ICY SHELL STRESS STATES CONSISTENT WITH HEMISPHERIC-SCALE RIFTING ON RHEA, TETHYS, AND DIONE.
P. J. McGovern [1] P. K. Byrne[2], P. M. Schenk[1], and G. C. Collins[3], [1]Lunar and Planetary Institute, Universities Space Research Association, Houston, TX 77058 (mcgovern@lpi.usra.edu), [2]Planetary Research Group, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695, [3]Department of Physics and Astronomy, Wheaton College, Norton, MA 02766.

Introduction: Saturn's mid-sized icy moons Rhea, Tethys, and Dione (collectively, RTD) all exhibit approximately north-south-oriented rift zones (or "chasmata"), concentrated in the moon's trailing hemisphere (on Rhea and Dione) or passing through the sub-Saturn point (on Tethys) [1]. The highly spatially concentrated distribution of extensional strain on these bodies can thus be characterized as having a strong "degree 1" component (i.e., a maximum and a minimum in a planetary circumference), with possibly a weak "degree 2" component (two maxima alternating with two minima) on Dione. Scant evidence is seen of a complementary compressional stress state of magnitude large enough to trigger crustal shortening on these moons. Further, no evidence is seen of strike-slip deformation that would result from horizontal orientations of the greatest and least principal normal stresses.

Here we consider physical mechanisms that might produce stress states in icy satellite lithospheres that are consistent with the observed surface strains. We assume that the lithosphere comprises only the outermost (coldest) layer of an icy moon, such that a shell is an appropriate modeling geometry. Our objective is to create models exhibiting east-west oriented extensional stresses over large fractions of their surface area, ideally for one hemisphere only (a degree-1 pattern).

Models: To evaluate stress state scenarios compatible with these observed strains, we constructed numerical models of a Dione-sized moon (radius R = 561 km) with the COMSOL Multiphysics finite-element code. These elastic models feature an icy lithosphere shell overlying an inviscid layer. Symmetry planes allowed calculation of the response of an entire moon with 1/8 and 1/4-sphere geometries, capable of handling loads up to degrees 2 and 1, respectively. Ice shell thickness variations were assumed to be isostatically compensated in order to calculate surface topography and shell basal relief. We also superpose stress from de-/re-spinning via appropriate perturbation to the gravitational acceleration [2]. We used a nominal shell thickness T_e of 50 km, although results for thinner shells are similar.

Results and Discussion: A 1/8 shell model with a (degree 2) shell thickness variation of form k cos(2 λ), where λ is latitude, shows similar stress patterns to the pure despinning case for positive k (thickening at the equator), but negative k (thinning at the equator) produces east-west-oriented principal extension over all but the polar region, and north-south-oriented principal compression everywhere (Fig. 1). This combination, under standard "Andersonian" criteria [3] yields a prediction of strike-slip faulting that is inconsistent with observations on RTD.

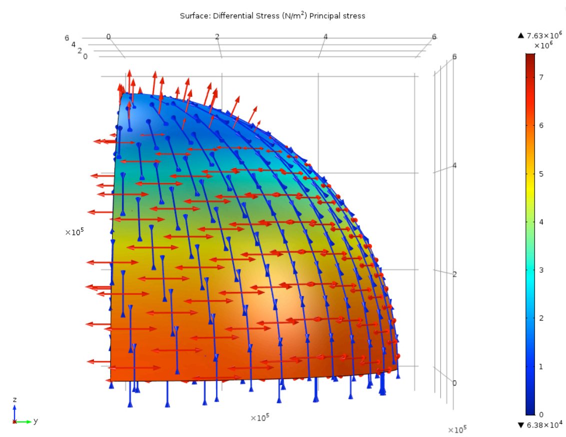

Figure 1. Differential stress (color scale with maximum at 7.63 MPa) and principal stress orientations (blue bars = most compressional principal stress axis; red arrows = least compressional axis) for a spherical shell model with degree 2 shell thickness variation (thicker at poles). Vertical (z) axis is rotation axis.

In contrast, 1/4 shell models with a degree 1 shell thickness variation (thickest and thinnest points on the equator) produce a zone of horizontal principal extension and vertical principal compression (i.e., a normal faulting regime) in the thick-crust hemisphere. The principal extension direction is oriented circumferentially about the maximum shell thickness point (Fig. 2), rather than having an east-west orientation as indicated by the north-south oriented normal faults seen on RTD. However, superposition with a stress state that exhibits east-west extension could produce a zone of elevated stress magnitudes around the point with thickest crust with east-west oriented extension, consistent with observations at RTD. Such stress states include those from spin-up (the complement to that shown by [2]) or from a degree 2 shell thickness variation in shell thickness that is thicker at the poles (Fig. 2.)

Degree 1 vs. 2: The observed distributions of tectonic strains at RTD show strong biases towards extensional and degree one (hemispheric) signatures. Extensional stress states are well known properties of elevated, compensated terrain (e.g. continents and crustal plateaus) that tends to spread outward. Models with degree-1 shell thickness variations produce a normal faulting regime in the thick hemisphere, consistent with this picture. Such results suggest that RTD rift systems form where shell thickness is greatest for each moon. However, the circumferential orientation of principal extension around the maximum thickness point is not a good match to the predominantly north-south-oriented chasmata at RTD. Further, compression in the opposite (thinner-shell) hemisphere is not consistent with any observed fault systems on RTD, although several mechansms (e.g., shell freezing/thicknening or thermoelastic stress) may account for a tensional stress bias in icy satellite lithospheres that would inhibit thrust faulting (and facilitate normal faulting) [4].

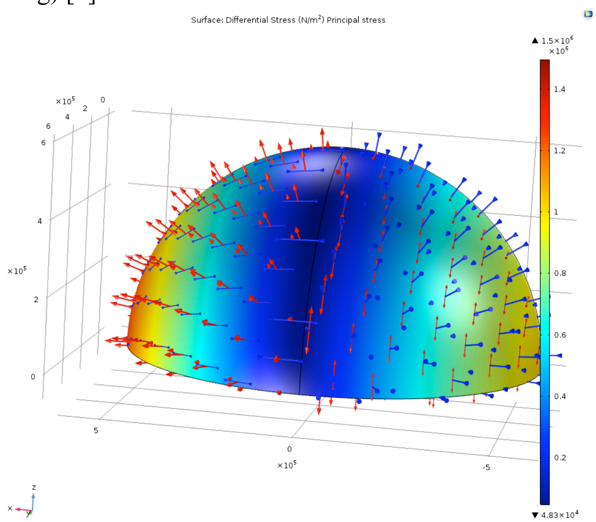

Figure 2. As in Fig. 1, for model with degree 1 shell thickness variation (thicker at right, thinner at left). Stress scale maximum is 1.5 MPa.

Degree 2 loadings such as de-/re-spinning stress and k cos(2 λ) shell thickness variations, although capable of producing horizontal extension, most often generate strike-slip regime stress states (Fig. 1) that are inconsistent with observed normal faulting. Scenarios of respinning and polar-thickened shells (negative k) in particular produce the east-west-oriented principal extension needed to produce north-south-oriented chasmata zones, but still suffer from exhibiting the wrong fault regime. More advanced stress tensor analysis [5] and inclusion of effects from initial stress state and time-dependent loading [6,7] may reduce the predicted extent of pure strike-slip mode faulting in such regions, but they are not likely to host strongly defined rift zones of the type seen at RTD. However, superposition of one of the the east-west extension-inducing degree-2 modes described above with the degree 1 shell thickness variation produces a zone of elevated differential stress combining the east-west extension of the former with the normal faulting stress regime of the latter near the center of the thicker portion of the shell.

Rhea and Tethys exhibit somewhat simpler and more spatially restricted rift systems than Dione [1]. Rhea's system has an orientation closest to north-south, and is centered near the center of the trailing hemisphere. The Tethys chasma is rotated slightly clockwise from north-south, and is centered near the sub-Saturn point. A degree one shell thickness origin for the Tethys rift system would have the associated center-of-mass to center-of-figure (COM-COF) offset oriented along the tidal axis, as seen at Earth's Moon [8], but for Rhea such a scenario would require the offset to be aligned perpendicular to the tidal axis, strongly departing from the minimum energy state [9]. We suggest that the original orientation of Rhea was changed by mechanisms including non-synchronous rotation (NSR) and relaxation of shell thickness variations (to avoid minimum energy problems in the current configuration).

At Dione, the rift system has greater spatial extent along and across strike and greater directional complexity. The system is roughly centered at 25°N, 80°E. A Rhea-like scenario would place this center originally at the sub-Saturn point, with NSR moving it in longitude and a small amount of polar wander moving it up to its current latitude. Alternatively, a spin-axis alignment of the COM-COF offset (similar to that of Mars [10] and possibly Enceladus, given expected variations in shell thickness [11]) would put the rift center at the north pole, where subsequent polar wander (rotating about the tidal axis, as expected [4]) would reduce the latitude of the center to its current value. Note that the radial orientation of several "spurs" of the Dione rift system to the proposed center is more consistent with a more purely degree-1 based scenario (Fig. 2, with "circumferential" principal extension) than those proposed here for Rhea and Tethys, which need the degree 2 contributions (Fig. 1) to produce one dominant (north-south) orientation.

References: [1] Byrne P. K. et al. (2015) *LPS, 46*, abstract #2251. [2] Melosh H. J. (1977) *Icarus, 31*, 221-243. [3] Anderson, E. M. (1936) *Proc. R. Soc. Edinburgh, 56*, 128. [4] Collins G. C. et al. (2010) in *Planetary Tectonics*, Cambridge University Press, 518 pp., Chapter 7. [5] Simpson R. W. (1997) *JGR, 102*, 17,909-17,919. [6] McGovern P. J. and Solomon S. C. (1993) JGR *98*, 23,553-23,579. [7] Freed A. M. et al. (2001), *JGR, 106,* 20,603-20,620. [8] Smith D. E. et al. (2010) *GRL, 37*, L18204. [9] Aharonson O. et al. (2012) *Icarus, 219*, 241-243. [10] Smith D. A. et al. (2001) *JGR 106*, 23,689-23,722. [11] Olgin J. G. et al. (2011) *GRL, 38*, L02201.