INTERACTION BETWEEN CONVECTION AND SHEAR HEATING IN ENCELADUS' SOUTH POLAR REGION.

Amy C. Barr[1] and William B. McKinnon[2], [1]Department of Space Studies, Southwest Research Institute, Boulder, CO (1050 Walnut St. Suite 300 Boulder CO 80302; amy@boulder.swri.edu); [2]Department of Earth and Planetary Sciences and the McDonnell Center for Space Sciences, Washington University, Saint Louis, MO 63130.

Introduction: Observations of Enceladus by the *Cassini* spacecraft indicate that this tiny satellite is geologically active, with plumes of water vapor and dust erupting from its south polar region (SPT) [1,2]. Enceladus' plumes are spatially associated with a region of increased local heat flux, with a total power output 5.8 ± 1.9 GW spread over an area of 70,000 km^2 [1,2], which corresponds to a regional heat flux of 55–110 mW m^{-2}. Much of the SPT heat flux is concentrated near the "tiger stripes," 4 quasi-parallel narrow features ~ 500 km long centered near the south pole, which show brightness temperatures near their centers of ~80-90 K [1]. In addition to the tiger stripes, the SPT is bounded by cycloidal arcs, with wedge-shaped regions of convergent tectonic activity at their cusps [3].

The activity in the SPR is undoubtedly the result of tidal dissipation within Enceladus. The observation of localized heating in the vicinity of the tiger stripes led Nimmo et al. [4] to suggest that shear heating due to cyclical strike-slip deformation along fault zones within the stripes could be a dominant source of heat generation in the SPT. Another possible scenario is that Enceladus' ice shell is tidally heated from within and vigorously convecting [5,6]. We find the idea of convection, rather than shear heating alone in a thin conductive ice shell, to be appealing because vigorous convection and associated crustal spreading may provide a natural explanation for the high heat flux and the convergent morphology at the SPT margins.

Here, we explore how solid-state convection beneath Enceladus' south polar region may interact with shear heating along the tiger stripes to produce the large regional heat flux and distinct morphology observed at the margins of the SPT. We also explore the hypothesis that the SPT represents a location where convective fluid motions come close to the surface of the satellite; in the language of solid-state convection studies, this regime of behavior is referred to as the "sluggish" or "mobile"-lid regime.

Convection Beneath the SPT: The viscosity of water ice is strongly temperature-dependent, so ice at the surfaces of outer planet satellites such as Enceladus and Europa is expected to be extremely viscous – so viscous that it remains essentially immobile, forming a "stagnant lid". The stagnant lid limits the heat flow out of a convecting ice shell, and essentially prevents convection from driving lithospheric deformation [7]. The presence of a stagnant lid, however, does not seem to be compatible with the observed surface morphologies on tidally flexed icy satellites such as Europa and Enceladus, which have numerous features suggestive of convective-driven resurfacing or complete lithospheric separation and mid-ocean-ridge-type crustal spreading [e.g., 3,8,9,10].

An ice shell with a Newtonian rheology will exhibit sluggish lid behavior if the effective viscosity of cold near-surface ice is less than ~10^4 higher than the warm basal ice [11], or $\Delta\eta$ < exp(8), where $\Delta\eta$ is the ratio between the surface and basal viscosity. This may be possible if the yield stress of the ice shell is very low [7,12], or if the ice shell is sufficiently pervasively fractured and damaged [13,14].

Methods. We have implemented the shear-heating model described by Nimmo et al., [4] and Nimmo & Gaidos [15] in the finite element convection model CITCOM [16]. Han and Showman [17] have recently modeled the interaction of convection and ridges on Europa; ours is an independent approach. To model ridge heating, we insert a dimensionless heat source $H' = \mu(T) g u_o D^2 / C_p \kappa \Delta T$ in near-surface elements where T < 220 K, with coefficient of friction μ, gravity g, strike-slip fault velocity u, ice shell thickness D, specific heat of ice C_p, thermal diffusivity of ice k, and temperature difference between surface and basal ice ΔT. We consider the coefficient of friction to be temperature-dependent, with μ=0.6 at the surface temperature, T_s=75 K declining to μ=0.1 at 175 K: use of the temperature cutoff and $\mu(T)$ allow us to mimic the transition from brittle shear heating to viscous heating in Nimmo & Gaidos [15]. To determine values of u_o and rheological properties likely to yield high surface heat fluxes, we performed a number of simulations of convection with shear heating in a basally heated 2D Cartesian domain 250 km wide and 50 km deep, and assumed that the tiger stripes are placed 50 km apart, at x=50, 100, 150, and 200 km. To study how the morphology of convective upwellings may be modified by the presence of heating along the tiger stripes, we are in the process of performing 3D Cartesian simulations (see Figure 2).

In our simulations we assumed a Rayleigh number Ra=10^6, varying $\Delta\eta$, and values of H' appropriate for u_o=5x10^{-5}, 10^{-6} and 2x10^{-6} m/s. In the sluggish lid regime, shear heating associated with these strike-slip velocities increased the regional heat flux to values above those observed by CIRS (see Figure 1). The tiger stripes increased the near-surface velocities by ~50%.

In the sluggish lid regime, a significant fraction of the total heat flux is carried by convection. However, as $\Delta\eta$ increases and the system enters the stagnant lid convection regime, the heat flux from the ice shell becomes dominated by the shear heating along the tiger stripes. To determine how the tiger stripes themselves contribute to the heat flux in the absence of convection, we modeled the thermal evolution of ridges in an ice shell with an extremely high melting point viscosity (or low *Ra*). The results are shown as stars in Figure 1. In the stagnant lid regime, the heat flux from the surface of the ice shell asymptotically approaches the value obtained in the absence of convection.

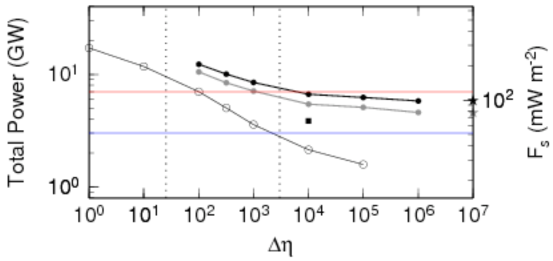

Figure 1. (open circles) Convective heat flux (F_s) and total power output over 70,000 km^2 as a function of Δη for an ice shell 50 km thick with $Ra=10^6$, corresponding to a melting point viscosity $\eta=10^{14}$ Pa s. In the sluggish-lid convection regime (within the dotted lines), convective heat fluxes are high, comparable to the average heat flux in the SPR. Range of total power and F_s observed in the SPR is denoted by the blue and red lines. (gray and black) If the tiger stripes represent locations of shear heating, the combined heat from ridges + convection can easily provide the total power output observed in the SPR, regardless of whether convection is sluggish or occurs in the stagnant lid regime. Black lines show the heat flux from ridges + convection if $u_o=2\times10^{-6}$ m/s, corresponding to ~1 m of fault motion per enceladean day; gray lines/symbols correspond to $u_o=10^{-6}$ m/s. Square shows the location in phase space of simulation in Figure 2. Stars show the heat flux from ridges in the absence of convection – note that the heat flux from ridges in the stagnant lid regime asymptotically approaches the value in the absence of convection, indicating that in the stagnant lid regime, there is no interaction between convection + ridges.

Acknowledgements: This work is supported by NASA Cassini Data Analysis Grant NNX07AE80G. Author Barr acknowledges support from the Southwest Research Institute.

Heat Flow Predictions: In the sluggish lid regime, the convective flow pattern is characterized by one or two broad upwellings with a very thin stagnant lid. The predicted surface heat flux shows a broad peak in the vicinity of the ridges (with due allowance for the conductivity of the actual SPT regolith, and the fact we do not properly model the surface radiation boundary condition). If convection on Enceladus is occurring in this regime, the SPT should show a ~100-200 mW m^{-2} regional heat flux in addition to the highly localized heat flux at the tiger stripes. In the stagnant lid regime, however, convective upwellings are "drawn to" the ridges, and the heat flux between the ridges is extremely small. If convection is occurring in the stagnant lid regime, or is not occurring at all, the SPT should have a negligible heat flux in the regions between tiger stripes and at its flanks. Heat flux measurements from the regions *away from* or *between* the tiger stripes can shed light upon their mode of formation.

References: [1] Spencer J. R. et al. (2006) *Science 311*, 1401-1405. [2] Porco C. C. et al. (2006) *Science 311*, 1393-1401. [3] Helfenstein, P. et al., (2006) *LPSC XXXVII* #2182. [4] Nimmo, F. et al., *Nature* 447, 289-291 (2007). [5] Barr A. C. and McKinnon W.B. (2007) *GRL*, v.24, L09202. [6] Roberts, J. and F. Nimmo (2008) *Icarus* in press. [7] Showman, A. P. and L. Han (2004) *Icarus* 177 425-437. [8] Pappalardo, R. T. et al. (1998) *Nature* 365-368. [9] Prockter, L. et al., (2002) *JGR* 107, 5028. [10] Stempel, M. M. et al., (2005) *Icarus* 177 297-304. [11] Solomatov, V. S. (1995) *Phys. Fluids* 7 266-274. [12] Moresi, L.-N. and V. S. Solomatov *GJI* 133, 669-682. [13] Tobie, G. et al., (2004) *Europa Icy Shell Workshop* #7033. [14] Landuyt, W. and D. Berovici (2007) *AGU Fall Meeting* #T44B-07. [15] Nimmo, F. and E. Gaidos (2002) *JGR* 107 10.1029/2000JE001476. [16] Moresi, L.-N. and V. S. Solomatov *Phys. Fluids* 7 2154-2162. [17] Han, L. and A. P. Showman (2008) *GRL* in press.

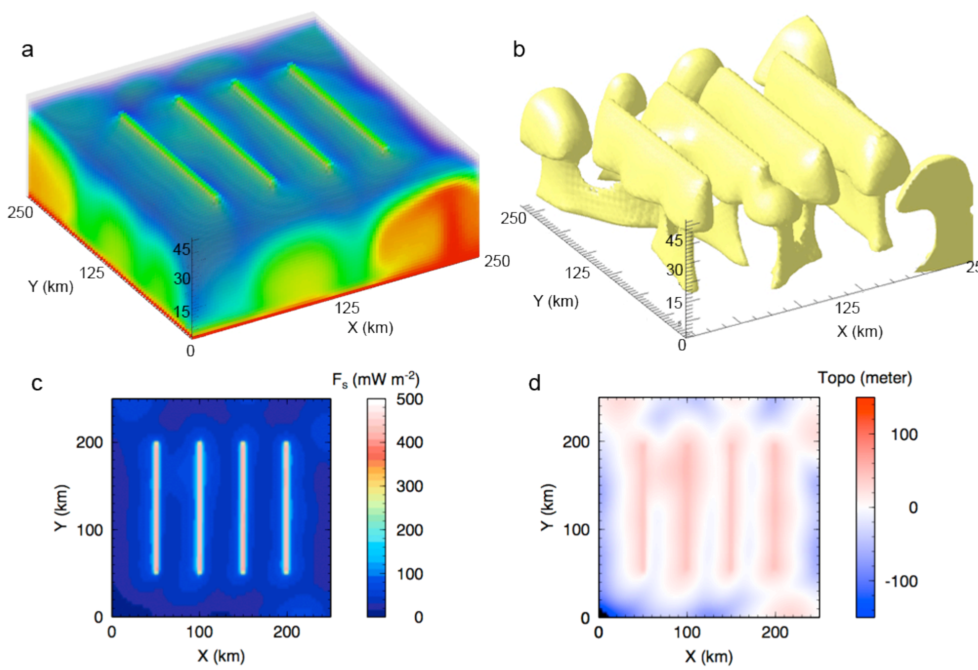

Figure 2. (a) Solid-state convection in a x=250, y=250, z=50 km thick ice shell on Enceladus with a viscosity contrast $\Delta\eta=10^4$ and heat sources in the near-surface ice appropriate for shear heating along tiger stripes with $u_o=5\times10^{-5}$ m/s. Warm upwellings (T~260 K) are shown in red, near-surface ice (T~80 K) is shown in blue. (b) Isosurfaces of residual temperature, showing upwellings ~10 K warmer than the horizontal average. Near the tiger stripes, the convective upwellings are pulled into the narrow fault zones. Away from the stripes, convective upwellings are isolated and domical, as expected in nominal stagnant lid convection. (c) Approximate surface heat flux as a function of location. Average power output is F_s=60 mW m^{-2}, corresponding to a total power output spread over the SPT of 4.4 GW. Our predicted heat fluxes are not directly comparable to those observed by CIRS because CITCOM uses a constant temperature boundary condition at its upper surface, rather than a more-appropriate radiative condition, and we have neglected the effects of an insulating regolith. (d) Dynamic topography. Here, the tiger stripes are associated with uplifts of ~50-70 meters.