The Keck Institute for Space Studies presents a short course on:

Accessing the Subsurface Oceans of Icy Worlds

Earth-Europa-Enceladus: Ocean/Rock Interactions and Prospects for Life

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Introduction

The case for Enceladus

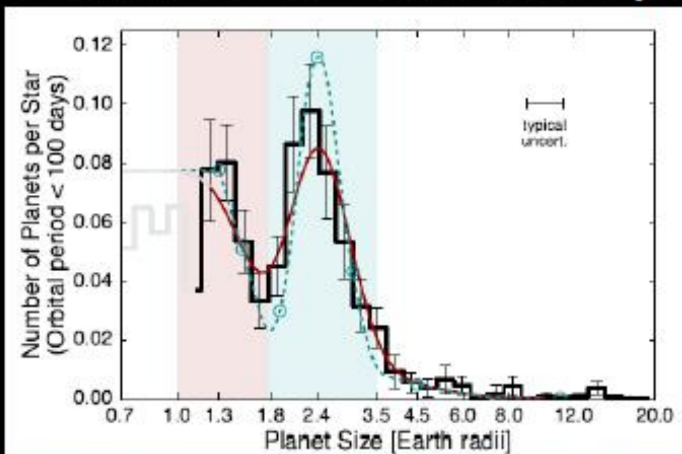
Serpentinization and hydrothermal circulation

Interior structure of Europa

Preliminary conclusions

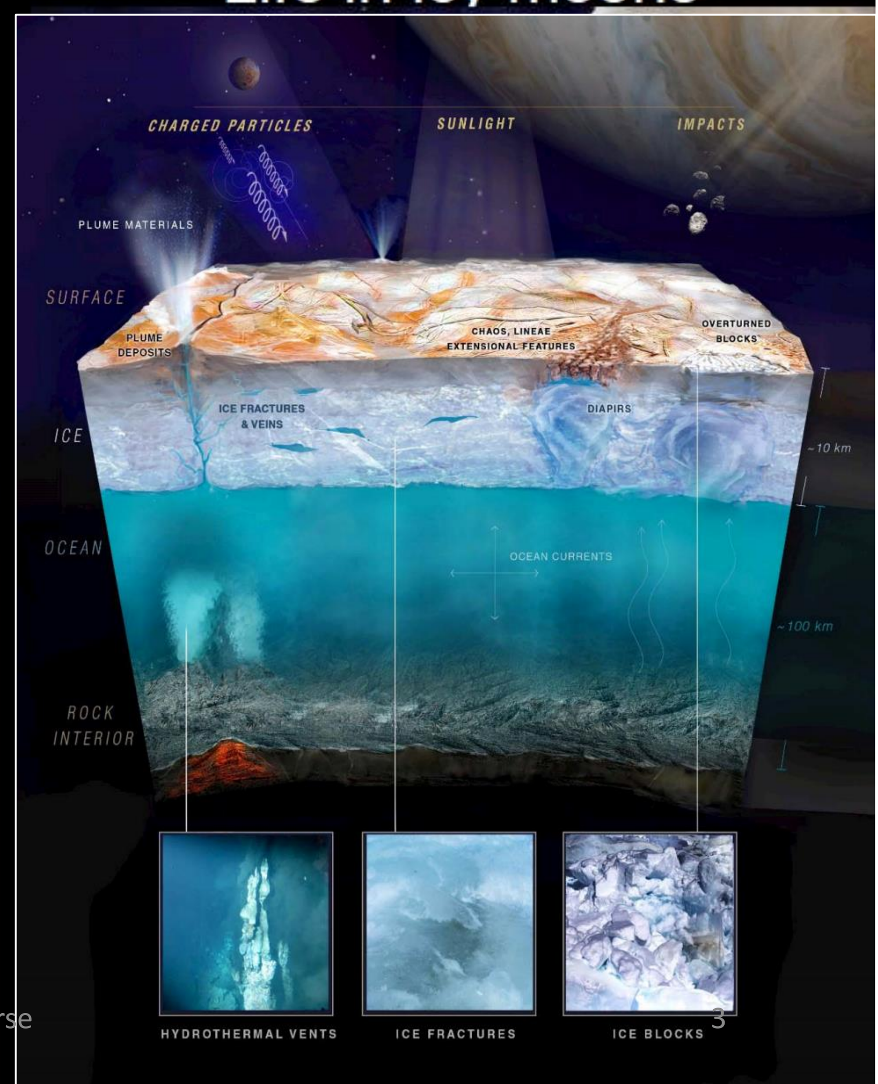
Most important question in Planetary Science:
Is there life somewhere else in the Universe?

Extra-solar habitable planets



Fulton et al., 2017

Life in icy moons



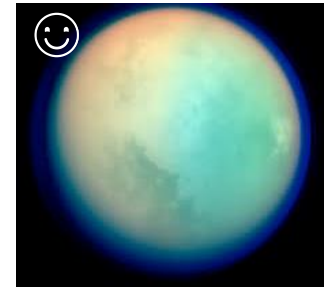
Ocean Worlds

How habitable are icy moons ?

WATER

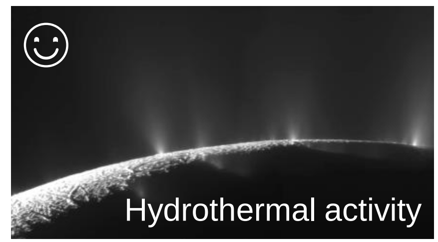






Galileo

HABITABILITY

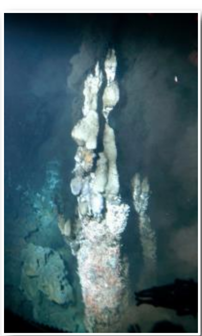
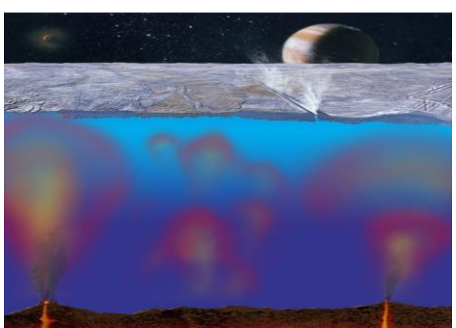
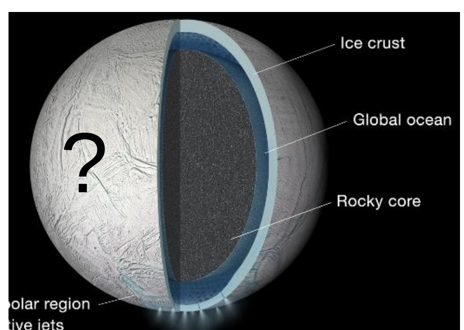


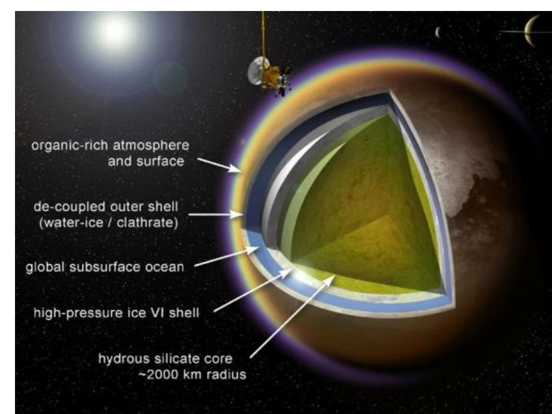
LIFE

Cassini

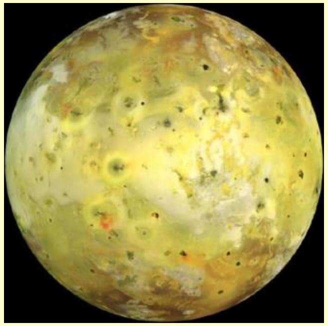
Sea-floor – Life as we know it

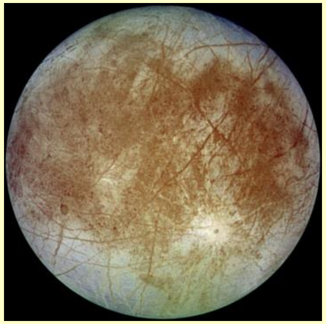
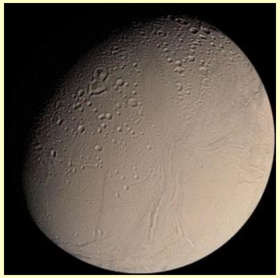
Other type of life ?



Some numbers for comparison

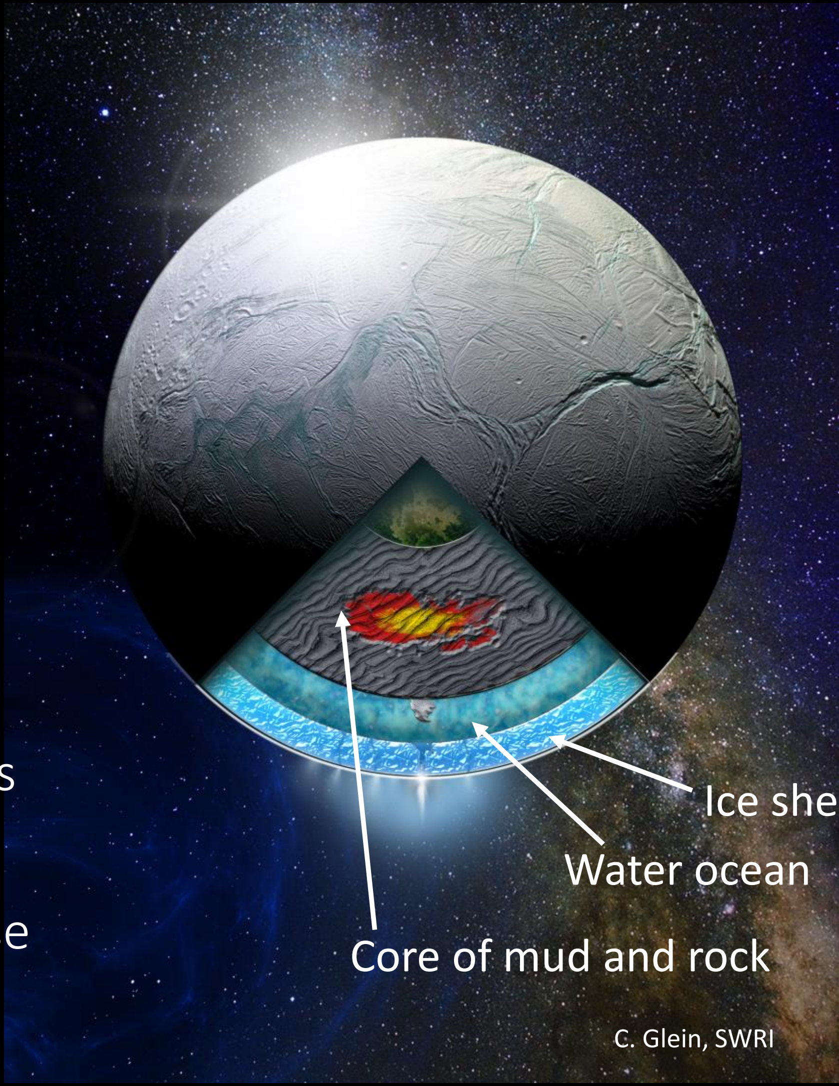
6371 km	1822 km	2575 km	1561 km	252.3 km
5.97 10^{24} kg	0.0894 10^{24} kg	0.1345 10^{24} kg	0.048 10^{24} kg	0.000108 10^{24} kg
5525 kg/m^3	3528 kg/m^3	1881 kg/m^3	2970 kg/m^3	1608 kg/m^3
2/3 Silicates and 1/3 iron	Silicates	H_2O & silicates	H_2O & silicates	H_2O & silicates
42 TW (75 mW/m2)	**108 TW (2 W/m^2)**	**750 GW**	**1 TW +**	**6 GW**

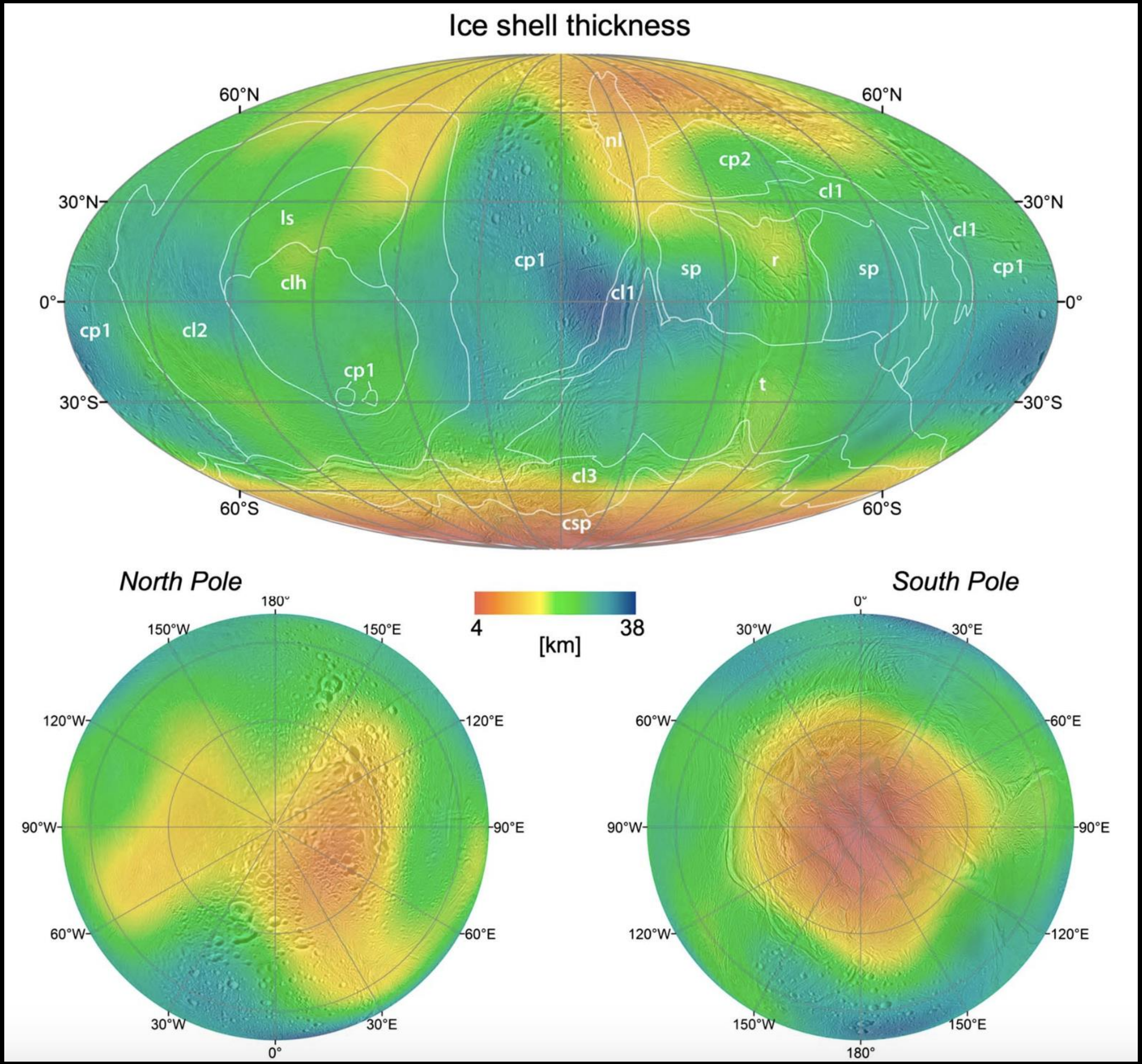
Radioactive power is proportional to the mass
Other internal heat sources include tidal dissipation, cooling, and latent heat

The Case for Enceladus

Cassini has

- Discovered a global interior ocean
- Flown *seven times* through its large plume
  - Detected salts, and thus ocean grains
  - Measured a variety of organic molecules
  - Found multiple lines of evidence for hydrothermal activity at the ocean's base



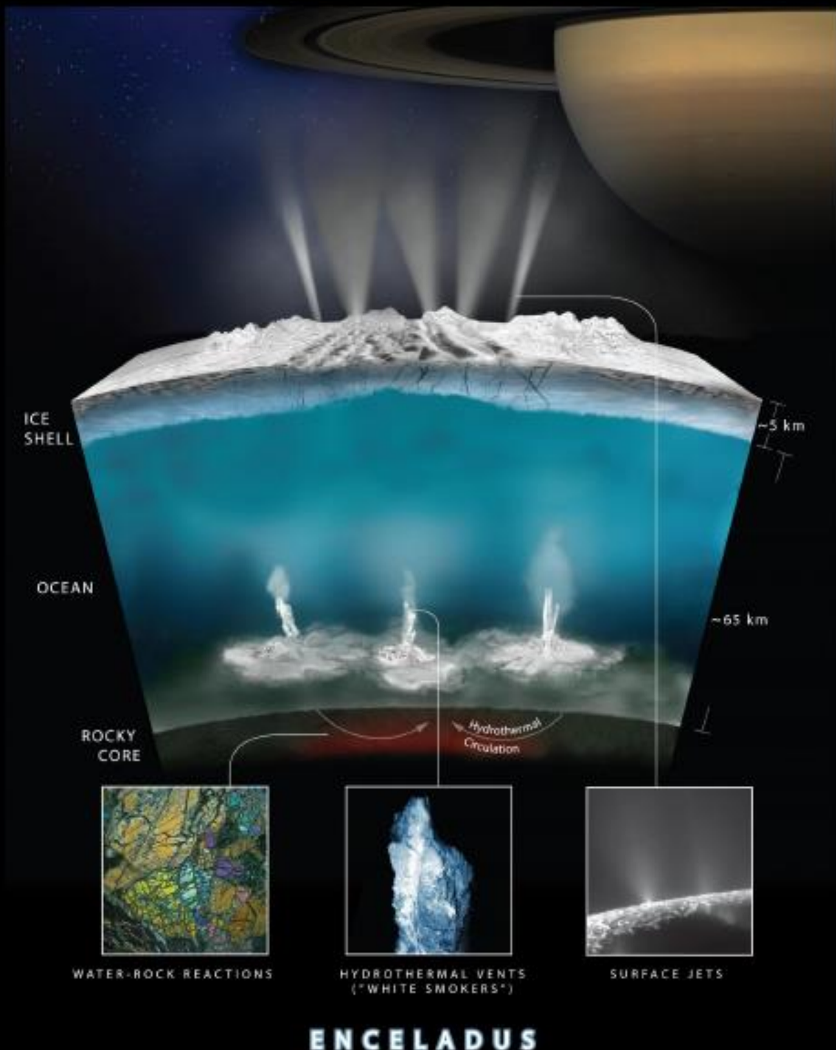


Thickness minimal at both poles (only a few kms beneath the South, (~10 km beneath the North),

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)

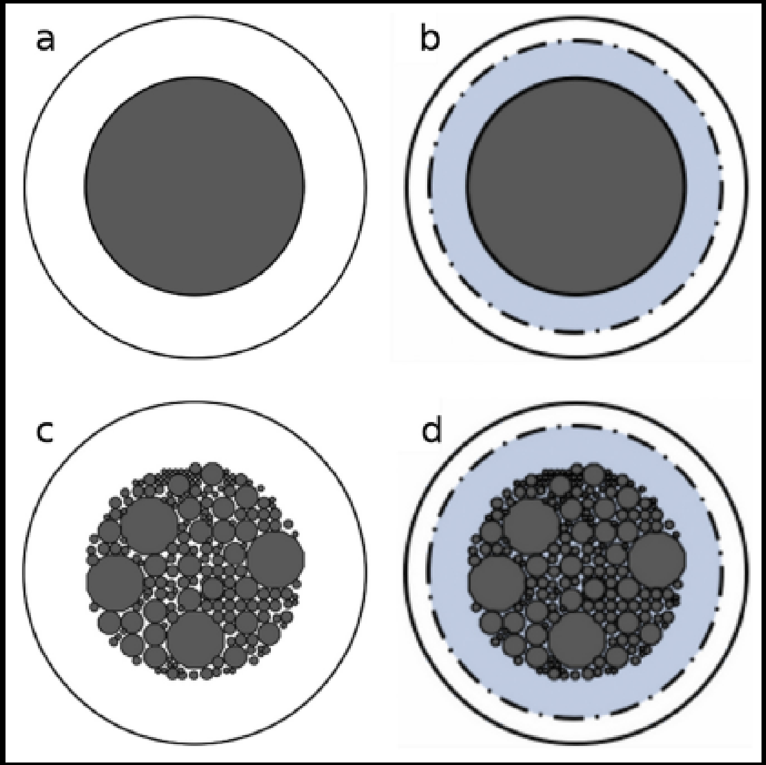
Chemical observations: INMS
modelcular hydrogen in the plume



- 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).

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.

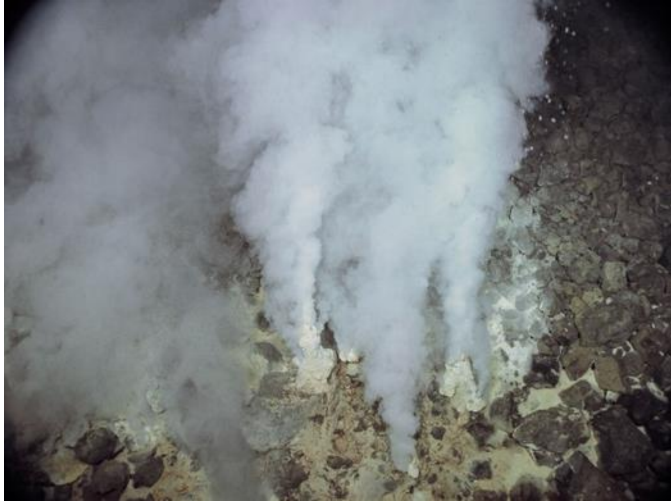


Roberts (2015)

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.

Serpentinization and hydrothermal processes

Water percolates into the oceanic crust, alters the minerals and brings material into the ocean

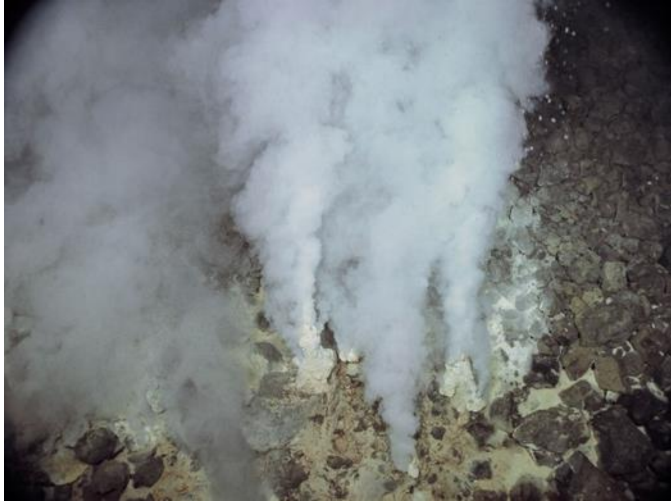


$$6(Mg_{0.75},Fe_{0.25})_2SiO_4 + 7\ H_2O \rightarrow 3Mg_3Si_2O_5(OH)_4 + Fe_3O_4 + H_2$$

$$3Fe^{2+} \rightarrow Fe^{2+} + 2Fe^{3+} + 2e^-$$

- 1 mole of H_2 for 6 moles of olivine (Andreani et al., 2007) – $5x10^{13}$ mole of H_2/year
- 7 moles of H_2O for 6 moles of olivine (12% of water in mass)
- For Earth, the reaction produces about 0.5 TW (1% of total flux)
- Sea water can percolate down to 4 to 10 km depth (Andreani et al., 2007; Boschi et al., 2006; Plumber et al., 2012), equivalent to pressure of 100 to 300 MPa on Earth

Hydrothermal processes at Enceladus' ocean / silicate interface



$$6(Mg_{0.75},Fe_{0.25})_2SiO_4 + 7\ H_2O \rightarrow 3Mg_3Si_2O_5(OH)_4 + Fe_3O_4 + H_2$$

$$3Fe^{2+} \rightarrow Fe^{2+} + 2Fe^{3+} + 2e^-$$

- $5x10^{13}$ mole of H_2/year on Earth – $5x10^{19}$ mole H_2 if all the core is hydrated
- 190 ppm of amino acids in the ocean if all the core is leached (more if the ocean is not global – assuming values of AA in Murchinson meteorite (Sephton, 2002)
- Similarly, 35 ppm of benzoic acid (Naraoka et al., 1996)
- Based on chondritic abundances in K, the total potential of ^{40}Ar is about $5.6x10^{12}$ kg.
- CDA measurements suggest that hydrothermal processes are active at present time
- However, Cassini won't be able to determine to which degree hydrothermal processes have evolved on Enceladus

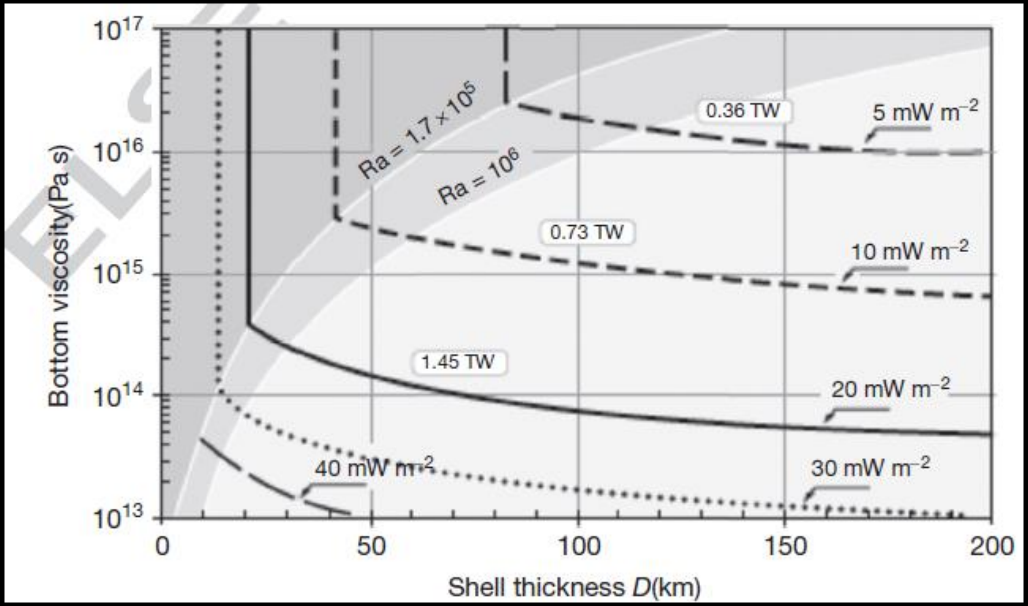
The Case for Europa

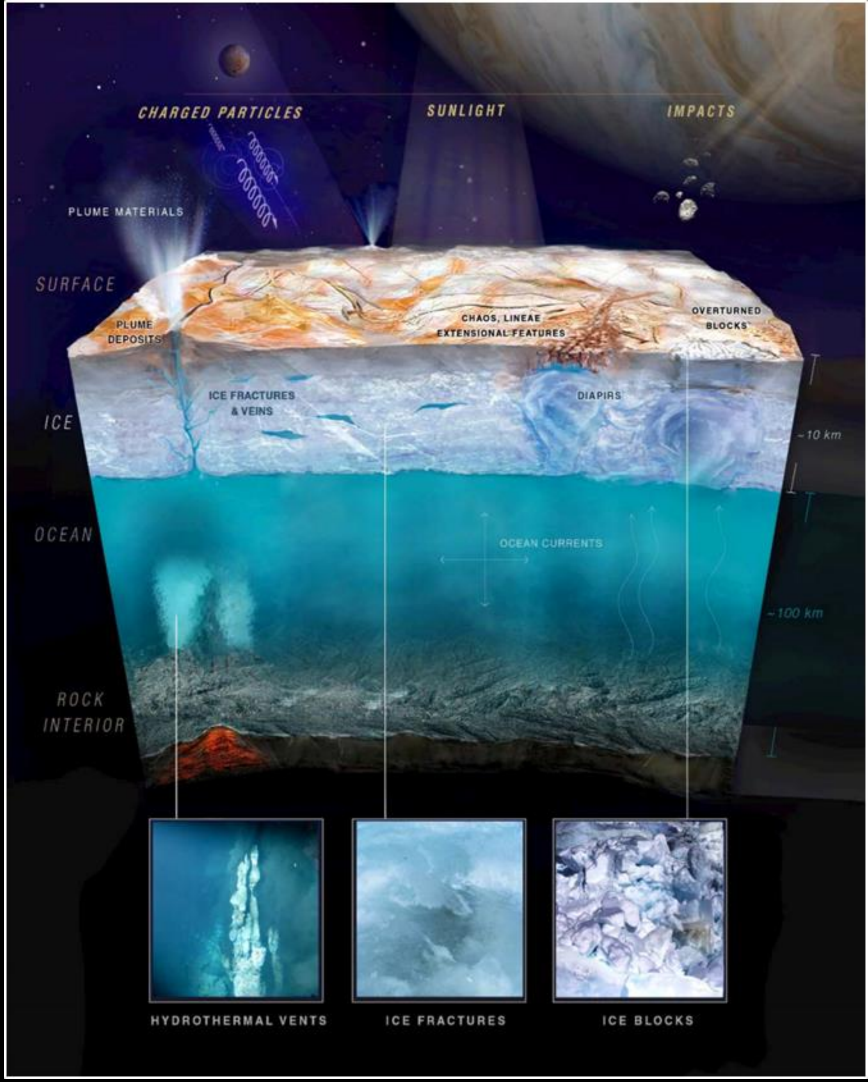
Galileo has discovered a global interior ocean

MoI suggests a differentiated interior

Models suggest tidal dissipation is located at the ice/ocean interface

Surface may be covered by oxidants



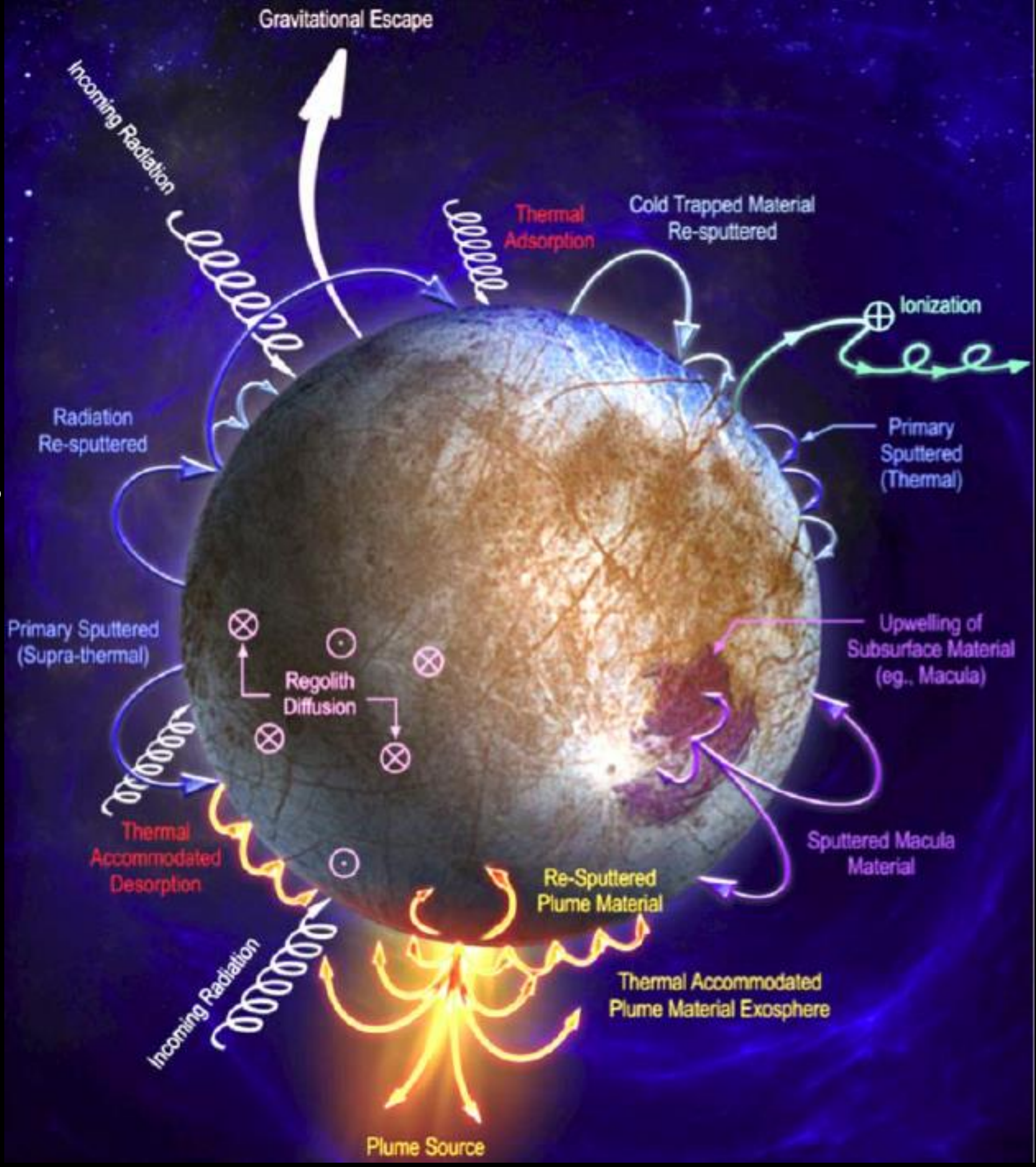


Europa Lander SDT

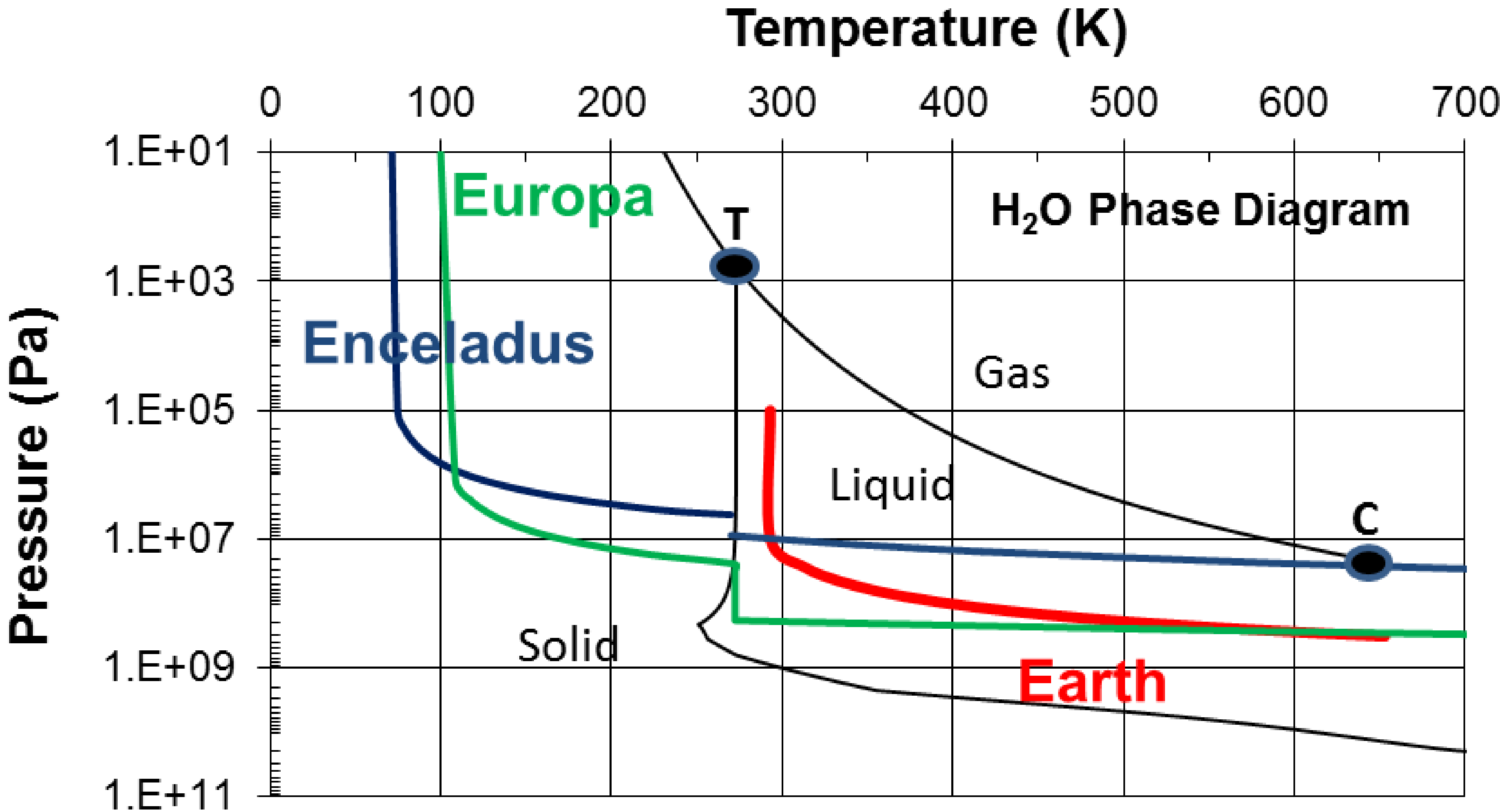
Hussmann & al. (2015)

The Case for Europa

Europa's surface is heavily modified by sputtering and radiolysis that occurs as a result of the ~125 mW/m2 of charged particle irradiation, most of which (>75%) is from energetic electrons (Cooper et al., 2001). The observation of plumes on Europa remains tenuous.



Europa Lander SDT – Image: Teolis et al. (2017)


Temperature (K)
0
100
200
300
400
500
600
700
1.E+01
1.E+03
1.E+05
1.E+07
1.E+09
1.E+11
Pressure (Pa)
Europa
Enceladus
T
H_2O Phase Diagram
Gas
Liquid
C
Solid
Earth

Summary and Conclusions

1. Ocean Worlds are numerous: Is life present in these oceans?
2. Enceladus and Europa are likely to have an ocean in contact with the rock. Titan may have one too and had such interface in the past.
3. Cassini demonstrated that H_2, a product of serpentinization, is produced inside Enceladus and is released into space.
4. Such processes may exist inside Europa. Still open question.
5. Exploring extraterrestrial oceans will provide the answer on the presence of life.
6. Need to know the characteristics of the ice crust to investigate the potential of drilling through it.