Cold-based glaciation at Pavonis Mons, Mars: Evidence for moraine deposition during glacial advance

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The three large volcanoes in the Tharsis region of Mars: Arsia, Pavonis, and Ascraeus Montes all have fan-shaped deposits (FSDs) on their northern or western flanks consisting of a combination of parallel ridges, knobby/hummocky terrain, and a smooth, viscous flow-like unit. The FSDs are hypothesized to have formed in the Amazonian during a period of high spin-axis obliquity which redistributed polar ice to the equatorial Tharsis region resulting in thick (>2 km), flowing ice deposits.

The ridged units in the FSDs are hypothesized to be deposited during glacial recession based on their similarity to terrestrial analogs in the Dry Valleys of Antarctica [1] and Iceland [2,3]. Crater age dates [4] suggest glacial recession took place slowly over hundreds of millions of years, but that recession episodically halted for a period of about a million years [4] in order to deposit an individual ridge. However, the 120 kyr periodicity in obliquity [5-7] is the most likely climate signal to influence the redistribution of ice and glacial dynamics. Therefore, there is an inconsistency between the million-year timescale attributed to ridge formation and the climate variation timescale. To investigate the process of ridge formation, we conducted numerical simulations of ice accumulation and flow using temperature and mass balance assumptions associated with Amazonian global circulation models [8] and laboratory experiments of ice sublimation under martian conditions [9].

We find that ice flow ceases during glacial retreat due to the reduction in ice thickness associated with the slow sublimation (0.5 mm/yr) of buried ice. Laboratory experiments of sublimation of buried ice supports this model assumption [9] as does the presence of remnant ice deposits within the Pavonis FSD. Because ice flow has ceased during glacial retreat, there is no mechanism to advect surface debris to form a ridge.

The model results, when combined with topography observations of a long sequence of ridges located interior of the Pavonis FSD, show that the ridged units were more likely deposited during one or more periods of glacial advance (instead of retreat) when surface temperature variations caused by 120 kyr periodicity obliquity oscillations propagated through the ice deposit resulting in a fluctuating ice flow rate. A model-derived ice flow rate of 3 cm/yr during glacial advance can deposit an average interior ridge in less than 100 kyrs if the supraglacial debris layer is two or more meters thick.

The pattern in ridge spacing observed at Pavonis Mons is more consistent with ridge deposition occurring during glacial advance. These ridges were overrun by the advancing ice, but remained preserved due to the cold temperatures at the glacier bed. Evidence supporting the preservation of ridges underneath an ice sheet comes from intersecting ridge sequences at Arsia and Pavonis [10], as well as the superposition of remnant ice (the smooth unit) on top of ridges.

Our hypothesis links the dominant, 120 kyr periodicity in obliquity to the time interval between adjacent ridges. By measuring the spacing between these ridges and dividing by the obliquity periodicity, we constrain the velocity of glacial margin to be between 0.2 and 4 cm/Earth yr - in close agreement with the numerical simulation. Furthermore, a comparison with a simulation conducted under terrestrial gravity confirms the prediction of steeper ice margins on Mars during glacial advance which may contribute to ridge deposition via mass wasting, although invoking mass wasting is not required by our hypothesis so long as the supraglacial debris layer is >2 m thick. This re-interpretation of the FSD ridged unit suggests that the timescale of FSD formation (and perhaps the duration of the Amazonian high obliquity period) was shorter than previously reported.

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