MARS HABITABILITY AND THE SIGNIFICANCE OF OBLIQUITY-DRIVEN COUPLING OF MAGMATISM AND ICE DEPOSITION: A CASE STUDY AT OLYMPUS MONS.

Alexander J. Evans[1] and Jeffrey C. Andrews-Hanna[1], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA, alex@lpl.arizona.edu.

Introduction and Background: Several lines of evidence suggest that water – an essential requirement for known life – was once abundant at the surface of Mars [1–8]. Yet despite the substantial evidence for the existence of water at the surface, early Mars may have been too cold for liquid water to have been continuously stable [1], and cold conditions appear to have dominated since the Hesperian. Several workers have attempted to reconcile this discrepancy by invoking episodic warming [8] of either the atmosphere or the ice, which could explain the ancient valley networks [2] and water-altered minerals [3,4]. The episodic presence of water across much of the surface also implies that Mars may have also have experienced episodic habitability.

Alternatively, episodically or continuously habitable environments on Mars may have existed for much of its history resulting from the interplay of long-lived magmatism [9-13] and obliquity-driven ice deposition [14,15]. Climate modeling of Mars [15,16] suggests that ice deposition at low latitudes likely occurred at periods of high obliquity ($\geq 45^\circ$) [14], leading to the preferential deposition of ice at a rate of up to several millimeters per year within the calderas and along the flanks of volcanic summits, such as those of Olympic Mons [15]. Given the obliquity period of ~120 kyr [14] and the timescale for construction of the volcanic edifices [17], the co-occurrence of glaciation and magmatism is highly probable.

Furthermore, if the stresses imposed on the magma chamber by the overlying ice are on the order of the magma chamber overpressure required to erupt basaltic lavas (~1 MPa) [18], glacial loading above magma chambers may have affected or modulated later eruptive activity, as has been suggested for Earth [18]. In such a scenario, observations of periodic bedding in volcanic materials that correlate with the modulation of the ~120-kyr obliquity period [19] may be evidence of previous cycles of glacial loading of a magma reservoir. Herein, we use Olympus Mons as a case study to examine subsurface magma reservoirs as a source of heat for the melting of ice deposits on Mars and the role of glacial loading on stresses around the magma chambers.

Modeling and Methodology: Using the COMSOL Multiphysics finite-element modeling code, we constructed a 2D axisymmetric model of the Martian lithosphere at Olympus Mons. We consider an 80-km thick lithosphere of density 2800 kg m^{-3} with a viscoelastic rheology that extends 900 km from the center of Olympus Mons. We loaded the lithosphere with the radially-averaged topographic profile [20] of Olympus Mons. Beneath the center of Olympus Mons, we included a 1270-K pressurized spherical magma chamber that is initially at equilibrium with the average pressure of the surrounding lithosphere. The magma chamber depth and radius are varied between 5 and 25 km, within the expected ranges for Mars [21]. The model includes gravitational loading [22] and lithostatic prestress [23] conditions assuming a mantle density of 3300 kg m^{-3}. We included a mantle heat flux into the crust (38 mW m^{-2}) and radioactive heat production within the crust (2×10^{-7} W m^{-3}) consistent with estimates for the early Hesperian [24]. Mesh elements are added and removed from the caldera surface according to the net ice accumulation curve of Figure 1b. The maximum thickness of the ice is 2 km and occurs at the caldera center.

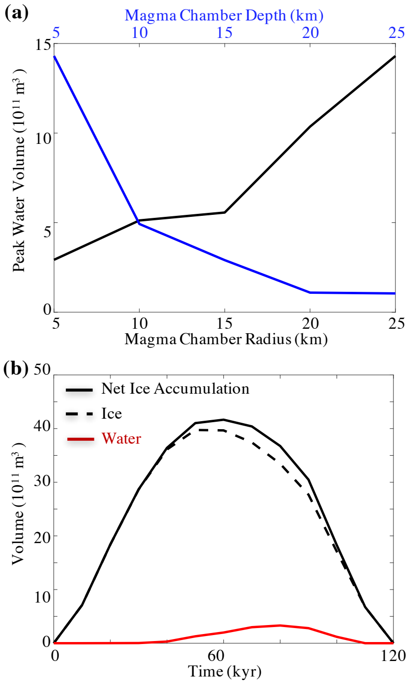

Figure 1. Ice accumulation within Olympus Mons caldera. (**a**) Peak water volume generated by melting of ice within the Olympus Mons caldera for a range of underlying magma chamber radii and depths, where chamber depths and radii vary between 5 and 25 km. (**b**) Net ice accumulation at Olympus Mons [15] (solid black) and the time-varying volume of ice (dashed black) and water (red) phases are shown for a magma chamber with a 25-km radius at a depth of 10 km. Maximum ice load thickness of 2 km occurs at the caldera center.

Effect of Magmatism on Melting Ice: For plausible ranges of magma chamber radii and depths, our results in Fig. 1a illustrate that ice deposition within the Olympus Mons caldera would likely result in the basal melting of ice, generating up to 1.5×10^{15} kg of water. In the specific case of a 25-km radius magma chamber that is 10-km below the surface of the Olympus Mons caldera (Fig. 1b), we find that it takes ~40 kyr for the overlying ice to begin to melt, with the peak volume of water occurring at ~80 kyr. Fig 1b. shows that obliquity-driven ice deposition could lead to the presence of water for at least 70 kyr of the 120-kyr obliquity period, although water storage in the subsurface may have allowed water remain within the caldera for a longer time interval.

Effect of Ice Loading on Magmatism: The radial and vertical stress change due to glacial unloading above a 25-km radius magma chamber 10-km beneath the surface of the Olympus Mons caldera is shown in Fig. 2a. For the same case, Fig. 2b shows the net change in the radial and vertical stresses at the top of the magma chamber. For this magma chamber, we find that the change in tangential (radial) stress at the top of the magma chamber exceeds 3 MPa. This single scenario highlights that the subsurface stresses imparted by glacial loading at Olympus Mons is sufficiently large, compared to the ~1-MPa overpressure required to erupt basaltic lavas [18], to have inhibited or modulated local extrusive activity and hence could conceivably lead to the obliquity-correlated, periodic bedding of volcanic deposits observed by [19].

Summary: Obliquity-driven ice deposition within low-latitude, high-altitude volcanic calderas may serve as a mechanism to systematically replenish water, potentially enabling past periods of long-term habitability. The ice deposited within calderas likely resulted in the melting of ice, generating water volumes of up to 1.5×10^{12} km^3 within a 120-kyr interval. The water generated would have persisted for 70-kyr of the 120-kyr obliquity period, and possibly longer if water flow into the warmer subsurface occurred.

Glacial loading of volcanic calderas would have also affected the eruptibility of basaltic magmas, possibly modulating the timing of volcanic activity. Accordingly, the periodic bedding observed within volcanic deposits [19] may be the consequence of prior glacial loading events within volcanic calderas.

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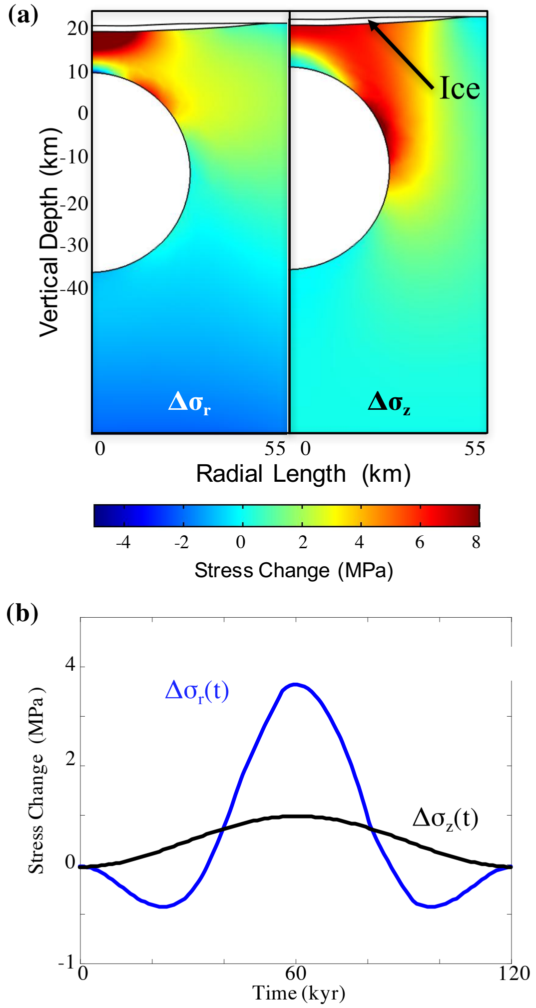

Figure 2. Stress results from axisymmetric model at Olympus Mons with a 25-km radius magma chamber at 10 km beneath the surface **(a)** Radial $\Delta\sigma_r$ (left panel) and vertical $\Delta\sigma_z$ (right panel) stress differences calculated during unloading (stress state at 120 kyr less the state at 60 kyr). Panels show upper lithosphere of Olympus Mons extending radially from the center of the caldera at 0 km to the rim of the caldera at ~55 km (model domain extends radially to 900 km). Magma chamber (white half-circle) is shown. Stresses are not modeled within magma chamber or ice. Tensile stresses are defined to be positive. (**b**) Time-dependent radial (blue) and vertical (black) stress change at the magma chamber crest.