Field and Laboratory Studies of the Rheology of Mount Etna Lava

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Field and laboratory studies of the rheology of Mount Etna lava

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Measurements have been made of viscosity and temperature for the 1971 and older lavas.

Viscosities were estimated by two complementary methods: the classical measurements of the flow rate, and a ballistic method, in which the apparent viscosity of the surface layers was deduced from the depth of penetration of a steel spear, perpendicularly injected into the lava flow. Laboratory measurements on lava samples have been made with rotating cylinder viscometers.

The principal result of the work indicates that between the bocca and the flow front the flow behaviour, and consequently the viscosity may vary considerably from lava to lava, even though the original magma varies little in composition.

It is suggested that the different types of flow arises from the fact that the overall viscosity depends not only on the temperature and composition of the residual vitreous phase, but to an even greater extent on the lava's crystal and bubble content. The devitrification, which is a determinant factor of the rheological properties, is in turn highly influenced by the temperature of eruption and the rate of cooling of the lava.

INTRODUCTION

Field analysis

Estimates of viscosity have been made on the assumption that flow in lava streams can be treated by the usual hydraulic equations (Becker 1897; Palmer 1927; Nichols 1939; Wentworth, Carson & Finch 1945; Wentworth 1954). Although the assumption is not quite valid, it made possible the first comparisons of viscosities and calculations of approximate values. The use of corrected formulas for flows in open channels permitted a better estimate of the viscosities of Hawaiian basaltic lavas (MacDonald 1953).

Estimates of viscosity of Etnean lavas have already been made by Tanguy & Biquand (1967), Walker (1967) and Gauthier (1971). Experimental field measurements have been made in the Makaopuhi lava lake (Shaw, Wright, Peck & Okamura 1968), and in the lava streams of Mt Etna (Gauthier 1971).

The present report describes some field experiments and observations designed to give more accurate data on the rheological properties of Etnean lavas. Viscosities were estimated using two complementary methods: (*a*) the classical measurements of the flow rate, in open channels or in pahoehoe flow units (Nichols 1939; Walker 1967; Shaw *et al.* 1968); and (*b*) a ballistic method, in which the apparent average viscosity of the surface layers were deduced from the depth of penetration of a steel spear, projected perpendicularly into the lava flow. The latter experiments represent an attempt to use fixed – but unknown – conditions of shear stress, by using known initial speeds of the spear, and to measure the effects of the consequent rates of shear as the natural lava is deformed.

It would appear important to obtain experimental comparative results in field conditions on the lava in its natural state, whose properties, because of its thermal history and volatile components, are very different from those of melts which are studied in the laboratory.

In our investigations, we have been interested in two problems: the understanding of the behaviour of the magma, by studying the properties of the initial lava, and the understanding of the rheological properties and their evolution during the cooling history of the lava.

As the different types of flow units come from the rheological properties of the initial magma and the dynamic characteristics of eruption, it is more important to study the physical and chemical characteristics of the initial lava at the boccas, because they will determine other parameters, such as thickness, lengths and volumes of flows, and consequently cooling history according to the slope.

We may remark that theoretical and experimental works in the viscosity range 10^2 to 10^7 Pa s (10^3 to 10^8 P) are not numerous, specially on heterogeneous fluids, a fact which does not make rheological investigations on lavas easy.

The meaning of viscosity

The rheologist generally defines different types of fluids by reference to the form of their flow curves (graphs showing the shear rate plotted against shear stress). The shear rate is the flow velocity gradient perpendicular to the direction of flow. The shear stress is the force per unit area acting in the flow direction.

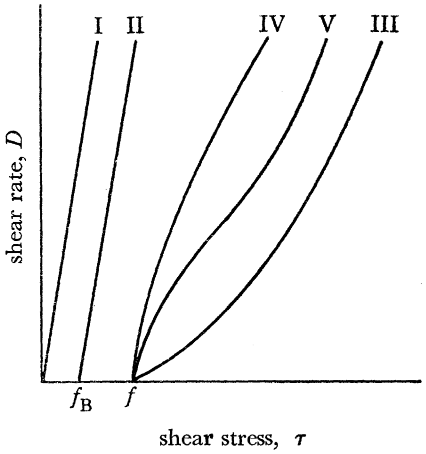

FIGURE 1. Rheogram: types of flow behaviour. Linear models: I, Newtonian flow; II, Binghamian flow (f_B is the Binghamian yield value). Non-linear models (with a similar yield value f): III, pseudoplastic flow; IV, dilatant flow; V, complex flow.

The major aspect of the rheological behaviour of a fluid may be characterized by the shape of the flow curve, and by the point of intersection with the stress axis, as shown in figure 1. One can thus distinguish Newtonian fluids and non-Newtonian fluids, such as Binghamian fluids, plastic or pseudoplastic fluids, dilatant fluids and complex fluids.

For large classes of fluids, the two linear models, the Newtonian fluid and the Binghamian fluid, provide adequate approximation for the initial portion of the flow curve.

The ratio of total shear stress to shear rate corresponds to the Newtonian viscosity in the Newtonian model, and to the apparent viscosity in other fluids, which in some cases may be characterized by the magnitude of a yield value.

In some fluids, the apparent viscosity decreases with time at constant shear rate, but recovers at zero shear rate. This phenomenon, called thixotropic effect, is different from pseudoplastic behaviour (shear thinning) in which the viscosity decreases when the shear increases, as in many fluids.

We shall distinguish viscosity values obtained with the rotating viscometer as Newtonian viscosity or Binghamian viscosity. The viscosity numbers obtained with the ballistic penetrometer by means of Newtonian calibration will be designated as instrument viscosity or consistency. They may present a large difference with other viscosities, which are significant for only one value of the shear rate – excepted in the linear models – because they integrate the shearing effects of the viscosity gradient presented by the fluid. The viscosity values reported under the term of overall viscosity (lava flows in open channels) are also equivalent to instrument viscosities for the same reasons.

1. Methods of analysis

(*a*) *Measurements of the flow rate*

To estimate the viscosity at the free surface of a plane laminar flow considered as a Newtonian homogeneous fluid, we used the same velocity equations as Goncharov (1964) and Shaw *et al.* (1968):

$$v = \rho g H^2 \sin \alpha / 2\eta .$$

The average velocity is given by $V = \frac{2}{3}v$. The slope and the depth are assumed to be constant, and the flow to be laminar and steady.

During our field work, the Reynolds numbers were always found to be lower than 500, so that it can be assumed that flow is laminar. It is generally accepted that laminar flow disappears at Reynolds numbers greater than 1500 in silicate melts (Wentworth *et al.* 1945; Kopecký & Voldán 1959; Van Wazer, Lyons, Kim & Colwell 1963).

The Newtonian viscosity can be uniform only if the flow is isothermal, and the fluid homogeneous in terms of chemical composition and concentration of suspended mineral and gas phases.

The difficulties of applying these equations to lava flows and streams are obviously numerous (Walker 1967), especially in view of temperature and viscosity gradients (Gauthier 1971). If the flow is rapid but still laminar, these equations may be used to obtain the overall viscosity, which has in theory the meaning of an apparent viscosity, only significant at one value of the shear rate observed during the measurement. The best interpretation will be made when the velocity is high and the channel or the flow very wide, because the boundary effects become nearly negligible.

In channels, we use equations with depth replaced by the hydraulic radius (surface section/wetted perimeter).

(*b*) *The ballistic viscometer*

In principle, the measurement consists of shooting a spear perpendicularly into the surface of an infinite liquid, and to relate the depth of penetration to the viscosity or the consistency.

In the laboratory calibration, the penetration is measured as a function of various parameters: the type of ferrule employed, the kinetic energy of the spear, the initial speed of the spear just before penetration – representing an unknown but reproductible initial shear rate and the rheological behaviour and properties of the standard fluids.

We have performed the calibration of the ballistic viscometer with fluids which present Newtonian behaviour at low shear rates: s.a.i.b. (sucrose acetate isobutyrate) and Aroclor 4465. Viscosity curves versus temperature are given in figure 2.

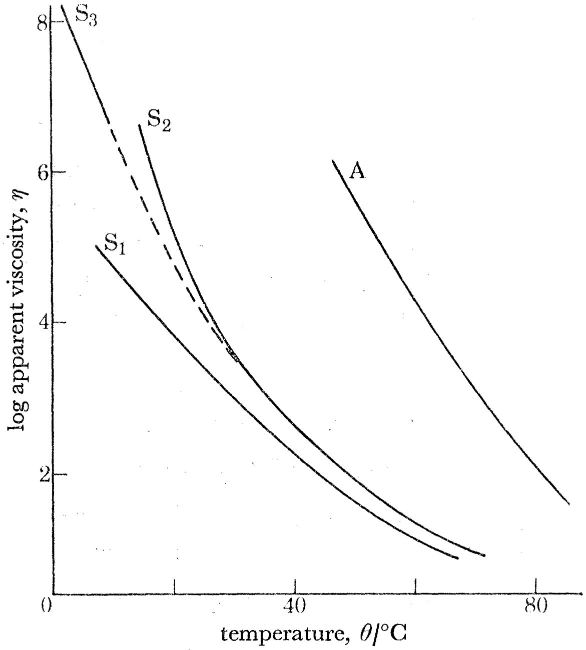

FIGURE 2. Viscosity–temperature curves of Aroclor 4465 and s.a.i.b. Curve A, Aroclor 4465; curves S_1, S_2, S_3, s.a.i.b.; - - -, extrapolated values. S_1, theoretical calibration; S_2, laboratory calibration with falling-sphere and rotating viscometer; S_3, laboratory calibration with falling-sphere (Stokes's law). Curve S_3, completed with the lower part of curve S_2 and extrapolated values, was taken as a significant average standard viscometric reference for this work (calibration of the ballistic viscometer).

2. CONDITIONS OF THE EXPERIMENTS

(a) *The volcanic context*

From 1966 to April 1971, the Mt Etna summit region displayed a regular persistent activity. Explosions at the NE crater were accompanied by the slow emission of lava flows from boccas situated on the base of the cone sometimes surmounted by hornitos. Explosive activity, at an open or blocked chimney, affected the central crater which often emitted grey cinders.

In 1968 a new vent, the Bocca Nuova, opened on the northwest flank of the central crater, and collapsed in 1970 (Guest, this volume).

This period of relatively moderate and somewhat fluctuating activity was concluded with paroxysmal activity beginning on 5 April 1971. First located at the south foot of the central crater, the eruptive activity migrated from a new vent (4 May) along a great tension fissure, where boccas and spatter-cones opened successively in the Valle del Leone (7 May) and finally in the Valle del Bove (11 May), near the Citelli refuge. The eruption ended on 12 June (see Tazieff, this volume).

Our studies concern the lavas of the persistent activity, and a part of the 1971 eruption; 2 to 7 May which was the end of the first-phase eruption; 4 to 9 May which marks the beginning of the second-phase eruption (flank fissure eruption) in the Valle del Leone.

(b) *Field measurements*

(i) *The flow rate*

To estimate the viscosity with velocity equations it is necessary to measure the other parameters.

The density of the incandescent lava, which has been experimentally determined in field conditions (Gauthier 1971), is taken as 2.5 g cm^{-3}.

Thickness of pahoehoe flow units were determined by surface morphology when spreading on a smooth and regular slope, or measured after cooling. In channels the depth is measured with a stainless steel shaft. When measurement is impossible, the depth is estimated: calculation of the geometry of an unknown cross-section from another known section in the same flow neighbouring the first one is based on the fact that the volume of lava pouring through the channel is constant over short periods. From the depth, or the width, and cross-section, the hydraulic radius may be determined.

In order to apply the velocity equations with the best accuracy, we estimate the thickness of apparent surface rigid layer or blocks and clinkers, the weight of which influences the distribution of shear in the viscous layers.

The flow rate is estimated at the centre of the channel, or at the front part which spreads faster in a pahoehoe flow unit, or when the lava pours out of a channel. In channels a scoriae or a graphite float is thrown on the surface. Time of movement between guiding marks on levees or trigonometric joining marks is accurately determined with a chronometer.

(ii) *The depth of penetration*

We have used the ballistic method in field conditions since September 1969. Usually, the lava flow presents a small dome at the emissive bocca. The spear is shot into the lava perpendicularly to the direction of flow, i.e. surface of the horizontal part of the convexity. The propeller may be inclined with an angle equal to the angle of slope. For flow fronts the spear is shot horizontally. In any case, it is possible to calculate the initial speed of the spear which is a little lower than with a vertical shot (minus 1 or 2 %).

The ballistic method permits measurements on flowing lavas because the speed of the spear (22 m s^{-1}) is higher than that of the lava flow (from 0.01 to 2 m s^{-1}). The order of magnitude of the time of penetration is 0.01 s. Heat transfer in direction of the ferrule is negligible, and lava rheological behaviour is not at all modified by any cooling during penetration. The ferrule does not have time to be corroded and incorporated into the lava and it retains a smooth surface and is easily extracted a second or so after the shot.

Lengths of penetration are directly read from graduations on the spear when the flow rate is low. Other methods have been tried, like aluminium or chalk coating, or a sliding steel marker, and are employed according to field conditions.

As the lava surface is irregular, because of thermal retraction due to cooling, the spear may penetrate into a smooth surface, native scoriae, or a fissure. Lengths of penetration are measured from the local level at the impact point. They are corrected and compared according to their place of impact point at the lava surface.

Objections to this method do not arise from difficulties of its application in field conditions, but from rheological interpretation of the lengths of penetration obtained in standard fluids. It is quite impossible to obtain standard liquids without any viscosity gradient in a reasonable time. So, our standard curve (figure 3) comes from the report of the length of penetration versus an average viscosity calculated from the viscosity gradient presented by the fluid layers penetrated by the spear during each calibration.

As it is impossible to develop an elementary theory of this method, its application must be considered as an empirical attempt to estimate, by comparison between lengths obtained in

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the lava and in standard fluids, the order of magnitude of the overall viscosity presented by the surface layers of some types of lava flows. Obviously, natural lavas present vertical viscosity gradients different from those obtained in the standard fluid during calibration.

Ballistic viscometer instrument viscosity is given in pascal seconds and in poises, in terms of s.a.i.b. or aroclor analogy, and is relative to one of the propellers employed (table 1).

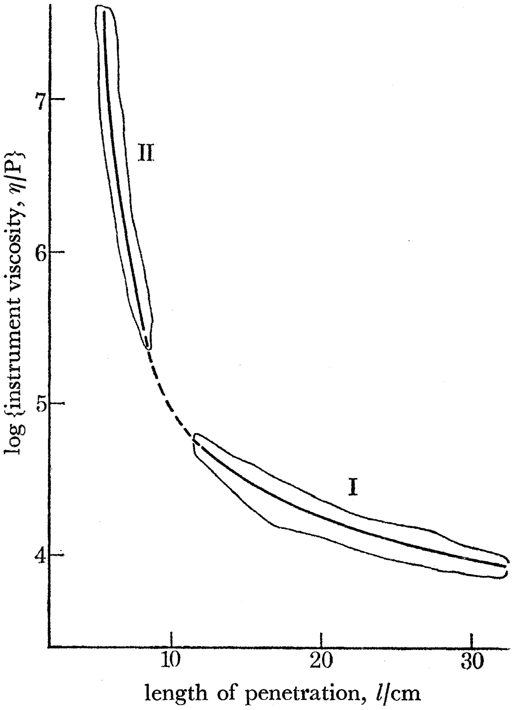

FIGURE 3. Viscosity–length of penetration curve for v.t. propeller and ferrule 1. Curve I, pure viscous flow; curve II, non-pure viscous flow with experimental shear rate; dotted line, transition zone; encircled area, experimental results.

TABLE 1. SPECIFICATIONS OF BALLISTIC VISCOMETER

type: pneumatic propeller with compressed air
tank air pressure before shooting = 29.4 kPa (30 kgf cm^{-2})
tank air pressure after shooting = 19.6 kPa (20 kgf cm^{-2})
lubricating oil: S.A.E. 10

steel spear, graduated in centimetres
    length = 91 cm
    mass = 460 g (with ferrule)
    initial speed = 22.3 m s^{-1}

stainless steel ferrules (type 1: half sphere)
    diameter = 1 cm
    length = 5.6 cm
    mass = 30 g

other ferrules: same characteristics, but with cone angle of 90, 60, 30°

Operating cautions: it is imperative to lubricate the cannon of the propeller for some shots to obtain a good reproductibility for the initial speeds; shots must be done in the same conditions (position of the shooter, distance of fluid, physical parameters of the experiment, etc., ...) in the laboratory and in the field.

(*c*) *Rotating viscometers*

During our laboratory investigations we have used two coaxial cylinder viscometers, whose cups are the internal faces of cylindrical platinium furnaces. The bob rotates with different constant speeds, and the resistance to flow is measured on its surface.

General specifications of the viscometers may be found in Van Wazer *et al.* (1963). Specifications of the experimental apparatus may be found in Gauthier (1971). Table 2 gives the specifications of the two viscometers as adjusted for use in the furnaces used.

As a result of these experiments the flow curves for Mt Etna lava have been established between 1100 and 1400 °C. In the field the red-hot lava samples were supercooled in air.

TABLE 2. SPECIFICATIONS OF THE ROTATING COAXIAL CYLINDER VISCOMETERS

type	Brookfield Synchro-lectric RVT		Epprecht Contravès RM 15 fc (Drage viscometer)	
bob diameter	0.952 cm		0.750 cm	
cup diameter (furnace)	2.54 cm		1.50 cm	
maximum torque (100 scale units)	7187 × 10^{-7} N m (7187 dyn cm)		39224 × 10^{-7} N m (39224 dyn cm)	
maximum shear stress (100 scale units)	178 N m^{-2} (1780 dyn cm^{-2})		2041 N m^{-2} (20410 dyn cm^{-2})	
apparent viscosity range	1–1200 Pa s (10–12000 P)		1–13000 Pa s (10–130000 P)	
speed	angular velocity (rev/min)	shear rate (s^{-1})	angular velocity (rev/min)	shear rate (s^{-1})
1	0.5	0.111	5.595	1·562
2	1.0	0.222	7.513	2.098
3	2.5	0.555	9.885	2.760
4	5.0	1.110	13.190	3.683
5	10.0	2.220	17.400	4.859
6	20.0	4.440	25.080	7.004
7	50.0	11.100	33.670	9.402
8	100.0	22.200	44.310	12.370
9			59.110	16.510
10			77.980	21.780
11			113.200	31.610
12			152.000	42.450
13			200.000	55.850
14			266.800	74.480
15			352.000	98.300

3. FIELD AND LABORATORY INVESTIGATION RESULTS

(*a*) *Measurement of the flow rate*

On 18 July 1970, the overall viscosity was measured on pahoehoe flow units pouring from the hornito situated on the north foot of the NE crater, which also fed a channel flow. These measurements permitted the determination of the viscosity variations on the same emissive bocca, and the comparison of the order of magnitude of viscosity values simultaneously obtained with thickness of pahoehoe flow units and with hydraulic radius in channel flow (figure 4).

From 4 to 7 May 1971 we studied the viscosity of the lava at emissive boccas on the south foot of the central crater. The altitude of boccas decreased during that time, from 2920 to 2800 m.

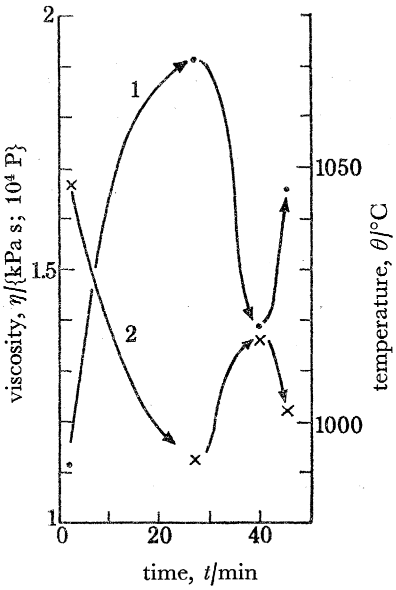

FIGURE 4. Overall viscosity and optical apparent temperature as a function of time. Curve 1, apparent optical temperature of lava surface; curve 2, viscosity calculated with thickness of pahoehoe flow units, during permanent emissive activity of the NE crater, 18 July 1970. Viscosity of the lava calculated from the channel with hydraulic radius 12 kPa s (12×10^4 P).

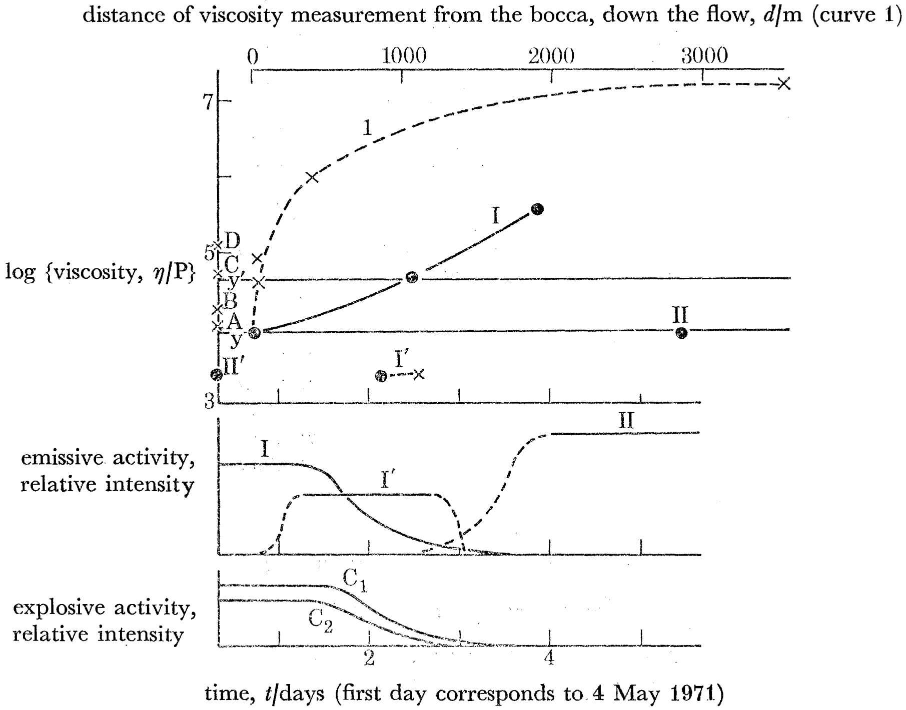

FIGURE 5. Viscosity of Mt Etna 1971 lava flows compared with permanent lava flows. Curve 1, viscosity down a flow (4 to 5 May 1971, end of first-phase eruption). Curves and values I, I′, II, II′ are relative to overall viscosity measured at emissive boccas, or very near, 1971 eruption. First-phase eruption: curve I, latest emissive bocca on the Piano del Lago (4 to 7 May); curve I′, 4 May vent, opened on the east foot of central crater. Second-phase eruption: average value II, upper hornito in the Valle del Leone (9 May); average value II′, upper bocca near Citelli refuge, 16 May (recalculated from Dr Tanguy's observations). Permanent lava flows: A–B, viscosity range observed on hornito, July 1970; C–D, viscosity range observed on resurgent boccas, July 1970; y–y′, viscosity range observed on emissive boccas, from 1967 to 1970. Velocity equations used with depth (×) or with hydraulic radius (●). Numbering of boccas on emissive activity graph and on viscosity–time graph are identical (I, I′, II). C_1, explosive activity of crater 1; C_2, explosive activity of crater 2. Craters are numbered with distance from emissive boccas of 5 May, near the observatory, towards the east. Crater 1 is the nearest. Maximum explosive activity corresponds to an order of magnitude of about one explosion per second (scoriae projected 50 m into the air).

The evolution of viscosity down the flow of a lava stream of the first-phase eruption, on the Piano del Lago, was also measured.

On 6 May an estimate of viscosity with hydraulic radius was made on lava pouring through levees, 10 m from the 4 May vent.

On 9 May it was possible to estimate the viscosity of the lava of the first stage of the second-phase eruption which was pouring out of the upper hornito in the Valle del Leone at an altitude of about 2680 m.

On 16 May the viscosity of the lava of the Citelli vents (upper bocca) were estimated from Dr Tanguy's observations (figure 5).

To complete the comparison between lavas of the 1971 eruption and those of the permanent activity, the viscosity range observed on hornitos from July 1967 to July 1970 have been incorporated on the graph (figure 5).

(*b*) *Conditions of flow and surface aspects of lava flows*

It has sometimes been possible to observe (1967, 1969, 1970) parabolic rolls affecting the surface layers of lava flows and these may be due to shearing effects resulting from viscosity gradients. Thus this might indicate a Newtonian behaviour if Poiseuille flow conditions are effective, if the flow pours through two vertical infinite walls (bottom effects negligible) or into an hemi-cylindrical channel. It is interesting to note that there is no flow against the walls (no Klikenberg effect).

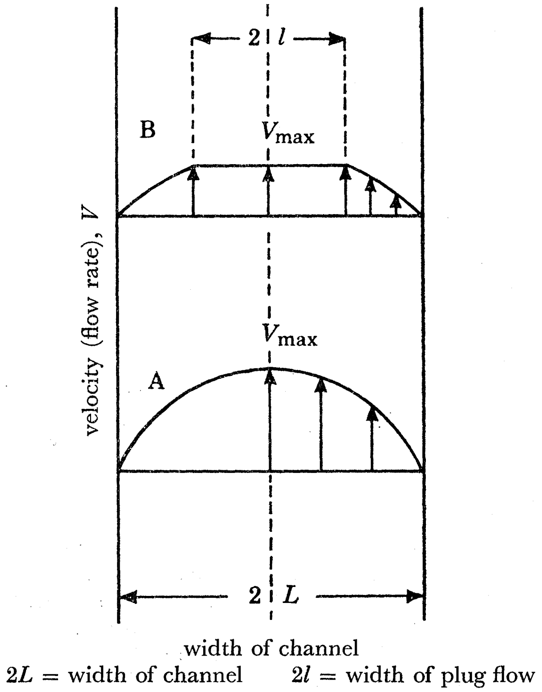

FIGURE 6. Velocity gradients at the surface of channel flows (homogeneous fluids). A, parabolic profile (fluids without a yield value). The shear rate increases with distance for the region of parabolic velocity profile. B, plug-flow. The velocity up to the distance $2l$ is constant, corresponding to plug flow. Velocity in the rest of the region is parabolic. The shear rate in the plug-flow region is zero. No slippage on the walls.

In lava channels between two levees the velocity distribution is not always parabolic, appearing as a surface ribbon which flows with a continuous speed (figure 6). In boundary layers the clinker may rotate on itself. At low rates of emission, when temperature of lava and volume poured out are low, the same phenomenon may appear near the bocca. It may be due to plastic rheological behaviour.

In September 1969, it was noted that the surface layers of permanent lavas could give 'string lavas', 10 m from the emissive bocca, when they gave at the emissive dome an initial instrument viscosity of about 3×10^5 Pa s (3×10^6 P) though the overall viscosity of the flow was about 10^4 Pa s (10^5 P).

TABLE 3

(*a*) 5 *May* 1971. First-phase eruption: lava flow front on the Piano del Lago, 500 m from the emissive bocca; altitude 2750 m

(i) viscous dome on the lava-flow surface with an apparent optical temperature of 1050 °C (± 4 °C)
length of penetration obtained, 27 and 27.5 cm ± 1 cm
consistency (analogous to an identical viscous resistance), 1.10 kPa s (1.10×10^4 P)
possible consistency range, 1.02 to 1.15 kPa s (1.02 to 1.15×10^4 P)

(ii) incandescent blocks in the lava flow front
lengths obtained into a cubic metre block (± 0.3 cm), consistency
(*a*) through initial surface 11.5 cm, 5.75 kPa s (5.75×10^4 P)
(*b*) after a first breaking 14 cm (through a new surface), 3.55 kPa s (3.55×10^4 P)
(*c*) after a second breaking 18 cm, 2.19 kPa s (2.19×10^4 P)
with an apparent optical temperature of 1080 °C on this new surface.

(iii) other incandescent blocks:
lengths (± 0.3 cm) 33.5, 8.3×10^2 Pa s (8.3×10^3 P)
33, 8.5×10^2 Pa s (8.5×10^3 P)
13, 4.26 kPa s (4.26×10^4 P)
10, 9.1 kPa s (9.1×10^4 P)
$\left.\begin{matrix}1\\0.5\end{matrix}\right\}$ much more than 10^7 Pa s (10^8 P)

overall viscosity (flow-rate measurement with thickness of 1 m and an approximate shear rate of 0.035 s^{-1}), 9.8×10^5 Pa s (9.8×10^6 P)

(*b*) 7 *May* 1971. End of first eruptive phase: emissive bocca 150 m westwards from Torre del Filosofo; altitude about 2850 m.
optical temperature (without correction of emissivity) on the surface of the bottom of a pit after lava incandescent sampling (10 cm depth), 1087 °C
thermoelectric temperature (thermocouple not calibrated) into the lava flow
at 9.5 cm depth, 1090 ± 14 °C
at 27.5 cm depth, 1097 ± 14 °C
at 45 cm depth, 1123 ± 14 °C
length of penetration obtained on a smooth surface (average of 4 successive measures executed during 6 min at the same place of the horizontal part of emissive dome), 6.6 ± 0.5 cm
instrument viscosity of surface layers (log viscosity = 6.3), 2.0×10^5 Pa s (2.0×10^6 P)
possible viscosity range (log viscosity = 6.05–6.8), 1.1 to 6.3×10^5 Pa s (1.1 to 6.3×10^6 P)
overall viscosity (flow-rate measurement with hydraulic radius = 50 cm, and approximate shear rate = 0.045 s^{-1}), 3.58×10^4 Pa s (3.58×10^5 P)

(*c*) 8 *May* 1971. Beginning of second eruptive phase: upper hornito of the Valle del Leone, altitude about 2680 m.
maximal optical temperature of lava in the hornito (quite black body, measured through gases), 1128 °C
thermoelectric temperature on the lava surface, 20 m from the bocca, at 30 cm depth, unknown
(1065 °C obtained very far from thermal equilibrium – time for measurement too low)
length of penetration, 19 cm, 18 cm (± 1 cm).
instrument viscosity of surface layers (viscosity log = 4.3), 2.0 kPa s (2.0×10^4 P)
possible viscosity range (4.25 to 4.38 for viscosity log), 1.78 to 2.40 kPa s (1.78 to 2.40×10^4 P)
overall viscosity flow-rate measurement with hydraulic radius = 36 cm, and approximate shear rate = 2 s^{-1}, 7.53×10^2 Pa s (7.53×10^3 P)

(*c*) *Measurements of lengths of penetration*

On 5 May 1971 during the first-phase eruption, the surface of a lava flow and its front was studied on the Piano del Lago (table 3).

On 7 May 1971 it was possible to realize a series of penetrations in the emissive dome of one of the smaller boccas on the Piano del Lago, at the end of the first-phase eruption, at an altitude of 2850 m, near the Torre del Filosofo. A thermoelectric measurement of the temperature of the flow completed the experiments.

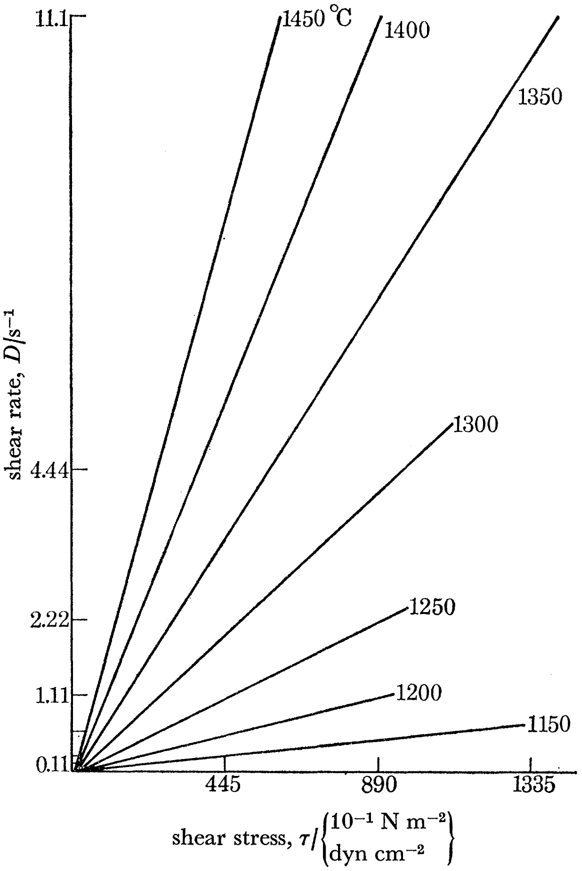

FIGURE 7. Rheogram: flow curves of a permanent lava. Scoriae, NE crater of Mt Etna, July 1967. Each flow curve is performed at the constant temperature indicated with the Brookfield viscometer. Accuracy 1%

On 9 May 2 or perhaps 3 days after the beginning of the second-phase eruption in the Valle del Leone, there were obtained two good measurements of length of penetration in the surface layers, 15 m from the upper hornito which was situated at an altitude of about 2680 m.

The apparent optical temperatures measured during these experiments must be regarded as the minimum possible temperatures of the lavas.

(*d*) *Laboratory viscometric results*

The flow curves and viscosity–temperature curves of Etnean permanent lava samples have been studied with rotating viscometers and a rising-ball viscometer (Kostka & Reinis 1958). One typical flow curve is given in figure 7, and viscosity–temperature curves are compared in figure 8. Chemical compositions of the samples studied are given in table 4.

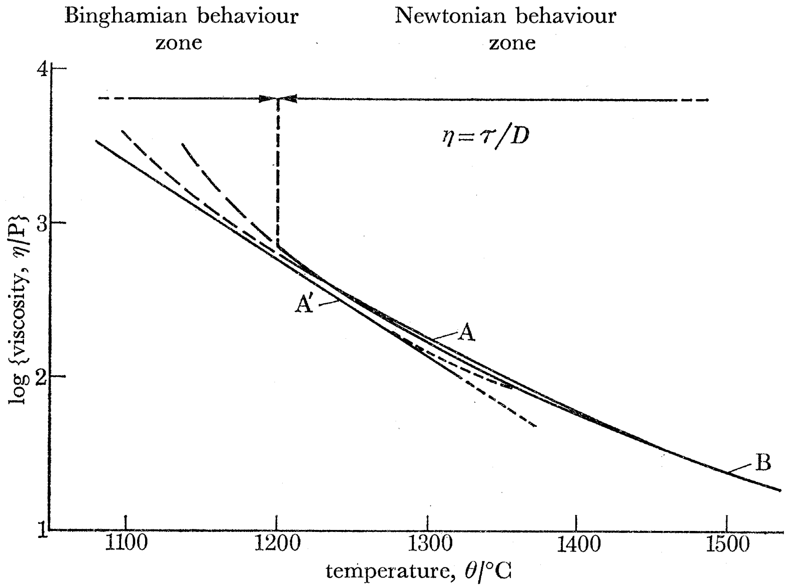

FIGURE 8. Viscosity–temperature curves of Etnean lavas. Curve A, scoriae, NE crater, July 1967, Brookfield viscometer; curve A′, apparent viscosity of the same scoriae, falling-ball viscometer; curve B, clinker, pahoehoe flow unit, SE slope of the NE crater, October 1968, contravès viscometer.

TABLE 4. A. CHEMICAL COMPOSITION OF MELTED SAMPLES (%)

	A	B
SiO_2	47.19	47.24
Al_2O_3	17.80	16.20
Fe_2O_3	8.81	4.71
FeO	2.95	6.09
MnO	0.06	0.16
MgO	5.11	5.32
CaO	10.06	10.41
Na_2O	4.31	4.30
K_2O	1.78	1.65
P_2O_5	0.31	0.56
TiO_2	0.48	1.74
H_2O^+	0.19	0.45
H_2O^-	0.26	0.57
total	99.21	99.40

Analyses performed by Laboratoire de Pétrographie et Volcanologie, Faculté des Sciences d'Orsay, analyst R. Duret (A) and C.E.A., B. David, unpublished, analyst Service minéralogie 97416 (B).

Samples used in the construction of curves in figure 8.

B. ESTIMATE OF THE HETEROGENEITY OF PERMANENT LAVA

A modal analysis performed on a permanent lava (analyst A. Demant) picked out of the bocca from a depth of 50 cm and cooled in free air (north slope of the NE crater, 20 July 1970) may indicate an order of magnitude of its heterogeneity:

solid phase, 44.6% (phenocrysts, 38%; microlites, 6.6%)
liquid phase, 22.8% (glass)
gas phase, 32.6% (bubbles).

(e) *Results*

The first field observation is that the overall viscosity of the initial magma, measured with flow rate at emissive boccas, varies with temperature (figure 4). Temperature affects viscosity of many fluids, which may change in type of rheological behaviour. Industrial glass, which is Newtonian at high temperatures (1150 to 1500 °C) may become plastic and viscoelastic as temperature decreases. Basaltic lava glasses may present the same properties if they are supercooled before devitrification.

It should be noted that the lowest values of overall viscosity obtained (Walker 1967) come from the estimates of flow rate with thickness on pahoehoe flow units pouring out from the main bocca. The overall viscosity deduced from velocity equations with depth replaced by hydraulic radius applied to the same lava, simultaneously pouring into levees or channel, is higher. This fact seems to be due to the importance of boundary effects and viscosity gradient shearing effects in emissive narrow channels.

The instrument viscosity values deduced from ballistic comparative measurements in surface layers in flows near the emissive bocca are always higher than the viscosity values obtained with flow-rate measurements, which illustrates the existence of a viscosity gradient in the flow, already illustrated by the difference between pahoehoe and channel flow measurements.

Another important result is, in my opinion, that the instrument measured viscosity of surface layers at the emissive bocca decreases at the same time that the overall viscosity estimated at the same place with flow-rate measurements using hydraulic radius.

In lava flow fronts, which present a very wide range of consistency, it is possible to find instrument viscosities lower than the overall viscosities because of their rheological heterogeneity. There are viscous layers beneath, and the boundary effects are very important because of the presence of scoriae, blocks and clinkers which are pushed and rolled and reduce the flow rate. The overall viscosity represents a pure viscous flow only when the surface layers may be considered as viscous (viscosity log lower than 10^{12} Pa s (10^{13} P)), i.e. in the initial parts of channels or flows, near the emissive bocca.

When the measurement is done 500 to 3500 m or more from the emissive bocca, the average overall viscosity value obtained is higher than the viscosity of the fluid layers. If a resurgent bocca appears, it is first fed with the most fluid layers which pour out under internal pressure effects. The viscosity may then be some orders of magnitude lower than the previous overall value.

It is interesting to compare the field viscosity values with the laboratory viscosity–temperature curves. The comparison of the chemical analyses of permanent lavas and 1971 lavas shows that the overall chemical composition of Etnean magmas for the last five years is quite constant. The small differences between the samples collected in 1971 and those of samples for which the flow curves are shown in figure 8, are of the same order of magnitude. The 1971 lavas present the same flow curves and viscosity–temperature curves as the permanent lavas, because the chemical compositions are too identical to be able to lead to significant differences in flow behaviour.

The differences shown in the rheological properties of lavas in field conditions may come from the different petrological compositions of the initial magma. The writer has not done any petrological studies on samples taken from the 1971 lava at emissive boccas. In this first rheological approach a petrological evolution will not be considered, which does not mean that this phenomenon has a negligible effect on magma flow behaviour.

The lowest overall viscosity values measured in the field (260 Pa s; 2600 P) seems to be in good agreement with the values obtained in the laboratory (figure 8) for identical lavas melted at the same temperature of 1130 °C (160 to 400 Pa s; 1600 to 4000 P). The other overall viscosities and instrument viscosities are higher because of devitrification and/or cooling of the vitreous fluid phase.

The typical flow curve of an Etnean lava (figure 7) shows a Newtonian behaviour at temperatures higher than the liquidus (around 1200 °C). At low temperatures it seems that the Binghamian behaviour appears and increases when the temperature decreases. The yield values are deduced at the intersection of the flow curve with the stress axis, supposing a linear behaviour at very low shear rate. The range obtained on samples melted at temperatures around 1200 °C is 4.5 to 30 N m^{-2} (45 to 300 dyn cm^{-2}). When the temperature decreases and devitrification appears, higher values may be found, but they increase with time.

Lava melts obtained in furnaces are modified with melting of initial phenocrysts (olivine, pyroxene, plagioclase), devitrification of the fluid glass phase, vesiculation and degassing, phenomena which affect the rheological behaviour of this non-equilibrated heterogeneous fluid.

Laboratory measurements are performed, in the temperature range 1100 to 1200 °C, on a supercooled liquid glass without bubbles, the phenocrysts being melted and the devitrification negligible. When a determinant rheological factor becomes variable, it is impossible to obtain a significant flow curve. Moreover, the rotating viscometer suffers from the large moment of inertia of its suspension assembly. This fact prevents measurements of rapid time-dependent effects when the melt properties are fastly varying, and makes measurements of yield values difficult or impossible (Van Wazer *et al.* 1963).

If the natural lava presents a yield value, the velocity gradient becomes zero at a point where the component of shear stress is equal to the yield value. This leads to the appearance of a rigid layer at the flow surface. In a narrow channel it may appear as a ribbon (figure 6). If the slope is very slight, this effect becomes important because of the low shear stresses. The thickness in an homogeneous fluid is given by

$$E = (H-y) = f_{\mathrm{B}}/\rho g \sin \alpha.$$

E depends on the yield value of the surface layers, which is a function of the temperature. Considering an average temperature in these surface layers it is possible to estimate an order of magnitude of the yield value in field conditions if E is known.

During the manipulations on the natural incandescent lava, E has been grossly estimated from 5 to 20 cm. The calculations give an order of magnitude of 50 to 200 N m^{-2} (500 to 2000 dyn cm^{-2}), corresponding to an apparent optical temperature range of 1080 to 1100 °C, measured on the lava surface. These values are ten times higher than those deduced from flow curves because of the presence of phenocrysts and bubbles in a glass phase, the viscosity of which is higher because its temperature is 100 °C lower and its composition different.

4. Remarks and suggestions on rheology

Natural incandescent lavas are heterogeneous melts having three phases: (1) an initial continuous and vitreous fluid phase, whose viscosity and composition will vary, because of cooling, devitrification, and probably gaseous transfer; (2) a dispersed crystalline solid phase, represented by the phenocrysts in the magma which may be considered in first approximation as solid spheres, and by a neocrystalline phase – considered as needles – due to the devitrification of the vitreous phase during the cooling of the lava; and (3) a dispersed gas phase, represented by rising bubbles and dissolved gases in the melt, whose percentage will decrease during spreading (table 4B).

As the rheological properties of such a complex fluid will be very difficult to measure in field conditions, experimental laboratory studies of many different fluids compared with theoretical considerations (Sibree 1934; Peeble & Garber 1953; Shaw *et al.* 1958; Sherman 1970) can help the rheologist to build approximate models for magma and lava.

If solid spheres or needles are added in a Newtonian fluid the viscosity of this dispersion will increase, and the flow behaviour will present a thin effect. If the percentage of solid phase increases a yield will appear. If bubbles are introduced in a Newtonian fluid which has a high superficial tension a yield value may appear, but the viscosity may decrease at high shear rate.

Each factor which may influence the viscosity does not act independently. Moreover, phenomena other than purely mechanical ones may exist between the different components of such a complex fluid. For example, the rheological theory of rising bubbles in homogeneous fluids is not yet well understood. In magma and lava three factors (viscosity of the glass phase, solid phase and gas phase) operate simultaneously, and the net effect differs in magnitude from the sum of the individual contributions. The net effect for the initial lava whose basaltic residual glass phase alone has a Newtonian behaviour, will supposedly be a complex plastic effect (figure 1V).

During free-air history, and according to the rate of cooling, the viscosity and the yield value will increase. A thin effect might appear because of the orientation of the needles. These reasons mean that the flow curve will change in slope and shape, and will be displaced towards the right on the rheogram during the structural evolution of the lava.

CONCLUSIONS

It seems, on the basis of the present study compared with others (Walker 1967; Shaw *et al.* 1968) that Etnean magmas and lavas must be considered to be plastic or pseudoplastic (complex flow behaviour) fluids. Yield value and flow behaviour evolve during the stages of their free-air history, the role of cooling upon the determinent parameters being essential. Lavas are consequently characterized by an extreme range of apparent viscosities and may, without significant changes of temperature, chemical and petrological compositions, and bubble and gas phase content of the initial lava at emissive bocca, appear more or less fluid.

For the 1971 eruption, it has been possible, in field conditions, to study for the first time some rheological properties of Etnean lavas during the different phases of a non-classical paroxysmal eruption. The measurements of flow rates, completed with the ballistic method results, and compared with experimental and theoretical considerations, enable one to obtain a better understanding of Etnean rheological operation.

Instrument measured viscosity of surface layers at emissive boccas decreased at the same time that the overall viscosity estimated with flow rate. This fact might be used to survey the viscosity fluctuations for any emissive phase. Viscosity seemed to increase slowly during the most important part of emission, and very quickly during the ultimate stage. The viscosity at the bocca of a new eruptive phase was lower (the viscosity value of the very first stage, when the bocca opened is not known) than that of a lava flow pouring out of a bocca of a previous eruptive phase.

The 1971 paroxysmal lavas were less viscous than permanent lavas. The lowest values measured on the 4 May vent, around 260 Pa s (2600 P), might be due to a greater bubble and gas content.

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