SHELL THICKNESS VARIATIONS AND THE LONG WAVELENGTH TOPOGRAPHY OF TITAN. F. Nimmo, *Dept. Earth & Planetary Sciences, U.C. Santa Cruz, Santa Cruz CA 95064 (fnimmo@es.ucsc.edu)*, B.G. Bills, *Jet Propulsion Laboratory, Pasadena CA 91109 (bruce.bills@jpl.nasa.gov)*.

Summary The long-wavelength topography of Titan has an amplitude larger than that expected from tidal and rotational distortions at its current distance from Saturn [1]. This topography is associated with small gravity anomalies, indicating a high degree of compensation [2]. Both observations can be explained if Titan has a floating, isostatically-compensated ice shell with a spatially-varying thickness. The spatial variations arise because of laterally-variable tidal heating within the ice shell [3,4]. Models incorporating shell thickness variations result in an improved fit to the observations and a degree-two Love number h_2 consistent with expectations [5], without requiring Titan to have moved away from Saturn. Our preferred models have a mean shell thickness of ≈ 100 km in agreement with the observed gravity anomalies, and a heat flux appropriate to a chondritic Titan [5]. Shell thickness variations of the magnitude inferred can only arise in the absence of convection; we therefore conclude that Titan's ice shell is not convecting at the present day.

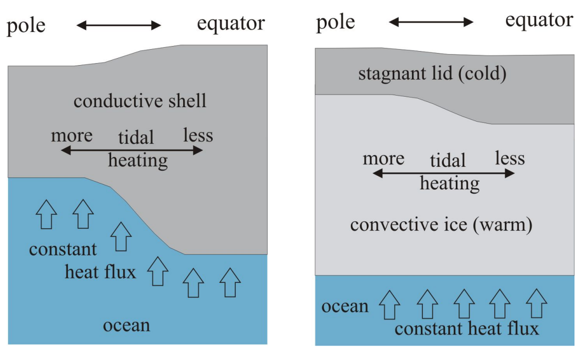

Figure 1: Sketch of ice shell properties for a conductive (left-hand) and convective (right-hand) ice shell. For a tidally-heated isostatic shell, a conductive shell will result in topographic lows at the pole, while a convective shell will yield topographic highs (see text).

Introduction If the bulk of tidal heating occurs in a thin ice shell, heating is maximized at the poles [3,6]. For a conductive shell, shell thickness variations will occur (Airy isostasy); the variable tidal heating will lead to a thinner shell at the pole, and thus negative topography. For a convective shell, the shell thickness will be constant but the mean shell density will vary (Pratt isostasy). The (cold) stagnant lid will be thinner at the pole, the (warm) convecting layer will be thicker, and topography will be positive. Figure 1 illustrates these arguments schematically.

Fig 2a shows the measured topography of Titan [1], and Fig 2b shows the predicted tidal/rotational topography for a reasonable Love number h_2=1.2 [5]. The observed topographic amplitude is larger, with the poles in particular being significantly more negative than expected. It therefore appears that a conductive shell is likely to match the observations much better than a convective shell. This conclusion will be true irrespective of the model details; if Titan's topography is isostatic and tidal heating is concentrated in the shell, then the fact that Titan's poles are low is strong evidence that the ice shell is not convecting.

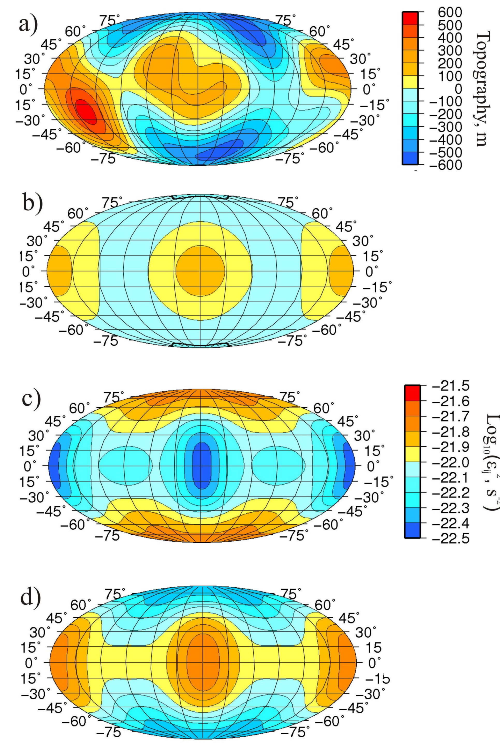

Figure 2: a) Titan topography, from $l = m = 4$ spherical harmonic solution of [1]. Colour bar and contour interval (100 m) apply to a),b) and d). Mollweide projection, centred at 180°, longitude is measured westwards. b) Topography due to tidal and rotational deformation alone assuming Love number $h_2 = 1.2$. The RMS misfit to the observed topography is 246 m. c) Square of time-averaged tidal strain rate (ε_{ij}^2, a proxy for the tidal heating rate) calculated using thin shell formulation of [3] and h_2=1.2. d) Model topography including tidal/rotational deformation and Airy isostasy. Here F_b=4.5 $mW\ m^{-2}$, h_2=1.2 and T_b=250 K; mean shell thickness is 100 km. The RMS misfit to the observed topography is 172 m.

Method and Results We use the method of [4] to calculate the topography arising from shell thickness variations generated by spatially-variable tidal heating, using parameters appropriate to Titan [5]. Fig 2c shows the variations in the square of the strain rate, demonstrating that heating is maximized at the poles [3,6]. We vary the basal heat flux F_b, basal temperature T_b and the tidal Love number h_2 to calculate the combined topography arising from shell thickness variations and tidal/rotational distortion. We compare this theoretical topography with that observed to determine the best-fit parameters. Fig 2d shows our best-fit model, which has h_2=1.2, F_b=4.5 $mW\ m^{-2}$, a mean shell thickness of 100 km and a basal temperature of 250 K. These values are all consistent with previous estimates of these parameters [5]. The RMS misfit to the observations is 30% smaller than the model shown in Fig 2b.

The fact that the tidal distortion (Fig 2b) and tidal heating (Fig 2c) have rather similar patterns suggest that there ought also to be a tradeoff between h_2 and F_b. Increasing F_b will result in smaller shell thickness variations and isostatic topography, while increasing h_2 will result in larger tidal/rotational topography. Fig 3 plots how the best-fit values of h_2 and F_b trade off against each other for different values of basal ice viscosity. As expected, an increase in F_b results in a corresponding increase in h_2 for the best-fit model.

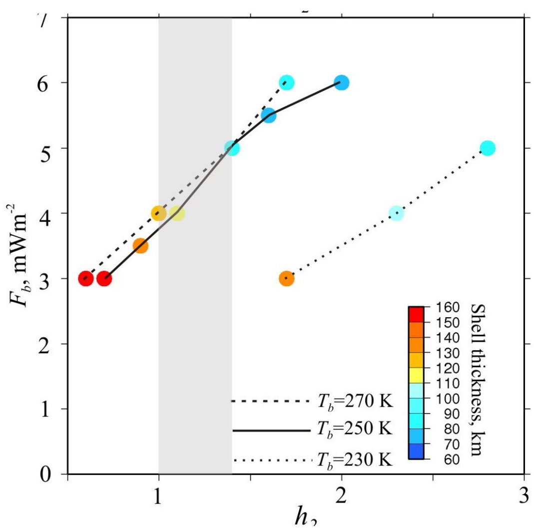

Figure 3: Minimum misfit F_b as a function of h_2 for three different basal temperatures T_b. Basal ice viscosity is 1.6×10^{15}, 1.5×10^{14} and 1.9×10^{13} $Pa\ s$ at T_b=230 K, 250 K and 270 K, respectively, for our nominal ice grain size of 0.15 mm (see text). Colours denote mean shell thickness $\bar{D}$. Shaded region denotes likely range of Titan Love numbers [1,5].

The results presented above all used the $l = m = 4$ expansion of [1]. We also carried out similar calculations with the $l = m = 3$ and $l = m = 6$ expansions to check that our results were robust. For tidal/rotational distortions only, the best fit h_2 values were 3.3 and 4.0, respectively, too large to be realistic. When shell thickness variations were included, taking T_b=250 K and F_b=4.5 $mW\ m^{-2}$ we obtained best fit values for h_2 of 1.1 and 1.2, respectively. These values are not significantly different from our nominal results, although the misfits are actually slightly worse in both cases (204 m and 187 m, respectively).

Implications An important assumption of our model is the existence of a subsurface ocean. Although such an ocean has already been advocated on both theoretical and observational grounds, our results provide another line of evidence that such an ocean does in fact exist.

Perhaps the most surprising conclusion of our study is that convection of the ice shell is not currently occurring. One likely explanation for this phenomenon is simply that Titan's ocean is ammonia-rich [5], and thus has a low temperature and a basal ice shell viscosity that is sufficiently high that convection is inhibited.

Lateral shell thickness variations will influence the moments of inertia of the satellite, which in turn will affect the tidal and rotational torques acting on it. Taking our preferred model (Fig 2d), we obtain a value of $(B - A)/C \approx 7 \times 10^{-8}$, suggesting that non-synchronous rotation is only marginally likely at best [7]. Titan's almost constant surface temperature results in a polar topographic low, while models for Europa predict a polar high [3,4]. This makes Titan rotationally stable, and unlikely to experience true polar wander.

Over time, eccentricity damping will result in a reduction in tidal heating and thus ice shell thickening. The current conductive timescale for such thickening is a few hundred Myr, implying that Titan's ice shell could have been much thinner in the relatively recent geological past. This possibility is important because of the measured concentrations of CH_4 and ^{40}Ar in Titan's atmosphere, thought to be indicative of outgassing from the interior [8]. A thick, conductive ice shell is likely to form a barrier to such transport. It has been suggested [8] that an episode of ice shell convection within the last 1 Gyr could transport sufficient CH_4 and ^{40}Ar to account for today's values. Since convection still implies the presence of a stagnant lid we suggest that, alternatively, transport may have occurred when Titan's ice shell was conductive, but thinner than the present day. Shell thickening can result in the development of large extensional stresses and fractures [9]; in a cold, high viscosity ice shell fractures may penetrate to significant depths and form pathways for volatile migration (as appears to happen at Enceladus). Investigating the full behaviour of a coupled thermal-orbital model is a complicated task [8] and will not be further pursued here.

References

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