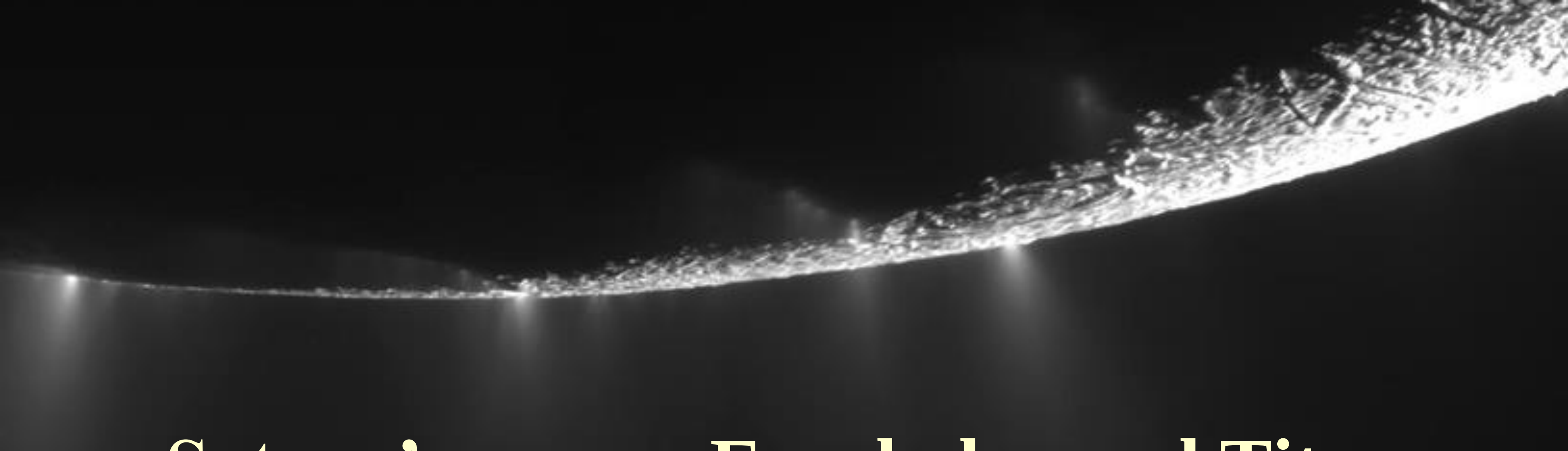
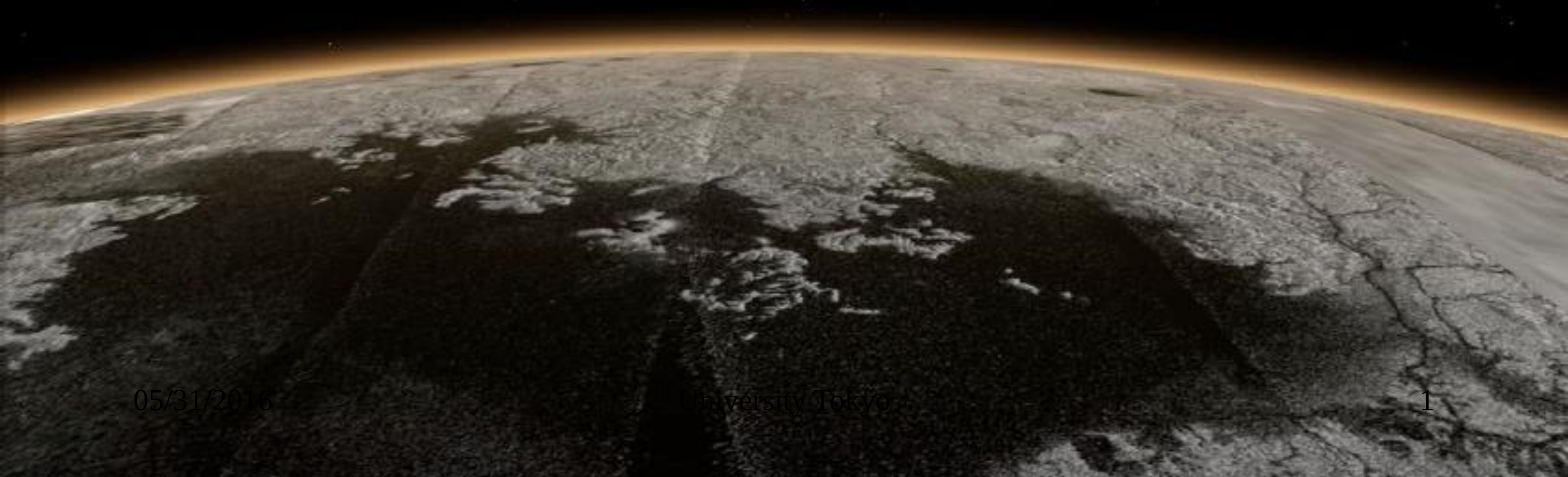


Saturn’s moons Enceladus and Titan

Christophe Sotin
Jet Propulsion Laboratory, California Institute of Technology (Pasadena, CA)



Saturn's moons Enceladus and Titan

- Introduction
- Titan: a large icy moon
  - Observations
  - Interior models
- Enceladus
  - Observations
  - Water-rock interaction
  - Comparison Earth-Enceladus-Europa
- Conclusions – Comparison between ocean worlds

How do we know that there are oceans ?

Mass and Volume require the presence of H_2O (ice or water)

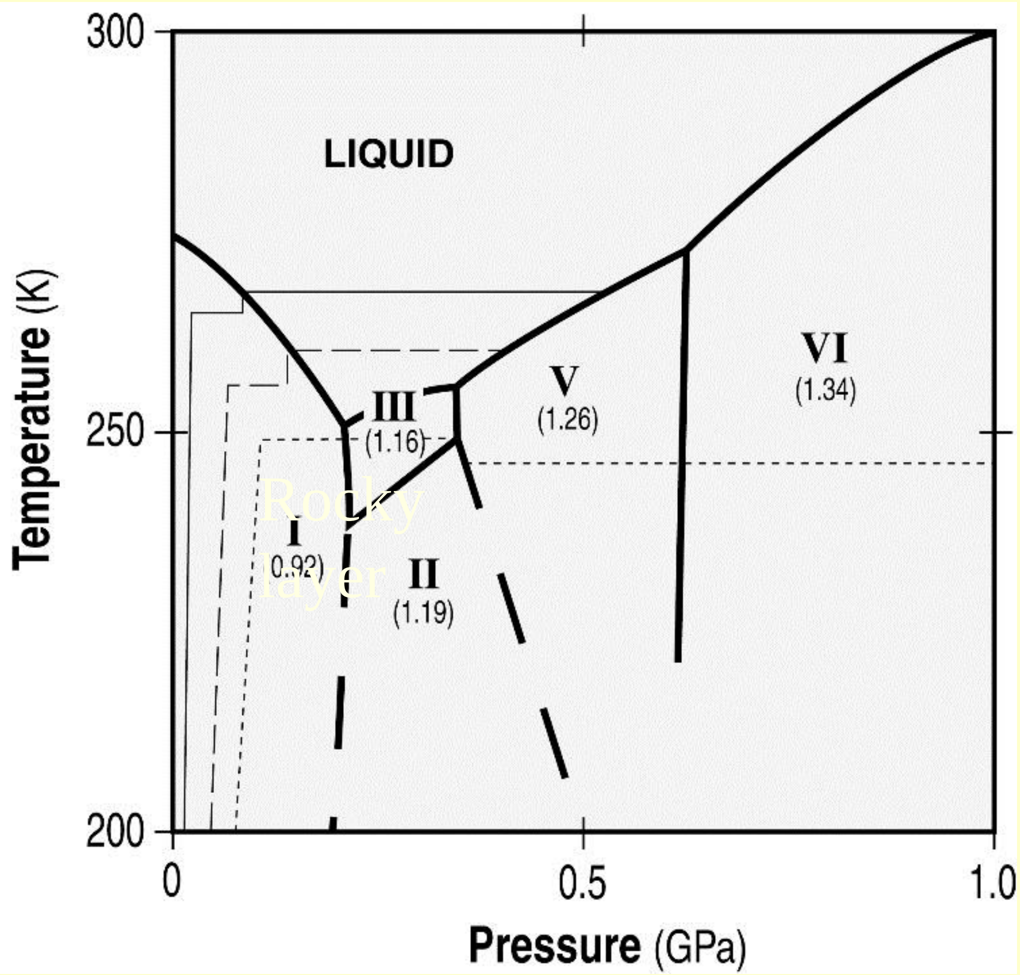
Moments of inertia (density profile) suggest that the moons are differentiated into a rocky core and an outer H_2O layer.

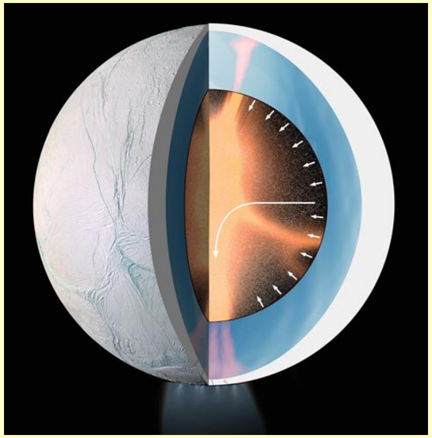
Schumann resonance (Titan) best explained by the presence of a deep ocean.

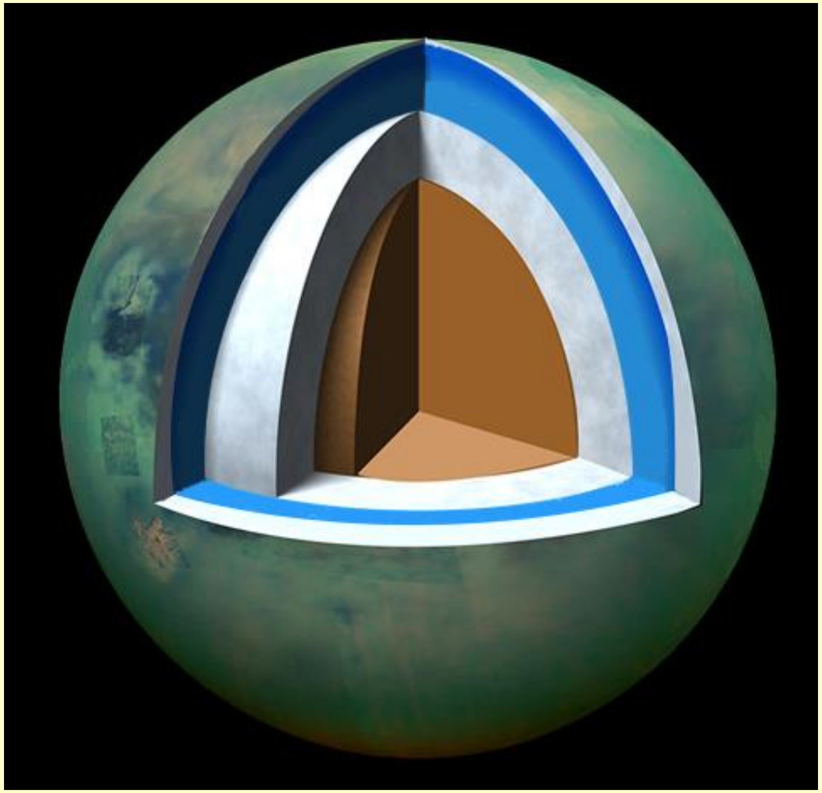
Decoupling between the ice crust and the solid interior is inferred from gravity coefficients and libration of the ice crust (Enceladus).

Oceans spewed out into space (Enceladus case)

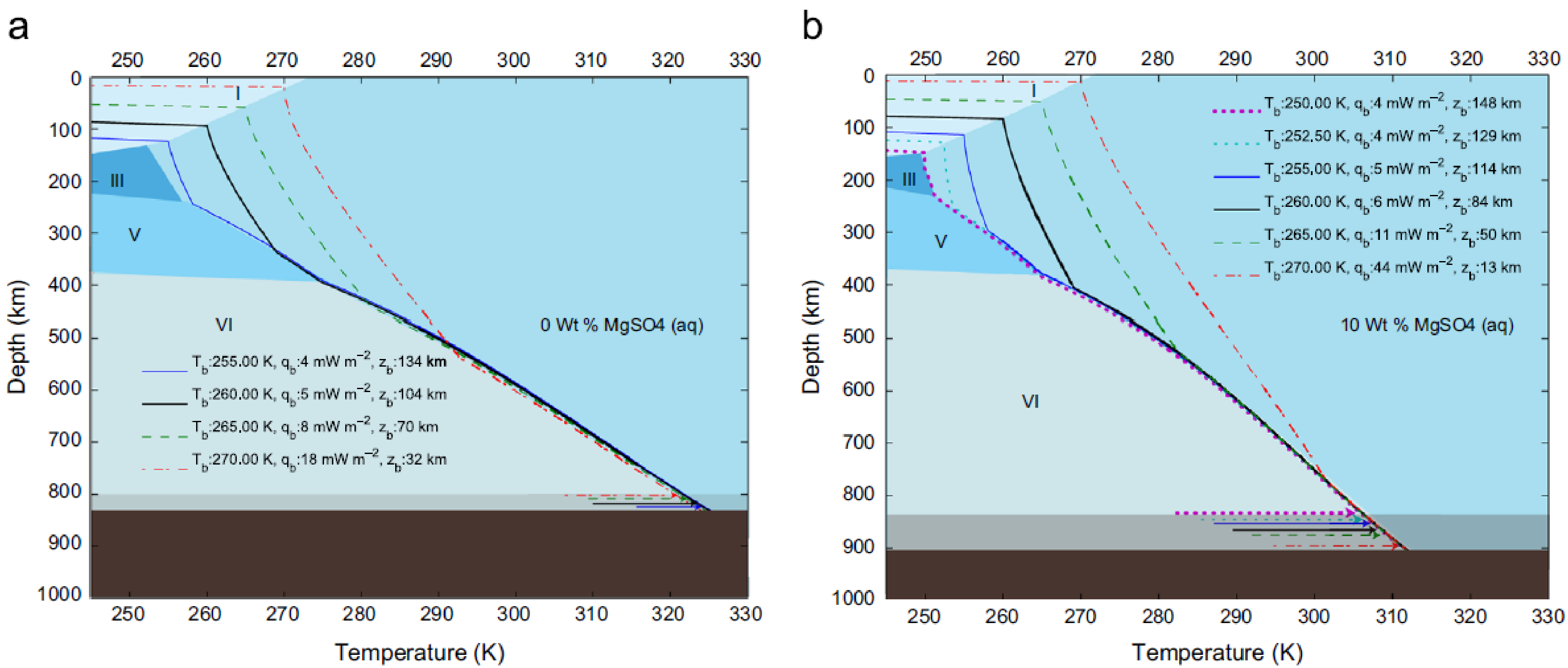
The depth of the liquid layer is controlled by H_2O phase diagram







Water-Ice phase diagram

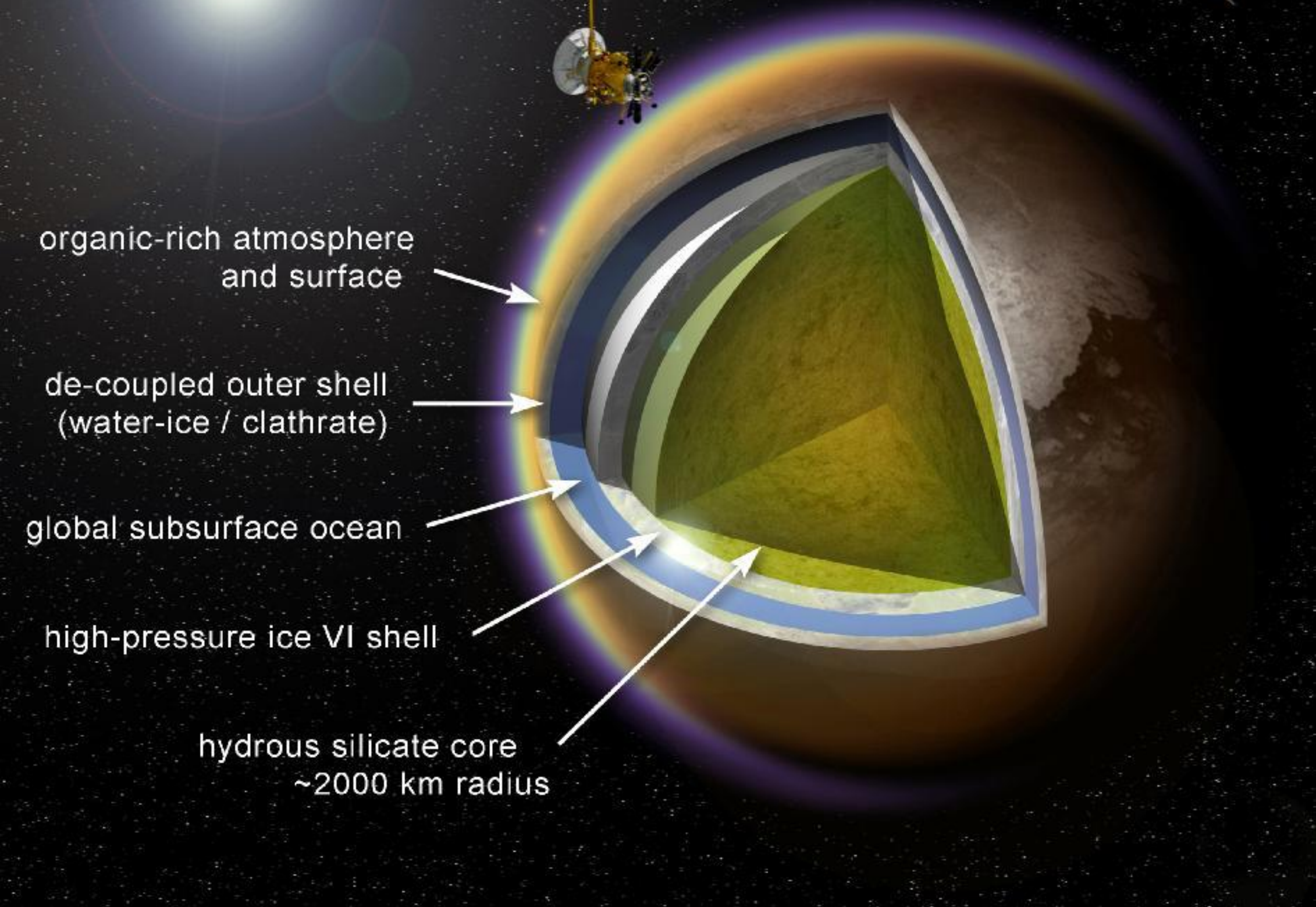


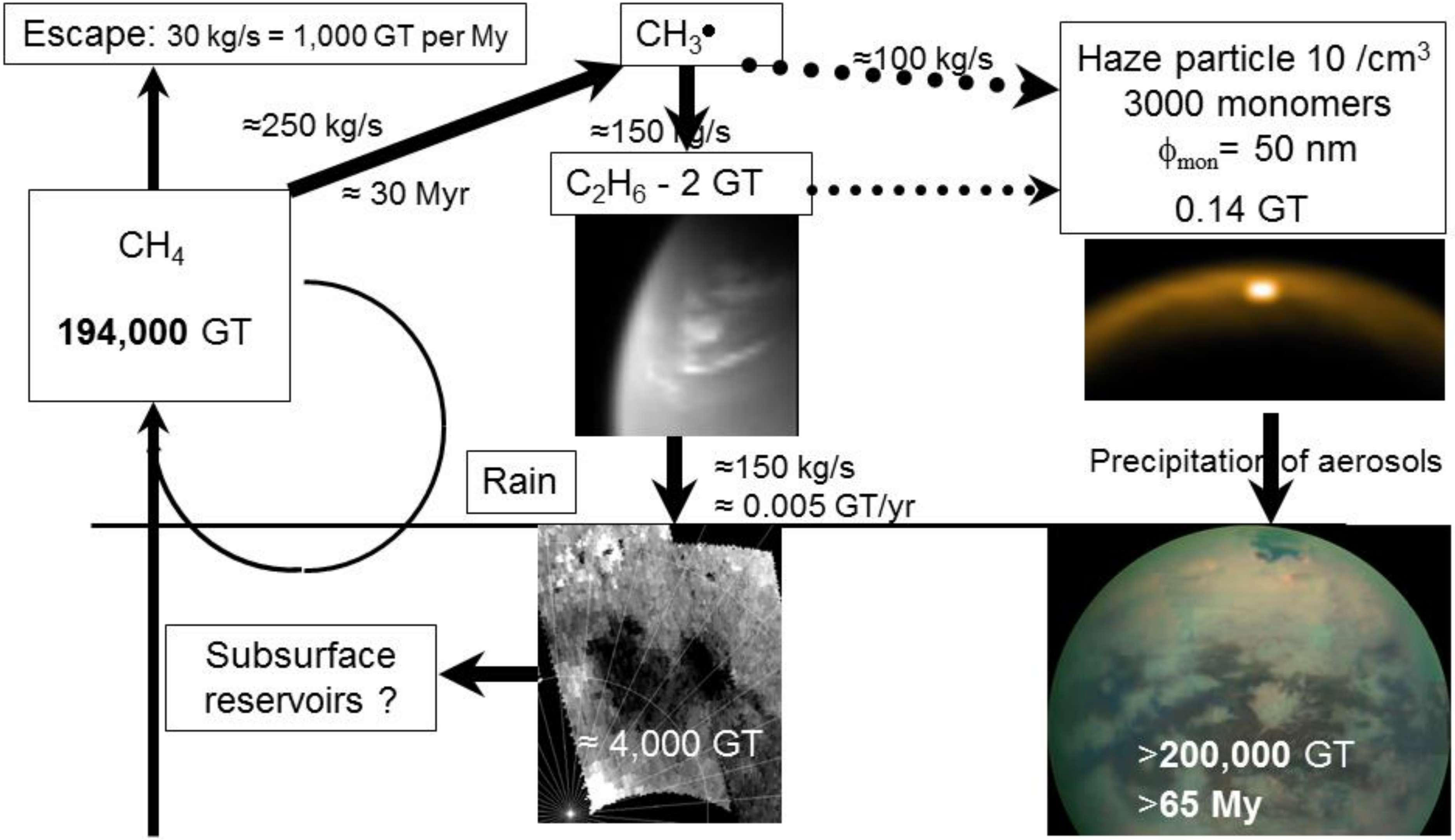
The thickness of the HPice layer depends on:

- The thickness of the ice I layer (ice crust)
- The composition of the ocean

(Vance et al., 2014)

Titan's interior structure

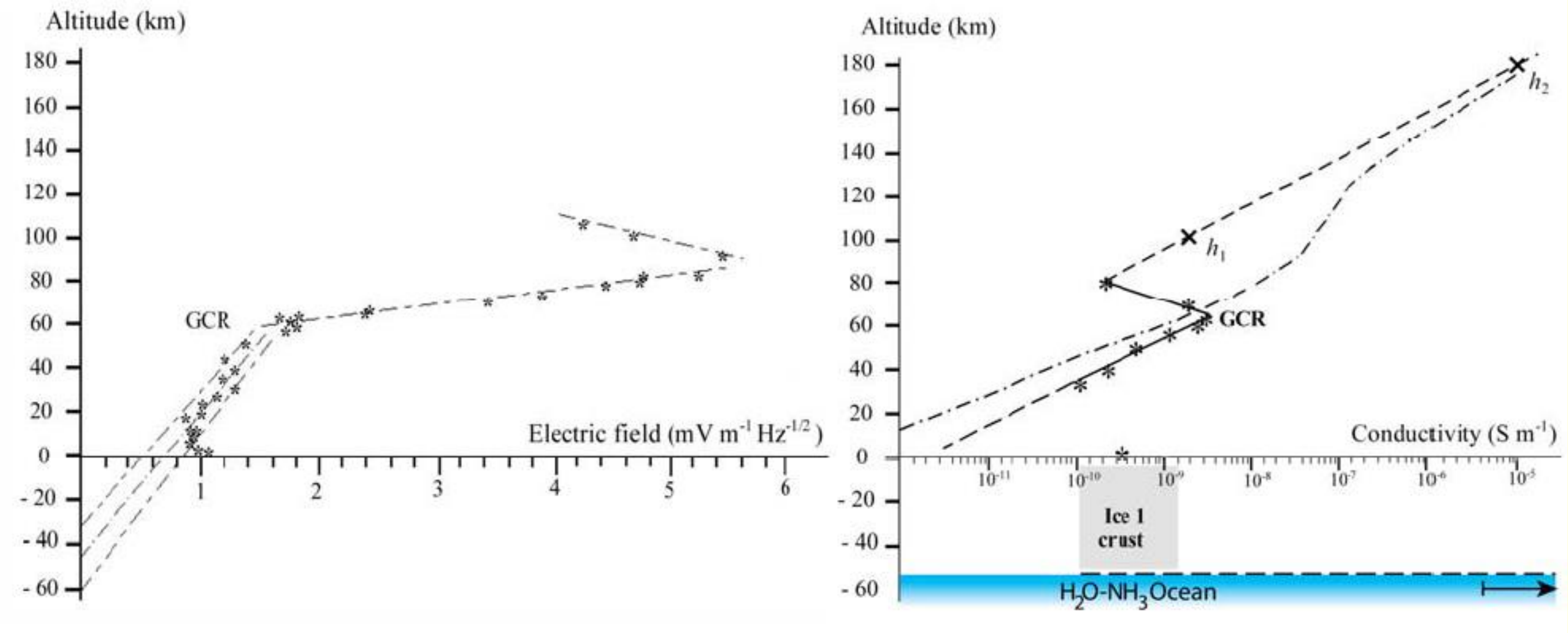




When? 500 My (isotopic ratios, density of impact craters, Titan's shape)
Where and how ? One catastrophic event or several large events (impact craters, cryovolcanism)

From Sotin et al., 2012

Electric field in Titan's atmosphere (Beghin et al., 2009, 2010)

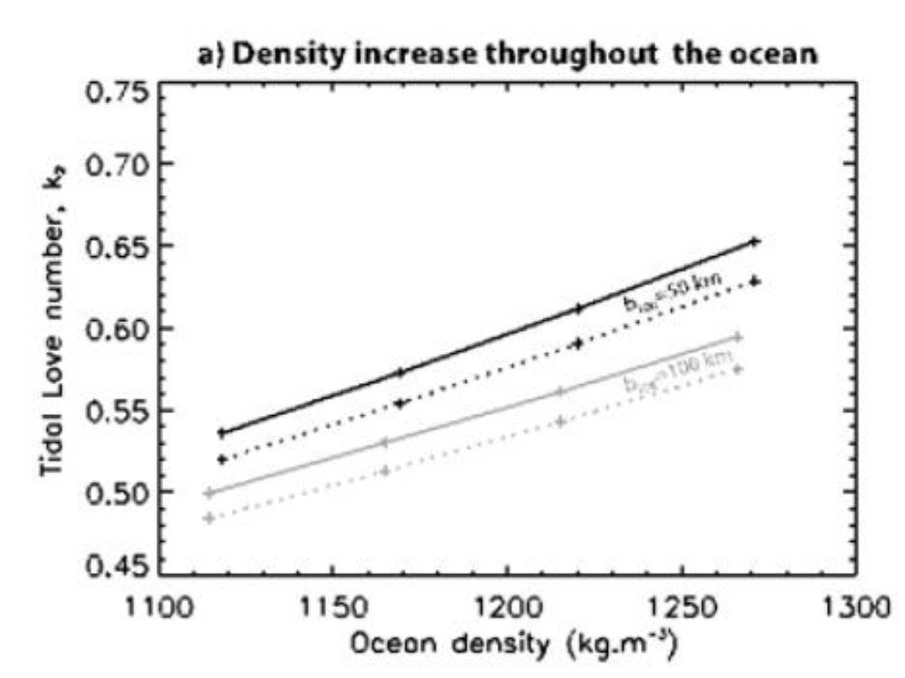


The decrease with altitude of the strength of the horizontal component of the 36 Hz electric field is consistent with the presence of a **Schumann resonance** triggered and sustained by ionospheric currents (Beghin et al., 2009 and 2010). It requires the presence of a conductive layer at 45 km depth: it could be a deep ammonia-rich ocean.

Degree 2 Love number (Iess et al., 2012)

Table 1. Titan's k_2 Love number, estimated from different data analysis procedures (see SOM) and representations of the gravity field: multiarc analysis and 3x3 gravity field (SOL1a); multiarc analysis and 4x4 gravity field (SOL1b); global solution with 3x3 gravity field (SOL2). SOL1 and SOL2 were produced independently by the Cassini Radio Science Team and the Navigation Team.

	Re (k_2) (value ± 1σ)		
SOL1a	0.589	±	0.075
SOL1b	0.670	±	0.090
SOL2	0.637	±	0.112



The value of the k_2 Love number is explained by a decoupling between the ice crust and the solid interior Iess et al., 2012). The large value requires a large density of the ocean (presence de salts) (Mitri et al., 2014).
No induced magnetic field has been found

Enceladus

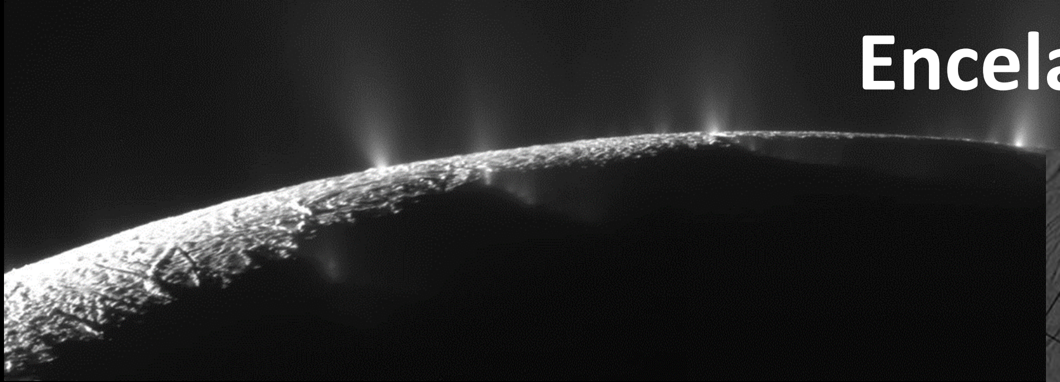
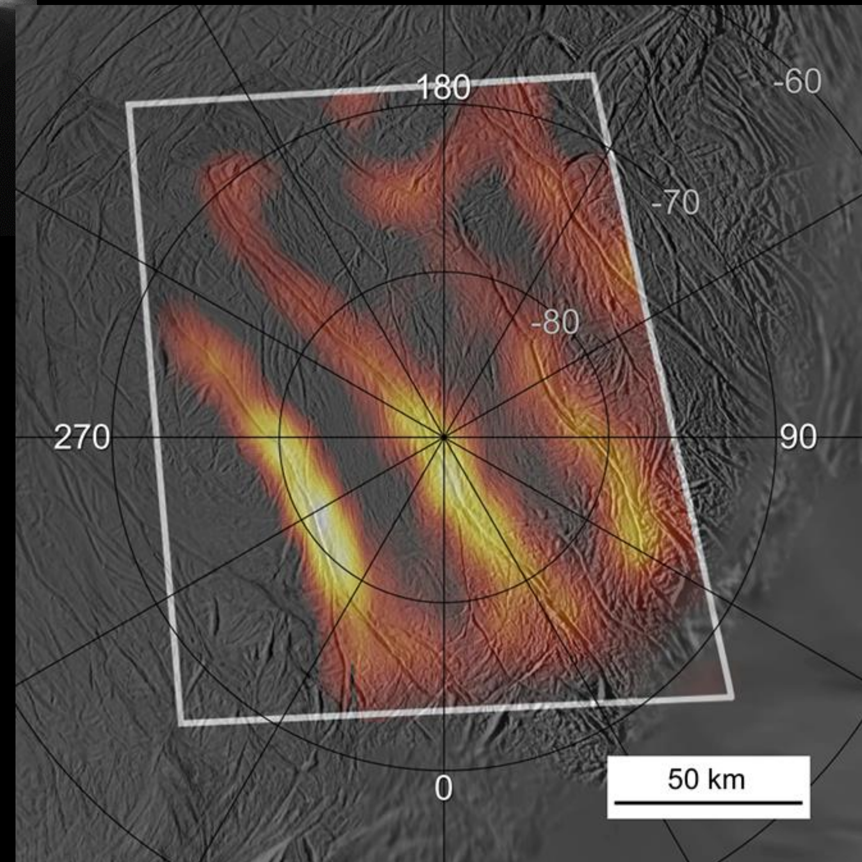


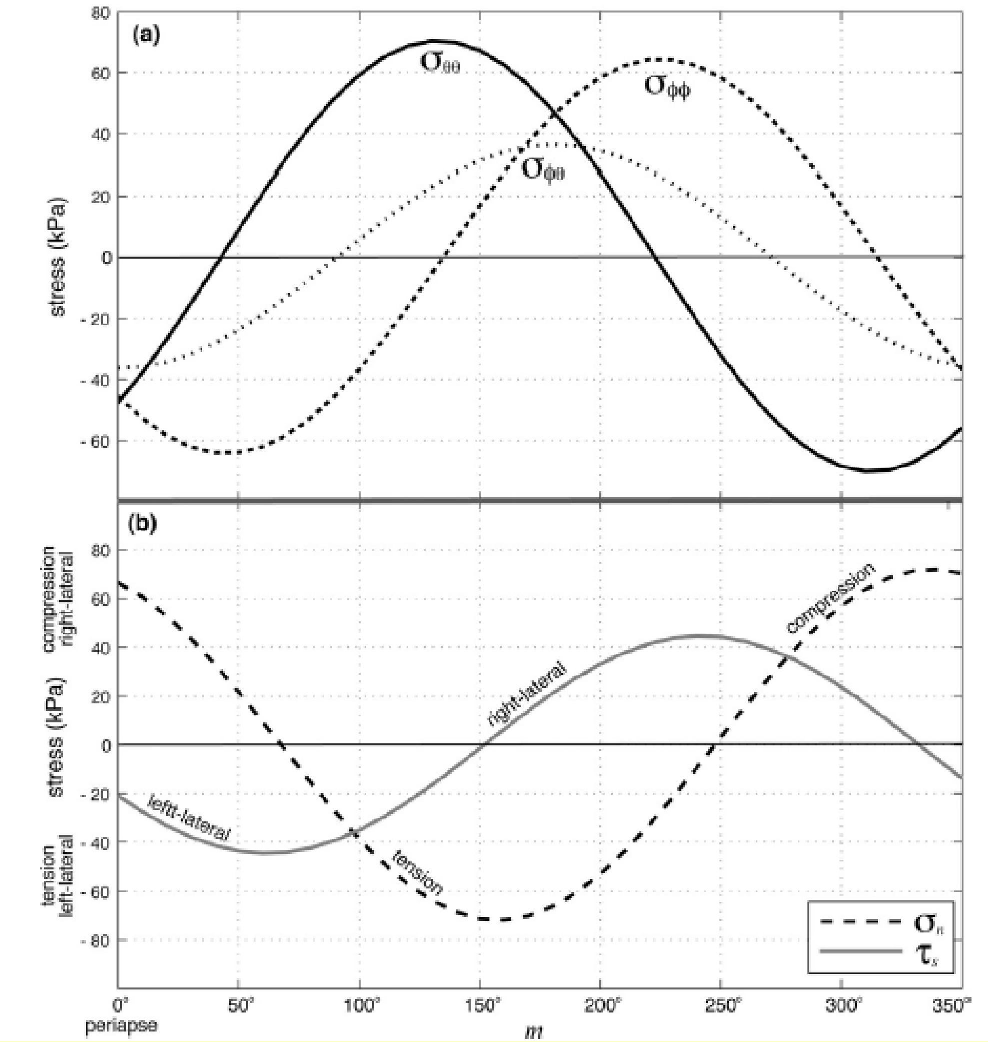
Table 1 The major species composition of Enceladus' plume gas. Volume mixing ratios are derived from Cassini INMS measurements [(20), sections 2.4 and 3.2].

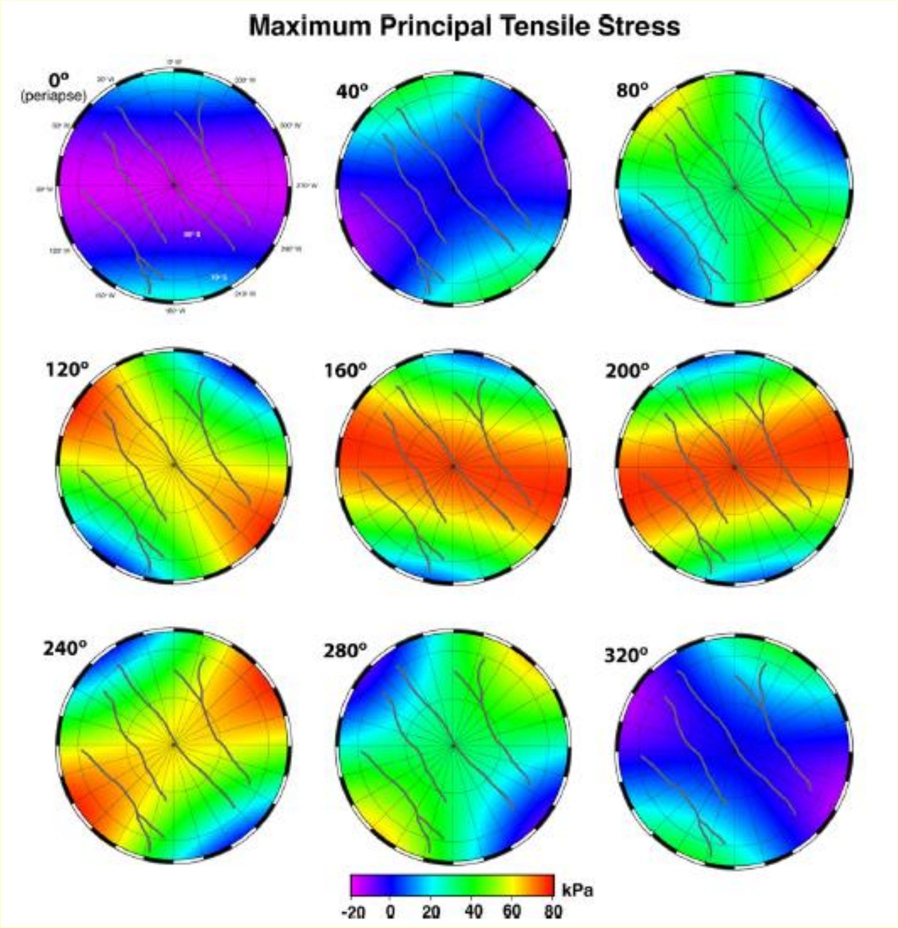
Constituent	Mixing ratio (%)
H_2O	96 to 99
CO_2	0.3 to 0.8
CH_4	0.1 to 0.3
NH_3	0.4 to 1.3
H_2	0.4 to 1.4



Cassini has discovered the geysers spewing out the ocean into space, the high values of the heat flow at the surface (6 GW), the presence of salts, nano particles of silicon, H2, and organics. Findings point to hydrothermal activity.

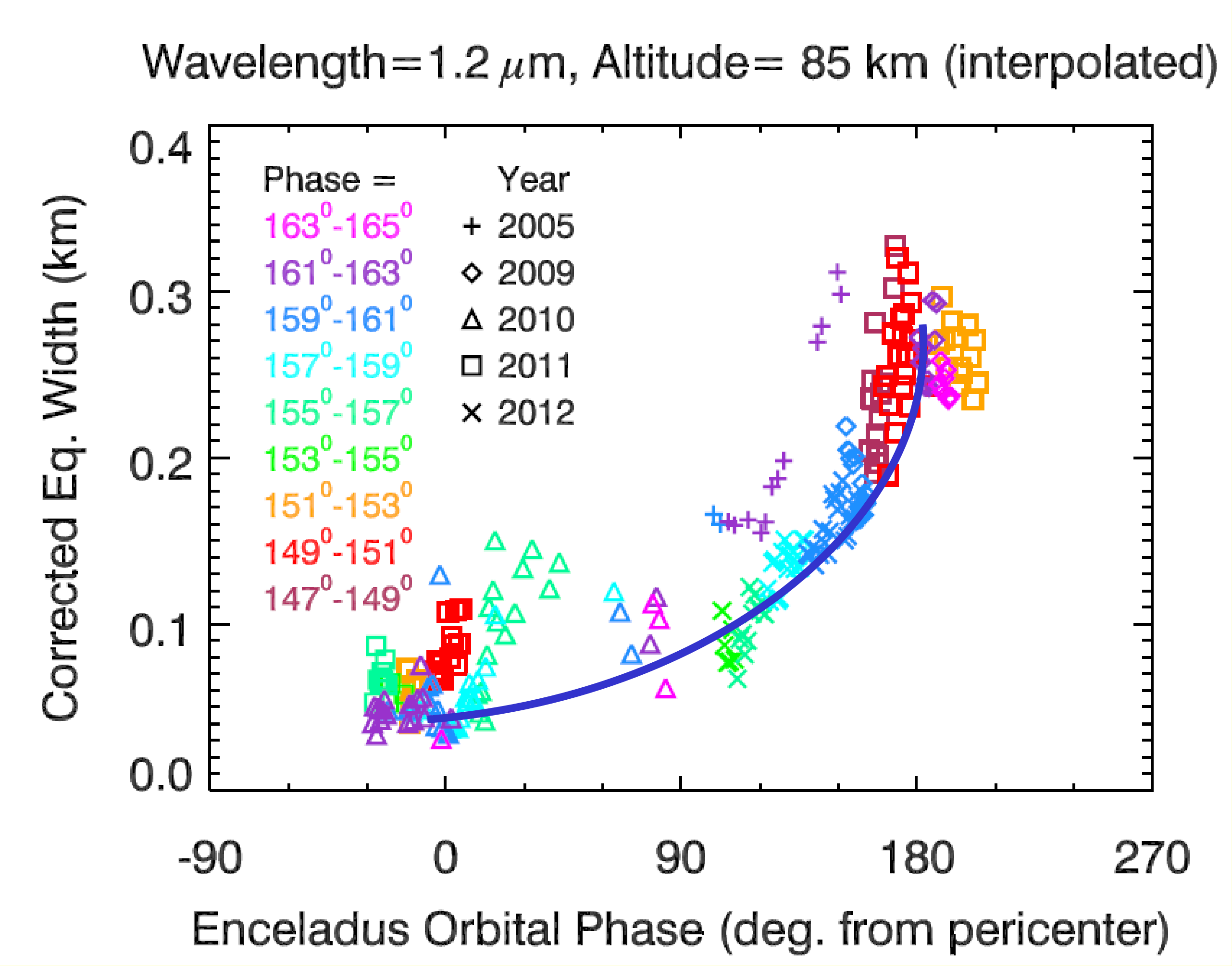
Calculations of the stresses during an orbit





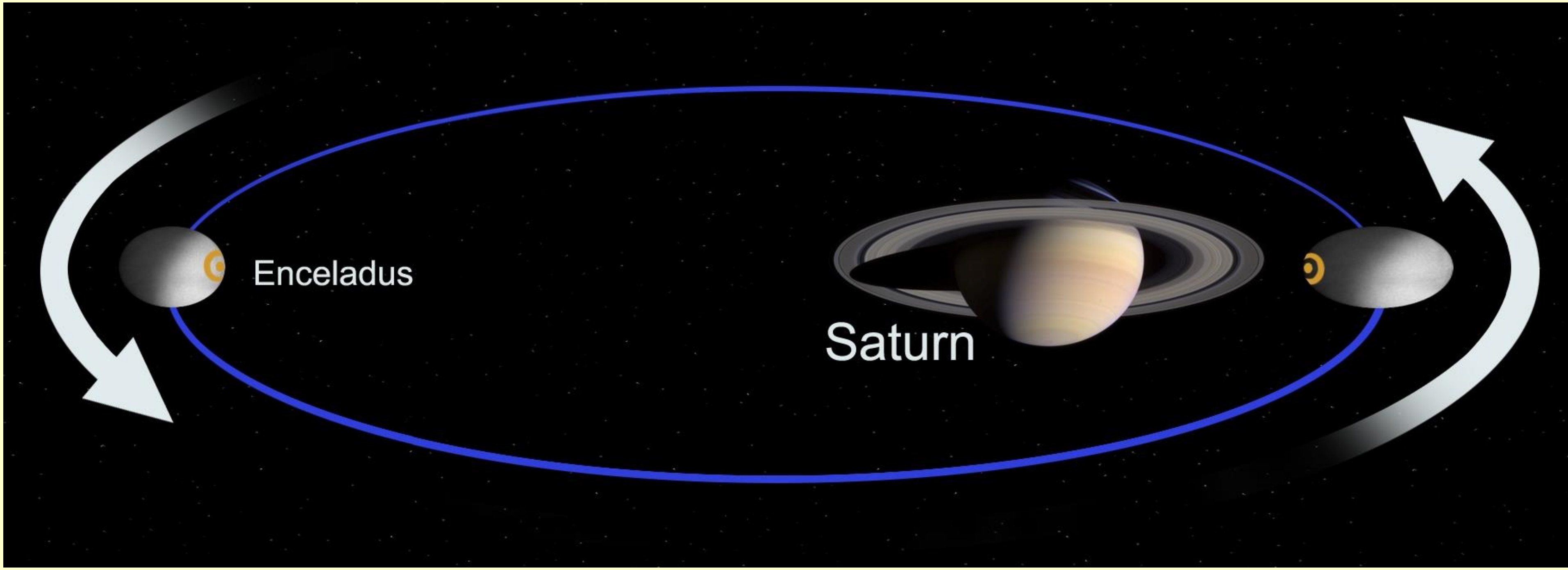
Hurford et al., 2007

VIMS observations

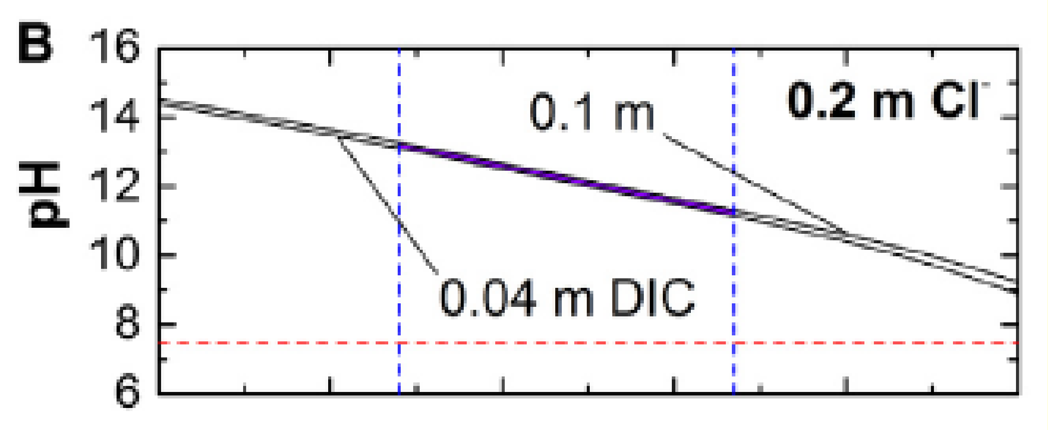


The plume is three times brighter at apoapsis (tension: faults open) than at periapsis (compression: faults close).

Tidal dissipation

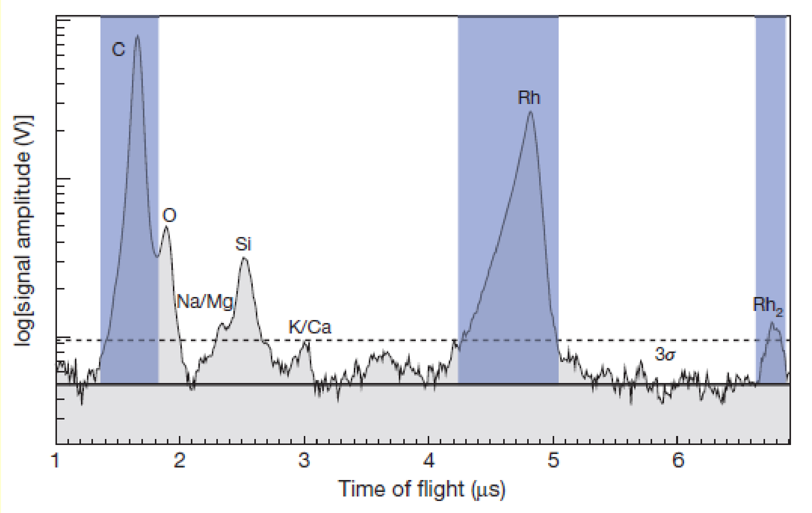


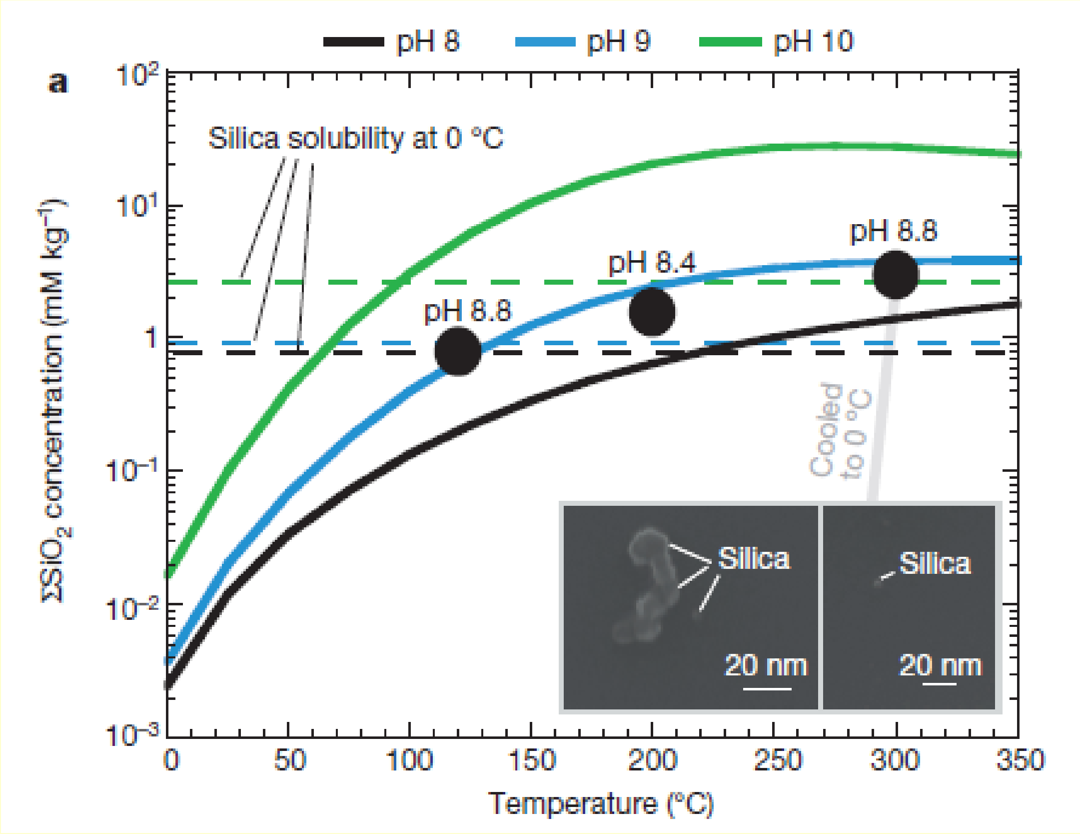
pH of the ocean



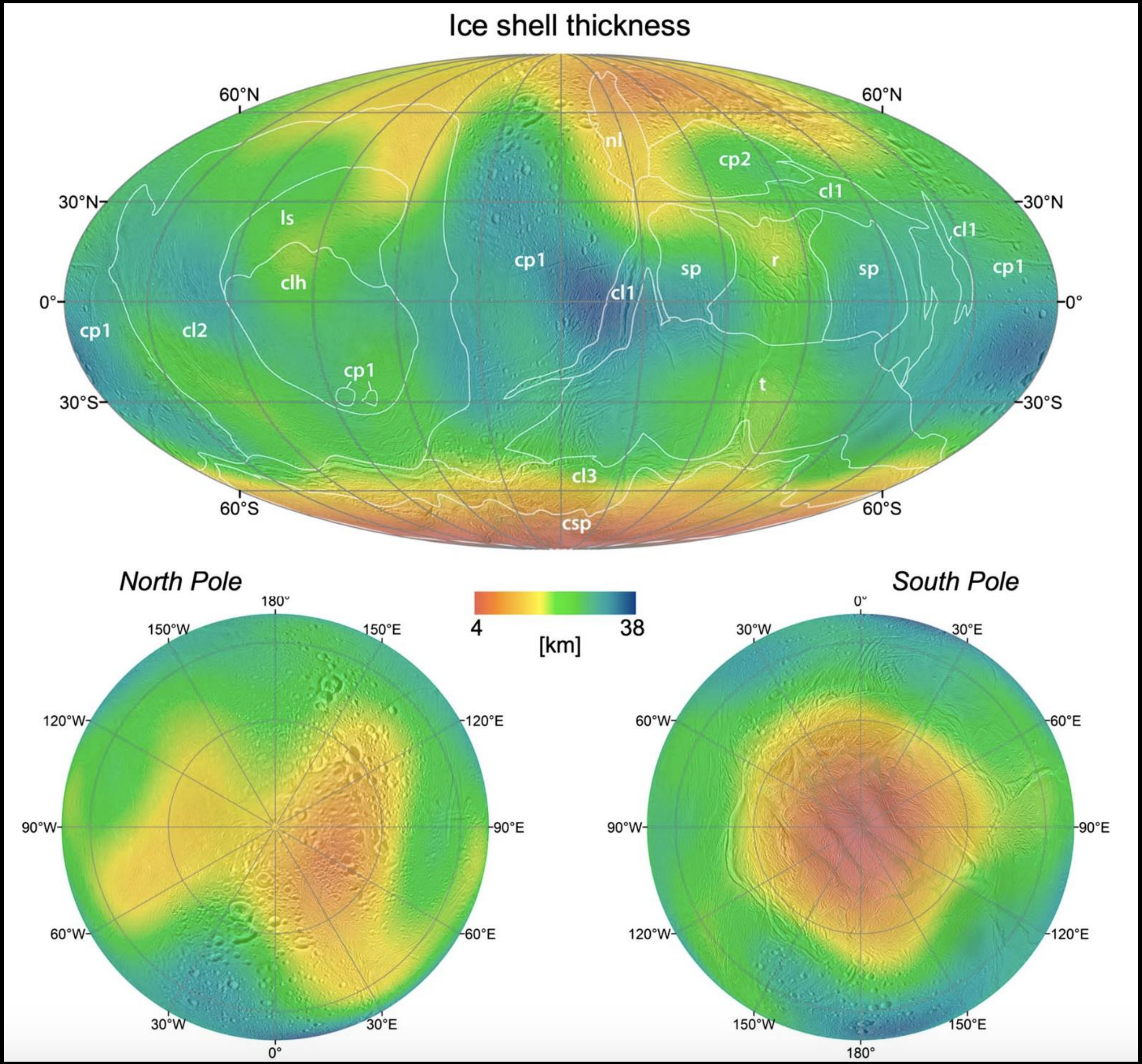
Glein et al., 2015 – pH from CO2

Hsu, Postberg, Sekine, et al., 2015 – silicon-rich nm-sized dust particles – ongoing hydrothermal activity





Nov 13, 2017



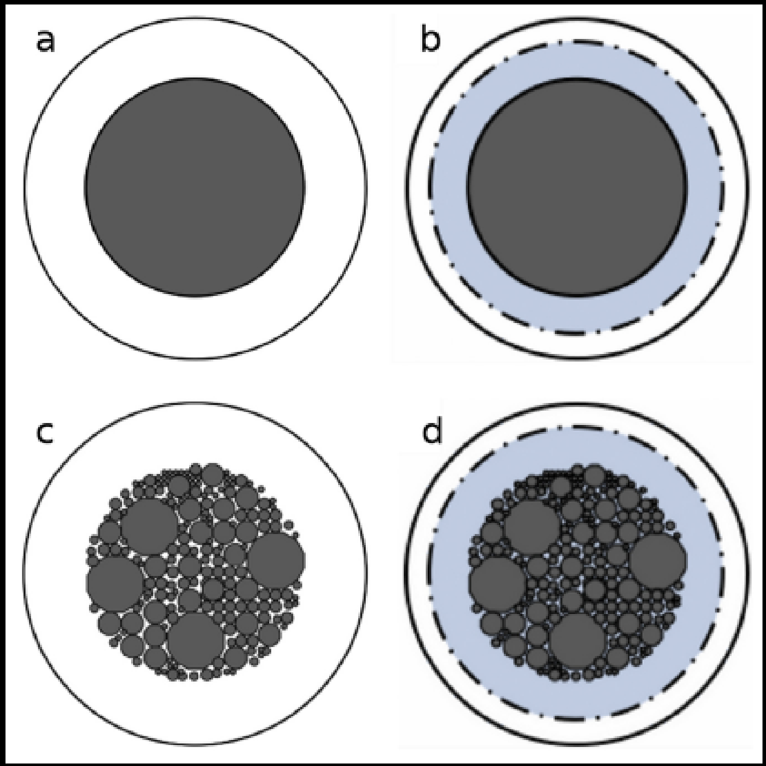
Thickness minimal at both poles (only a few kms beneath the South, (~10 km beneath the North),

Ice shell thickest at the sub and anti-saturnian points at the equator (~40 km).

Enceladus' crustal thickness - inference of ice shell thickness from gravity data and the libration constraint (Cadek et al., 2016; Beuthe et al., 2016)

Tidal heat production in Enceladus' deep interior

- due to low central pressure, Enceladus' core is likely unconsolidated,
- first gravity measurements (less et al., 2014) yield $\rho_{core} \simeq 2.4$ g cm^{-3} $\rightarrow$ porosity could be as large as 20-25 %,
- porosity in excess to 20 % weakens the core with ice/water controlling the deformation,
- at present, a few GW could be generated by viscous dissipation in the core filled with ice.



Roberts (2015)

How much heat can be dissipated in a porous core filled with liquids? Choblet et al. (Nature Astronomy, 2017) find that between 25 – 50 GW can be dissipated. Water temperature is around 100 C – The whole ocean is processed in 10s to 100s Myrs.

nature astronomy
LETTERS
https://doi.org/10.1038/s41550-017-0289-8

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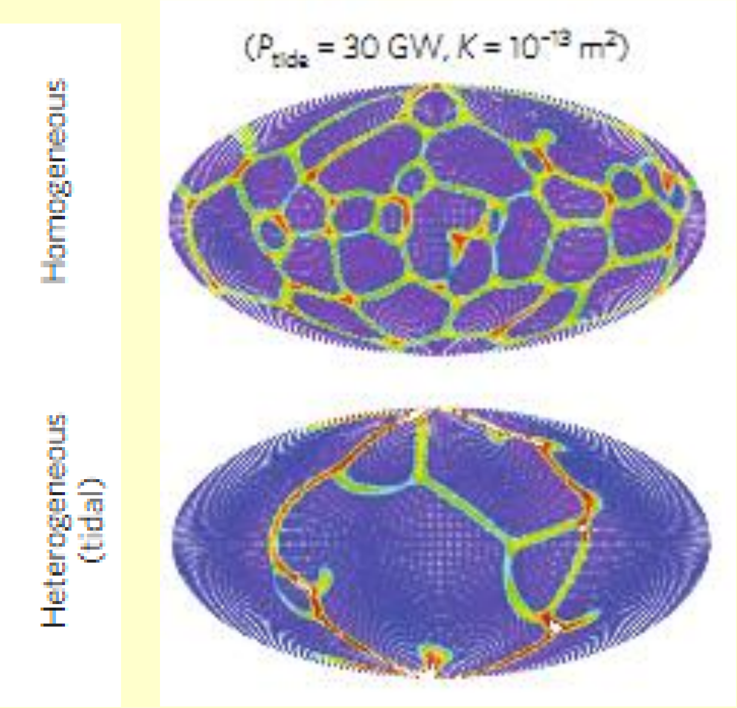
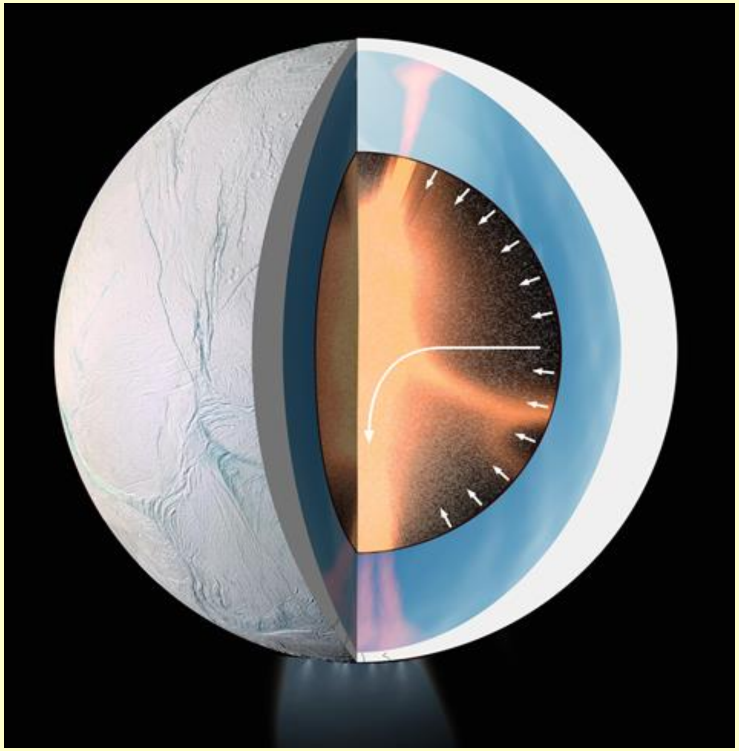
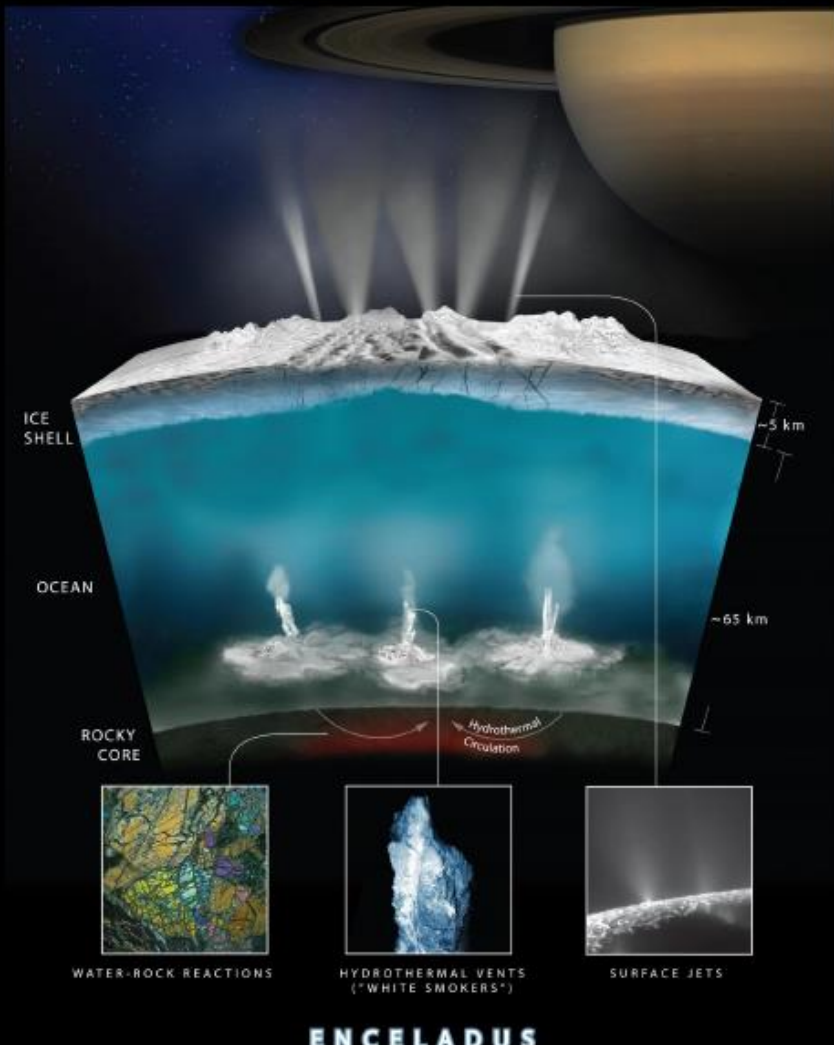
Powering prolonged hydrothermal activity inside Enceladus

Gaël Choblet[1*], Gabriel Tobie[1], Christophe Sotin[2], Marie Běhounková[3], Ondřej Čadek[3], Frank Postberg[4,5] and Ondřej Souček[6]





Chemical observations: INMS
modelcular hydrogen in the plume



- E2: serendipitous measurement of the plume's composition (dominated by water, $\sim$ 3% CO_2) (Waite et al. 2006),
- refined results (E14-E18) in "closed source mode": 96%-99% H_2O, CO_2,CH_4,NH_3 all less than 1%),
- "open source mode": gas ionized on the fly w/o interaction with the instruments' walls - detection of 0.4-1.4 % H_2
- hydrogen native in Enceladus possibly a product of ongoing hydrothermal reactions of rock containing reduced minerals and organic materials (serpentinization) (Waite et al., 2017).

Deep ocean within icy moons

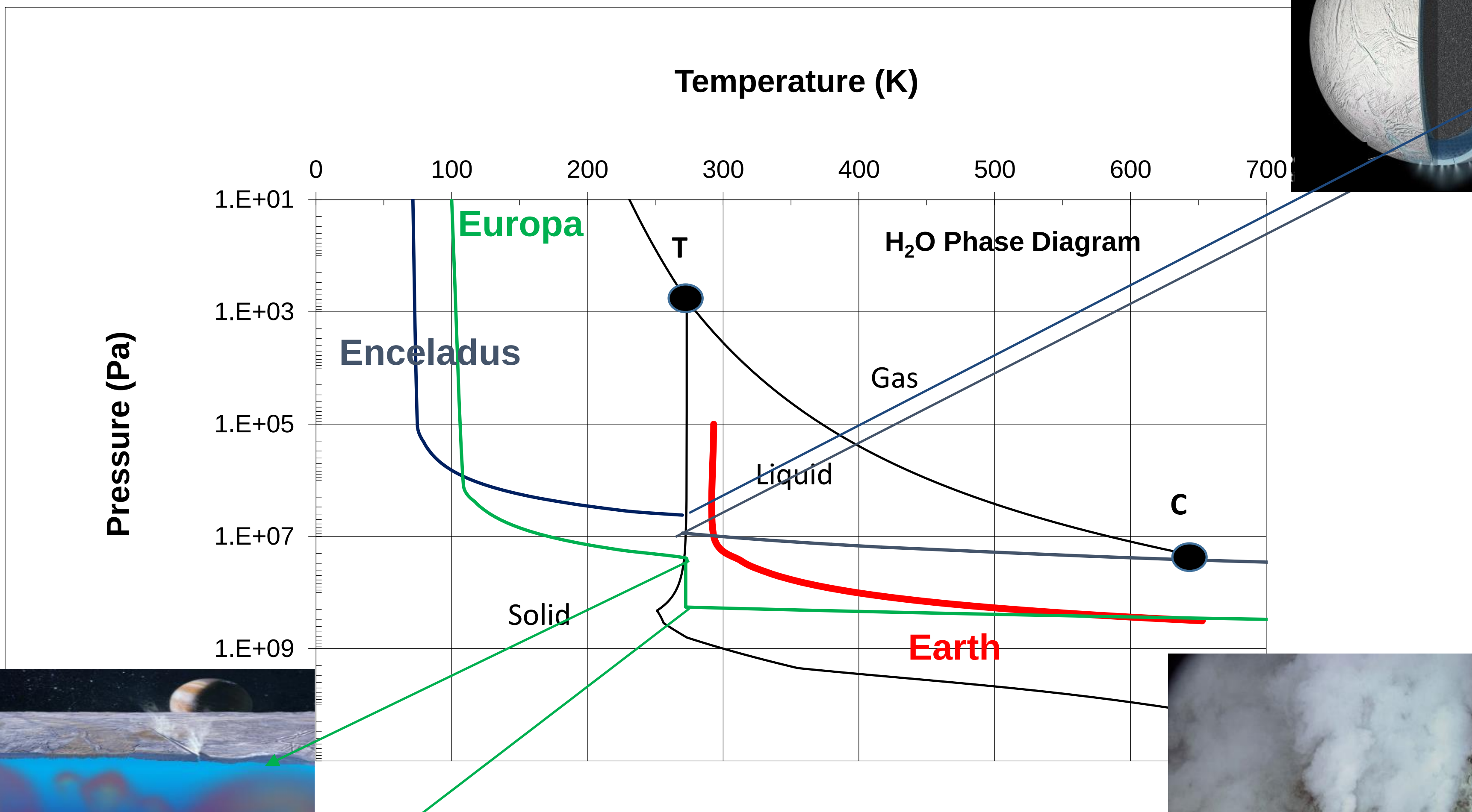
Enceladus, because it is small, is very likely to have water in contact with the silicate core.
Observations show that hydrothermal activity is present
It is one of the preferred locations to search for extraterrestrial life.

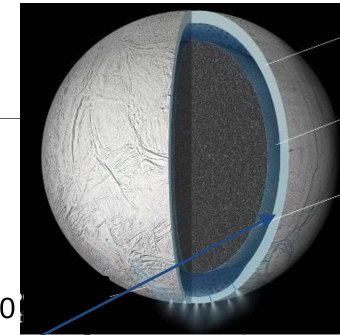
Can Life Begin on Enceladus?
A Perspective from Hydrothermal Chemistry

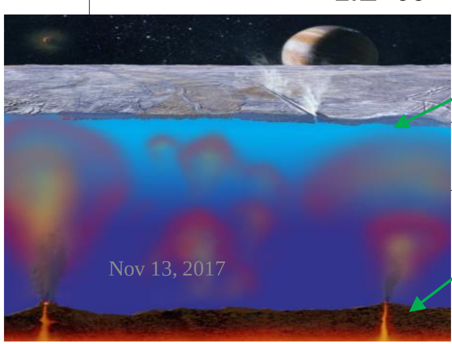
David Deamer and Bruce Damer

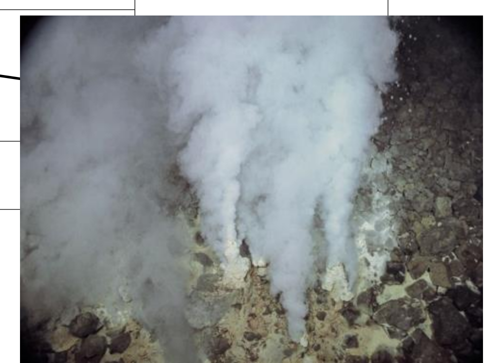
hydrothermal vent origin would allow life to begin in the Enceladus ocean, but if the origin of life requires freshwater hydrothermal pools undergoing wet-dry cycles, the Enceladus ocean could be habitable but lifeless.

Phase diagram and temperature profiles

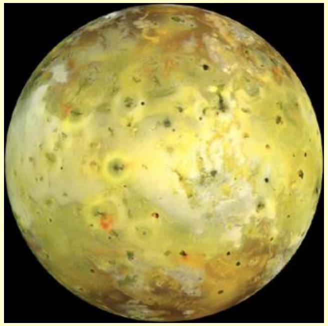


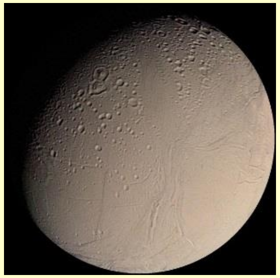






Some characteristics of Titan & Enceladus /Earth & Io





6371 km	1822 km	2575 km	252.3 km
$6\ 10^{24}$ kg	$0.0894\ 10^{24}$ kg	$0.1345\ 10^{24}$ kg	$0.000108\ 10^{24}$ kg
5525 kg/m^3	3528 kg/m^3	1881 kg/m^3	1608 kg/m^3
2/3 Silicates and 1/3 iron	Silicates	Ice and silicates	Ice and silicates
42 TW	**108 TW (2 W/m^2)**	**750 GW**	**30 GW (6 GW SPT)**

Radiogenic power is proportional to mass
Other heating sources include tidal heating, cooling, & latent heat

Deep ocean within icy moons

There are good arguments for oceans but additional measurements are required to determine the depth of the liquid layer, its thickness, and its composition.

Ocean should quickly freeze if convection processes are as efficient as predicted. However, such oceans can survive over geological time scales if:

- Additional heat source is present (tidal heating) – case of Enceladus
- And/or ammonia (anti-freeze compound) is present in the water – Titan.

Titan: the presence of a high-pressure ice layer would isolate the deep ocean from the silicate core – but transfer of volatiles and salts is still possible by convection. the ocean may have been, and may still be, in contact with the rocky core.

Enceladus, because it is small, may have water in contact with the silicate core. It is one of the preferred locations to search for extraterrestrial life.