INTERIOR THERMAL STATE OF ENCELADUS INFERRED FROM THE VISCOELASTIC STATE OF ITS ICY SHELL. S. Kamata[1*] and F. Nimmo[2] [1]Creative Research Institution, Hokkaido University, Kita 21, Nishi 10, Kita-ku, Sapporo, Hokkaido 001-0021, Japan, [2]Dept. Earth and Planetary Sciences, University of California Santa Cruz, 1156 High St, Santa Cruz, CA 95064, USA (*kamata@mail.sci.hokudai.ac.jp).

Summary: We investigate the interior thermal state that can maintain a regionally thick subsurface ocean underneath the South Polar Terrain of Enceladus by comparing timescales of melting of ice and of viscoelastic deformation of topography at the base of the shell. We found that a basal heat flux about ten times higher than that due to radiogenic heating is necessary if the icy shell is in an equilibrium state.

Introduction: The South Polar Terrain (SPT) of the Saturnian satellite Enceladus is one of the most geologically active regions among icy worlds [e.g., 1]. The regional heat flux observed over the SPT of order 200 mW/m^2 is much higher than the equilibrium value estimated considering radiogenic and tidal heating for conventional Q values of Saturn [e.g., 2, 3]. Despite a number of studies since the discovery of plumes emanating from this region, the heat production mechanism that can account for this anomalously large heat flux is still unclear. For a better understanding of Enceladus' heat budget, we investigate the current interior thermal state assuming an equilibrium condition as a starting point.

The thermal state inside the icy shell can be inferred from its viscoelastic state [e.g., 4]; warmer ice has a lower viscosity, leading to more rapid relaxation?, and vice versa. Geodetic data of Enceladus obtained by the Cassini spacecraft suggest that the icy shell is thinner around the SPT [5]; thus, the icy shell has large-scale topography not only at the surface [6] but also at its base. Since the basal temperature of the ice shell is the melting point, the basal viscosity of the shell would be low, and thus the timescale of viscous relaxation should be short. Lateral flow at the in the shell should therefore efficiently remove basal topography, but this is apparently not consistent with geodetic observations. A likely mechanism to maintain basal topography is melting of the shell near the SPT; the timescale of melting and that of viscous relaxation would need to be comparable.

A previous comparison of these timescale [7] assumed a regional ocean and extremely large heat fluxes from the core. In this study, we compare these timescales assuming a global ocean, which is suggested from a recent study of Enceladus' libration [8], and a wide variety of heat fluxes and temperatures at the base of the shell.

Timescale of melting: The timescale of melting τ_{melt} can be estimated analytically:

$$\tau_{\mathrm{melt}} = \rho L V / P_{\mathrm{melt}}$$

where ρ, L, V, and P_{melt} are the density of ice (= 950 kg/m^3), the latent heat of ice (= 0.33 MJ/kg), the volume of ice to be melted, and the power used for melting, respectively. The volume V is assumed to be the regionally thickened portion of the subsurface ocean. We assume that the icy shell is completely isostatically compensated and calculate the basal topography adopting the surface topography [6] and the density of ocean of 1000 kg/m^3. We found that $V \sim 8.2 \times 10^{14}$ m^3. If P_{melt} is equal to the conventional long-term limit of tidal heating P_{tide} = 1.1 GW [3], $\tau_{\mathrm{melt}} \sim 7.4$ Myr (Figure 1).

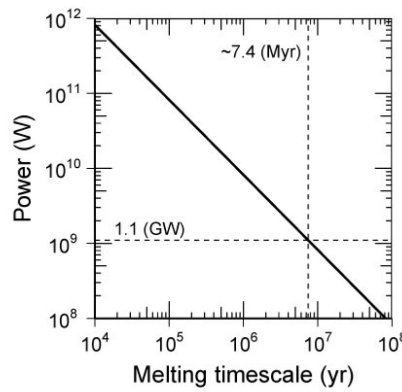

Figure 1: The timescale of melting as a function of the power used for melting.

Timescale of viscoelastic deformation: In contrast to the timescale of melting, that of viscoelastic deformation, τ_{rel}, needs to be estimated numerically. We assume a three-layer incompressible Enceladus model consisting of an icy shell, a global subsurface ocean, and a rocky core. The layers are assumed to be a Maxwellian viscoelastic body, an inviscid fluid, and a purely elastic body, respectively. A wide range of icy shell thickness D_{sh} is considered while the radius of Enceladus, the ocean thickness, and the mean density are fixed; the density of the core is calculated from these values.

The viscosity profile of the shell is obtained from the temperature profile. We assume that the icy shell is currently in a thermally equilibrium: heat from the core and heat production due to tides in the shell are balanced with heat transportation due to thermal conduction [9]. We apply the rheology of pure water ice to this thermal profile and calculate the viscosity as a function of depth. Reference viscosity η_0 of ice, temperature T_{base} at the base of the icy shell, and strain rate $\dot{\varepsilon}$, which is required to calculate the tidal heating rate, are free parameters. The basal heat flux q_{base} is a function of D_{sh} and these parameters. Although the interior structure adopted in this study is simple particularly below the icy shell, the timescale of viscoelastic deformation depends only weakly on the deep interior structure. Thus, the use of a more realistic deep interior structure model would not change our conclusion significantly.

We calculate the time evolution of topography at the base of the icy shell using a semi-analytical code involving spherical harmonic expansion [4]. Results for harmonic degree n = 2 are shown in Figure 2. As expected, we found that a thicker shell and a lower reference viscosity both lead to a shorter relaxation timescale. We also found that a thick icy shell with a low reference viscosity cannot be in an equilibrium state (i.e., a negative basal heat flux is required). Note that the deformation timescale of basal topography is longer for a lower harmonic degree (i.e., longer wavelength) [e.g., 10]. Thus, results for n = 2 shown in Figure 2 provide the upper limit for the viscoelastic deformation timescale.

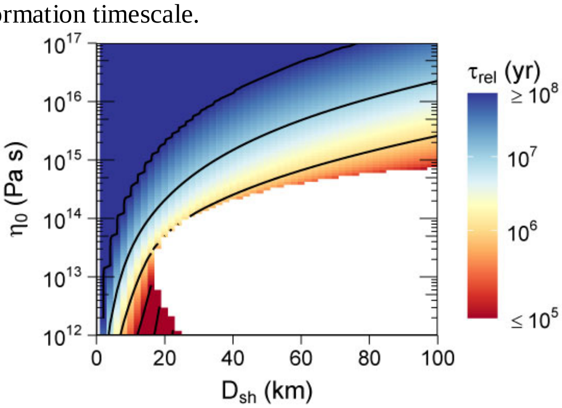

Figure 2: The timescale of viscoelastic deformation at the base of the icy shell. Results for n = 2, T_{base} = 270 K, and $\dot{\varepsilon}$ = 4 × 10^{-10} s^{-1} are shown. The white area has no solution.

Comparison and discussion: Figure 3 summarizes the relation of these two timescale. Here P_{tide} (= 1.1 GW) is used not only to melt the shell but also to maintain the shell temperature. The amount of power used to warm the shell can be calculated from the thermal profile. We found parameter conditions that can lead to $\tau_{\mathrm{rel}} = \tau_{\mathrm{melt}}$ only if $q_{\mathrm{base}} \gtrsim 5$ mW/m^2 (the green shaded area in Figure 3); below this basal heat flux, relaxation is faster than melting, leading no basal topography. Note that this is based only on results for n = 2; higher degree topography relaxes faster, leading an expansion of the red shaded area in Figure 3. Thus, a much higher basal heat flux is needed to maintain a regionally thick ocean.

The minimum basal heat ~5 mW/m^2 is about one order of magnitude larger than that expected from radiogenic heating in the core. A possible additional heat production mechanism in the core is hydrothermal reaction [11], though it is unlikely that it can produce sufficiently large amount of heat.

A recent interpretation of astrometric data suggests a tidal heating rate about one order of magnitude higher [12]. We repeated the above analysis varying the value of P_{tide} and found that q_{base} can be as low as that expected from radiogenic heating if $P_{\mathrm{tide}} \gtrsim 10$ GW. Thus, if most of tidal heat of ~10 GW is used to melt the icy shell below the SPT, a regionally thick ocean can be maintained without invoking anomalously large heat production in the core. Nevertheless, this model may be difficult to reconcile with the current state of another satellite, Mimas [1].

This work assumes a current equilibrium (i.e., steady-state) Enceladus and requires a large amount of additional heat – either enhanced tidal heating or a heat source of unspecified origin in the core. The actual Enceladus may not be in such a state; episodic heat production [13], which is not modeled in this work, may largely contribute not only to the observed high surface heat fluxes but also to the presence of such a subsurface ocean.

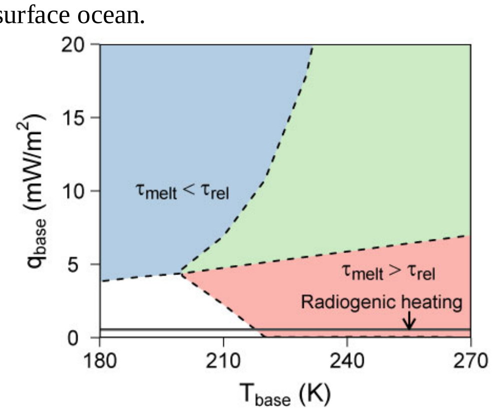

Figure 3: Comparison of timescales of meting and viscoelastic deformation of the icy shell. Results for n = 2 and P_{tide} = 1.1 GW are shown. Parameter conditions that can lead to $\tau_{\mathrm{rel}} = \tau_{\mathrm{melt}}$ can be found only in the green area.

References: [1] Spencer and Nimmo (2013) Annu. Rev. Earth Planet. Sci., *41*, 693–717. [2] Roberts and Nimmo (2008) *Icarus*, *194*, 675–689. [3] Meyer and Wisdom (2007) *Icarus*, *188*, 535–539. [4] Kamata and Nimmo (2014) *JGR*, *119*, 2272–2289. [5] Iess et al. (2014) *Science*, *344*, 78–80. [6] Nimmo et al. (2011) *JGR*, *116*, doi:10.1029/2011JE003835. [7] Collins and Goodman (2007) *Icarus*, *189*, 72–82. [8] Thomas et al. (2016) *Icarus*, *264*, 37–47. [9] Ojakangas and Stevenson (1989) *Icarus*, *81*, 220–241. [10] McKenzie et al. (2000) *JGR*, *105*, 11029–11046. [11] Hsu et al. (2015) *Nature*, *519*, 207-210. [12] Lainey et al. (2012) *ApJ*, *752*, 14. [13] O'Neill and Nimmo (2010) *Nat. Geosci.*, *3*, 88-91.