CONSTRAINING THE HEAT FLUX *BETWEEN* ENCELADUS' TIGER STRIPES: NUMERICAL MODELING OF FUNISCULAR PLAINS FORMATION. M. T. Bland and W. B. McKinnon, Department of Earth and Planetary Sciences and McDonnell Center for Space Sciences, Washington University in St Louis, MO 63130 (mbland@levee.wustl.edu).

Introduction: Recent measurements by the Cassini CIRS instrument indicate that the endogenic thermal emission from Enceladus' Tiger Stripes is roughly 5 GW [1,2]. Earlier wide-field measurements of the thermal emission from the South Polar Terrain (SPT) indicated a thermal emission of nearly 15 GW [3]. The substantial difference between the two measurements has suggested that there is significant thermal emission *between* the Tiger Stripes themselves that has not been accounted for [1,2]. The terrain between the Tiger Stripes has a unique, ropy morphology (i.e., funiscular plains) observed nowhere else on Enceladus or the rest of the outer Solar System. [4] suggested that this unique morphology results from folding of a very thin lithosphere associated with uncommonly high heat flow. Here we numerically simulate the formation of the funiscular plains in order to more fully evaluate its origin, the plausible heat flux between the tiger stripes, and the geophysical evolution of the SPT over the past million years. Our modeling so far suggests a heat flux in excess of 300 mW m^{-2} is required to reproduce the morphology of the funiscular plains.

Funiscular (ropy) Plains: Enceladus' SPT is a quasi-circular depression located within ~35^{o} of the pole [5]. The ~1-Ma-old SPT [6] contains extensive tectonic deformation, including the four linear, evenly spaced (~35 km) fractures dubbed Tiger stripes. Between the Tiger Stripes are the funiscular plains, characterized by moderate-amplitude (50-100 m), tightly-hinged, ridges and troughs with a characteristic spacing of 1 km (Fig. 1 and [4]). The ridges generally trend roughly parallel to the Tiger Stripes, though in places intersect them at small angles. Along-strike ridge morphology can be complex. Notably, the funiscular morphology is unique to the regions directly between the Tiger Stripes themselves [e.g., 7].

Funiscular Plains Formation: Based on the similarity in morphology between the funiscular plains and ropy pahoehoe lava, [4] suggested that the funiscular ridges form via thin-skinned folding of a very thin lithosphere over ductile ice. Such a mechanism would require a lithosphere only 250-500 m thick to recreate the 1 km fold spacing observed [4]. Their preliminary analysis suggested such folding was a plausible mechanism for funiscular terrain formation, but did not fully address ridge formation or the mechanical/rheological requirements for such thin-skinned tectonics.

In order to provide a more robust investigation we simulate the formation of moderate-amplitude, short-wavelength folds under Enceladus-like conditions. Using the finite element model Tekton we simulate compression of an ice lithosphere in two geometries. First, a two-layer model, simply posits a thin (250-500 m), constant viscosity (T=70 K) stiff layer over ductile (T=220 K) ice (conditions more similar to [4]). The second utilizes more realistic thermal structure with the mechanical properties controlled by the imposed heat flux. In these cases we assume a temperature dependent thermal conductivity [8]. The model is viscoelastic-plastic (non-associative [9], with strain weakening [10]) with all of the relevant flow mechanisms for ice I (d=1 mm). We impose up to 20% shortening with a strain rate of 10^{-13} s^{-1}.

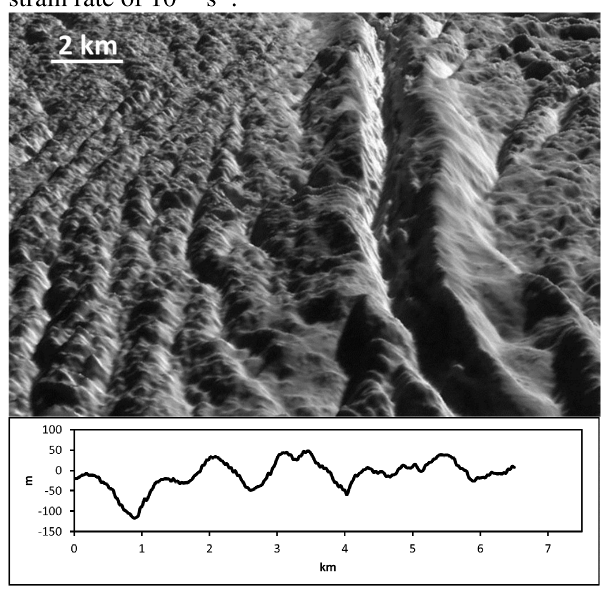

Fig. 1: Top. *Perspective view of the funiscular terrain near Damascus Sulcus.* ***Bottom.*** *Topographic profile across funiscular ridges with a wavelength of 1 km and an amplitude 110 m. Courtesy of Paul Schenk, LPI.*

Model Results: Our current "best case" two-layer simulation reproduces the basic characteristics of the funiscular terrain (Fig. 2 and 3). After 10% shortening the lithosphere is deformed into periodically spaced ridges and troughs with an amplitude of 80 m and a wavelength of 1.3 km. Fold crests tend to be somewhat rounded, whereas fold troughs are v-shaped.

Reproducing funiscular terrain morphology requires a very thin brittle layer of 250-500 m, and relatively weak near-surface ice (a yield strength of ~100 kPa). Thicker or stronger brittle layers result in longer wavelength folds and/or fault-like behavior.

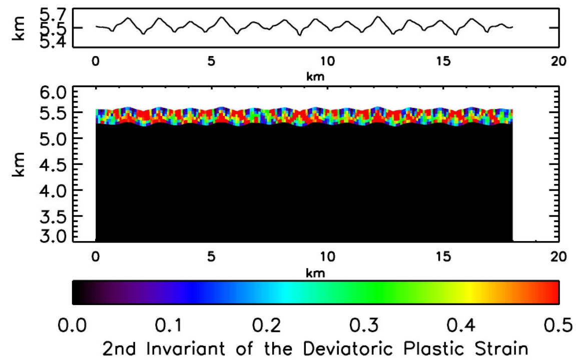

Fig. 2: *Surface deformation (top) and distribution of brittle failure in the lithosphere (bottom) in a simulation after 10% shortening. Initial brittle layer was 250 m thick with a yield strength of 200 kPa.*

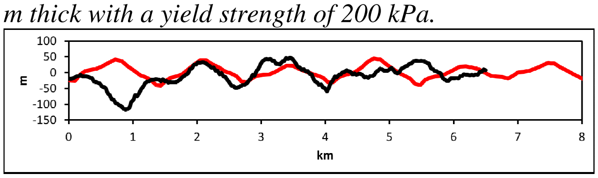

Fig 3: *Comparison of simulated topography (red) with actual funiscular terrain topography.*

Reproducing funiscular terrain morphology is more challenging when a more natural thermal profile is used (Fig. 4). Even for heat fluxes as high as 400 mW m^{-2} the lithosphere is more than 1 km thick (for the thermal conductivity assumed, see below) and relatively strong, due to internal friction. Shortening of this thick layer results in fault-like deformation, wherein strain is accommodated in discrete, linear bands. The surface deformation is blocky, and less periodic, though deformation amplitudes are consistent with the funiscular terrain.

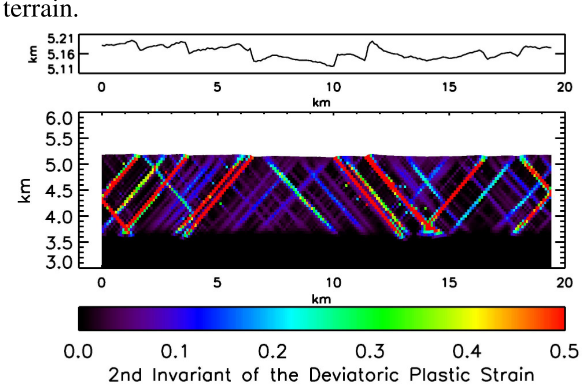

Fig. 4: *As in Fig. 2 but for a simulation after 3% shortening, with a heat flux of 400 mW m^{-2}. Even with this high heat flow, the lithosphere is too thick to produce funiscular-like ridges.*

Discussion: Our simple, initial two-layer models reproduce funiscular terrain morphology with a brittle layer thickness of just 250 m. However, such a thin lithosphere is difficult to achieve under realistic conditions (e.g., Fig. 4) if intact ice is assumed. In this case a 250 m thick lithosphere this would require a heat flux of ~1 W m^{-2}, a clearly unrealistic value. Instead, we suggest that the thermal conductivity of Enceladus' SPT lithosphere (which is likely porous and well fractured) is substantially lower than that of intact ice. The thermal conductivity of ice with 30% porosity can be reduced by a factor of three or more [11]. Assuming a lower thermal conductivity, a brittle layer 250 m thick is consistent with a heat flux of ~300 mW m^{-2}. This porosity effect is currently being incorporated into our more realistic simulations.

If the entire 10 GW discrepancy between the SPT [3] and Tiger Stripes [1,2] thermal emission was the result of unaccounted for heat flux between the Tiger Stripes, the expected flux in that region would by ~400 mW m^{-2}, consistent with our inferred heat flux. However, the *current* funiscular terrain heat flux is unlikely to be so high [Spencer, J. personal communication]. Instead, the high heat fluxes required to produce the funiscular plains may have occurred earlier (though within the last ~1 Ma), during the initial formation of the plains unit. The current heat flux may therefore be lower than implied by the funiscular terrain morphology. The extremely high heat fluxes required to produce funiscular like ridges may explain the limited spatial extent of the terrain type and its proximity to the warm Tiger Stripes.

In addition to high heat fluxes, forming the funiscular terrain via lithospheric shortening requires locally compressive stress between the Tiger Stripes (which are assumed to be tensile fractures). Thus, the broader SPT cannot have formed simply by regional extension, but rather involved locally accommodated extension and compression of the lithosphere.

Acknowledgments: Supported by NASA CDAP.

References: [1] Spencer J.R. et al. (2013) *AAS DPS,* 45, #403.03. [2] Howett C.J.A. et al. (2013) *AGU Fall Meet,* #P53E-06. [3] Howett C.J.A. et al. (2011) *JGR,* 116, E03003. [4] Barr, A.C., and Pruess, L.J. (2010) *Icarus,* 208, 499-503. [5] Schenk P.M. and McKinnon, W.B. (2009) *GRL,* 36, L16202 [6] Porco C.C. et al. (2006) *Science,* 311, 1393-1401. [7] Helfenstein P. et al. (2011) *Enceladus Workshop Abs.* [8] Petrenko, V.F. and Whitworth, R.W. (1999) Physics of Ice, Oxford Univ. Press. [9] Bland, M.T. and McKinnon W.B. (2014) *Icarus*, submitted. [10] Bland, M.T. et al. (2010) *Icarus*, 210, 396-410. [11] Shoshany Y. et al. (2002) *Icarus,* 157, 219-227.