Hydrothermal Activity in the Solar System's Ocean Worlds

Steve Vance (svance@jpl.caltech.edu), Mohit Melwani Daswani

Jet Propulsion Laboratory, California Institute of Technology, Pasadena

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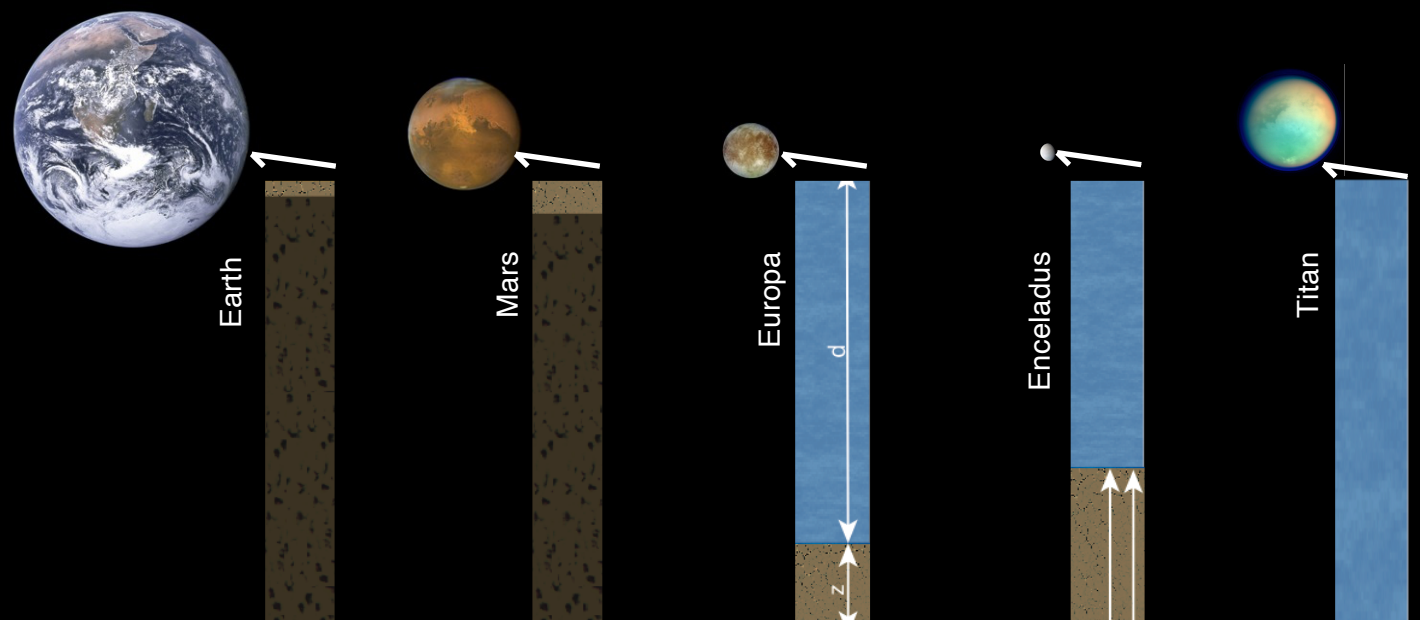
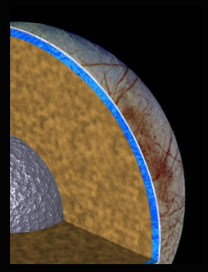
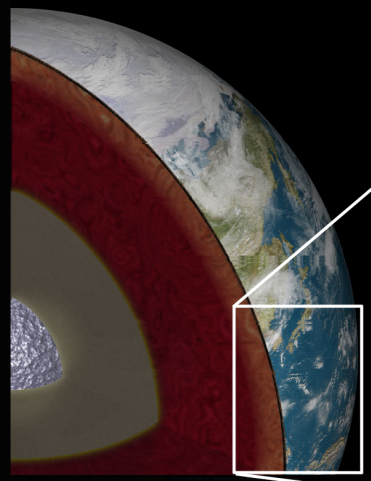


Introduction

- Icy ocean worlds (and Mars) may undergo high or low temperature hydrothermal activity
- Their redox evolution is tied to hydrothermal activity
- We are coupling geophysical models to geochemistry to investigate these topics

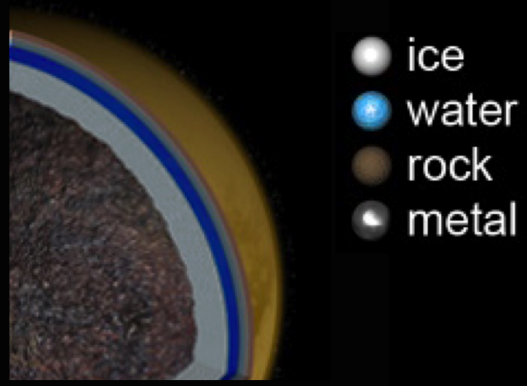


Europa



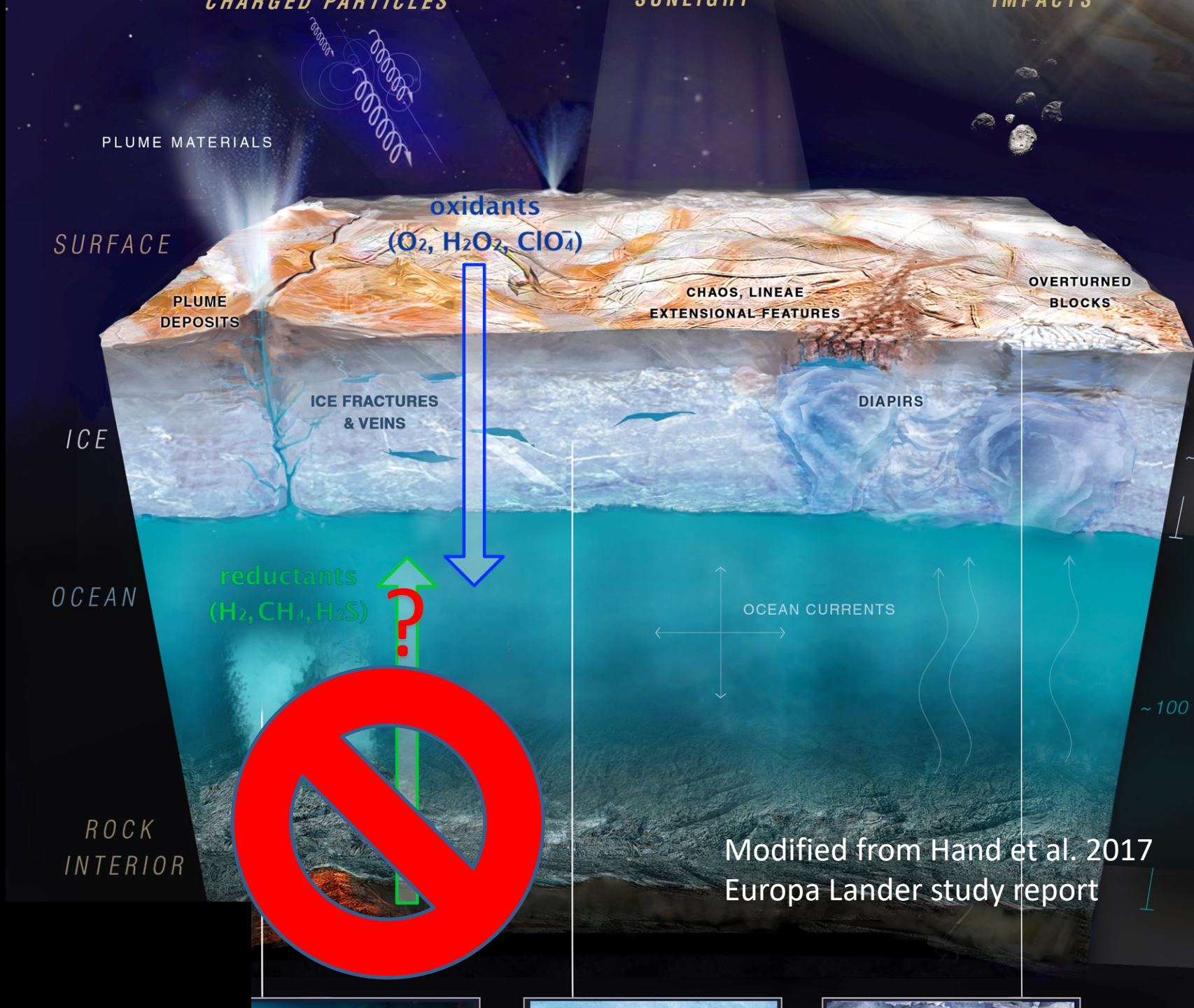
Earth

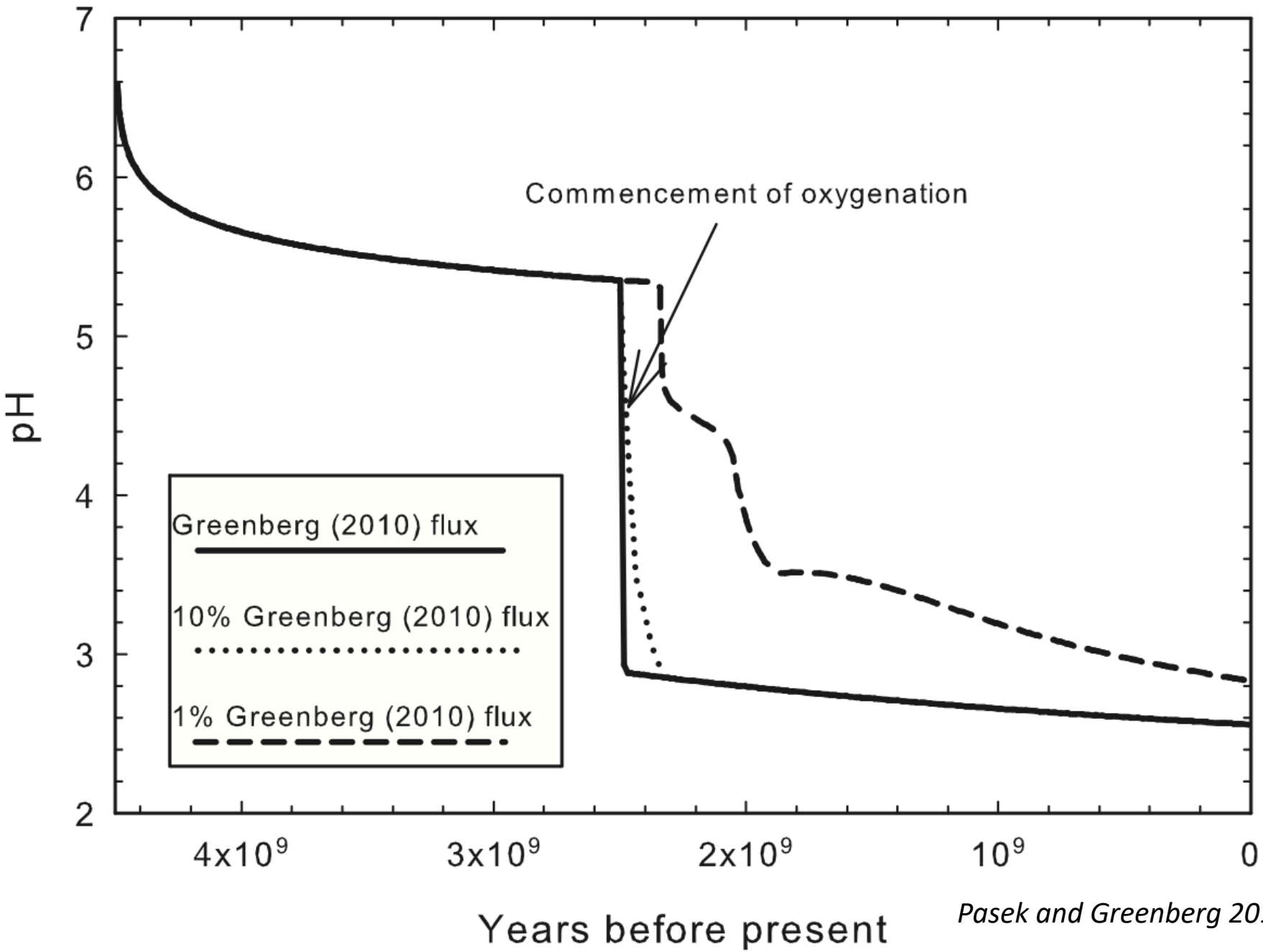
Earth to Scale



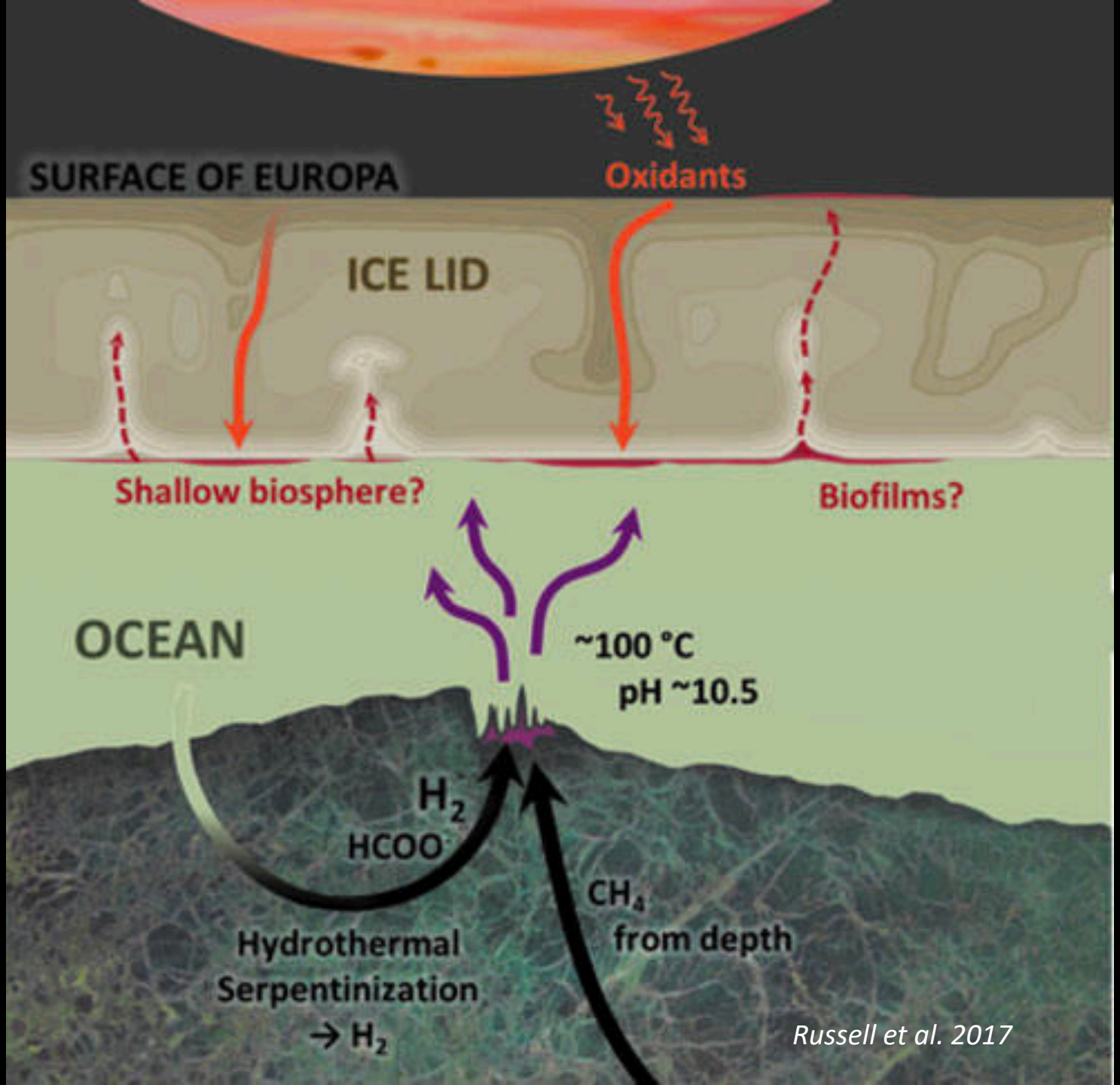
Titan

Enceladus


CHARGED PARTICLES
SUNLIGHT
IMPACTS
PLUME MATERIALS
SURFACE
oxidants
(O_2, H_2O_2, ClO_4^-)
PLUME DEPOSITS
CHAOS, LINEAE
EXTENSIONAL FEATURES
OVERTURNED BLOCKS
ICE FRACTURES & VEINS
DIAPIRS
ICE
OCEAN
reductants
(H_2, CH_4, H_2S)
?
OCEAN CURRENTS
~100
ROCK INTERIOR
Modified from Hand et al. 2017
Europa Lander study report



Pasek and Greenberg 2012

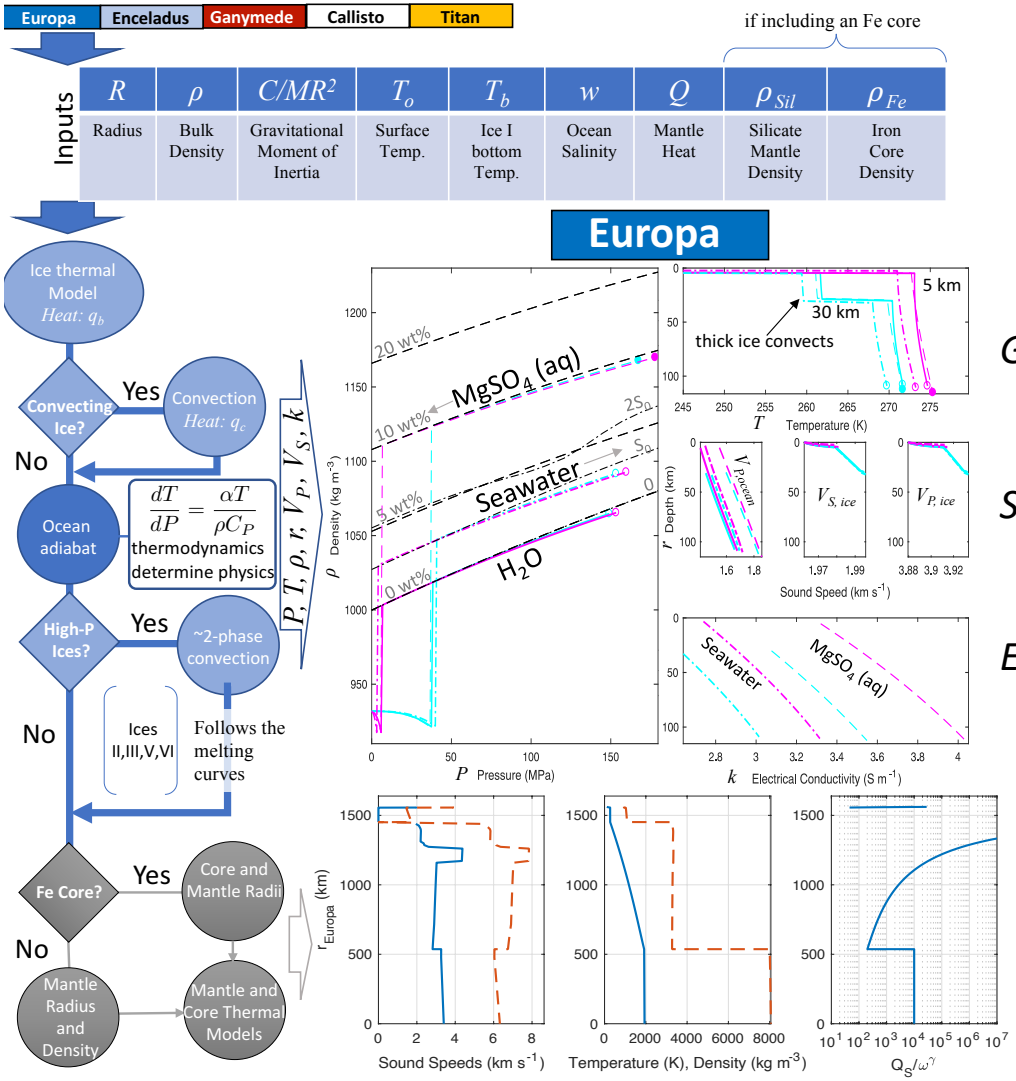


Russell et al. 2017

PlanetProfile

github.com/vancesteven/PlanetProfile

Geophysical methods can test for results of water-rock interaction

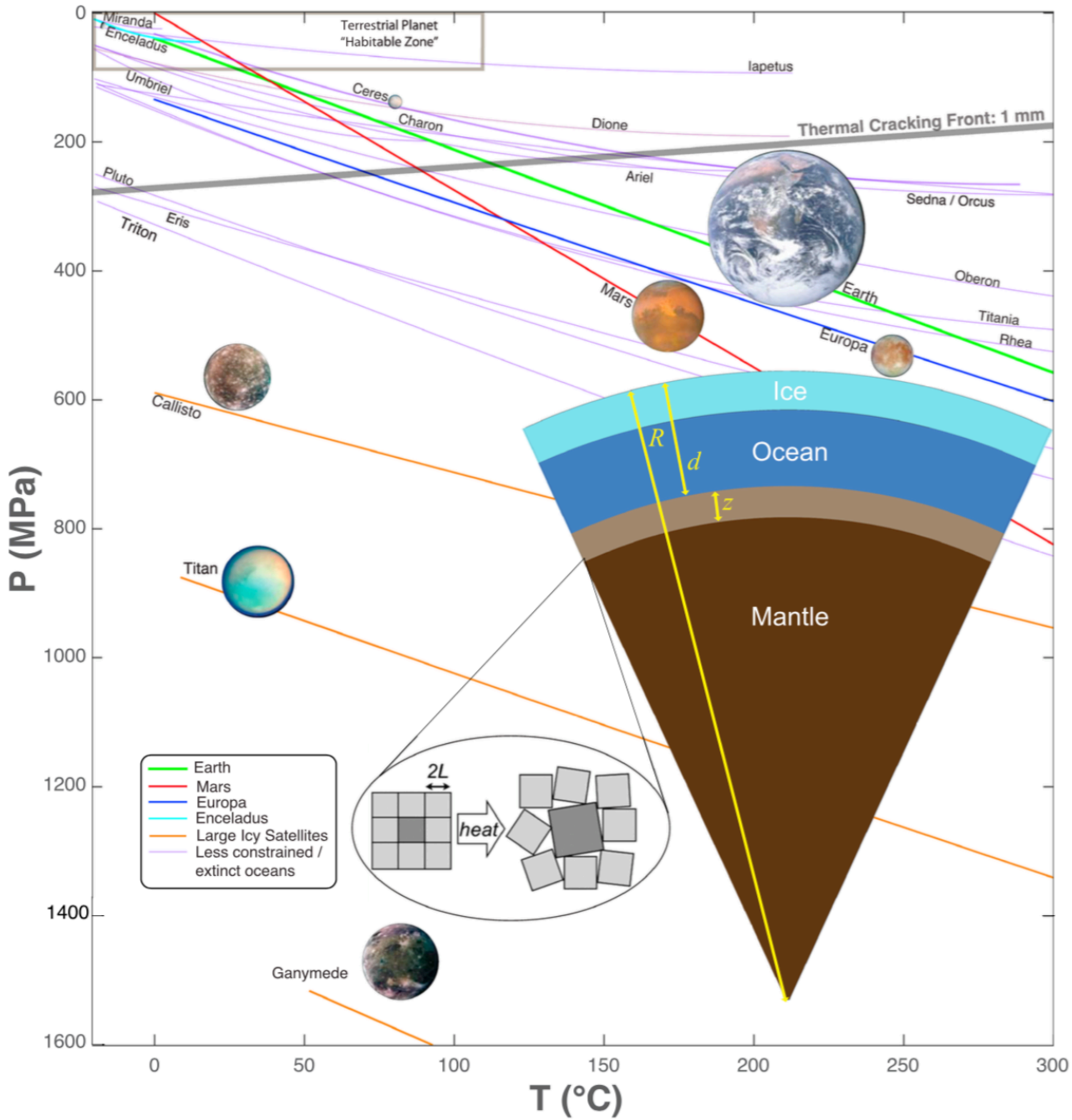


Gravity: e.g. Oral P52B-04

Seismology: e.g. Poster P53D-3479
(Enceladus)

EM sounding: e.g. Poster P53D-3473,3477

Vance et al. 2018 JGR: Planets



Vance et al. 2016

$$3Fe_2SiO_4 + 2H_2O = 2Fe_3O_4 + 3SiO_2(aq) + 2H_2(aq)$$

fayalite + water = magnetite + silica + hydrogen

$$3FeSiO_3 + H_2O = Fe_3O_4 + 3SiO_2(aq) + H_2(aq)$$

ferrosilite + water = magnetite + silica + hydrogen.

H_2

$$2Mg_2SiO_4 + 3H_2O = Mg(OH)_2 + Mg_3Si_2O_5(OH)_4$$

forsterite + water = brucite + serpentine.

Heat
41 kJ/mol olivine

$$V(t) = 4/3\pi(R_{sf}^3 - R_h(t)^3)$$

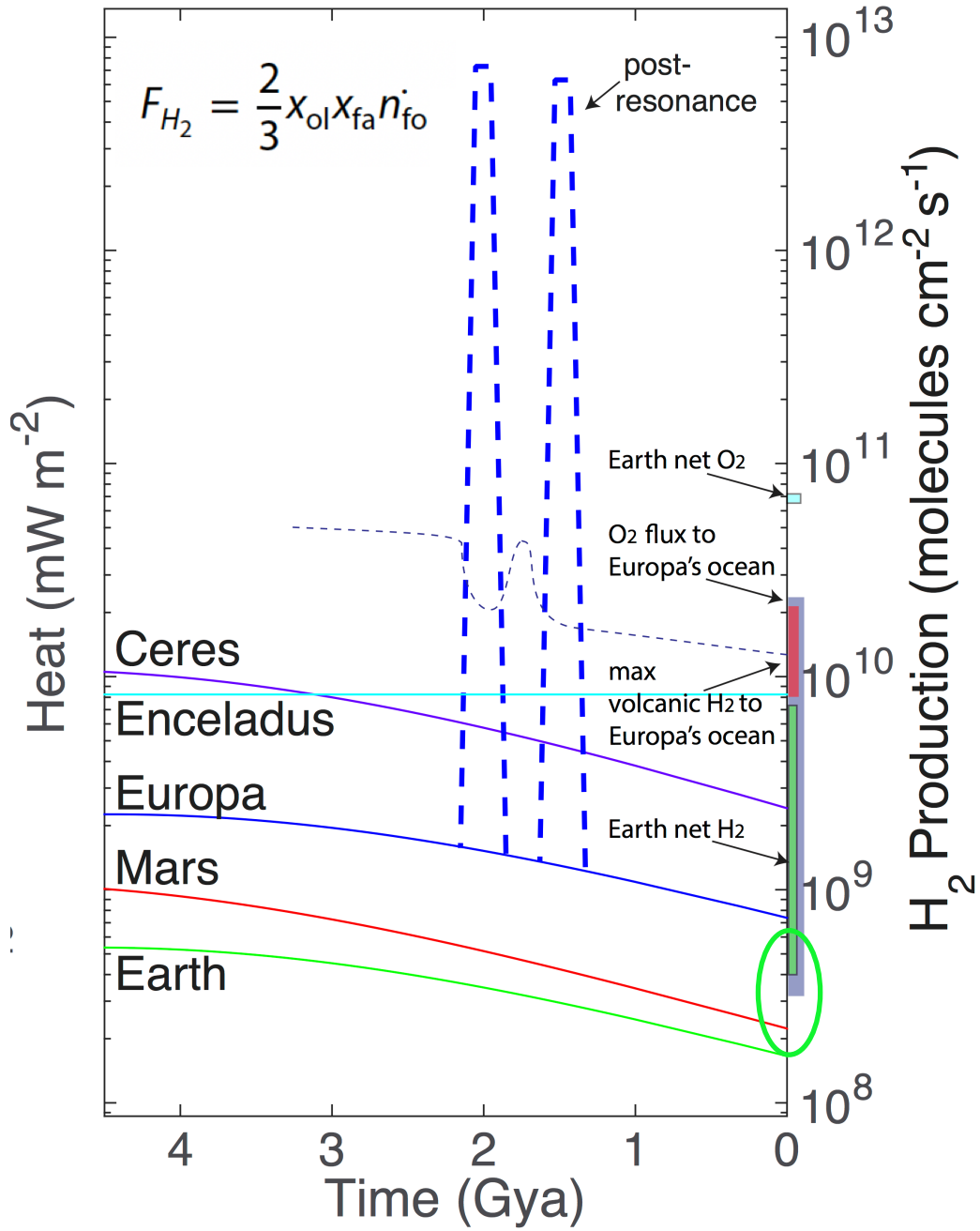
$$\dot{n}_{fo} = \dot{V}/V_{fo}$$

$$H_{serp} = x_{ol} L_{serp} \dot{n}_{fo}$$

$$F_{H_2} = \frac{2}{3} x_{ol} x_{fa} \dot{n}_{fo}$$

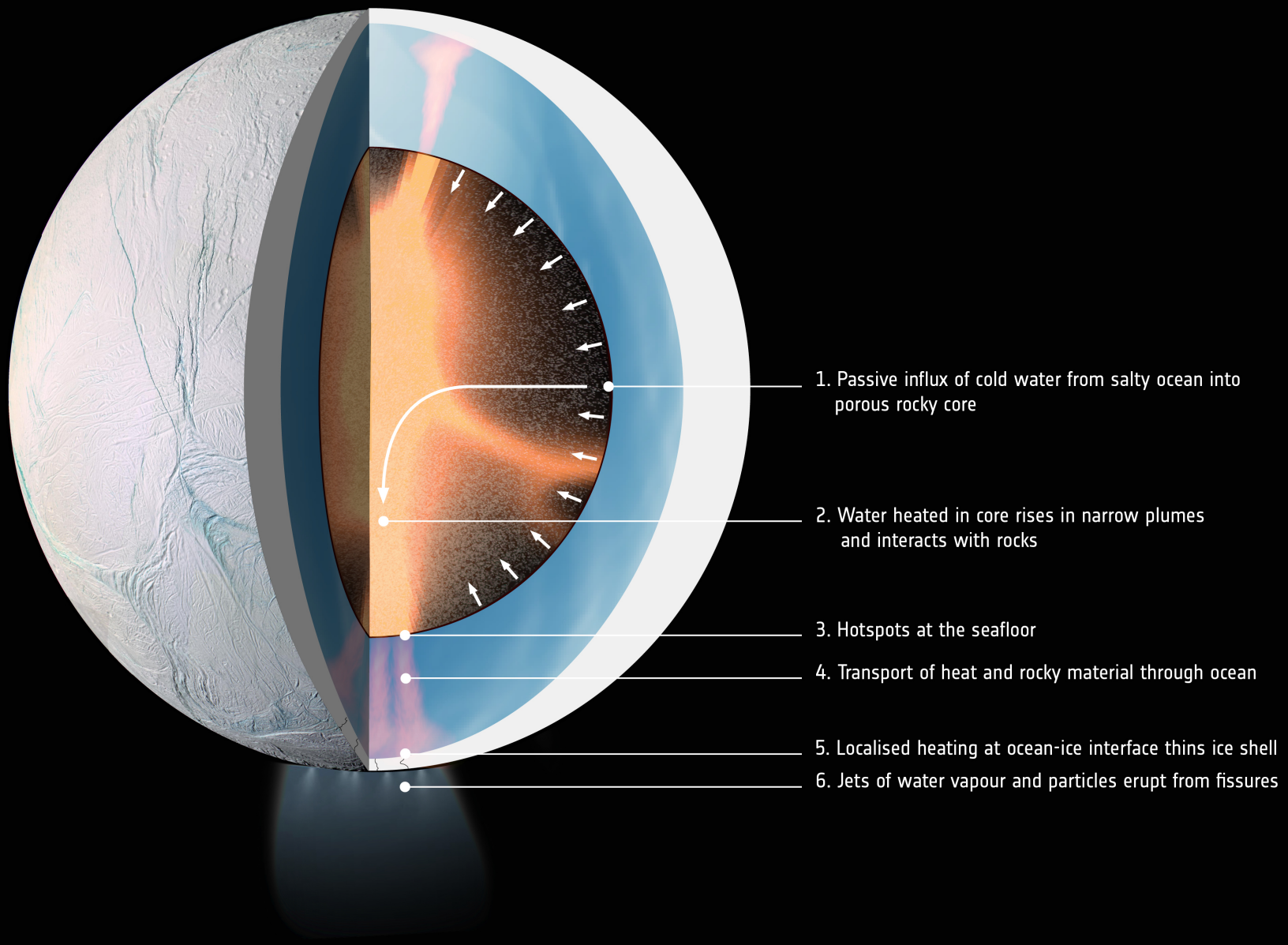
$x_{ol} = 0.7$

$x_{fa} = 0.1$



Vance et al. 2016

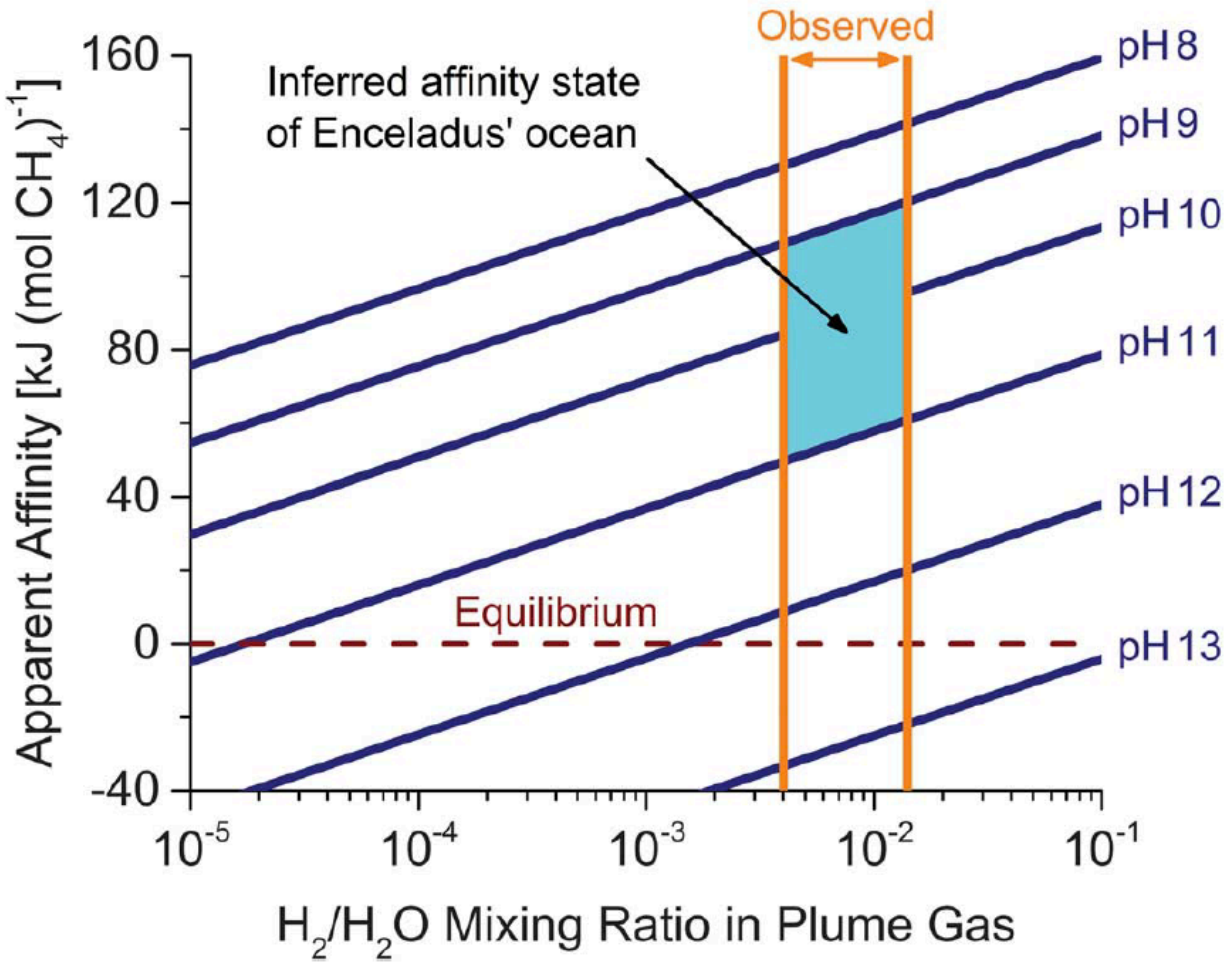
Choblet et al. 2018
Hsu et al. 2015



NASA/JPL/ LPG-CNRS/U. Nantes/U. Angers/ ESA

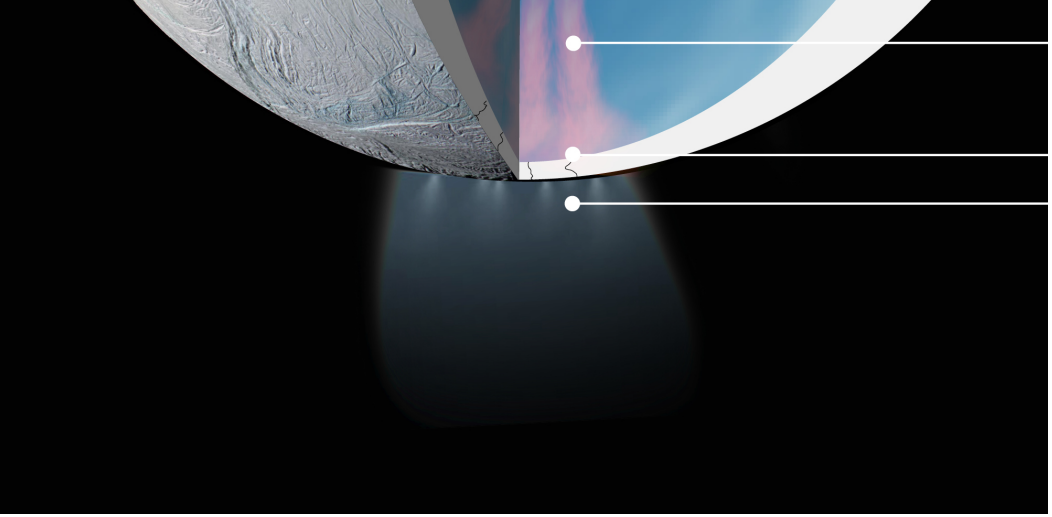
Plume composition measured by INMS

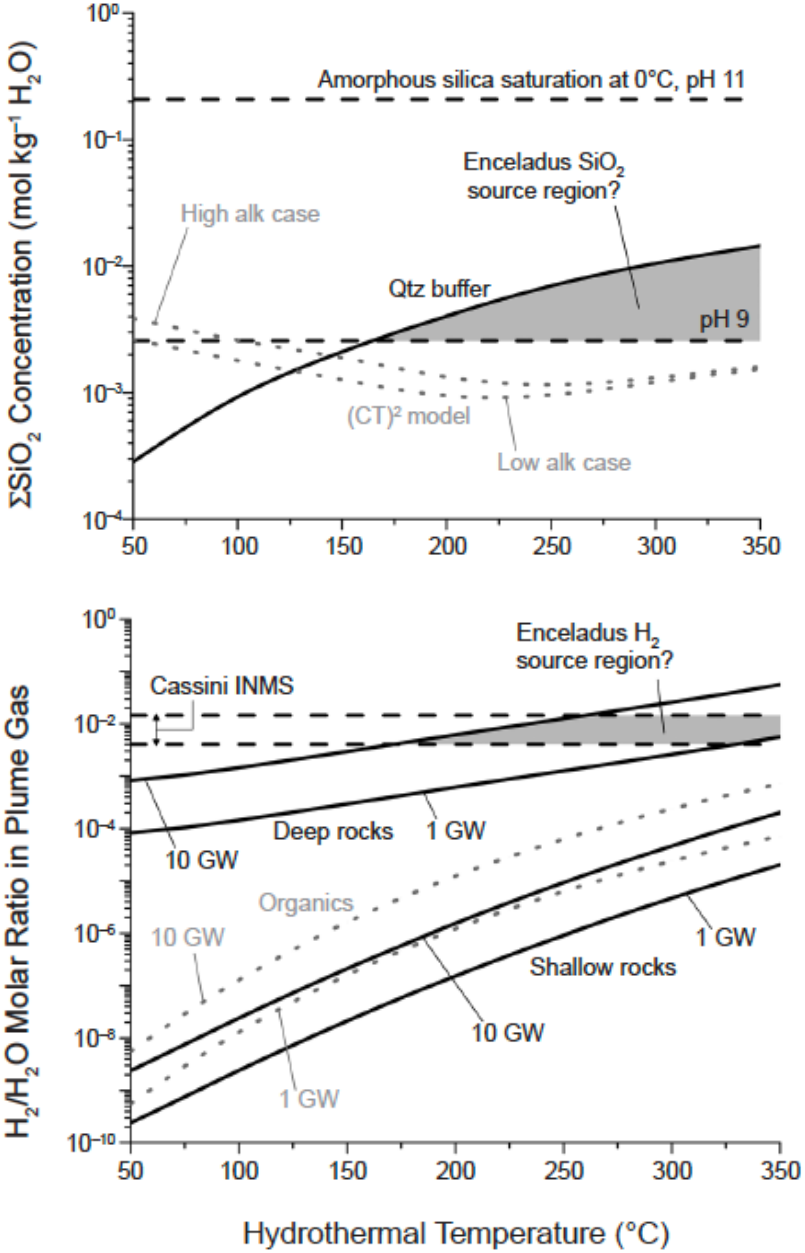
Constituent	Mixing ratio (%)
H_2O	96 to 99
CO_2	0.3 to 0.8
CH_4	0.1 to 0.3
NH_3	0.4 to 1.3
H_2	0.4 to 1.4



$$CO_2(aq) + 4H_2(aq) \rightarrow CH_4(aq) + 2H_2O(l)$$

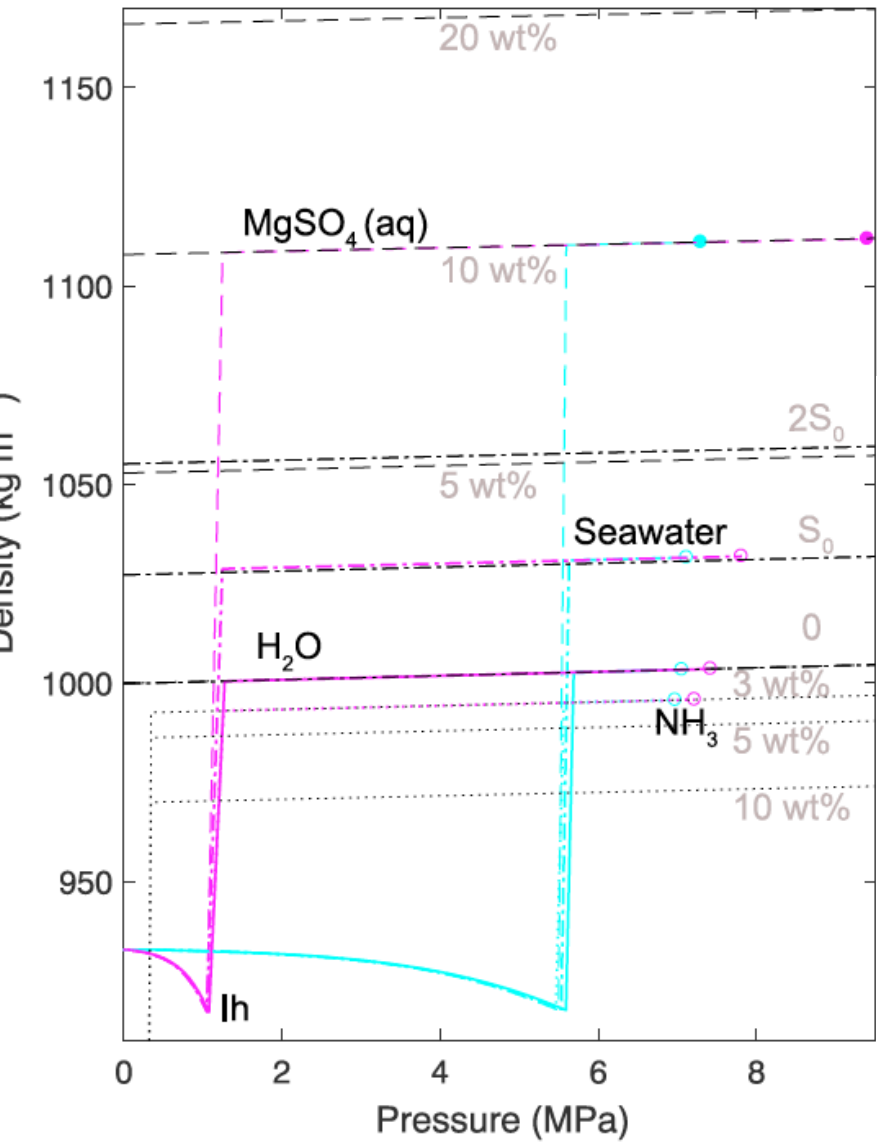
Waite et al. 2017



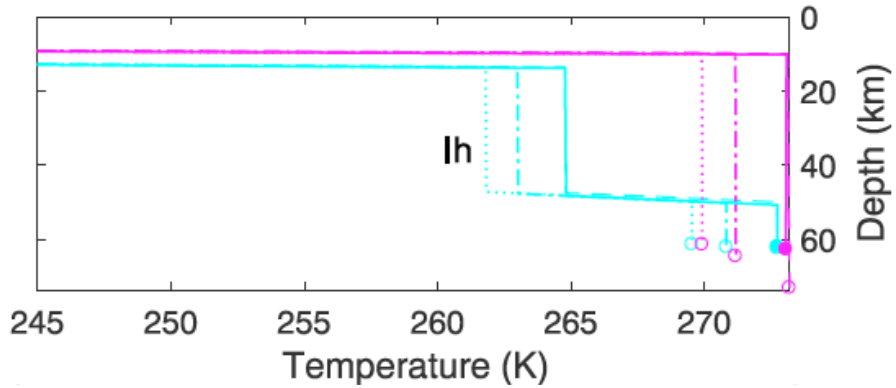


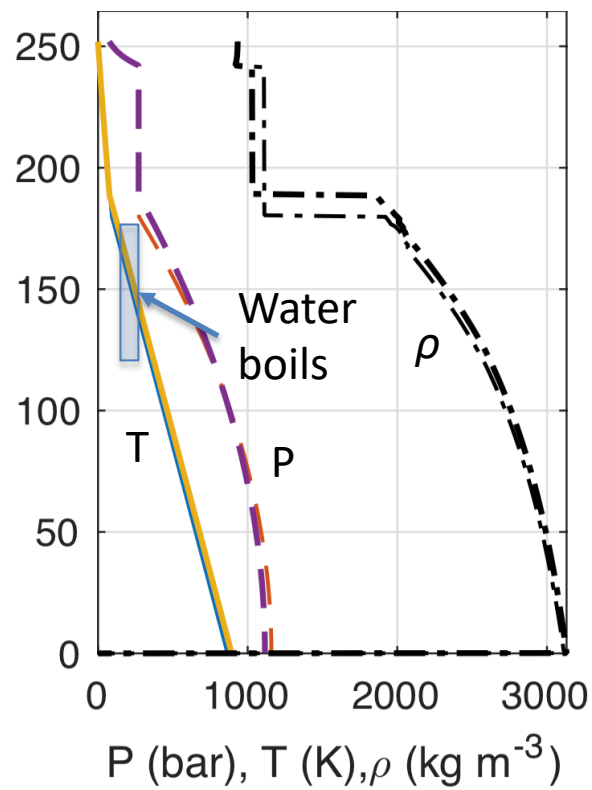
The Enceladus plume appears to place constraints on the temperature of water-rock interaction

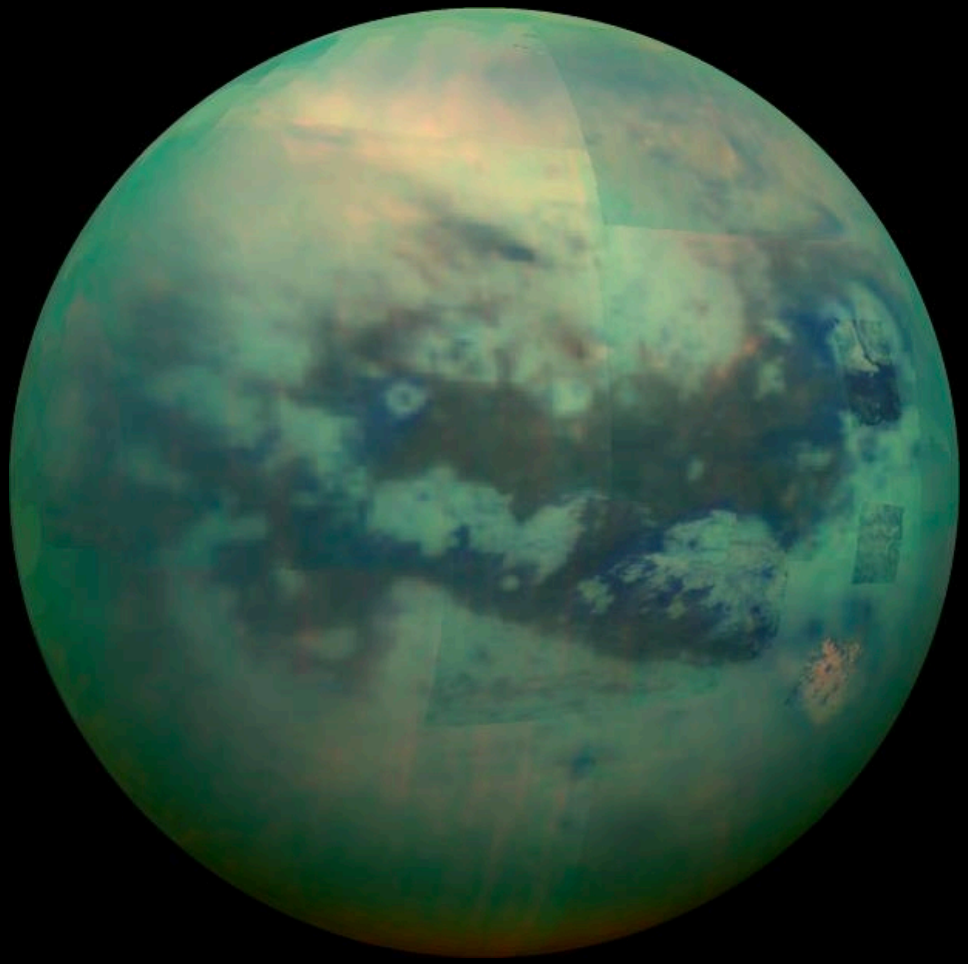
Glein et al. 2019



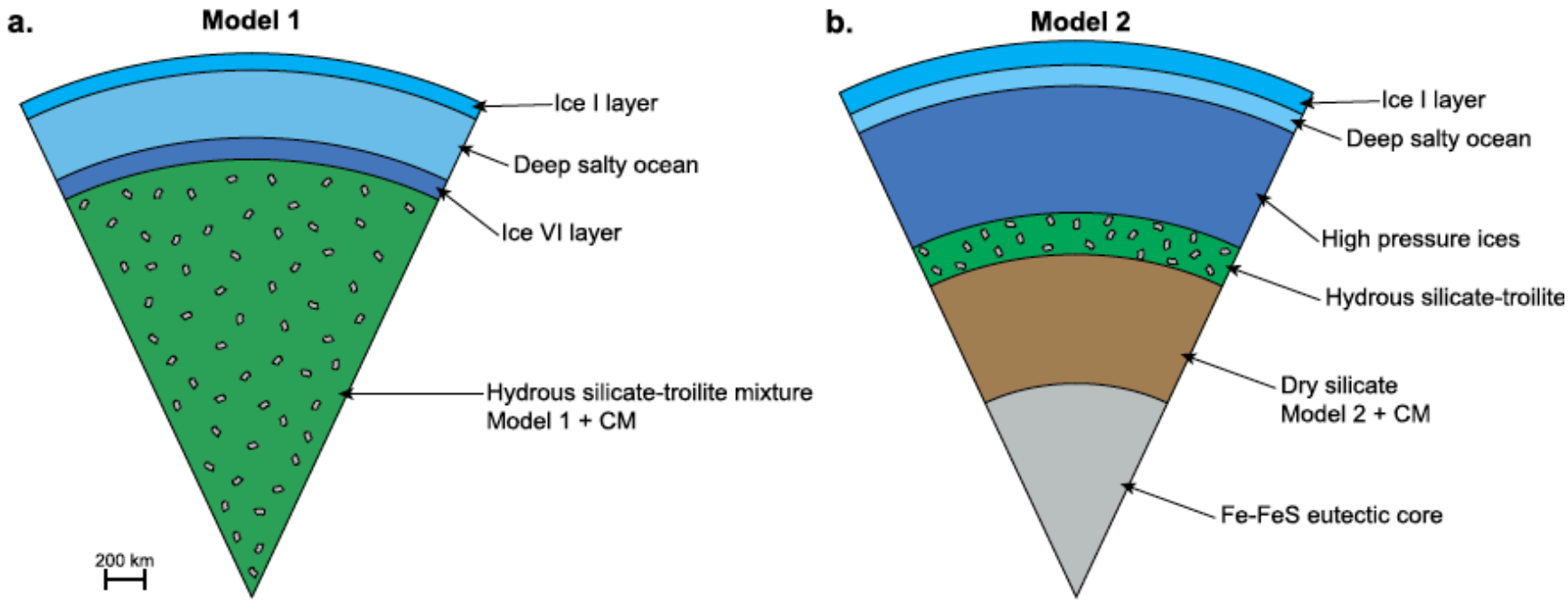
modified from *Vance et al. 2018*







Titan:
density structure (*Neri et al. 2020*)
atmospheric Ar and N (*Miller et al. 2019*)
are evidence of an organic-rich interior

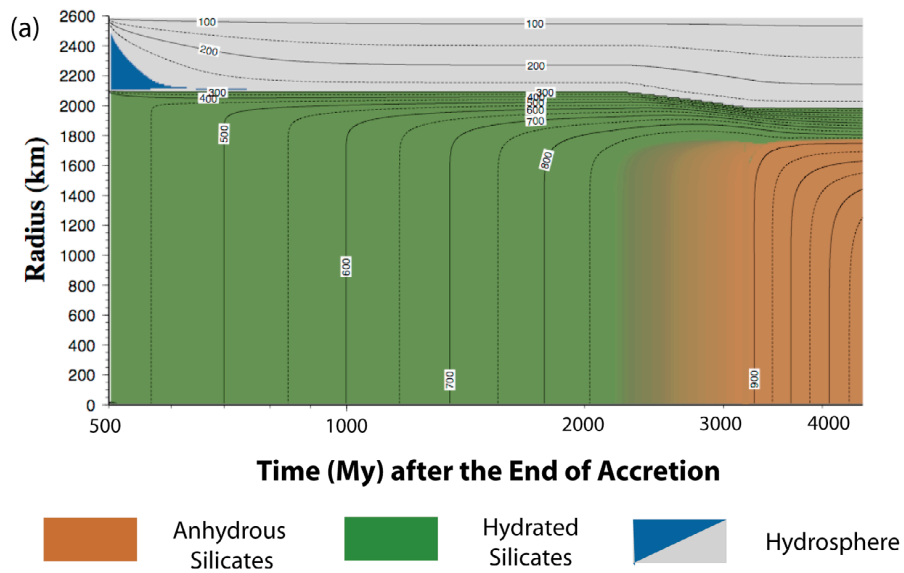


Neri et al. 2020 (oral P52B-04)

High-density ocean and thin ice shell are required by *Cassini* gravity data (*Mitri et al. 2014*)

This seems to imply early leaching of materials into Titan's ocean (*Leitner and Lunine 2019*)

Which would have consequences for the thermal and compositional state of the interior (*Castill-Rogez and Lunine 2010*)

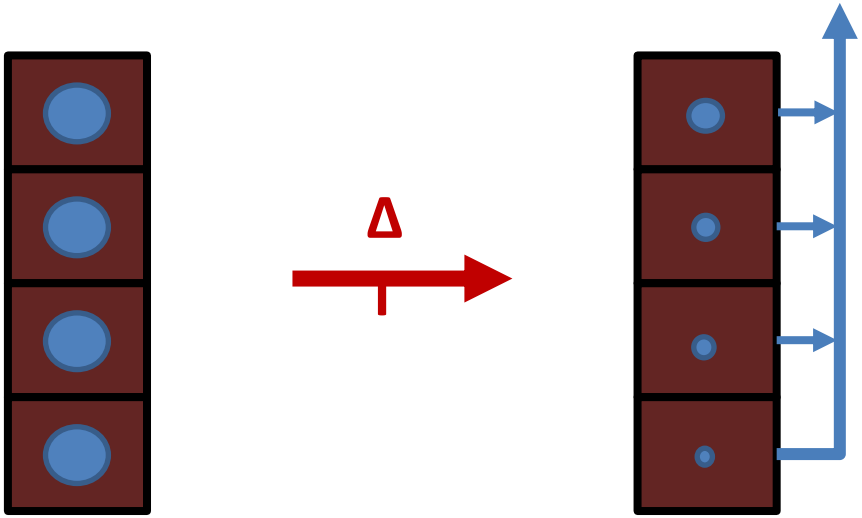


Castillo-Rogez and Lunine 2010

Interior heating models

C, H, O, S (N to be implemented)
extracted from the interior, forming the ocean

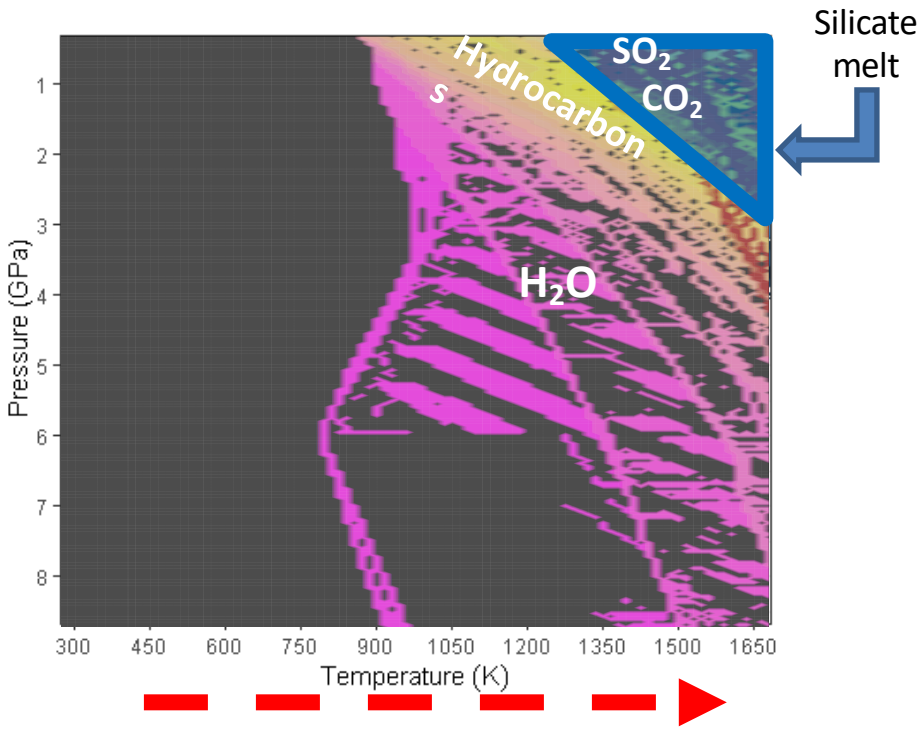
Bulk composition approximated as rock "parcels" from surface to core

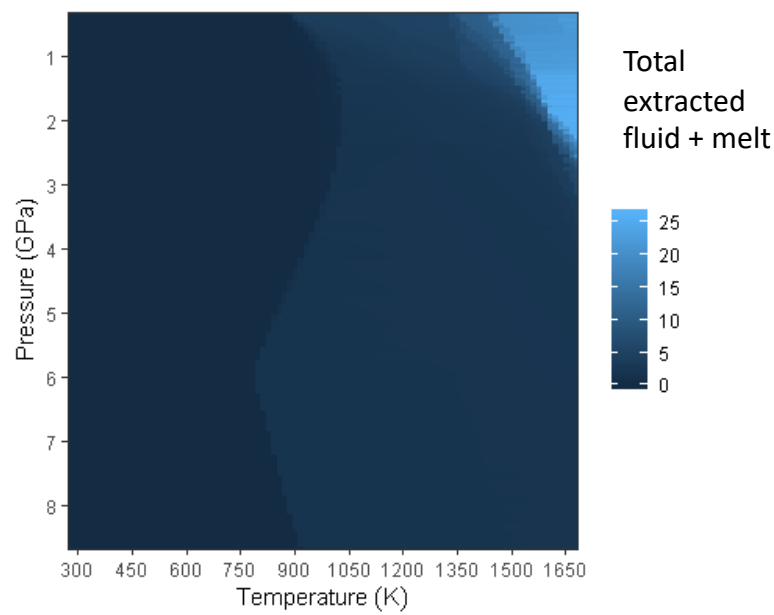


Heating in the interior caused by radioactive decay and/or tidal dissipation

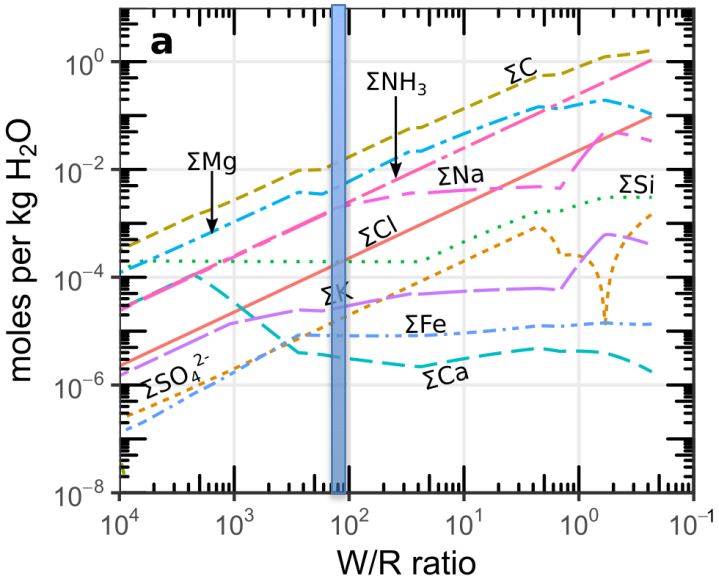
Differentiation

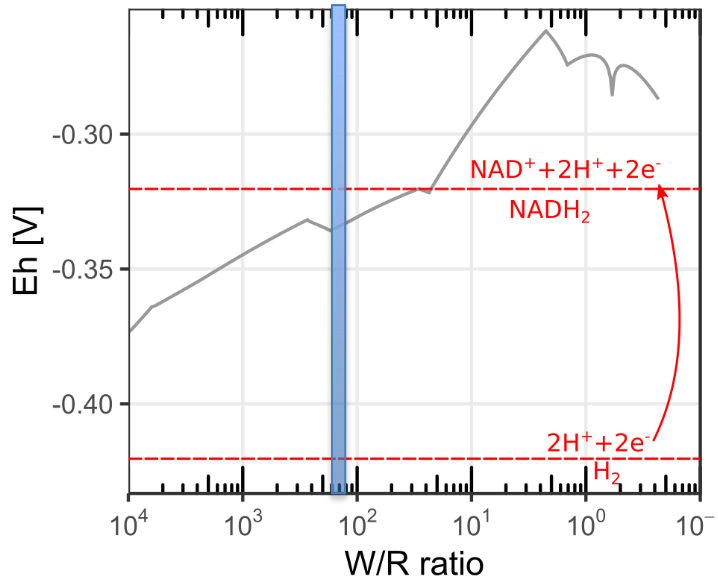
Cumulative fluid and melt in Europa





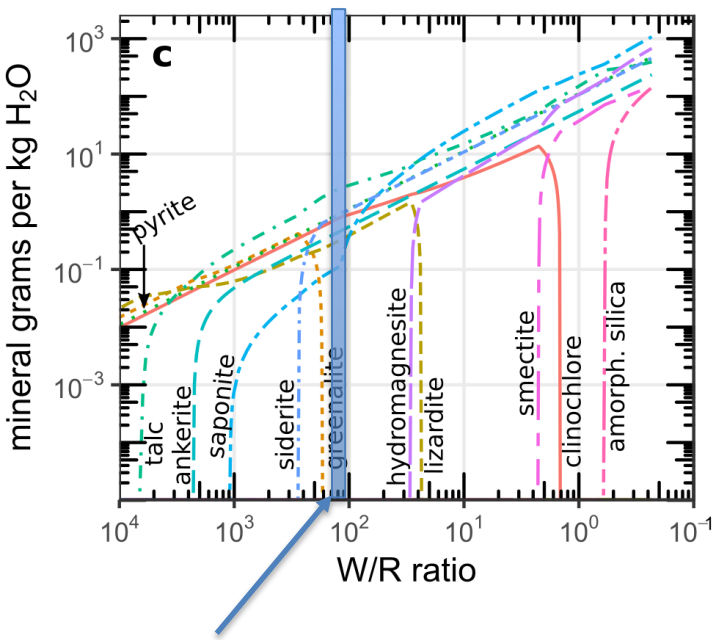
Heating homogeneously (left to right on graph).
Fluids are removed from the system as they are produced.
Calculated using free energy minimization with Perple_X
(*Connolly 2005, EPSL; 2009 G³; Connolly and Galvez 2018, EPSL*).

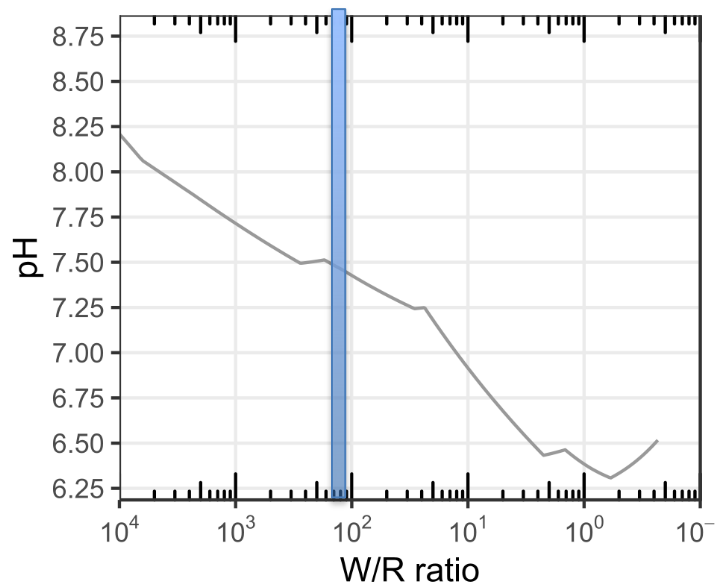




50° C reaction between water and CI-chondrite-like rock

Computed with CHIM-XPT (*Reed 1998*)





Water-rock interaction at Europa's seafloor…

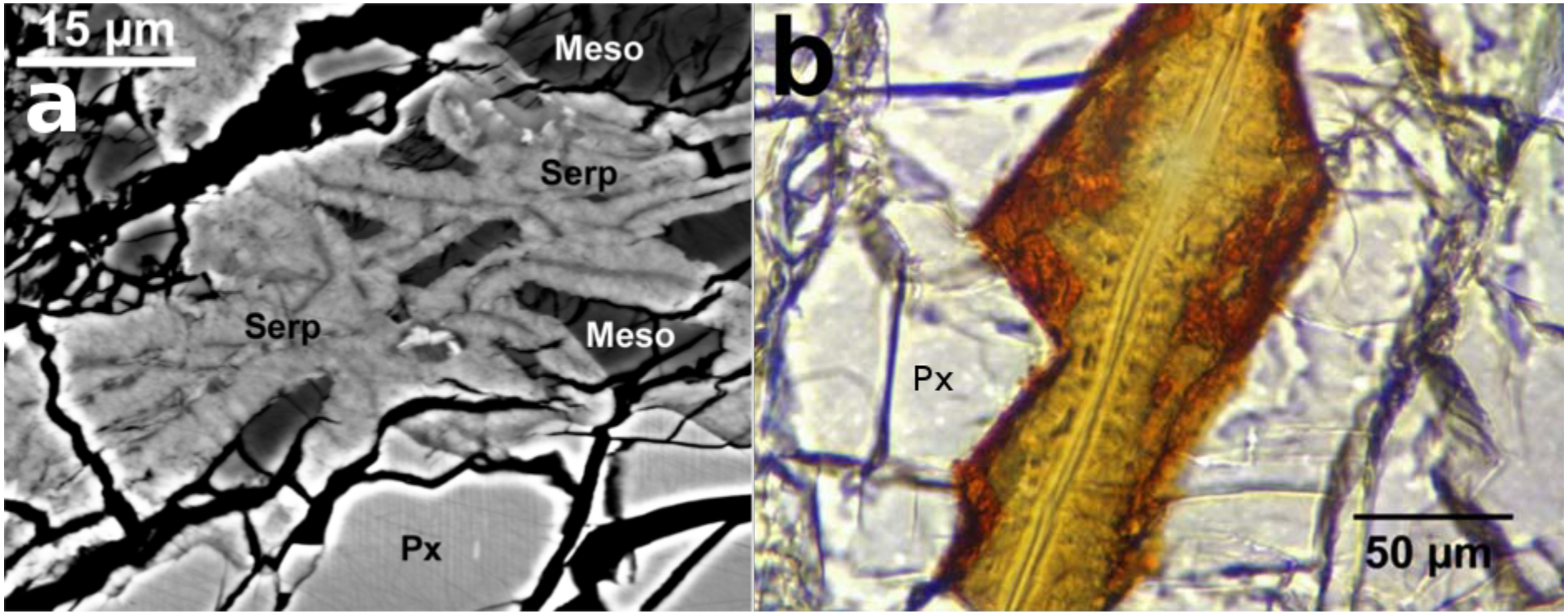
Energy for biological reactions?

Earth's seawater

Conclusions

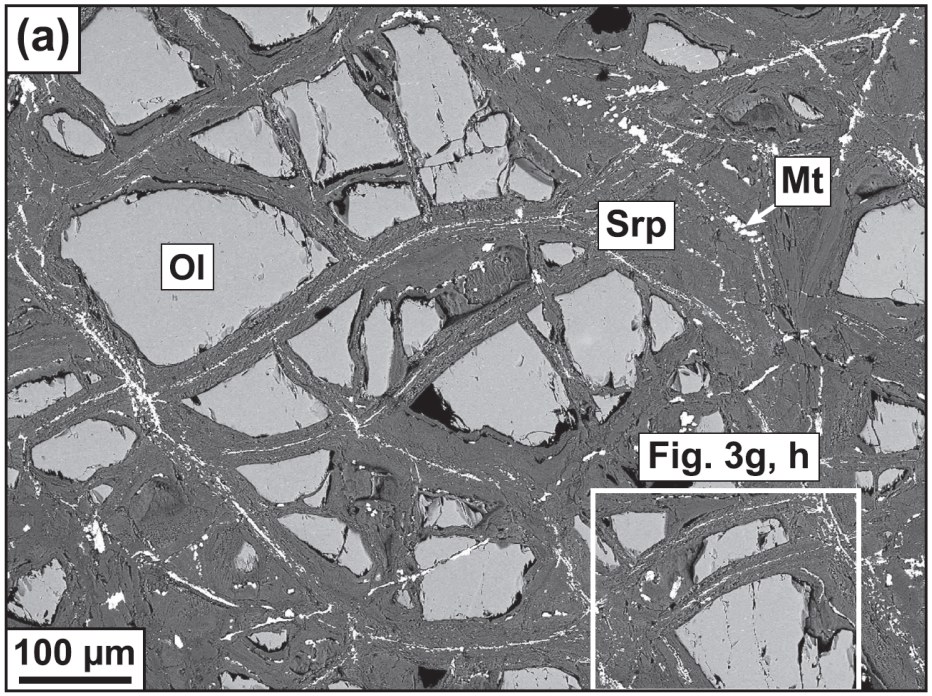
- Hydrothermal activity may be a major source of reductants, and thus key to habitability
- Hydrothermalism generally determines the chemical conditions in ocean worlds
- Future missions will help us understand hydrothermal activity in ocean worlds
- We can use models to anticipate the signatures of different hydrothermal scenarios

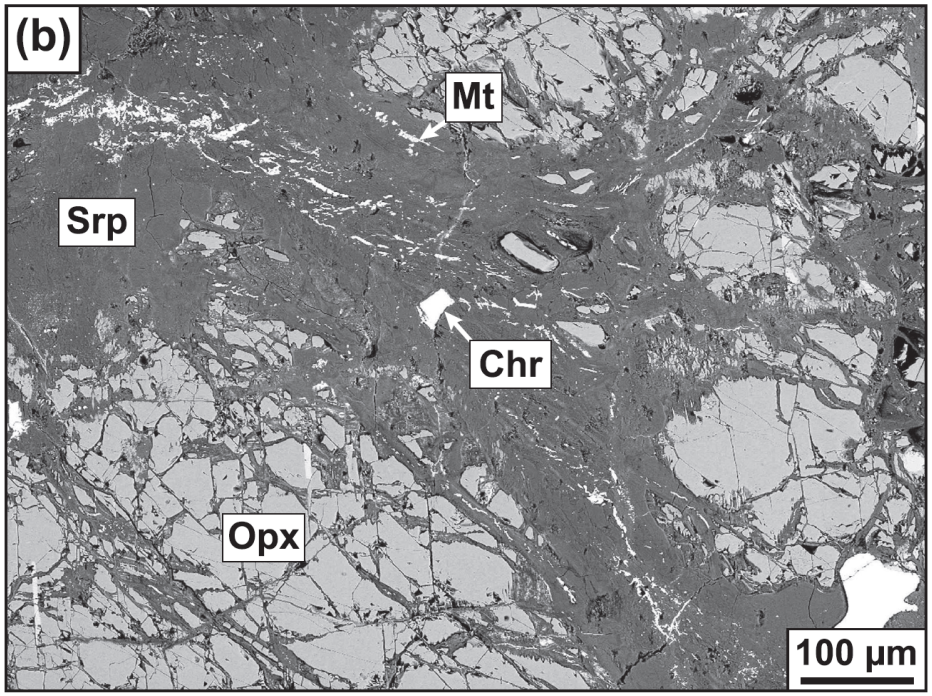
Hand sample evidence for serpentinization occurring on Mars



a) Serpentine in the Lafayette nakhlite. (Hicks et al. 2014, *Geochim. Cosmochim. Acta.*)
b) "Iddingsite" and siderite in Lafayette. (Treiman 2005, *Chem. Erde.*)

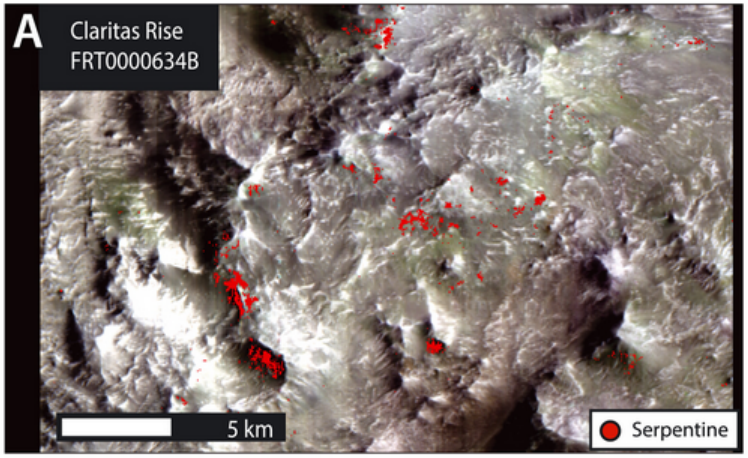
Examples of serpentine-filled cracks in terrestrial ultramafic rocks

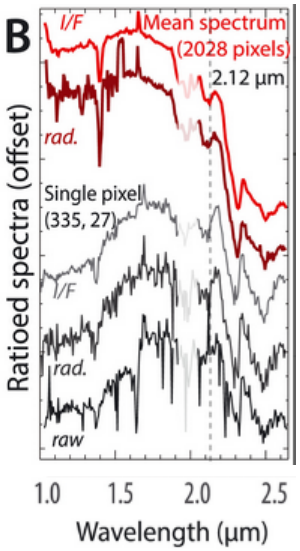


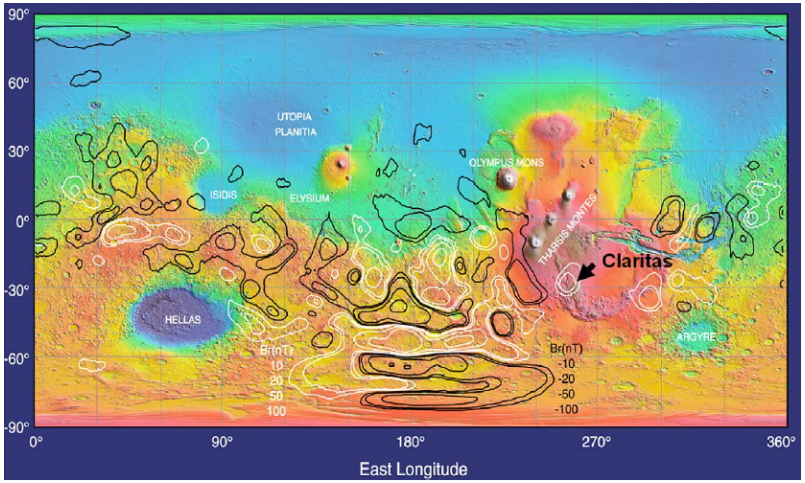


Backscattered electron images of partially serpentinized peridotite from the Josephine ophiolite (Sonzogni et al. 2017, *J. Min. Pet. Sci.*)

Geologic setting of the hydrothermal system: Serpentine is mainly located in Noachian terrains



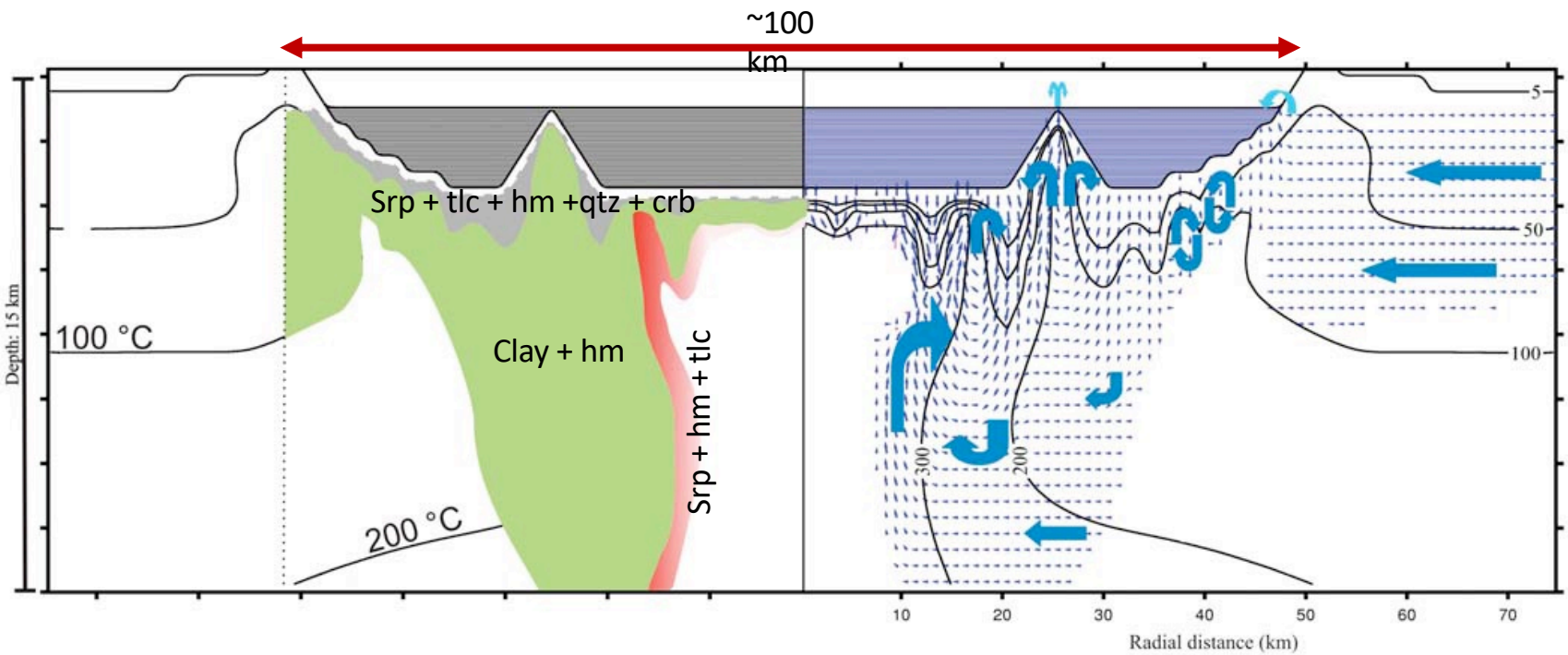




Leask et al. 2018 Geophys. Res. Lett.

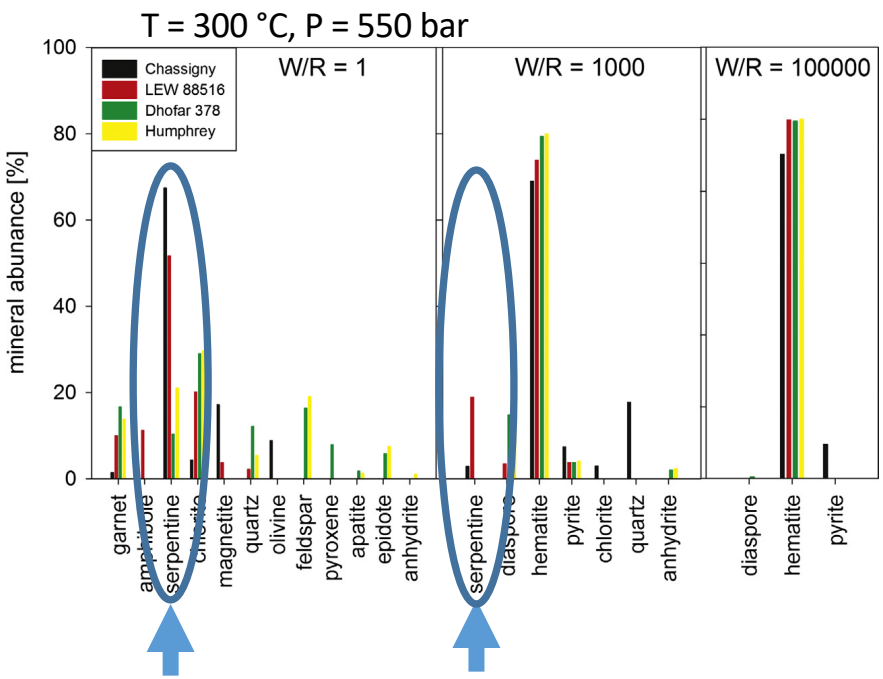
Dohm et al. 2009 J. Volcanol. Geotherm. Res.

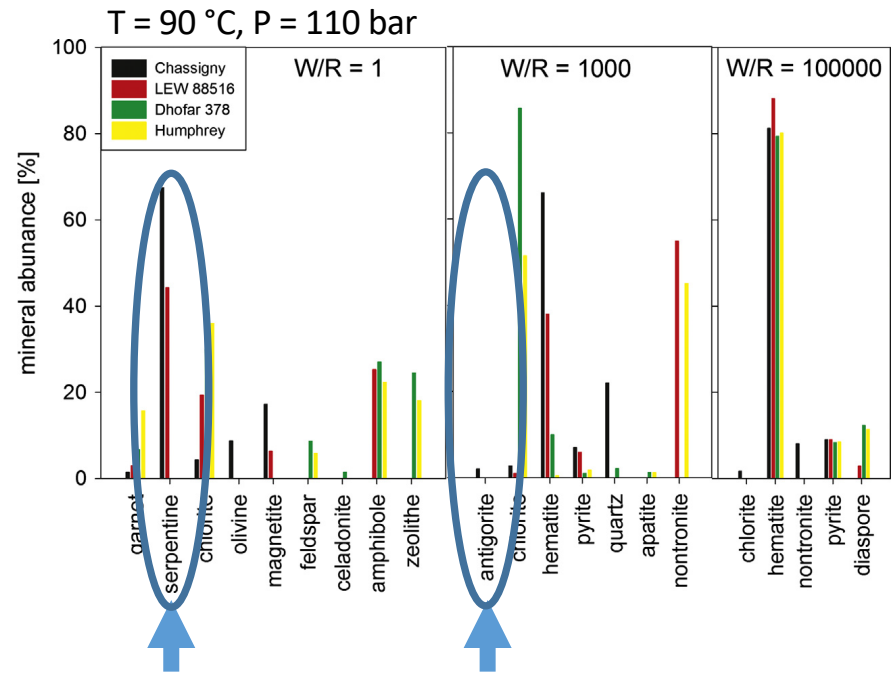
Impact-generated, or volcanic hydrothermal systems?



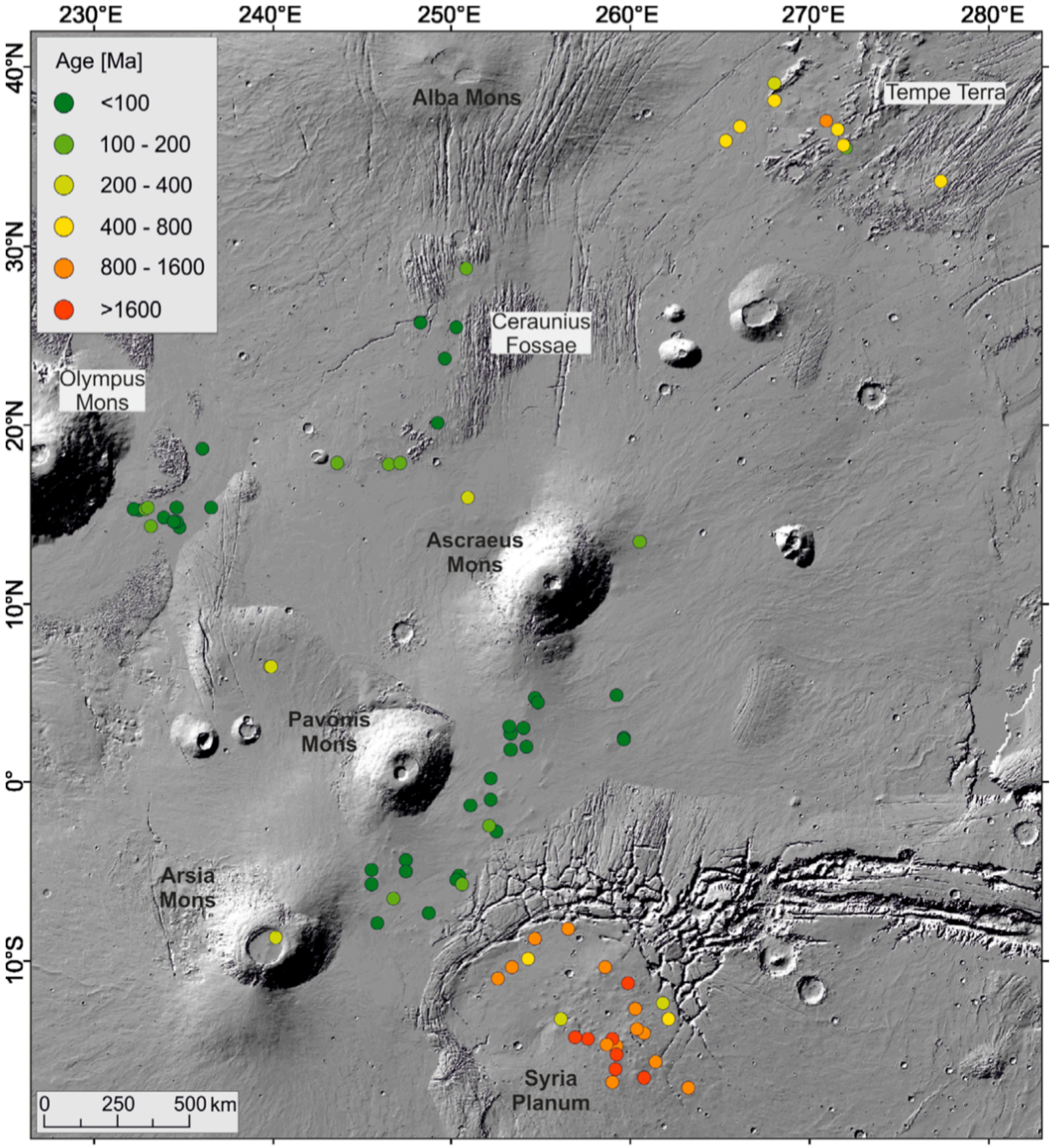
Temperature distribution and direction of fluid flow 20,000 yr after impact.
Maximum lifetime of a 100 km crater hydrothermal system ≈ 290,000 yr.
Schwenzer and Kring 2009 Geology; *Abramov and Kring 2005 J. Geophys. Res.*

The host rock composition and water-to-rock ratio determine if serpentine formation is favored or not





Ultramafic martian meteorites (Chassigny) produce more serpentine than martian basalts (Humphrey).
Batch water-rock equilibrium models from Schwenzer and Kring, 2013 (*Icarus*).

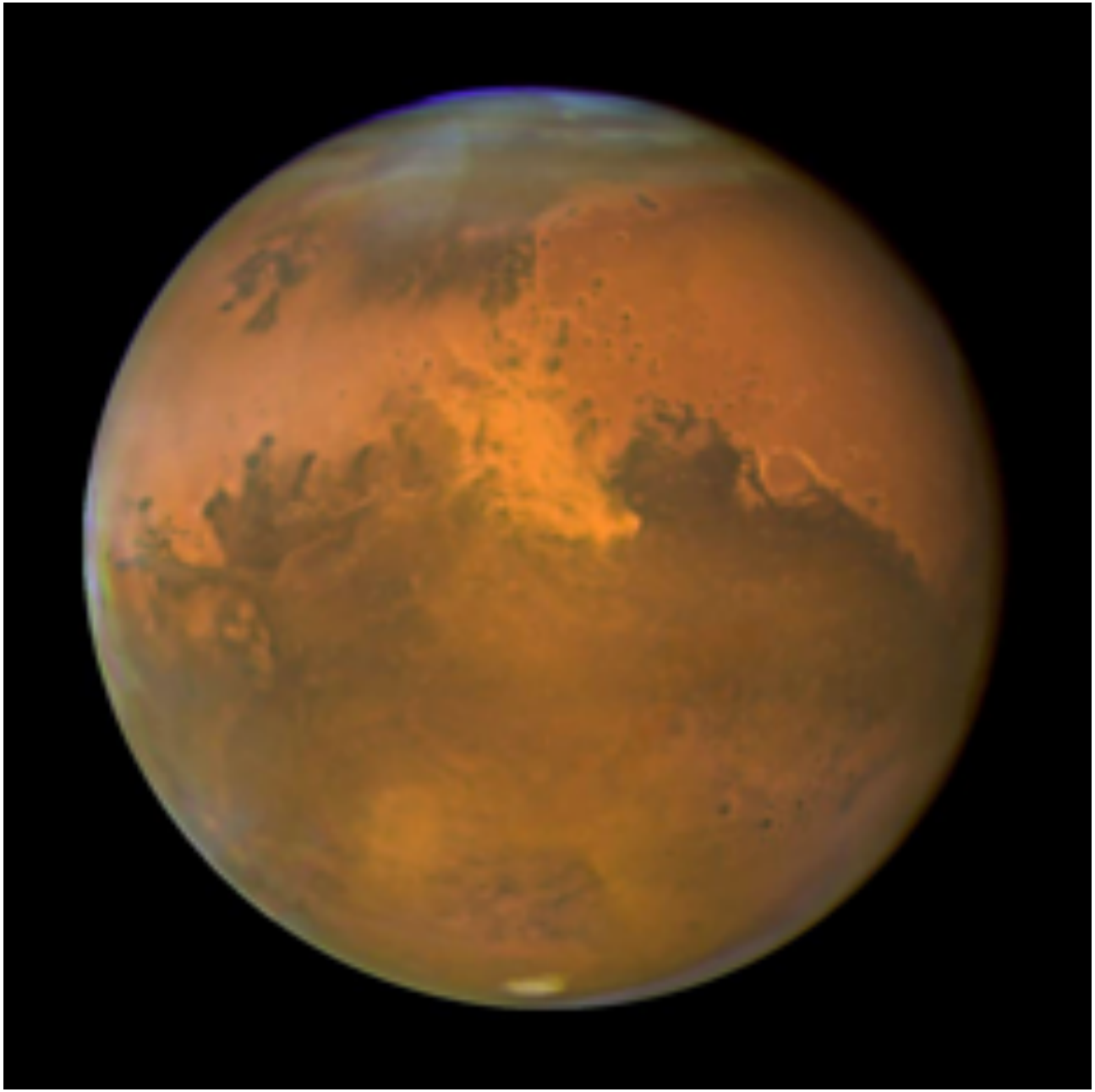


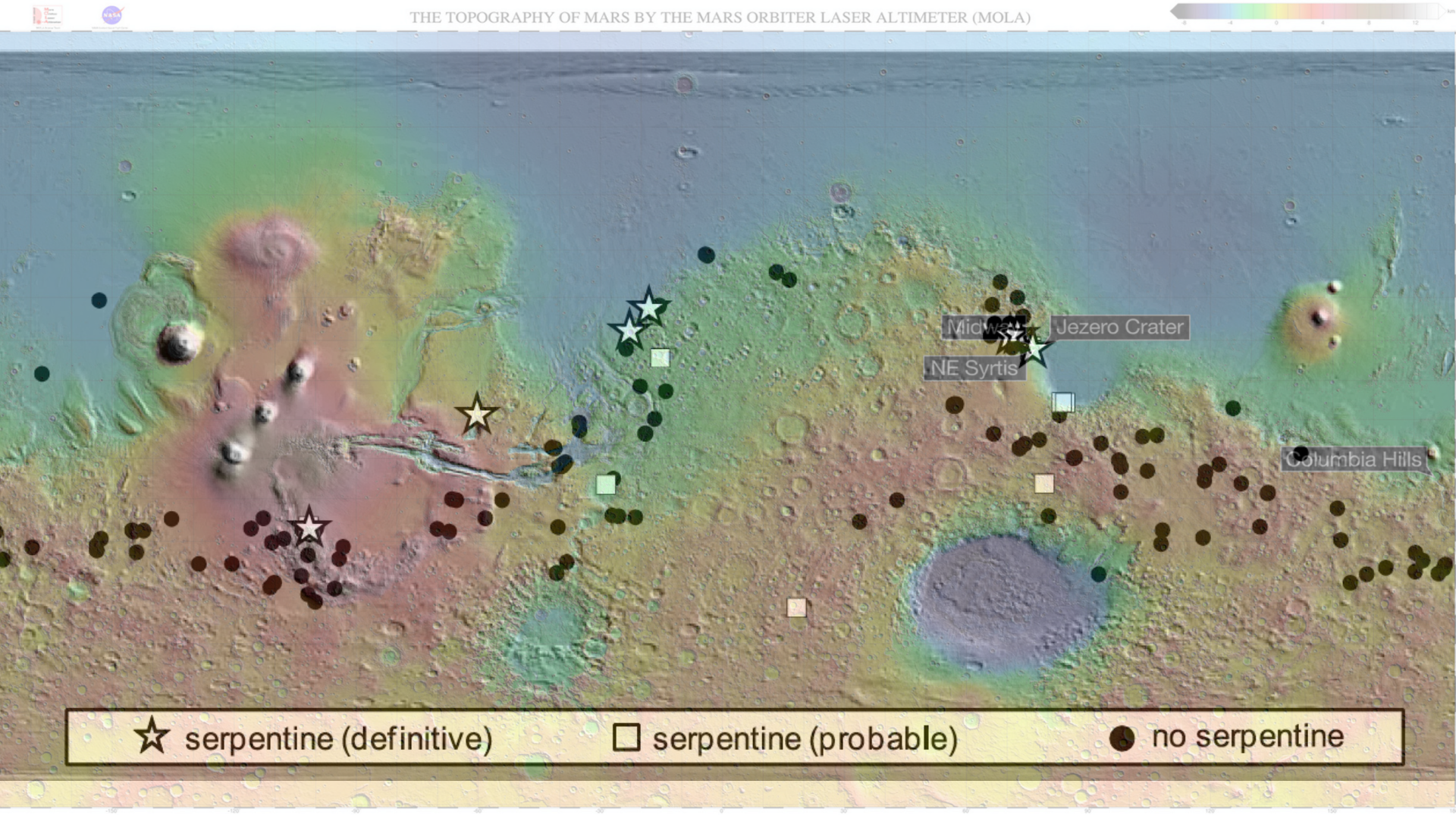
Possible locales of high-temperature hydrothermal activity.

Are there warm regions with near-surface fluids today?

Hauber et al. 2011

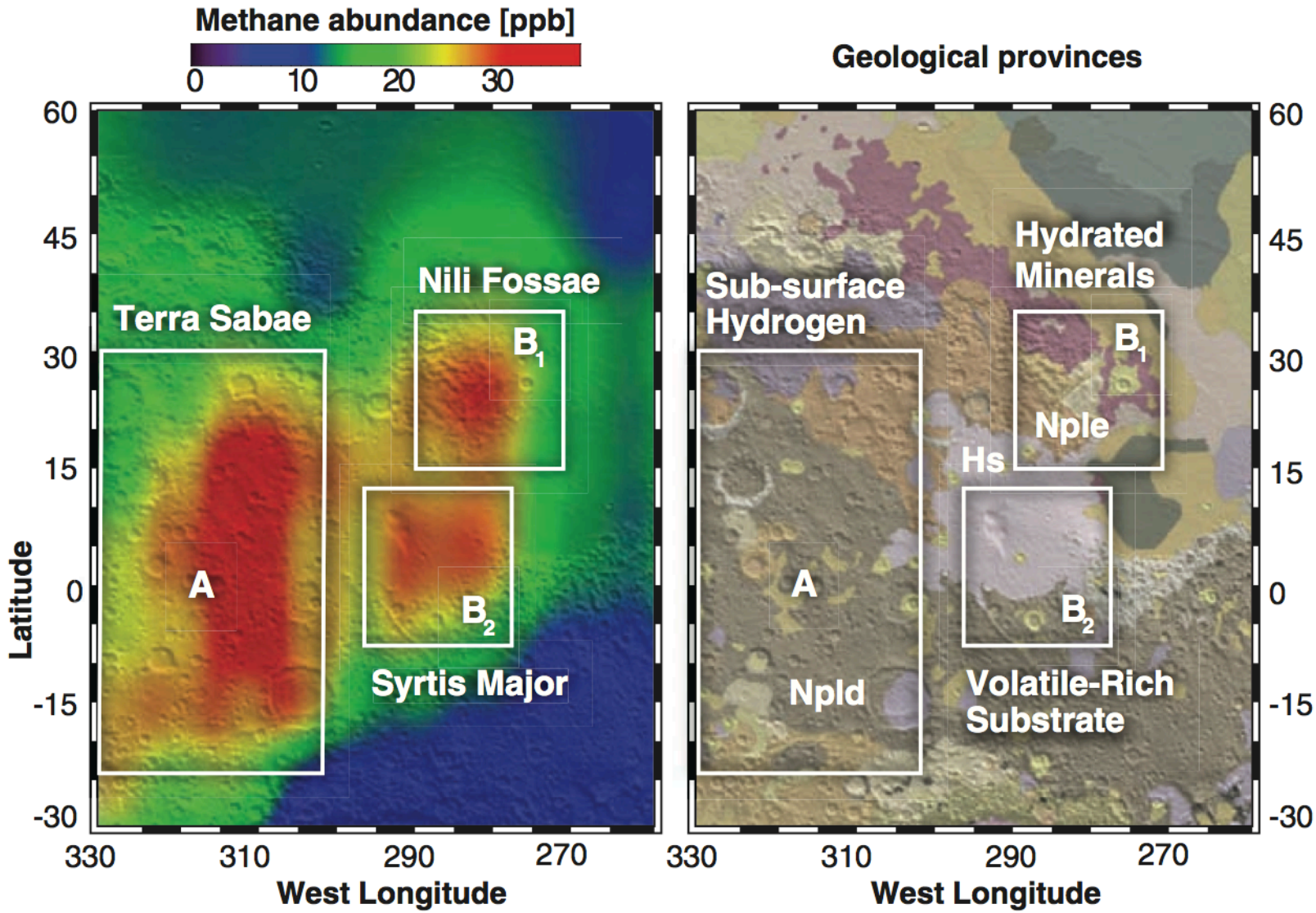
The end





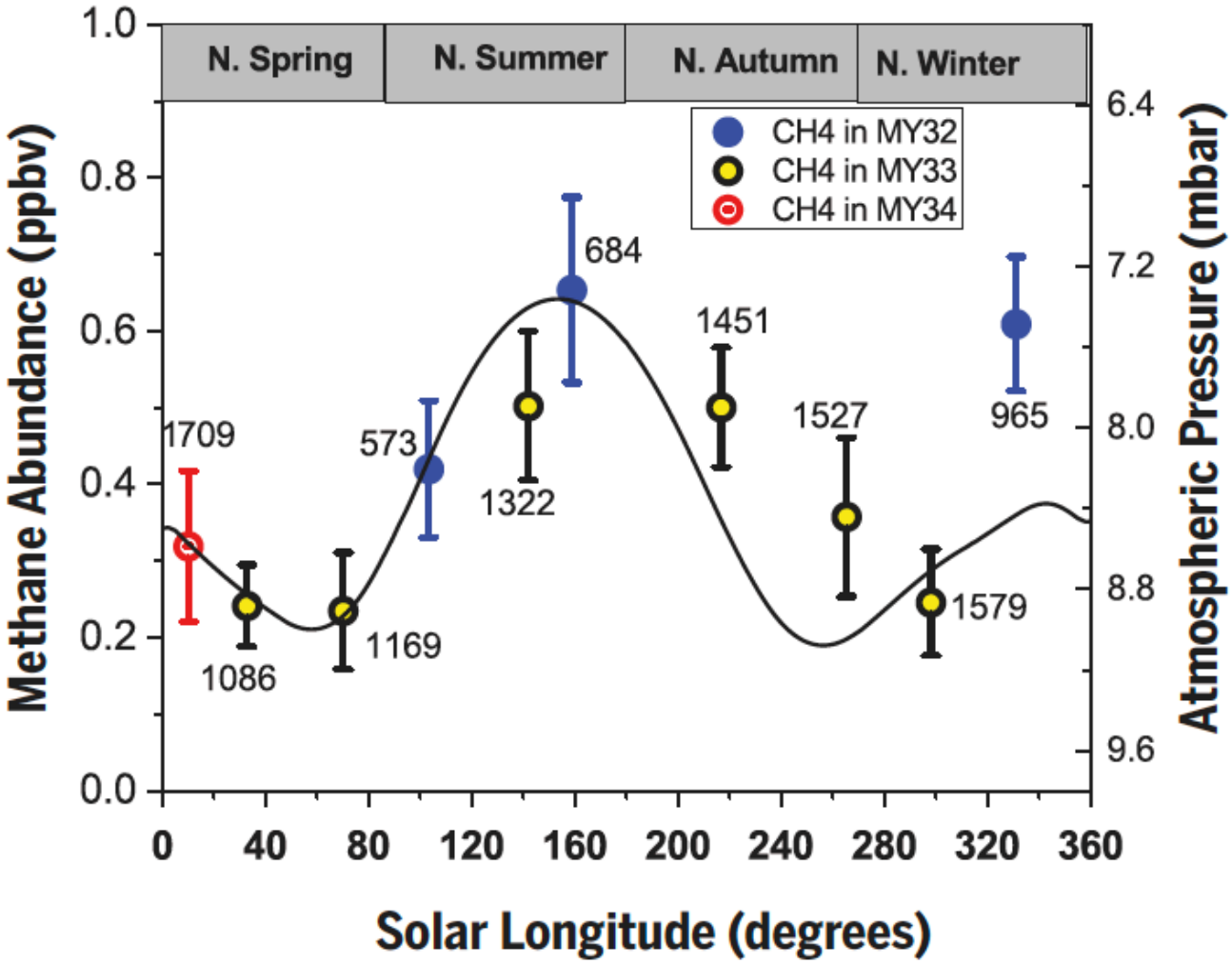
Ehlmann et al. 2010

Martian Methane

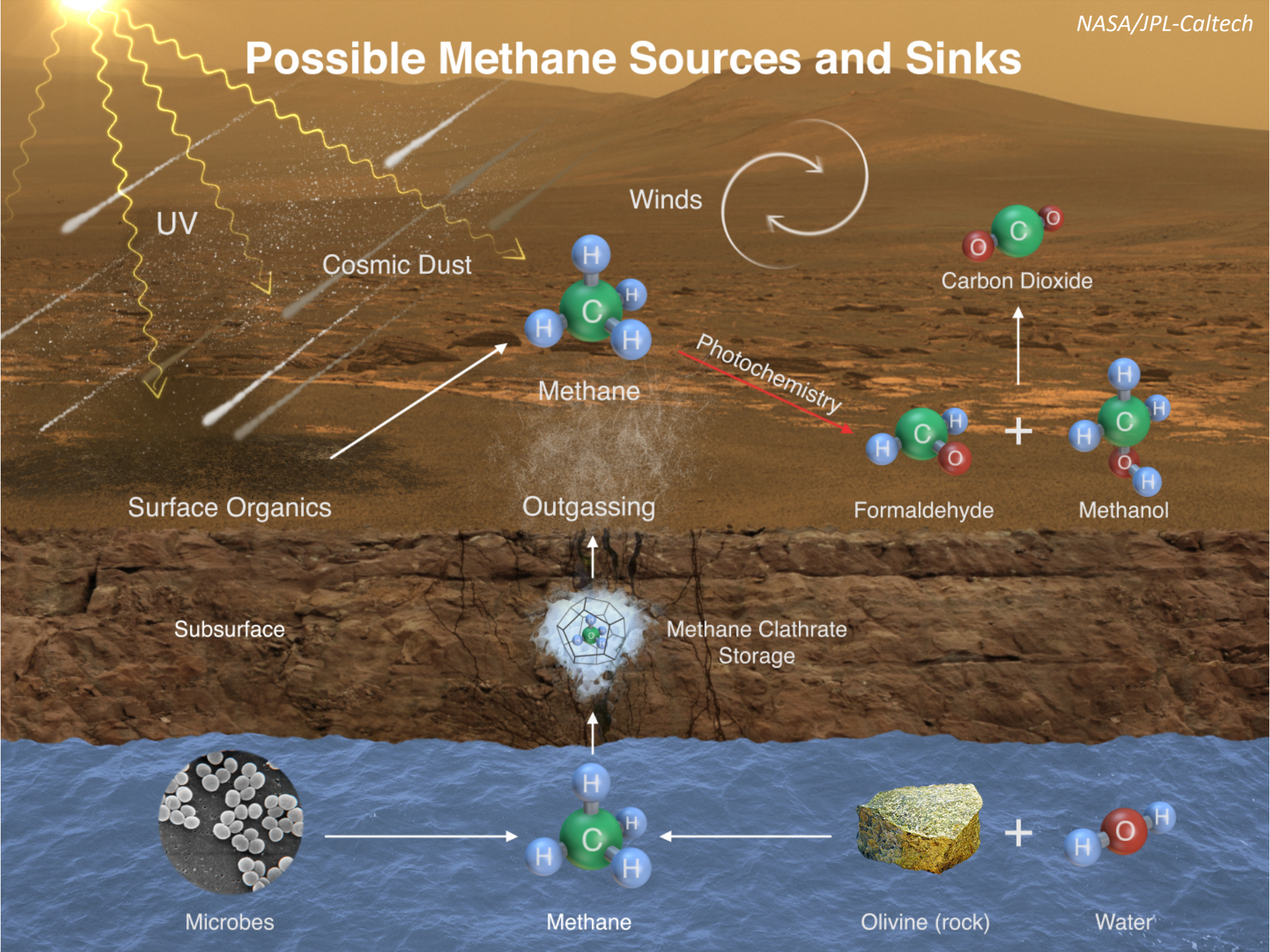


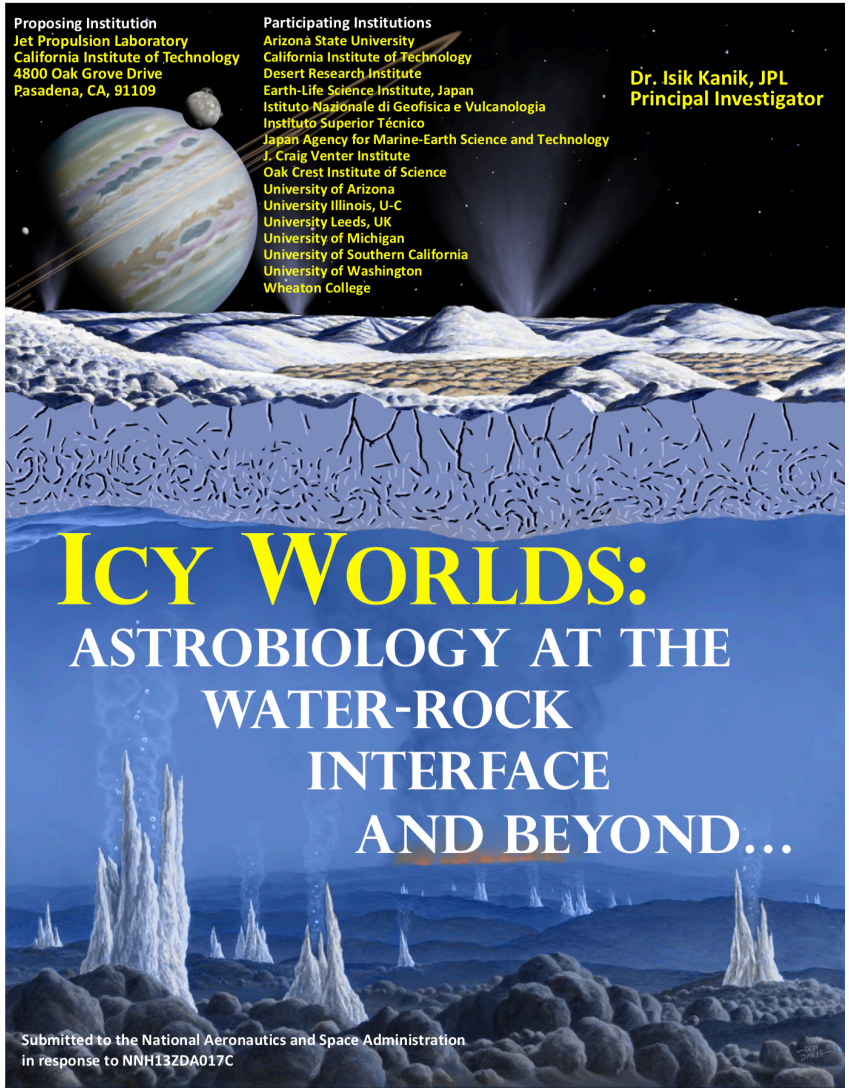
Mumma et al. 2009

Martian Methane



Webster et al. 2018


NASA/JPL-Caltech
Possible Methane Sources and Sinks
UV
Cosmic Dust
Winds
Carbon Dioxide
Methane
Photochemistry
Formaldehyde
Methanol
Surface Organics
Outgassing
Subsurface
Methane Clathrate Storage
Microbes
Methane
Olivine (rock)
Water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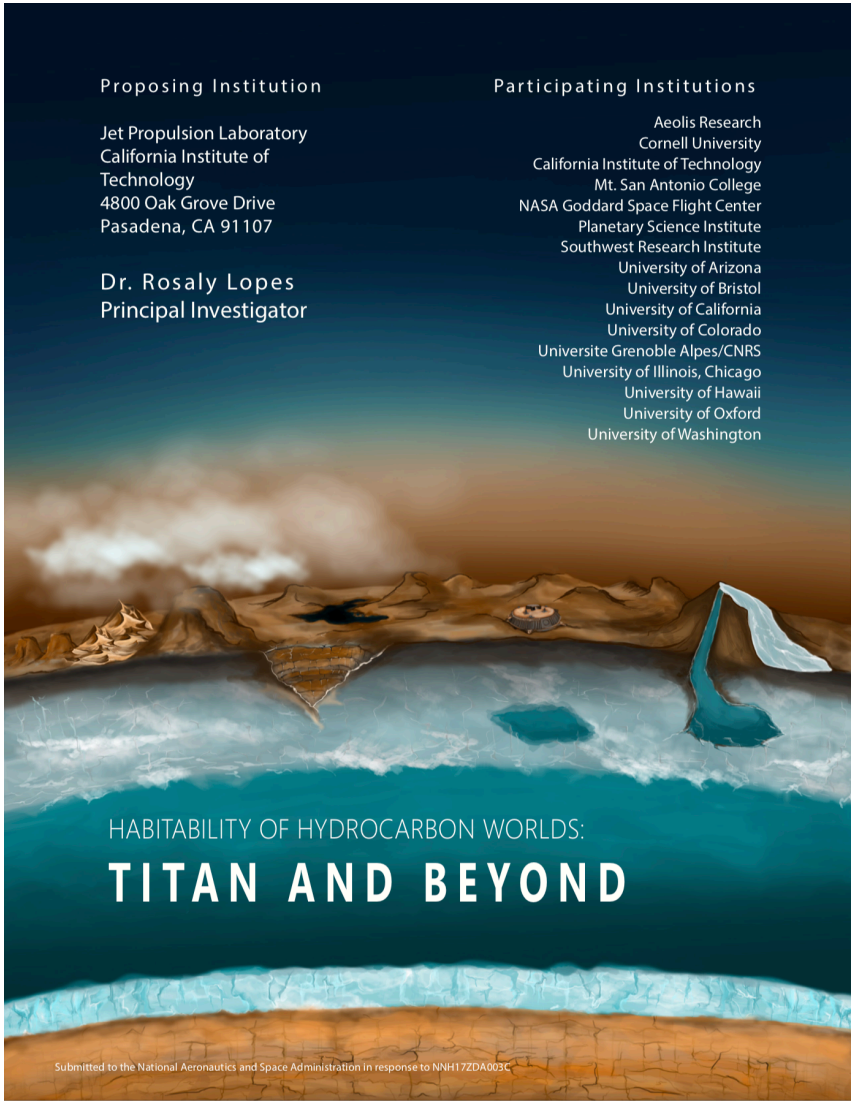
ICY WORLDS:
ASTROBIOLOGY AT THE WATER-ROCK INTERFACE AND BEYOND...
Submitted to the National Aeronautics and Space Administration in response to NNH13ZDA017C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Southwest Research Institute
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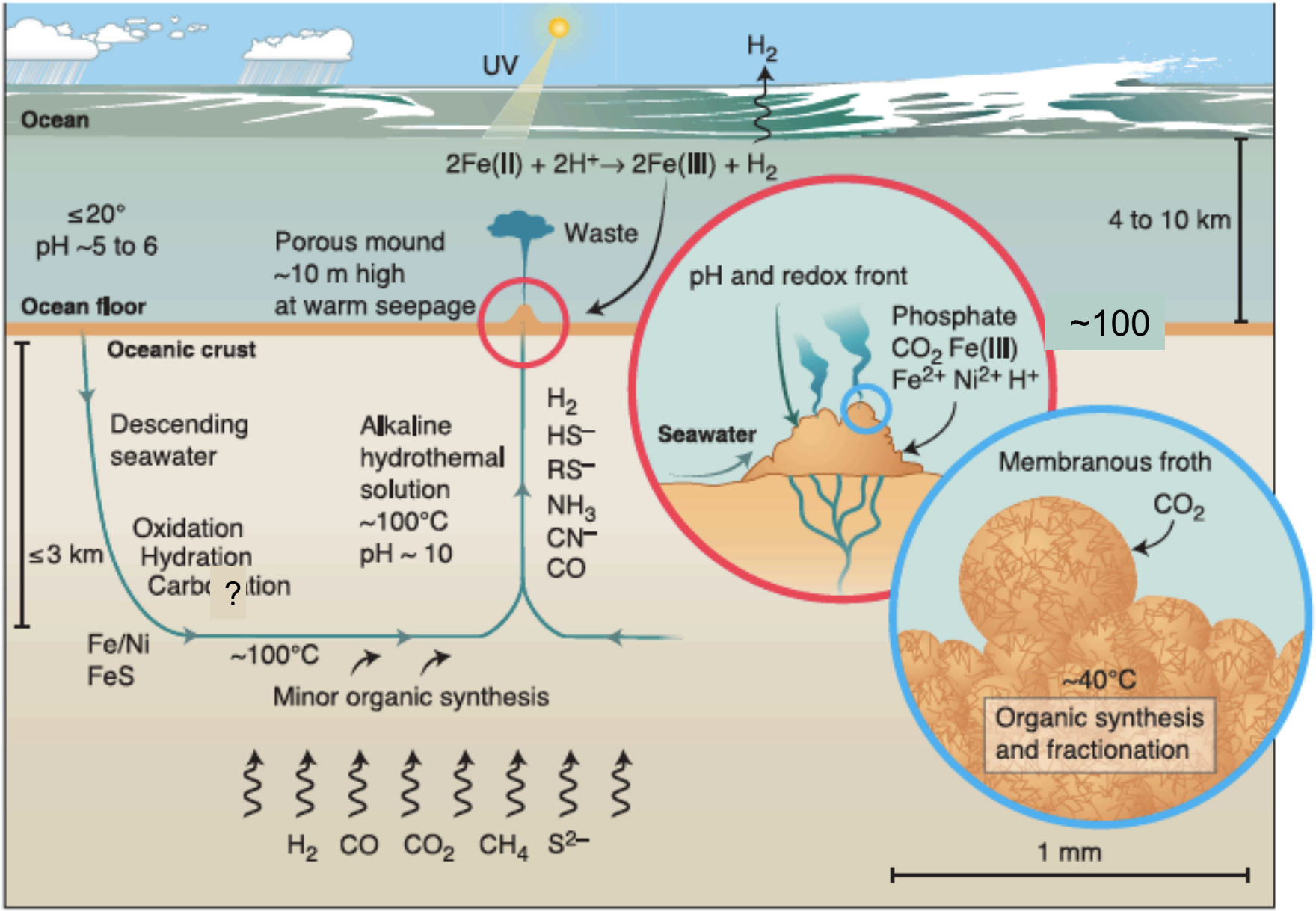
HABITABILITY OF HYDROCARBON WORLDS:
TITAN AND BEYOND
Submitted to the National Aeronautics and Space Administration in response to NNH17ZDA003C

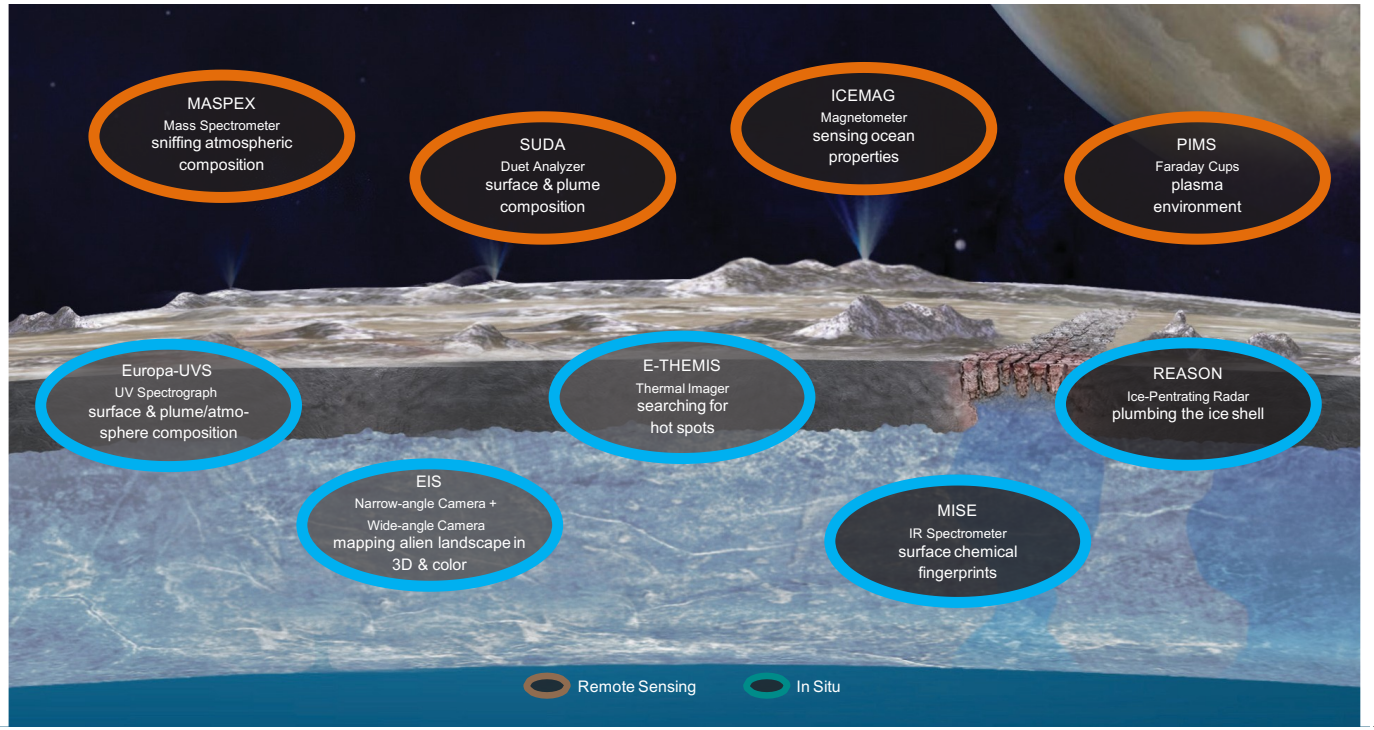
Support:

- NASA Outer Planets Research, Solar System Workings, Habitable Worlds Programs
- NASA Astrobiology Institute: Icy Worlds, Titan
- Tokyo Institute of Technology, Earth-Life Science Institute



(Martin and Russell, 2007)

NASA-Selected Europa Instruments



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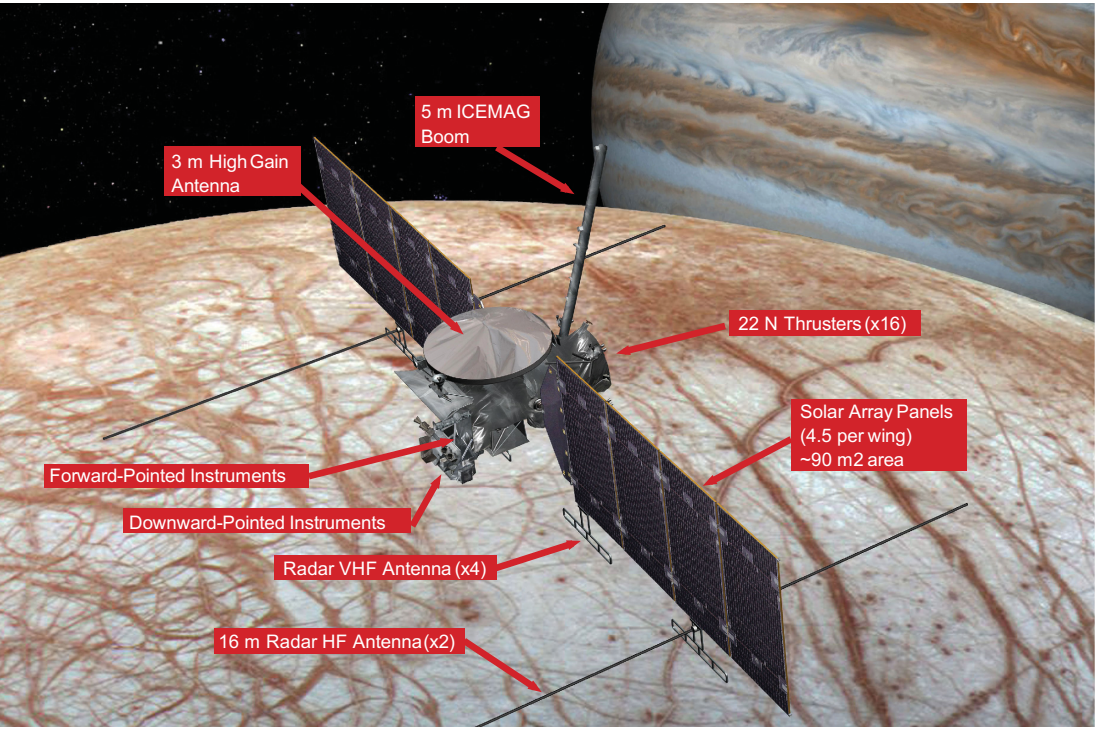
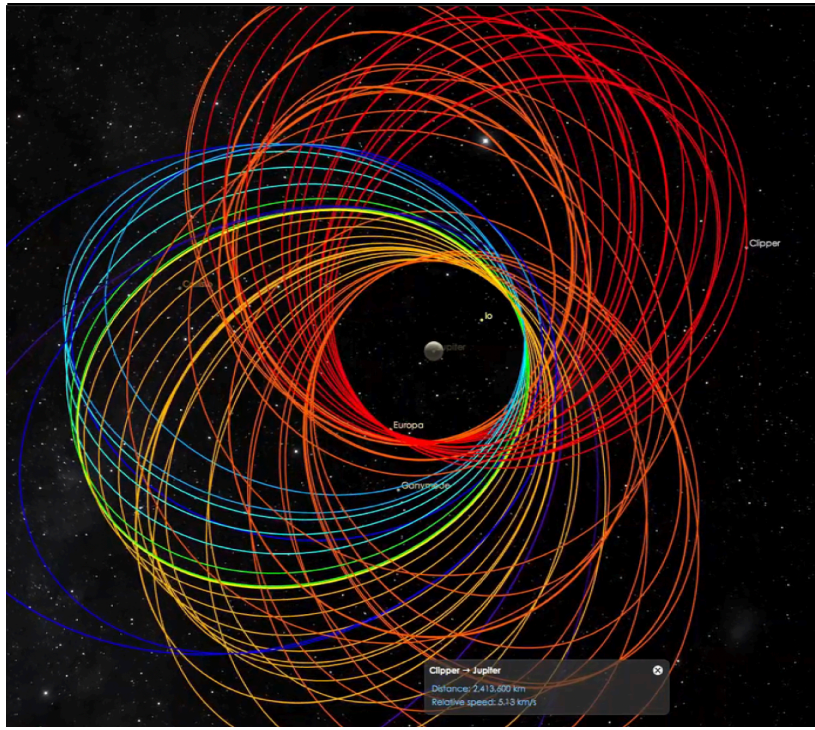
Europa Clipper Spacecraft and Flybys





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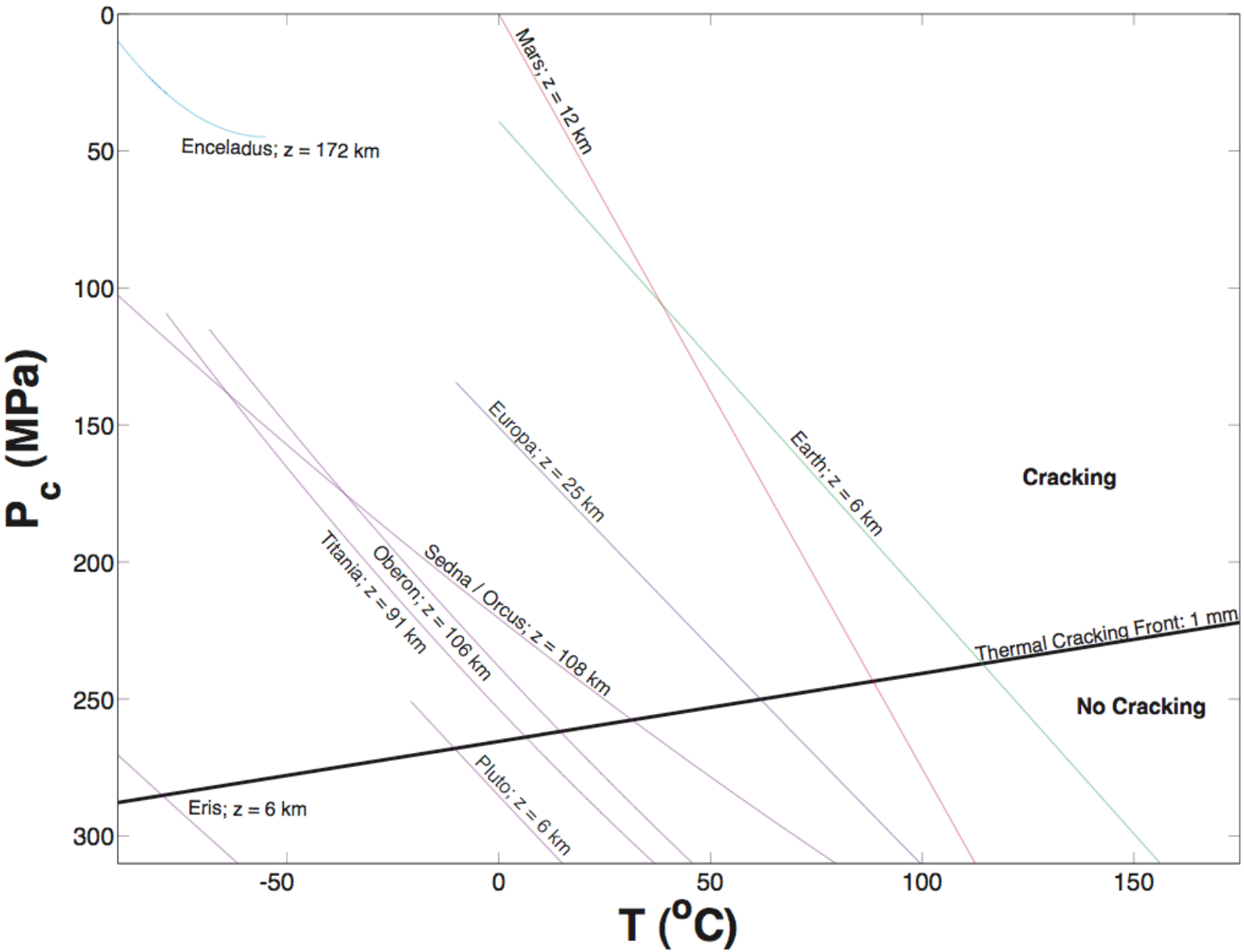
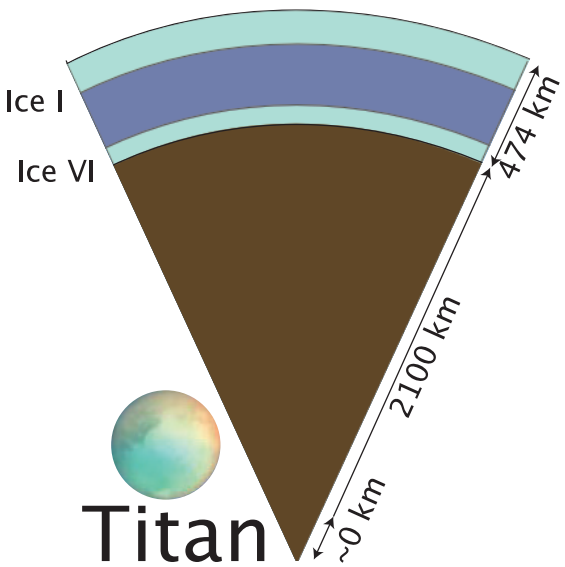
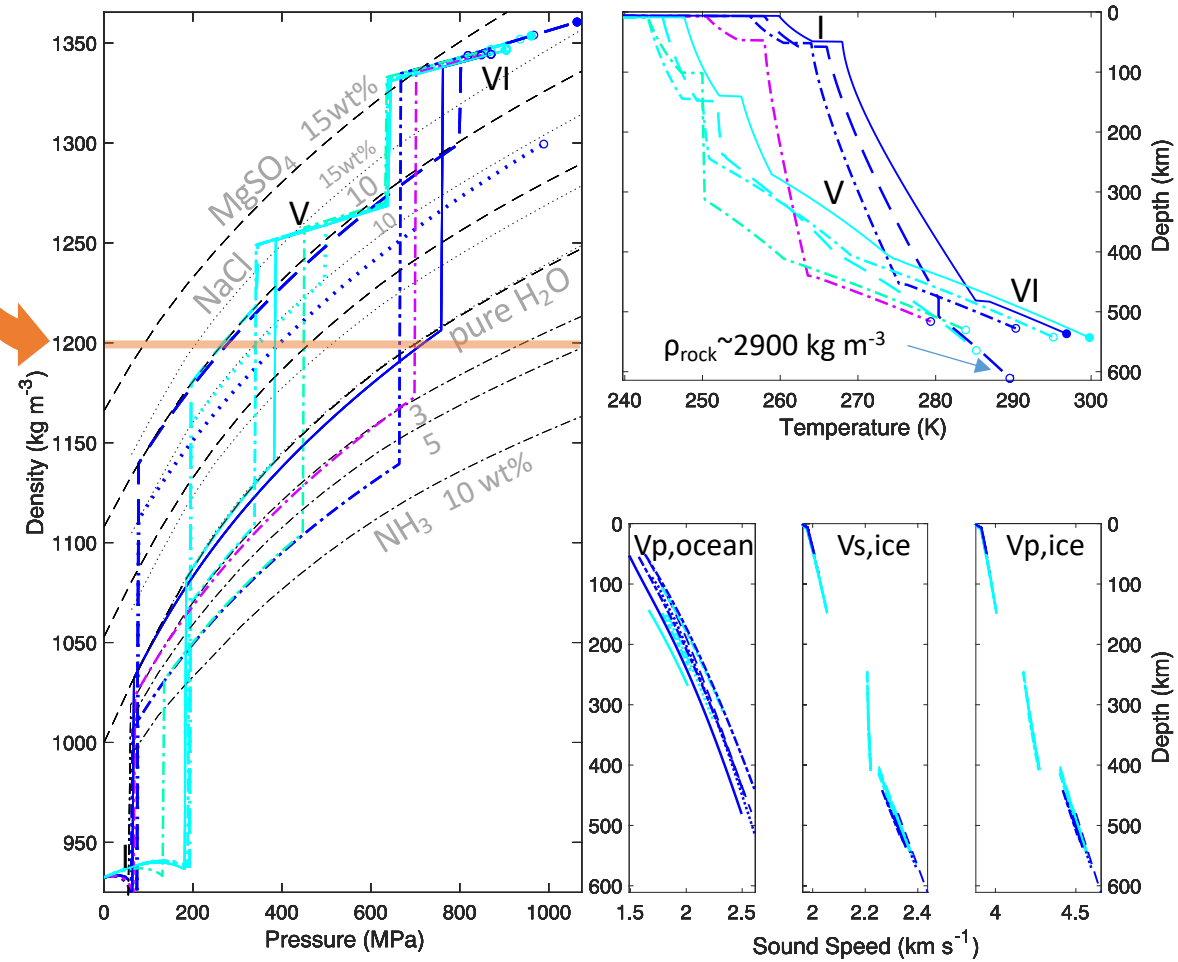


Vance *et al.* 2007



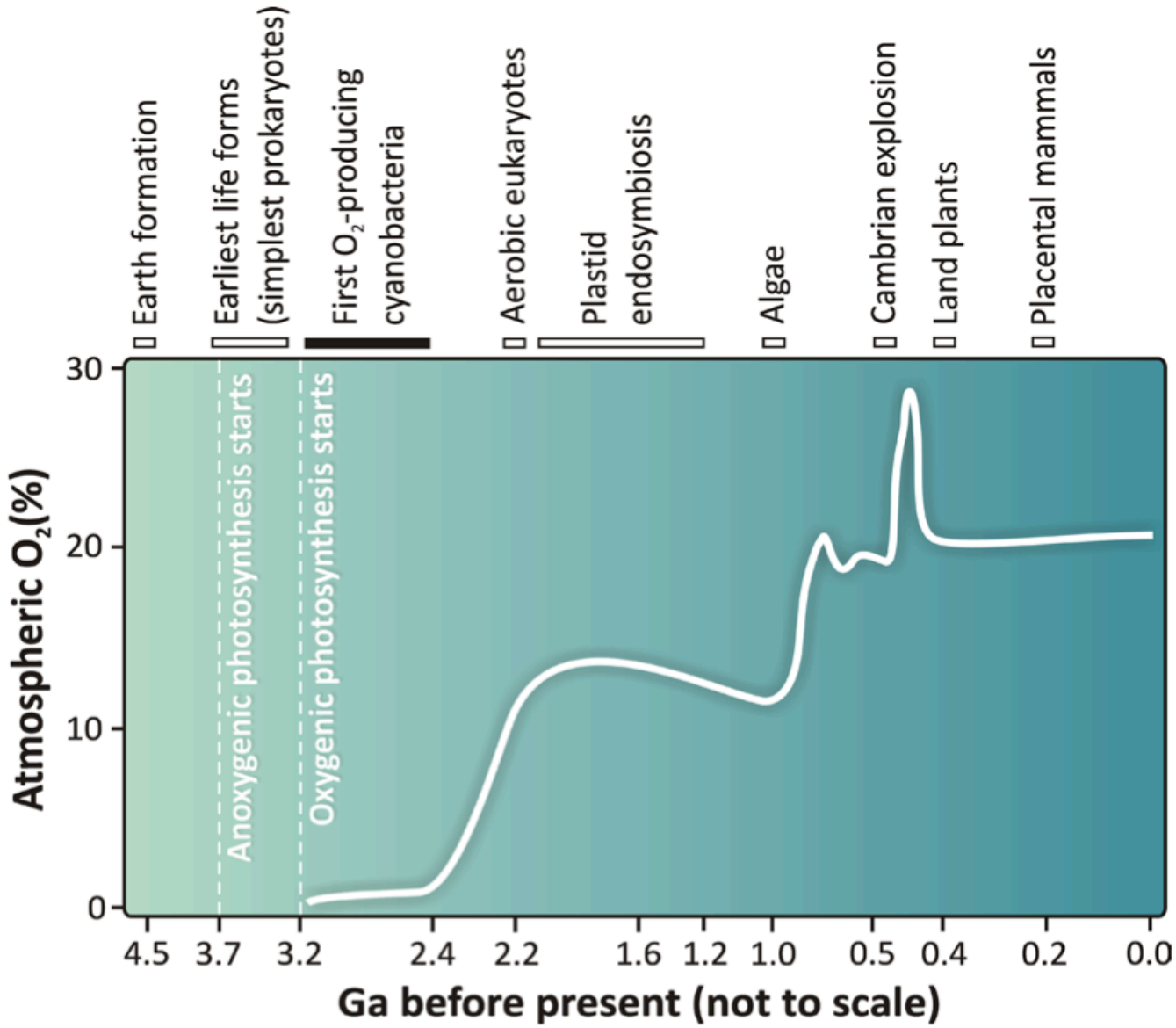
Mitri et al. 2014



Moment of Inertia = 0.3318

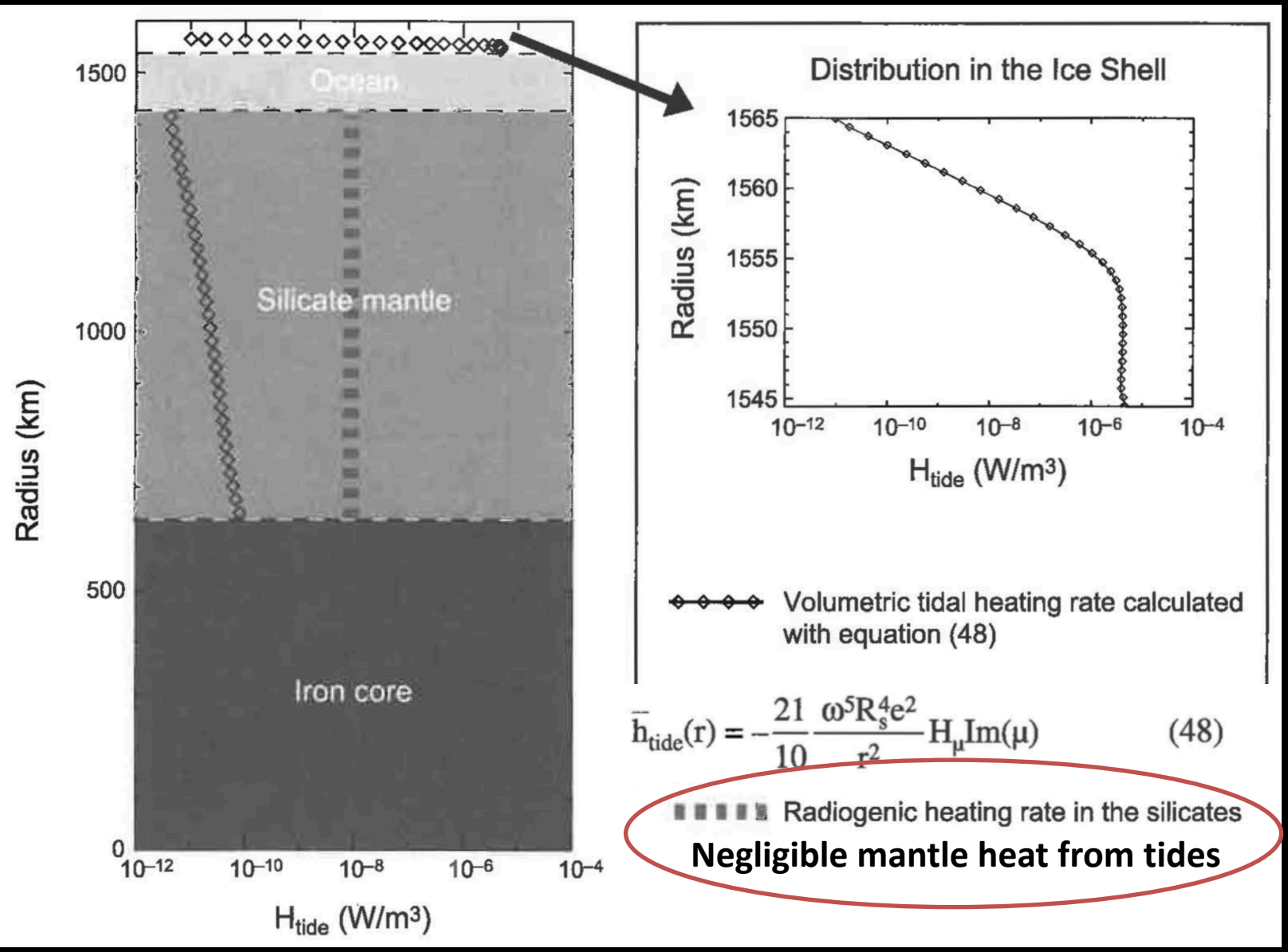
ρ_{rock}~2900 kg m^{-3}

Vance et al. 2018 JGR: Planets



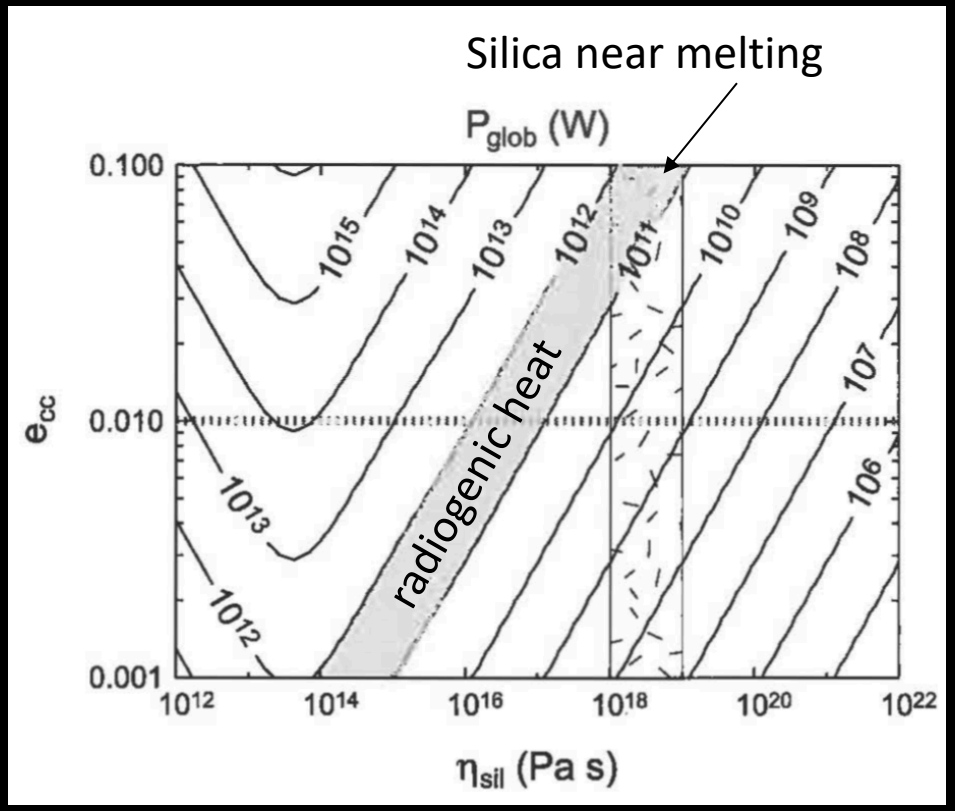
From “Adventures with cyanobacteria: a personal perspective,“ Govindjee et al. 2011

Tidal Heat in Present Day Europa

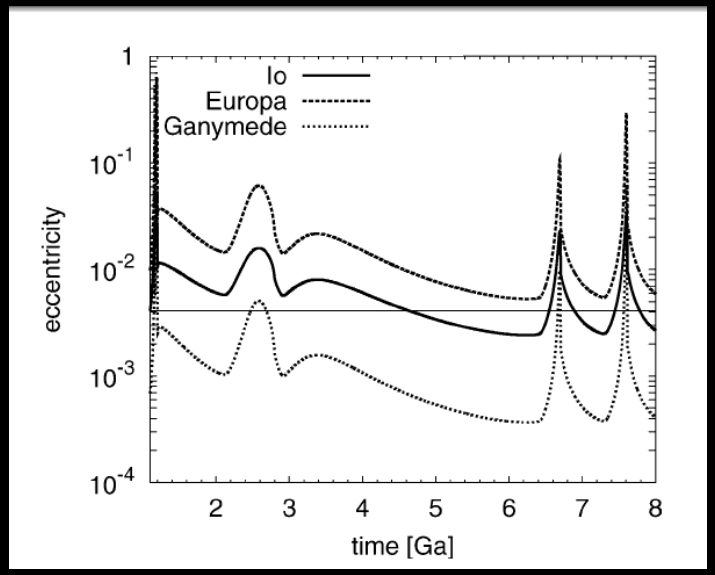


Sotin et al. 2009, Tobie et al. 2003

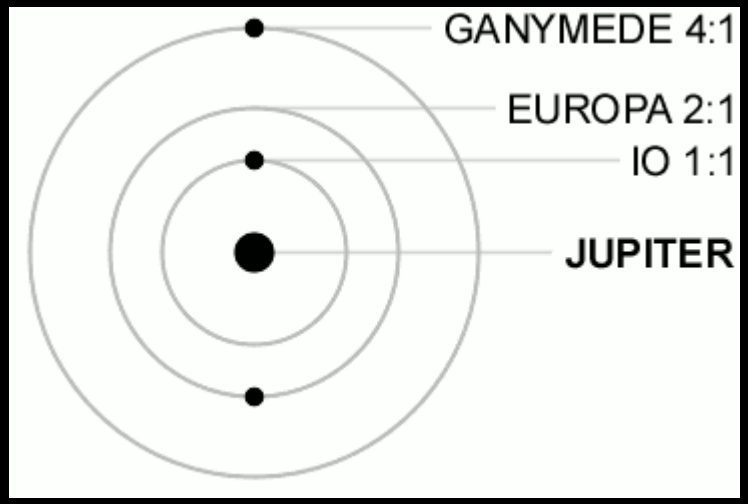
Tidal Heat in Present Day Europa

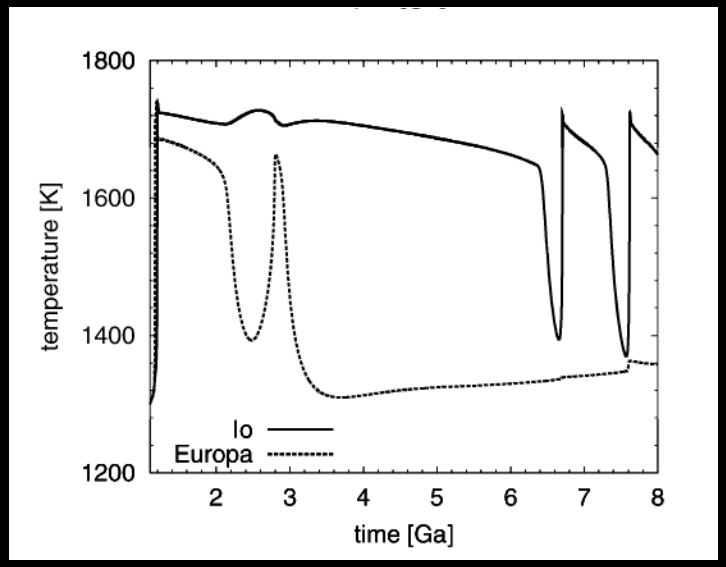


Sotin et al. 2009, Tobie et al. 2003



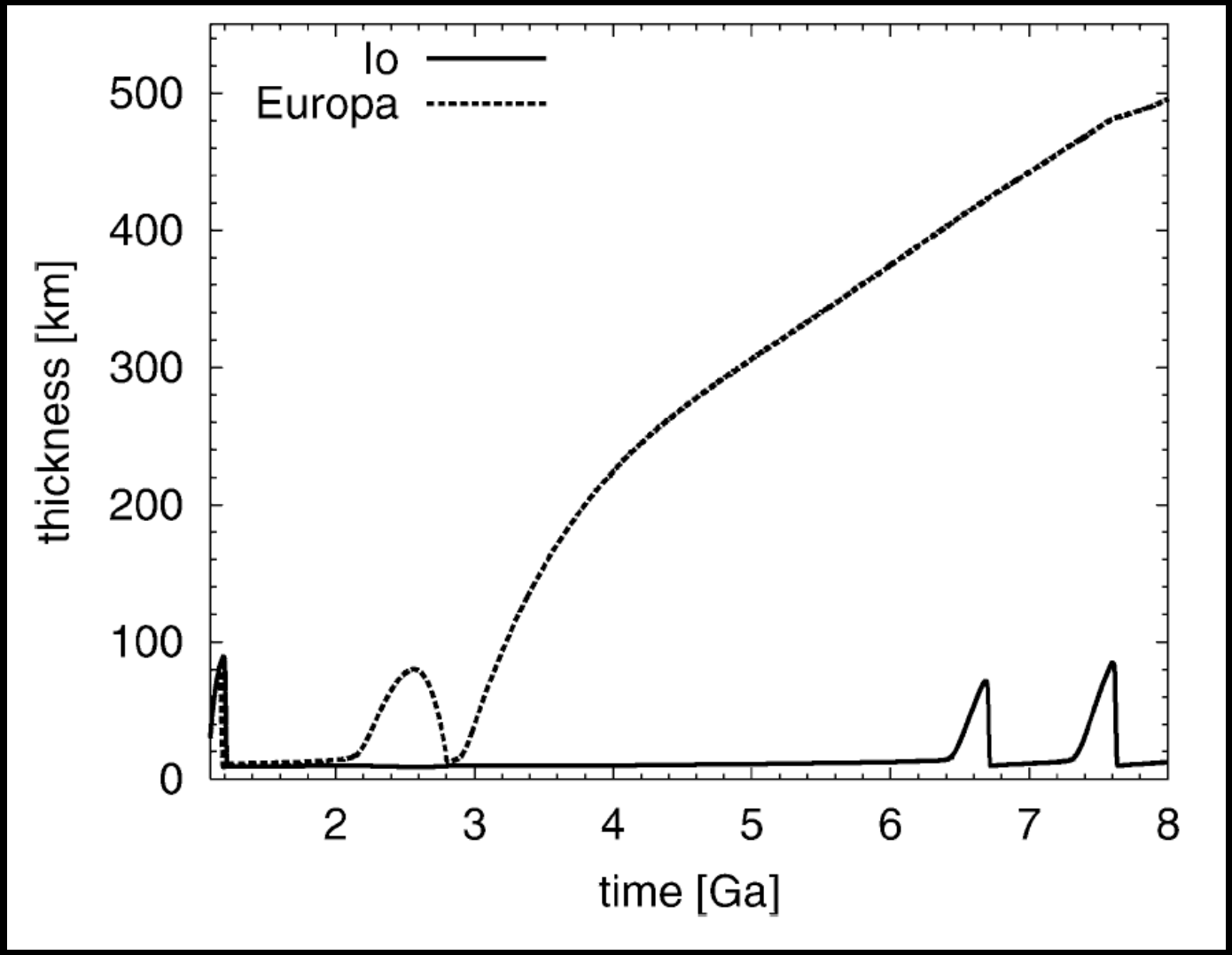
eccentricities evolved through time





(average) mantle temperature changes in response to changes in tidal forcing.

Hussmann *et al*. 2004



Hussmann *et al.* 2004

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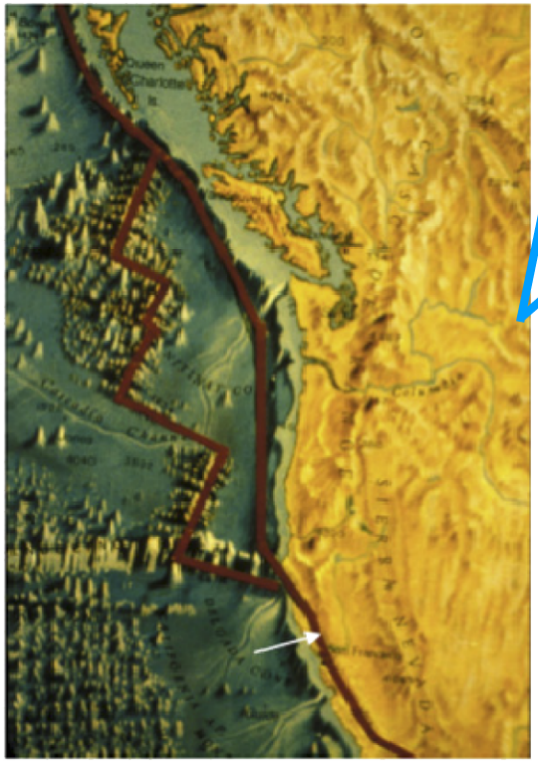
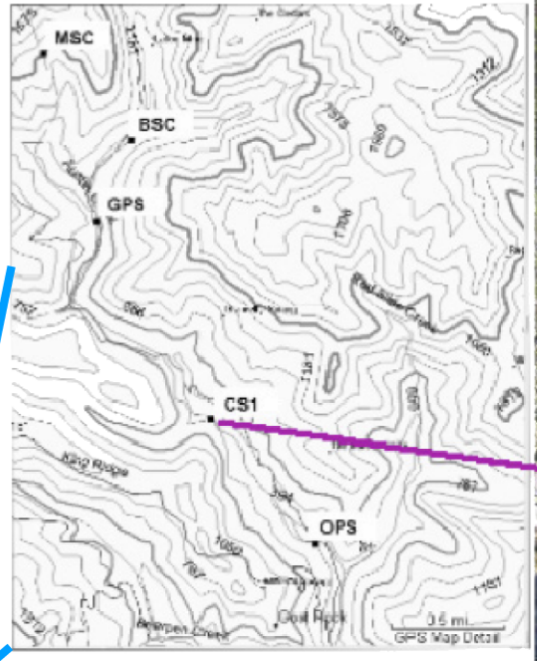
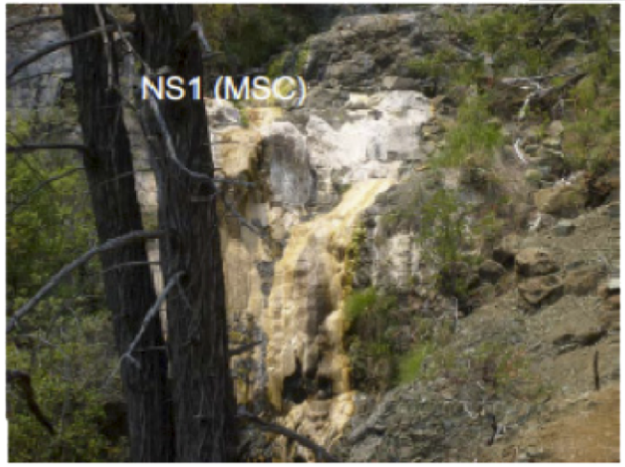
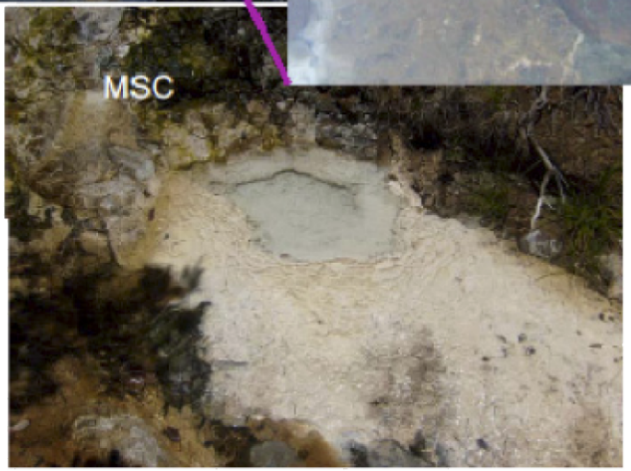
The Cedars, CA





(Morrill et al. GCA, in revision)





Nipple Spring