EROSION BY LAVA AT RIMAE POSIDONIUS ON THE MOON.
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Introduction: Rimae Posidonius is a sinuous rille located on the western edge of the 100-km-diameter Posidonius impact crater (lat. 31 48'N, long. 29 54'E) on the Moon. It lies on top of older, smooth mare lavas that bury part of the crater floor and much of the western crater wall. Using an analytical approach, Hulme [1] suggested that the lunar sinuous rilles may be the result of erosion by low-viscosity, high-density and high-temperature turbulent flows of mare basalts. The highly sinuous shape of Rimae Posidonius is particularly suggestive of an erosional process by turbulent lavas. Huppert and Sparks [2] focused on terrestrial Archean komatiite lavas and combined laboratory experiments with mathematical modeling to assess erosion by turbulent lavas. The rigorous analytical-numerical model develop by Williams et al. [3, 4] to investigate thermal erosion by turbulent lava under various conditions on the Earth and the Moon involves both a physical and geochemical approach to address the question. The model is written in the C language and calculates erosion rates and depths with time, as a function of distance from the source. The flow is one-dimensional (in the x-direction) with thermal erosion in the z direction. Lava erupts as a turbulent flow with a thermally mixed interior, convective heat transfer occurs to the top and the base of the flow, and thermal erosion occurs at the base of the flow. This model represents an important advance compared to previous work because 1) it includes the effects of lava rheology changes due to assimilation of eroded substrate and crystallization of mafic minerals in the flowing lava, 2) the lava temperature decreases as the flow moves downstream, and 3) flow thickness increases as velocity decreases (thickness is used as proxy for flow rate that is conserved from source to terminus). Here we adapt and apply the Williams et al. [4] model to the formation of Rimae Posidonius. Before doing so, we will extract key topographic data at this rille site, which will enable us to compare model results with data obtained through observations.

Method: High-resolution (≥50 m/pixel) Narrow-Angle Camera (NAC) footprints, stereo Digital Terrain Models (DTMs), and Lunar Orbiter Laser Altimeter (LOLA) tracks from NASA's Lunar Reconnaissance Orbiter Camera (LROC) were the key sources of topographical input parameters for the model. The process of data collection (rille slope, depth, width, length) was facilitated by an extensive use of the ArcGIS™ software, which enables creation of stacks of individual image layers. Lava thicknesses were not definitely constrained by high-flow marks on exposed rille walls, thus we choose a value of 10 m, consistent with previous estimates on individual lunar flows [5, 6], and allow for thickness to vary down to 3 m, to explore how flow regime varies as a function of lava thickness as well as distance from lava source.

Modeling. The modeling begins with choosing a major oxide composition for the lava and substrate, the composition of lunar sample 12002, an Apollo 12 low-titanium picritic basalt [7, 4]. Its high liquidus temperature (~1440°C) and low dynamic viscosity (0.75 Pa s) well suit a turbulent emplacement regime. Lava is assumed to flow over a homogeneous, massive substrate, given that the rille lies on top of mare lavas covering part of the crater floor to some depth. Another key input parameter of the model is the slope of the ground. Calculated erosion rates are then multiplied by specific values of elapsed time t since flow began to yield the erosion depth into the substrate. The duration of the flow is constrained by looking at the total distance traveled by the flow (rille length). Finally, the acquired rille width along with the assumption that flow rate is conserved are used to constrain the total volume of lava erupted.

Results: Depth values of 55-65 m are found at the rille source region. As we move downstream, depths decrease to ~35-40 m until values of 30-35 m are measured near the rille terminus. At a few rille sections, the measured depth is much smaller, which appears to be due to flows that have partially filled the area. The slope of the ground varies over the length of the rille, ranging between ~0.8° and 1.6°, which are used as upper and lower end values. The width of the rille varies between ~200 and ~300 m and an average value of 250 m is chosen. After accounting for the meandering path, the rille length is determined to be ~180 km.

Model results. Results confirm that channelized 5-10-m-thick lavas could have erupted as turbulent flows on the Moon, if erupted near their liquidus temperature. Laminar flow takes over for thicknesses values lower than 5 m and at distances of ~130 km downstream from the lava source, with flow viscosities of order 5.0 Pa s and temperatures of ~1350°C. If the slope of the ground varies between 0.8° and 1.6°, erosion rates range from 0.32-1 m/day for a 10-m-thick lava flow; this dictates erosion depths of 46-63 m at the source and 19-28 m at the rille terminus (over a 60-

day time period, which is the minimum time required to explain observations, Fig. 1).

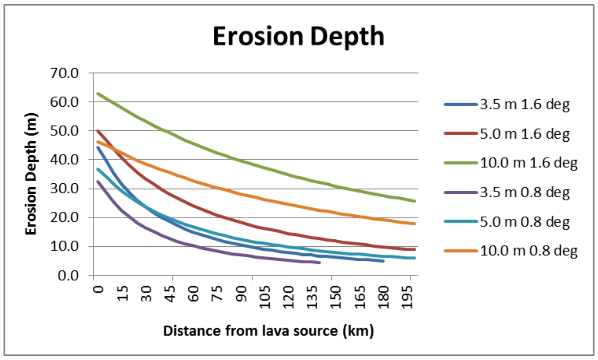

Figure 1: Graph showing how erosion depth varies as a function of ground slope as well as distance from lava source, for lava flows of thickness in the range 3.5-10 m. All values are for a 60-day time period (minimum time that explains observations).

By assuming a 90-day time period, erosion depths of 69-94 m and 29-42 m are found at the lava source and the rille terminus, respectively. A flow period of 60-75 days better explains observations (if we assume the flow has a thickness of 10 m). For 5-m-thick flows, a time of 90 days is sufficient to match erosion depths at the source, but downstream and rille end values are always lower than 10-15 m, i.e., lower than those measured. This discrepancy reinforces the case for ~10-m-thick flows. In this scenario, erosion rates are higher than those found by Williams et al. [4] (up to ~13 cm/day at the source), because of the lower slope of the ground (~0.1°) assumed by the latter authors. Volume rates of $9.2 \times 10^3 - 2.9 \times 10^4$ m^3 s^{-1} are found, if considering 5 and 10 m thick flows, respectively. The total volume of lava involved in the formation of Rimae Posidonius (estimated over a 60-75-day period) ranges between 151 and 189 km^3 for a 10-m-thick flow. These values fall within the range obtained in modeling the Rima Prinz sinuous rille [8], or represent a lower end estimate as applied to the largest sinuous rilles on the Moon [9]. As the flow moves downstream, it cools and develops a crust over its surface, which becomes progressively thicker. For a 10-m-thick flow, the thickness of the crust reaches maximum values of 3-5 cm, for ground slopes of 1.6° and 0.8°, respectively. Holding other parameters constant, a thicker crust develops at a lower flow thickness and a lower slope of the ground.

Discussion: The substrate is modeled as homogeneous and unfractured. Yet, it is likely for the rille to have flowed over portions of substrate that were at least partially fractured because of the whole area being an impact crater. Allowing for partial fracturing would yield reduced times for the flow to generate the observed erosion depths to the extent that could be found. Another way to produce higher thermal erosion rates is by emplacement of superheated lavas. For example, lavas heated to 200°C above their liquidi generate much higher erosion rates over substrates of the same composition [4]. This process requires that magma ascends rapidly through the lithosphere [10]. Importantly, superheated magma could enable denser lunar basalts to erupt through the crust by buoyancy alone [11]. Elements from available mechanical and thermo-mechanical models of erosion by lava could be incorporated into an advanced version of the model. The Proterozoic komatiitic basalt lava channel of the Cape Smith Belt in New Quebec, Canada [12] exhibits erosion through soft sediment at the tops, bottoms, and sides of the conduit; a similar mode of erosion could produce the meanders characterizing Rimae Posidonius.

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