SHEAR HEATING IN THE OUTER SOLAR SYSTEM. F. Nimmo, J.H. Roberts, *Dept. Earth & Planetary Sciences, U.C. Santa Cruz, Santa Cruz CA 95064 (fnimmo@es.ucsc.edu)*, J.R. Spencer, *Dept. Space Studies, SWRI, Boulder CO 80302*, R.T. Pappalardo, *Jet Propulsion Laboratory, M/S 183-301, Pasadena CA 91109*, L.M. Prockter, *Applied Physics Laboratory, Laurel, MD 20723*, M.E. Mullen, *Dept. Astrophysics & Space Phys., U. Colorado, Boulder CO 80309*.

Strike-slip motion is predicted to be a consequence of diurnal tidal stresses [1], and strike-slip offsets are ubiquitous on Europa [2]. For satellites with low rigidities, non-zero eccentricities and short orbital timescales, strike-slip motion is expected to be relatively rapid and can thus lead to heating through friction or viscous dissipation [3]. Here I will review three consequences of shear heating: 1) double ridge formation; 2) vapour production on Enceladus and Europa; 3) its effect on convection.

Double Ridge Formation

Double ridges are a ubiquitous tectonic feature on Europa [4], and similar features, though at a larger horizontal scale, are also observed on Triton [5] (Fig 1). Shear heating leads to locally elevated temperatures in the subsurface, which could cause elevated topography along the shear zones. However, this topography would decay due to thermal diffusion unless shear heating was continuous. Thus, to maintain long-term topography requires either a permanent density contrast (e.g. due to melting and removal of dense salts [3,6]), or viscous upwelling which then gets frozen in as heating ceases [7]. The central trough of double ridges might be caused by melt drainage downwards and subsequent compaction of the overlying ice [3].

Vapour production

If heated ice is exposed directly to a vacuum, then sublimation and vapour production, rather than melting, will result. Thus, whether melting or vapour production occurs depends on the porosity and permeability of the subsurface ice, which in turn depends on pressure and temperature. In the case of Enceladus, it has been suggested [8] that shear heating is responsible for the vapour plumes [9] and high heat fluxes [10] observed at the south pole. An important consequence is that the majority of the heat observed is being advected by vapour which then recondenses in the near-subsurface [11]. Thus, in this case the permeability and porosity structure of the near-surface ice play a major role in the surface observables.

Since shear heating is inferred to have been important at both Europa and Enceladus, an important question is whether Europa might also be generating vapour plumes. The main differences between Europa and Enceladus are that the former has a higher surface temperature, higher gravity and likely a lower shear velocity. Figure 2 shows the output from a model identical to that in [8] except for these three parameters. It results in a brittle layer thickness of 2.4 km, a maximum subsurface temperature anomaly of 32 K and a total vapour production rate of 1 kg/s per km. The weighted vapour temperature is 137 K, resulting in a thermal velocity (0.44 km/s) much less than the escape velocity (2 km/s). Vapour which escapes the subsurface would thus rise $\sim$70 km above the surface before falling back, potentially generating detectable surface albedo features [12]. Vapour which instead recondenses in the near subsurface in a region 5 km wide would result in a surface temperature increase of 1.7 K, probably too small to be detectable with *Galileo* instruments.

The largest unknown affecting these results is the permeability structure of the subsurface ice on Europa, because it controls the degree to which vapour produced in the subsurface is mobile.

Effect on convection

Just as the insulating terrestrial continents have an effect on mantle convection [13], one might anticipate that a zone of near-surface shear heating affects convection in the underlying ice shell [7]. Figures 3 and 4 show the results from two Citcom [14] models of a tidally-heated convecting ice shell appropriate to Enceladus. Figure 3 shows the local tidal heating and Figure 4 the accompanying temperature structure. In each case the right hand panels include a shallow, near-surface zone of heat production similar to that inferred to be operating at Enceladus.

Even though the extra south polar heating is confined to shallow levels, it is clear that the deeper temperature structure is profoundly affected. The figures show that the stagnant lid is significantly thinned, there is an enlarged hot spot beneath the South pole, and the temperatures achieved suggest that local melting may be taking place [cf. 15].

Near-surface heating can thus affect deeper convection. Furthermore, the scenario shown here may help to explain the polar location of the hotspot on Enceladus [16]: a low-density diapir of the kind shown can cause reorientation. Alternatively, drainage of melt-water could result in subsidence and a subsurface sea [17]. Thus, near-surface shear heating can affect the global dynamics of icy satellites.

References

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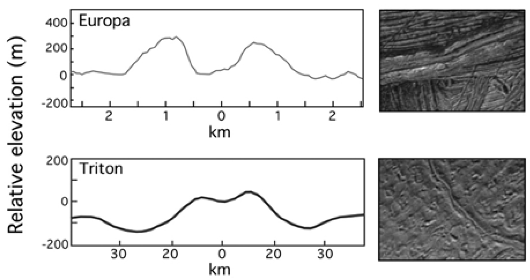

Figure 1: Topographic ridge profiles and images for Europa and Triton. From [5], Figure 2.

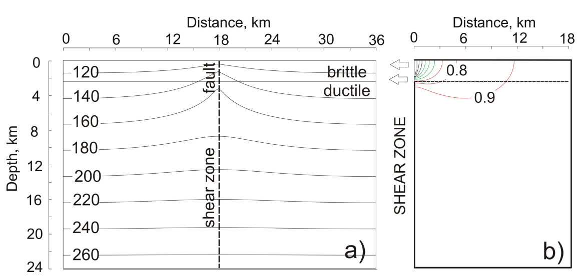

Figure 2: a) Temperature distribution due to shear heating for Europa. Model parameters are identical to Fig. 1 in [8] except $g = 1.3\ m\ s^{-2}$, shear velocity $u = 8 \times 10^{-6}\ m\ s^{-1}$ [3] and $T_s = 110$ K. Resulting vapour production rate is 1 kg/s per km of fault (α=0.1). b) Vapour density (normalized to maximum value of 2.6 $kg\ m^{-3}$ for the case in which vapour escape (arrows) only occurs laterally into shear zone.

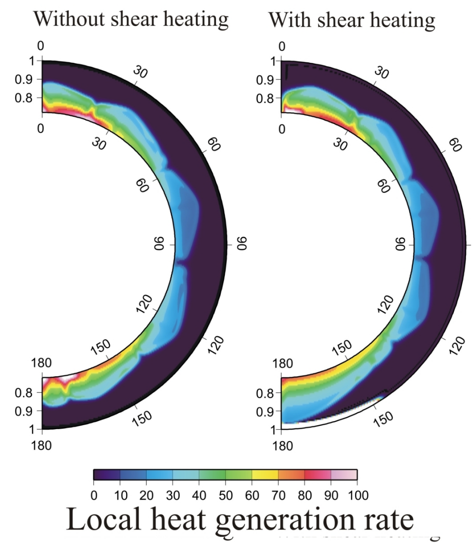

Figure 3: Laterally-averaged tidal heat generation rate in a convecting ice shell appropriate to Enceladus. Interior structure is from [16]. Tidal dissipation is calculated using approach of [18] assuming a constant ice shell viscosity of 3×10^{13} Pa s, and then modified based on the local temperature [15]. Note that no significant dissipation occurs in the stagnant lid (black). Units of heat generation are dimensionless; multiply by 1.2×10^{-8} to get $W\ m^{-3}$. Left-hand panel shows base case; right-hand panel includes a zone of shallow South polar heating. Heating is concentrated in the top 5 km and varies as $\sin^2 \theta$ south of $55°$S, where θ is latitude. Total shallow heat production is 7 GW. Note that the stagnant lid is thinned near the South pole.

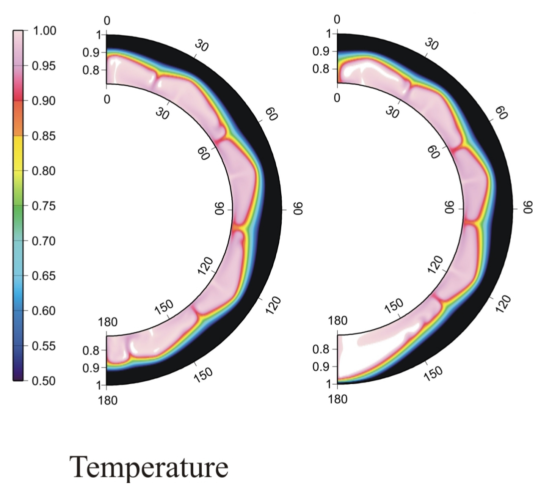

Figure 4: As for Fig 3, except plotting dimensionless temperature. Convective calculations carried out using Citcom in 2D. Note the large temperature increase beneath the South pole in the right-hand panel.