Martian North Polar Cap: Compositional Constraints and Geodynamical Response.

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Introduction: While radar data has been able to provide a compositional constraint on the north polar layered deposits (NPLD) [e.g., 1], the bulk composition of the underlying basal unit (BU) has been difficult to ascertain. The BU is a low-albedo, sand-rich ice deposit lying stratigraphically between the NPLD and the underlying Late Hesperian aged Vastitas Borealis Interior Unit [2]. The BU represents a time before formation of the modern ice cap, therefore, understanding its composition may provide insights into more ancient epochs of Martian climate history.

Here, we utilize the available Martian gravity and topography data to constrain the bulk density of the north polar ice cap. We then combine the gravity-derived bulk density estimates with previously published radar data [3] to isolate the bulk density and composition of the BU. The density estimate of the north polar cap also allows us to estimate the stress imposed by the weight of the polar cap on the underlying lithosphere. We model the response of the lithosphere to the stress imposed by the north polar cap and estimate of the present-day mantle heat flow in the north polar regions of Mars. Mantle convection influences crustal tectonics and volcanism, thus, constraining the thermal state of a planet's mantle is important for understanding planetary thermal evolution.

Methods: ***(Density of the polar cap)*** The gravity field of a planet can be used to invert for geophysical properties such as the density of a surface load and elastic thickness of the lithosphere. This is typically done by examining the transfer function between gravity and topography (called admittance) in the spectral or spatial domain. In this work, we first localized the gravity and topography signature of the north polar ice cap by multiplying the global gravity and topography fields [4] of Mars by a localization window in the spatial domain. Localized admittance functions from our region of interest are compared with forward models to constrain the density of the north polar cap. The forward models were constructed by assuming that the lithosphere is a thin shell that deforms elastically in response to surface loads. By combining the results from gravity inversion with radar derived thickness maps, it is possible to estimate the density/composition of the BU. Previously, similar techniques have been used to constrain the density of the south polar cap of Mars [5].

(Mantle heat flow) The lack of appreciable lithospheric deflection in the north polar region of Mars by the weight of the polar ice cap is suggestive of low heat flow [6]. Here, we place an upper limit on the local mantle heat flow in the north polar region of Mars by modeling the flexural response of the Martian lithosphere to the stress imposed by the weight of the north polar cap using state-of-the-art finite element techniques. We use the commercially available Marc-Mentat finite element package (http://www.mscsoftware.com) to model the flexure of the lithosphere under various thermal and mechanical conditions. We treat Planum Boreum (PB) and Gemina Lingula (GL) as axisymmetric distributed loads emplaced on top of the Martian crust. We input the 2D stress profiles from PB and GL into finite element models to constrain the heat flow required to produce the roughly 100 – 200 meters of deflection observed in radar data [6]. The finite element modeling consists of three parts: i) building a finite element mesh, ii) running a thermal simulation, and, iii) running a mechanical simulation. All three aspects of the model are run in Marc-Mentat finite element package/ .

Results: ***<u>(Density of the polar cap)</u>*** We found two windows within the north polar ice cap with sufficient gravity-topography correlation to allow density estimation. For each location, we ensured that over 99% of the gravity and topography signals was from within our region of interest. Figure-1 shows an example of one such location where we used angular radius of 7° and a harmonic bandwidth of 37. Here, the comparison between observed and the synthetic admittance was conducted over the spherical harmonic degree of 46 and 59, where correlation is above 0.7 (Fig. 1 (b)). The best fit load-density within 1-σ of the observed admittance corresponds to 1205 $\pm$ 145 kg m^{-3} for any T_e greater than 75 km. To ensure that our estimates are devoid of biases from gravity models and regional gravity setting, we use multiple localization windows, techniques, and gravity models. The results from different datasets, locations, and gravity models do not vary significantly and yield an average bulk density of 1,126 $\pm$ 38 kg m^{-3} [7]. Combining the bulk density estimates with radar-derived thickness maps of the polar units, we find the density of the BU to be 2,050 $\pm$ 450 kg m^{-3} [7].

<u>(Mantle heat flow)</u> We first consider a scenario in which we set the crustal heat flow (q_c) and lithospheric mantle heat flow (q_m) to zero and only vary the heat flow provided by the lower mantle to the base of the lithosphere (q_b). This is a non-physical scenario as both the crust and lithospheric mantle can be large sources of planetary heat. However, this scenario enables us to place an upper limit on q_b. Using hydrous rheology, crustal thickness of 35 km, and thermal conductivity of 3 and 4 W m^{-1} K^{-1} for the crust and mantle respectively, our models show that q_b higher than 7 mW m^{-2} leads to lithospheric deflection larger than 100 m at Gemina Lingula and 200 m at Planum Boreum (Fig. 2). For a thick (>350 km) stagnant lid such as expected in present-day Mars, the heat produced in a thin crust (~35 km), as expected in the north polar region from gravity data [8], has a minor influence on the magnitude of the lithospheric deflection (Fig. 2). To verify this, we set q_c to 13 mW m^{-2} and found the crustal heat flow to have a negligible influence on the magnitude of the lithospheric deflection (Fig. 2). There are several different parameters involved in our models such as conductivity, density, rheology, and thickness of the crust and mantle, however, reasonable variations in these parameters do not significantly affect our upper limit of the mantle heat flow. A comprehensive discussion of the various parameters and their effect on our mantle heat flow will be presented at the meeting.

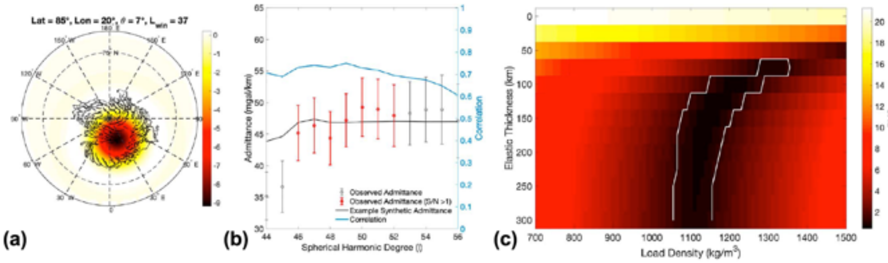

Fig. 1. (a) A single taper of L_{win} of 37, localized within the geographical boundary of the north polar ice cap centered at 85°N and 20°E. The color scale shows the magnitude of the taper. (b) Admittance spectrum and correlation spectrum of the region shown in (a). The admittance is plotted in gray where the correlation spectrum is below 0.7 (S/N < 1). The vertical bars show error associated with the admittance estimates.

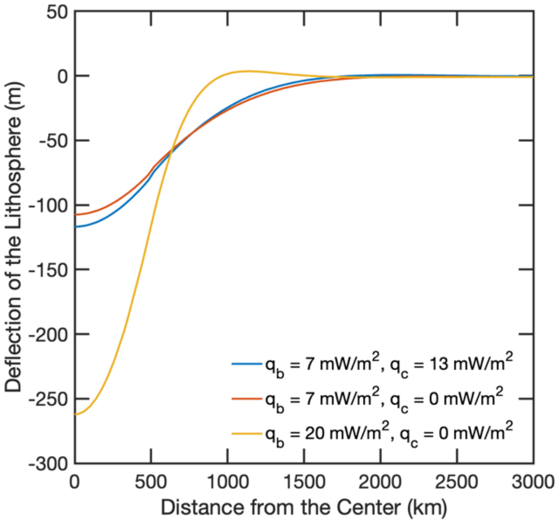

Fig. 2. Lithospheric deflection expected from the weight of Gemina Lingula for various values of q_b and q_c.

Discussion: The relatively higher density of the BU compared to the overlying NPLD confirms the findings of previous studies in that the two units have remarkably different compositions [2]. The relatively lower density of the BU compared to basaltic dust (~3200 kg m^{-3}) suggests the BU to either contain a large amount of air or ice within its pore space. Assuming the density of H_2O ice and lithics to be 930 kg m^{-3} and 3200 kg m^{-3} respectively, our best-fit density estimate (2050 $\pm$ 450 kg m^{-3}) requires the BU to be composed of 31 – 71 % H_2O ice. The bulk dielectric constant of the basal unit in Olympia Planum is equivalent to a mixture of 38% basalt and 62% water ice, whereas, in the main lobe of Planum Boreum, water ice is the dominant fraction (80% - 90%) of the basal unit [3]. Our average density of the BU is thus in general agreement with the radar results.

We find that the mantle heat flow likely does not exceed 7 mW m^{-2} in the northern polar region of Mars. The mantle heat flow constraints from our models are lower than values predicted by numerical thermal evolution models that assume the abundances of the heat producing elements in the Martian interior to be relatively proportional to the chondritic values. This implies that either the bulk abundance of the heat producing elements on Mars is lower than expected from the chondritic model, that a larger proportion of the bulk HPE has been fractionated into the crust, that there are large-scale spatial heterogeneity in mantle heat flow, or any combination thereof. If the tentative upper limit on the mantle heat flow from our work is globally representative of Mars, then the strong fractionation between the crust and mantle on Mars may have precluded the mantle from undergoing late-stage widespread melting, significantly affecting the geological history of Mars. Future gravity investigation of the polar caps, thus, has the potential to significantly advance our understanding of the ancient Martian climate and geophysical evolution.

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