EXPLORING MEANDER DEVELOPMENT IN PLANETARY SINUOUS RILLES. Vincenzo Cataldo[1] and David A. Williams[1], [1]School of Earth and Space Exploration, Arizona State University, Tempe, Arizona, 85287-1404 (Vincenzo.Cataldo@asu.edu).

Introduction: Planetary sinuous rilles are meandering channels interpreted to form by either construction [1] or thermal [2] or thermo-mechanical erosion [3, 4] by turbulently flowing lava. They are thought to be associated with effusive, high-volume volcanic events [5] and have relatively steep slopes and flat bottoms. Their meanders have cuspate inner bends and show no bifurcation, braided bars, levees, oxbows, point bars, or deltas [6]. Their width to depth ratio is large, 0.07-0.2, much deeper than terrestrial rivers [6]. On the Moon, model results show that thermal energy dominated over kinetic energy in the formation of sinuous rilles because the low lunar gravity contributes insignificantly to lava flowing on slopes < 3.5° [5]. But how did rilles' meanders form? And, how can we use our knowledge of the process of meandering in rivers on Earth to investigate rille formation? This abstract discusses our initial results of applying a model of supraglacial meander formation to planetary sinuous rilles.

Background: The inception of river meandering is the result of the complex interaction between flow, bed sediment, and bank material. In alluvial settings, variations in boundary shear stresses that exceed the threshold for sediment motion drive bank erosion and deposition [7]. Meanders are also observed in supraglacial streams, where no similar mechanism for deposition of bank material exists and generally little sediment (ice or rock) with which to mechanically erode the channel is found [7]. Supraglacial streams thus exemplify a problem long recognized in bedrock river channels [8]. Understanding the morphodynamics of these streams thus informs in a broader sense the study of sinuous channels on other terrestrial planets, where the substrate characteristics, melt composition, and volumes are often poorly constrained [7]. How does channel sinuosity evolve in the absence of bank deposition? The Karlstrom et al. [7] model addresses the generation of supraglacial meanders, and shows how they may form as a result of thermal erosion only. Their work is a parameter-sensitivity test that aims to identify a physical mechanism for the onset of meander instabilities, rather than a study of broader-scale channel sinuosity development. Here, we briefly describe the approach adopted by these authors along with that adopted by Williams et al. [9] in their model of thermal erosion by turbulently flowing lava. The objective is to create a hybrid model that may simulate the initiation and evolution of rille meandering by adapting and modifying the Karlstrom et al. [7] approach for a scenario of thermal erosion by turbulently flowing lava. We will also explore the amount of vertical incision associated with bank erosion, something that is not accounted for by Karlstrom et al. [7].

The Karlstrom et al. [7] model: The supraglacial streams of Karlstrom et al. [7] migrate through the interaction of two erosional processes: thermal erosion occurring over the entire glacial surface forced by solar radiation, and thermal erosion within the channel. Channelized melt-water attains a higher mean temperature than the surrounding ice due to its lower albedo and the heat dissipated by flow. The origin of meandering is an instability driven by channel curvature that enhances heat transfer (hence melting) along the outside of bends. Channel bends locally decrease the thickness of the boundary layers separating flowing melt-water and glacial ice, increasing lateral temperature and velocity gradients. This mechanism thus provides a positive feedback that increases frictional dissipation and heat transfer in regions of high channel curvature that leads to increased thermal erosion. The meander wavelength and amplitude are modulated by the glacier's surface slope, which sets the total potential energy available for flow, a result suggested by some field studies [10]. Karlstrom et al. [7] develop depth-averaged conservation equations, studying the initial perturbations to straight channels with erodible boundaries. They assume constant channel width and slope and neglect vertical structure within the flow, the latter assumption holding true for channels wider than they are deep, a condition satisfied by both supraglacial streams and rivers [11].

Karlstrom et al. [7] results: The authors model both the flow within a supraglacial stream and the substrate melting that drives lateral migration of the channel bank. The channel aspect ratio, ß, generally exerts greatest control on meander wavelength. Increasing ß generally decreases meander wavelength, while increasing the Froude number Fr (ratio of the flow inertia to the product of acceleration due to gravity by a "characteristic length"), decreases the meander wavelength. The transition to meandering occurs around Fr ~0.2 for ß ~1 and around Fr ~0.4 for ß ~5. Meander wavelength generally increases with increasing water temperature difference, although the dependence diminishes for large temperature differences. At low velocities, increasing water temperature difference can shut off meandering. Predicted depth perturbations are antisymmetric with respect to the channel centerline, deepening on the outside edges of bends and shallowing on the insides. It is the addition of background lowering of the channel from solar forcing that sets the balance between lateral and vertical incision. Importantly, Karlstrom et al. [7] neglect the vertical incision of channels with respect to the surface, due to dissipation of heat in the stream and albedo differences between water and ice.

The Williams et al. [9] model: This rigorous analytical-numerical model calculates erosion rates and depths with time, as a function of distance from the lava source. The flow is one-dimensional in the horizontal direction, with thermal erosion in the vertical direction. Lava erupts as a turbulent flow with a thermally mixed interior, and convective heat transfer occurs to the top and base of the flow. The model accounts for the effects of lava rheology changes due to assimilation of eroded substrate and crystallization of mafic minerals; the lava temperature decreases as the flow moves downstream; flow thickness increases as velocity decreases (thickness is used as proxy for flow rate that is conserved). Key input parameters of the model include: 1) lava and substrate compositions; 2) lava thickness; 3) substrate slope.

The new model: We plan to create a new model that, while adopting the Karlstrom et al. [7] approach, may simulate a process of thermal erosion by turbulently flowing lava by incorporating a thermal erosion component similar to that adopted by Williams et al. [9]. Karlstrom et al. [7] developed two sets of governing equations: the first set of equations for momentum and mass conservation provides depth-averaged velocities and downstream and cross-stream shear stresses, and the second set gives a final energy equation that balances the divergence of heat from the channel cross-section boundary with internal frictional dissipation. Our objective is twofold: we want to adapt the first set of equations for a scenario of turbulently flowing channelized lava, and modify the second set to account for a source of heat associated with flowing lava. The second set will simulate thermal erosion and vertical incision of an initially consolidated substrate as well as lateral bank erosion. We will then explore a range of flow depths and flow parameters consistent with those thought to have characterized the emplacement of lava in sinuous rilles formation on Mars and the Moon. A similar range of flow depths and parameters is expected to yield various meander wavelengths and amplitudes, thus showing a trend similar to that obtained by Karlstrom et al. [7] for supraglacial streams. At this stage, we are not concerned with the geochemical and physical evolution of the turbulent lava flow with increasing downstream distances from the lava source.

Discussion: The Karlstrom et al. [7] and Williams et al. [9] models differ in many respects. Although the Karlstrom et al. [7] approach is potentially applicable to any fluid and natural channelization features that exhibit meandering, there is a non-trivial difference in aspect ratio between supraglacial streams, river channels and planetary sinuous rilles, which is expected to have an impact on modeled meander wavelengths and amplitudes. In the case of supraglacial streams, the channel aspect ratio, ß, has greatest control on meander wavelength and thermal parameters appear to have a much smaller effect. Still, meanders form because advective terms dominate conductive losses through ice when balanced against dissipation. For a turbulent lava flow, advective terms could be higher, and potentially yield a much higher potential for thermal erosion, especially if conductive losses through lava substrate increase to a limited extent. Interestingly, Karlstrom et al. [7] find that it was necessary to choose a low temperature difference between stream water and boundary ice to generate meandering wavelengths that match field data. We do not know if a similar thermal constraint could apply to a scenario of turbulently flowing lava, which makes it a critical test case. Another parameter that has a potential to affect meandering formation and wavelength is ground slope. In the Karlstrom et al. [7] model, slope is held constant. Because meander wavelengths are not generally constant over the full length of a river, the model predicts that as increasing slope increases average streamwise velocities, dominant meander wavelengths will get smaller. However, all else constant, the velocity dependence of meander wavelength becomes negligible for high velocity flows.

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