

ICE-RIDGE PILE UP AND THE GENESIS OF MARTIAN “SHORELINES”. C. J. Barnhart¹, S. Tulaczyk¹, E. Asphaug¹, E. R. Kraal¹, J. Moore², ¹(Department of Earth Sciences, University of California Santa Cruz, 1156 High Street, Santa Cruz, California, 95064, barnhart@es.ucsc.edu, asphaug@es.ucsc.edu), ²(NASA Ames Research Center, MS 245-3, Moffet Field, CA 94035-1000, jeff.moore@nasa.gov).

Introduction: Unique geomorphologic features such as basin terraces exhibiting topographic continuity have been found within several Martian craters as shown in Viking, MOC, and THEMIS images. These features, showing similarity to terrestrial shorelines, have been mapped and cataloged with significant effort [1]. Currently, open wave action on the surface of paleolakes has been hypothesized as the geomorphologic agent responsible for the generation of these features [2]. As consequence, feature interpretations, including shorelines, wave-cut benches, and bars are, befittingly, lacustrine.

Because such interpretations and their formation mechanisms have profound implications for the climate and potential biological history of Mars, confidence is crucial. The insight acquired through linked quantitative modeling of geomorphologic agents and processes is key to accurately interpreting these features. In this vein, recent studies [3,4] involving the water wave energy in theoretical open water basins on Mars show minimal erosional effects due to water waves under Martian conditions. Consequently, other formation mechanisms need to be considered.

Glacial Geomorphology: As a formation mechanism we propose the flow of an ice-plug on a perennially frozen lake as the erosional agent responsible (see Figure 1). Despite subfreezing temperatures, terrestrial Antarctic lakes (i.e. Lake Vostok) do not completely freeze because of solar and geothermal heat, as well as latent heat generated by water freezing to the underside of the ice-plug [5]. It has been suggested that, in combination with an aquifer as a source for groundwater recharge via seep, ice covered paleolakes could be maintained in a similar fashion early in Mars’ history [5]. Currently, a thermodynamic model (via the MGCM) for the freezing of a lake (considered as a monolayer) is in development (see Santiago et al., this LPSC).

Ice pile-up along shores acts as a significant morphological agent by creating ridges [6,7,8]. To competently interpret morphological evidence for crater degradation by ice, an understanding of ice rheology is in order. Three factors strongly influence the strain rate and flow of ice: stress, temperature, and ice purity [9]. Energy balance equations, in which an ice mass’ potential energy overcomes the friction associated with the shore, have been developed to calculate the maximum landward extent of ice pile-up [10]. Simulations of ice flow over a

sub-glacial lake flattens the surface, produces a local velocity increase over the lake, and creates a deviation of the ice flow from the main flow direction [11]. These consequences of ice flow are observed at Lake Vostok, Antarctica—an excellent Martian analogue [11]. Martian observations include reticulate terrain exhibiting sharp inter-connected ridges speculated to reflect the deposition and reworking of ice blocks at the periphery of ice-covered lakes throughout Hellas [12]. Our model determines to what extent ice, a terrestrial geomorphologic agent, can alter the Martian landscape.

Method: We study the evolution of crater ice plugs as the formation mechanism of surface features frequently identified as shorelines. In particular, we perform model integrations involving parameters such as ice slope and purity, atmospheric pressure and temperature, crater shape and composition, and an energy balance between solar flux, geothermal flux, latent heat, and ablation. *Our ultimate goal is to understand how an intracrater ice plug could create the observed shoreline features and how these features and their formation mechanism would then preserve a quantitative record for Martian climate.*

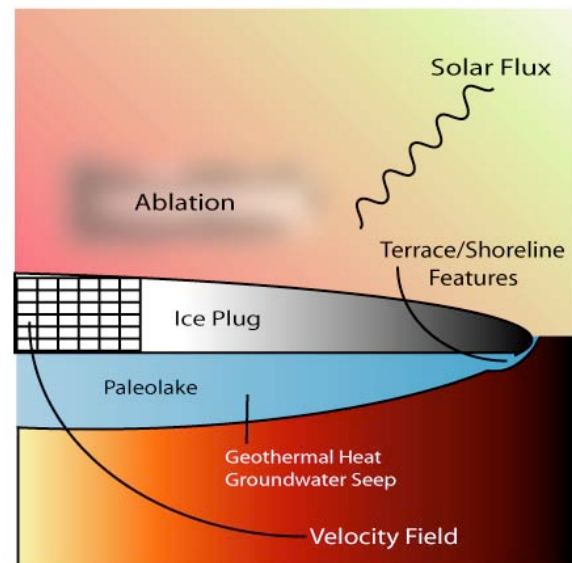


Figure 1: Schematic illustration of an ice-plug as a “shoreline” formation mechanism. Sources and sinks for energy and mass are indicated. Adapted from McKay et al. (1985) [5].

Ice flow is modeled by adapting terrestrial models used to describe ice flow across subglacial lakes to Martian conditions [11]. In short, the model determines the velocity field of a thermodynamically coupled two-dimensional ice sheet in radial symmetry. The sheet's flow is governed by equations that maintain force balance (1) and conservation of mass (2).

$$\bullet \quad 4\eta \frac{\partial^2 \mathbf{u}}{\partial r^2} + \eta \frac{\partial^2 \mathbf{u}}{\partial z^2} = \rho g S_0 \quad (1)$$

$$\bullet \quad \frac{\partial(qr)}{\partial r} + r \frac{\partial h}{\partial t} = \dot{a}r - \dot{b}r \quad (2)$$

Equation (1) describes the velocity (\mathbf{u}) at any point throughout the ice plug and communicates that velocity to adjacent points with subsequent model iteration. In equation (1) S_0 is the radial slope of the ice plug, ρ is the ice density, g is the acceleration due to gravity, and η is the effective viscosity of the ice. The effective viscosity depends on ice temperature, crystal orientation, impurity content, and the presence of Newtonian or non-Newtonian stresses as related by Glen's Law. Until further assessment, we will assume pure non-Newtonian stress in agreement with other studies [9].

Equation (2) is a mass balance equation, which states that ice flow is inextricably tied to basal freeze and ablation rates. The variable $q = \mathbf{u}h$ is the mean velocity at a particular radius and h is the total height of the plug at that radius. The time derivatives of (a) and (b) are the basal freeze and ablation rates respectively.

Once the velocity field is determined, modeling resultant shoreline erosion is relatively straightforward (see equation (3) below).

$$\bullet \quad L = \sqrt{\frac{mu^2}{\rho g h b (\sin \beta + \mu \cos \beta)}} \quad (3)$$

Equation (3), describes the maximum landward extent of ice that occurs when an ice mass' potential energy overcomes the friction associated with the shore [10]. The maximum landward extent, L , is dependent upon ice mass (m), ice velocity (u), ice density (ρ), ice thickness at the shore (h), shore width (b), shore slope angle (β), and the coefficient of friction (μ). After modeling the forcing of the ice plug (1) together with the maximum landward extent (3), we will present preliminary geomorphologic results.

Astrobiological Discussion: The exploration of potential sites of astrobiological interest on Mars is one of NASA's main directives. A primary goal for the next decade is the acquisition of sample returns from the most promising areas of astrobiological interest on Mars. Certain craters are identified as potential landing sites [13] because of the possibility

that they previously held water [1,2,12,14,15, and others]. Our model argues that, by comparison to an intracrater ice plug, lacustrine systems on Mars are rather transitory [3,4]. It is more probable, then, that life would have a greater opportunity to proliferate in an aqueous environment under an ice plug rather than in ephemeral lakes exposed to the myriad hostilities of Mars' surface: UV radiation, sub-arctic temperatures, and the extreme, oxidizing nature of surface chemistries [16].

Conclusion: The glacial geomorphology of crater features is a rich key to the Martian past, yet, despite the wealth of imagery, the interpretation of surface morphology lacks the insight and definition that a quantitative model would provide. Our model explores geomorphic systems that posit ice plugs as the formation mechanism for shoreline features. The development of a quantitative model that describes this system will provide new insights—climatic, hydrological, astrobiological—into Mars' history.

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