AN INTEGRATED MODEL OF THE FORMATION OF LARGE-SCALE LAVA FLOWS AND SINUOUS RILLES ON THE MOON.

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Background: Lunar lava flows have volumes of 100-300 km^3 (Mare Imbrium [1, 2]) to ~1500 km^3 (the Oceanus Procellarum flow sampled by Chang'e 5 [3]). Flow thicknesses range from 15 to 60 m [4, 5] and may include inflation [6]. Flows are typically ~20 km wide [1, 2], emplaced on slopes ranging from 7×10^{-4} to 3×10^{-3} radians. Meandering lines of pits in some flows may indicate lava tube roof collapse [7]. Distinct from these are sinuous rilles, continuously open-topped channels, commonly < 1 km wide, <200 m deep and < 100 km long [8]. Based on morphology and spatial associations with other volcanic features, these are inferred to imply thermo-mechanical erosion of the pre-existing surface by turbulent lava flows [9]. Vents feeding major lava flows are often hidden when low viscosity [10] lunar lava causes late-stage vent drowning [11]. Even so, some 5-20 km long, ~1-2 km wide, parallel lines of positive deposits [11] are probably spatter ramparts formed along the sides of fissures by pyroclast accumulation during waning stages of eruptions. Sinuous rilles vents are commonly circular, less often oval, depressions up to 5, very rarely 10, km in diameter [8]. These are evidence of turbulent lava ponds formed by coalescence of hot pyroclasts from optically-dense Hawaiian fire fountain eruptions of low volatile-content magma [12]. Lunar lavas commonly show negligible evidence of chemical contamination and cooling during ascent despite passing through the anorthositic lunar crust [13]. They likely erupted at close to their liquidus temperatures with viscosities of ~0.2 to ~7 Pa s [10, 14].

Analysis: We begin by showing that almost all mare lava flows must have been turbulent as they left the vent. The data referenced above suggest that we initially model flows as resulting from the eruption of crystal-free Newtonian magma at its liquidus with a viscosity μ of 1.2 Pa s from a vent L = 10 km long on a slope of $\alpha = 1.5 \times 10^{-3}$ radians to form a flow with thicknesses D = 20 m. Note that these parameters have a range of values both larger and smaller than the nominal values by a factor between about 2 and 6.

The laminar speed U_l of a Newtonian fluid is

$$U_l = (\rho\ g\ D^2 \sin\alpha) / (3\ \mu) \quad (1).$$

If the motion is turbulent the speed U_t is

$$U_t = [(2\ g\ D \sin\alpha) / f]^{1/2} \quad (2)$$

where ρ is the lava density, ~2900 kg m^{-3}, g the acceleration due to gravity, 1.62 m s^{-2}, and f a friction factor which is a function of the Reynolds number:

$$Re = (4\ \rho\ U\ D) / \mu \quad (3)$$

given by

$$f = 0.001337 + 0.1226\ Re^{-0.32} \quad (4)$$

Whichever of equations (1) and (2) gives the smaller speed is the appropriate formula [12] and this defines whether the flow is turbulent or laminar.

With the above nominal values, we find U_l = 783 m s^{-1}, implying $Re = 1.5 \times 10^8$, clearly not consistent with laminar flow, and U_t = 5.9 m s^{-1}, implying $Re = 1.15 \times 10^6$, clearly consistent with turbulent flow. Hence the speed is in fact 5.9 m s^{-1} and the flow is fully turbulent. Conservatively assuming that the flow is initially no wider than the length of the vent, 10 km, the dense rock equivalent volume flux of lava leaving the vent is (L U D =) 1.2×10^6 m^3 s^{-1}.

We now change parameters to those minimizing turbulent flow, i.e., D = 10 m, $\alpha = 7.5 \times 10^{-4}$, μ = 7 Pa s. We find U_l = 16.8 m s^{-1}, implying $Re = 2.8 \times 10^5$, clearly not consistent with laminar flow, and U_t = 2.1 m s^{-1}, implying $Re = 3.5 \times 10^4$, clearly consistent with turbulent flow. Hence the speed is 2.1 m s^{-1}, the flow is again fully turbulent, and the erupted volume flux is 2.1×10^5 m^3 s^{-1}. We infer that the vast majority of mare lava flows left the vent as turbulent flows. The large volume fluxes, ~10^5-10^6 m^3 s^{-1}, are consistent with models of the rapid rise of large-volume dikes from partial melt zones in the mantle [15].

Next, we consider how far from the vent turbulence may persist. Heat loss by conduction at the base of a lunar lava flow is very small compared with radiation from the surface [9]. The temperature, T, varies with distance, x, along the flow as

$$dT/dx = - (s\ \varepsilon\ T^4) / (\rho\ c\ U\ D) \quad (5)$$

s is the Stefan-Boltzmann constant, 5.67×10^{-8} W m^{-2} K^{-4}, the emissivity ε = 0.96 [16], and the density ρ and specific heat c are obtained from the lava composition. Cooling induces a crystal fraction X which increases the viscosity and causes non-Newtonian behavior. We characterize the rheology as that of a Bingham plastic [17], with a plastic viscosity η and yield strength Y. Using experimental data [18, 19, 20]:

$$Y = 0,\ X < 0.021 \quad (6)$$

$$Y = 2.95\times10^{-4}\ \{[(X/0.021) - 1] / [1 - (X/0.45)]\}^{3.509},\ X > 0.021 \quad (7)$$

$$\eta = f_v\ (1477.15 / T)^{10.0207} \quad (8)$$

$$f_v = [1 - (X / 0.6)]^{-2.5},\ X < 0.317 \quad (9)$$

$$f_v = \exp\{[2.5+(X/(0.6 - X))^{0.48}] (X/0.6)\},\ X > 0.317 \quad (10)$$

Y and η influence the flow regime via the Reynolds number, now

$$Re = (4\ \rho\ U\ D)/\eta \quad (11)$$

and the Hedström number [18]

$$He = (16\ D^2\ Y\ \rho) / \eta^2 \quad (12)$$

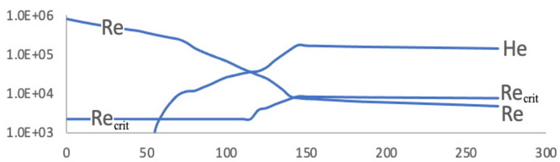

Figure 1. Variation of the Reynolds number, Re, Hedström number, He, and critical Reynolds number, Re_{crit}, with increasing distance in km from a vent.

Figure 1 shows how decreasing T increases X, which increases He, and increases the critical Reynolds number, Re_{crit}, that must be exceeded to allow turbulence. Simultaneously, increasing X causes a decrease in Re from its initially high value. When Re is < Re_{crit}, turbulence ceases, the flow becomes laminar, and thermal boundary layers grow at all flow margins. The isothermal core of the flow is insulated and preserves the non-Newtonian rheology that it had at the moment of turbulent-to-laminar transition, typically Y = 45 Pa and η = 85 Pa s. For the earlier examples, if the eruption rate is 1.2×10^6 m^3 s^{-1}, turbulence continues for 85 km; if the flux is 2.1×10^5 m^3 s^{-1} that distance is 30 km.

This is a critical issue: after turbulence stops, the laminar lava will have an unsheared layer - a plug - extending down from its surface to a depth P, where

$$P = Y / (\rho \, g \sin \alpha) \quad (13)$$

This causes the laminar flow speed formula to change:

$$U_l = [(\rho \, g \, D^2 \sin \alpha)/(6 \, \eta)] \, (2 - 3 \, j + j^3) \quad (14)$$

where j = P/D. The value of P for the 20 m deep flow above is 6.4 m, about 1/3 of the flow depth. For the 10 m deep flow the plug occupies almost all of the flow.

Implications for mare lava flows: Cooling by radiation from the surface of a turbulent flow is very efficient at cooling the entire volume of the flow at a rate of order 10 K/hour for ~10 hours. After becoming laminar, the flow completes its cooling to ambient temperature at rates of ~10 K/year over at least a decade. This should leave a signature in the growth rates of crystals in the flow.

Implications for sinuous rilles: Many sinuous rilles meander across extensive lava flow sheets. E.g., Rima Sharp is intimately associated with the lava flow sampled by Chang'e 5 [3]. We propose that this example, and likely many others, are cases where the following sequence of events has occurred:

1) a fissure eruption has emplaced a flow in which the bulk of the lava has been through a turbulent phase with rapid heat loss and has then become laminar, so that the laminar flow is crystal-rich and has a high viscosity and yield strength, The yield strength creates a rigid, but still liquid, plug extending down from the flow surface after turbulence decays;

2) the flow may or may not have inflated as it ponded within pre-existing topography; the fissure vent has become much shorter as the discharge rate of magma through the underlying dike has declined;

3) intrusion of magma into the inflating flow, if it occurred, has become energetically unfavored, and uncooled lava has spilled onto the surface of the inflated flow within at most a few days of the start of the eruption;

4) this lava has formed a narrow turbulent flow that has readily melted though the < 1 m thick solid crust and encountered the ~40% crystallized still-hot lava, which it has thermally eroded to form a sinuous rille.

5) erosion of lava with a temperature corresponding to ~40% crystals only needs the lava to be heated by a few 10s of K: this decreases the crystallinity to ~20%, which drastically reduces the yield strength, allowing easy deformation and removal at erosion rates of many 10s of μm s^{-1}. This is in stark contrast to erosion of cold ground, which requires the ground to be heated by many 100s of K, so that erosion rates are at best 1-2 μm s^{-1} [10].

6) additionally, the finite yield strength of the hot lava inhibits collapse of the exposed walls of the channel as erosion occurs.

7) the extreme meandering of some rilles may reflect the fact that they are eroded into a recently-erupted, nearly flat, pristine lava surface unaffected by impact processes.

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