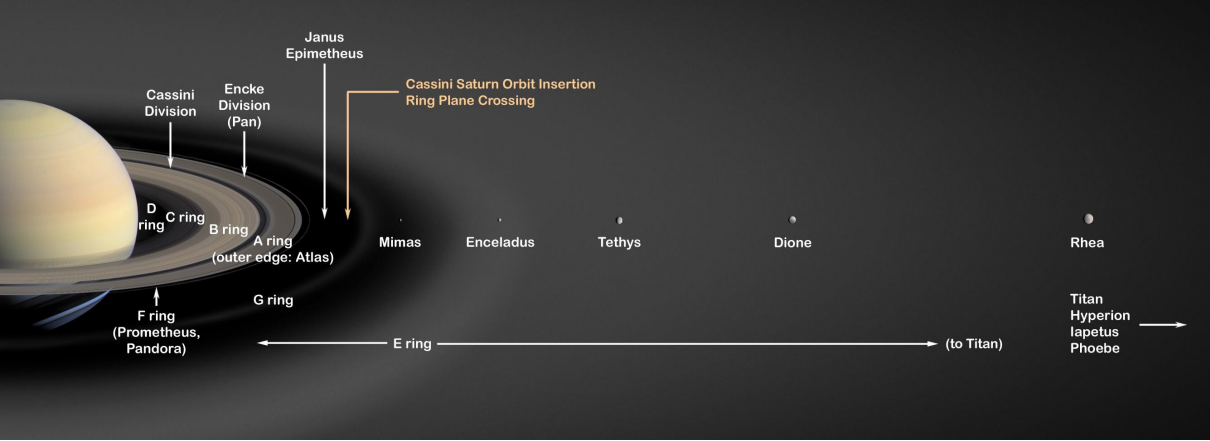
The jets of Enceladus

- discovery
- what the faults they emerge from tell us
- what their pulsatility tells us
- what their composition tells us

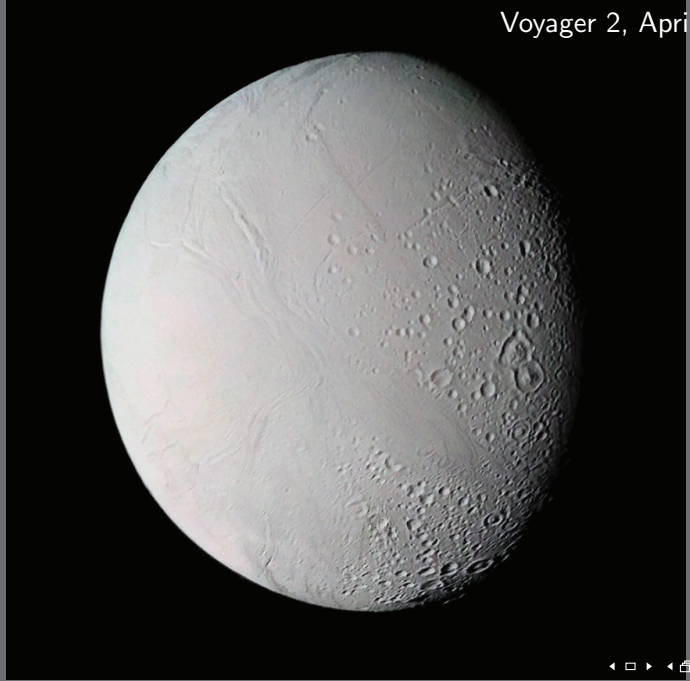


Enceladus in the Saturn system

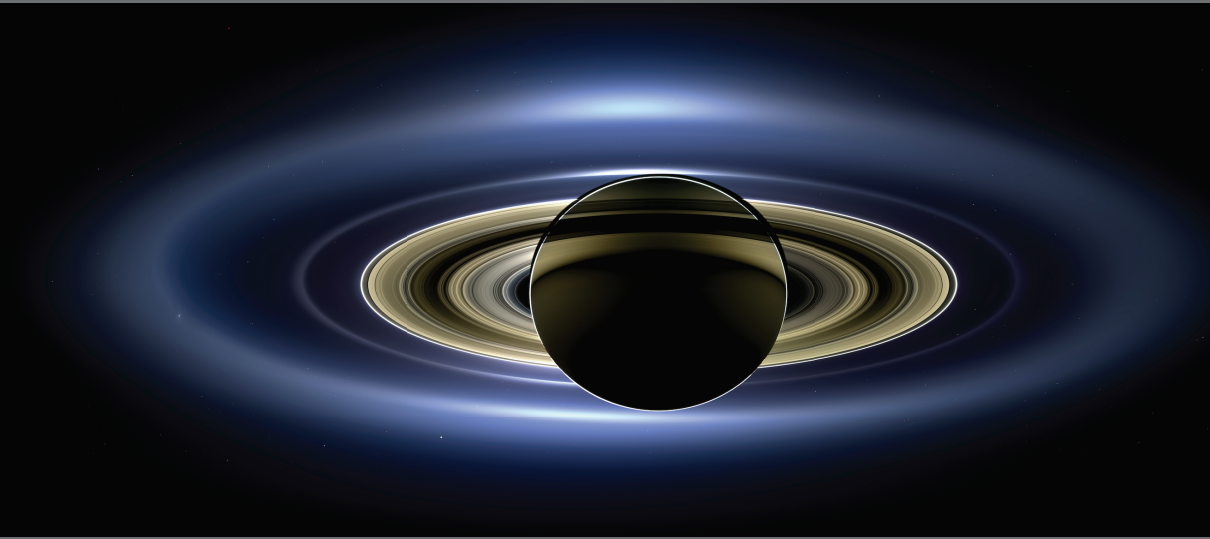
Saturn's (♄) sixth moon, $R_s = 252$ km, $T \simeq 33$ h, $e \simeq 5 \times 10^{-3}$

embedded in the densest part of Saturn's diffuse E-ring,

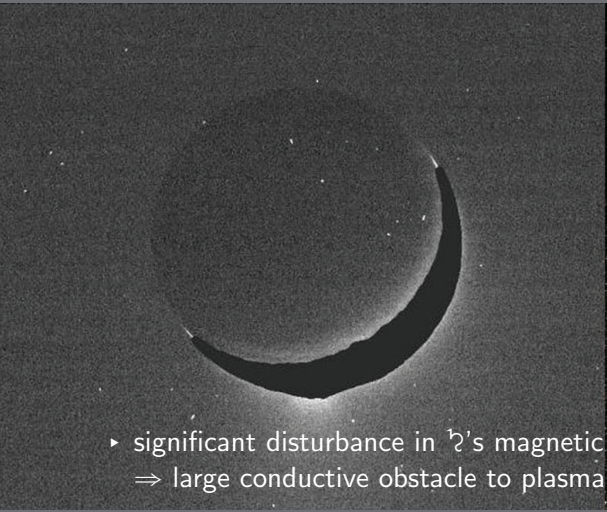
Voyager 2: contrast between relatively young regions near equator and older, high latitude regions, very much unlike Mimas' ancient cratered surface.

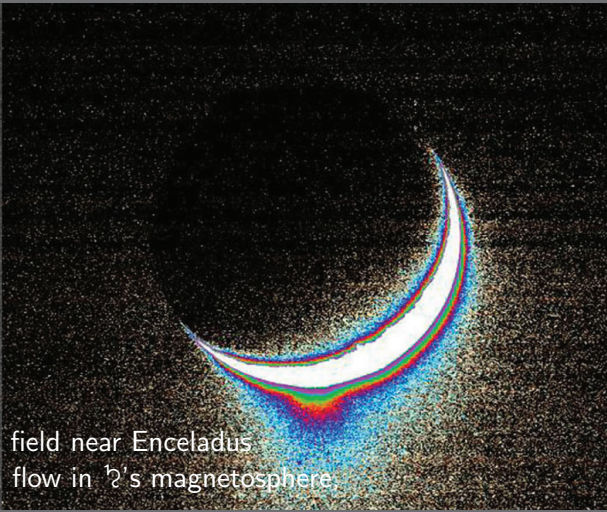

Voyager 2, April 26, 1981

Parc de VERSAILLES – Bassin de l'Encelade

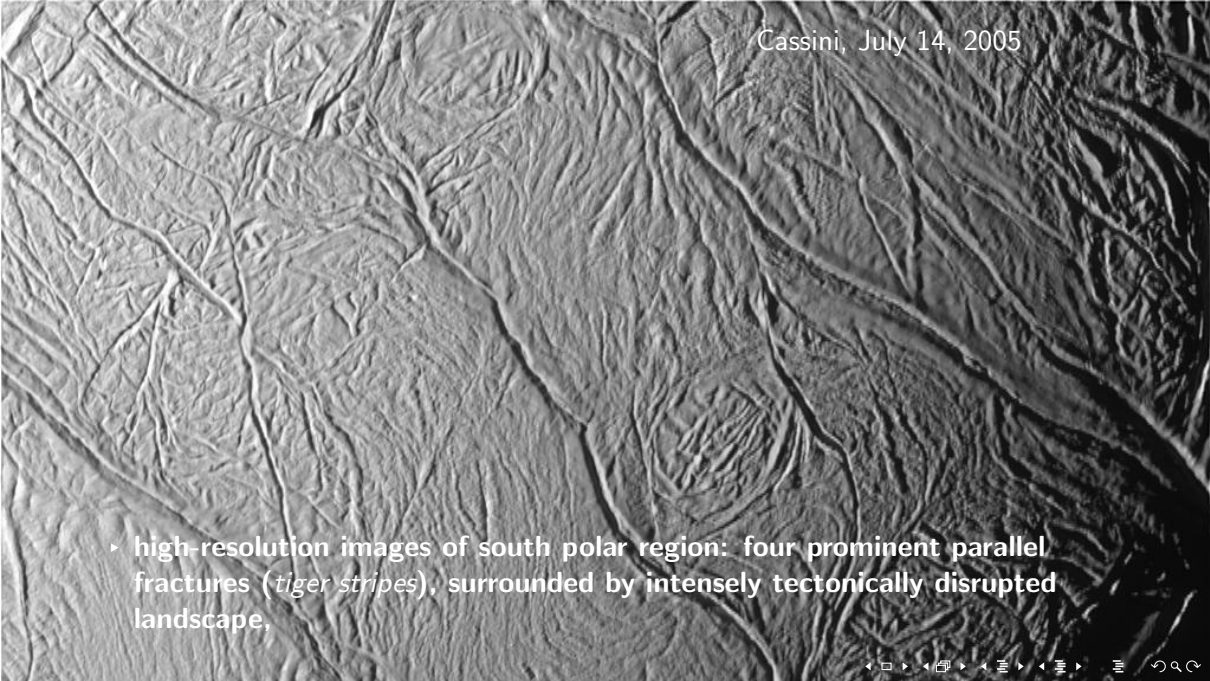


Enceladus by Cassini



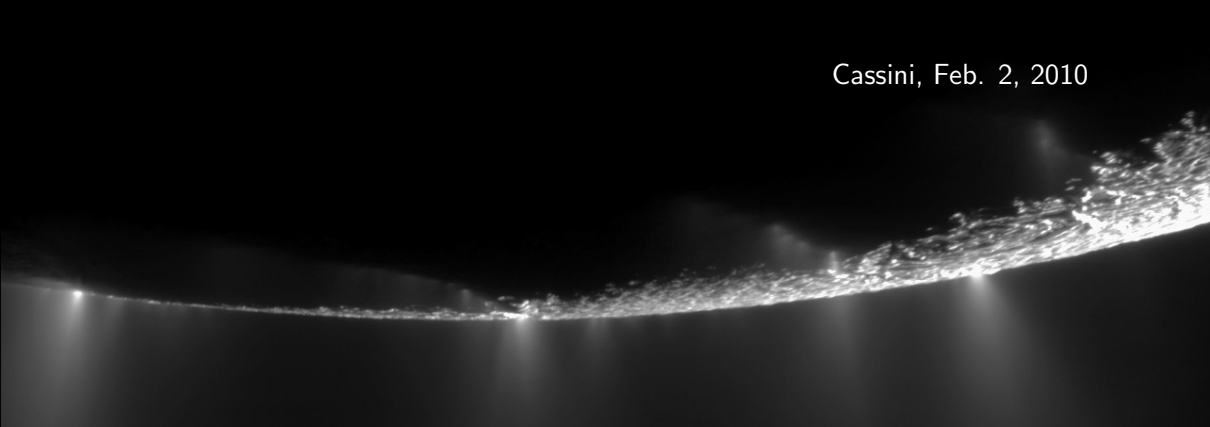


- significant disturbance in ♄'s magnetic field near Enceladus
  $\Rightarrow$ large conductive obstacle to plasma flow in ♄'s magnetosphere.
- distant imaging: evidence for cloud of material above south pole.



- **high-resolution images of south polar region: four prominent parallel fractures (*tiger stripes*), surrounded by intensely tectonically disrupted landscape,**

- thermal emission maps from infrared meadurements:
  tiger stripes much warmer than surroundings,



plus (especially during extended mission after 2008), further characterization from distant imaging:

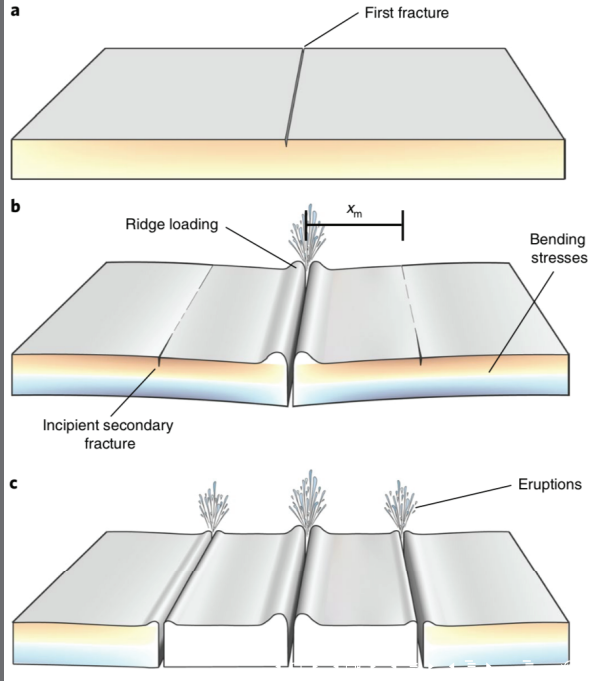
- UV spectroscopy: absorption by water vapor,
- narrow angle camera: individual jets emanating from tiger stripes.

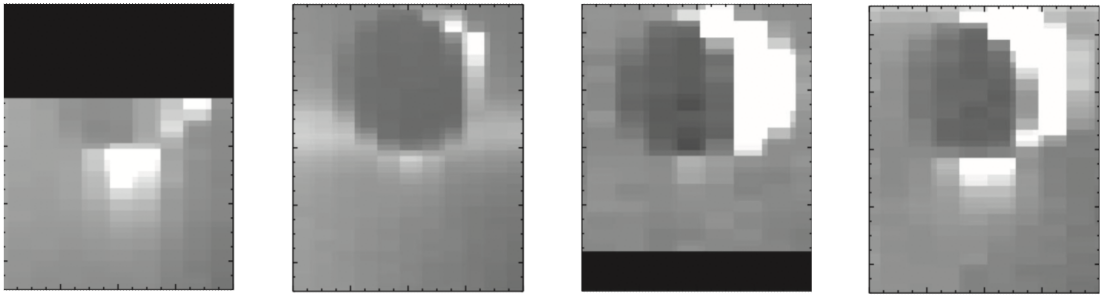
it is likely that the faults (their origin, their geometrical pattern) are indicative of Enceladus' history

the formation of the first fault at one of the pole (thinner ice shell) might imply overpressurization of the ocean during a stage of ice shell thickening (Hemingway et al., 2019) ,

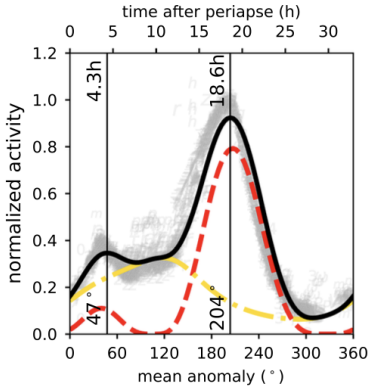
other cascading parallel fractures would then be produced by loading of the ice by erupted ice,

how/when such a hydrosphere cooling stage occurred remains unknown. . .

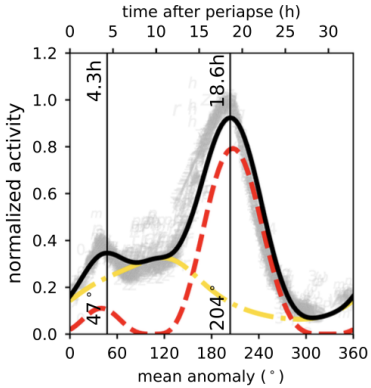




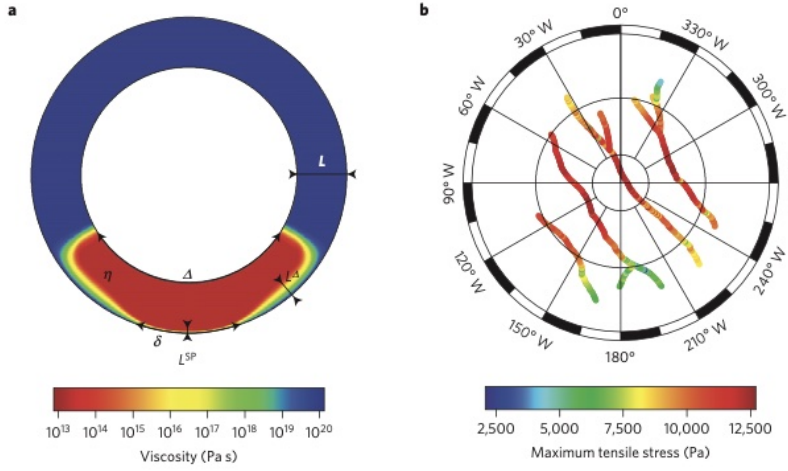
the plume is brighter near the apocenter of its orbit which suggests tidal control of its activity (cf. Hedman et al., 2013).



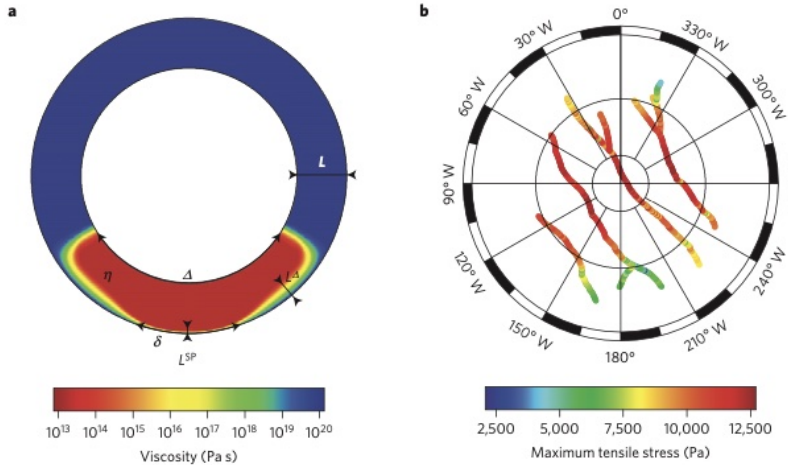
but the maxima are shifted compared to a purely elastic response of the interior (here a figure from Souček et al. (2024) - ignore the red and and yellow curves for now!)...



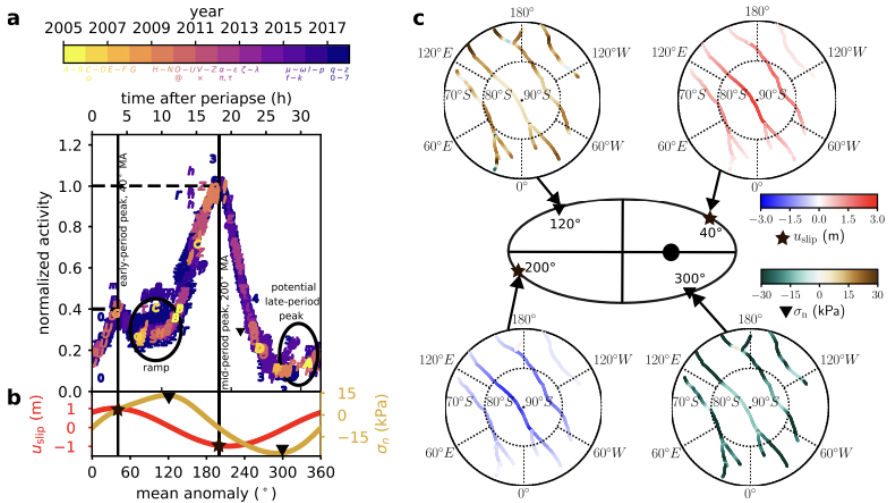
this enables in principle some form of rudimentary tomography of Enceladus interior.



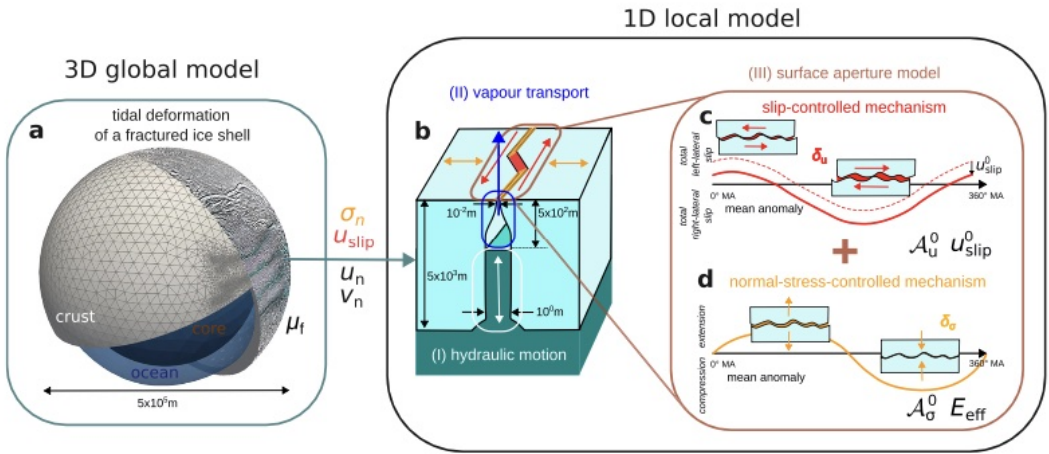
an old attempt by Běhounková et al. (2015)



an old attempt by Běhounková et al. (2015) (proved wrong a few weeks after publication when proof of a global ocean was inferred from the libration of Enceladus).



a more recent attempt by Souček et al. (2024) focussing on the dynamics of the tiger stripes: normal stress and slip



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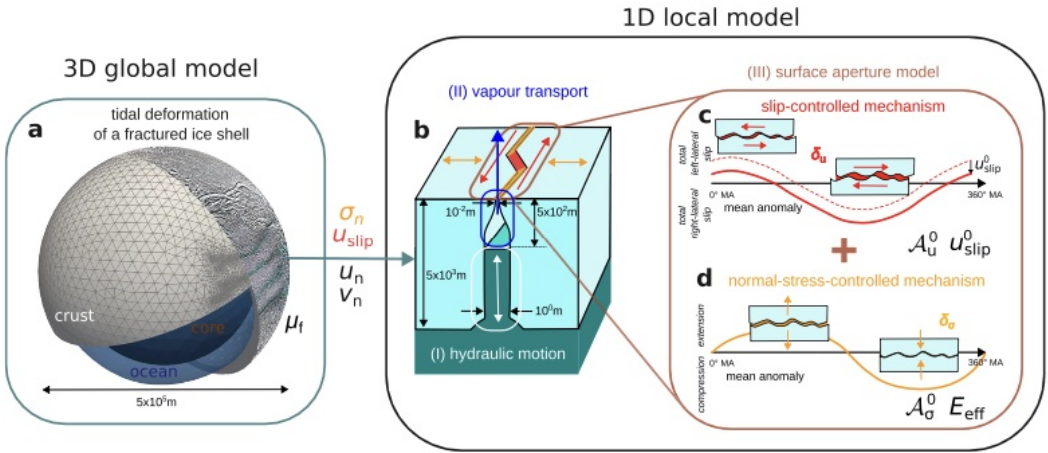
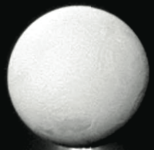
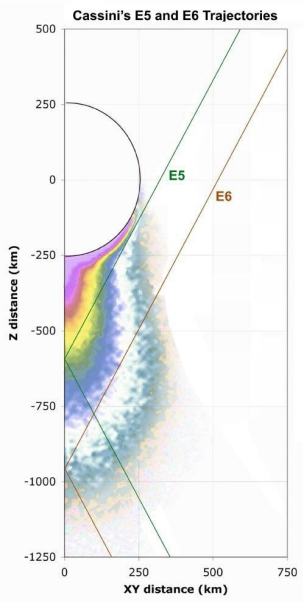


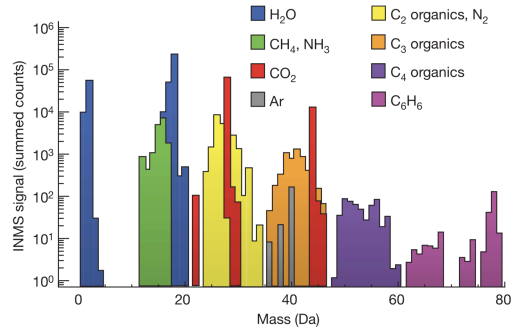
a more recent attempt by Souček et al. (2024) focussing on the dynamics of the tiger stripes: normal stress and slip (not wrong yet!).

Cassini, July 25, 2011 (plume lit by Sun, Enceladus lit by Saturn)

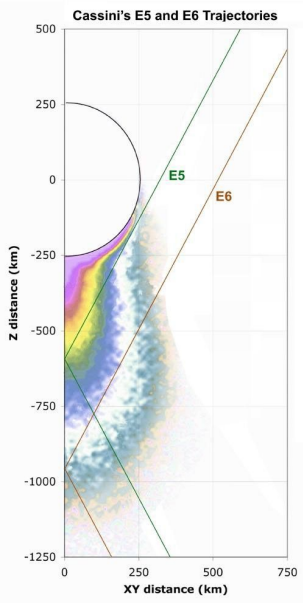


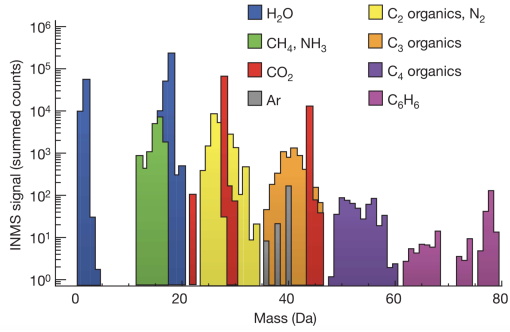
besides UVIS, in-situ chemical analysis has been performed via the Ion and Neutral Mass Spectrometer (INMS) for the gaz phase and the Cosmic Dust Analyser (CDA) for the solid grains $\Longrightarrow$ these reveal an ocean composition for the plume





INMS gas composition during the E5 flyby (Oct. 9, 2008) as interpreted by Waite et al. (2009) (later proved to be affected by fragmentation of solid grain with organics, especially for masses larger than 40 Da).

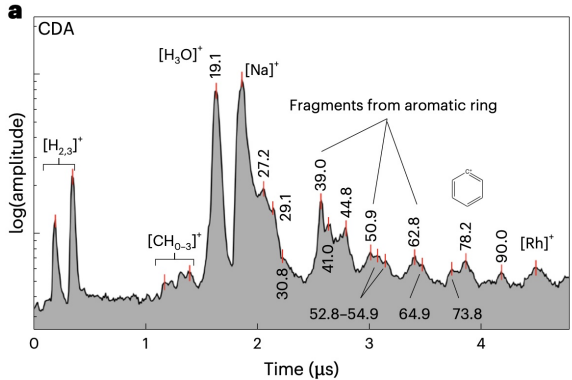




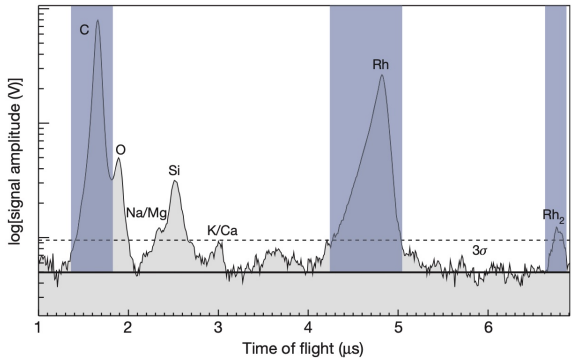
H_2O	CO_2	CH_4	NH_3	H_2
96-99 %	0.3-0.8 %	0.1-0.3 %	0.4-1.3 %	0.4-1.4 %

Cosmic Dust Analyser: the E-ring as a storage ring for plume particles

three families of grains: pure water ice, organic-bearing ice, ice with salts (used to infer ocean composition)



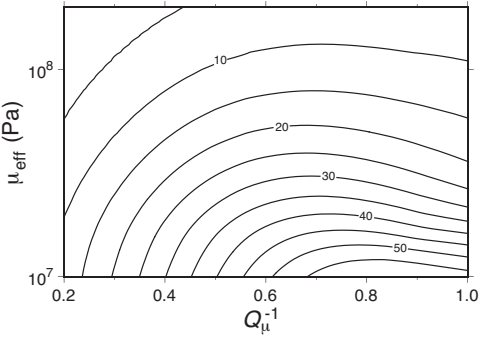
CDA measurements on freshly erupted grains within the plume confirm these findings, here for an organic rich grain during E5 (Khawaja et al., 2025).

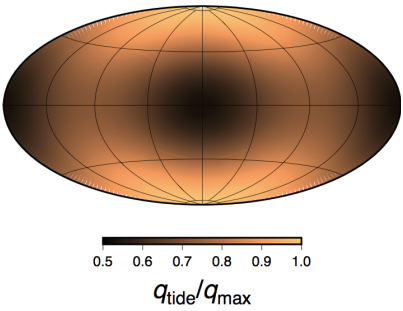


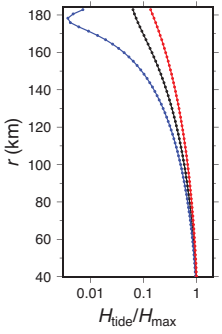
CDA also measured the presence of nanometer size grains (2-8 nm) interpreted as pure silica (Hsu et al., 2015):

$\Rightarrow$ suggestive of interaction of hydrothermal fluid (90°C) with a cold alcaline ocean,

$\Rightarrow$ implies very fast ocean transport (40 km, months to years).

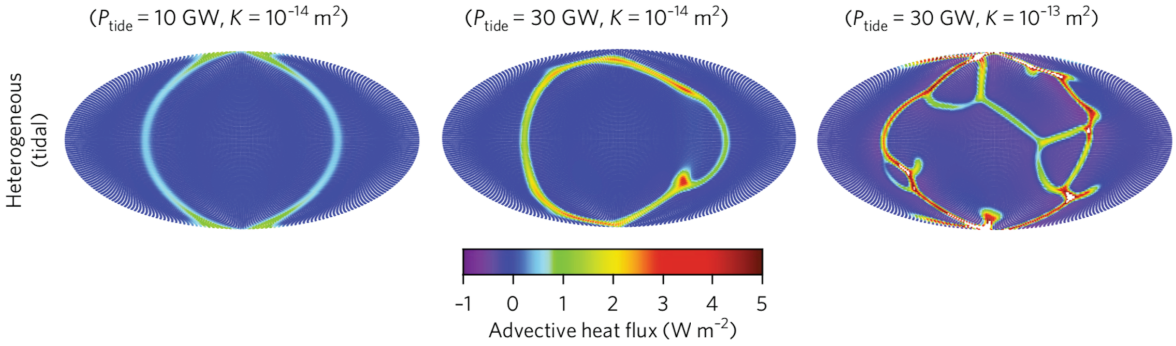






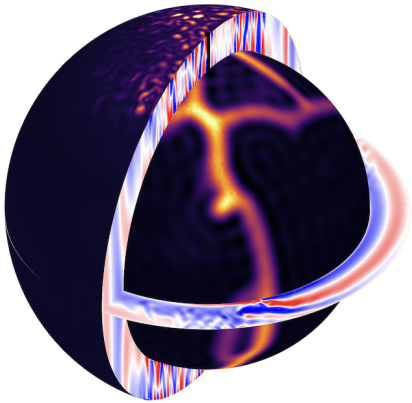
what about the ocean?

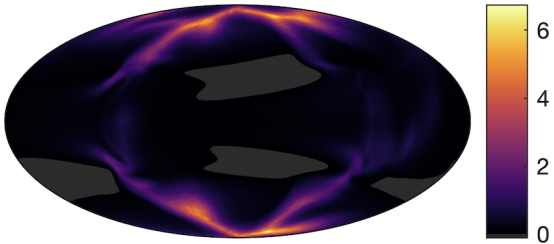
we modeled tidal dissipation in Enceladus porous core (rocky grains and interstitial water): it should produce enough heat to match the observed budget (10s of GW), it also displays a specific pattern (Choblet et al., 2017).



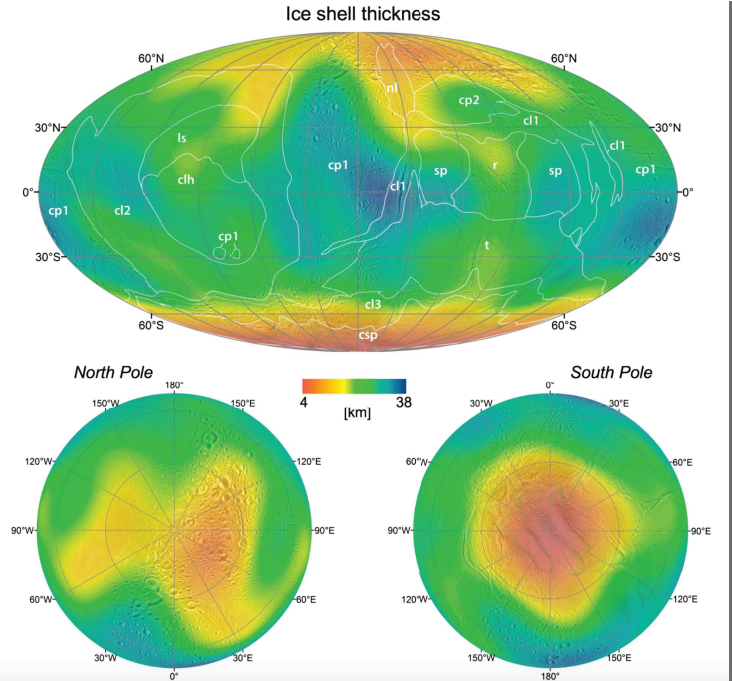
we also modeled porous convection of interstitial water in the core to infer hydrothermalism: temperatures of about 100°C (and more) are easily reached,

the seafloor heat flux pattern is shaped by that of tidal heating in the core but much more focused.

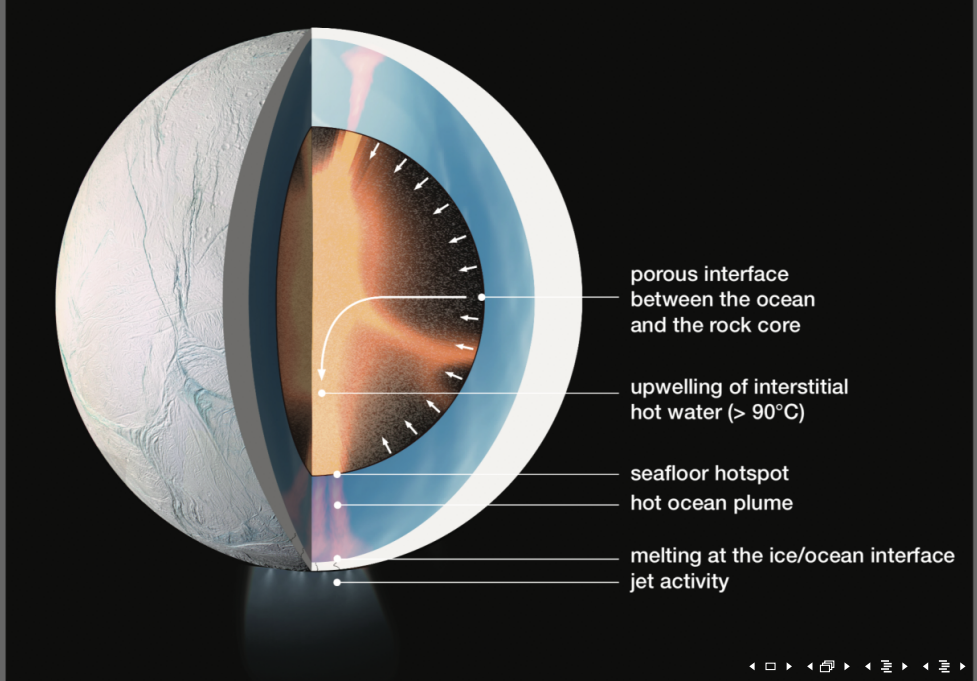


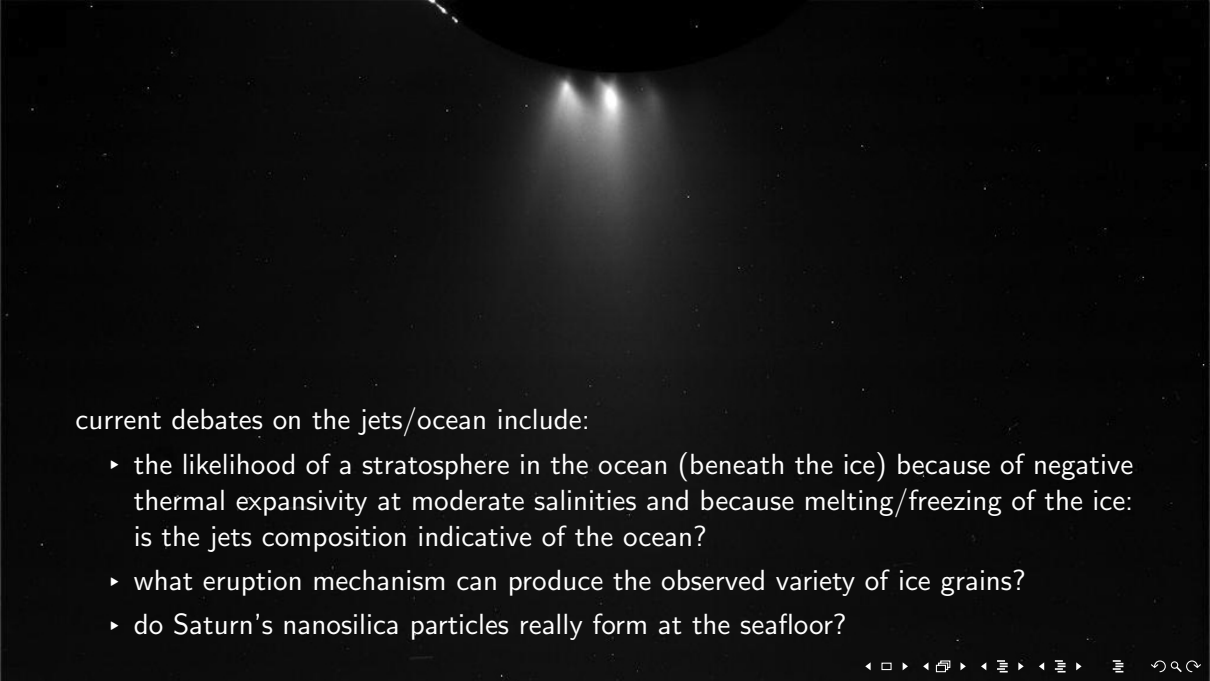


we finally modeled ocean flow driven by this seafloor heating (Bouffard et al., 2025).



the simulated ocean flow seems in line with the ice shell structure (thinner under the poles and along the sub- and anti-saturnian meridians, cf. e.g. Čadek et al., 2016),


porous interface
between the ocean
and the rock core
upwelling of interstitial
hot water (> 90°C)
seafloor hotspot
hot ocean plume
melting at the ice/ocean interface
jet activity



current debates on the jets/ocean include:

- the likelihood of a stratosphere in the ocean (beneath the ice) because of negative thermal expansivity at moderate salinities and because melting/freezing of the ice: is the jets composition indicative of the ocean?
- what eruption mechanism can produce the observed variety of ice grains?
- do Saturn's nanosilica particles really form at the seafloor?

yet, overall:

- sampling the jets of Enceladus provides a mean to access the ocean (even if stratified),
- this has fueled research on hydrothermalism and ocean flow,
- years after Cassini, further modeling work is possible (e.g. on the ice/ocean interface, on stratification),
- ultimately, better sampling of the plumes and the surface will be required.