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The Mechanism of the Lava Field Formation at the Predskazannyĭ Parasitic Eruption (Klyuchevskoĭ Volcano, 1983)

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This is an analysis of the main features of the formation of the lava field at the Predskazannyĭ eruption. A new lava flow pattern, a moving lava dam, is described, and the mechanism of its formation and further evolution is discussed. The role of dams in shaping the lava field's general configuration and surface structure is investigated, and the mechanism of lava tube birth with the participation of dams is analyzed.

GENERAL DESCRIPTION

Lava was the main issue of the 112-day Predskazannyĭ parasitic eruption. The volume of extruded lava is estimated at about 0.15 km^3 and that of the cinder cone at about 0.0003 km^3, or 0.2 percent of the total volume of solid material. There were practically no fine pyroclastics.

At maximum, the lava stretched for 5 km: that is the length of two narrow, thin flow-units. Most of the flow-units superposed one another to form a massive lava field about 3 km long and over 1 km wide. The thickness of the lava field averages approximately 40 km and is evidently much greater in the axial part [3].

The lava sheet is an anastomosing network of superposed and branching flow-units; some begin just beneath the cinder cone while others originate at distances of several hundred meters to 2 km from it. Figure 1 is a scheme of part of the lava field. A flow-unit measures 1.5–2

to 8–10 m in width†, with levees rising up to 10m above the flow surface and up to 15–20 m above the surrounding lava field surface.

The pattern of migration of the flow heads, the morphology of the lava field, and direct field observations suggest that throughout the eruption lava was supplied from the same source (under the cinder cone), and the many flow-unit heads can be attributed to horizontal lava transport through tubes formed within the lava field. Lava tubes are a well-known phenomenon, typical mainly of fluid basalt lavas. Their formation has been described for Hawaiian Volcanoes and Mount St. Helens [5], [6], as well as for Tolbachik Volcano in Kamchatka [1], [2], [4]. No lava tubes have been reported so far for Klyuchevskoĭ parasitic eruptions.

Our observations showed that the tube formation, like the formation of large landforms in the lava field at the Predskazannyĭ eruption can be related primarily to the non-Newtonian rheological properties of lava in a flow. However, the mechanism of lava tube formation at Predskazannyĭ differed substantially from that at Hawaiian Volcanoes or at Tolbachik Volcano.

BRIEF CHARACTERISTICS OF THE LAVA FIELD FORMATION

The eruption occurred on the eastern flank of Klyuchevskoĭ Volcano about 2900 m above sea level. The even underlying surface was a slope about 20° steep with parallel low (10 to 20 m) stony ridges stretching downward and resembling moraines. Both the ridges and the wide depressions between them were formed by the intercalation of ice and loose lava material and can be regarded as an overall ice cap. The proportion of ice and firn in the depressions is slightly greater than in the ridges, and at least the upper layer, up to several meters thick, is formed by compact firn with only a small amount of stony material. The eruption originated in one of the depressions and the chief portion of the lava was distributed over the main flank of Klyuchevskoĭ Volcano. About 3 km downhill from the eruption site the heads of two deep gullies, Northern and Southern, cut the slope and long narrow tongues of lava flowed into them.

† The width of a flow does not vary by more than a hundred percent.

The lava discharge varied considerably during the eruption, with a general tendency to decrease, and averaged 15 m^3/s. At the beginning of the eruption, the discharge in some lava rivulets reached its maximum of 20 m^3/s, and it was about 10 m^3/s during the middle and the end of the eruption [3, Figure 9]. The variations in the mode of lava distribution (in open channels or through lava tubes) coincided with drastic changes in the lava discharge.

Considering a set of parameters, the lava flow-units formed two distinct groups, viz., large and small flow-units with a discharge of $\geqslant$ 1.5 m^3/s and $\leqslant$ 0.1 m^3/s, respectively. The low discharge, short existence, and higher viscosity of the small flows suggest that they originated from some reservoirs within the body of the lava sheet that were completely disconnected, or only partly connected, with the deep-seated source. We observed peculiar formations, which we called "moving dams"; they were generated by the lava flowing in the channels, and we shall discuss them in more detail in the following section.

The effective lava viscosity, measured at the heads of the lava rivulets from the parameters of their flow, was $(1-3) \times 10^5$ P in all large flows and one or two orders greater in the small ones. In several cases, the

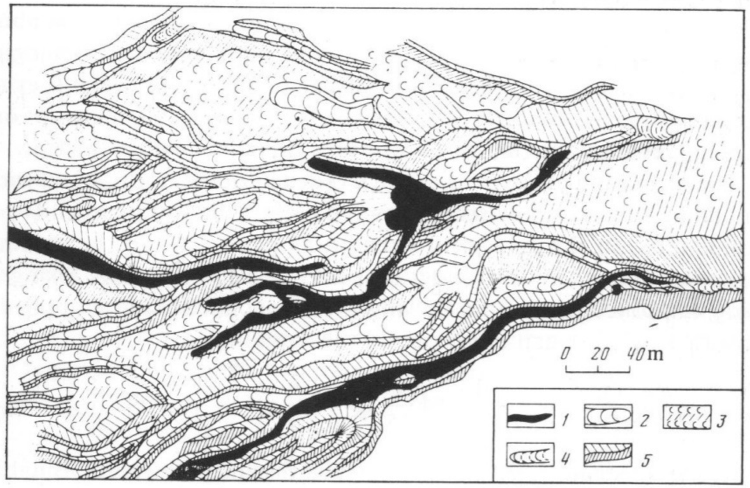

FIGURE 1 Scheme of a part of lava field surface. 1 - flowing lava river; 2 - lava river at rest; 3 - surface covered by relatively shallow solidified lava flows and loose material; 4 - advancing (or formerly advancing) lava dam; 5 - levees spread on lava flow sides.

viscosity at the lava rivulet heads was also measured by a penetrometer. The results showed a fairly good agreement with the estimates derived from the parameters of the flow, the former as a rule being 1.5 to 2 times less. The effective viscosity of the moving dams, measured from the parameters of their movement, was about 10^9 P.

Lava parameters according to the Bingham model (see the paper by Panov, Slezin, and Storcheus, *Volcanology and Seismology* (a cover-to-cover translation) No. 1 (1985)) were determined in the flows from their velocity profile and the dimensions of the levees. The values of yield strength and plastic (Bingham) viscosity were found to be about 10^4 dyne/cm^2 and 10^5 P, respectively.

THE DEVELOPMENT OF A FLOW-UNIT

A lava field consists of a great number of flow-units, each being a narrow, distinctly pronounced lava rivulet bordered by high levees. An almost invariable channel width and a strong branching tendency are the main features of the rivulets.

The original advance of a flow-unit follows a common pattern: behind a thickened front with a continuously crumbling blocky clinker crust there moves a flow with stationary levees rising 0.5 to 1 m above the lava surface. The original levees are, possibly, of a rheological nature [7], but even at the very beginning of their formation they are accreted by crumbling blocks (very rarely by veneer-like incrustation), accompanied by fluctuations in the lava discharge within the flow.

The formation of the rheological levees determines the original width of channels with minor subsequent changes. The width depends predominantly on the lava yield strength and the slope of the channel; however, the underlying topography may be also important. Using the Bingham concept of a fluid flowing over an inclined plane as applied to lava flows [7], we can easily obtain the equation.

$$\frac{R\eta_B (g\rho)^3}{\tau_0^4} = \frac{1}{(\sin\alpha)^4}\left(\frac{2}{15}Q^5 - \frac{1}{4}Q^4 + \frac{1}{6}Q^2 - \frac{1}{20}\right) \qquad (1)$$

where $Q = \sqrt{g\rho d/\tau_0}\sin\alpha$, R is the lava discharge, η_B is the Bingham viscosity, g is free fall acceleration, ρ is the lava density, τ_0 is the yield strength, α is the gradient (slope) of the underlying surface, and d is the flow width.

It follows from (1) that the greater the slope of a flow bed, the narrower the flow. For example, an increase in the slope from 10° to 30° should result in a reduction of the flow width by nearly one half. Approximately similar relationships between changes in the slope and the flow width were actually observed during the eruption, which confirmed the leading role of the rheological factor. However, the absolute values of the flow width measured during the eruption were somewhat lower than the predicted ones; this is apparently due to the underlying surface topography, the lava flow moving through elongated depressions, i.e., channels, rather than along an inclined plane.

The subsequent evolution of a flow-unit is associated with the above dams. We observed about 40 such formations. The term "dam" was proposed because this lava formation resembles an earth dam in outward appearance and, partly, in function. A lava dam, like an earth dam, creates an afflux in the flow. The lava level rises so high that the lava overflows the dam crest and the levees (its surface blocky layer crumbles over them) despite the fact that 0.5 to 0.9 of the total discharge runs off through the channel beneath the dam.

The dam crest grows together with the rise of the lava level behind it and is built up by the same lava (although its properties are slightly changed). Besides, a lava dam can move. These features made the lava formation mechanism under discussion outwardly similar to a solitary running wave. Such waves are formed, for example, by a thin layer of water flowing over a smooth inclined plane.

The front of the advancing dam rises as much as 10 m (and more) above the flow, and its slope, reaching 45° to 50°, is commonly greater than that of the angle of repose. The crest can rise 2 to 3 m above the levees. Figure 2 is a photograph of a dam that recently ceased moving. The rate of the dam's steady movement did not exceed 1 cm/s. The flow-unit regains its shape at a distance of 50 to 100 m upstream from the dam and differs from the original shape only in the levees being 0.5–1.5 m higher. The levees are higher both above the surrounding surface of the lava field and above the moving lava surface, but the increase in height in the second case is smaller. After repeated passages of dams the levees may become very high; at the same time, the lava level in a flow-unit may rise considerably while the channel width, lava velocity, and discharge remain constant. Evidently, in some cases the flow bottom is accreted along with the levees: the lava begins to flow as if along a railroad embankment. The similarity is even stronger because

this "embankment" tends to level off the slope of the area: it grows more intensely in the depressions and practically does not grow at all over the convex parts.

Dams appeared regularly in all the large flows, typically several hundred meters from the point of issue but sometimes only a hundred meters or less from it. At times a succession of two or three dams advancing within the same flow-unit was observed.

A dam advanced a distance varying from several dozen to several hundred meters, after which one of the following three events took place.

1) The dam was eroded, tumbling down to many incandescent, slightly plastic blocks up to 5–6 m in size; the blocks floated along the lava river, gradually breaking and sinking into the liquid lava. This was the most common finale.

2) The dam stopped and the lava began to overflow one or both levees upstream, gradually forming a new branch channel (in some cases, two new channels on either side of the dam were formed). The flow in the old channel under the dam coexisted for some time with the new one(s), but it soon ran dry and the entire discharge went into the new channel(s). This was how most of the branchings observed on aerial photographs occurred. In the final geological effect, such branching is very similar to the formation of a new flow-unit (at a small lava discharge in the source), as described by Walker [9], but the formation mechanism is different. In Walker's case the flow stops from the front to the source (or almost up to the source), the flow front being the first to stop; then a new flow-unit bursts out near the source and may flow close to the old one or above it. As to the dam, the difference is that it is formed and halts in the middle reach of the flow (probably even nearer to its downstream end), and, only after a branching appears, does the advance of the original flow below the dam cease, the front being the last to stop. Since the dam can stop only when the levees are very high, the flow branching upstream from the dam is always adjacent to the old one rather than superposed on it.

3) The dam stopped, but the flow continued to move under it, carrying off all the lava discharge. The crust consolidated upstream from the dam up to the source, and a lava tube was formed. Later the tube roof was usually accreted by squeezed-out material, brief flows extruded in the area of the original source, and by other flows.

The formation of a lava tube is the rarest case. A dam producing a tube can only be formed in a well-developed canyon with high walls built up by repeatedly passing and collapsing dams. A lava tube built in such a manner had a very thick roof, especially near the tube mouth. For example, the front of the dam which formed a tube on June 16–17 was more than 15 m high. Approximately 100 m above the lava bocca which was active for more than 3 weeks and was located 1400 m from the cinder cone, there appeared a small vertical opening in the lava conduit roof, a vertical well through which we could see the lava flowing along the tube. The walls of the well were formed by alternate lava layers of different thickness (0.2 to 1.5 m) and layers of the same thickness of more or less welded lava fragments. The measured depth of the well was 10.5 m.

THE EFFECT OF DAMS ON THE GENERAL CONFIGURATION AND LANDFORMS OF THE LAVA FIELD

The formation of dams drastically increases dissipation of the lava heat energy. A moving dam continuously rolls down incandescent blocks over both outer flanks of the levees for several dozen meters, thus considerably enlarging the heat dissipation surface. In fact, a moving dam takes away 10 to 50 percent of the lava river discharge. Besides, the flow issuing beneath the dam has no crust, which greatly increases heat dissipation from its surface. These factors account for the small length of the lava field with its great width and thickness despite the appreciable slope, high discharge, and fairly low lava viscosity within the flows.‡

Another similar result of the dams is channel migration, which makes lava advance again over a cooled and uneven surface rather than through an old, heated channel.

Dams are also directly involved in lava tube formation; they produce an opposite effect on lava distribution, but their importance at this particular eruption was relatively small.

Lava field landforms, generated mainly by the dams, are represented by embankments 15 to 20 m high, elongated downslope. The stronger roughness of the original topography becomes flattened, and large scarps across the slope are partially smoothed as well. However, steep local scarps, up to 20 m high, are formed by dams that cease moving.

A relatively high proportion of crushed blocky material in the lava sheet also owes its presence to intense dam activity: the dams rework, as it were, the massive lava of the flow into loose material which builds up the high ridges of embankments.

THE DAM MOVEMENT MECHANISM

The above viscosity of a dam is effective viscosity. This is a very important specification because the movement of a dam differs greatly from that of a viscous fluid. Direct field observations show that a dam moves almost like a solid, sliding down the canyon walls and the bottom surface on a rather thin layer of a viscous "lubricant". Traces of the sliding (furrows) left by a passing dam can be noticed on the canyon walls. Fairly frequent full halts of dams caused by very slight changes in the environment imply that maximum stresses within a moving dam were just a little greater than the yield strength.

Both upstream and downstream from a dam, the lava flowed like a fluid with an effective viscosity of about 10^5 P. The collapse of a dam restores this flow over the entire length of the lava river.

The above observations suggest that the growth of effective viscosity during dam formation can be attributed to an increase in the yield strength τ_0 at an almost constant plastic (Bingham) viscosity η_B. Apparently, τ_0 grows mainly owing to the formation of fairly rigid macrostructures incorporating crustal fragments and detached masses of the levees submerged in the lava. Thus, this is a case where the so-called bulk yield strength [8] comes into play which makes sense only for megaobjects (a flow or a dam) as a whole.

Although we could not observe the process of dam formation from the beginning to the end, we can describe it more or less accurately. The first prerequisite for this process is a canyon, formed by levees rising 1.5 to 2 m above the flow level. Both the growth of the levees preceding the

‡ The snow and ice covering the surface had a certain effect on the distance of lava distribution at the very beginning of the eruption. However, this influence was unimportant, which is evident from a comparison between flow-units advancing over the snow-ice slope and those moving over the surface of the newly formed lava field. Most of the large flows were within the lava field and nowhere contacted snow. Snow and ice did not affect the length of the lava tongues that advanced far through the two gullies because they had been scoured by lahars at the early stage of the eruption.

dam formation and the deepening of the canyon occur together with fluctuations in the lava discharge and the surface level in the lava rivulet and, possibly, at the expense of the deepening of the channel. A short-term rise of the lava level above the levees and its subsequent drop result in the lava overflowing the outer flanks of the levees, and in the accretion of thin lava layers on the inner walls. The thickest layers are observed near the upper edge of a levee: they narrow the canyon a little and thus increase the steepness of its inner walls. The structure of the inner draping of layered lava is well exposed on the partly collapsed walls of emptied canyons (Figure 3).

A levee accreted in such a way, is not strong, and fluctuations in the lava discharge make possible its partial destruction through the exfoliation and detachment by the lava flow of large blocks and slabs of solid material from the inner walls. Such exfoliation was repeatedly observed in the areas where dams were formed. Joining the flow, these blocks and slabs are crushed and mixed with it, stimulating the growth of a dam. The dam material appears to become essentially homogeneous; no conglomerate-like megastructure can be seen on fresh shear surfaces when a collapsing dam breaks into large blocks.

The yield strength of the dam material can be roughly estimated using the equation for a flat layer [2]

$$\eta_{eff} = \frac{\eta_B}{\left(1 - \dfrac{\tau_0}{\tau_{max}}\right)^2},$$

whence

$$\frac{\tau_0}{\tau_{max}} = 1 - \left(\frac{\eta_B}{\eta_{eff}}\right)^{1/2} \tag{2}$$

Substituting the values of parameters $\eta_B = 10^5$ P and $\eta_{eff} = 10^9$ P into (2), we obtain $\tau_0/\tau_{max} = 0.99$, i.e. practically $\tau_0 = \tau_{max}$.

For a flat layer, $\tau_{max} = \rho g h \sin\alpha$, where ρ is the density of the lava, g is free fall acceleration, h is the thickness of the layer, and α is the slope of the lava bed. Substituting typical dam values, namely, h = 10 m and α = 20°, into the equation for τ_{max}, we get $\tau_0 \approx \tau_{max} \approx 10^6$ dyne/cm^2.

Let us consider the balance of forces acting on a uniformly moving dam. The driving force is produced by the dam weight and the flow passing under the dam. We can write

$$F = \rho g S \sin\alpha + fd, \tag{3}$$

where F is the driving force per unit length of the dam, S is the area of the dam cross-section, f is the force exerted by the liquid lava on the dam per unit area of the lava surface, and d is the width of the stream channel.

The braking force F_T is produced by friction of the dam against the levees. Since the dam moves, in effect, as a solid, we can write

$$F_T = P_T \tau_{max}, \tag{4}$$

where P_T is the "braking perimeter", i.e., that part of the perimeter of the dam cross-section which is involved in the braking.

Equating the right-hand sides of (3) and (4) yields

$$\tau_{max} = \frac{S\rho g \sin\alpha + fd}{P_T}. \tag{5}$$

As a first approximation for qualitative estimates, we can assume that the cross-section of the canyon, equal to that of the dam, is rectangular. Then S = hd and P_T = 2h, and accordingly,

$$\tau_{max} = \frac{d}{2}\left(\rho g \sin\alpha + \frac{f}{h}\right). \tag{6}$$

Using equation (6) we can analyze how variations in individual flow parameters affect the behavior of a dam.

An increase in d (a widening of the channel), with growing τ_{max}, leads to a higher rate of the dam movement and hence to its stretching and a decrease in its height. The corresponding deformation contributes to the collapse and erosion of the dam.

Variations in f, i.e., the tractional force of the flow passing under the dam, produce the same but quantitatively less important effect, with a drop in f being most pronounced. A decrease in lava discharge in a fairly narrow channel may result in separation of the flow from the foot of the dam, so that the dam overhangs the lowered flow surface. In such a case f abruptly falls to zero, and correspondingly τ_{max} drops just as abruptly, so a complete halt of the dam with the formation of a lava tube is very likely.

With an increase of the levee height h τ_{max} decreases, and this provides conditions favorable for the halt of a dam. Indeed, the halt of a dam was always preceded by the passage of a number of collapsing dams which had accreted the levees.

All other conditions being equal, an increase of the slope favors a collapse of the dam; however, one point should be mentioned here. When the lava flow first reaches a surface with a varying slope it forms a channel bordered by levees of a rheological nature, and the greater the slope of the bed, the smaller the width of the channel (see above). Thus α and d in (5) offset each other in a certain way. Indeed, dam formation was observed at various slopes of the stream channels but predominantly when the slope was rather gentle. In particular, the embankments overlying the concave parts of the channel were in the main accreted owing to dam formation in the areas of smoothed topography.

Since several factors simultaneously affect the behavior of a dam, we could distinguish no single reason for a particular trend in its evolution. Another essential point is that variations in parameters d, h, and f are qualitatively different. The width of the stream channel actually does not change in time but changes in space (although within certain limits) in the direction of the flow: it is larger within more gentle areas and smaller within steeper areas. The height of the levees h above the flow surface varies both in time and space. As a rule, the levees are the highest in the concave parts of the stream channel at the beginning of its flattening. The height of the levees increases due to variations in the lava discharge and to the action of the moving dams. The value of f varies irregularly in time and space, and its changes are mainly associated with variations in the lava discharge.

The factors underlying one or another trend in the evolution of a dam are as follows. The erosion of a dam occurs mainly at the end of the flattening part of the flow bed before a new increase in the slope of the bed, because this is where the flow is the widest and the levees are usually the lowest. Besides, here begins the convex part of the longitudinal profile of the flow, which favors the stretching and rupture of the dam. This is confirmed both by direct observations of collapsing dams and the resultant smoothing of the longitudinal profile (the levees are of maximal height in the concave parts of the profile and of minimal height in its convex parts).

The halt of a dam accompanied by the branching of the flow and the appearance of a parallel channel is most likely when the levees are sufficiently high and the discharge increases. The halt of a dam with the formation of a lava tube can be expected where the channel is most narrow with high levees and a decrease in the lava discharge. Observations show that the mouths of the lava tubes are always situated between high levees at the end of the steeper part of the channel before the beginning of a more gentle part, at a site where the width of the channel is minimal and the depth is maximal.

CONCLUSIONS

Our main aims were to describe a peculiar pattern of a lava flow, which we called a moving lava dam, and to analyze the mechanism of the formation, advance, and halt of such a dam. Lava dams were shown to be a decisive factor in the lava field formation at the Predskazannyĭ eruption.

A dam crest generally rose above the levees; its full height above the flow could be more than 10 m. A dam on a flow-unit traveled a distance of several dozen to several hundred meters, and then either collapsed or halted. In the latter case, the lava either overflowed a levee above the dam or continued to pass under the dam through a lava tube. This mode of formation of lava tubes has not been reported earlier.

Solidified blocks of the crust and levees participate in the dam formation. The dam movement mechanism is fairly complex, but to a first approximation it can be described as a flow of a Bingham liquid, with a yield strength of 10^6 dyne/cm^2 and plastic viscosity of 10^5 P.

Dams play an active role in the formation of the channels of flow-units by accreting the levees up to 20 m; they promote branching of flow-units, smooth out the longitudinal profile of channels, and thus develop the general topography of the lava field. The main effect produced by the dams is a considerable increase in heat dissipation from the lava surface, which decreases the extent of the lava field and increases its thickness. This effect was strongly pronounced at the Predskazannyĭ eruption despite the counteracting influence of lava tubes, which owe their formation to the dams.

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