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Mechanical Properties of Lava Extruded in the 1983 Predskazannyĭ Eruption (Klyuchevskoĭ Volcano)

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This paper describes the technique for measuring the apparent viscosity, yield strength, and Bingham viscosity of lava along with the results of field work carried out during the 1983 Predskazannyĭ eruption. The apparent viscosity of lava at the moment of extrusion at the surface was of the order of 10^5 P during the entire eruption; in open channels viscosity grew by nearly an order of magnitude over a distance of about 1 km from the vent. The yield strength measured near the vent was several times 10^4 dyne/cm², and Bingham viscosity, about 10^5 P.

During the eruption measurements were made of apparent lava viscosity η defined as the viscosity of a Newtonian liquid behaving like lava in the specific conditions of a given flow, and also possessing the rheological properties of lava when it could be assumed that it answered the characteristics of a Bingham substance (yield strength τ_0 and plastic or Bingham viscosity η_B).

Measurements of apparent viscosity were made mainly on the basis of lava flow parameters, the same way it was done during the recent eruption of Tolbachik Volcano [1], [2], although certain changes were introduced in the method to suit the specific conditions of the Predskazannyĭ eruption. In some cases viscosity was measured with a simple penetrometer. Yield strength and Bingham viscosity were calculated from a transverse velocity profile measured at one of the largest flows, and from the size of the primary pressure ridges [5].

The conditions for measuring the viscosity at the Predskazannyĭ Bocca were unfavorable (as compared, for example, to those at the Southern Bocca during the 1975–1976 eruption of Tolbachik Volcano). Considerable difficulties were created by the severe weather obtaining at high altitudes in winter, and also by the character of the lava flowing mostly along deep canyon-like fissures and often melting its way through glaciers. Viscosity measurements were therefore not quite regular, but still they covered practically the entire period of the eruption.

APPARENT VISCOSITY

Lava viscosity is generally computed from the well known equations for a plane liquid layer:

$$\eta = \frac{\rho g h^2 \sin \alpha}{2V}, \tag{1}$$

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

where ρ is lava density; h is the depth of the lava flow; and α is the angle between the bed of the flow and the horizon; V and $\bar{V}$ are, respectively, the maximum and mean velocities of the lava flow measured across the flow; and g is gravity acceleration.

Equation (2) is used to measure the speed of advance of the lava front. During the Predskazannyĭ eruption it was employed only to estimate the apparent viscosity of moving lava dams. Velocity V in equation (1) was derived from the time it took a marker to travel the distance between two prestaked points on the axis of the lava flow. Angle α was measured with a miner's compass. The mean density of lava was assumed to be 2.5 g/cm³. The flow depth h was determined least accurately. In most cases it could only be estimated from indirect data, such as the height of the pressure ridges (in a newly formed flow) or the changes in the level of the flow surface caused by changes in the rate of the lava discharge. The flow depth, h, could be determined more or less accurately only when the lava dragged along its bed irregularly shaped cold lumps of rock far exceeding the flow depth in size.

Both formulas (1) and (2) give satisfactory results only if the width of the flow is several times greater than its depth which was by no means the case during the Predskazannyĭ eruption. Minakami [6] suggested that for a flow with commensurate width and depth, the following formula for a semicircular cross-section could be used:

$$\eta = \frac{\rho g h^2 \sin \alpha}{4V}. \tag{3}$$

The more general formula for a channel of an elliptical cross-section [3] can also be applied to a semiellipse because of its symmetry:

$$\eta = \frac{\rho g \sin \alpha}{2V} \frac{a^2 b^2}{a^2 + b^2}, \tag{4}$$

where b and a are the ellipse semiaxes (the halfwidth and depth of the flow), and V is maximum lava velocity at the surface of the flow.

Just as equation (1), equation (3) is based on the approximation of the flow cross-section by a simple geometrical figure and requires the measurement of only one linear parameter. Although this parameter may be the halfwidth of the flow, the error depends on the depth estimate, since it is the depth that determines the representation of the cross-section by a semi-circle.

Equation (4) contains two linear parameters one of which is again the depth. The real shape of the cross-sections of the flow channels (according to observations of empty channels) is closer to a rectangle than to a semiellipse. Therefore the simplest equation (1) should be used in the case of wide and shallow flows. For narrow flows whose depth cannot be reliably estimated it would be more reasonable to employ equation (3). In some cases, however, the representation of a cross-section by a semiellipse makes it possible to obtain additional information on, and more accurate estimates of both the lava viscosity and the rate of lava discharge precisely owing to the two linear parameters in the expression for viscosity.

A procedure for estimating apparent viscosity which eliminates the depth term in the final formula was suggested by Storcheus. It consists in measuring the velocity and width of the flow at two closely situated sections differing by the slope of the channel bed. It is then assumed that in both sections the cross-section of the flow is a semiellipse and apparent viscosity, the rate of lava discharge, and lava density are constant. Equation (4) written for each section of the flow, coupled

with an expression for the rate of lava discharge based on the speed of the flow and the dimensions of the cross-section, gives a system of four equations with four unknowns (viscosity η, lava discharge R and depths a_1 and a_2):

$$\eta = \frac{\rho g \sin a_i}{2V_i} \frac{a_i^2 b_i^2}{a_i^2 + b_i^2}, \; R = \frac{\pi}{4} \rho a_i b_i V_i, \; i = 1, 2. \tag{5}$$

These equations can be solved using the following formulas:

$$\eta = \frac{\rho g b_2^2 \left[\sin \alpha_2 - (b_2/b_1)^2 (V_2/V_1)^2 \sin \alpha_1\right]}{2V_2 \left[1 - (V_2/V_1)^2 (b_2/b_1)^4\right]}, \tag{6}$$

$$R = \frac{\pi}{4} b_1^2 V_1 \left(\frac{\rho g b_1^2 \sin \alpha_1}{2V_1 \eta} - 1 \right)^{-1/2}. \tag{7}$$

Two of our assumptions — constant rate of discharge and constant density — must be quite realistic because these parameters are very unlikely to change appreciably over a short portion of a steady flow. The error introduced by the first assumption (that the cross-section of the flow is a semiellipse) is obviously insignificant since the figure most distinct from a semiellipse would be a rectangle described around it. The greatest unpredictable error may stem from the assumption that lava viscosity is constant which is valid only for a Newtonian liquid. Unlike the viscosity of a Newtonian liquid, lava viscosity depends on factors causing deformation and in principle cannot be identical within sections of the flow having differently inclined channel beds. The difference in viscosities could be smoothed by selecting such stretches of the flow that would not differ much in slope, but this would greatly enhance the error in calculations according to equation (6). Actually, good results can be obtained if the lava flow is near-Newtonian, i.e., when the rate of discharge and the velocity of the flow are sufficiently high. The conditions were the closest to this requirement at the beginning of the eruption, i.e., the time the technique outlined here was applied.

Apart from estimating viscosity on the basis of the flow parameters, viscosity was measured directly with a simple penetrometer. The penetrometer was a steel rod, 14 mm in diameter and 2 m long, and had a rounded end. The speed with which the rod penetrated the lava under a known pressure was measured. In practice this amounted to measuring the time intervals between the submersion of the marks calibrated on the end part of the rod. The force acting on the rod was the combined weight of the rod and special attachments. In many instances when conditions did not allow the use of the weights, the rod was inserted by muscular effort which was estimated by comparing it with the action of the weights used in places convenient for measurements.

The measurements showed that the speed of submersion of the rod in the lava was virtually constant under the action of a constant force and was independent of the length of the submerged part of the rod. The friction between the sides of the rod and the lava was evidently negligibly small as compared with the drag force of the lava to the advancing end of the rod. The rod could be withdrawn with ease. The hole it left in the lava had a slightly bigger diameter which is due to the chilling of a thin lava crust at contact with the cooler rod. A chilled crust was also formed near the end of the rod, thereby actually enlarging its diameter which controlled viscous drag. It was estimated therefore that the diameter of the end of the rod should have an extra 1 or 2 mm added to it when calculating viscous drag.

With all these considerations taken into account, viscous drag can be assumed to be equal to one-half of Stokes' force acting on a sphere falling through a viscous medium:

$$F = 3\pi\eta u r_{eff} \tag{8}$$

from which

$$\eta = \frac{F}{3\pi u r_{eff}}, \tag{9}$$

where F is viscous drag equal to the force applied to the rod; r_{eff} is the effective radius of the rounded rod end; and u is the speed of submersion of the rod.

The use of Stokes' formula (8) here is appropriate because with the submersion speed of a few centimeters per second the flow around the rod end is laminar.

Viscosity measured with a penetrometer coincided in the order of magnitude with the estimates made on the basis of the flow parameters, in some cases being lower than the latter by a quarter or a half. Since the conditions under which viscosity was measured by the two methods were widely different, and also bearing in mind that lava is essentially a non-Newtonian liquid (that is why we say "apparent viscosity"), the

grounds for comparing the results deserve special consideration.

First of all, a penetrometer gives a local value of viscosity (practically the value at a point), whereas measurements based on the flow parameters yield a value for a considerable section of the flow. In the latter case the results may be affected by large-scale inhomogeneities, such as solidified lumps of crust or cold lumps sheared off the walls of the fissure. We compared only the measurements made near the lava vent where no crust was formed yet (this was the only place where a penetrometer could be employed at all), and only when there were no cold lumps in the flow. Furthermore, unlike Newtonian viscosity, apparent viscosity depends not only on the properties of the medium, but also on shear stress. The maximum shear stress values obtained in a 1.5–2 m-thick lava flow with the rod submerged under a pressure of several kilograms per cm^2 of the rod end surface were roughly similar.

It follows that in our case a comparison of the results of viscosity measurements using the two techniques is justified. The satisfactory agreement between the results is indicative of their reliability. We proceeded from this assumption when we determined the depth and rate of discharge of the lava flow. The viscosity value obtained with the aid of a penetrometer was substituted into formula (1), from which the flow depth was derived.

The results of all viscosity measurements during the eruption are given in Table I.

It is clear that virtually all measurements made on large flows gave nearly the same values of apparent viscosity: several times 10^5 P. Measurements near the outflows of small lava streams and also on large flows at distances of 500 to 1000 m from the vents yielded viscosity values higher by an order of magnitude, i.e., several times 10^6 P. In two measurements the values were of the order of 10^7 P. In one case it was viscosity at the front of a small lava flow, and in the other, in the last portions of the lava one day before the eruption ceased completely.

Judging by the bulk of the data viscosity does not change when lava flows along channels in the body of a fresh lava flow. This value turned out to be the same in the lava appearing at the surface from bocche situated both directly beneath the cone and at various distances from it, up to 1.8 km. At the same time the apparent viscosity increased in wide open channels by an order of magnitude over a distance of about 1 km. Along with some other characteristics, lava viscosity in smaller flows suggests that these flows issue from isolated reservoirs completely or

TABLE I

Date	Distance between bocca and base of cinder cone	Distance between bocca and measurement point	Type of flow	Viscosity, P	No. of formula (measurement procedure)	Comments
March 25	0	1000	Large	$(3+9)\cdot10^6$	1	Measurements were made at two points in accordance with the requirements of the procedure. The points were closely spaced along the flow; the zero in the second column indicates a lava bocca beneath the cone
March 27	0	100	Large	$3\cdot10^5$	6	
March 29	0	—	Large	$(3+7)\cdot10^3$	1	
March 29	0	—	Large	$(1.8+3.5)\cdot10^4$	1	
March 29	0	50 + 100	Large	$1.6\cdot10^5$	6	
March 29	0	50 + 100	Large	$2.2\cdot10^5$	6	
March 29	0	100 + 150	Large	$1.2\cdot10^5$	6	
March 29	0	100 + 150	Large	$1.1\cdot10^5$	6	
March 29	0	100 + 150	Large	$1.3\cdot10^5$	6	
March 29	0	150 + 200	Large	$1.4\cdot10^5$	6	
March 29	0	150 + 200	Large	$1.1\cdot10^5$	6	
March 29	0	50 + 100	Large	$(0.5+2.5)\cdot10^5$	1	
April 2	0	100	Large	$1.2\cdot10^5$	6	
May 17	700–800	30–50	Small	$4.3\cdot10^5$	1	
May 21	500	800	Large	$1.4\cdot10^6$	1	Flow No. 1
May 23	1000	5–10	Small	$2.6\cdot10^6$	1	Flow No. 2
May 23	1000	5–10	Small	$3.6\cdot10^6$	9	Flow No. 2
May 23	1000	100	Small	$1.3\cdot10^7$	2	Measurements at the front of a small Flow No. 4
May 24	500	30–50	Large	$3.4\cdot10^6$	1	Flow No. 1
May 25	1400	50	Large	$5.5\cdot10^5$	1	Flow No. 3
May 25	1400	300–400	Large	$5.6\cdot10^6$	2	Small branch of Flow No. 3
May 25	1400	300	Large	$1.5\cdot10^5$	1	Measurement at the base of a dam advancing along Flow No. 3
May 25	1400	500	Large	$1.9\cdot10^6$	1	Flow No. 3
May 27	1400	30	Large	$1.2\cdot10^5$	9	Flow No. 3
May 27	1400	80	Large	$1.6\cdot10^5$	1	Flow No. 3
May 27	1800	15	Large	$1.0.10^5$	12	Flow No. 5, Bingham viscosity
May 27	1800	15	Large	$1.1\cdot10^5$	9	Flow No. 5
May 27	1800	15	Large	$5.4\cdot10^5$	10	ditto

TABLE I *cont'd*

Date	Distance between bocca and base of cinder cone	Distance between bocca and measurement point	Type of flow	Viscosity, P	No. of formula (measurement procedure)	Comments
May 27	1800	35	Large	$2.2\cdot10^5$	12	ditto, Bingham viscosity
May 27	1800	35	Large	$2\cdot10^5$	9	ditto
June 27	1800	35	Large	$4.4\cdot10^5$	10	ditto
June 4	0	1000	Large	$4\cdot10^6$	2	Small branch of
June 4	0	200	Large	$1.4\cdot10^5$	2	Flow No. 15
June 9	0	200	Small	$5.6\cdot10^6$	1	Same but at a considerably lower rate of discharge
June 12	0	700	Large	$2.8\cdot10^6$	1	Section of
June 18	100	700	Large	$1.5\cdot10^6$	1	Flow No. 15 in the vicinity of advancing dam
June 19	100		Small	$1.8\cdot10^5$	2	Small lava
June 19	100	50	Large	$6.0\cdot10^5$	3	tongue over-
June 21	100	300	Large	8.10^5	3	flowing the side of Flow No. 15
June 23	100	100	Large	$0.9\cdot10^6$	3	Measurements on Flow No. 15 made when the rate of discharge decreased before cessation of eruptive activity at the bocca
June 23	0	20	Large	$7\cdot10^5$	3	Flow No. 16,
June 26	0	20	Large	$4.6\cdot10^7$	1	measurements made 6 h after its appearance at the surface

Note. A flow is considered to be large if its rate of discharge is no less than 1 m^3/s, if it continues for at least one week, and if it is more than one km long; a flow is small if its rate is 0.2 m^3/s or lower, if it is observed for not more than 3 days, and if it is a few hundred meters long (no flows with intermediate characteristics were observed). Asterisks denote flow numbers that were introduced for specific measurements on different flows.

partially cut off from the original source.

Two measurements should be noted especially. They were made on March 29 at negative distances from the vent and yielded the viscosities of 10^4 and 10^3 P. They were obtained by employing a miner's compass to estimate the flow width through "windows" in the roof of the lava channel, and the rate of discharge (it was found to be several meters per second).

The rate of lava discharge observed through a "window" was assumed to be equal to the rate measured in an open channel a few tens of meters downstream. The flow depth was calculated from the volume of discharge divided by the velocity and width of the flow, and the viscosity was then determined according to (1).

PLASTIC VISCOSITY AND YIELD STRENGTH

According to [4], [7], [8], the Bingham substance with two rheological parameters—plastic (Bingham) viscosity η_B and yield strength τ_o—is much more suitable for describing lava flows than the Newtonian liquid model. The apparent viscosity η defined by formula (1) is related to Bingham viscosity and yield strength through equation [4]:

$$\eta = \frac{\eta_B}{\left(1 + \frac{\tau_0}{\tau_{max}}\right)^2}, \tag{10}$$

where $\tau_{max} = \rho gh \sin \alpha$.

The yield strength is a property of lava is manifested in many specific features of lava flows and their morphology, some of which can be used for a quantitative determination of the Bingham rheological characteristics. Appropriate estimates were made for the Predskazannyĭ parasitic eruption by Panov and Slezin who employed two methods of calculations, one based on the velocity distribution at the surface of a moving lava flow and the other, on the width of the emergent "rheological" ridges [5].

Transverse velocity profiles were measured on one of the large flows issuing from a bocca located 1.8 km from the cone. The plan view and longitudinal section of the flow are schematically presented in Figure 1. The Figure also indicates the intervals (14, 38 and 50 m from the lava vent) within which velocity profiles were measured.

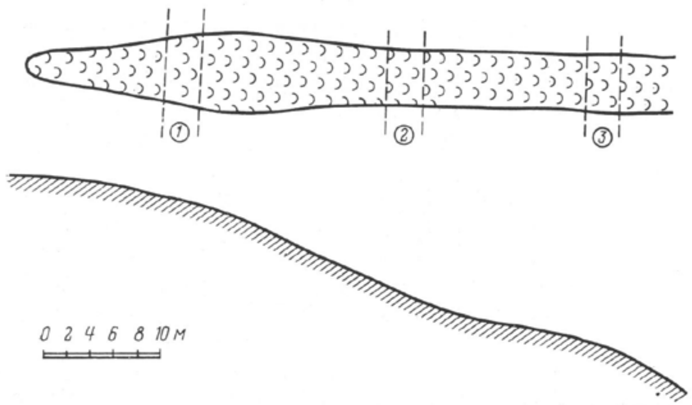

FIGURE 1 Plan view and longitudinal profile of the flow along which a transverse velocity profile was measured. This flow is marked No. 5 in Table I. Encircled numbers indicate channel marks (see Table II).

The results are given in Figure 2 in dimensionless coordinates. In each of the three profiles a gradientless core is clearly discernible (profile section with $V/V_{max} = 1$) which is indicative of yield strength in lava. In order to estimate the value of yield strength from the dimensions of the core the cross-section of the flow was assumed to be a semicircle with a radius equal to the channel halfwidth. Calculations were then made according to the formula for the flow of a Bingham substance through a tube [3]:

$$\tau_0 = \frac{1}{2} \rho g r_0 \sin \alpha, \tag{11}$$

where r_0 is the radius of the gradientless core, and α is the angle between the channel bed and the horizon.

With the same assumptions concerning the shape of the flow cross-section, Bingham viscosity for lava was defined as

$$\eta_B = \frac{\rho g y^2 \sin \alpha}{4V_0}, \tag{12}$$

where y is the distance from the side of the channel to the boundary of the core, with lava flow velocity V_0. The results of calculations

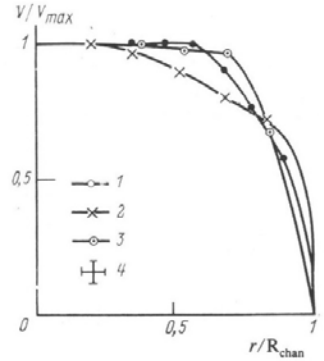

FIGURE 2 Transverse velocity profiles in a lava flow. 1-3—results of measurements at corresponding channel marks (see Figure 1 and Table II); 4—velocity and distance measurement error (same for all points).

according to (11) and (12) are given in Table II for the three intervals indicated in Figure 1.

The error in the velocity measurements did not exceed 5-7 percent. The total error for the τ_0 and η_B values was much higher. Because of the uncertainty in delineating the gradientless core, this error may be as great as 20-40 percent, and the difference between the real shape of the flow cross-section and a semicircle may make it even higher. Thus the values given in Table II should be considered approximate, guaranteeing the order of magnitude only. Nevertheless the agreement between the values of plastic viscosity calculated from (12) and of apparent viscosity measured with a penetrometer, as well as the positive correlation between the viscosity and the slope are noteworthy. This

TABLE II
Measurements of yield strength and Bingham viscosity

Characteristics	Numbers of intervals		
	1	2	3
α, degrees	15	19	13
τ, 10^4 dyne/cm^2	5.2	$2 \div 3.5$	$2.8 \div 5$
η_B, 10^5p	1.0	2.2	0.5-1.8
η_{penetr}, 10^5 P	1.1	2.0	—

TABLE III
Results of measurements and calculations of yield strength

Slope in degrees	Width of pressure ridge, cm	τ_0, dyne/cm^2
16	150	$6.7 \cdot 10^4$
33	60	$8.6 \cdot 10^4$

correlation may indicate that in the conditions described above lava possesses the properties of a dilatant liquid.

Determination of yield strength from the width of the pressure ridges is usually made more difficult by the fact that very few ridges are purely rheological. As a rule they are completely overlapped by heaped lumps of rock and overwashes (tongues and fingers) of lava. Reliable measurements of the width of what were definitely primary rheological ridges were made only once, on June 4, on one of the flows advancing along the northern edge of the lava field, not far from the cone. The measurements were carried out at two sections of the flow having different slopes. Yield strength was calculated in accordance with equation [5]

$$\tau_0 = \frac{1}{2} \rho g \delta \sin^2 \alpha, \qquad (13)$$

where σ is the width of a pressure ridge. The results of the measurements and calculations are given in Table III.

Thus the measurements of yield strength carried out by different techniques produced approximately similar results. Though the parameters were measured at different times and different flows, the conditions were largely similar: the rates of discharge and the distances between the points and the vent were almost the same and as is obvious from Table I of effusive viscosities, it is only changes in these parameters that produce a substantial effect on the mechanical properties of lava.

CONCLUSIONS

1) About 50 measurements of apparent lava viscosity carried out by

various techniques during the Predskazannyĭ parasitic eruption showed that

(a) lava inlarge flows (with a rate of discharge of more than 1 m^3/s) at the moment of appearance at the surface had a viscosity several times 10^5 P during the entire eruption. An appreciable increase in viscosity was observed only one day before the end of the eruption;

(b) viscosity values were identical for the flows issuing directly from beneath the cone and those coming to the surface at distances over 1.5 km from it, which meant that viscosity did not change during the prolonged transport of lava through lava tubes.

This conclusion is at variance with the results of two measurements made by Storcheus when observing the flow through "windows" in the roof of the lava tube directly beneath the cone. According to those measurements viscosity dropped by 1.5 orders over the last few tens of meters of the tube;

(c) lava viscosity in wide open channels increased by an order of magnitude over a distance of about 1 km;

(d) lava viscosity in small flows (with rates of discharge below 0.2 m^3/s) was of the order of 10^6 P at the moment lava was extruded to the surface and did not depend on the distance from the cone. It was assumed that the reservoir feeding such a flow was completely or almost completely cut off from the primary lava conduit.

2) It is shown that the flowing lava possessed the properties of a Bingham liquid. Its characteristics — $\tau_o = n \times 10^4$ dyne/cm^2 and $\eta_B \cong 10^5$ P—were measured by two different techniques.

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