Estimates for Tethys' moment of inertia, present day heat flux, and interior structure from its long-wavelength topography

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Abstract

Which outer solar system satellites have sub-surface oceans is an important geophysical and astrobiological question. We developed a technique that translates a moon's long-wavelength topography (Nimmo et al. 2011) into an inferred heat flux distribution, indicating whether there is a rigid or liquid layer beneath the ice shell (Beuthe 2013). Our technique independently detects Titan and Enceladus' sub-surface global oceans and finds moment of inertia (MoI) and heat flux estimates consistent with past results (Iess et al. 2010; Nimmo & Bills 2010; Iess et al. 2014). Here we focus on Tethys (for which gravity information is lacking) and infer a normalized MoI of 0.33 and no ocean. We find a present-day surface heat flux of 1.1 mW/m2 that implies either a highly dissipative interior or a higher obliquity than predicted (Chen et al. 2014). To translate topography into tidal heating, we first remove the effects of tidal stretching and rotational flattening—a function of the moon's MoI. We then invoke isostasy (constant pressure at depth per Hemingway & Matsuyama 2016) to translate the residual topography into tidal heating, approximated as basal heat flux under the ice shell. As tidal heating only varies in spherical harmonic degrees 2 and 4, we only translate the topography of these degrees. The inferred variation in basal heat flux necessary for surface topography depends on the assumed average basal heat flux as well as whether we assume Pratt (density-variation-driven) or Airy (buoyancy-driven) isostasy. We only expect a sub-surface ocean with Airy isostasy. Finally, we perform a multi-linear regression upon the basal heat flux distribution to characterize it in terms of the weights of three basis functions (Beuthe 2013) that describe spatial variations in tidal heating, and subsequently if there's an ocean. We explore the parameter space of average basal heat flux and MoI to determine the best-fit interior, and check density profiles for viability. We conclude that Tethys undergoes Pratt isostasy and obliquity tides. Our best-fit model of Tethys' internal structure is a 66 km thick layer of porous ice, atop 165 km of solid ice, with an ice/rock core of 300 km radius. We have also applied the model to Mimas but will need to use a numerical tidal code to determine which of two conflicting results is more likely.

P53C-3471: Estimates for Tethys' Moment of Inertia, Present Day Heat Flux, and Interior Structure from its Long-Wavelength Topography

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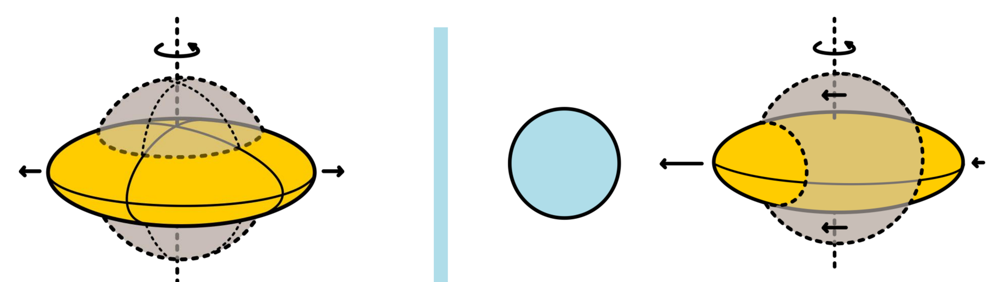
1. Does Tethys have a Sub-Surface Global Ocean?

- Whether or not a moon has a sub-surface global ocean can provide insights on its formation, history, and habitability. Titan and Enceladus have such oceans.
- Tethys' large-scale topography (shape) is strong in the same wavelengths as tidal heating (Nimmo *et al.* 2011, Beuthe 2013). **We developed a method to translate topography to heating distribution**, which indicates if there is an ocean.
- Our model detects Titan and Enceladus' oceans, but **no ocean for Tethys**.

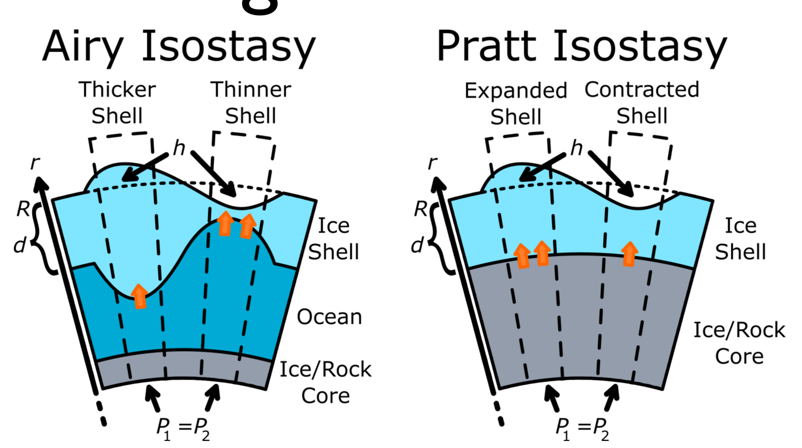
2. Translating Shape to Tidal Heating

2A. Remove Major Contributions to Shape



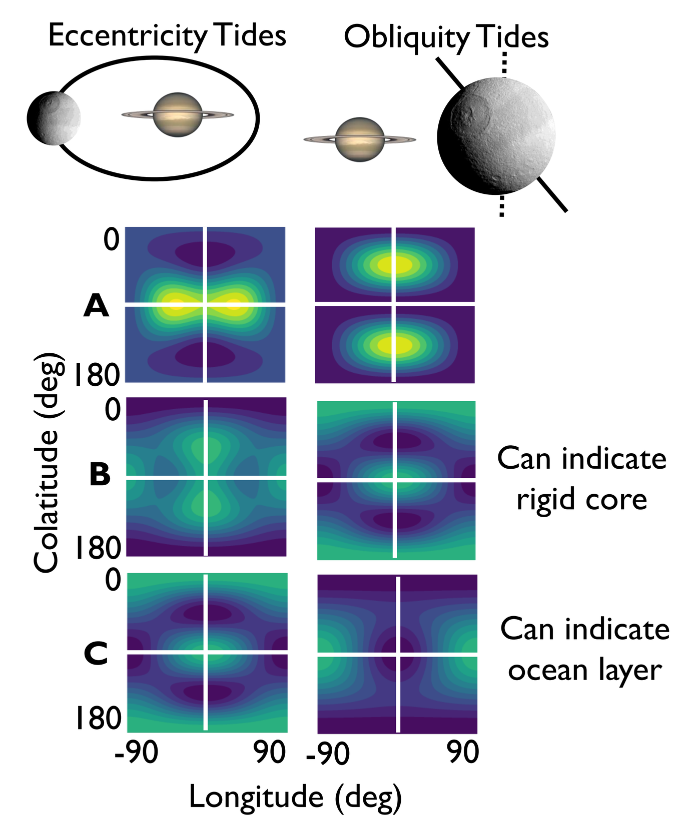
Rotational flattening (left) and the tidal bulge (right) both contribute major Degree 2 (wavelength = circumference/2) shapes to topography. Both relate to moment of inertia.

2B. Translate Residual Shape to Heating Distribution



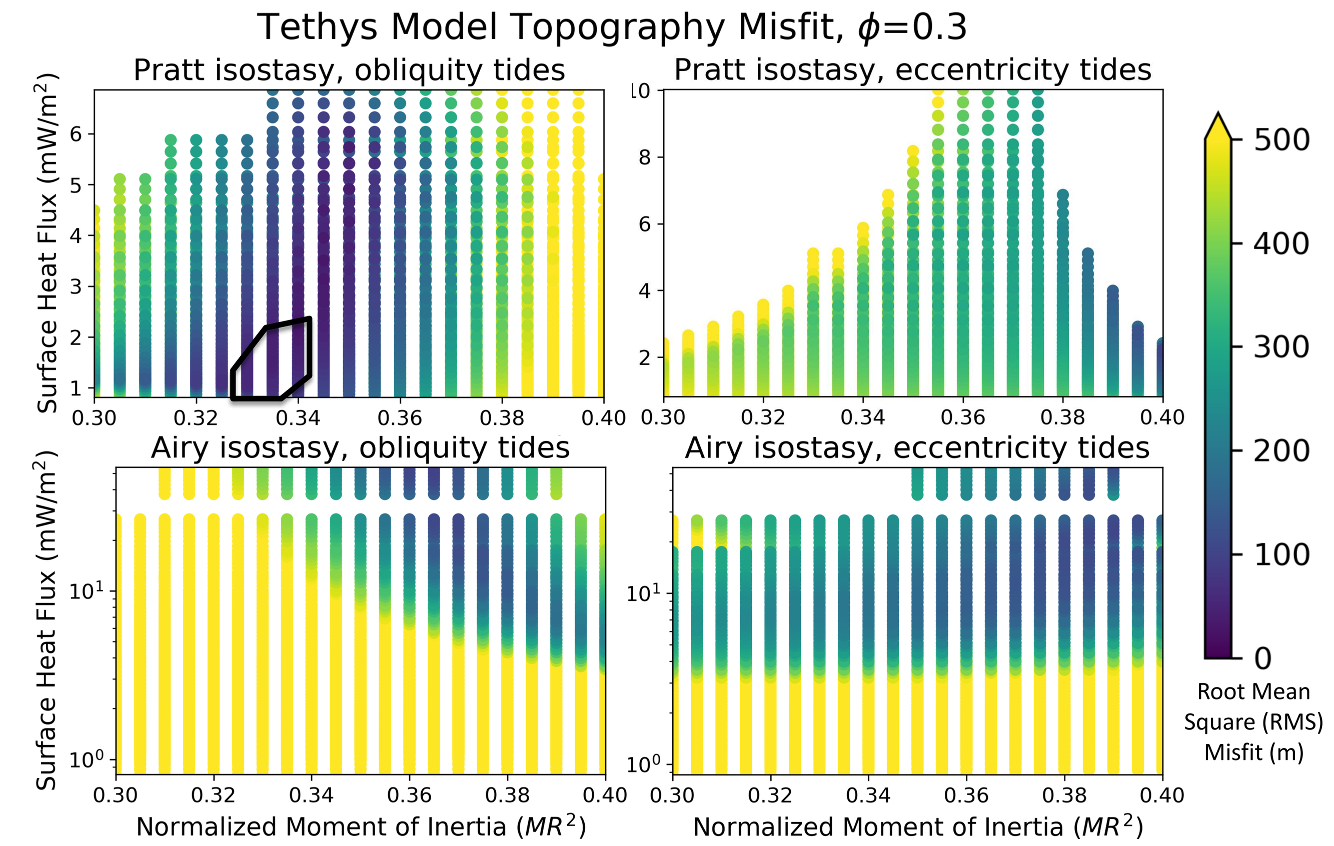
Topography translates to heating (represented relatively as orange arrows above) via isostasy: the principal that pressure at depth is constant (e.g. Hemingway & Matsuyama 2017). Airy isostasy assumes a more-fluid compensating layer. Pratt isostasy assumes density variation due to thermal expansion or contraction of the ice shell.

2C. Fitting for Tidal Heating Patterns

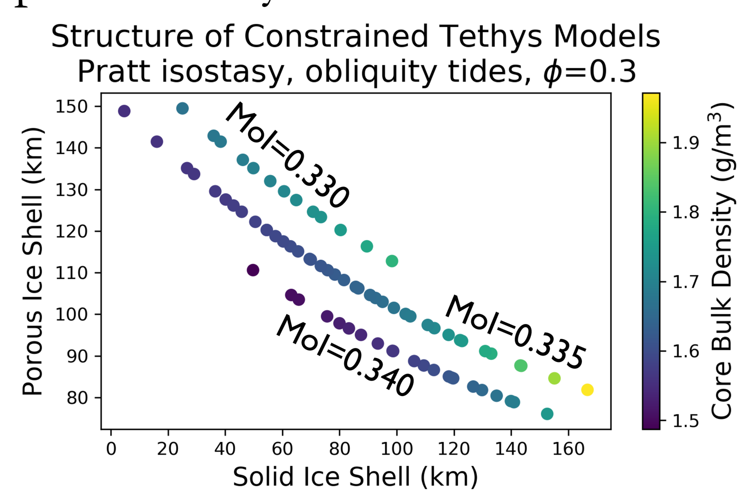


Beuthe (2013) demonstrated tidal heating is the linear combination of 3 heating patterns (A, B, C). These patterns are different if tides are from eccentricity (left) or obliquity (right). We perform a multi-linear regression on our inferred heating pattern to check if it is tidal heating (*i.e.* a high goodness of fit), and to calculate is heating pattern weights. These indicate if the layer beneath the ice shell is rigid or liquid.

3. Results



For each isostasy and tide type combination, we vary upper layer porosity, total ice shell thickness, average temperature at the base of the ice shell, and Tethys' moment of inertia (MoI). All but MoI are captured in the average heat flux. **Above** are all results for the 30% upper layer porosity (φ). **The enclosed region** contains results where spherical harmonic coefficients of forward modeled topography are within 3 standard deviations of that observed, the derived heating pattern is closest to what may be caused by tidal heating, and where ice shell thicknesses match between those predicted by thermal conduction and the moment of inertia.



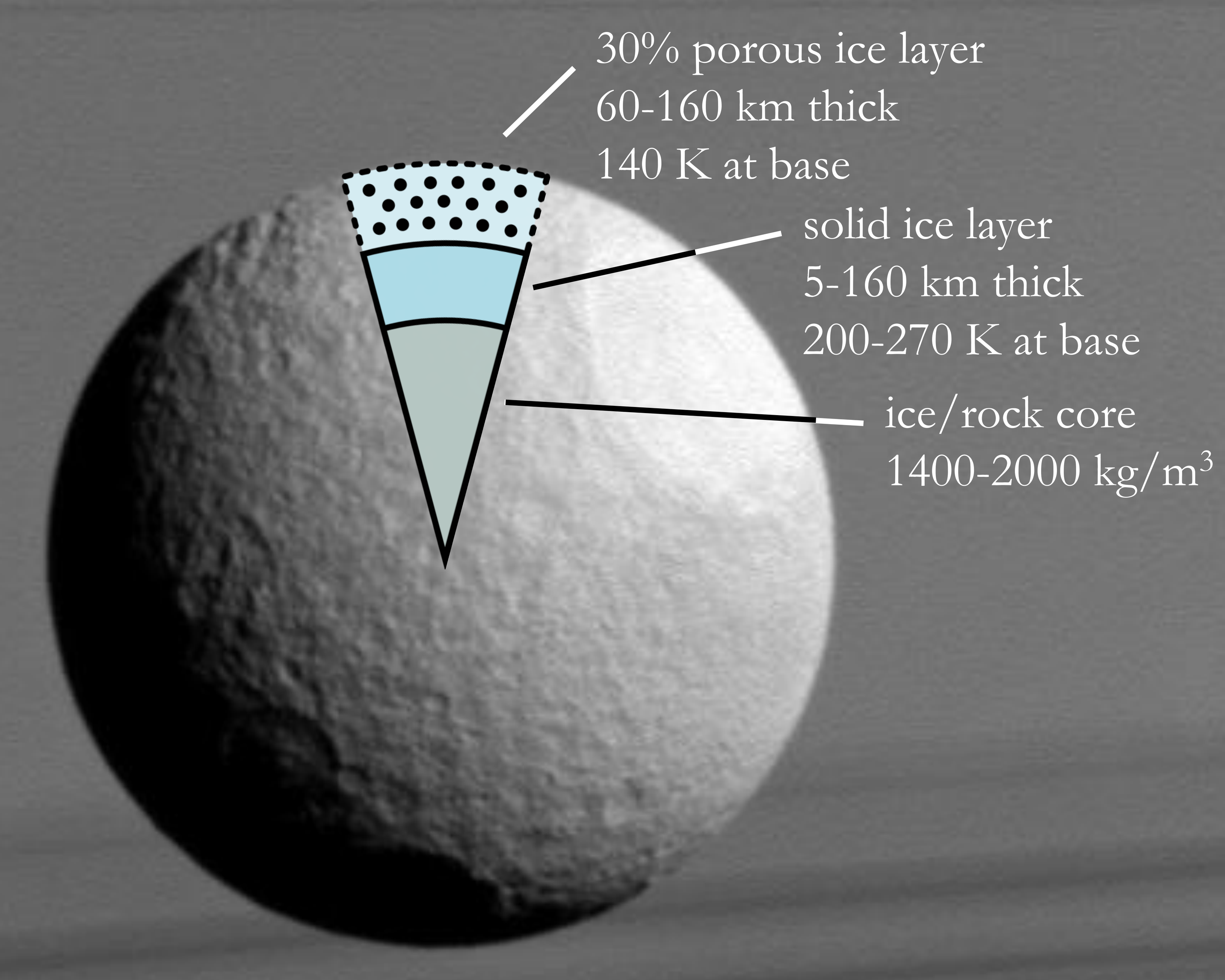
Left, we survey the range of porous and solid ice shell thicknesses from the best-fitting results and calculate the resulting core's bulk density. The thinnest solid ice layers have an average basal temperature of 200 K, the thickest 270 K.

To achieve an average surface heat flux of 1-2 mW/m², **Tethys is either highly dissipative or has a higher obliquity** than predicted by a Cassini state (Chen *et al.* 2014). The shape may be frozen-in from an earlier period of heating.

Works Cited: Beuthe (2013) *Icarus 223*, 308. Chen *et al.* (2014) *Icarus 229*, 11. Hemingway & Matsuyama (2017) *GRL 44*, 7695. Nimmo *et al.* (2011) *JGR: Planets 116*(E11)

Conclusion:

Tethys' shape implies a **thick porous surface layer** and **strong tidal heating**; the latter due to a higher **obliquity** than currently expected. There is **no subsurface global ocean.**



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