The role of Subsurface Ocean Freezing in the Stress State of Pluto’s Ice Shell. A. L. Nguyen1 and P. J. McGovern2, 1Washington University in St. Louis, St. Louis, MO, 63130, 2Lunar and Planetary Institute (USRA), Houston, TX, 77058.

Introduction: During the New Horizons’ encounter of Pluto in 2015 [1], high-resolution imaging data led to the production of stereographic topography [2]. Studies showed that the surface lacked compressional features [3] and was dominated by extensional stress regimes [1, 4, 5].

Recent work [5] has described the deformation and faulting around the Sputnik Planitia (SP) impact basin as primarily radially normal (propagating orthogonal to the rim of SP basin). The presence of widespread extensional deformation across Pluto’s encounter hemisphere may be aided by the freezing of a subsurface ocean at the base of the shell that pushes the lithosphere up and causes global expansion [6, 7].

The extent that ocean freezing affects the stress state of the lithosphere is not well-understood. No prior work has attempted to quantify the magnitude to which ocean freezing contributes to the stress budget of the shell. Through numerical [5] and analytical [8] modeling, we seek to quantify the stresses in the shell induced from shell thickening due to freezing and examine how this interacts with other mechanisms such as the N2 ice-loading of the SP basin.

Methods: Numerical Models. We used Finite Element Method (FEM) axisymmetric spherical shell-loading models adopted from [5] in COMSOL MultiPhysics to explore the stress magnitudes associated with different shell and loading scenarios over various shell thicknesses (30 to 70 km from [5, 9]). To study subsurface ocean freezing, we added a uniform pressure parameter, $P_c$, to the ocean-shell boundary (OSB).

To quantify the maximum stress contributions of each type of loading (basin topography, basin and compensation, and N2 ice loading) in isolation, we input a value of 0 Pa for $P_c$ in the shell with no variation or N2 ice loading (uniform), only basin topography (basin), and the shell with basin topography and isostatic compensation of the subsurface ocean (compensated) cases. We ran the fully solved N2 ice loading basin and the N2 ice loading basin and compensation models with 0 Pa for $P_c$ to determine the maximum radial and out-of-plane stresses.

Given these stress maximums, we performed a parametric sweep of potential fractions (0 to 125% at 25% steps) (“Input Stress Vector” in Table 1) of the stress maximums that could be added to the OSB due to subsurface ocean freezing.

We seek models with stress states that predict fault orientations and extents that match the observed preponderance of normal faulting oriented radially to the SP basin, and reject models that predict fault regimes of significantly different mechanisms and extents.

Analytic Models. We adapted a model of shell thickening and corresponding stress [8] to Pluto freezing conditions for a range of shell thickening, $\Delta t_c$, (0 to 5 km at a .2 km step) at various initial shell thicknesses, $t_c$ (30, 50, and 70 km based on [5, 9]) and calculated the horizontal stress components. To understand the relationship between shell thickening and the horizontal stress components, we used the baseline 10 kPa [10] on a uniform shell to calculate the regression. Using this regression, we then input our stress vectors (Table 1) determined by numerical modeling [5, 9] to find the corresponding shell thickening.

Results: Numerical Models. For our successful uncompensated and compensated basin models (Fig. 1), as $P_c$ increases, the predicted faulting becomes increasingly radial normal, the stress magnitudes increase, and the depth of failure into the shell increases.

Analytic Models. Our model results (Table 1) show an increase in crustal thickening from freezing as a function of $P_c$. With successful models having 1.1 – 1.7 km shell thickening and 0.5 – 0.9 km shell thickening for C50N and C70N, respectively.

Table 1: Input stress maximums and corresponding crustal thickening [8] for our model suite. Note. 1-letter prefix of model names refer to uncompensated or compensated initial basin topography, the 2 digits following represent the far-field elastic shell thickness, $T_c$, in km and the N refers to the nominal case of a pan-shaped basin with an initial depth of 3 km and no crustal collar buoyant load [5].

Discussion: Subsurface ocean freezing at the OSB adds an isotropic component to the horizontal principal stresses in the shell. Thus, the magnitude relationship between the horizontal stresses does not change, and the only changes in fault regime [12] will occur with respect to the relationships of the horizontal stresses with the vertical stress. For example, ocean freezing stresses
raise the magnitudes of both horizontal stress components above that of the vertical component (Fig. 1B), thereby changing the far-field fault regime from strike-slip (green) to radial normal (yellow) in Fig. 1A and C, while maintaining the status of the radial component as the most extensional (which controls the normal fault orientation). This model ($T_e = 50$ km, compensated basin topography) provides a prediction of entirely radial normal faulting in the region beyond the SP basin without needing to invoke trans-tensional failure in a nominal strike-slip zone [e.g., 5]. High values of added stress (100% of loading maximum in Fig. 1C) can predict pervasive failure of the upper shell, in conflict with the moderate amount of observed faulting around SP, but lower amounts (e.g., 50%, 75% in Fig. 1C) can provide the advantage of the absence of concentric normal or strike-slip regimes with more reasonable extents of failure.

**Figure 1:** Visualizations of stress state and fault type characterization parameter $A_v$ for 2 models of SP loading with superposed basal ocean freezing. (A., D.) Wedge plots show a bird’s eye view of $A_v$ [11] at the surface for 6 different model results by sweeping through the stress fraction parameter. Moving counterclockwise over each wedge shows increasing $P_e$. The gray area represents extent of SP, and the distance on the bottom axis represents surface distance away from SP. (B., E.) Stress profiles are at the surface of the shell and display normal stress components $\sigma_h$, $\sigma_l$, and $\sigma_v$ representing out of plane, in-plane horizontal, and vertical directions corresponding to blue, red, and black colors, respectively. Positive values of stress mean extension, and negative values mean compression. (C., F.) Simpson $A_v$ fault and extent of failure profiles/cross sections [11]. The color bar is from [5], and the black contour represents the depth and extent of failure, as determined by the achievement of the Mohr-Coulomb failure criteria. A., B., and C.: model C50N. D., E., and F.: model C70N.

The addition of freezing stresses to the shell do not significantly expand the parameter range of successful stress models compared to previous work [5]. For example, models rejected based on excessive stress levels (e.g., the low $T_e$ models of [5]) will not benefit from increased shell stresses. Further, models rejected based on fault types not observed around SP (e.g., the high $T_e$ models of [5] that predict substantial normal faulting in circumferential geometry) are not benefited by addition of isotropic shell extension because the orientation-determining relationship between the relative stress magnitudes [12] is not changed.

**Conclusions:** By implementing freezing stress in our basin-loading models, we found bounds on the amount of shell thickening from ocean freezing, the amount of maximum applied stress in the form of said freezing, and improved potential ranges for Pluto’s shell thickness.

Our results suggest that there is a role for the subsurface ocean freezing stress applied to the OSB of Pluto, and that accounting for it improves our understanding of scenarios for the development of the observed fault systems around SP.

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