# INVESTIGATING TETHYS' HEAT FLUX HISTORY BY ANALYZING ITHACA CHASMA FLEXURE.

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**Introduction:** The surface of the mid-sized (*D*: 1062 km) Saturnian satellite Tethys is dominated by impact craters and the hemisphere-spanning Ithaca Chasma, which is a system of large extensional faults (Fig. 1a-c). Heat flux estimates derived from flexure associated with the equatorial section of Ithaca Chasma's northern limb (18-30 mW m$^{-2}$ [1]), are higher than expected from thermal history models [2].

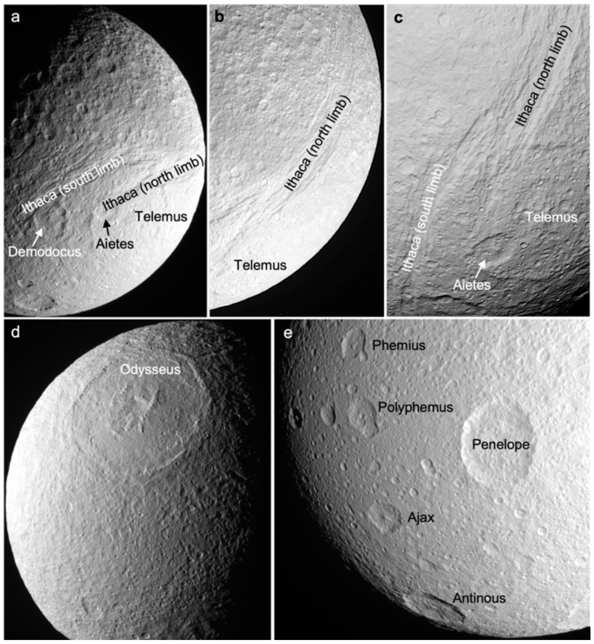

*Fig. 1: Cassini ISS images of Tethys.*

Perhaps Tethys' elevated heat flux could be a result of a 3:2 paleo resonance with Dione resulting in a higher past eccentricity [3]. A 2:1 mean motion resonance may have also occurred and could explain the high heat flux and the formation of Ithaca [4]. As discussed in [5], this former resonance may have broken due to the impact event that formed Odysseus basin (*D*: 445 km, Fig. 1d), possibly resulting from a low velocity collision with a neighboring satellite. Therefore, Tethys may have experienced a heat pulse before the formation of Odysseus. As summarized in [6], the high relaxation fractions of some impact basins (Fig. 1c-e) show that high heat fluxes affected some regions on Tethys, but may have varied spatially and/or temporally.

**Motivation:** We further investigated how Tethys' heat fluxes varied temporally and spatially. Telemus is overprinted by Ithaca Chasma in the southern mid-latitude region (Figs. 1c & 2a), showing that this basin predates the chasma. This overprinting relationship allows us to compare heat flux estimates for two different periods in Tethys' history, without needing to account for spatial variations. This analysis also provides an opportunity to investigate whether there are spatial heat flux variations between Ithaca's northern and southern limbs, which provides insight into whether these two regions formed at similar times and/or under similar conditions. We also investigated whether $NH_3$-bearing species are exposed on Tethys' surface from ground-based observations, and how lithospheric $NH_3$ may affect the resulting heat fluxes. Addionally, we investigated how lithospheric porosity modifies our heat flux estimates.

**Flexural Modeling:** We used flexural modeling to estimate the elastic thicknesses and heat fluxes of Ithaca Chasma in six locations (Fig. 1a) by utilizing a similar technique to studies that have investigated flexure on icy bodies [e.g., 1, 7-10]. The elastic thicknesses reflected by Ithaca Chasma flexure in our study area range from 4.1±0.3 km to 6.4±0.4 km (Fig. 2b).

The elastic thicknesses are similar spatially across the six locations (a-f) analyzed. The region with the highest heat fluxes, and therefore the lowest elastic thicknesses, correspond to Study Locations c, d, and f. Study Location f most directly overprints Telemus Basin, and is located on the east rim of Ithaca Chasma.

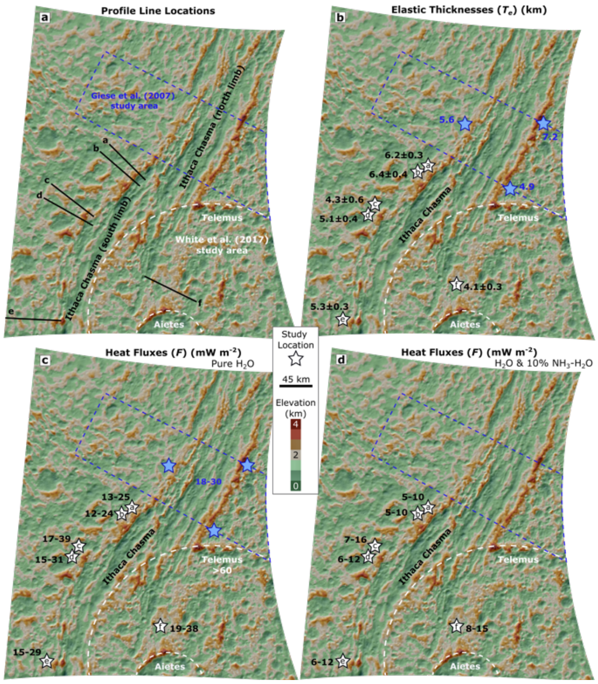

*Fig. 2: Digital elevation model (DEM) showing profile line locations and results for elastic thicknesses and heat fluxes.*

If Tethys' lithosphere is composed of mostly pure $H_2O$ ice, then the resulting heat fluxes in our study area range from 12-39 mW $m^{-2}$. In contrast, if the lithosphere consists of small amounts of ammonia hydrates mixed with the $H_2O$, then the estimated heat fluxes are lower, ranging from 5 to 16 mW $m^{-2}$ for a thermal conductivity of 2 W $m^{-1}$ K assuming 10% ammonia hydrates. These heat fluxes are even further reduced if more ammonia hydrates are present. However, we find little evidence for ammonia hydrates on Tethys in ground based spectra collected by SpeX, so the estimates assuming ammonia hydrates within the lithosphere are unlikely.

If lithospheric porosity is assumed for Tethys', then the estimated heat fluxes are reduced. In this scenario and assuming a pure $H_2O$ ice lithosphere, the heat fluxes in our study region would range from 12-38 mW $m^{-2}$ for 5%, 11-35 mW $m^{-2}$ for 15%, and 10-33 mW $m^{-2}$ for 25% porosities. However, if a lithosphere with 10% $NH_3$-hydrates is assumed, the heat fluxes would range from 5-15 mW $m^{-2}$ for 5%, 4-14 mW $m^{-2}$ for 15%, and 4-13 mW $m^{-2}$ for 25% porosities.

**Possible Heat Flux History:** We developed a possible timeline that displays how Tethys' heat fluxes may have changed over its geologic history (Fig. 3). We developed this timeline by investigating relative and modeled (absolute) age estimates of surface features. We incorporated the absolute age estimates derived from crater counts (assuming a lunar-like cratering chronology) for Ithaca [1] and Odysseus [11], and the relative age estimates between the impact features [6].

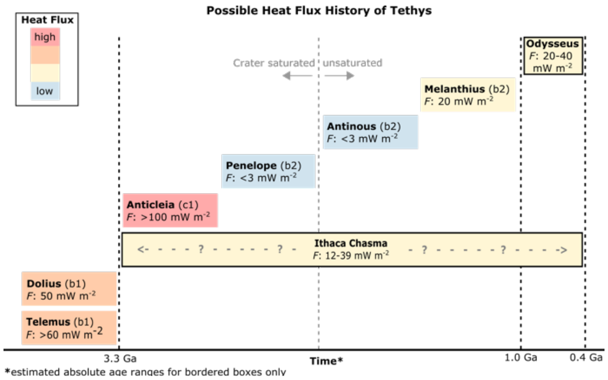

*Fig. 3: Possible heat flux history of Tethys (assuming pure $H_2O$ ice and 0% porosity). Absolute ages [1, 11] assume a lunar-like cratering chronology. However, recent work [13] indicates that Saturn-orbiting debris resulted in higher than expected crater densities. Therefore, future work may point to younger modeled (absolute) age estimates.*

However, the relative age estimates based on crater densities are only applicable for basins that are not near crater saturation (Antinous, Melanthius, and Odysseus), while those near crater saturation (Telemus, Dolius, Anticleia, and Penelope) are indistinguishable from each other using this crater counting technique [6]. Therefore, to estimate the relative ages between these four crater saturated impact features, we utilized estimated ages of Tethys' geologic units determined by [12]. As summarized in [12], the most ancient basin and crater materials are Units b1, the heavily degraded basin material, and c1, the heavily degraded crater material. The younger basin and crater materials include Unit b2, the partly degraded basin material.

Based on these absolute and relative ages, it is possible that Telemus and Dolius impact basins formed around similar times in Tethys' history and before the formation of Ithaca Chasma (Fig. 3). Telemus and Dolius have similar heat fluxes of >60 and 50 mW $m^{-2}$, respectively [6] and are not proximal (Fig. 1). Following the formation of these basins, Anticleia may have formed, and reflects a high heat flux ($F$: >100 mW $m^{-2}$ [6]), and Ithaca Chasma ($F$: 12-39 mW $m^{-2}$) may have formed around this time (although it could be younger). Next, Penelope and then Antinous may have formed, and they both reflect low heat fluxes ($F$: <3 mW $m^{-2}$ [6]). Subsequently, Melanthius ($F$: 20 mW $m^{-2}$ [6]) followed by Odysseus ($F$: 20-40 mW $m^{-2}$ [6]) formed.

Heat flux estimates for Ithaca Chasma are comparable to Melanthius and Odysseus, Tethys' two youngest impact basins. If heat fluxes were spatially consistent between these features when they formed, then perhaps Ithaca formed around the same time as Melanthius and Odysseus. However, crater densities [1, 11] and Odysseus' degradation state and spectral properties [12] suggest that this impact basin is younger than Ithaca. Therefore, perhaps the age of Ithaca Chasma is most comparable to Melanthius (Fig. 3).

However, perhaps there were significant spatial variations Tethys' heat fluxes in addition to temporal variations. Spatial variations in heat fluxes may reflect nonuniformity of Tethys' internal structure, variations in lithospheric porosities or compositions, and/or variations in regolith thicknesses. Therefore, additional studies that compare geologic features of similar ages are needed to determine how heat fluxes varied spatially in order to better constrain Tethys' thermal history.

**References:** [1] Giese et al. (2007) *GRL*, 34, 24. [2] Multhaup & Spohn (2007) Icarus, 186, 2. [3] Chen & Nimmo (2008) GRL, 35, 19. [4] Hussmann et al. (2019) Icarus, 319, 407-416. [5] Zhang & Nimmo (2012) Icarus, 218, 1, 348-355. [6] White et al. (2017) Icarus, 288, 37-52. [7] Ruiz (2005) Icarus, 177, 2. [8] Peterson et al. (2015) Icarus, 250, 116-122. [9] Beddingfield et al. (2022) PSJ, 3, 5, 106. [10] Beddingfield et al. (2022) PSJ, 3, 7, 174. [11] Kirchoff & Schenk (2010) Icarus, 206, 2, 485-497. [12] Stephan et al. (2016) Icarus, 274, 1-22. [13] Ferguson et al. (2020) JGR: Plan., 125, 9.