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THE MORPHOLOGY AND RHEOLOGY OF MODERN KLYUCHEVSKOI PARASITIC LAVA FLOWS

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The general morphological features of the Klyuchevskoi parasitic lava flows are considered. The lava flows are grouped into three types on a morphological basis. A two-component rheological model is proposed to explain quantitatively the origin of the major morphological features. Both components of the flow are assumed to be Bingham liquids which have different yield points. It is presumed that the properties of the components remain almost invariable during the lava movement, but the proportion of their volumes changes. The comparison of the rheological properties of the external components of the lava flows of two main types has revealed that having almost equal yield points they differ essentially in plastic viscosity.

INTRODUCTION

The aims of this research were to examine the rheological properties of the lavas and study the flow mechanisms of the Klyuchevskoi parasitic lava flows. Besides comparing the lava flows of

different eruptions, an attempt was made to determine the factors responsible for differences in their morphology. The lava flow morphology was studied by field measurements and air photograph interpretation. The objects of study were eleven lava flows produced by recent parasitic eruptions from Kirgurich in 1932 to Predskazannyi in 1983 and also the lava flow erupted in 1985 from the summit crater. The analysis of data was based on a rheological model modified after Bingham's model, and on the theory of a Bingham liquid flowing down a sloping plane developed by Hulme [12] with references to lava flows.

The three problems to be solved are closely related to one another. This makes their solution difficult and, at the same time, facilitates it, because one can pass from the morphology of a lava flow to the rheological properties of lava only through the mechanism of the lava movement which, in turn, can only be examined on the basis of a rheological model. Using a model one can identify the rheological properties that can be determined from morphological features. The choice of a suitable model is made largely by intuition drawing on one's experience, as well as by analyzing the lava flow morphology and comparing the morphological features of the lava flows that outpoured under different conditions. Comparison is based on the assumption that the lavas have the same properties. As this assumption is not obvious, the third of the above mentioned goals of the research was to ascertain the degree to which differences in the lava flow morphologies are related to the conditions of the lava outpouring, such as the rate of discharge or steepness of the slope, and the degree to which they are related to the rheological properties of the lava.

The research prcedure was prioritized as follows: (1) identify and measure the major morphological features of the lava flows; (2) classify the flows into groups on the basis of their morphology and, to a first approximation, of the rheological properties of lavas; (3) choose and describe a rheological model; (4) test the model and previous assumptions by estimating quantitatively the rheological properties and geometrical parameters of the lava flows; (5) compare the rheological properties of the lava computed in terms of the chosen model with the rheology and morphology observed in the previously identified groups of the lava flows.

The prioritization is not strictly observed in the text that follows: the steps listed above are discussed in non-preferential order. For instance, the description of the lava flow morphology begins with lava flow classification, because it is convenient to compare the quantitative characteristics of minor details determined for different morphological groups. Similarly, the model is tested concurrently with the comparison of the computed rheological properties of the lavas from different lava flow groups in the section "Numerical Estimates".

MAJOR MORPHOLOGICAL FEATURES OF LAVA FLOWS

The term "lava flow" is commonly used to mean a single-event process which involves a hydraulically coherent area resulting from a continuous outpouring of molten lava from a single vent. It is also used to denote a solidified body or field of rock that is formed as a result of a single eruption event. Walker [15] suggested the terms "simple" and "compound" for lava flows. He also applied the term "flow unit" to a simple flow as a constituent element of a compound flow. This term can also be interpreted as a unit flow. We will stick to this terminology in the discussion that follows, except that the term "flow" without the adjective "lava" will be used to mean a lava field produced by a single eruption event, no matter whether it is a simple or a compound flow.

Most of the flows produced by the parasitic eruptions of Klyuchevskoi Volcano are compound lava flows. Their outlines in plan are depicted on a common scale in Figure 1. The principal characteristics of the flows are given in Table I. The outlines of the lava flows have been plotted from the data reported in [2, 4, 5, 9 and 11]. The tabulated data were borrowed from the same papers with some corrections and modifications made by I.V. Melekestsev (private communication).

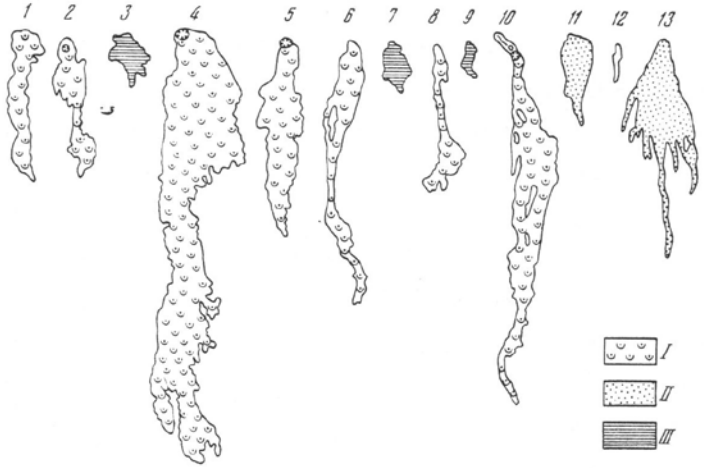

Fig. 1. Outlines of lava flows from Klyuchevskoi parasitic eruptions. 1 - Kirgurich, 1932; 2 - Tuila, 1932; 3 - Biokos', 1932; 4 - Bilyukai, 1938; 5 - Zavaritskii, 1945; 6 - Apakhonchich, 1946; 7 - Bylinkina, 1951; 8 - Belyankin, 1953; 9 - Vernadskii and Krzhizhanovskii, 1956; 10 - Piip, 1966; 11 - IV NCV, 1974; 12 - March 8, 1980; 13 - Predskazannyi, 1983. I - flows of group I; II - flows of group II; III - flows of group III.

All lava flows of Klyuchevskoi Volcano can be divided into three groups in terms of morphology.

1. Compound flows with a well-defined, broad-channel, main flow unit traceable practically from the source to the terminus. This main flow unit determines the form and length of the whole lava field. The other flow units are either small, lateral finger flows, or terminal lava portions superposed over the main flow near the source. The flow

structure of this kind was observed at the Kirgurich, Tuila, Bilyukai, Zavaritskii, Apakhonchich, Belyankin and Piip flows. This type is most widespread among the flows produced by the parasitic eruptions of Klyuchevskoi Volcano.

2. Compound flows consisting of a large number of relatively narrow, ramified and interlaced flow units with well-defined channels, among which no main flow can be identified. This group includes the flows produced by two parasitic eruptions: one named after the 5th National Conference of Volcanologists (IV NCV) and the other Predskazannyi.

3. Short simple flows which have no easily identifiable channels, nor marginal ridges. This group comprises the flows produced by the Vernadskii, Krzhizhanovskii, Bylinkina and Biokos' bocca eruptions. The mechanism of these flows was not examined in this research.

Two flows among those studied by the writer fell out of the classification because they did not fit any of the three groups. These are the flow produced by the March 8 bocca eruption and the flow that descended from the summit crater along a deep, steepsided valley, resembling a barranco, on the southeastern slope of the volcano. Judging by the morphology of the channels and the character of the flow, they resemble most of all the Predskazannyi flow and might be included in the second group, if it were not for the absence of channel ramification, a feature characteristic of that group.

A single solidified lava flow is, in its upper and middle reaches, a channel bounded on both sides by longitudinal marginal ridges or levees. The flow channels of the first group are dozens of meters or, occasionally, 200-300 m wide, whereas the width of the second group channels is a few meters or 20-30 m at most. The terminal segments of the first group flows range between a few hundreds of meters and 1 km in length and those of the second group, between a few dozens and a few hundreds of meters. The flows of the second group do not have well-defined channels in the terminal segments, their cross

TABLE I

Principal Characteristics of Lava Flows Produced by Recent Klyuchevskoi Parasitic Eruptions

Year	Lava flow	Height of bocca above sea level, m	Slope, deg.		Length, km	Area, km^2	Vol., mill. m^3	Duration of outpouring, days	Mean rate of discharge, m^3/s
			Source	Terminus					
1932	Kirgurich	580	7.4		3.75	1.75	35	76	5.3
1932	Tuila	500	7.1		3.38	1.53	31	112	3.2
1932	Biokos'	580	7.6		1.4	0.72	14	-	-
1938	Bilyukai	950	7.6	4.6	10.8	13.1	340	395	10.0
1945	Zavaritskii	1130	7.6	3.2	4.6	3.1	62	24	29.9
1946	Apakhonchich	1500	13.2	3.5	7.0	2.4	48	29	19.2
1951	Bylinkina	1000	6.0		1.2	0.5	15	10	17.4
1953	Belyankin	1300	7.6	3.8	4.0	1.1	17	11	17.9
1956	Vernadskii and Krzhizhanovskii	1400	9.5		0.8	0.19	3	6	5.8
1966	Piip	1900	14.0	3.5	9.0	4.5	90	80	13.0
1974	IV NCV	3300	24.0	10.3	2.3	1.1	22	120	2.1
1980	March 8	1740	25.0		1.1	0.05	0.3	7	0.5
1983	Predskazannyi	2900	24.0	12	5.0	2.34	60	112	6.2

Note. Areas and volumes of lava flows are given as measured by I.V. Melekestsev, except for March 8 and Predskazannyi.

profiles being convex. Commonly, the ends of the flows broaden and have the form of a "paw" with a few "fingers". Similar "fingers" fringe the middle portions of some flows to form festoon patterns.

The flows are bounded on both sides by longitudinal asymmetric ridges whose outer slopes usually have a steepness of a natural slope (30-35°) and inner slopes are much steeper (60-80°, occasionally 90°). The steep, monolithic inner slopes show longitudinal grooves, lines and scratches left by the moving lava flow. At some of the main channels of the first group flows, the ridges have stepped inner slopes or consist of several parallel ridges. The ridges rise 5 to 20 m and more above the surrounding terrain and 0.5 to 15 m above the flow channels, the maximum heights being observed within small stretches of the channels. As a rule, the right- and left-hand ridges are equal in height. At the flows of the first group, the height of the marginal ridge above the channel is always essentially smaller than the channel width, whereas at those of the second group, the reverse may be observed.

The flows of the first group often have finger-shaped offshoots, tens or even hundreds of meters long, extending beyond and overlapped by the marginal ridges.

A distinctive feature, common to all single lava flows, are conspicuous transverse ridges or steps resembling the fronts of block lava flows and extending across the whole width of the channels. Flowing from beneath them are secondary lava flows having smoother surfaces and narrower widths at the source. The flows of the first group exhibit few of such steps (one or two within a distance of several kilometers), their heights being much lower than those of the marginal ridges. The steps observed on the second group flows are more numerous and higher than the marginal ridges. They resemble the lava dams described by Panov and the writer [8].

In terms of rheology, such steps reflect a nonuniform motion of lava and are probably of the same origin as the steps and secondary

lava outflows described by Pinkerton and Sparks [13] with reference to the small lava flows produced by the 1975 eruption of Etna and by the writer and co-authors [1] with reference to the large flows of the 1975-1976 Great Tolbachik Fissure Eruption.

RHEOLOGICAL MODEL AND INTERPRETATION OF LAVA FLOW MORPHOLOGY

Earlier, flowing lava was described as a Newtonian liquid and characterized by one rheological parameter only — viscosity. Later, it became obvious that the behavior of lava in motion is more complex and Bingham's model was proposed for its description, a model that remains thus far the most complex mechanism used for numerical estimations.

The Bingham parameters (yield point τ_0 and plastic viscosity η_B) of lava were measured by different methods; a review of these measurements with the description of the techniques employed was presented in [10]. The techniques were classified into two groups: one consisting in measurements at a given point with a special-purpose instrument and the other in the determination of τ_0 and η_B from the flow parameters of the whole lava flow. Pinkerton and Sparks [14] were the first to note differences between the values obtained using these two approaches. The yield points measured at a point inside a lava flow are inevitably lower than those determined for the whole flow. Pinkerton and Sparks found these differences to be objective and introduced the concepts of the interior and bulk yield points designating them as τ_{0i} and τ_{0b}, respectively. Having studied the morphology of lava flows in terms of its relation to the rheological properties of lava, Hulme [12] demonstrated that the formation mechanism of major morphological features can be explained, to a first approximation, by treating lava as a Bingham liquid flowing down a sloping plane; in his model he assumed the rheological properties of lava to be invariable in space and time. Hulme's model allows one to estimate quantitatively the rheological properties of lava from the morphology of lava flows. It explains the observed final widths and thicknesses of flows and the presence of marginal ridges, but is unable to account for some important morphological processes, such as a flow channel subsidence or the formation of various kinds of scarp-shaped transverse ridges or steps with secondary lava streams flowing from beneath them.

In the general case, it would be probably correct to describe the behavior of lava in a state of strain using the generalized rheological model suggested for plastic dispersed systems [10] by Pavlov and Vinogradov [6], even though in view of its high complexity it can only be used for qualitative interpretations. Moreover, none of the models of whatever complexity is able to describe adequately enough the motion of a lava flow, if it treats the flow as a homogeneous body.

The model proposed in this paper is based, as earlier, on the assumption of lava to be a Bingham liquid, but accounts for (1) the existence of two lava components having different yield points, τ_{0i} and τ_{0b}, and (2) an essential variability of the rheological properties of lava throughout a flow.

Let us consider these two features in more detail. Although the overall yield point is related to the formation of a solidified crust, here we deal not only with the tensile strength of the crust which was estimated by Hulme [12]. The lava flows of the Klyuchevskoi parasitic eruptions have a rough, fragmented surface of various configurations, resembling in many localities the surface of classical aa flows. In the course of lava motion, cooled blocks mix with the plastic "groundmass" in the surficial lava layer to form a thick heterogeneous crust, a material whose yield point is much higher than that of the underlying lava. The lava flow, thus, acquires a two-component structure. The assumption of a lava stream being a two-component flow is the gist of our model. Both components are treated as Bingham liquids with τ_{0i} being a yield point of the internal component and τ_{0ex} a yield point of the external component. The quantity τ_{0b} measured from the flow parameters describes the overall effect of the simultaneous flow of the two components.

An obvious separation of the components can be observed, where "moving lava dams" are formed [8]. The yield point estimated in [8] for the material of moving dams is close to τ_{0ex}. The process of step formation also leads to the separation of the components.

The variation of the rheological properties of the material in time and space, to which changes in the flow morphology and the origin of some minor features are related, is explained within the framework of this model primarily as a change in the proportion of the components in the flow. In particular, it is assumed that before the flow comes to a halt, its terminal portion consists almost wholly of the external component and that the thickness it has when it stops can be used to estimate the lower τ_{0ex} limit. The τ_{0ex} estimates thus obtained from the dams and flow termini for the Klyuchevskoi parasitic eruptions lie between 10^4 and 10^5 H/m^2, i.e. much higher than τ_{0i}.

Obviously, with the passage of time, the volume of the external, "rigid" component increases and that of the internal, "fluid" component decreases. Spatially, the volume of the external component increases toward the flow terminus and borders. Actually, the end portion of the flow moves in terms of Hulme's model as a homogeneous Bingham liquid with the yield point τ_{0ex}. In this process, natural inhomogeneities in the flow and the roughness of the ground surface make the advance of the flow uneven resulting in the formation of offshoots — "fingers".

When the flow width, controlled by τ_{0ex} and the angle of the slope, becomes constant, the motion at the margins ceases and a channel forms in the middle. As the overall lava discharge, which was sufficient for a broad-front motion, is now concentrated in a considerably narrower "living" channel, the speed of the flow increases and, with the rms viscosity invariable, the lava level must rise. This often occurs during some initial time interval and leads to the building of lava blocks on the marginal ridges, as they fall from the top of the flow. As a result, the ridges take the form of an embankment and their primary rheological origin becomes masked. However, the acceleration of the flow and a decrease in heat release at the expense of the marginal ridges lead to a decrease in the overall yield point and rms viscosity of the lava in the channel and, accordingly, to the lowering of the lava level. Thus forms a typical lava flow channel with the marginal ridges rising above it on both sides.

The growth of the flow length, changes in the rate of discharge, and the addition of cold material from the marginal ridges as they collapse may involve significant changes in the proportion of the flow components. With the growing amount of the external component, the contact area between the moving flow and the immobile marginal ridges, and under certain conditions between the moving lava and the stagnating base, increases, too. The extreme conditions may arise when the external component of the flow comes to a halt, while its interior remains liquid and moves forward. In this case, a step is formed with a secondary source. The flow mechanism in the narrow channels of the second-group flows is controlled by the contact area between the moving lava and the marginal ridges. The process of dam development occurring in such cases was discussed in [8]. As the lava motion in the wide channel of the first-group flows is strongly dependent on the contact with the floor, the width of the secondary flow issuing from beneath the step must be considerably smaller than that of the primary flow. And this is what we actually observe.

NUMERICAL ESTIMATES

All estimates that follow are based on Hulme's theory [12], a model which describes the stationary flow of a Bingham liquid down a sloping plane. The real process of lava flow is complicated by the ground surface ruggedness, a lava flow heterogeneity, and changes in

the rate of discharge. This makes the model much more complex, restricts many numerical estimates to rather general, averaged values, and imposes constraints on the choice of sites for measuring morphological parameters, as well as on the choice of the parameters themselves.

The most representative and widespread morphological features of the Klyuchevksoi parasitic lava flows, which are directly related to the rheology of the volcano, are the marginal ridges. Primary marginal ridges form as the frontal lava flow advances. According to our model their dimensions vary with the yield point of the external component τ_{0ex}. G. Hulme's expressions for the height h_b and width w_b of a marginal (border) ridge are:

$$h_b = \frac{\tau_{0ex}}{\rho g \sin \alpha}, \tag{1}$$

$$w_b = \frac{\tau_{0ex}}{2\rho g \sin^2 \alpha} = \frac{h_b}{2 \sin \alpha}, \tag{2}$$

where α is the slope of the underlying surface, ρ the lava density, and g the gravitational acceleration. It should be emphasized that, apart from being controlled by the lava density and the slope, the height and the width of marginal ridges are influenced by the yield point. They are independent of the other rheological parameters and of the rate of discharge and either of them can be used to determine τ_{0ex}.

Each of the geometrical characteristics of the marginal ridge has its own source of errors. The advance of the ridge is uneven owing to the ground surface ruggedness and the flow material heterogeneity. Its outer edge is not an even line but a series of festoons or tongues of various length which make it difficult to derive its pure, "theoretical" length. The height of the ridge does not remain constant, either. Soon after it has been formed, the ridge may be raised by the accretion of loose rubble or, occasionally, deformed and partially destroyed. Evidently, the growth of marginal ridges at flows of the first group takes place immediately after they have been formed and may occur later only in connection with dam development in rare instances. At flows of the second group, this process may take place throughout the existence of an active lava channel [8].

Obviously, the height of the marginal ridge, formed on even, undeformed channel stretches, must be somewhat larger than the original "rheological" height, this difference being greater in the flows of the second group. Generally, the height of the marginal ridges in the flows of the Klyuchevskoi parasitic eruptions is less variable than the width and gives an upper, obviously overestimated yield point value. For this reason, τ_{0ex} is computed here in terms of the ridge height by the formula

$$\tau_{0ex} = h_b \rho \sin\alpha \tag{3}$$

Using the relation (2), we can compute the "rheological" width of a marginal ridge which it would have had if a variety of real factors had not distorted it as compared to the ideal model situation. The full width of the flow can be obtained by taking the sum of the doubled ridge width and the channel width w_{ch}

$$w = w_{ch} + 2w_r \tag{4}$$

The full flow width thus obtained is the width of a simple unit flow of a Bingham homogeneous liquid flowing down a sloping plane. The comparison of this result with the measured, average, width of the flow gives a measure of its "complexity", or a degree of its ramification. The averaged measured width of the flow, w_m, can be found from an area-length ratio and the theoretical width, w, computed for the largest of the flow units. The w_m/w values thus obtained for the flows of some Klyuchevskoi parasitic eruptions are presented in Table II.

As seen from the table, this ratio ranges in the neighborhood of 2 for all flows of the first group, except for Bilyukai which was produced by a thirteen-month eruption and gave a value of 3.8. For the flow of the second group, Predskazannyi, it is as high as 7.1, although the eruption did not last long. It should be noted that the w_m/w value for this flow is obviously underestimated because of the topography of the area: the flow consists of the main lava field and a number of long, very narrow tongues which found their way into deep canyons. The tongues are very small in volume and area but taken together, they account for about half the flow length thus decreasing essentially the mean flow width. Obviously, in areas of equally flat topography, the difference between the two groups of flows would have been greater.

The comparison of the ratios of the measured and computed cross-sections of the flows makes this difference even more pronounced. The measured cross-section area S_m can be found as a ratio of the total lava volume to the flow length and the computed area from the expression

$$S = \frac{2}{3}\sqrt{\frac{\tau_{0ex} w^3}{\rho g}}\,. \tag{5}$$

The S_m/S values are given in Table II. The total width of a flow unit, w, depends not only on the yield point, but also on the Bingham viscosity η_B and on the volumetric rate of lava discharge Q, or, to be more exact, on the product $Q \times \eta_B$. According to Hulme's theory, these parameters are related as

$$Q\eta_B (g\rho)^3 \left(\frac{\sin\alpha}{\tau_{0ex}}\right)^4 = \frac{2}{15}\left(\frac{w}{2w_B}\right)^{5/2} - \frac{1}{4}\left(\frac{w}{2w_B}\right)^2 + \frac{1}{6}\left(\frac{w}{2w_B}\right) - \frac{1}{20}\,. \tag{6}$$

The product $Q \times \eta_B$ can be found using this relation.

TABLE II

Characteristics of Some Lava Flows Computed from Their Morphology

Lava flow	w_m, m	w, m	S_m, m^2	S, m^2	w_m/w	S_m/S	$Q\eta_B$, 10^7 Pa per m^3	η_B, 10^6 Pa per s	τ_{0ex}, 10^4 H/m^2
Kirgurich	470	258	9,330	3430	1.8	2.7	8.3	16.0	3.9
Tuila	450	200	9 170	2280	2.3	4.0	2.2	7.1	3.7
Bilyukai	1210	314	31 480	4920	3.8	6.2	5.8	6.1	4.4
Zavaritskii	670	283	13 480	4114	2.4	3.2	3.9	1.4	4.2
Apakhonchich	340	220	6 860	3280	1.5	2.1	2.3	1.2	5.2
Piip	500	212	10 000	3263	2.4	3.0	4.4	3.5	6.2
Predskazannyi	470	64	12 000	560	7.1	21.3	0.15	0.25	7.2

It is impossible to estimate Q and η_B separately on a morphological basis, though independent, at least average, Q estimates are usually available for the contemporaneous flows whose outpouring and movement were observed. The division of $Q\eta_B$, computed for different lava flows, by an appropriate rate of discharge gives η_B. As in the case of τ_{0ex}, this will be an upper, obviously overestimated value, because τ_{0ex} has been found for the largest, main flow channel and, for lack of more accurate data, an averaged estimate has been used for the rate of discharge.

The results of computation given in Table II show that for all flows of the first group η_B lies within 10^6-10^7 Pa per s and for the Predskazannyi flow, representing the second group, is 2.5×10^5 Pa per s, i.e. an order of magnitude smaller than the average for the first group flows. The difference is significant, even though it was not determined with certainty for lack of statistics and a great spread in data. Nonetheless, it cannot be ruled out that it is the difference in the η_B values, with the nearly equal τ_{0ex} estimates, that is responsible for differences in the lava flow morphology between the two groups.

All above mentioned estimates hold for the outer, high-viscosity flow component having a high yield point. Obviously, estimates for the inner, easily flowable component can only be obtained by instrumental measurements inside a moving flow. No such measurements have been made during the Klyucevskoi parasitic eruptions, except for the measurements of the Bingham parameters carried out by Panov, Storcheus, and the writer [8] on a moving flow near the source of the Predskazannyi eruption. The values obtained were an order of magnitude smaller than those estimated for the external component: $\tau_0 = (2\text{-}5)\times10^3$ H/m^2 and $\eta_B = (1\text{-}2)\times10^4$ Pa per s. The internal component can be characterized by the effective viscosity values obtained by measurements near the source [7]. Apart from these, it is worth mentioning $\eta = 2.5\times10^4$ Pa per s reported by Droznin [3] who found it for the lava of the Piip parasitic eruption from the dynamics of the nucleation and growth of bubbles near the bocca.

As mentioned above, under some conditions, a distinct separation of the components takes place: one of them (external) begins to move slowly or comes to a halt, while the other keeps on moving. In such cases, at the flows of the second group the external layer forms "moving lava dams" [8] and at those of the first group, steps with secondary outflows arise. In contrast to the dams, the steps are much lower in height than the marginal ridges, and the width of the secondary lava flows is usually much smaller than that of the original channel. The model proposed here enables one to correlate the geometry of the resulting lava flow morphology with the rheological properties of the external component of the flow.

A cross-section of a step is shown diagrammatically in Figure 2. The external component ceases to move, when the driving force is counterbalanced by the resistance force

$$F_d = F_r. \tag{7}$$

The driving force is composed of the external layer weight component directed down the slope at the ange α with the horizontal and the driving force of the internal layer which continues to move and tends to carry the overlying layer along

$$F_d = \rho g S_{ex} \sin\alpha + \rho g S_i \sin\alpha \, \frac{w_i + 2h_i}{2(w_i + h_i)} \,. \tag{8}$$

The cross-section area of the external component

$$S_{ex} = k w_{ch} h - w_i h_i \tag{9}$$

The cross-section area of internal component

$$S_i = w_i h_i \tag{10}$$

The notations h, h_i, w_i, and w_p are clear from Figure 2, and the factor k accounts for the convex or concave surface of the flow. The second term of the right-hand side of (8) represents the driving force of the internal component, which is assumed to be uniformly distributed over its periphery.

The resistance force (which we relate to a flow length unit, as the driving force) is equal, at the halt instance, to the product of the yield point τ_{0ex} by the "resistance perimeter"

$$F_r = \tau_{0ex}(2h + w_{ch} - w_{si}). \qquad (11)$$

Substituting (9) and (10) into (8) and (8) and (11) into (7) and making some simple rearrangements, we obtain

$$\frac{\tau_{0ex}}{\rho g \sin\alpha} = \frac{2kw_p h\,(h_i + w_i) - w_i^2 h_i}{2\,(2h + w_p - w_i)\,(h_i + w_i)}. \qquad (12)$$

The equation (12) gives τ_{0ex}, if the geometrical parameters of the step and secondary flow are known, and, conversely, any of these parameters, if τ_{0ex} is known. If the area was not surveyed in detail prior to and after the eruption, it is difficult to determine h and h_1. As none of the flows produced by the Klyuchevskoi parasitic eruptions is provided with precise survey data (except for the smallest and simplest March 8 flow [2]), we can only estimate some of the parameters to prove the consistency of the model.

We will use a secondary flow, 50 m wide, which issued approximately in the middle of the main channel of the Bilyukai flow from beneath a 5-meter step, where the slope is 6°. Using these data and rearranging (12) we will determine the depth of the flow

$$h = \frac{2A\,(w_p - w_i)\,(w_i + h_i) + w_i^2 h_i}{2\,(w_i + h_i)\,(kw_p - 2A)}, \qquad (13)$$

where

$$A = \frac{\tau_{0ex}}{\rho g \sin\alpha}.$$

Substituting $\alpha = 6°$, $\tau_{0ex} = 4.4\times10^4$ H/m^2 (determined from the height of the marginal ridge), $w_{ch} = 100$ m, $w_i = 50$ m, and $k = 1$, we obtain $h = 14.4$ m for $h_i = 5$ m, $h = 15.1$ m for $h_i = 7.3$ m, and $h = 15.8$ m for $h_i = 10$ m. These values are in satisfactory agreement with the thickness of the flow measured in that locality.

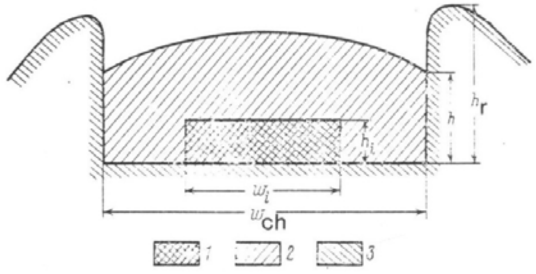

Fig. 2. Diagrammatic section across a lava flow with a step and a secondary outflow. 1 – internal component yielding secondary outflow; 2 – external component forming a step; 3 – floor and marginal ridges. Designation as in the text.

CONCLUSION

In his studies of the fluid mechanics of lava, lava flow morphology, and heat transfer, Hulme [12] came to the conclusion of the dominant role of the rheological properties of lava which, in his opinion, could be regarded, to a first approximation, to be invariable throughout the process of lava eruption and spreading. He used the Bingham model to describe the behavior of lava in a flow. In his model he assumed the width and thickness of the flow to be dependent on the yield point and the length on the slope and the total volume of the erupted lava.

This simple model, however, did not explain the mechanisms of the subsidence of the flow channel and the formation of steps with secondary lava flows issuing from under them. Both mechanisms point to a substantial dependence of the rheological properties of lava on time and/or the distance along the flow. Later Pinkerton and Sparks [14] noted a difference between the yield point measured instrumentally inside the lava flow and the yield point estimated from the movement of the flow as a whole. Finally, Panov et al. [8] described the process of "moving lava dams", during which two components of the lava flow moved simultaneously but separately along some stretches of the flow channel.

To account for the above mentioned facts and still adhere, as far as possible, to Hulme's theory, the following model is proposed as a next approximation: the lava flow consists of two components each being a Bingham substance. The internal component forms the core or the lower layer of the flow and has a much greater fluidity than the external one. As the flow moves down the slope or changes take place in the rate of discharge, the properties of both components remain nearly constant but the proportion of their volumes may vary. The frontal portion of the flow consists for the most part of the external component, as do the steps in the channels of the first-group flows and the dams in the channels of the second group. The marginal ridges bounding the channel are also formed of the material of the external component in conformity with Hulme's theory. The movement of the lava flow within the stabilized channel is controlled to a considerable extent by the internal component.

The model provides a satisfactory description for the basic forms of lava flows. Moreover, as the morphology of stopped lava flows depends primarily on the external component, the model enables one to estimate its rheological parameters, whereas the rheological parameters of the internal component can only be determined by measurements on a moving flow.

Using the rheological parameter values found through the geometry of the lava flow morphology, an attempt has been made to compare the lavas of different flows produced by the recent Klyuchevskoi parasitic eruptions. The flows were classified, in terms of morphology, into three groups. Suitable for comparison are only groups I and II, because group III seems to comprise the flows that had not attained stability by the time they were examined.

Groups I and II differ in complexity, i.e. in the degree to which they differ from a simple flow. Whereas the flows of group I exhibit a well-defined main channel many dozens to hundreds of meters wide, those of group II consist of a large number of narrow (less than a few dozens of meters), branching and interlaced channels. The feature the group-II flows have in common is the presence of lava dams the formation of which was favored by the narrow channels and relatively high marginal ridges.

The absolute heights of the marginal ridges are approximately equal in the flows of both types, as are, accordingly, the yield points of their external components. The width of the flow, or, to be more exact, of its "living" stable channel, depends, to a considerable extent, on the rate of discharge, slope, and plastic (Bingham) viscosity.

Three factors are responsible for the formation of narrow channels at the second group flows: a steeper slope, a low rate of discharge, and a low viscosity of lava. Indeed, the IV NCV and Predskazannyi flows (group II) moved down the steepest slopes and the rates at which the lavas were erupted were rather low. Yet, the calculation based on the proposed model has shown that these two parameters alone are not enough to account for the narrowness of the group-II channels. An important point is that the plastic viscosity of their lavas is an order of magnitude lower than that of group I, even though the two types of lavas have the same yield point. Although this statement is not supported by adequate statistics and there is still a great spread in data, it is advisable to undertake a closer study of the lavas, because there may be differences in their composition and especially in the degree of crystallinity, a factor known to have a great effect on the Newtonian rheological properties of lavas.

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