WAX MODELING OF THERMAL EROSION IN LOW-VISCOSITY LAVA FLOWS ;

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Summary: Potential thermal basal erosion of lava channels is greater beneath lava flowing under turbulent as opposed to laminar conditions because internal heat transport outward is much greater. This study assessed the qualitative differences in erosional features produced by hot fluid flows over a bedrock modeled by polyethylene glycol (PEG) wax. Erosion rates increased as the flow transitioned from laminar to turbulent conditions, but there was little change in erosional morphology until higher flow regimes were attained, in which irregular scallops were cut into the channel floor and sides.

Background: Lava flows can enlarge their channels by purely thermal erosion or by a combination of thermal and mechanical erosion. On Earth, thermal erosion has been observed in carbonatite flows [1] and has been inferred to occur at the base of komatiites [2], but has not been observed during active basalt flow emplacement. Thermomechanical erosion has been invoked for the formation of lunar sinuous rilles [3, 4] and long venusian channels [5]. In general, long sinuous channels suggest emplacement by a low-viscosity, rapidly-flowing fluid, but this raises a dilemma. The low flow viscosity implied by long flow distances implies that flow conditions were likely to have been turbulent, yet turbulence significantly increases the rate of internal heat loss, making long flows less likely. A turbulent flow may erode thermally more efficiently than a laminar flow because there is only a thin sub-laminar layer between the ground and the hottest fluid and there is a large quantity of heat being delivered to the top of the thermal boundary layer by the internal turbulence of the flow. There is a sharp temperature gradient over a short distance , the temperature at the flow/ground interface is above its solidus, and the ground melts. In a laminar flow the hottest part of the fluid is in the center of the flow, thus, the temperature gradient traverses a longer distance for the same flow thickness. The temperature at the ground interface is lower, making it harder to rise above the ground's solidus and so, basal melting is less certain. Even so, there was sufficient heat available in the 1988 carbonatite eruption to cause basal erosion, even though the flow was laminar [1]. This study focuses on modeling low viscosity lavas and whether turbulent conditions lead to thermal or thermomechanical erosion. The resulting morphologies are assessed for forms that are sufficiently different to be detectable in nature.

The assessment of terrestrial flow regimes utilizes two dimensionless parameters, the Reynolds number (Re) and the Froude number (Fr). Re is the ratio of the inertial forces acting on a given parcel of fluid to the internal viscous forces within the fluid that resist flow. A rule of thumb for open channel flows, is that when Re<500 the flow is fully laminar and when Re>2000 the flow is fully turbulent. Fr is the ratio of the inertial to gravitational forces acting on the flow. At Fr<1, gravity forces are greater than inertial forces, the fluid's surface is relatively undisturbed and the flow is considered "tranquil". At Fr>1, standing waves and other features may occur and the flow is said to be "rapid" [6]. Terrestrial basalts and komatiites have Fr<1 and are, hence, tranquil flows at most places in their channels. The wax flow speeds required for turbulent flow also produce an Fr>1; future modeling is required to assess thermal erosion under modeled tranquil flow conditions.

Procedure: Polyethylene glycol (PEG) waxes have been used to imitate lavas in several studies [2, 7, 8,9]. PEG has been used before because it is a Bingham non-Newtonian fluid and it can form surface crusts under prevailing laboratory conditions. Several different weights of PEG were used in this study, including water and a 50% water/PEG 200 mixture, in order to simulate lavas of different viscosities. The model lavas were extruded into rectangular channels (3 cm deep x 6 cm wide x 170 cm long) in a base of solid PEG 3350. Test runs of different waxes were made with varying temperatures and slopes in order to cover the widest possible ranges of Re and Fr. Erosion runs were then made at a flow temperature of 100° and a slope of 10° for maximum thermal erosion and Re (see Table 1). Flow depths were measured along the length of the channel during a run and the surface flow velocity was measured by motion picture analysis.

Results: All runs produced erosion of the original channel. However, there were distinct differences in erosion rate and channel morphology with increasing Re. PEG 3350 (the most viscous wax) produced an Re of ~100. Downward erosion was 2-5 mm and lateral erosion was 4-5 mm in ~10 minutes. The channel shape was smooth, with a rounded channel floor, similar in cross-section (Figure 1) to channels produced by [2]. Runs conducted with PEG 200 had an Re of 4000-6000, well into the turbulent range. The erosion rate was much higher than with PEG 3350, (with approximately double the amount of cutting in one third of the time), yet, the eroded channel shape was qualitatively the same as in the laminar flow. The 50% water/PEG 200 mixture had an Re of 7750 (despite having a slower velocity than the more viscous PEG 200). This run caused the same amount of sidecutting as the turbulent PEG 200 in the same time but the downcutting rate was three times as great. The channel morphology was also changed. Scallops ~3 cm in size were eroded into the base of the channel and irregular scallops were cut into the sides. The pure water run had an Re of 39000 and was the most erosive, downcutting 2-3 cm and sidecutting 0.5-1 cm in two minutes. The channel shape had many small, random scallops (~1 cm) on the base and sides (Figure 1).

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Conclusions: Thermal erosion was produced under both laminar and turbulent conditions. The flow state controls the rate of erosion to a certain extent, but not the channel morphology. Instead, the style of erosion changes at high Reynolds number (Re>6000); this behavior is analogous to sedimentary deposition where the style of deposition changes from plane beds to anti-dunes in the upper flow regime. Future work planned includes more accurate determination of model thermal properties for better quantitative modeling of natural thermal erosion.

References: [1] Dawson, J.B. et al. (1990) Geology, 18, 260-3. [2] Huppert, H.E. and Sparks, R.S.J. (1985) Journal of Petrology, 26, 694-725. [3] Hulme, G. (1973) Modern Geology, 4, 107-117. [4] Carr, M.H. (1974) Icarus, 22, 1-23. [5] Baker, V. et al. (1992) JGR, 97, 13421-13443. [6] Briggs, L.I. and Middleton, G.V. (1965) in Middleton (ed.) SEPM Special Publication 12, 5-16. [7] Hodgson, G.W. (1981) Unpublished M.S. manuscript, Air Force Institute of Technology, Wright-Patterson AFB, Ohio. [8] Greeley, R. and Womer, M. (1981) LPSC XII Proceedings, 651-662. [9] Griffiths, R.W. and Fink, J.A. (1992) JGR, 97, 19729-19737.

Table 1. Summary of Erosion Runs

Run #	Material	Slope	L m	V m/s	ν m/s	Duration sec	Re VL/ν	Fr V/√(Lg)	Erosion Rate mm/min SIDE	BASE	Comments
501	PEG 3350	10°	9.4(-3)	0.84	7.0(-5)	544	110	2.8	0.4-0.5	0.2-0.5	Smooth floor and side erosion (U-shaped)
503	PEG 200	10°	1.4(-2)-9.2(-3)	1.85	4.3(-6)	219	4000-6000	5.0-6.1	1.9-2.5	1.4-2.7	Same morphology as in 501 but erosion rate was higher
504	50/50 mix of PEG 200 & H_2O	10°	6.3(-3)	1.59	1.3(-6)	210	7750	6.4	2.0-3.5	~8	Scalloped floor erosion; there is some periodicity to the scalloping downstream (λ ~ 3 cm)
502	H_2O	10°	7.0(-3)	1.61	2.8(-7)	136	3.9(4)	6.1	2.2-6.2	8.8-12.3	Severely scalloped (random) erosion
	Basalt	0-10°	3.3	1-5	1.8(-2)		180-890	0.17-0.87			
	Komatiite	0-10°	4.5-25	0.1-4.0	3.3(-5)-3.6(-3)		125-7.5(4)	0.015-0.6			

L = cross-sectional area / wetted perimeter, V = flow speed, ν = kinematic viscosity; Scientific notation exponents in parentheses.

Figure 1. Cross- section and longitudinal sections of typical erosion channel. The initial sections are shown at the top, the laminar/turbulent case in the middle, and the very turbulent case on the bottom. The laminar run duration was 550 seconds and the very turbulent run duration was 140 seconds. Dotted lines indicate the pre-flow surface.