CONDITIONS IN LUNAR ERUPTIONS PRODUCING SINUOUS RILLES. L. Wilson[1] and J. W. Head[2], [1]Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK (L.Wilson@Lancaster.ac.uk), [2]Dept. of Geological Sciences, Brown University, Box 1846, Providence RI 02912, USA (James_Head@Brown.edu).

Introduction: If the inference [1, 2] that lunar sinuous rille channels were formed by thermo-mechanical erosion of pre-existing volcanic surfaces is correct, sinuous rille morphologies can give information about conditions in the eruptions that formed them [3]. Morphologies of rille channels [4] and source depressions [5, 6] support the thermo-mechanical model. The addition of detailed treatments of lava thermal properties and boundary layer heat transfer [7] to lava erosion models greatly clarified how the process works, but critically Hulme's original model [1] allows the variation of rille channel depth Y with distance X from source to be used to determine a range of eruption parameters.

Method: Hulme [1] relates Y / Y_0 to X / X_m by

$$\frac{Y}{Y_0} = \left(1 - \frac{T_s}{T_e}\right)^{-1} \left(1 + \frac{X}{X_m}\right)^{-2} \left[\left(1 + \frac{X}{X_m}\right)^{-\frac{1}{3}} - \frac{T_s}{T_e}\right]$$

where Y_0 is the rille depth close to the source depression and X_m is the total rille channel length. Hence measurements of fractional depth as a function of fractional distance down-rille can yield T_s / T_e. For lunar basalts with $T_s = 1335$ K, T_e is thus obtained and then the lava viscosity η can be found from a simple model:

$$\eta = \left\{2^{-\frac{1}{3}} T_e^{-1} A \left[1 + \left(T_e / T_s\right)^3\right]^{\frac{1}{3}}\right\}^{15}$$

where [1] $A = 1635$ K fits data from [8]. [1] relates rille length X_m to lava flow rate per unit rille width, Q, thus:

$$Q = \frac{3 \sigma e X_m T_s^3}{\rho c \left(1 - \left(T_s / T_e\right)^3\right)}$$

where σ is the Stefan-Boltzmann radiation constant, e is the emissivity of liquid lava (~1) and ρ and c are the density and specific heat of the lava. Q is related to the volume flux, F, of lava eroding the floor of the channel by $Q = F / W = U D$ where W is the channel width and D and U are the depth and speed of the lava. Assuming that the motion of the lava on the channel floor is turbulent with a friction factor, f, ~10^{-2}, D is given by

$$D = Q^{2/3} \left[\frac{f}{2 g \sin\alpha}\right]^{1/3}$$

and the flow speed is then found from $U = Q / D$. In practice once first estimates of D and U are known, the

Reynolds number $Re = (4 D U \rho) / \eta$ can be found and f can be improved by recursively calculating

$$f^{-1/2} = 3.2 \log_{10}\left(Re_H f^{1/2}\right) + 1.2$$

Finally [1] gives the channel floor erosion rate Y_0' as

$$Y_0' = \left(4 \times 10^{-5} / D\right)\left(\left(T_e / T_s\right) - 1\right) Q^{0.8} \left(T_e / T_s\right)^6$$

Dividing the rille depth Y_0 by Y_0' gives the eruption duration τ and multiplying τ by F gives the total erupted lava volume V.

Additional information on a rille-forming eruption can be obtained from the size of the depression at the rille source. We infer that these depressions form by thermo-mechanical erosion at the base of a turbulent lava pond fed by accumulating pyroclasts from optically dense lava fountains [10]. The size of the pond (radius if circular from a localized vent, half-width if elongate and formed by a fissure eruption) is defined by a combination of the mass eruption rate of magma and the eruption speed of the pyroclasts, in turn controlled by the magma volatile content. A model of the formation of such ponds [10] allows erupted mass fluxes deduced from the rille channel analyses coupled with direct observations of source depression sizes to be used to infer source pond erosion rates Y_s' and magma volatile contents, n, given an assumption about the dominant magma volatile composition [5, 6]. The results of this analysis are also given in Table 1, assuming that CO from smelting reactions dominates the gas phase [11].

Results: We used Lunar Orbiter images to measure depth as a function of distance for 8 sinuous rille channels (numbers 2, 3, 4, 5(a), 5(b), 6, 7 and 18 from [9]) and lunar orthophoto maps to find slopes. We fitted the morphological measurements to the above equations to obtain values for the parameters in Table 1. All of the rille-forming lavas have Re within a factor of 1.5 of 10^5, implying fully turbulent flow thus making the model self-consistent.

Channel floor erosion rates of 5 to 36 μm/s are derived; rille depths then imply eruption durations of 49 to 540 days and erupted lava volumes of 16 to 2300 km^3.

Source pond bed erosion rates range from 3 to 24 μm/s and are always about two thirds of the corresponding rille channel floor erosion rate, reflecting the somewhat lower efficiency of erosion in the pond. Magma CO volatile contents are 150-400

Magma CO volatile contents are 150-400 ppm, consistent with findings from Apollo sample analyses [11].

Eruption mass fluxes range from 1.2×10^7 to 2.9×10^8 kg/s, corresponding to dense lava volume fluxes of 4000 to 10^5 m^3/s.

Discussion: One obstacle to the acceptance of long-lived turbulent lava flows as the originators of sinuous rilles has been the requirement that the flows be unusually narrow. The evidence for the small width comes from observations of rilles cutting highland terrain where no sign of a precursor lava flow is visible. The absence of narrow flow levees can be understood as the result of thermo-mechanical erosion undercutting the sides of a deepening channel. However, this process could not eliminate levees wider than some fraction of the channel depth, at most a few hundred meters, implying that the pre-cursor flows of many sinuous rilles must have been no more than 1-3 km wide.

The lava effusion rate values we find for the sinuous rille-forming eruptions are about one order of magnitude smaller than those deduced for normal mare lava flows, 10^5-10^6 m^3/s [12]. We infer that the main difference between the typical relatively broad mare lava flows on the one hand and the narrow flows that were the precursors to sinuous rille erosion on the other was a combination of eruption rate and topography. Mare lavas were typically emplaced on slopes of ~0.001 radians [12], whereas the range for the rilles analyzed here is 0.008 to 0.05 (Table 1). Steeper slopes encouraged formation of faster flows, and this, combined with smaller volume fluxes, allowed those flows to be narrower, while maintaining turbulence.

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Table 1. Parameters deduced for rille-forming eruptions. X_m: rille length; α: slope of ground in which rille forms; Y_0: depth of rille near source; W_{av}: mean rille width; T_e: lava eruption temperature; η: viscosity of lava; D: depth of lava on channel floor; U: speed of lava on channel floor; M: lava mass eruption rate; Re_H: lava Reynolds number; Y_0': channel bed erosion rate; τ: duration of eruption; V: volume of lava erupted; Y_s': source crater floor erosion rate; n: magma CO mass fraction.

Variable	Units	2	3	4	5(a)	5(b)	6	7	18
X_m	km	76	51	40	110	70	55	80	74
α	radian	0.010	0.015	0.020	0.024	0.013	0.012	0.008	0.050
Y_0	m	260	200	110	280	100	180	300	330
W_{av}	m	330	510	180	830	330	760	1120	300
T_e	K	1380	1520	1480	1400	1390	1480	1460	1460
η	Pa s	13.8	4.2	5.8	11.6	12.6	5.8	6.9	6.9
D	m	15.9	4.8	4.4	12.0	12.3	6.3	9.8	5.1
U	m/s	9.2	5.9	6.3	12.6	9.1	6.0	6.3	11.3
M	10^7 kg/s	9.0	3.5	1.2	29.4	8.7	7.5	19.0	4.0
Re_H	10^5	1.27	0.81	0.57	1.56	1.07	0.78	1.07	1.00
Y_0'	μm/s	5.6	36.7	26.1	12.0	7.4	23.5	17.8	32.3
τ	days	540	63	49	271	156	89	195	118
V	km^3	1400	64	16	2300	390	190	1070	140
Y_s'	μm/s	3.4	23.6	17.6	7.1	4.6	15.2	11.0	20.2
n	ppm	280	190	180	400	150	300	210	200