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# Effusion Rates and Rheology of Lunar Lavas

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*Phil. Trans. R. Soc. Lond. A* 1977 **285**, 227-234
doi: 10.1098/rsta.1977.0059

*Phil. Trans. R. Soc. Lond.* A. **285**, 227–234 (1977) [ 227 ]
*Printed in Great Britain*

# Effusion rates and rheology of lunar lavas

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[Plate 1]

Flow shapes in Mare Imbrium, Copernicus, Tycho and Aristarchus have been related to lava properties by assuming that lavas have Bingham rheology. A universal formula which expresses flow dimensions in terms of fluid properties, flow rates and slopes has been derived theoretically and tested by means of experimental models and data from terrestrial lava flows. It is now possible to determine flow rates and yield stresses – both of which are related to the composition of lavas – from photographs of flow remnants. Results are presented for the lunar flows under study. Flow rates in Mare Imbrium are found to be very high by terrestrial standards. This is an important clue to the mechanism of formation of lunar sinuous rilles, which may be products of erosion by melting beneath turbulent lava flows.

## 1. The lava flows of Mare Imbrium

Recent work has led to the identification of extensive lava flows that cover a large part of Mare Imbrium. A description of the flows to be found on the N.A.S.A. Lunar Orbiter IV and V photographs was given by Fielder & Fielder (1968, 1971) but the source regions of these flows were not identified. Following R. G. Strom (figure 1 in Fielder 1971) it was supposed that these, and some other, flows in Mare Imbrium originated from crustal fractures with which neighbouring mare ridges were associated. According to Strom, other flows derived from a major fissure near to the crater Euler.

Detailed photogeological mapping of the flows in Mare Imbrium became possible following the receipt of Apollo 15 and 17 orbital photographs (figure 1, plate 1). By using photogrammetry to determine the heights of flow scarps, and dating flow units by the method of Soderblom & Lebofsky (1972) as calibrated by Soderblom & Boyce (1972), Schaber (1973) mapped numerous flows and suggested that they had been produced during three major eruptive periods. Considering the youngest of these lava series, Schaber confirmed, essentially, Strom's proposed fissure source to the west of Euler.

Further source areas – together with many specific sources for both old and relatively recent lavas – have now been identified by Todhunter (1975) in an extensive photogeological analysis of the flows of Mare Imbrium. Lavas were extruded from identifiable fissures, faults, cones and craters, some of which are breached. Major fault blocks sank as the lavas were extruded. This work is described, in part, in Fielder & Wilson (1975).

In some places (figure 1) the lavas carved channels through older lava deposits. Elsewhere the same lavas, and other lavas, generated deposits which assumed sheet forms and tongue forms. Some of the channels are observed to be bordered by banks; others are essentially negative features. In order to extract the maximum amount of information about these diverse landforms from the lunar photographs it is necessary to supplement the published

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photogeological descriptions with quantitative knowledge about the major effects which limit the flow of lava. With this combined input of data it is possible to evaluate certain relevant properties of the lunar lavas and their effusion rates.

## 2. The cooling of flowing lava

Cooling apparently exerts a dominant influence on the shaping of lava flows. The exposed surface of a flow cools by the radiation of heat to its surroundings. Radiation is so effective compared with thermal conduction within the lava that the surface temperature is maintained close to the ambient external temperature. Heat loss by conduction to the ground over which the lava flows is of negligible importance in comparison with that lost from the exposed surface. Field observations indicate that lava flows are generally laminar and so the cooling problem is similar to the Graetz–Nusselt problem of the cooling of a laminar flow of warm fluid moving through a cool pipe – the exposed boundary of the lava replacing the pipe.

At the entry to the cool pipe temperature is uniform across the flow. The fluid close to the walls is the first to be cooled and the distance from the wall to which cooling penetrates increases with downstream distance. The effect is that a layer of cool fluid, which thickens steadily downstream, develops close to the wall. The temperature at the centre of the flow remains essentially constant until the thickening, cool layer extends to the centre of the flow. The temperature distribution across the flow is described by a dimensionless quantity known as the Graetz number, $Gz$, which is inversely proportional to downstream distance and which, in a lava flow may be put equal to $ud^2/(\kappa x)$ where $u$ is the mean flow velocity, $d$ is the depth of the flow, $\kappa$ is the thermal diffusivity of the lava and $x$ is the distance from the vent. The effusion rate, $F$, of a flow is approximately given by

$$F = wdu,$$

where $w$ is the flow width and, hence,

$$Gz = (F/\kappa x)\,(d/w). \tag{1}$$

This expression for $Gz$ is similar to that for the case of flow in a pipe except for the inclusion of the $d/w$ term, which is the aspect ratio of the lava flow. This reflects the fact that thinner flows will cool more rapidly than deeper flows. When $Gz$ has fallen to about 100, approximately one third of the interior of a flow will remain uncooled. Walker (1973) has shown that the distances travelled by flows are related to effusion rates. It is possible that this is due to the effect of cooling. Walker's data is consistent with flows coming to rest when $Gz$ has fallen to about 300.

The implication is that the temperature within a lava flow is uniform and close to the temperature at which the lava was erupted. Over most of the flow cool lava is present only in thin layers at the surface and base of a flow. Only at the front of a flow, where there has been time for a sufficiently large volume in the central regions of the flow to lose heat, does the effect of cooling limit the flow of lava. Although the length of a flow is probably dependent on the rate of cooling, all other dimensions of a flow must be determined by a different mechanism.

## 3. Lava flow theory

Hulme (1974*b*) argued that the principal effect governing the shaping of flows is the non-Newtonian rheology of lavas. Shaw (1969) showed that basaltic lava was rheologically similar to a Bingham liquid. For a Bingham liquid there is a finite stress – the yield stress – which must be applied before any flow occurs. For greater stresses the (stress)/(rate of strain) characteristic is linear and its gradient has the dimensions of viscosity – here called the plastic viscosity.

The unconfined flow of Bingham liquids on slopes was compared with the flow of lava (Hulme 1974*b*). For a Bingham liquid to flow downhill it must form a layer deep enough for the shear stress at the base to exceed the yield stress. Lateral spreading of the flow may occur only while the transverse shear stress at the base, due to the pressure gradient produced by the lateral thinning of the flow, exceeds the yield stress. The flow therefore quickly assumes a transverse profile which remains constant with downstream distance provided that the slope and effusion rate remain constant. Close to the lateral margins the depth is not great enough for downhill flow to occur. As a result, banks of stationary liquid occur along the margins.

The depth and width of a flow, and the width of each stationary bank, are related to five independent initial conditions. A convenient set of parameters are to be found in the effusion rate, $F$, the slope, $\alpha$, and the three properties of the liquid – namely, plastic viscosity, $\eta$, yield stress, $S_y$, and specific weight, $g\rho$, where $g$ is the acceleration due to gravity and $\rho$ is the density of the liquid. The dependence of the flow dimensions on these conditions was shown to be approximately of the form

$$\mathscr{F} = 2W^{\frac{5}{2}}/15 - W^2/4 + W/6 - 1/20, \tag{2}$$

where $\mathscr{F}$ and $W$ are dimensionless parameters given by

$$\mathscr{F} = F\eta(g\rho)^3\alpha^4/S_y{}^4, \tag{3}$$

which is independent of flow dimensions, and

$$W = g\rho\alpha^2 w/S_y, \tag{4}$$

where $w$ is the total width of the flow. The combined width of the stationary banks, $2w_b$, is given by

$$2w_b = S_y/(g\rho\alpha^2) \tag{5}$$

and, hence,

$$W = w/2w_b. \tag{6}$$

The critical depth which must be exceeded for any flow to occur is given by

$$d_c = S_y/(g\rho\alpha) \tag{7}$$

or

$$d_c = 2w_b\alpha. \tag{8}$$

Thus all flow dimensions except length may be related to effusion rate, slope and properties of the lava. This theory was tested experimentally by making measurements on flows of kaolin suspensions which are close to being Bingham liquids. Figure 2, plate 1, shows one of these flows. The parallel sides and stationary banks may be seen. It was established that equations (2), (5) and (7) were consistent with the experimental observations.

Parallel-sided flows with central channels and lateral banks are common features in the field. This supports the hypothesis that lava behaves essentially like an isothermal Bingham liquid. The data available from active lava flows, which allow $\mathscr{F}$ and $W$ to be determined independently, are very few so that, at present, the relation between $\mathscr{F}$ and $W$ has not been rigorously verified for lava flows although the data that are available are consistent with equation (2). It seems that the foregoing theory is a first approximation which is adequate for application to the determination of lava properties and effusion rates from measured flow shapes.

Since yield stress effectively determines the depth of a flow and the width of the stationary banks it is clearly an important property of a lava. Using equation (7), the yield stresses for several lavas have been estimated from the depths of their flows and the slopes on which they occur. Silica content – plotted in figure 3 against the yield stress of a lava – has previously been found to be closely related to the rheology of magma (Bottinga & Weill 1972). This is because silica tetrahedra tend to combine together to give long range order to the molecules of the magma. As demonstrated in figure 3, the greater the silica content, the stiffer will be the magma.

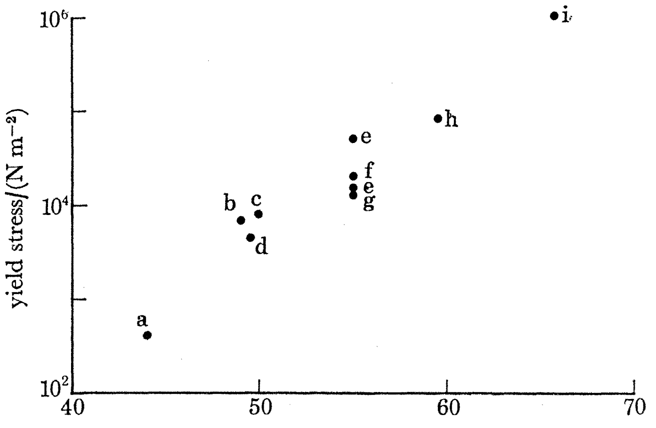


FIGURE 3. Graph of yield stress against silica content. The data are from the following lavas: a, Mare Imbrium; b, Etna 1966; c, Mauna Loa 1942; d, Oo-sima 1951; e, Tristan da Cunha; f, Hekla 1947; g, Paricutin 1945–6; h, Teide; i, Chao dacite, Chile.

Yield stress, like other rheological properties, is strongly dependent on temperature. To maintain some kind of temperature control the data used for the plot all relate to positions on flows which are distant from their vents, where it is assumed that the temperatures are all similar relative to the liquidus and solidus temperatures of the various magmas. Data from lava lakes and from stations close to vents do not fit the trend of the plot. An indication of the composition of a lava may be gained from figure 3 if the yield stress can be determined.

The quantity $W$ is the ratio of the total width of a flow to the combined width of the stationary banks (equation (6)). This ratio can be measured readily from a satellite photograph of a flow. If the slope and properties of the lava are known its effusion rate can be found from equations (2) and (3). This theory of lava flow formation has been used to interpret the shapes of several lunar lava flows.

## 4. The interpretation of lunar lava flow shapes

Some of the vast flows of south west Mare Imbrium display channels and broad banks. The slopes down which these lavas flowed were so small and the lavas so fluid that they spread a long way laterally to produce wide, flat banks enclosing relatively narrow channels. The total widths and channel widths were measured for three of the flows near Mons La Hire (figure 1). The slope of this region was estimated from Apollo 15 and 17 laser altimeter measurements to be about 1/300. Possibly the slope was different from this value at the time of the emplacement of the lavas. The yield stresses of the lavas were then calculated to be about 400 N/m². Returned

FIGURE 1. Lava flows near Mons La Hire in Mare Imbrium. Apollo 15 metric frame 1157.

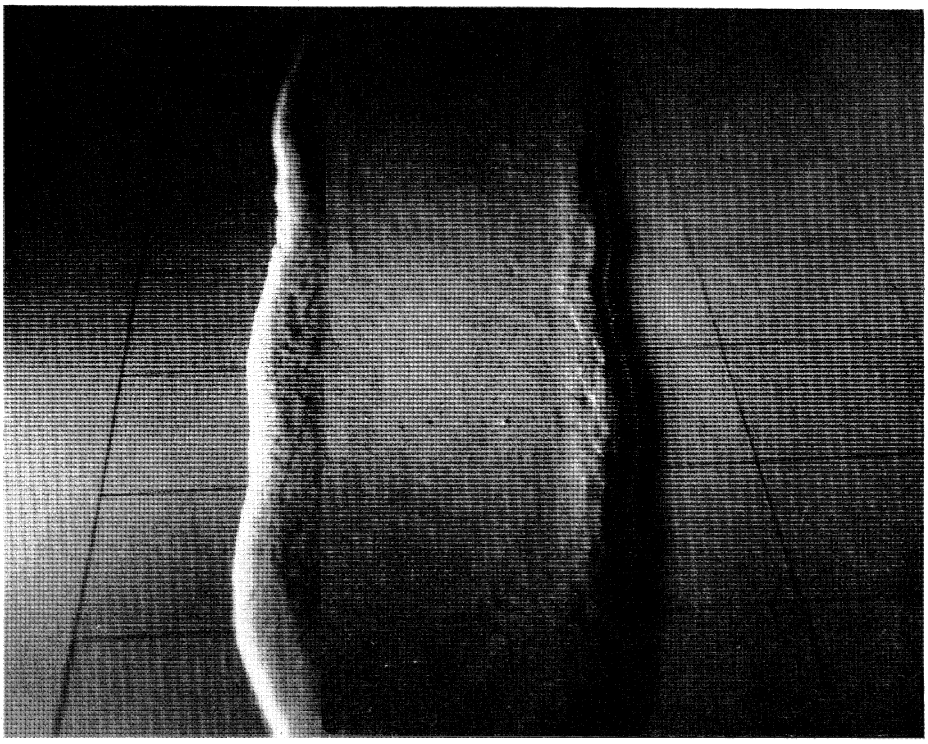

FIGURE 2. Flow of kaolin suspension. Note the parallel sides and lateral banks. The grid is 10 cm square.

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samples of Mare Imbrium lava (Apollo 15) indicate a silica content of about 44 % so that the lavas plot well on the graph of yield stress against silica content. The depths of the flows were calculated using equation (8) and found to be about 25 m, which is consistent with other estimates of the depths of these flows (Schaber 1973).

In order to calculate effusion rates the plastic viscosity of the lava was assumed to be of the order of 10 Pa s (100 poise) which is approximately equal to the Newtonian viscosity of the Apollo 15 basalts at their liquidus temperature as predicted by the method of Bottinga & Weill (1972). The results of the calculations are given in table 1. The high effusion rates are comparable with the estimated effusion rates of some Columbia River flood basalts. The flows travelled for 400 km and it may be seen that this is well within the limits enforced by the cooling of the lava.

Table 1. Mare Imbrium flows

| $w$ / km | $2w_b$ / km | $W$ | $\mathscr{F}$ | $S_y$ / N m$^{-2}$ | $d_c$ / m | $F$ / m$^3$ s$^1$ | $x(Gz = 300)$ / km | $u$ / m s$^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| 9.0 | 7.4 | 1.22 | $4.4\times10^{-4}$ | 410 | 24.7 | $8.2\times10^{4}$ | $1.5\times10^{3}$ | 0.5 |
| 9.6 | 7.2 | 1.33 | $1.5\times10^{-3}$ | 400 | 24.0 | $2.5\times10^{5}$ | $4.2\times10^{3}$ | 1.4 |
| 10.2 | 8.0 | 1.27 | $8.2\times10^{-4}$ | 440 | 26.7 | $2.1\times10^{5}$ | $3.6\times10^{3}$ | 1.0 |

Table 2. Yield stresses of crater lavas

| flow | | $d_c$ / m | $2w_b$ / m | $\alpha$ | $S_y$ / N m$^{-2}$ |
|---|---|---|---|---|---|
| Copernicus | a | 40 | 450 | (0.09) | $1.8\times10^{4}$ |
| Tycho | b | 50 | 630 | (0.08) | $2.0\times10^{4}$ |
| | c | 6.5 | (140) | 0.05 | $1.5\times10^{3}$ |
| | d | 20 | 200 | (0.10) | $1.2\times10^{4}$ |
| | e | 2 | 50 | (0.04) | $4\times10^{2}$ |
| Aristarchus | f | 3.5 | (58) | 0.06 | $1.0\times10^{3}$ |
| | g | 2.6 | (40) | 0.06 | $8.4\times10^{2}$ |
| | h | 17 | 115 | (0.15) | $1.3\times10^{4}$ |

Many lunar impact craters have lava flows associated with them. A flow with a well-defined channel occurs on the inside of the northern rim of Copernicus. Tycho and Aristarchus possess many flows. These have been described by Strom & Fielder (1970). Where possible, the depths and bank widths of these flows were measured in order to estimate the yield stresses of the lavas. In some cases only one of the two quantities was available and it was then complemented by the slope. In the case of Aristarchus slopes were estimated from A.C.I.C. contoured lunar charts; the work of Turner (1970) was used for estimating slopes in the Tycho region. The measurements appear in table 2. The quantities in brackets have not been measured but have been calculated according to equation (8). In every case the calculated values are consistent with the photographic evidence.

It is seen that the yield stress values fall into two distinct sets: one set of values is of order $10^3$ N/m$^2$ and the other set is of order $10^4$ N/m$^2$. It is easy to distinguish the two types of lava by eye. The value of the calculations is that they quantify the yield stresses and allow the direct comparison of lavas from different craters. Both types of lava are present at all three craters although only one flow of the lava of higher yield stress can be detected at Aristarchus. The more fluid of the two lavas is more fluid than terrestrial tholeitic basalt but less fluid than the Mare Imbrium lavas. The less fluid of the two lavas is rheologically similar to terrestrial lavas intermediate between basalts and andesites.

Three of these flows showed the channel and banks morphology well enough to allow the estimation of effusion rates in the manner described at the end of §3. The plastic viscosities of the lavas were assumed to be similar to those of terrestrial lavas of similar yield stress. Table 3 lists the quantities in the calculation. As a check on the values of $F$ minimum values, $F_{min}$, which would have allowed the lavas to have travelled the observed distances before cooling, were estimated. It may be seen that the calculated effusion rates are all greater than the minima rates necessary, and by about the same factor in each case.

Table 3. Effusion rates of crater lavas

| flow | | $w$/m | $W$ | $\mathscr{F}$ | $\eta$/Pa s | $F$/$m^3\,s^{-1}$ | $F_{min}$/$m^3\,s^{-1}$ | duration/days |
|---|---|---|---|---|---|---|---|---|
| Copernicus | a | 810 | 1.80 | 0.020 | $10^6$ | 260 | 30 | 15 |
| Tycho | b | 1220 | 1.94 | 0.034 | $10^6$ | 1060 | 70 | 13 |
| Aristarchus | g | 130 | 3.25 | 0.38 | $3\times10^2$ | 300 | 30 | 0.2 |

Many of the flows associated with craters have approximately parallel sides indicating that the lavas were effused at steady rates. Estimates of the times for which these effusions lasted are to be found in table 3. It may be seen that, in some cases, the steady effusion of lava must have continued for several days. This fact argues against the lavas being splash-out from a meteoric impact. It supports the findings of Strom & Fielder (1970) who showed that the lavas were generally much younger than the craters on which they occurred.

It is thought that the lavas are the product of partial melting during the isostatic recovery of the craters. It has been shown (Hulme 1974*a*) that viscous dissipation in the lunar lithosphere during recovery of a crater could have given rise to partial melting at depths of about one quarter of the diameter of that crater.

## 5. Sinuous rilles

Sinuous rilles are a common feature of mare lava fields. These relatively narrow, sinuous and sometimes meandering channels have remarkably parallel sides. They bring to mind terrestrial lava tubes; but most sinuous rilles appear never to have been roofed, and they are generally much larger than lava tubes. The sinuous rille channels are, however, characteristic of channels formed by a diffusional erosion process such as solution or melting. Terrestrial examples of such channels are solutional drainage channels in limestone and meltwater channels on glaciers. All are smooth, parallel-sided channels which maintain their forms for great distances. These features distinguish them from channels, such as rivers, formed by abrasion. A diffusional erosion process is smoothed by the inherent diffusional time constant. Moreover, the diffusivity, whether it be of heat or ions in solution, does not change in time and varies very little with material. These two factors help to produce the characteristic smooth, regular channels. Erosion by abrasion is susceptible to rapid changes in shear rate at the banks and, also, the erosion rate depends on properties such as cohesivity and plasticity, which vary in time (depending on water content, for example) and change with position to a marked degree. The abrasion process also creates sediment which, along with the great local fluctuations in erosion rate, helps to produce channels which have rough sides and forms that change markedly over short distances.

If rilles are diffusional erosion channels it is probable that they are the result of the melting



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of the ground by flowing lava. This has recently been observed in lava tubes on Kilauea (Peterson & Swanson 1974). Lava tubes are also in the class of diffusional erosion channels which accounts for the similarity between tubes and sinuous rilles. For a laminar lava flow to melt its bed it must flow continuously for some time before the ground is heated to its melting temperature. Thereafter, erosion proceeds at a slow rate of about one to two metres per month. This rate seems too slow to have formed the larger lunar rilles. If the flow were turbulent, on the other hand, the heat transfer coefficient between lava and ground would be much greater and melting would commence sooner and proceed more rapidly.

The existence of meanders is evidence for turbulent flow in sinuous rilles. Regular meanders form, with a wavelength of $2\pi$ times the channel width, when the largest turbulent eddies are perturbed and re-ordered by irregularities of the channel (Yalin 1972). Meander wavelengths in lunar sinuous rilles are consistent with this theory (Schubert, Lingenfelter & Peale 1970).

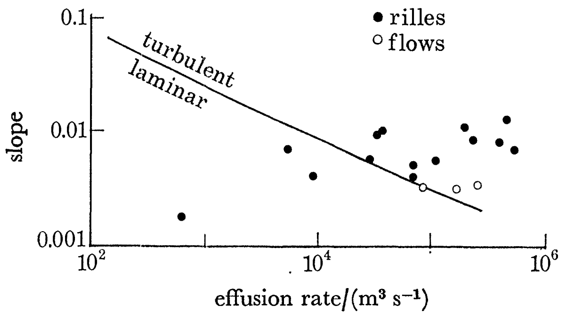


FIGURE 4. Effusion rate against slope for Mare Imbrium lava. The line separates the regions of laminar and turbulent flow.

Accordingly, Hulme (1973) calculated erosion rates incident on the turbulent flow of lava, and the possible lengths of the resulting channels, for given effusion rates. It was found that, given large effusion rates, it was possible to produce rilles of the required lengths and to achieve erosion rates of the order of 10 m per month.

The theory of § 3 may be used to predict the conditions under which transition to turbulence will occur. Generally it is harder to induce turbulence in Bingham liquids than it is in Newtonian liquids. Turbulence does not set in at a fixed Reynolds number in Bingham liquids. Experimentally it has been found that transition occurs at a fixed value of the friction factor, which is a function of Reynolds number and yield stress.

In § 3 it was shown that a flow may be described using five independent parameters. If the relevant physical properties of the lava are specified only two further parameters are required to describe a flow. The two most logical ones to use are the effusion rate and slope since they are independent of flow dimensions. It is therefore possible to place all the flows of a particular type of lava on a two-dimensional plot of effusion rate against slope. It is also possible to place the criterion for the transition to turbulence on this plot. Such a plot, shown in figure 4, has been made for the fluid lava which occurs in the lava flows of south-western Mare Imbrium and, it is assumed, was involved in the formation of sinuous rilles, many of which are found in this region. The channel width and total width of a flow were the two parameters used to place it on the plot. In the case of the rilles, the parameters used were the channel width and the slope. Slopes were determined, with difficulty, from the contoured N.A.S.A. lunar orthophotomaps. It is, again, possible that the slopes have changed since the cutting of the rilles.

In spite of the uncertainties two points are clear. First the flows and rilles appear in the same region of the plot, with rilles occurring on somewhat steeper slopes, and, secondly, the transition criterion passes through the region. The implication seems to be that flows and sinuous rilles are remnants of similar effusive events. Where slope and effusion rate were high a flow became turbulent. The central channel of the flow began to meander and was deepened by erosion due to melting. Under optimum conditions of illumination some sinuous rilles are seen to be flanked by banks.

## 6. Conclusions

The hypothesis that lavas behave as isothermal Bingham liquids has helped to explain the salient features of lava flow morphology. It has also provided a method for determining yield stresses, which are related to composition, and effusion rates from satellite photographs of flow remnants. The application of this method to the Moon has confirmed the existence of different types of lunar lava and has indicated their approximate yield stresses, which may help in their identification. The lava which apparently fills, and certainly covers parts of, the maria was a very fluid type. It was erupted rapidly and was able to travel great distances. It formed thin, wide flows which were probably close to breaking down to turbulent flow. When this did occur it seems possible that the central channels were eroded by melting to produce sinuous rilles. The lavas associated with impact craters are less fluid and these lavas experienced lower rates of effusion. The lavas associated with craters are possibly the product of partial melting induced by dissipative heating during the isostatic recovery of the craters. Indeed, mare lavas may have been produced during the recovery of the mare basins. The variations in lava type and quantity may reflect differences in depths of origin of the lavas as a consequence of the differences in crater diameters.

We wish to acknowledge support from the Natural Environment Research Council, under whose sponsorship this work was conducted. Lunar photographs were provided through the courtesy of the Director of World Data Center A for Rockets and Satellites.

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FIGURE 1. Lava flows near Mons La Hire in Mare Imbrium. Apollo 15 metric frame 1157.

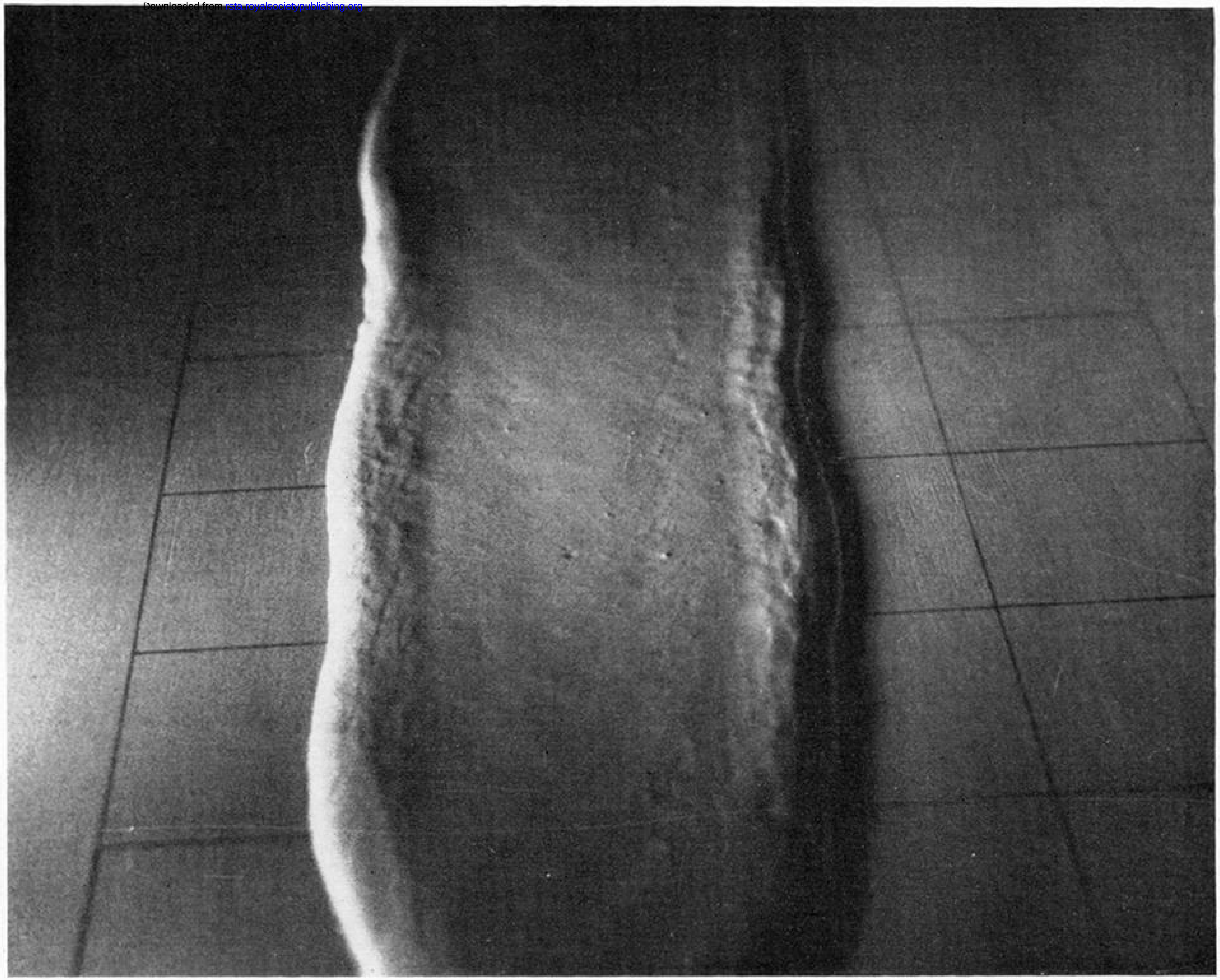

FIGURE 2. Flow of kaolin suspension. Note the parallel sides and lateral banks. The grid is 10 cm square.