VISCOELASTIC FINITE-ELEMENT SIMULATIONS OF THE FLEXURE UNDER THE NORTH POLAR CAP OF MARS. A. J. Dombard[1] and R. J. Phillips[2], [1]Dept. of Earth & Environmental Science, Univ. of Illinois at Chicago, 845 W. Taylor St. (MC-186), Chicago, IL 60607 (adombard@uic.edu), [2]Planetary Science Directorate, Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, CO 80302 (roger@boulder.swri.edu).

Introduction: The north polar plateau of Mars, named Planum Boreum (PB) and consisting of the North Polar Layered Deposits (NPLD) and the underlying Basal Unit (BU), represents a substantial load on the underlying lithosphere, so it was a surprise when analysis of data from the Shallow Radar (SHARAD) aboard the Mars Reconnaissance Orbiter (MRO) revealed the rocky surface (likely the Vastitas Borealis formation [VBF]) at the base of the NPLD to be undeflected, to within the measurement error (~100 m) [1]. Support of this load without obvious flexure necessitates a thick mechanical lithosphere. Phillips et al. [1] determined that the effective elastic lithosphere thickness (T_e) must be greater than 300 km at present, thicker than previous estimates elsewhere on Mars. By means of moment-matching techniques, Phillips et al. [1] converted this T_e into a thermal profile, finding that the bulk composition of heat-producing elements (K, U, Th) of Mars is only ~70-80% that of the ordinary chondrite meteorites (~20-30% subchondritic).

A difficulty with using elastic lithospheric models to investigate the response of planets to loads is this conversion to a thermal profile. For instance, the moment-matching technique used by Phillips et al. [1] entails construction of a Yield Strength Envelope (YSE) and thus requires an estimate of the effective strain rate for the viscous creep at the base of the YSE. In that analysis, a strain rate of 10^{-14} s^{-1} was used, consistent with the loading rate for a 5 Myr age of the NPLD based on climate modeling [2]. Here, we employ finite-element techniques to study the viscoelastic response of Mars to the PB load. Such methods bypass the above difficulties, because the thermal state is directly input into our simulations, and the lithosphere naturally develops with a variable strain rate in response to thermal and mechanical state of the system. The thermal profile, and thus strain-rate, has a dominant influence on the mechanical, and hence effective elastic, thickness of the lithosphere.

We find that it is possible to limit the deflection of the surface to less than ~100 m if the crust and mantle in the northern hemisphere of Mars are subchondritic and if the heat-producing elements are strongly fractionated into the crust under PB. We propose that such fractionation may be a consequence of deep melting associated with the formation of the crustal dichotomy via a large impact on ancient Mars [3-5].

Methods: We use the MSC.Marc finite-element package, which we have used many times to study lithospheric dynamics throughout the solar system [6-8]. We simulate an axisymmetric, planar system with a 35-km thick crust (density of 2900 kg m^{-3}) over a mantle (density of 3500 kg m^{-3}). Given the horizontal scale of the load, planetary curvature is not significant. The side and bottom boundaries are placed far enough away to not affect the mechanical solutions, and the simulated space is divided into 8000-10000 elements. The basic procedure involves first obtaining a thermal solution and then piping those results into a mechanical solution for the flexure under PB.

Thermal Solution. We find the balance between a surface temperature (always 155 K), basal heat flux, and radiogenic heat production. Our base state uses the nominal thermal structure at present, as determined by Hauck and Phillips [9], adapted for the thinner crust and lower surface temperature of the north polar region. When we consider a subchondritic Mars, we reduce the basal heat flux and the heat production in the crust and mantle by a prescribed fraction. Cases investigating fractionation of heat-producing elements maintain the total heat production through the crust and ~1800 km of mantle material. The thermal conductivity of both the crust and mantle is 4 W m^{-1} K^{-1}.

Mechanical Solution. Here, we find the quasi-steady state (inertial terms are negligible) balance between the PB load, the strength of the lithosphere, and buoyant restoring forces (included as part of the adopted large-strain formulism). The boundary conditions are free-slip on the sides, a Winkler restoring force on the base, and a distributed load on the surface equivalent to a cosine-shaped polar cap 500 km in radius with a maximum height of 2 km (density of 1000 kg m^{-3}), fully grown at the start of our simulations. Gravity is applied with an acceleration of 3.71 m s^{-2}.

The rheology is viscoelastic. The elastic Young's modulus and Poisson's ratio in the crust are 65 GPa and 0.25, and 140 GPa and 0.25 in the mantle. A viscous flow law for wet [10] and dry [11] Maryland diabase is used in the crust, and we adopt wet and dry flows laws of olivine [12]. For numerical expediency, we limit the minimum viscosity to 10^{21} Pa s. Ostensibly, we should also include plasticity, a continuum approximation of discrete brittle faulting; however, the

small degree of curvature limits the magnitude of the bending stresses such that brittle failure is minimal.

Results: Our starting case, using a wet rheology and adapting the current thermal state of Mars as modeled by Hauck and Phillips [9], experiences several hundred meters of displacement at 5 Myr. The flexure develops quickly; in only 100 kyr, it reaches ~90% of the displacement at 5 Myr. This rapid response is a general result and argues against the possibility that the lack of observed flexure under PB is because the response time of the lithosphere is longer than the assumed age of the cap (5 Myr), as also determined by Phillips et al. [1]. This rapid response also mitigates the unphysical nature of our instantaneously emplaced PB load. Were it to grow over 5 Myr, the lithosphere would respond largely in step with the growth.

Following [1], we test a subchondritic Mars by scaling the basal heat flux and heat production back to 70%. The simulation with a wet rheology still produces ~190 m of displacement at 5 Myr, while a dry rheology yields ~140 m. These results indicate that simply assuming a subchondritic Mars is insufficient.

But the northern hemisphere of Mars may not simply be subchondritic. The notion that the crustal dichotomy is a product of a large ancient impact early has recently been reinvigorated [3-5]. A result of impact modeling is that the northern hemisphere experienced deep melting [4, 5]. Given that K, U, and Th are lithophilic, fractional crystallization of the northern hemisphere's crust could have resulted in a strong enrichment of heat-producing elements in the crust, and a complementary depletion of the mantle.

Thus, we consider the chondritic case of 50% depletion of the mantle, which results in an ~15-fold enrichment of the crust. While the thermal gradient in the crust is now very steep, the mantle gradient is far shallower, which drags lower temperatures to deeper levels, with the expectation of thicker lithospheres. Indeed, a chondritic Mars with this strong fractionation and a dry rheology is ~130 m at 5 Myr, much less than for an unfractionated chondritic Mars but still insufficient. Thus, we also simulate a 70% chondritic Mars with strong fractionation. Here, the displacements at 5 Myr for the wet and dry cases are ~110 m and ~90 m, within range of the SHARAD errors.

Discussion: The conclusions that we draw are 1) the crust and mantle beneath PB (if not the whole planet) are subchondritic, and 2) some process strongly fractionated heat-producing elements into the crust in the north polar region, a giant impact being the most obvious mechanism. Thus, the minimal flexure under PB may be corollary evidence for a Borealis Basin.

Technically, our results also indicate that the crust and mantle are dry, which could also be a natural consequence of the formation of the Borealis Basin. We do not, however, consider this result to be robust. The amount of displacement in the wet case (~110 m) is close enough to the limit to be acceptable, especially since our planar simulations do not include membrane support, which we estimate to add ~10% support.

Moreover, we do not consider our numbers for the degree to which the region is subchondritic or the depletion of the northern mantle to be robust. They are just guesses without supporting modeling, and it is certainly conceivable that a chondritic northern hemisphere with stronger fractionation (> 50% mantle depletion) or an unfractionated northern hemisphere in a more subchondritic northern hemisphere (> 30%) could result in suitably low amounts of flexure. There are likely limits, however, to how subchondritic the planet or how depleted the mantle can be. Our results indicate that at the levels we investigate, either condition by itself is insufficient.

This strong fractionation also provides an explanation for why such thick elastic lithospheres (~300 km) are not found anywhere else on Mars. The degree of fractionation would have been strongest near the center of the Borealis Basin, in the vicinity of the north polar region. At lower northern and at southern latitudes, there would be greater heat production within the mantle, resulting in thinner lithospheres. A gravity/topography spectral study of the flexure caused by the South Polar Layered Deposits found a best-fit T_e of ~140 km, less than half the value at the NLPD, though any value > 102 km satisfies the observational constraints [13]. Phillips et al. [1] used the SPLD substrate topography mapped by the MARSIS radar [14] to estimate a T_e lower bound of 275-300 km, although observation of substrate flexure is confounded by rough topography in the Southern Highlands.

Thus, there appear to be large lateral variations in the thickness of the lithosphere of Mars, an idea also advanced by others [15, 16]. Such variations could be due, at least in part, to the presence of large lateral gradients in the composition of the mantle of Mars.

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