POWERING TRITON'S RECENT GEOLOGICAL ACTIVITY BY OBLIQUITY TIDES: IMPLICATONS FOR PLUTO GEOLOGY.

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Summary: If Triton was captured early, its young, deformed surface cannot be due to release of heat generated during capture. Instead, we argue that Triton's high inclination produces an obliquity high enough to generate significant heating in a subsurface ocean. This heating is sufficient to drive surface yielding and deformation. In contrast, Pluto is unlikely to be experiencing significant tidal heating of this nature; *New Horizons* is therefore unlikely to see young, deformed surfaces at Pluto.

Introduction: Triton's surface is lightly cratered [1] and characterized a variety of tectonic (or possibly cryovolcanic) features [2]. Elsewhere in the solar system (Io, Europa, Enceladus), such characteristics are thought to be due to tidal heating. Solid-body obliquity tidal heating was previously suggested for Triton by [3], but here we focus on dissipation in a subsurface ocean, following an approach developed by [4,5].

Primordial Heating: Triton was probably captured [6], releasing gigantic amounts of heat as its orbit was circularized [7]. However, because of Triton's relatively small size, the heat released during this event is lost rapidly compared to the age of the solar system, even in the conservative case of pure conduction. Unless Triton was captured recently, which is unlikely for several reasons, stored primordial heat cannot explain its youthful appearance.

Radiogenic Heating: As with Pluto [8], a conductive Triton can maintain a subsurface ocean through heating via radioactive decay, unless the radiogenic abundance is significantly sub-chondritic [9]. Radiogenic heating, however, is insufficient to cause surface yielding (see below).

Convection and Yielding: Sufficiently large convective stresses will cause yielding and deformation of the near-surface. We assume here that this mechanism is responsible for the observed features at Triton (though other resurfacing mechansims such as cryovolcanism are also possible). Convective stresses vary inversely with the square of the thermal boundary layer thickness [10]; we can therefore write

$$F_c = C(\sigma_y / \eta_b)^{1/2} \qquad (1)$$

where F_c is the critical convective heat flux required to exceed the yield stress σ_y, η_b is the basal viscositiy of the convecting ice shell and C is a constant derived from numerical models [11,12].

Fig 1a shows how the minimum shell thickness for convection to occur varies with basal temperature/basal viscosity (here taking the viscosity at 273 K to be 10^{14} Pa s). Fig 1b shows the corresponding critical convective heat flux required for yielding to occur (equation 1). The minimum heat flux required is about 10 mWm^{-2}. This value exceeds (by a factor of at least 3) the likely radiogenic heat production. However, the higher heat flux associated with tidal heating can generate yielding (see below).

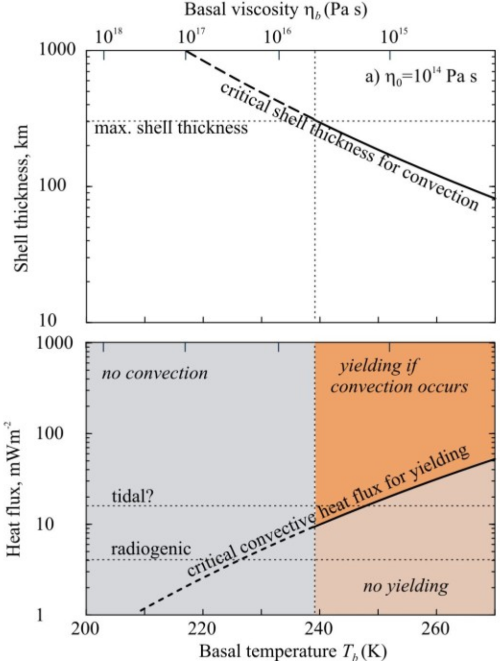

Figure 1. a) Shell thickness required for convection to occur as a function of basal temperature/basal viscosity. b) Critical convective heat flux required to initiate yielding as a function of basal temperature (equation 1).

Obliquity Tidal Heating: Assuming that Triton occupies a damped Cassini state, its high inclination implies that its obliquity should be about 0.3° if it is solid [3], and roughly 0.7° if it contains a subsurface ocean [5]. Sustained heating via obliquity tides is allowable because the timescale of inclination damping is long compared to that of eccentricity damping.

We focus on dissipation in a subsurface ocean, where we parameterize our results using a drag coefficient C_D [5]. This formulation is frequently used for the Earth, where C_D~0.002 [13]. An approximate expression for obliquity tidal heating in an ocean is given by:

$$\dot{E} \approx 8\pi\rho R^5 C_D n^3 \theta^3 \approx 100\,\mathrm{GW}\left(\frac{\theta}{0.35^o}\right)^3$$

where R is the radius of Triton, ρ is the fluid density, n is the mean motion and θ is the obliquity. For comparison, estimated radiogenic heating is 70 GW.

Figure 2 shows how tidal heating varies with obliquity, both for the approximate solution given above and the full solution [5]. An obliquity of 0.7^o yields a heat flux of 14 $\mathrm{mWm^{-2}}$, sufficient to drive convective yielding and surface deformation (Fig 1). Note that the implied ocean temperature of roughly 250 K implies the presence of an antifreeze, for instance a few weight percent ammonia. This situation represents a steady-state: the convective heat loss is balanced by tidal heating, thus allowing an ocean on Triton to persist for billions of years.

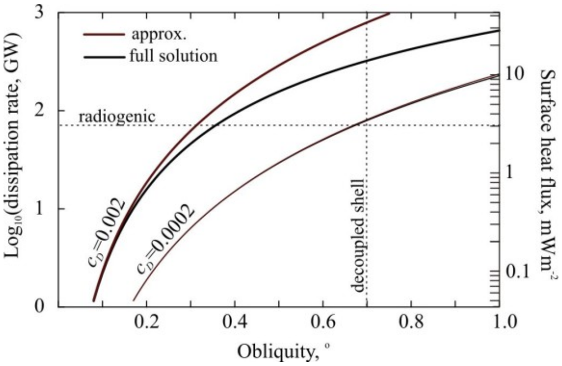

Figure 2. Obliquity tidal heating as a function of obliquity and drag coefficient C_D. Approximate expression is given in text; full solution is from [5].

Implications for Pluto: Figure 1 demonstrates that for Triton (and also for similarly-sized Pluto), radiogenic heating alone is insufficient to drive convective yielding. Adding obliquity tidal heating, however, does allow yielding to take place.

Although its obliquity is currently unknown, tides on Pluto are expected to be much smaller than tides on Triton due to the tidally relaxed state of the Pluto/Charon system. As a result the mechanism which permits deformation to occur at Triton will not operate at Pluto, irrespective of the temperature of the putative ocean. As a result, we do not anticipate that Pluto will have young, recently-deformed surfaces. This is not to say that Pluto will be geologically uninteresting: ocean freezing and/or shell cooling can lead to large stresses and tectonic deformation [8]. But such tectonic activity is likely to be ancient.

References: [1] Schenk and Zahnle, Icarus 192, 135-149, 2007. [2] Croft et al., in Neptune and Triton, pp.879-947, 1995. [3] Jankowski et al., Icarus 80, 211-219, 1989. [4] Tyler, Icarus 211, 770-779, 2011. [5] Chen et al., Icarus 229, 11-40, 2014. [6] Agnor and Hamilton, Nature 441, 192-194, 2006. [7] Ross and Schubert, GRL 17, 1749-1752, 1990. [8] Robuchon and Nimmo, Icarus 216, 426-439, 2011. [9] Gaeman et al., Icarus 220, 339-347, 2012. [10] Van Heck and Tackley, EPSL 310, 252-261, 2011. [11] Hammond and Barr, Icarus 227, 206-209, 2014. [12] O'Neill and Nimmo, Nature Geosci. 3, 88-91, 2010. [13] Taylor, PTRSL-A 220, 1-33, 1920.