kilauea which began in May 1969 appears (from what little information has been published) to depart from the Hawaiian norm in having a relatively low effusion rate averaging about 2 $m^3 s^{-1}$, and this eruption is reported to have built a localized lava shield (Mauna Ulu) which by the end of 1970 had a diameter of about 1 km and a thickness of 100 m. This lava extrusion appears to be broadly similar in form to the monogenic compound lava shields of Iceland, exemplified by Skjaldbreidur, some of which are 300 to 600 m thick in the centre.

There seems to be a tendency for the relatively high-fluidity pahoehoe flows to be shorter than the somewhat more viscous aa flows, and it was this tendency which first suggested to the present author that some factor other than viscosity controls the length of lava flows. However, the amount of factual data available on the lengths of pahoehoe and aa flows is too small to test statistically the reality of this tendency.

This tendency, if real, could be related to a relatively high rate of heat loss per unit volume from thin flows of pahoehoe as compared with thicker flows of aa. The strong tendency for the former to build up compound lavas could be due to the same cause.

Appendix 1

The concept of *aspect ratio* has long been useful in aeronautics to express the relative dimensions of aircraft wings, and is the ratio of the span to the chord. Although it has not hitherto been applied in volcanology it can be a very useful means of expressing the relative dimensions of objects such as lava extrusions or the fiamme in ignimbrites. It is here defined as the ratio of the horizontal extent, H, to the thickness, V; i.e. H/V. For a Quaternary lava extrusion undissected by erosion, H may be taken as the diameter of a circle covering the same area as the lava, while V may be taken as the average height of the flow-front or, in the case of an extrusive lava dome, the height of the dome.

The aspect ratio of different lava extrusions varies from less than 2 to more than 1000. Extrusions called domes or tholoids have a ratio less than about 8, and coulees and lava flows more than 8. This limiting aspect ratio of 8, though it has not hitherto been expressed numerically, is in good accord with current usage of the terms, and likewise a limiting aspect ratio of about 50 separates coulees from lava flows *sensu stricto*.

In ramp structure the flow planes, which are more or less parallel with the base of the lava body at or near the base, curve upwards until they are steep or vertical at the top.

Appendix 2

Summary of field viscosity measurements on lavas. The figure gives the logarithm (base 10) of the viscosity in poises. Where several values are available, it is the minimum which has been taken.

group B	basalt (SiO_2 < 53%)	Capelinhos 1958	4.5
		Etna 1966	4.5
		Etna 1966‡	4.7
		Etna 1967‡	4.1
		Kilauea 1952	4.3
		1955	3.3
		1965	2.8
		La Palma 1949	2.8
		Lopevi 1963	7.2†
		Mauna Loa 1887	4.7
		1919	4.6
		1940	3.5
		1942	3.5
		1949	3.7
		1950	3.8
		1952	4.5
		Oosima 1937	4.7
		1950	3.7
		1951	3.7
		1952	4.5
		Sakurajima 1946	6.0†
		Surtsey 1964	3.7
	mafic feldspathoid-bearing types	Nyiragongo 1948	4.5
group I	basaltic andesite (SiO_2 = 53–58%)	Hekla 1947	4.0
		Miyakesima 1940	5.8
		Paricutin 1945/6	5.0
	phonolite	no data available	
group A	trachyte	no data available	
	andesite/dacite (SiO_2 = 58–70%)	Trident 1953	10.8†
		Usu 1945	9.0
	rhyolite	no data available	

† Measured at a considerable distance from the vent, and probably higher than the initial viscosity.
‡ Tanguy & Biguand (1967); Walker (1967); Silvestri (1968).

Appendix 3

The length has been measured from the centre or presumed centre of the vent to the extreme limit attained by the lava. 25% has been arbitrarily added to the length of lavas which terminate in the sea, but those which have entered the sea from a vent very close to it have not been included. Extrusive domes may be over-represented, as explained in appendix 4. Data on the dimensions of lava extrusions are very hard to come by in the literature, and it is doubtful if good data exist on much more than 100 separate extrusions, although the dimensions can often be measured on a topographic map. Most data on group B lavas have come from Auckland, the Azores, Canary Islands, Comore, Etna, Fuji-san, Hawaii, Iceland and Vesuvius. Most data for group A have come from the Azores, Ethiopia, and Socorro (trachytes); the Aleutian

Islands, the Antilles and Japan (andesites and dacites); and California, Ethiopia, Iceland, Japan, Lipari and New Zealand (rhyolites and rhyolitic obsidians).

Appendix 4

The flow-front height of group B lavas is seldom quoted in the literature but probably averages 5 to 10 m. The thickness of Tertiary or older lavas as seen in cross-section probably averages about 10 m. The height of group A lavas can often be measured from topographic maps and the median height for the examples plotted on figure 1 is about 150 m. However, it is likely that extrusive domes are over-represented compared with thinner coulees because domes tend to survive as recognizable topographic features much longer, and the sample of extrusions plotted on figure 1 is not representative; 100 m is therefore thought to be a more realistic figure for the median thickness.

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Discussion

A. T. Huntingdon: In this most useful paper, it was concluded that the most important factor, besides chemical composition, was rate of effusion of lava, in controlling the length of lava flows. It seems to me from my limited experience that the rate of cooling of the lava after extrusion will be important. Obviously this is highly dependent on rate of effusion and 'contained' within the effusion term. However, in extreme cases, such as the formation of lava tubes or tunnels such as occur on Etna, and more particularly on Hawaii, very long flows can occur with small rates of effusion, and in this circumstance the rate of cooling may be the factor which determines the length of flow. I was interested because I have speculated on ways of controlling lava flows (A. T. Huntingdon 1972, The eruption of Mount Etna; *Sci. Prog.* **60**) and have suggested rapid cooling by water spraying as a means of flow modification. It now seems that this is most likely to initiate lava tube formation rather than restricting the flow to a small area.

G. P. L. Walker: It is the rate of cooling which determines the rate of increase in viscosity which in turn controls the length of a lava extrusion, and it is probably true that the rate of cooling is reduced if the lava flows through a tube. However, I suspect that the proportion of lava which flows through tubes is much the same in all pahoehoe flows. If so, the cooling of different pahoehoe flows is delayed by a comparable percentage time. My impression is that flowage in tunnels is important only in pahoehoe flows. I question whether a very long flow ever does occur with a low effusion rate.

Cooling of a lava by water spraying could be a very effective means of flow modification. Whether it would initiate tube formation would no doubt depend on the character of the lava (whether pahoehoe or aa) and on which part of the lava was sprayed. Spraying of the advancing flow front should simply create a lava dam.

A. T. Sanders: Is the formation of central ridges in fast flowing basaltic lava flows directly attributable to 'whirlpool and eddy' effect of the lava against the country rock of the channel that the flow occupies? If so, would the ridges be a function of low viscosity as determined by the slope?

Dr Walker: The central ridge of cooler material often observed on a lava below its bocca may well result from a sideways motion of lava to either side of the central 'parting', causing fracturing and the constant exposure of hotter material there. Alternatively the ridge may be due to the inflation of the surface crust by gases in the central part (the gases here cannot escape through rents in the crust), thus reducing the rate of flow of heat to the surface.

Dr J. L. Dinsdale: I was very interested in Dr Walker's new look at existing hypotheses and his original paper stimulated me to put forward my own suggestion. Dr Walker suggested the rate of effusion was a more important factor than viscosity in affecting lava flow distances; would not the distance lava travelled be more directly related to the movement of the material within the flow itself, which they would both effect? For example, would it be correct to say, at the initial high temperature flow would probably be linear (laminar); also with increasing volumes of lava being extended the heat would be conserved aiding this linear flow? As soon as cooling becomes appreciable at the top and at the advancing end of the flow, with the aid of friction at the base would not internal rotational flow result, slowing down the lava quickly; because the cooling of lava would be increased, and internal friction would act as a further braking system?

This possibility may best be looked at by considering the following suggestions of three stages:

(*a*) The lava at the volcano vent would be at its most mobile state. The initial movement would be the result of the effusion, and the flow would tend towards that of a linear or laminar type. Velocity would increase downslope as a result of gravitational force. In its progress it would collect vent material and xenoliths of country rock that were not pushed out of the way, or carried in front. As the lava progressed freezing would become important at the base of flow because of heat loss. Here drag would become of significant importance in the slowing of the flow. It would also accentuate the difference of speed between the upper and lower layers of the lava.

(*b*) The continual contact with extraneous material and the freezing proceeding would result in areas of nucleation and differentiation in the lava mass which will itself show density and viscosity variation. These combined effects would result in a change of flow pattern to the rotational motion of turbulence, which would be aided initially by the increased velocity difference of upper and lower layers. When the irregular flow is significant this extra circulation would result in a much more rapid heat loss, as heat would not only be transmitted from the centre to the surface by conduction but by rotation in the lava body itself bringing material from the hot interior to the surfaces.

This process I suggest would continue to very near the front (*c*), where progress would probably be by block movement, sliding over the country rock, with little or no flow circulation, in the areas of enclosed melt.

Thus it may be that the internal flow pattern and the time of transition from stage (*a*) to (*b*) to (*c*) could be a very important factor in determining the distance lava flows will travel and also its velocity. The type of flow and its variation will be related to other factors such as the rate of effusion, the viscosity throughout the flow, xenolith content, cross-sectional area with related dimensions and also the initial temperature of the flow.

Dr Walker: Certainly as a lava cools a braking system comes into play, and most of the factors mentioned may contribute to bringing the flow to a halt; but a railway train with its brakes fully applied travels farther before coming to rest than a motor car travelling at the same initial velocity, and though this analogy is not an exact one something similar operates in lava flows. It is loss of heat from a lava which causes braking and (for a flow in which the thickness is small in relation to the lateral extent) the rate of heat loss per unit volume from a flow fed at a low rate is the same as that for one (of the same thickness) fed at a high rate only if the latter covers a proportionately larger area. This is the basic reason why the latter extends farther than the former. Experiments with melted paraffin wax released at different rates are very instructive.

The onset of cooling probably does not produce turbulent flow (see the paper by B. Booth & S. Self, in this volume).

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