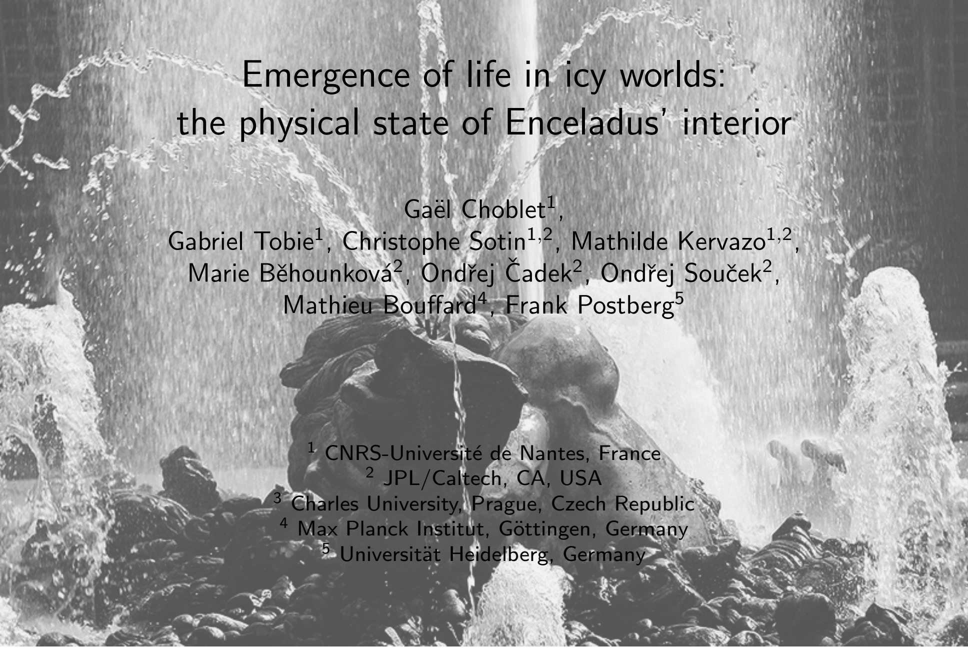

Emergence of life in icy worlds: the physical state of Enceladus' interior

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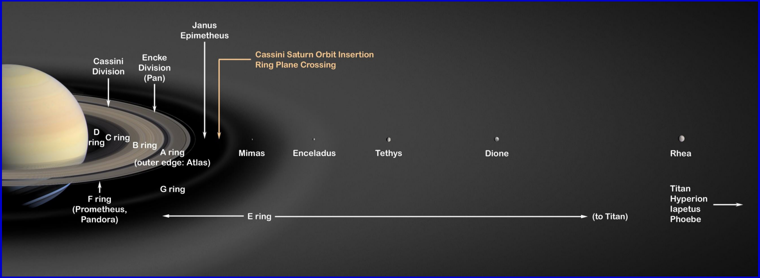
October 16, 2018

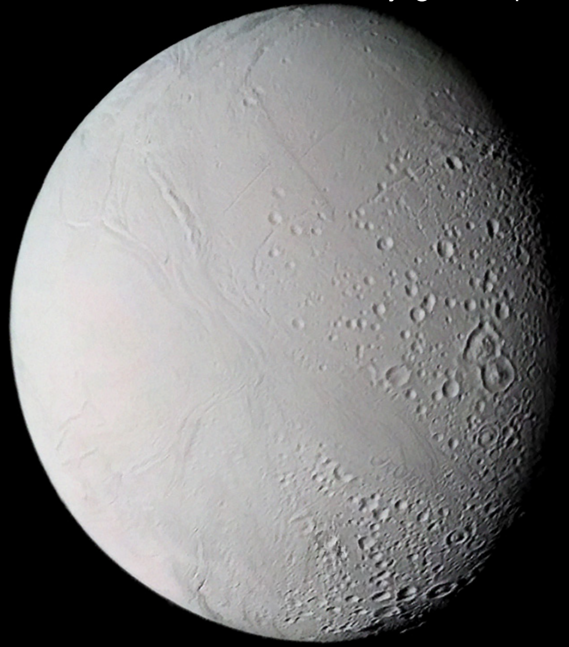
Enceladus in the Saturn system



- 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,

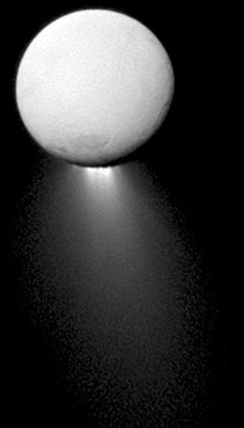
$\Rightarrow$ is Enceladus the source of E-ring's material ? (Terrile and Cook, 1981)

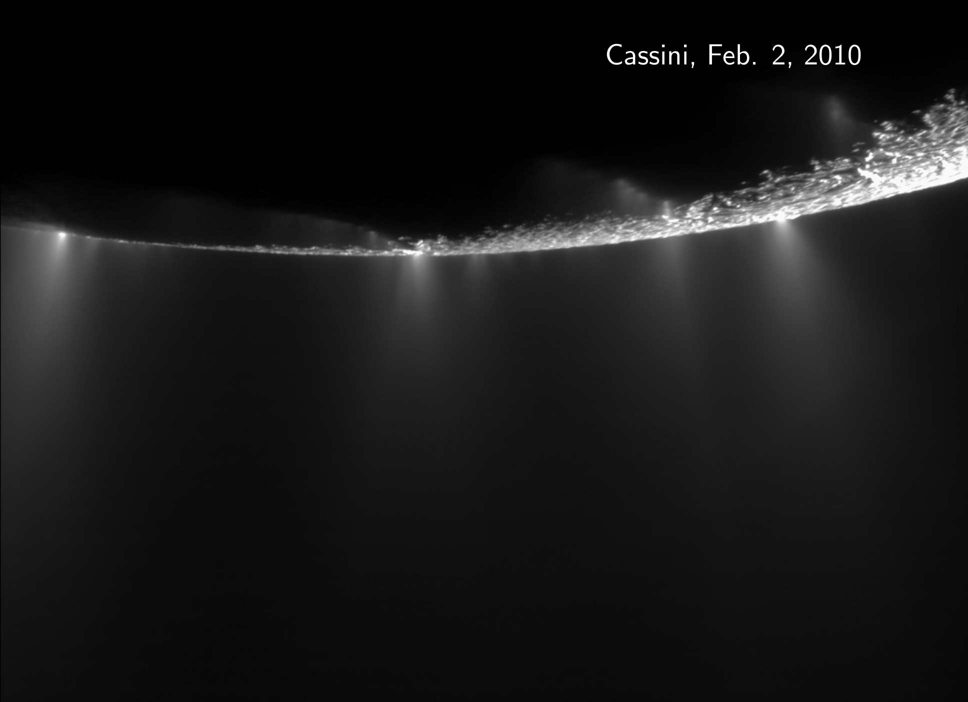
Voyager 2, April 26, 1981

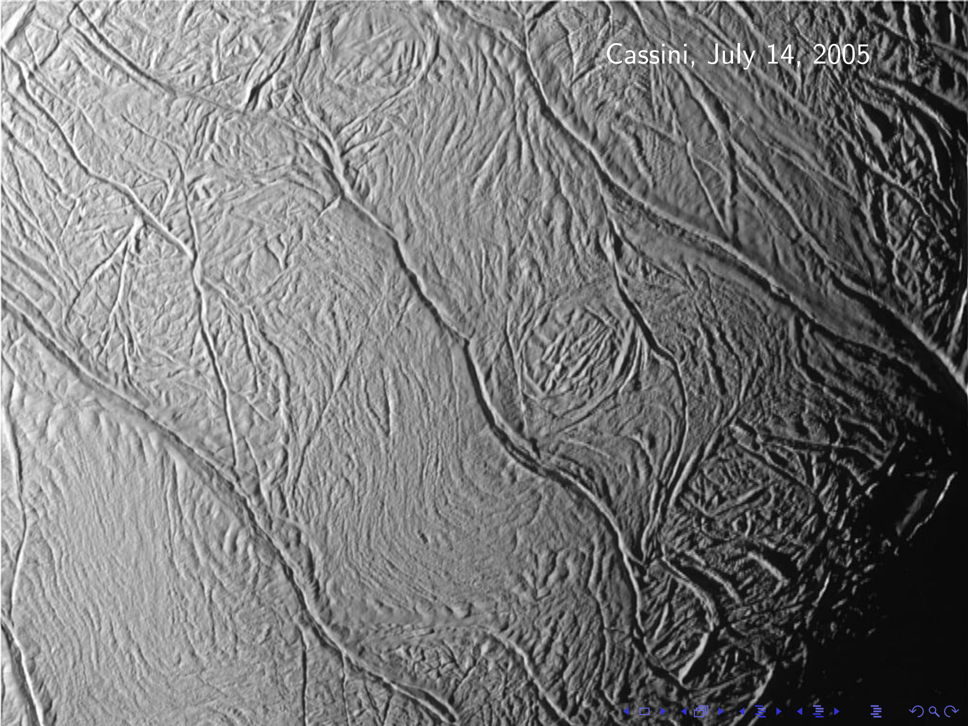


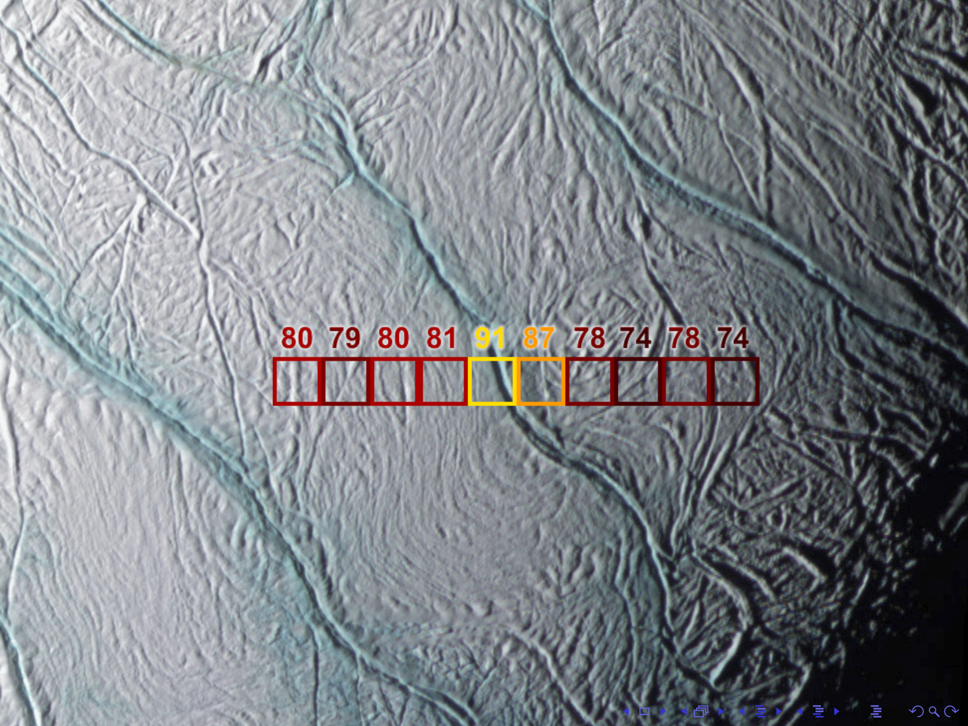
Cassini, January 16, 2005

Cassini, Jan. 7, 2013



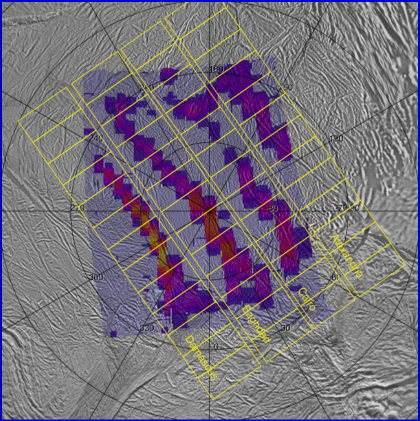

Cassini, Feb. 2, 2010


Cassini, July 14, 2005


80 79 80 81 91 87 78 74 78 74

A paradoxical heat budget ?

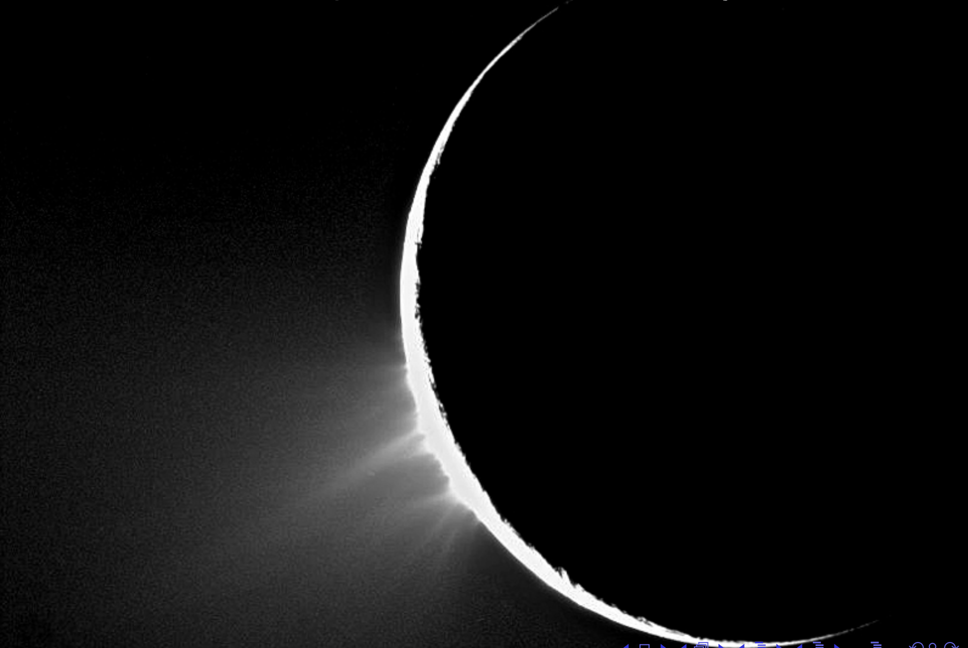
Howett et al, 2011



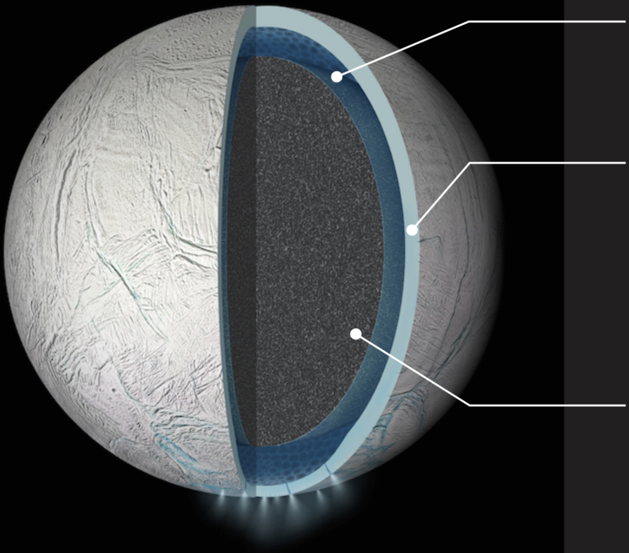
- endogenic power from south polar terrain: 15.8 ± 3.1 GW (Howett et al., 2011)
- radiogenic power within rocky core: ~ 0.3 GW
- equilibrium tidal power: $1.1(18,000/Q_S)$ GW (Meyer and Wisdom, 2008)

$\Rightarrow$ heat transfer or/and eccentricity may not be at equilibrium at present

What mechanisms power this intense activity ?



Enceladus' interior at the end of Cassini: structure



buried global ocean

30-40 km thick
(Thomas et al., 2016)

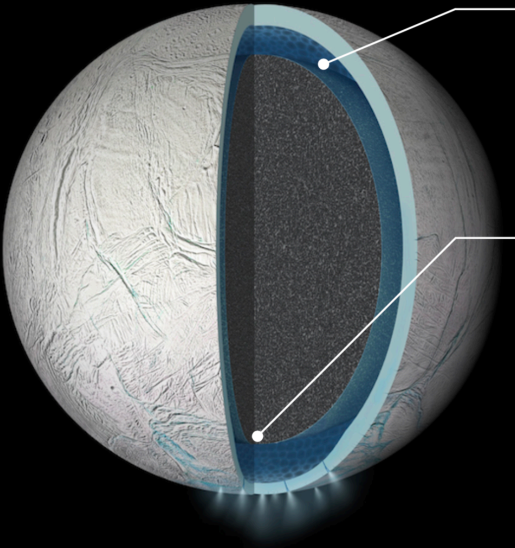
very uneven ice shell

25-30 km thick in average
up to 35 km at equator
less than 5 km at south pole
(Čadek et al., 2016 ;
Beuthe et al., 2016)

porous rock core

filled with 20-30 % water
(e.g. Roberts, 2015 ;
Waite et al., 2017)

Enceladus' interior at the end of Cassini: composition



ocean is salty

Na (and K) salts in E-ring
(Postberg et al., 2009)

salts and organics in plume
(Postberg et al., 2011)

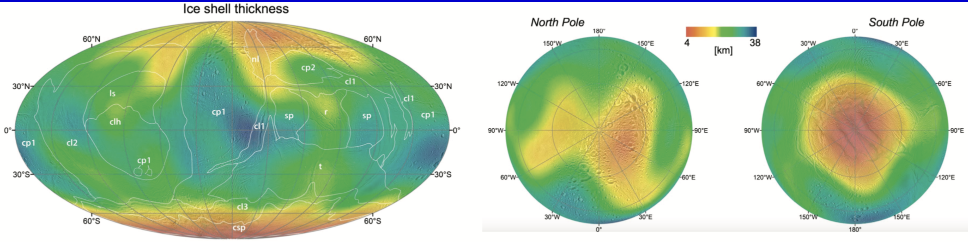
deep hydrothermalism

nano-silica particles
in Saturn's environment
⇒ 90°C, > 40 km deep
(Hsu et al., 2015)

H_2 in the plume
⇒ hydrothermal reactions
(Waite et al., 2017)

Revisiting the heat budget

Čadek et al. (2016)



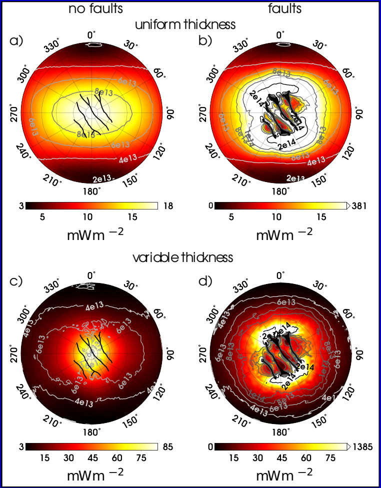
Diffusive equilibrium in a thin ice shell

- South Polar Terrain (SPT): heat flux $\gtrsim$100-150 mW m^{-2} or a total power of 3-5 GW
- heat flux at low latitudes: $\sim$20-40 mW m^{-2}
- global heat loss outside the SPT: $\sim$20-25 GW

$\Rightarrow$ Total power lost by diffusion $\sim$ 23-30 GW
What/where are the heat sources ?

Tidal dissipation within an ice shell of varying thickness

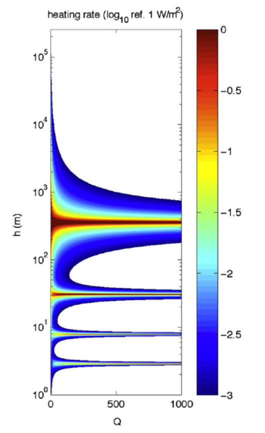
- thinning at the South Pole strongly enhances tidal dissipation by viscous friction,
- optimal heat production obtained for ice shell thickness ranging between 1 and 3.5 km for ice viscosity between 10^{14} and 10^{13} Pa s,
- tidal friction further enhanced by the presence of faults,



Běhounková et al. (2017)

⇒ Dissipation large enough to counterbalance heat loss in the SPT, but not at moderate/northern latitudes.

Tidal heat production in Enceladus' deep interior (1): the ocean



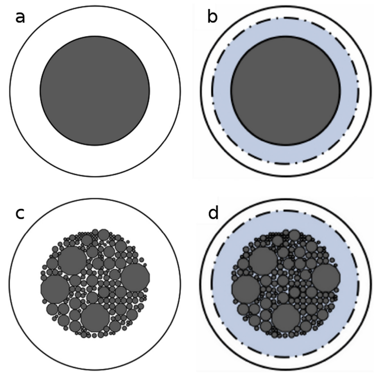
Tyler (2010)

- dissipation of resonant waves as a response of the subsurface ocean to both eccentricity and obliquity components of tidal forcing (Tyler, 2010 ; Matsuyama et al., 2018),
- significant heating obtained for very thin ocean and "inconsistent" pattern (Matsuyama et al., 2018),

$\Rightarrow$ overall, unlikely to generate 20-25 GW in the present geometry…

Tidal heat production in Enceladus' deep interior (2): the core

- due to low central pressure, Enceladus' core is likely unconsolidated,
- first gravity measurements (Iess 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.

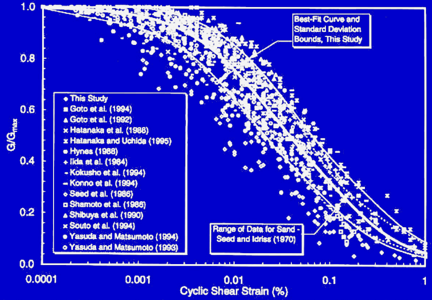


Roberts (2015)

$\Rightarrow$ what power could be produced by dissipation in a core filled with liquid water ?

Dissipation of a water saturated mixture of sand/gravel

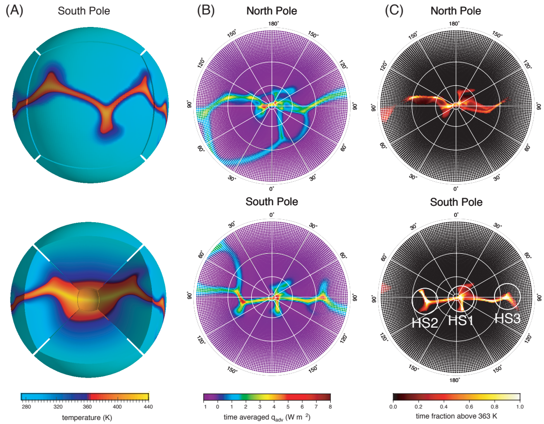
Rollins et al. (1998)



- possible mechanisms: inter-granular friction during grain rearrangements or/and frictional sliding along microcracks,
- anelastic properties of such materials classically parameterized with effective shear modulus and the damping ratio (or dissipation function),

- a strong decrease in elastic modulus (and increase in dissipation function) is expected when cyclic strain exceeds ∼ 0.01 % (typical value for Enceladus tidal deformation in the core, see after),
- laboratory mechanical tests performed however at larger frequency and lower pressure than those prevailing in Enceladus' core: we expect enhanced dissipation at the very low tidal frequency (creep effects) and a moderate effect of pressure.

Hot spots at the seafloor



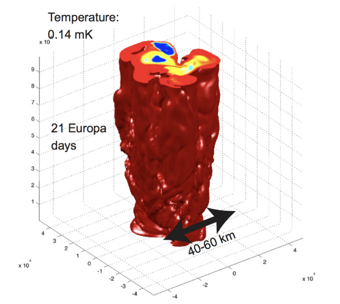
⇒ a significant volume fraction is above >100°C implying efficient aqueous alteration,

⇒ persistent hotspots (1-5 GW) are anchored beneath the poles and along specific meridians (regions with a thinner ice shell above).

Polar ocean plumes: scaling results

	Goodman et al (2004) *(scaling and laboratory experiments)*	Goodman and Lenferink (2012) *(numerical experiments)*
l_{cone}/H	0.15	0.2
$V_p/(Hf')$	0.01	$3\ 10^{-3}$
$(\Delta T_p g_o \alpha_o)/(Hf'^2)$	$3\ 10^{-4}$	$4\ 10^{-5}$
l_{cone} (km)	8.25	11
V_p (cm/s)	6	2
ΔT_p (mK)	5	0.7

Table: Characteristics of the oceanic thermal vents.



- temperature variations within the ocean of a few mK,
- estimated transport time from seafloor to the source of jets beneath SPT ice shell: a few weeks to months,
- compatible with the growth rate of nano-silica *(Hsu et al., 2015)*

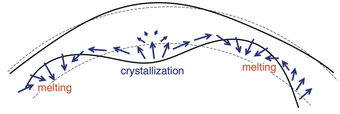
Temporal perspective

stability of the hydrothermal activity

- the latest estimate of Saturn's dissipation function yields an equilibrium heating of 10- 50 GW (Lainey et al., 2017 ; Fuller et al., 2016)
- hydrothermal activities could be sustained for billions of years for $P_{tide} > 15$ GW and for at least 20 Myr for $P_{tide} < 15$ GW.

mass/chemical flux in the hydrosphere

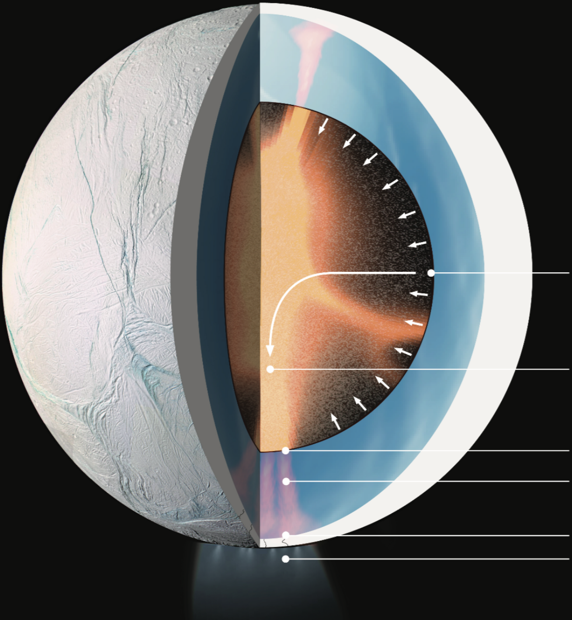
- the entire ocean would be processed in the core at temperatures higher than 363 K in 25-250 Myr,



Čadek et al., (2017)

- the entire volume of ocean would be exchanged with the ice shell through melting/freezing on the same time scale.

Summary

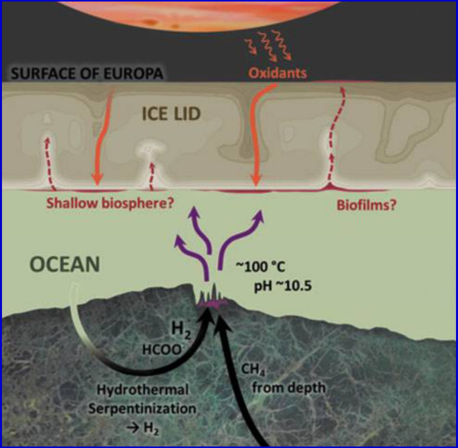


Choblet et al., 2017

The possible emergence of life ? (Russell et al., 2017)

a simplified geochemical utility of life on Earth:

- hydrogenation of CO_2,
- hastening a flow of hot electrons into available acceptors,

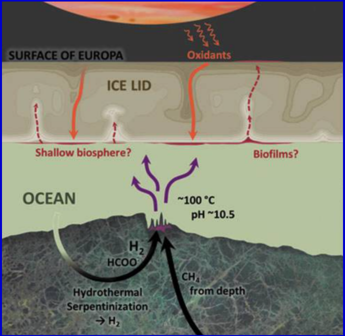


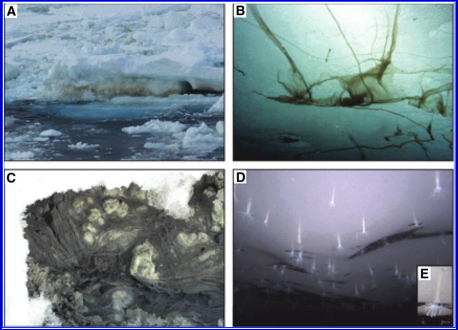
hydrothermal mounds on Enceladus and Europa at 100°C:

- hydrothermal fluids (e^- bearing hydrogen, methane), further reduced volatiles (CO_2, NH_3, H_2S), transition metals for catalysis,
- mound interacting with ocean as an electrogeochemical reactor (proton and redox gradients).

The possible emergence of life ? (Russell et al., 2017)

endogeneous (tidal, radioactive) heat from rock cores replaces sun heating, but possible lack of powerful oxidants...





- these (NO^{2-}, NO^{3-}, SO_3^{2-}, SO_4^{2-}) could result from reaction between H_2O_2 (radiolysis of pure ice at surface) and H_2S/NH_3 *(left)*,
- oxidants could be dissolved in ocean - if too scarce (oxidants crisis), biofilms would form at sites where hydrothermal vents interact with the ice ceiling *(right)*.

Conclusions

- very ancient (3.8-4.2 Gyr ago) evidence for life in Earth's oldest submarine-hydrothermal vents (Dodd et al. 2017),
- after Cassini, observations/models for Enceladus interior are (and will remain) agnostic about the presence of life,
- a (supplementary) key unknown: the age and formation process of Enceladus and mid-sized moons,
- a key Enceladean asset: ocean so easy to access...