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Thickness and Viscosity of Etnean Lavas

THE thickness of a lava flow depends, in general, on three factors: the viscosity of the flowing lava; the angle of slope of the surface over which the lava is flowing; the local topography, that is, whether the lava is ponded in a depression or not. The thickness is seldom recorded by volcanologists, and even more seldom used as a tool (for example, in the interpretation of old volcanoes in which, owing to subsequent folding or tilting, the present attitude of the lavas may differ from the original attitude). No systematic study appears to have been made of the thickness and its relationship to the viscosity and angle of slope, and this communication, which records the results of a brief study recently made of the lavas of the Italian volcano, Etna, is a first attempt to explore this inter-relationship.

Etna was chosen for this study for the reasons that there are extensive spreads of young lavas on its slopes; these lavas are rather uniform in chemical composition

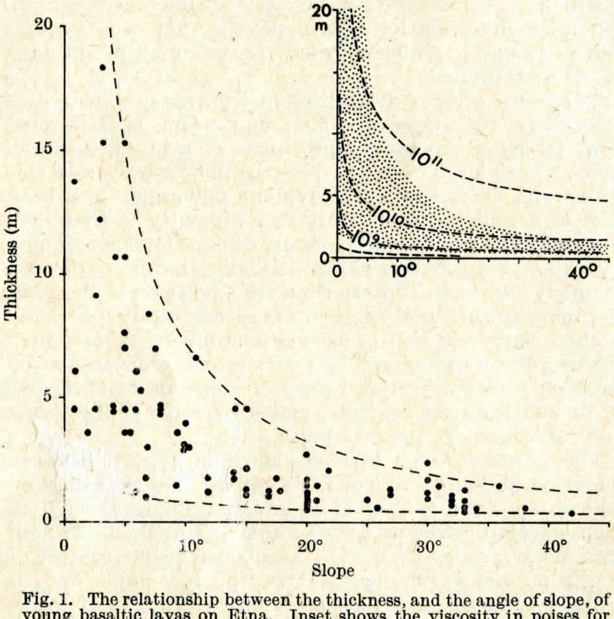

Fig. 1. The relationship between the thickness, and the angle of slope, of young basaltic lavas on Etna. Inset shows the viscosity in poises for which the rate of flow of the lava is 10^{-3} cm/sec.

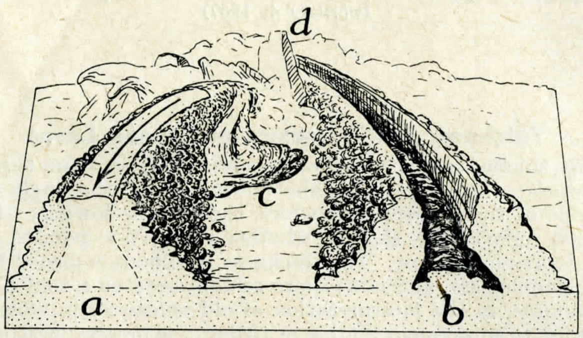

Fig. 2. Block diagram illustrating features on the 1966 Etna lava field. *a*, Lava stream in which the lava is flowing between levées standing about 1·5 m above the general level; *b*, abandoned, and largely drained-out, lava channel; *c*, pahoehoe flow-unit, too thin to be viable; *d*, older lava upraised at the time that the *boccas* feeding lava streams *a* and *b* were formed.

(they are basaltic, near hawaiite: Rittmann, A., personal communication) and, it is supposed, in initial temperature and viscosity; eruptions take place quite frequently during which the viscosity can be determined; a great range of angles of slope is found, from 0° to >40°; there are numerous small quarries, road cuttings, and other sections in which the thickness of the young lavas may be measured. When the investigation was made, the 1966 eruption was still in progress, which allowed the viscosity of the lava to be determined.

There are certain difficulties in the measurement of a meaningful thickness of a lava flow. One is that most flows on Etna are compound, made of a number (sometimes a very large number) of separate flow-units; in this study the thickness of individual flow-units has been measured and recorded. Another difficulty is that lava channels which have been partially drained out are common on slopes steeper than about 10°, and the floors of such channels are much thinner than the levées on either side. For none of the eighty flow-units measured in this study is there any reason to suspect ponding of a lava in a topographic depression. All the measurements are on lavas on the southern and eastern slopes of Etna, nearly all of which are of aa type, and all are on young flows, most of which are historic lavas.

The graph in Fig. 1 shows the relationship between thickness and angle of slope. It can be seen that only on gentle slopes of less than 7° do lava flows more than 10 m thick develop, while no flow exceeding 5 m thick is found on a slope steeper than 15°. The considerable scatter of points on the graph, greatest at the low angle end, is probably a result of variations in viscosity. The viscosity of a flowing lava is least when it emerges from the vent: cooling, partial crystallization and loss of gases very quickly increase the viscosity and the resulting lava flow is correspondingly thicker.

Table 1. VISCOSITY OF ETNA LAVA, MAY 1966

No. of lava stream	Approximate distance from *bocca* (m)	Timed distance (m)	Velocity V (cm/sec)	Approximate thickness of flow h (cm)	Angle of slope α (degrees)	Viscosity $\eta \times 10^{-5}$ (poises)
1	5	4·8	44	150	19	0·8*
1	10	3·3	47	150	28	1·1*
1	20	10·5	23	200	11	1·6*
2	2	6	6·7	120	14	2·6*
5	5	1	25	60	35	0·4*
7	2	3	11	120	8	0·9*
7	6	5	6·5	120	15	2·8*
8	5	3	20	120	12	0·7*
8	7	4	20	130	11	0·8*
8	1·5	3	21·5	120	12	0·7*
8a †	6	5	5·3 *FF*	30	20	0·4
8a †	10	4	6·1 *FF*	30	20	0·3
8a †	10	5	12·5	60	15	0·5
3	>50	1	1·7 *FF*	60	16	3·8
7	100	7	0·37 *FF*	70	22	3·2
8	100	4	11	120	10	1·5
4	>100	4	7	150	8	2·9
8	50	3	14·3	150	16	2·8
6	500	15	0·55 *FF*	150	33	150

* Lava flowing in narrow channel (between levées), for which a different formula is used (see text).

† Pahoehoe flow resulting from burst levée.

FF, Flow front; otherwise all measurements are of the movement of the top surface of lava streams.

Flow 1 measured on May 22; 2–5 on May 24; 6 on May 27; and 7–8 on May 29, 1966.

The 1966 eruption of Etna, which began in mid-January, was still in progress in late May when this study was made. Lava was found to be flowing quietly from about five *boccas* (openings), and for the first few tens of metres below a *bocca* the lava typically flowed in a narrow stream 1–2 m wide between levées raised 1–1·5 m above the general level (Fig. 2). The angle of slope and velocity of flow were measured on eight different lava streams (see Table 1) and the viscosity derived from the formula

$$\eta = \frac{g \rho h^2 \sin \alpha}{3V}$$

where η = the viscosity in c.g.s. units (poises); g = 980·6 cm/sec^2; ρ = density of flowing lava, taken as 2·0 g/c.c.; h = thickness of flow, in cm; α = angle of slope, in degrees; V = velocity of flow, in cm/sec.

For the narrow streams just below the *boccas*, where the width of the stream is comparable with the thickness, and internal friction becomes significant, the formula

$$\eta = \frac{g \rho h^2 \sin \alpha}{4V}$$

is more appropriate (ref. 1).

The lowest values for viscosity were given by a pahoehoe flow which resulted when one of the levées of a lava stream a few metres below a *bocca* suddenly collapsed. The measurements were made hurriedly, but the value for viscosity that they give (0·4 × 10^5 poises) is believed to be more realistic than the 0·7 to 0·8 × 10^5 poises given by the same lava stream where flowing between levées, in which the effect of internal friction by the walls may be greater than has been allowed for by the formula. In any event, the values recorded in Table 1 can be relied on only to give the correct order of magnitude of the viscosity.

Traced down the flow, the viscosity of a lava stream increases rather rapidly, and the highest value (1·5 × 10^7 poises) was measured on a flow-front about 500 m below the *bocca*. The viscosity at which flow virtually ceases (a flow rate of 10^{-3} cm/sec, that is, rather less than 1 m/day, has been chosen) is plotted on the inset to Fig. 1 for different thicknesses and angles of slope, and lies between 10^9 and 10^{11} for most Etnean lavas.

Three observations which have a bearing on the structure and thickness of lava flows were made on the 1966 lava field. One concerns the life and size of a flow-unit. Most of the *boccas* from which lava was flowing were secondary, being fed by lava tunnels the course of which could be traced by fumaroles at the surface. The *boccas* proved to be very impersistent. As one ceased to erupt lava, it was replaced by the appearance of another. No *bocca* erupting on the first day of observation was still erupting seven days later. Not only did the location of active *boccas* change, but also the lava streams from each *bocca* changed in position. During the period of observation, several streams were seen to be born, and as many were seen to die by ceasing to flow. It was estimated that about five substantial flow units, each with a volume of the order of 10^3 to 10^5 m^3, were added to the lava field per day (the total rate of production of lava being about 1 m^3/sec), plus a considerable number of smaller units. Thus the 1966 lava field must be built up of hundreds or even thousands of flow-units. Such compound flows are so common on basaltic volcanoes that they should be regarded as characteristic of basaltic eruptions.

A second observation was that there are certain minimum dimensions, best termed "minimum viable dimensions", for a lava stream that is able to flow for a considerable time (a day or more) and to reach a considerable distance from the *bocca*, as distinct from a stream that flows for only a short time and reaches only a short distance from the *bocca* before congealing. The minimum viable thickness on a slope of 10°–20° proves to be about 60 cm for the 1966 Etna lava, and the minimum cross-sectional area of a viable lava stream on the same slope about 1·2 m^2. These minimum viable dimensions are for lava of viscosity close to 4 × 10^4 poises; the viable dimensions are likely to be smaller for less viscous lavas, such as the basaltic lavas of Hawaii, and greater for more viscous lavas, such as the andesitic and rhyolitic lavas of other volcanoes. The minimum viable thickness for Etnean lavas on different slopes is probably given by the lower curve of Fig. 1 (assuming that none of the lava flow-units measured for the construction of Fig. 1 were impersistent, non-viable units, thinner than the minimum viable thickness).

A third observation was that a ropy, pahoehoe-type, lava surface was preserved only on flows within a few tens of metres of a *bocca*. The data in Table 1 suggest that the corresponding limiting viscosity is about 2 × 10^5 poises; with higher viscosity, a surface of aa type developed instead.

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[1] Minakami, T., *Bull. Earthqu. Res. Inst., Univ. Tokyo*, **29**, 487 (1951).

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