LAVA HEATING AND LOADING OF ICE SHEETS ON EARLY MARS: PREDICTIONS FOR MELTWATER GENERATION, GROUNDWATER RECHARGE, AND RESULTING LANDFORMS.

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Introduction: A broad range of geologic evidence [e.g. 1-5] has been interpreted to suggest that the surface/near-surface environment of Mars during the Noachian period was “warmer and wetter” [e.g. 6] than at the present. These interpretations conflict with results from climate modeling studies which predict a “cold and icy” early Mars climate characterized by the formation of regional ice sheets throughout the high elevation (above +1 km) regions of Mars [7-9]. The formation of these “icy highlands” regional ice sheets is predicted to occur during the transition from the Late Noachian to Early Hesperian (LN-EH) periods of Mars history, a time of dramatic change in the geologic and climate evolution of Mars [4]. This transitional period is characterized by changes in the dominant mineralogic weathering style [4], a sharp decrease in the evidence for flowing surface water [1], and a major peak in volcanic flux [10]. Volcanic activity during this period primarily involved the emplacement of the Hesperian Ridged plains (HRP), a series of effusive flood basalt deposits which resurfaced a significant portion of the martian surface during this time [11]. This LN-EH volcanic activity coincides in space and time with the formation of the predicted “icy highlands” ice sheets.

Here, we explore possible relationships between extensive LN-EH flood volcanism and predicted “icy highlands” ice sheets. Widespread interaction between volcanic activity and surface ice deposits during this time would have resulted in the formation of characteristic landforms [e.g. 12, 13] that may be preserved in the geological record. Observation of these features would provide information about the climate during the LN-EH transition by indicating the presence of surface ice deposits. Using Hesperia Planum (HP) as a type area, we develop a supraglacial ice sheet lava heating and loading model to quantitatively assess the thermal interactions and melting processes and to provide predictions for resulting landform generation. We apply the conceptual model to a study area within the HP region and compare predictions derived from the model to the observed geology.

Lava Accumulation Timescales and Thicknesses: The most important factors controlling the ice sheet lava heating and loading process are the timescale over which lava is accumulated, and the total thickness of lava deposited. The timescale for HRP emplacement has been estimated at ~100-200 Myr, with active eruptions occupying ~0.01% of this duration [14]. This is similar in nature to the terrestrial large igneous provinces which are generally analogous to the HRP in terms of scale, volcanic style, and eruption duration. Measurements of buried and partially buried craters within the HP region suggest lava thicknesses ranging from ~500 to 2,000 m [13]. Thicknesses of individual lava flows are not readily observable in the HP region, therefore we assess a range of flow thicknesses from 1-200 m, encompassing the range of observed lava flows thicknesses in terrestrial large igneous provinces [13].

Lava Heating: The emplacement of lava flows atop an ice mass results in conductive heat transfer from the superposed lava to the underlying ice, inducing top-down melting. Heat transfer and melting rates are estimated for the adopted range of lava flow thicknesses through the use of analytical solutions to the 1-D transient heat conduction equation [13]. Analysis of heat transfer as a function of lava flow thickness indicates that peak heat transfer rates decrease as lava flow thickness increase, but the duration of heat transfer, and therefore the total amount of melting, increases.

![Figure 1. Ice melted versus time [13] due to the emplacement of a series of lava flows (a) 10 m thick, and (b) 100 m thick.](image-url)

Following the emplacement of the initial lava flows (those emplaced directly atop the ice) subsequent lava flows will transfer much less heat to the underlying ice due to the intervening chilled initial lava flow. Thermal analysis results showing the amount of ice melted versus time following lava flow emplacement are shown for a sequence of three lava flows, each 10 m and 100 m in thickness (Figure 1). These results suggest that heat transfer from thin lava flows is rapidly limited because heat must be conducted through more chilled lava. Heat transfer from thicker lava flows is much more efficient and a series of only five 100 m thick lava flows could completely melt the upper-bound thickness of “icy highlands” ice sheets (~1 km) [15-16].

If the accumulating lava flows are relatively thin (~1-10 m), meltwater is nominally predicted to be absorbed into the ice sheet firn layer [17]. However, if the accumulating lava flows are very thick (>100 m) the lava will rapidly melt through the firn down into the impermeable ice mass. As a result, meltwater is predicted to collect around the lava flow and drain towards the ice sheet base or across the surface through gradual flow or by episodic flooding. Melting and
removal of meltwater causes subsidence of the superposed lava flows which will result in deformation and degradation of the lava flows leading to the formation of characteristic collapse-related features including: fracture systems, wrinkle ridges, depressions, and chaotic terrain.

Lava Loading: While continued accumulation of thick lava flows causes complete top-down melting of the predicted “icy highlands” ice sheets, continued loading of thin lava flows proceeds differently. In cases of thin lava flow accumulation, top-down melting will become negligible as lava flow accumulation continues and the total ice sheet thickness will not be greatly reduced. Instead, further lava accumulation will construct a thermally insulating cap above the ice sheet acting to raise the the ice-melting isotherm [18] causing cryospheric melting, and potentially inducing bottom-up ice sheet melting. We explore the effects of lava loading and ice sheet insulation through the implementation of a 1-D finite difference heat conduction model. We model two nominally end-member lava loading scenarios: (1) A crater interior scenario in which total ice and lava thickness are greater (1 km and 2 km, respectively) and lava accumulation is rapid (10 Kyr) [13]. (2) An intercrater plains scenario in which ice sheet and lava thicknesses are reduced (300 m and 500 m, respectively) and the lava accumulation timescale is greater (100 Myr) [13].

We find that the accumulation of ~2 km of lava in the nominal crater interior scenario provides sufficient insulation to raise the melting isotherm to the base of the superposed lava. This leads to complete bottom-up melting of the cryosphere over ~0.5 Myr, followed by “deferred melting” of the ice sheet (melting which initiates after lava accumulation has completed) over the next ~0.75 Myr. In contrast, in the intercrater plains scenario, there is not sufficient insulation to raise the melting isotherm to the ice sheet base and melting only takes place in the cryosphere.

Meltwater is nominally predicted to infiltrate into the porous mega-regolith substrate, but may collect at the base of the ice if the substrate is impermeable. Meltwater collected at the base of the ice sheet will be highly pressurized and may rupture confining material at the margins of the ice sheet leading to the release of flooding events. In either case, melting and removal of the buried ice will cause subsidence of the superposed lava flows leading to the formation of collapse-related features as previously outlined.

Example Application: We apply the ice sheet lava heating and loading model to a study area in northern HP centered approximately at 106.5 °E and 6.2 °S (Figure 2) to test the model predictions. Within this area are two craters flooded with up to ~2 km of HRP lava. Under the nominal crater interior scenario, this thickness of lava is predicted to accumulate rapidly (~10 kyr), and involve relatively thick individual lava flows (~100 m). This is predicted to cause rapid top-down melting of the entire ice sheet without significantly effecting the cryosphere. As a result, melt is predicted to collect around the lava flow sequence and drain towards the ice sheet base or across the surface through gradual flow or by episodic flooding. The predicted melting and drainage will lead to subsidence of the superposed lava sequence giving rise to collapse-related features and the formation of fluvial channels where meltwater emerges from the ice sheet margins. The study regions shows evidence consistent with this scenario (Figure 2): 1) Large fracture systems are observed within the volcanic crater fill. 2) A large fluvial channel is seen to emerge from the northwestern portion of Crater A.

Figure 2. Context image of the study area in northern HP [13] showing heavily fractured volcanic crater fill (Feature 1.), and an associated fluvial channel (Features 2. & 3.).

Conclusions: 1) Top-down melting generated by supraglacial lava emplacement and heating is limited unless lava flow thicknesses are very large (~>100 m). 2) Significant bottom-up melting from lava loading is only predicted to occur within crater interiors. 3) Melting of buried ice causes subsidence and deformation of superposed lavas leading to the formation of collapse-related features. 4) Geologic features observed in the study area include heavily fractured volcanic crater fill and an associated fluvial channel. 5) Lava-ice interactions are predicted to form a wide variety of distinctive aqueous/thermal mineralogic alteration products.