THERMAL AND ORBITAL EVOLUTION OF TETHYS AS CONSTRAINED BY SURFACE OBSERVATIONS.

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While the origin of Ithaca Chasma has been debated, the heat flow required to form such an extensive surface feature has not received much attention [1,2]. Recent flexural modeling shows that Ithaca Chasma was formed during a period of high local surface heat flux (between 18 to 30 mW/m^2) [3]. Tethys' density is close to that of pure ice; radiogenic and accretional heating are unable to provide the amount of heat associated with the formation of Ithaca Chasma. Tidal heating is the most likely source of this heat. While Tethys' zero eccentricity makes it tidally inactive currently, this state is not necessarily primordial and Tethys' orbit and internal structure may have been different in the past.

To determine under what conditions Ithaca Chasma could have formed, we considered a model of Tethys consisting of four layers: a silicate core, a liquid water ocean, a viscous icy mantle and a rigid icy crust. This structure is consistent with a convecting ice shell, as suggested by the high surface heat flux. The radius of Tethys is 533 km; the silicate layer and the base of the elastic rigid layer were fixed at 110 km and 526 km radius, respectively. The position of the ice-water interface was allowed to vary between models. We solved for the complex tidal Love number, k_2, and the resulting heat flow values as a function of the viscous layer thickness using reasonable values for ice viscosity (η=10^{13}-10^{15} Pas). In addition, we looked at the effect of having no liquid ocean on total tidal deformation using a three-layer model.

Figure 1 shows the total tidal heat production predicted with an orbital eccentricity e = 0.005. A thinner viscous layer is more easily deformed and has a greater tidal heating rate. However, total heat production is also dependent on the total volume of the viscous layer. The result of the two competing processes is a critical viscous layer thickness where there is maximal tidal heat production. This thickness is dependent on viscosity, but for the viscosities modeled, the critical thickness is relatively thin (<50 km) compared to the total thickness of the water layer. Once the layer becomes very thick (>250 km) the satellite is resistant to tidal deformation and increasing the volume of the viscous layer has little effect on total tidal heat production. The removal of the liquid ocean has a very small effect because of this rigidity.

Varying the eccentricity in these models will simply shift the curves up and down, since tidal heat production is a function of e^2 [4]. The required thickness of the ice layer for a given heat flux value is extremely sensitive to both the viscosity and the orbital eccentricity, both of which are poorly constrained. However because these curves tend to occupy different regions of parameter space, future models that constrain the orbital eccentricity would be able to predict the internal structure and vice-versa.

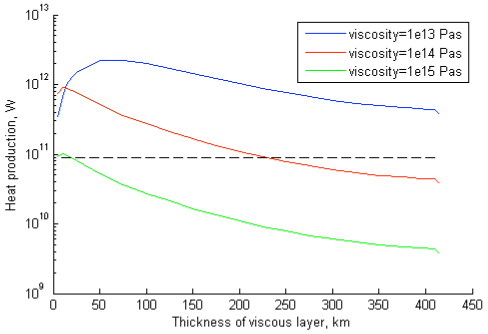

Figure 1: Total heat production with fixed orbital eccentricity of 0.005 predicted from tidal heating models of Tethys. Dashed line shows the total heat production calculated from flexural modeling of Ithaca Chasma [3].

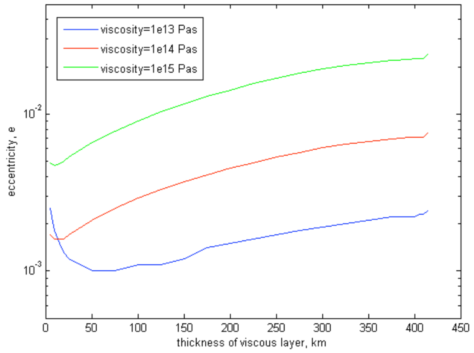

Figure 2: Required eccentricity for a surface heat flux of 25 mW/m^2 as a function of the viscous layer thickness.

For a surface heat flux of 25 mW/m^2, the required orbital eccentricities range from .001 to .02, depending on the viscosity and internal structure (Figure 2). These values are similar to present day eccentricities of various icy satellites. Tethys likely passed through a resonance with Dione at some point in its orbital history. This would have been a 3:2 e-resonance, although how much this would have perturbed Tethys' orbital eccentricity is still uncertain [5]. However, the heat flux generated by a Tethys-Dione two-body resonance in equilibrium could not account for all the heat associated with the formation of Ithaca Chasma [6]. A similar problem has been observed for Enceladus, and non-equilibrium oscillations may generate the additional heat required [7].

Crater dating suggests that Ithaca Chasma and the surface of Tethys are relatively old (around 4 Ga) [3]. The eccentricity damping time for the eccentricities calculated in Figure 2 are shown in Figure 3. These values are not constant since the interior will cool as the orbit decays. However, the decay time is relatively short (between 1 and 10 Ma) for any viscosity structure. Thus, if a resonance passage had occurred early in Tethys' history, it would have little effect on Tethys' current state.

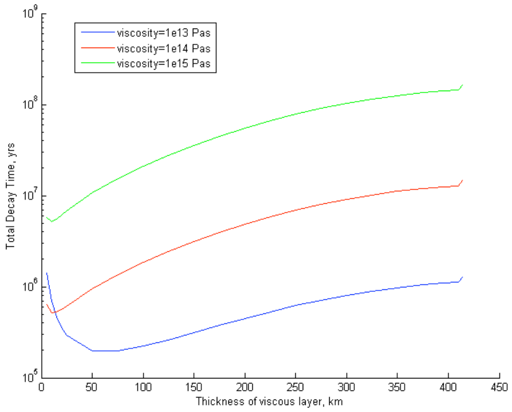

Figure 3: Total time for orbital eccentricities to decay from required eccentricities in Figure 2 to zero. The internal structure of the model was held fixed for this calculation.

From tidal heating models, there is a minimal difference in tidal heat production between a three-layer model and a four-layer model with a relatively thick viscous layer. However, tidal stressing alone cannot account for the MPa stresses associated with flexure of the rigid crust [3]. Diurnal tidal stresses are negligible if the viscous layer is thick, and even with a thin ice shell these stresses are two orders of magnitude too small (Figure 4). On the other hand, solidification of a liquid ocean could easily generate the MPa stresses required [8].

Our preliminary results suggest that Tethys most likely is a differentiated body and has had a liquid ocean in its past. The eccentricity of Tethys' orbit was likely perturbed early in its history, perhaps by a resonance with Dione, causing the satellite to heat up through tidal forcing. Subsequent circularization of the orbit would have frozen the interior of the satellite and generated large extensional stresses. Further investigation of the orbital evolution and its coupling with the interior structure will likely provide a more detailed history of Tethys.

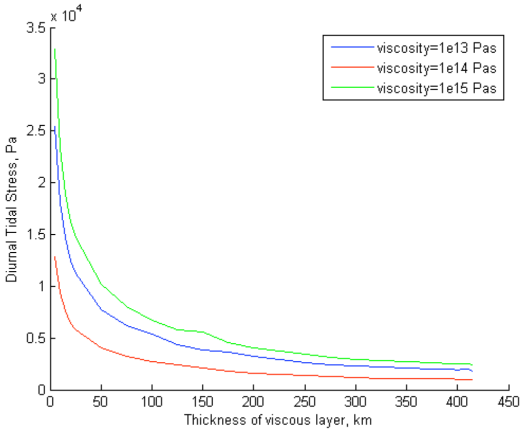

Figure 4: Diurnal tidal stresses as a function of viscous ice layer thickness. The stresses are a function of the internal structure, h_2, and the eccentricities from Figure 2.

References:

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