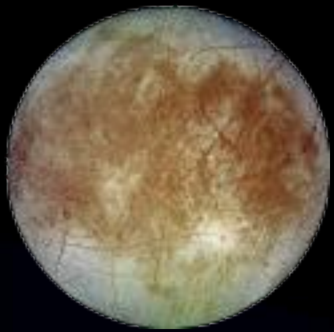
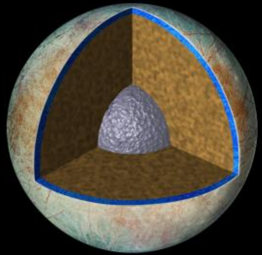
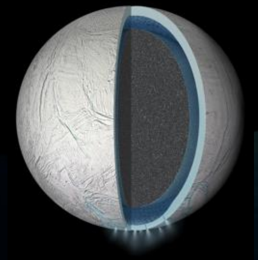
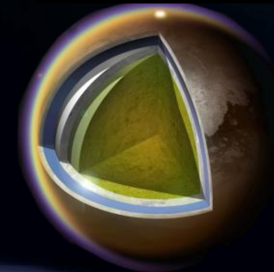


Alexander G. Hayes
Assistant Professor
Cornell University

Habitable Environments Across the Solar System: Toward an Ocean World Exploration Strategy

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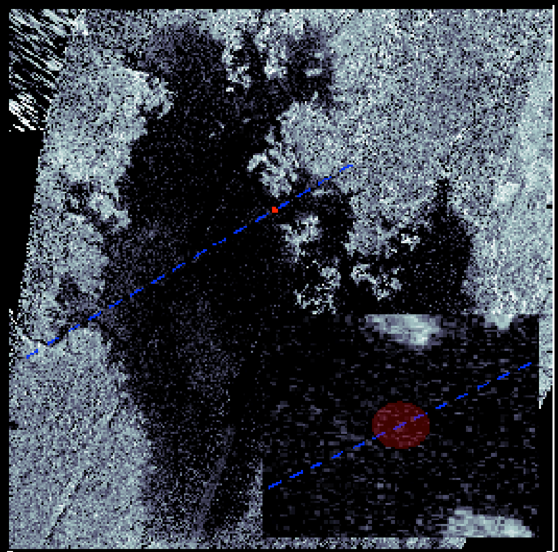
ExOceans Symposium
Paris Observatory
11/13/17

Sherwood, B., Lunine, J., Sotin, C., Cwik, T., and Nadeiri, F. 2017 Program options to explore ocean worlds, Global Space Exploration Conference (GLEX 2017), Beijing, China, 6-8 June 2017. GLEX-17,6.4x36541

RADAR Bathymetry of Titan's Ligeia Mare

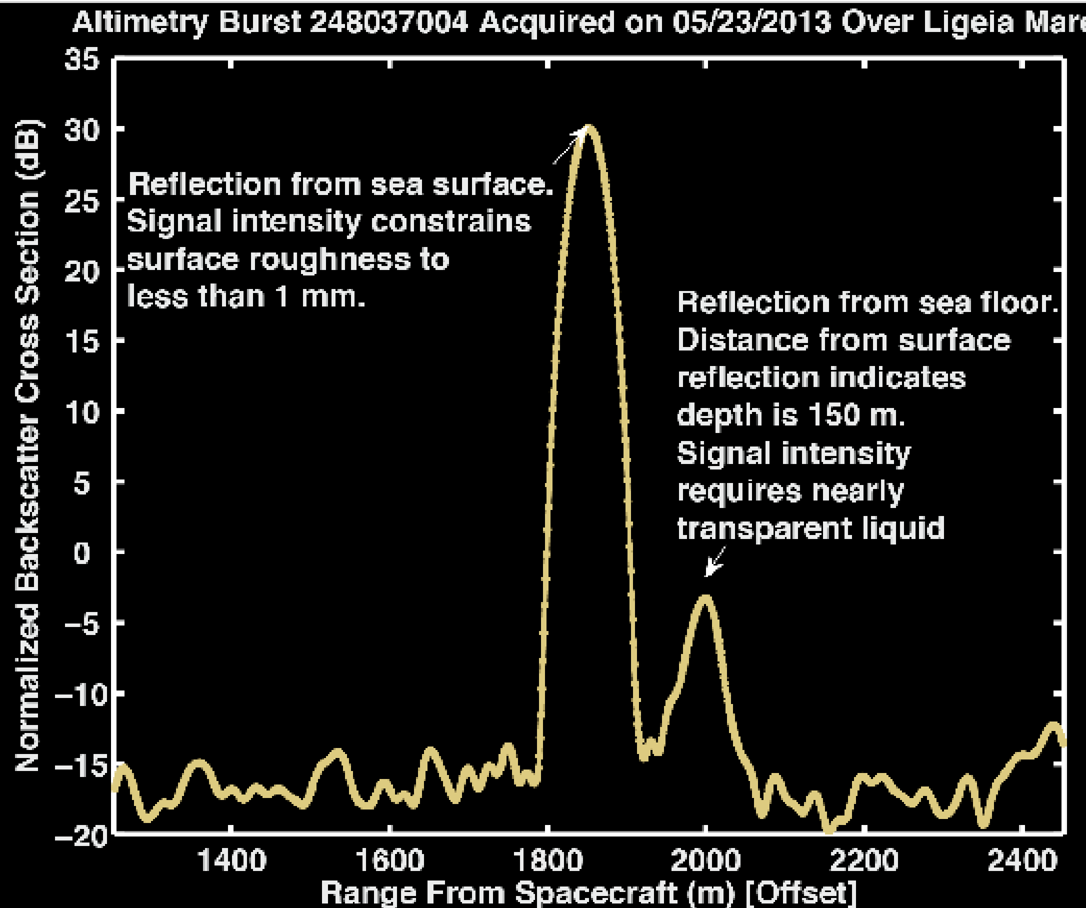
The *first* determination of the depth of a Titan sea

Ligeia Mare



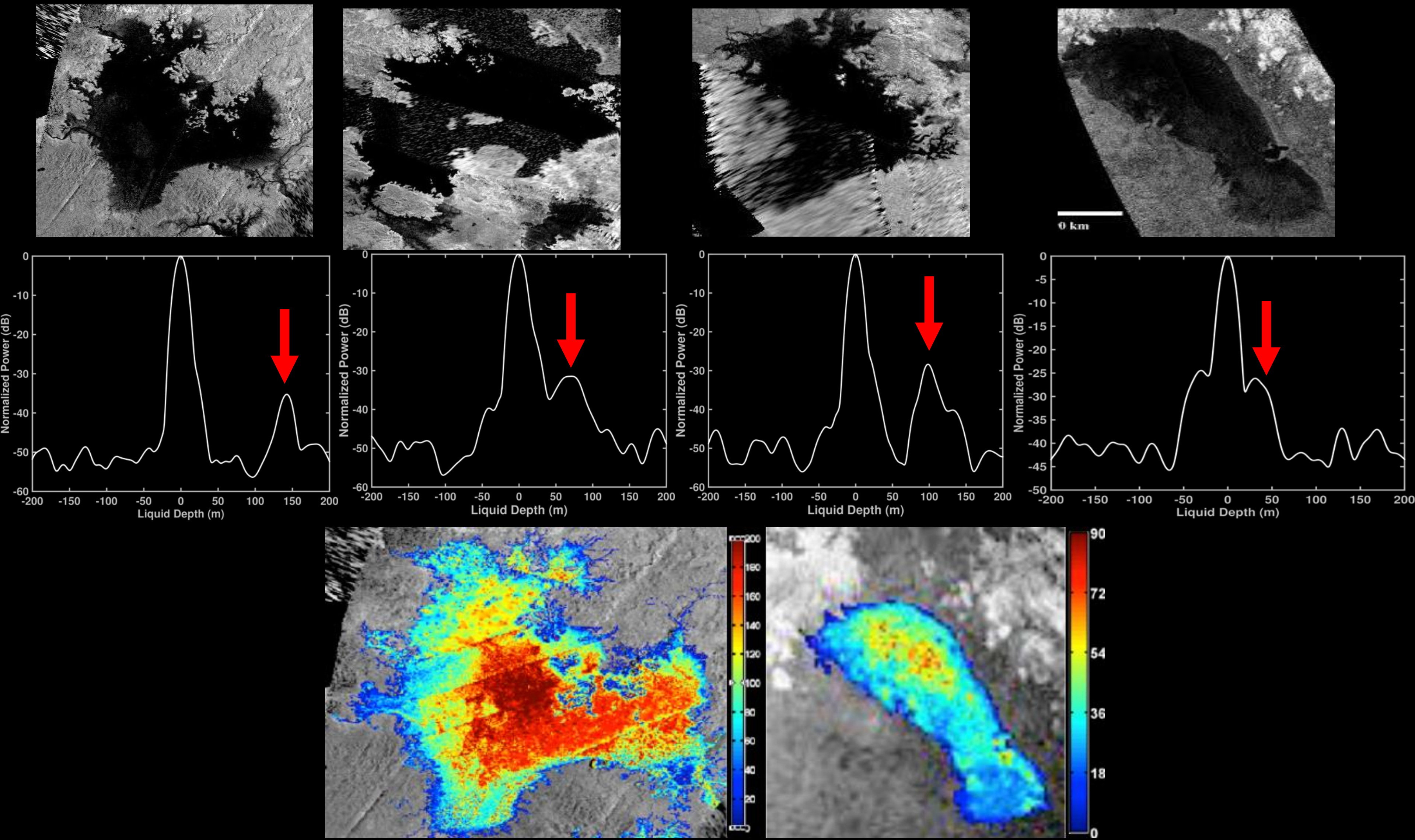
Making this measurement required:

- *Discovery of the seas (2007)*
- *Successful test of altimetry mode over a southern lake (2010)*
- *Planning and execution of new altimetry modes and means of echo extraction (2013)*



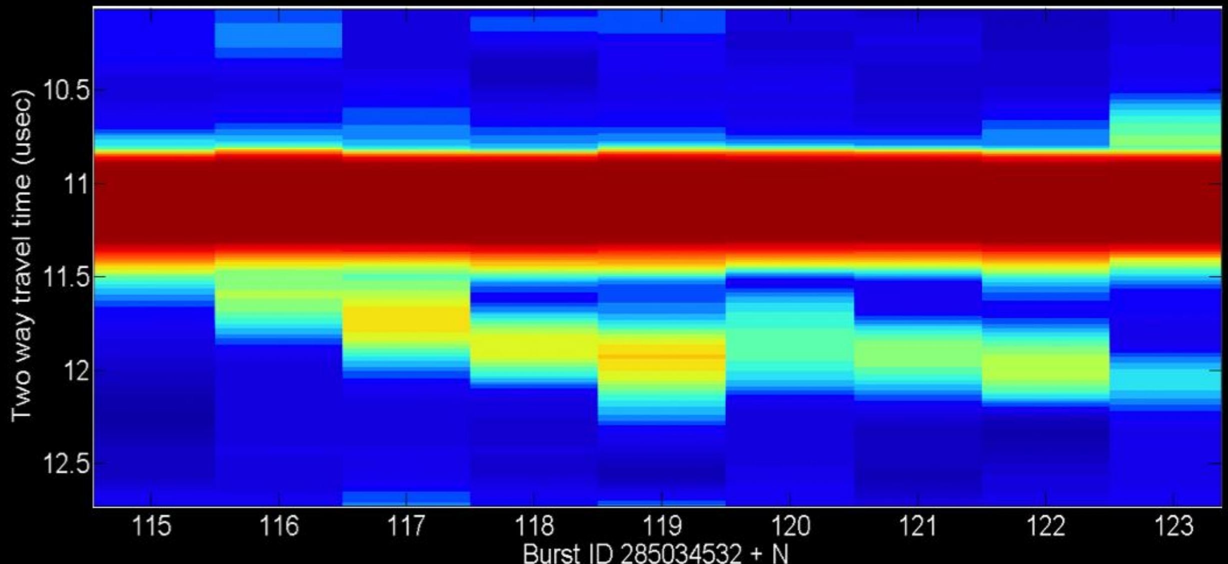
- **Altimetry-mode observations of Ligeia Mare unexpectedly showed a second peak arising from reflection off the seafloor, providing an unambiguous measure of depth (~150 m).**
- **This secondary reflection can only be observed in radar-transparent liquid, constraining liquid composition to be nearly pure methane/ethane with little to no suspended particles.**
- **Similar measurement of Kraken Mare, Titan's largest sea, are possible in fall 2015 (T105).**

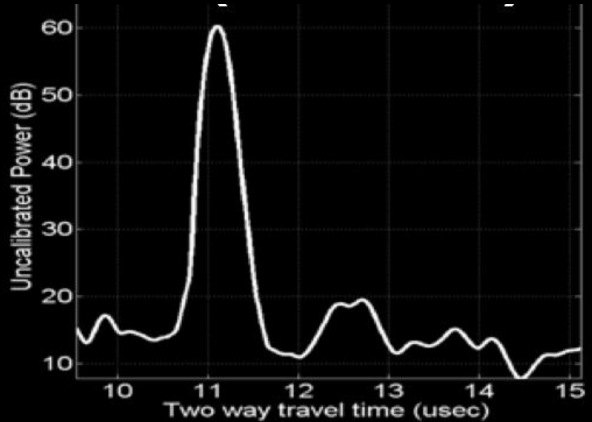
Cassini's Bathymetry Campaign

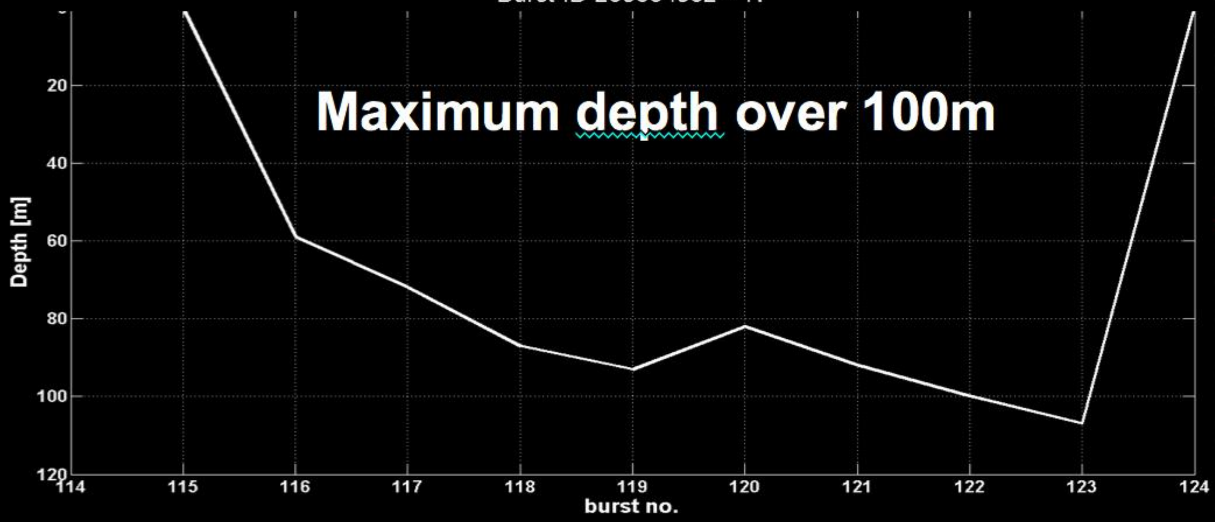


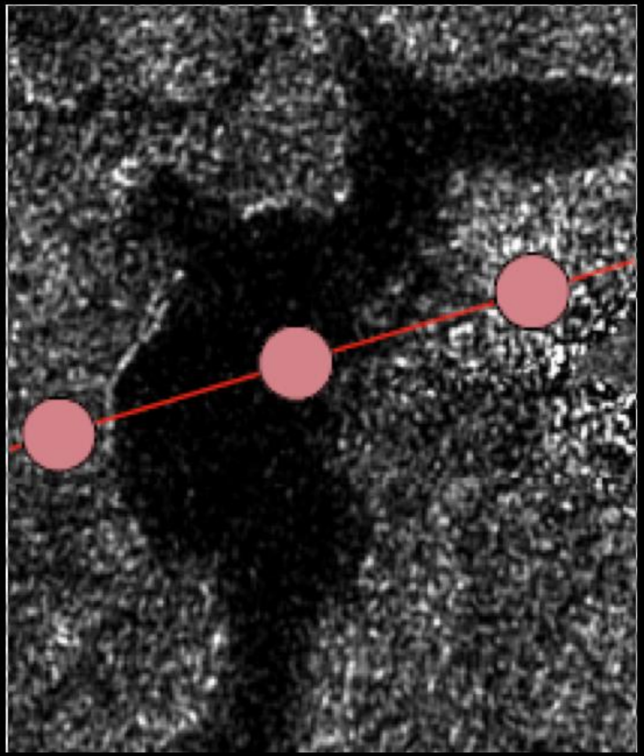
Mastrogiuseppe, Hayes, Poggiali et al., GRL 2014; GRL 2016, IEEE 2016; Icarus 2017; Icarus sub.

So Long and Thanks for all the Lakes



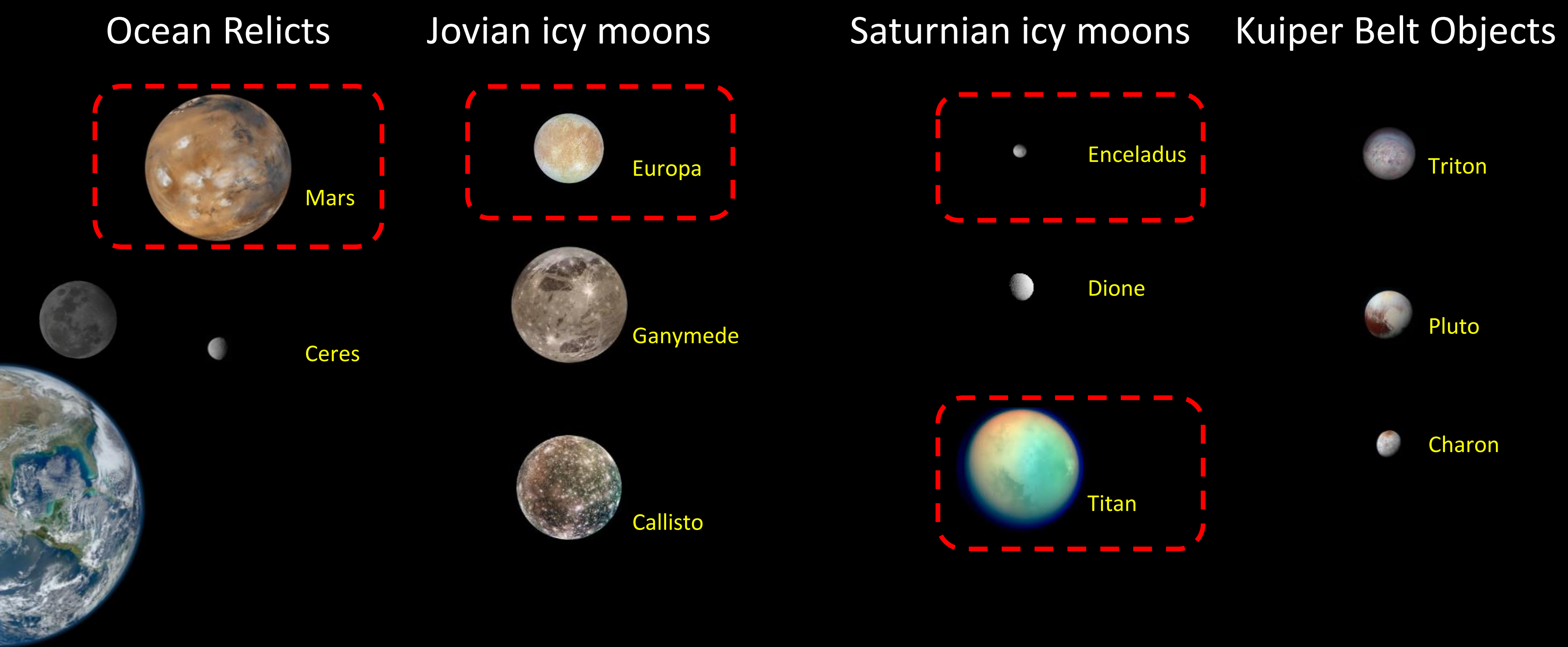






Ocean Worlds Across the Solar System

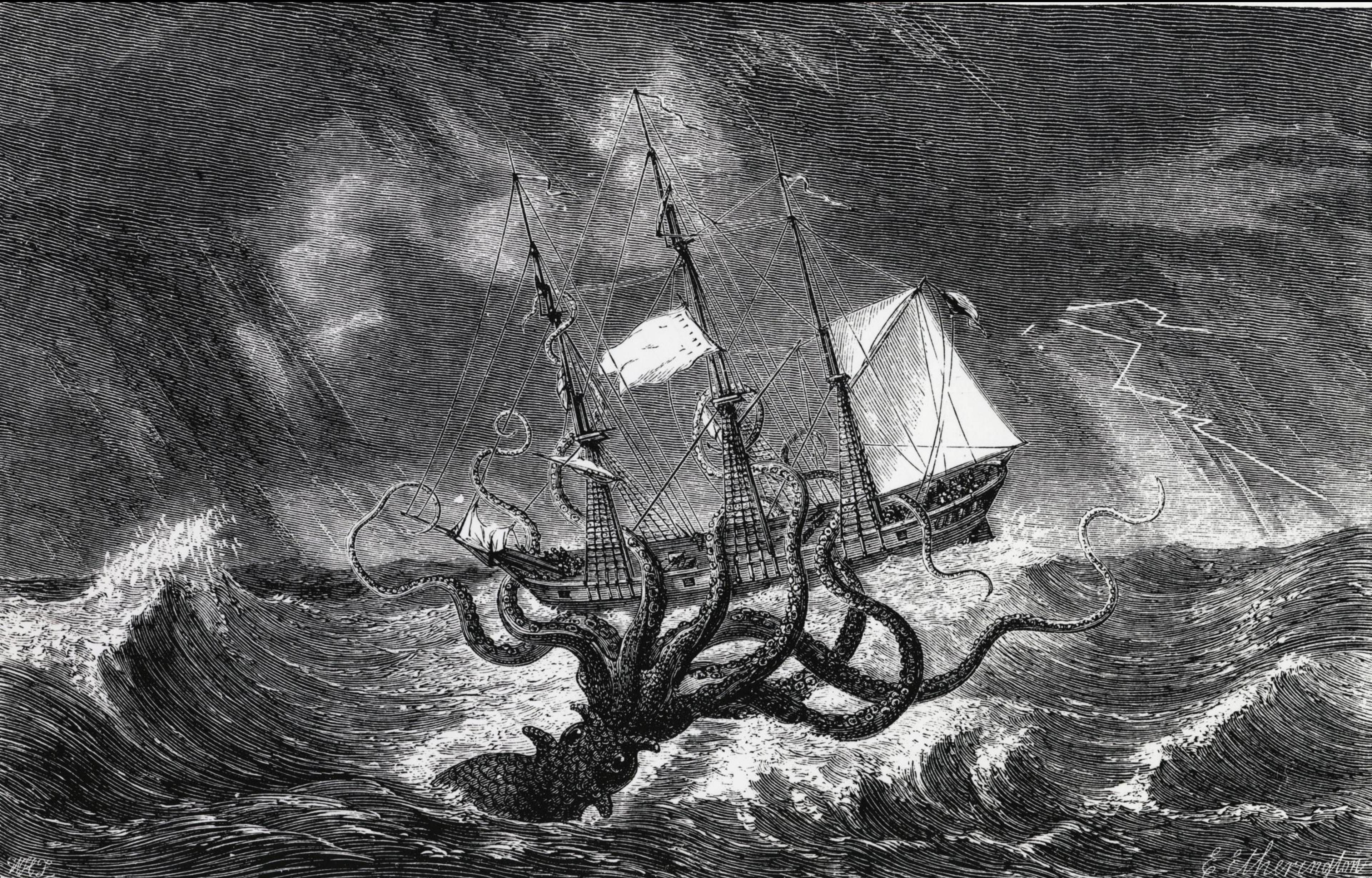
More than a dozen Ocean Worlds are within reach



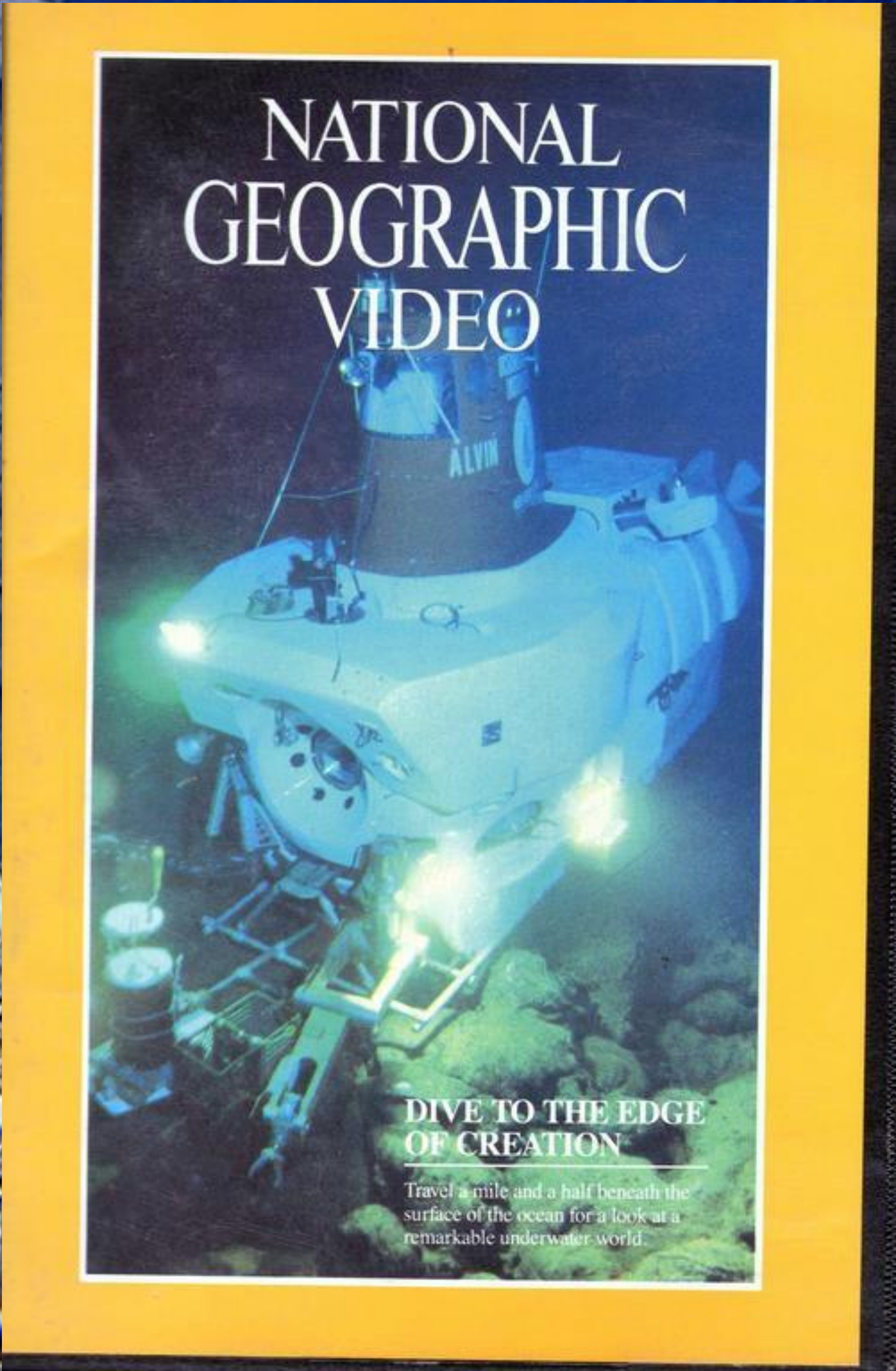
But Three (Four Including Mars) are of Special Interest

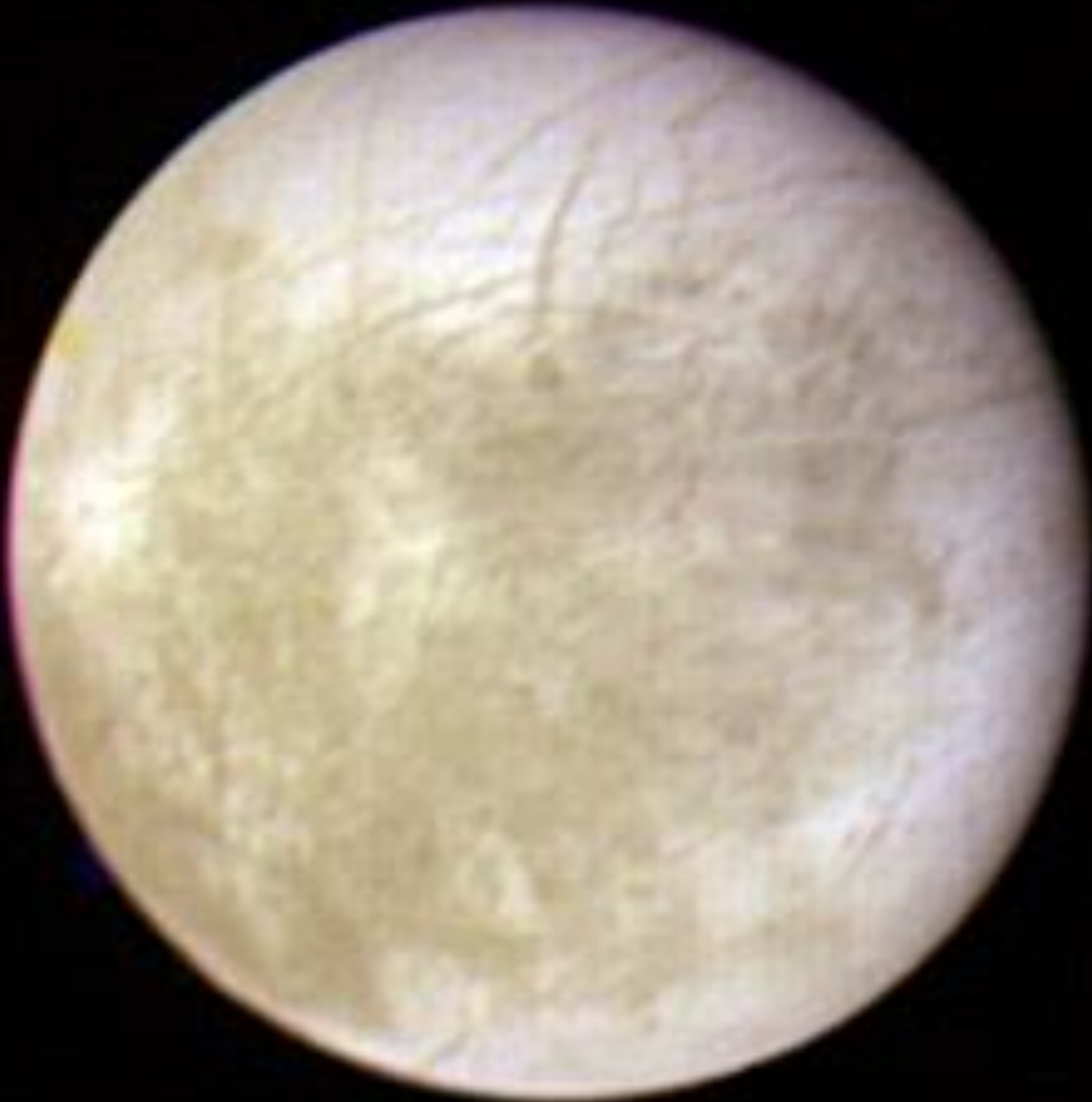
Craft an Ocean Worlds Exploration Progam (OWEP) in Response


Mars
Ancient Life?: Bring Back a Sample
Europa
Best Place for Conventional Life?: Look for organic-filled cracks and ice-ocean exchange
Enceladus
Easiest to Explore, Most Studied Ocean: Sample plume for life signs
Titan
The Once and Future Earth: Follow the organics.



Credit: http://history.com


NATIONAL
GEOGRAPHIC
VIDEO
ALVIN
DIVE TO THE EDGE
OF CREATION
Travel a mile and a half beneath the surface of the ocean for a look at a remarkable underwater world.

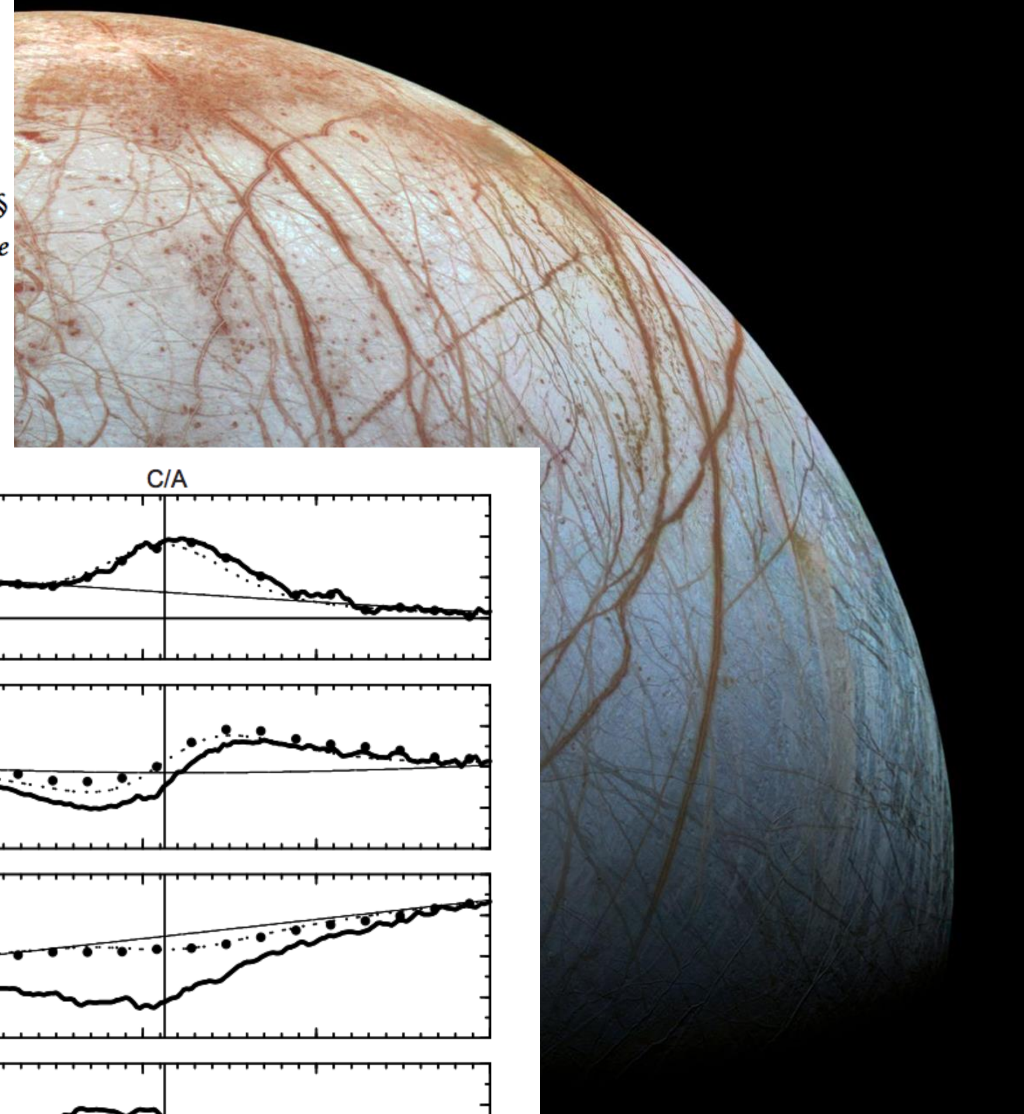


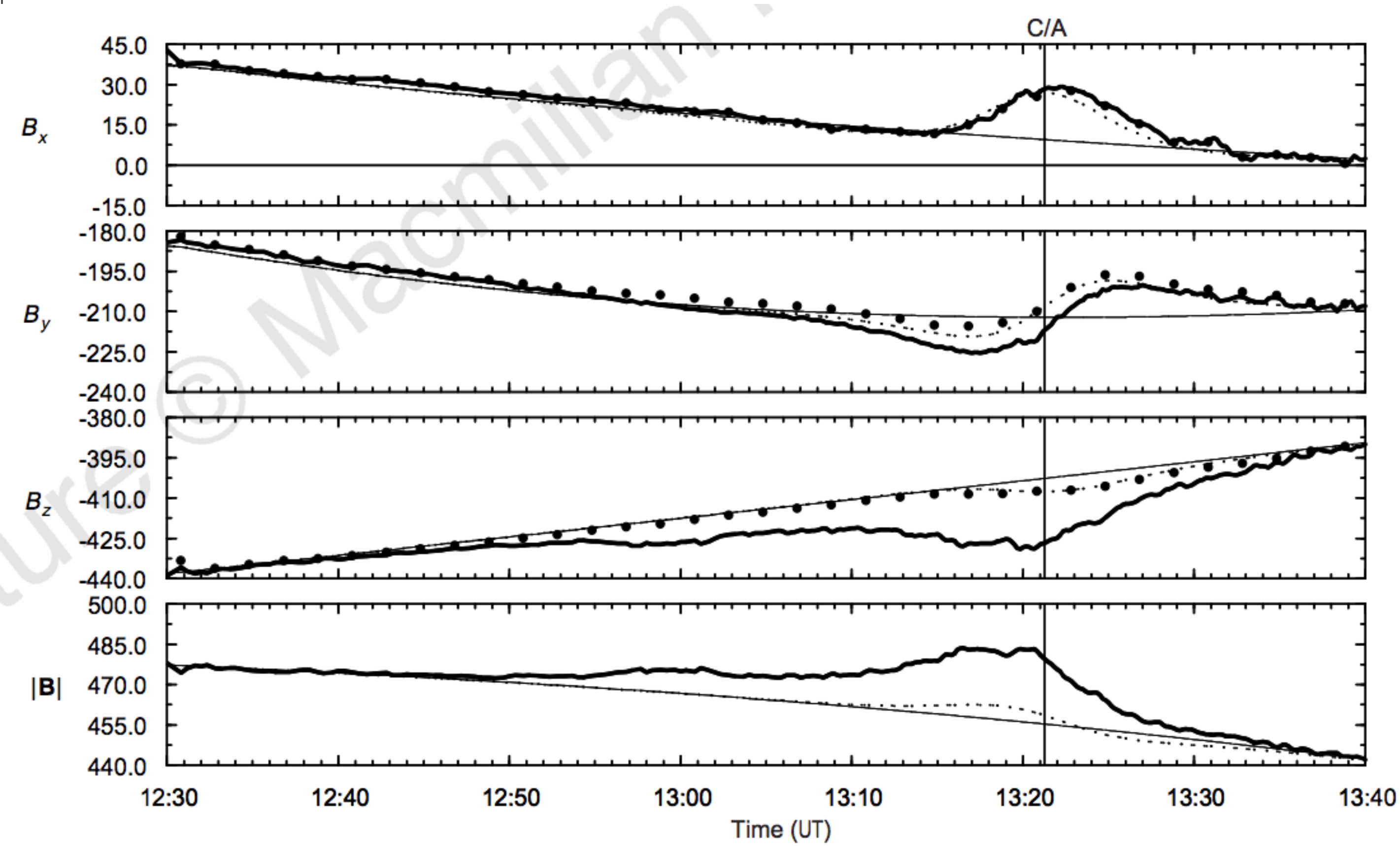
Credit: JPL / NASA

Induced magnetic fields as evidence for subsurface oceans in Europa and Callisto

K. K. Khurana*, M. G. Kivelson*†, D. J. Stevenson‡, G. Schubert*†, C. T. Russell*†, R. J. Walker* & C. Polanskey§

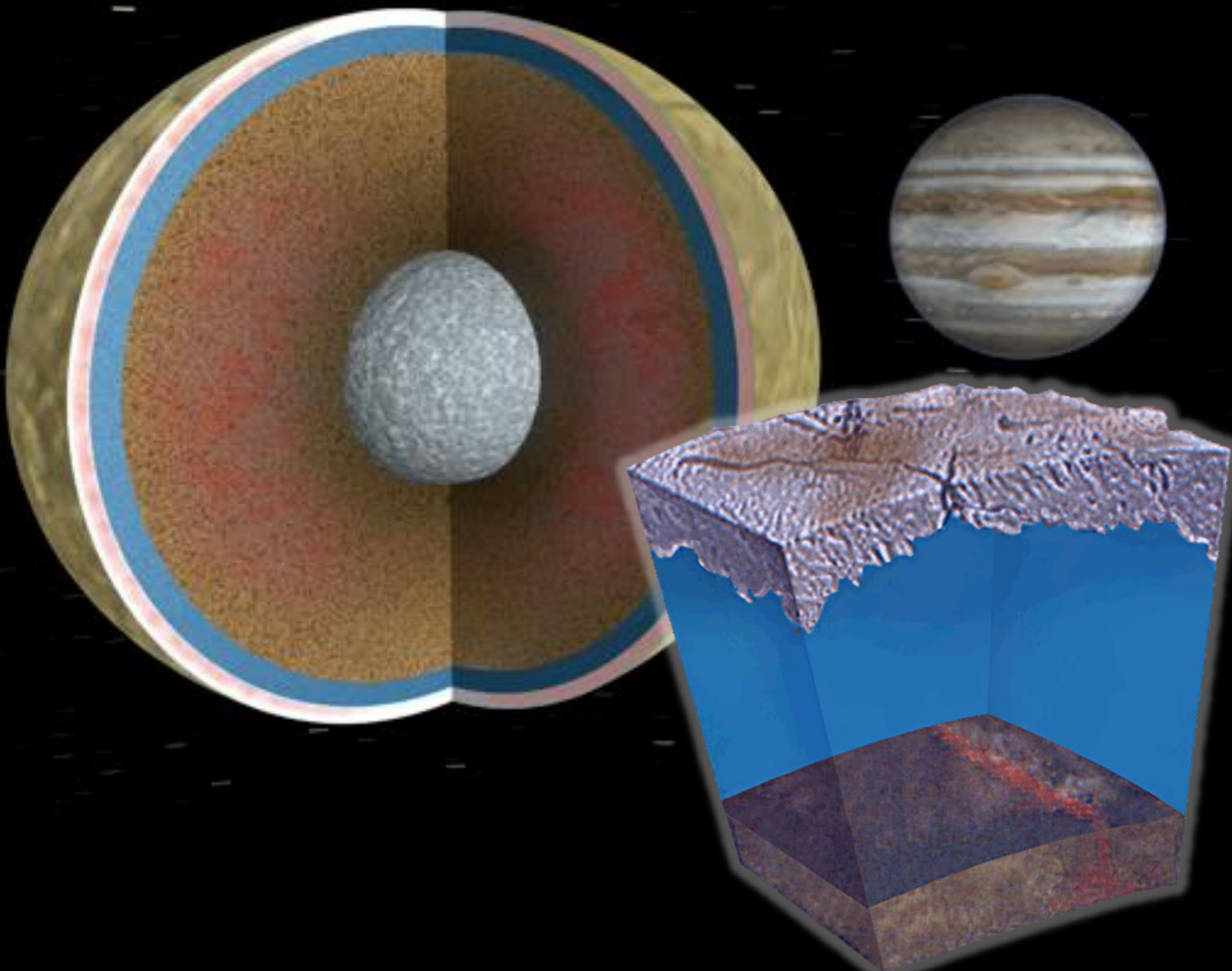
* *Institute of Geophysics and Planetary Physics,* † *Department of Earth and Space Sciences, University of California, Los Angeles, California 90095, USA*
‡ *Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA*
§ *The Jet Propulsion Laboratory, 4800 Oak Grove Road, Pasadena, California 91109, USA*

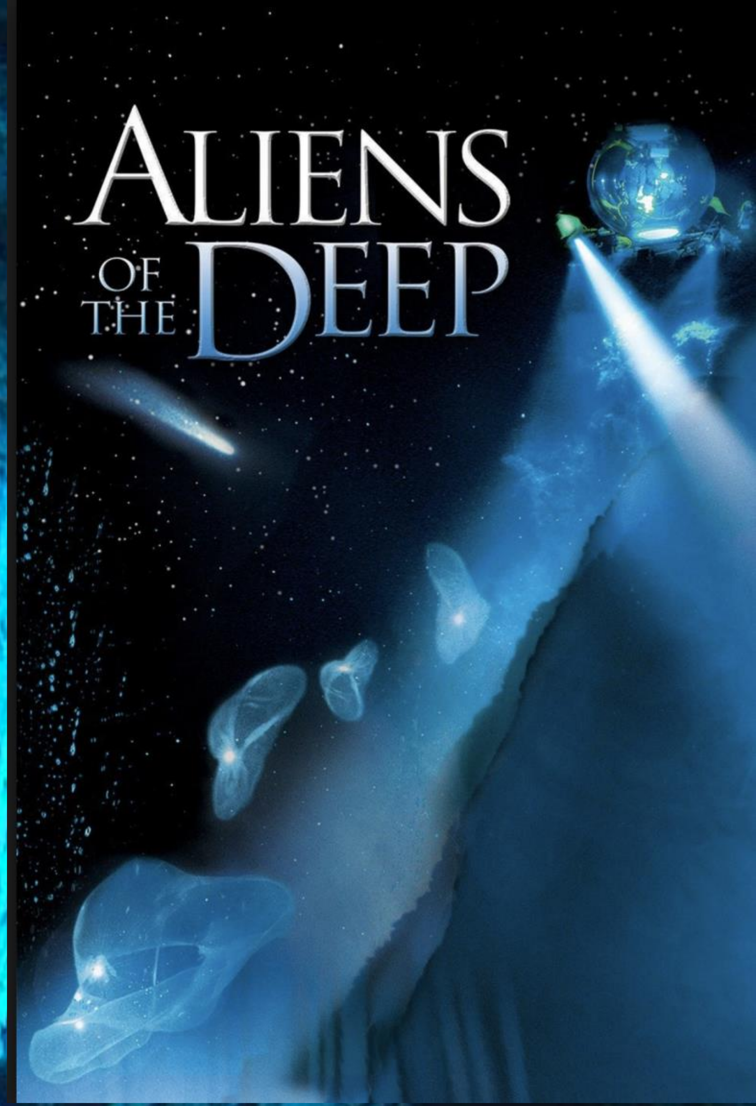




Credit: JPL / NASA

Europa’s Interior



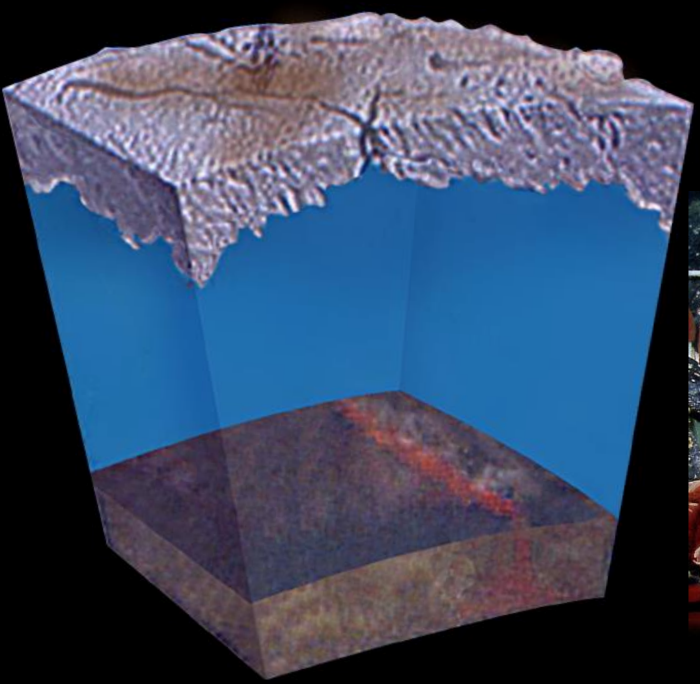


Credit: University of Washington / Lost City Science Team

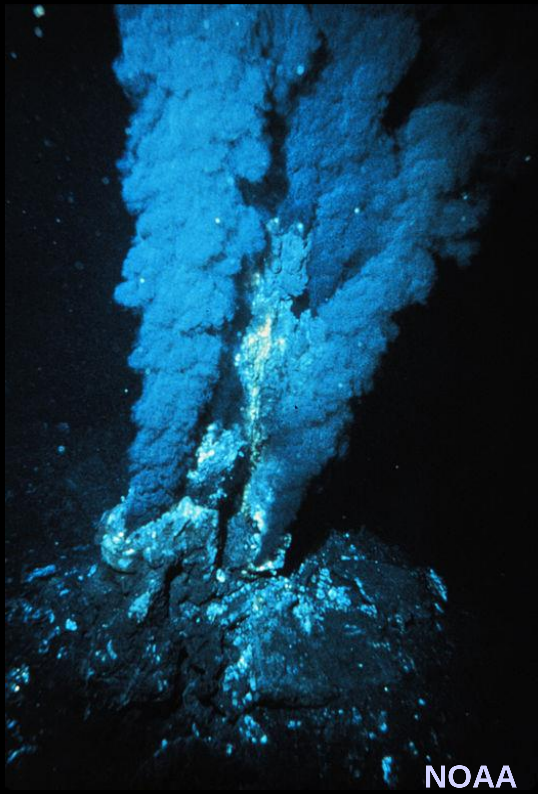
Ingredients for Life?

- Water: *~2x Earth's oceans*
- Essential elements: *From formation and impacts*
- Chemical energy: *From above and below*
- Stability: *"Simmering" for 4 billion years*

Europa's ocean



Earth's ocean floor



Chaos

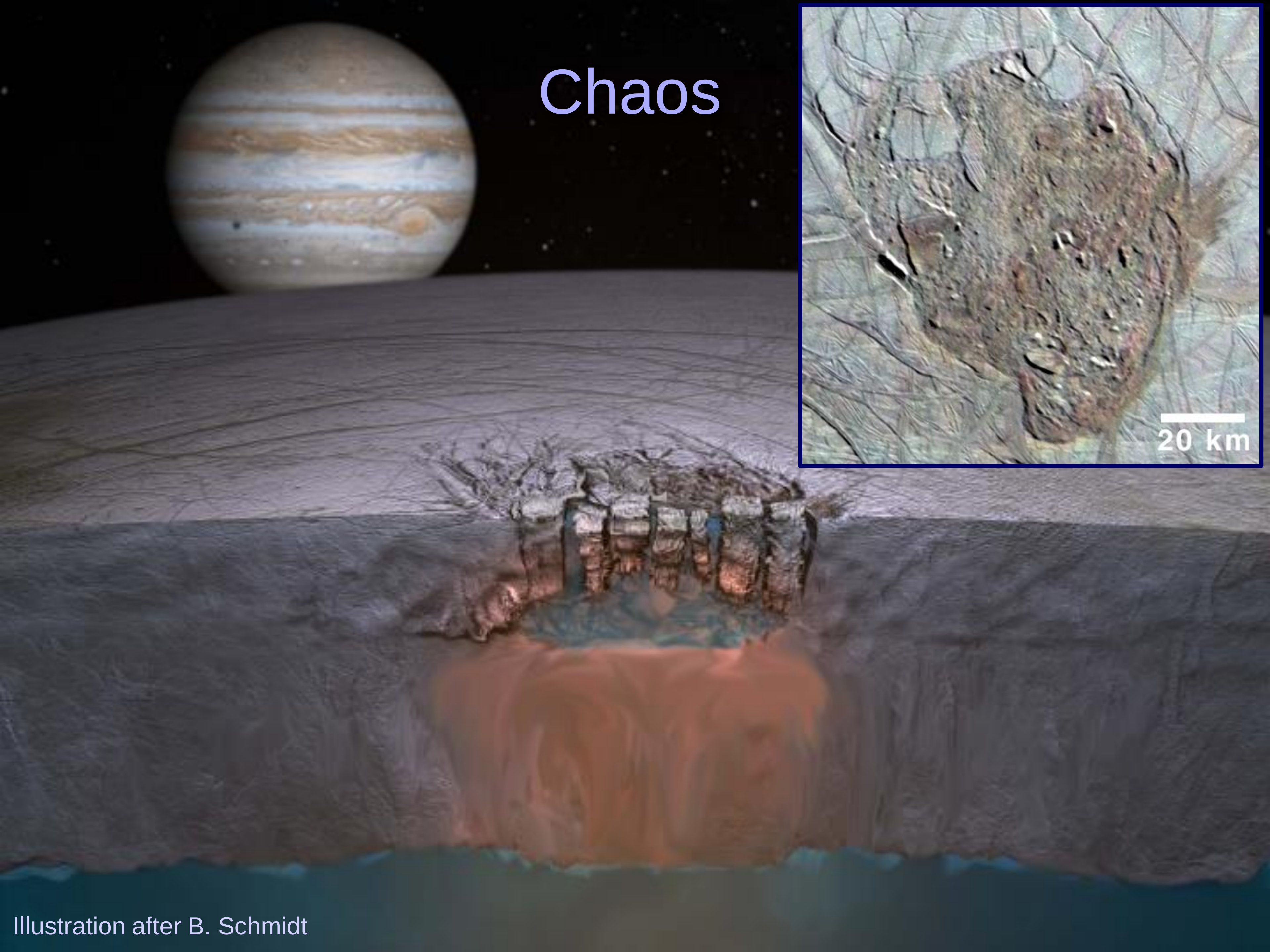
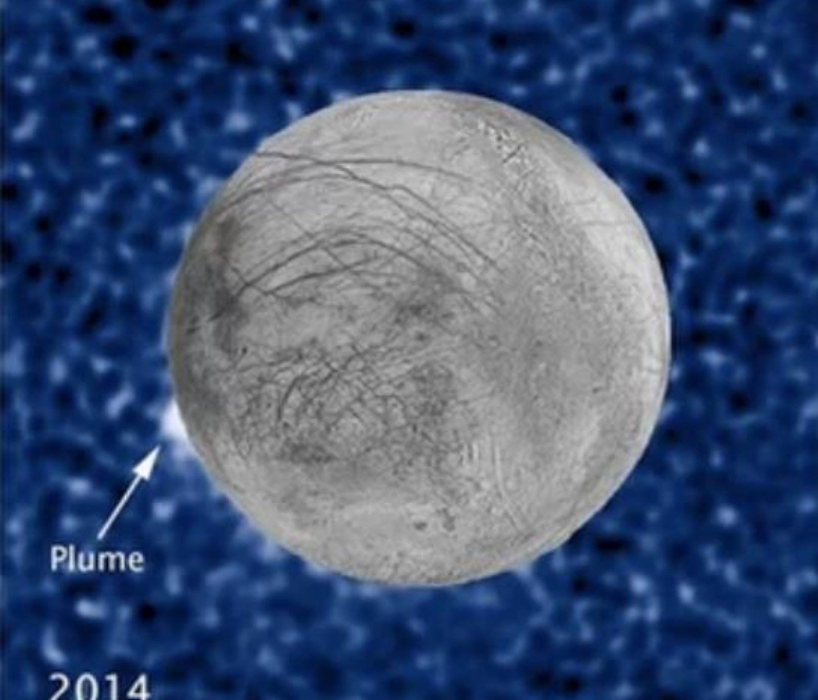
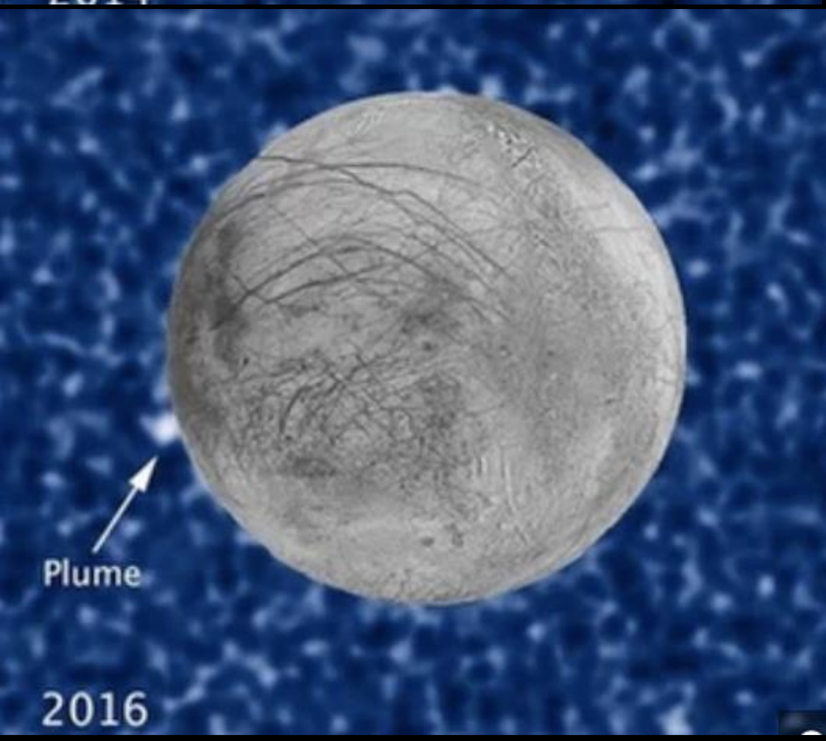


Illustration after B. Schmidt

Plumes?

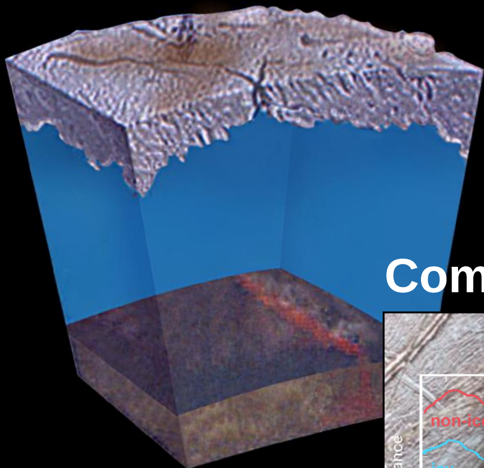




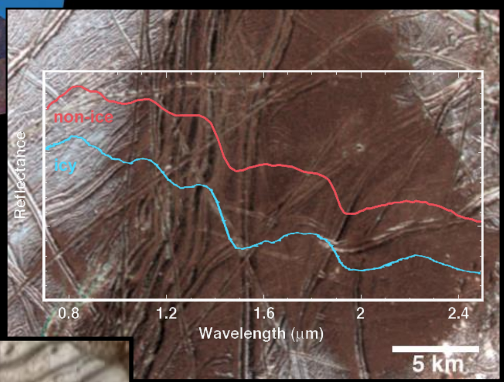
Europa Clipper (Launch 2022?)

Goal: Explore Europa to investigate its habitability

Ocean & Ice Shell

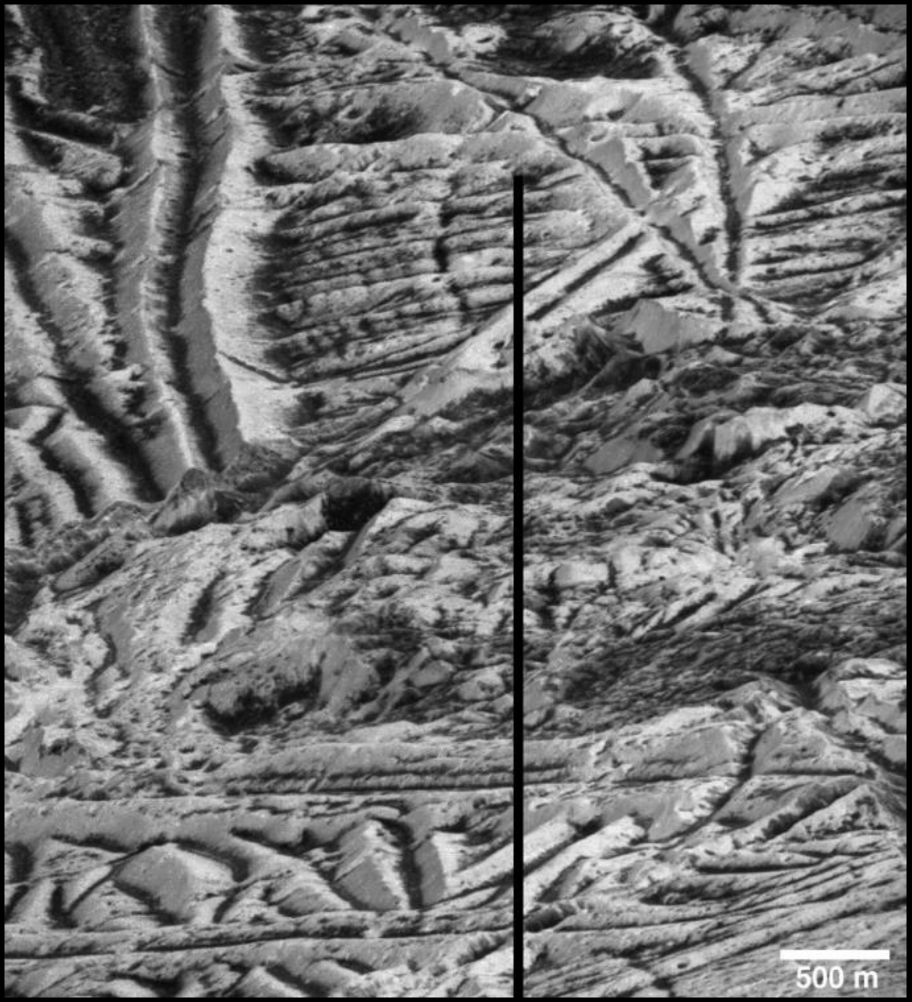


Composition

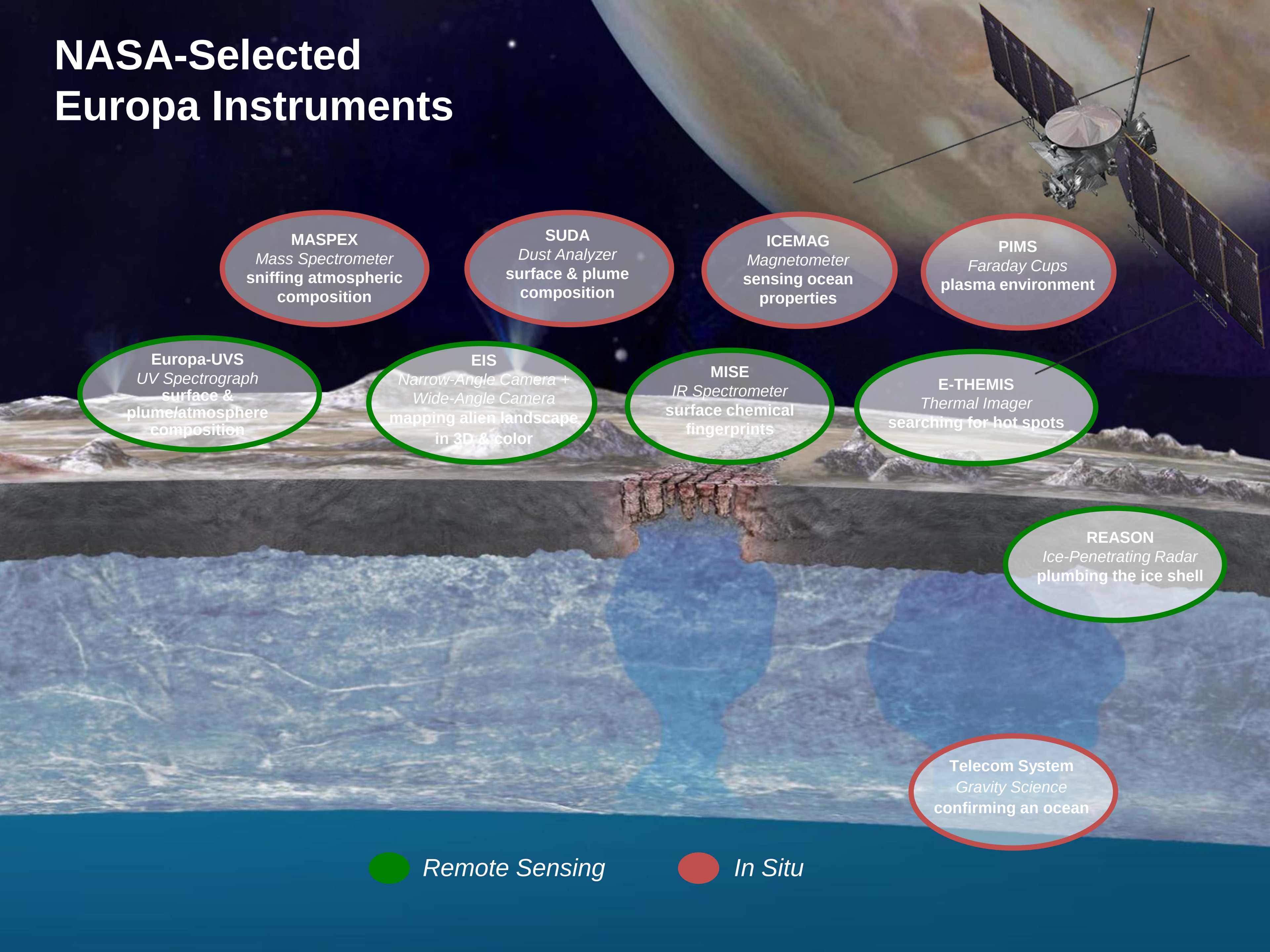


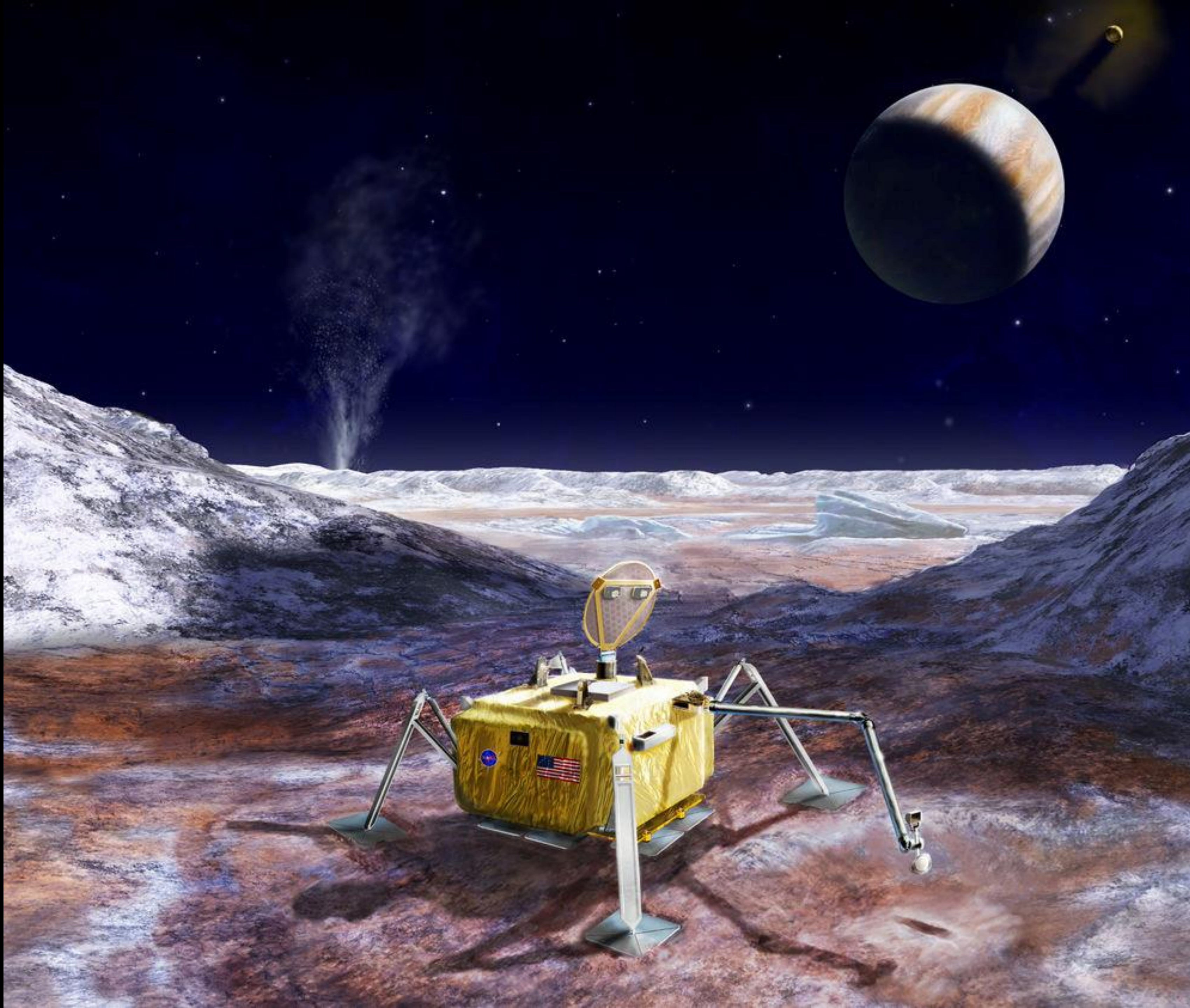
Geology

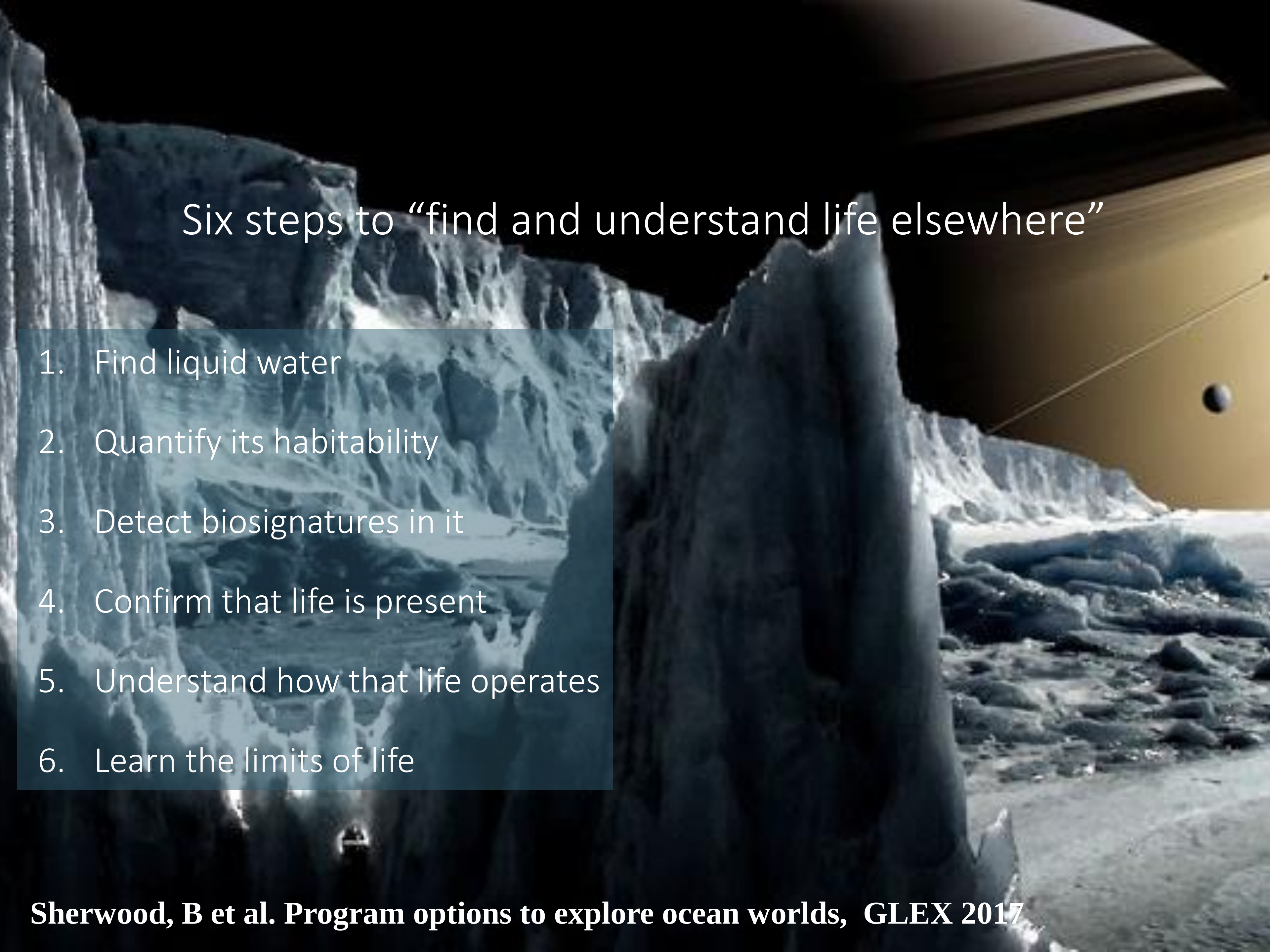
Reconnaissance



NASA-Selected Europa Instruments







Six steps to “find and understand life elsewhere”

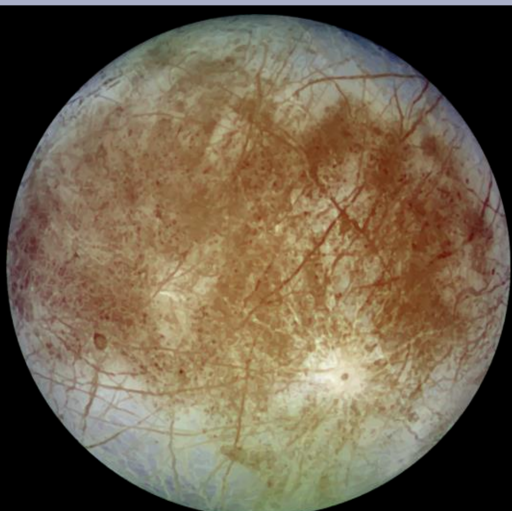
1. Find liquid water
2. Quantify its habitability
3. Detect biosignatures in it
4. Confirm that life is present
5. Understand how that life operates
6. Learn the limits of life

Sherwood, B et al. Program options to explore ocean worlds, GLEX 2017

A Europa program in three steps

Comprehensive investigation of the icy moon's habitability

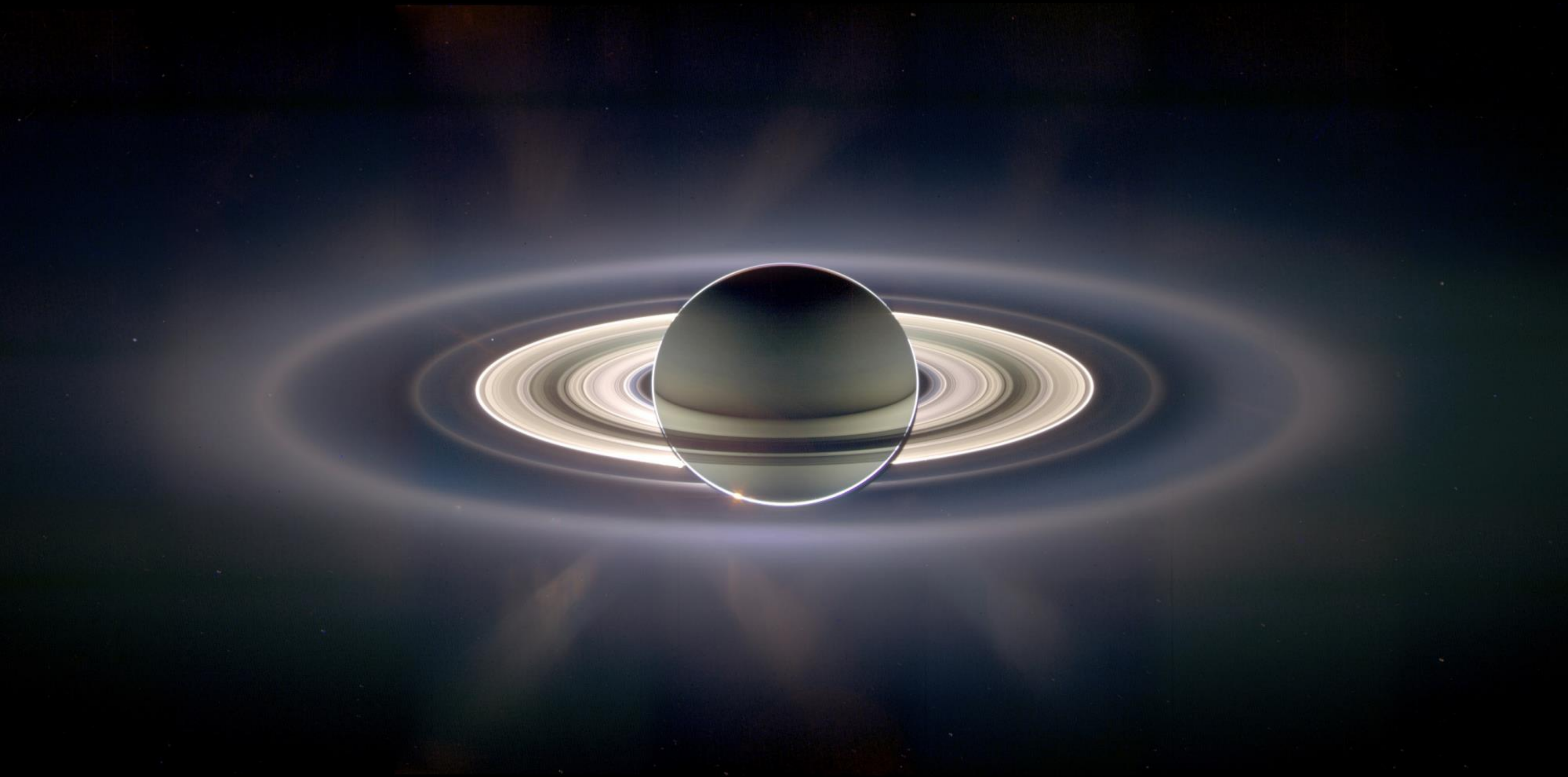
- Clipper suite for ocean habitability, history of crus
- Lander-scale surface



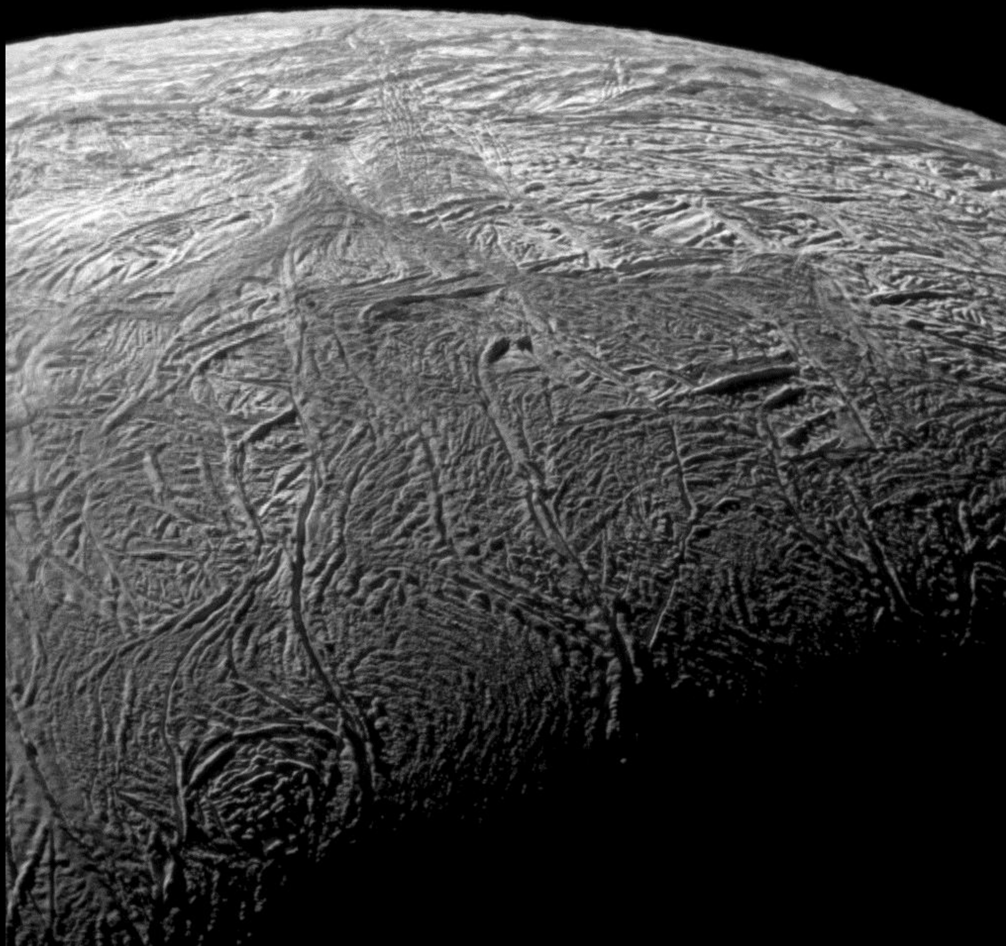
- Land at ocean-surface exchange zone
- Mobility around touchdown point
- Subsurface access to pursue fresher material
- Trans-shell probe into ocean, sample return
- Under-ice exploration of ocean ceiling
- Open ocean exploration, including seafloor

Sherwood, B et al. Program options to explore ocean worlds, GLEX 2017

Credit: JPL / NASA

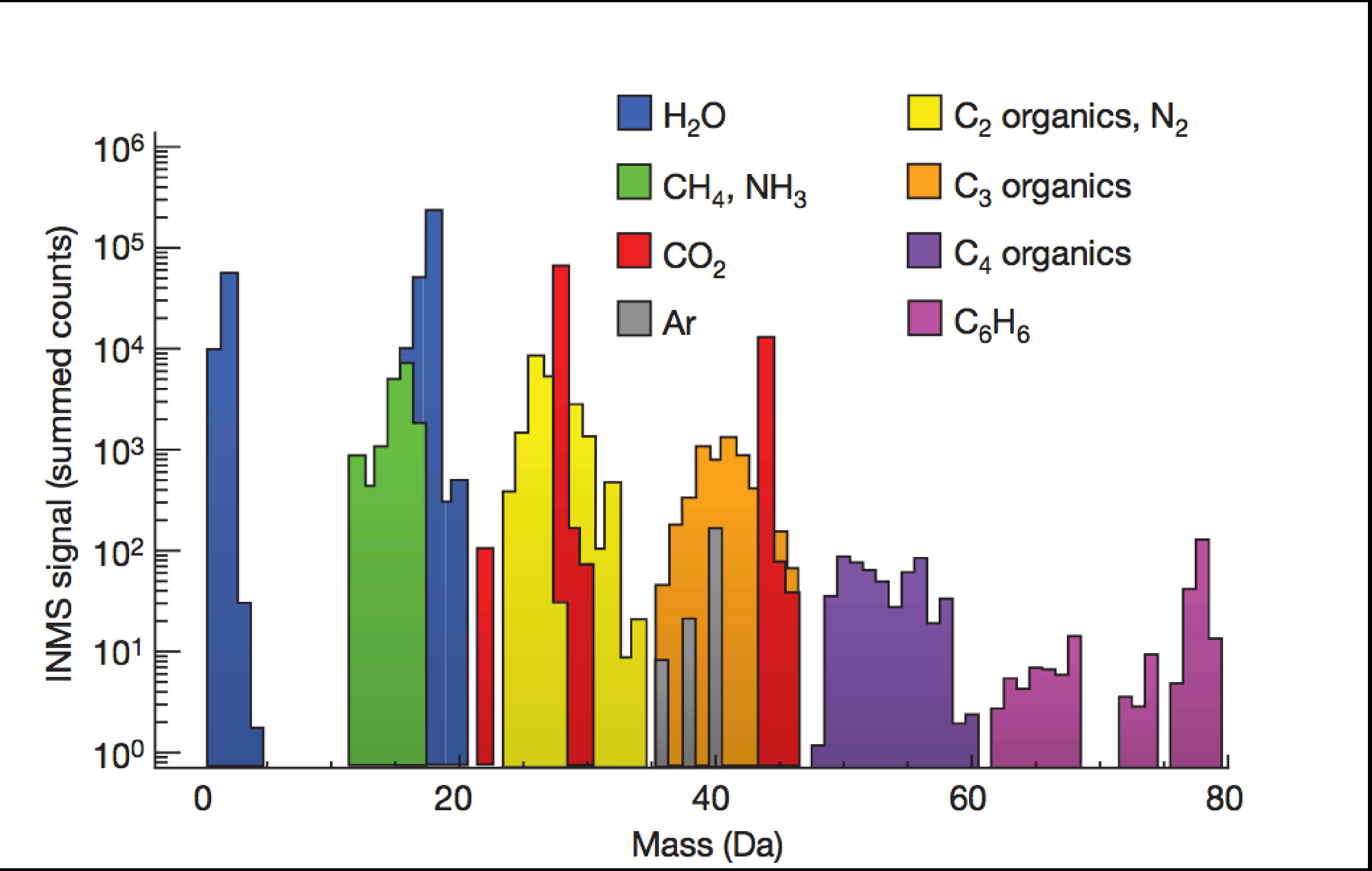


2005: Cassini discovers the plumes and the south polar fracture system…but…



…is the source liquid water or warm ice?

2008: Cassini GCMS discovers organics, ammonia by flying through plume

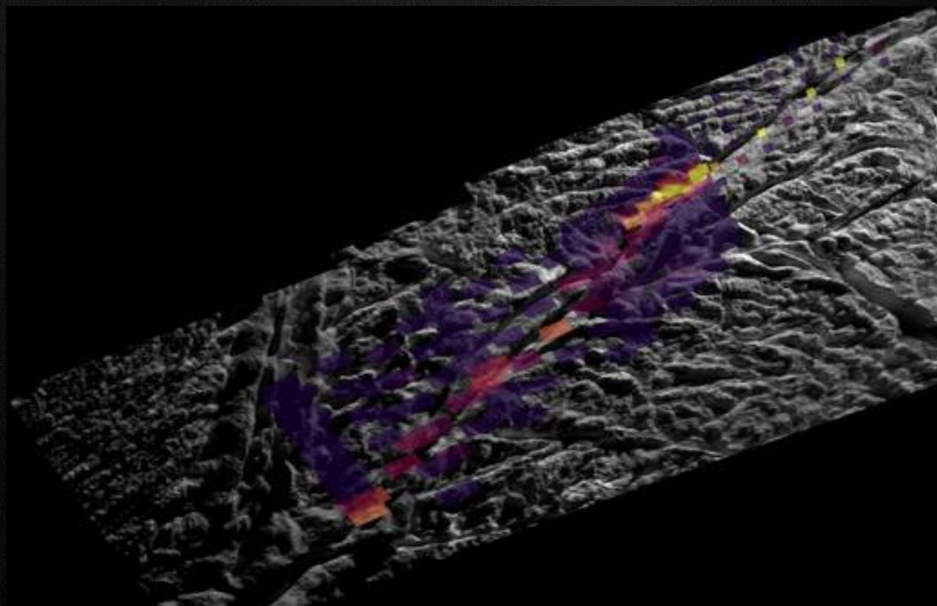


Waite et al, *Nature*, 2009.

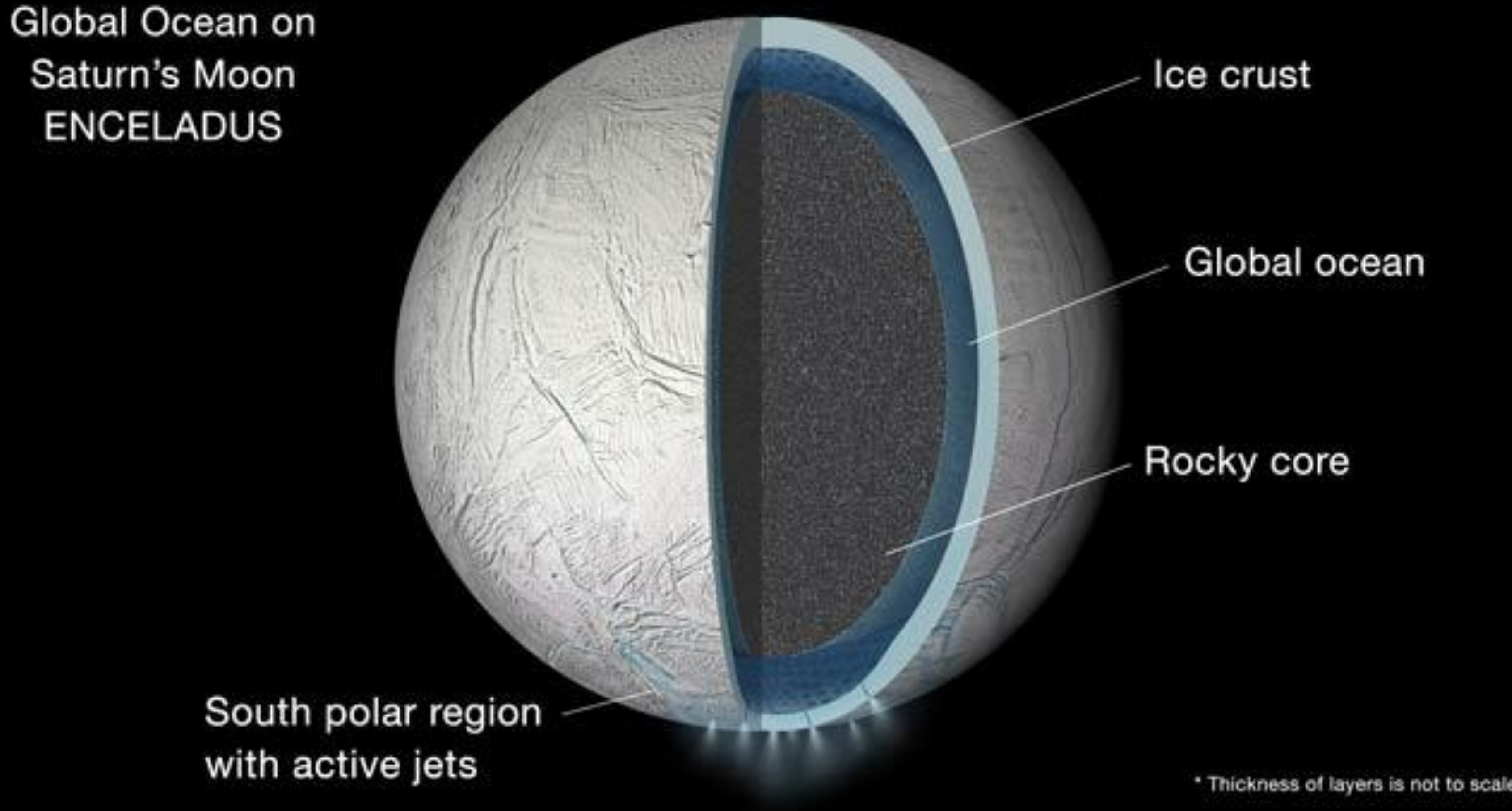
2010-2011:

- Cassini finds sodium and potassium salts in the plume material
  - Concentration comparable to Earth's ocean water. Simplest interpretation is that the largest icegrains are frozen seawater.
- High heat flow from the south polar region measured by Cassini

Conclusion: It's liquid water, with salts and organics, but how much? Is it long lived?



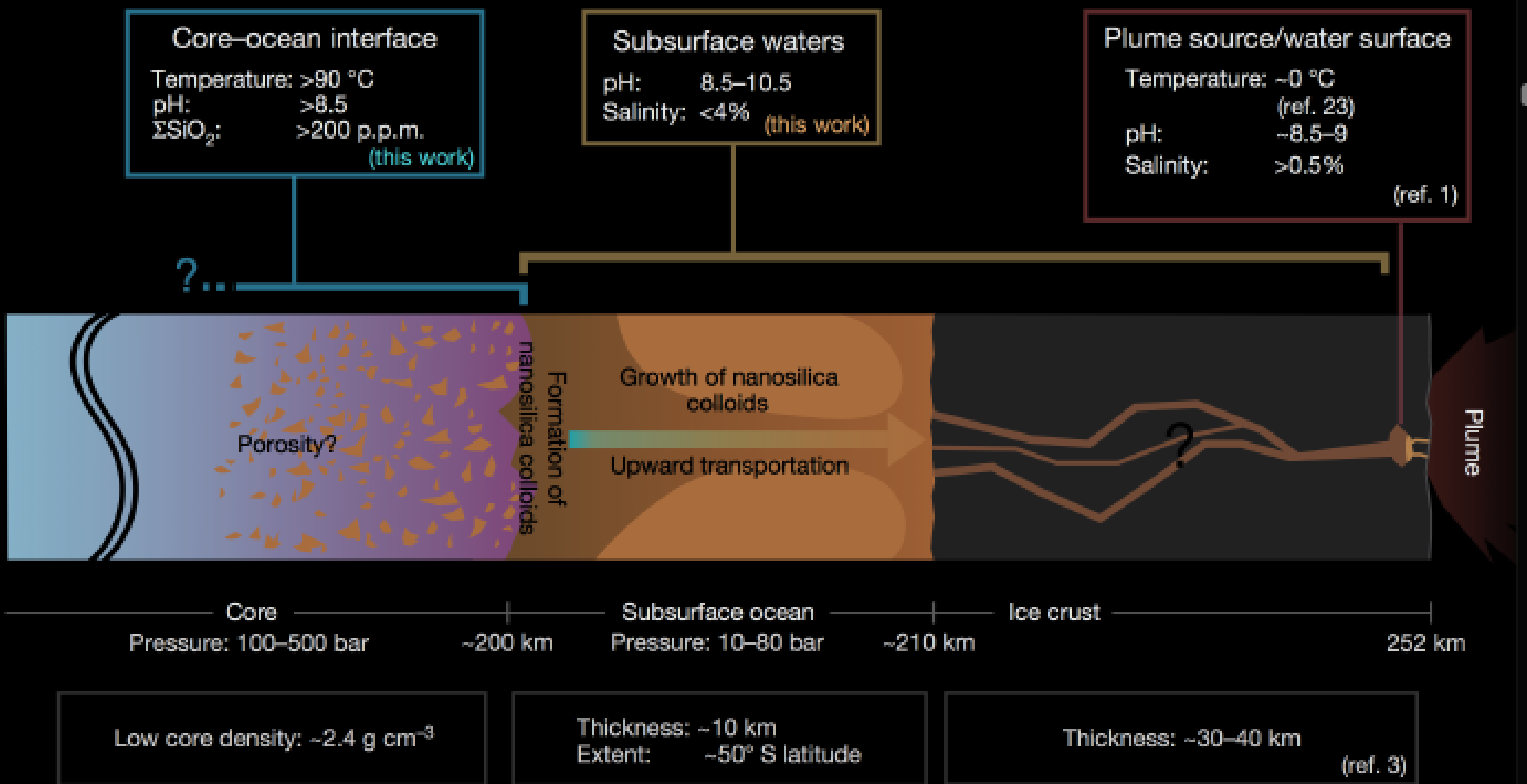
2014-5: Global Ocean under the Ice



Cassini radio science combined with topography and rotational data discovers a global ocean, perhaps thicker at the south pole: the smoking gun that beneath the jets is a region of liquid water, stable for very long time periods.

Iess et al., 2014. Science; McKinnon 2015; Thomas et al. 2015, Icarus

2015: Nanometer-sized silica-rich grains detected by Cassini CDA suggest hot water in Enceladus (Hsu et al 2015)



RESEARCH

RESEARCH ARTICLE April 14, 2017

PLANETARY GEOLOGY

Cassini finds molecular hydrogen in the Enceladus plume: Evidence for hydrothermal processes

Serpentinization

$$\underset{\text{fayalite}}{3\,Fe_2SiO_4} + \underset{\text{water}}{2\,H_2O} \rightarrow \underset{\text{magnetite}}{2\,Fe_3O_4} + \underset{\text{quartz}}{3\,SiO_2} + \underset{\text{hydrogen}}{2\,H_2}$$

Is H_2 used for food??

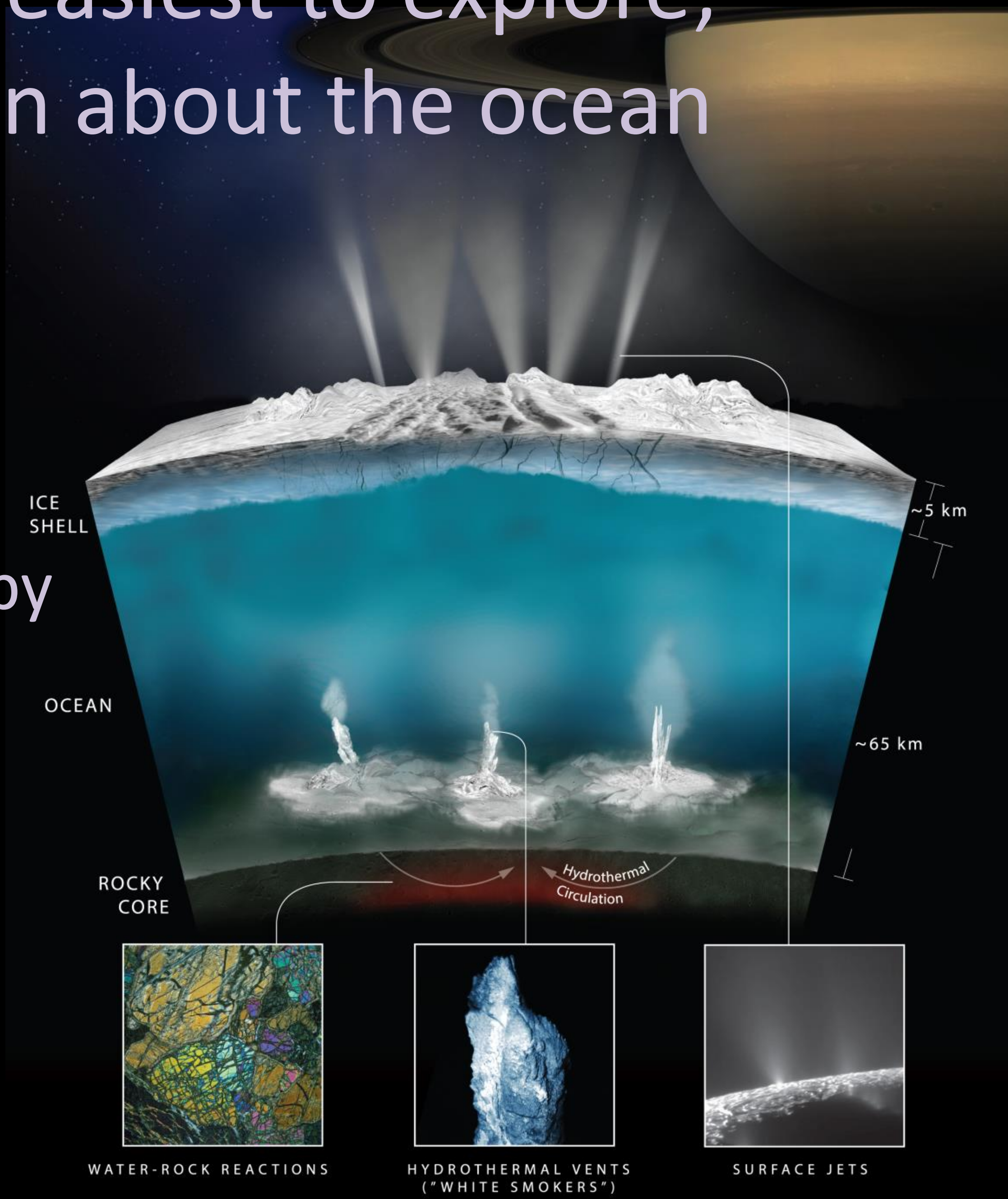
$$CO_2(aq) + 4H_2(aq) \rightarrow CH_4(aq) + 2H_2O(l)$$

Enceladus: easiest to explore; most known about the ocean

- Salt-water ocean with established hydrothermal activity

- Ocean reliably expressed into space by a big plume, ability to sample demonstrated by Cassini

- By today's standard, the most habitable place known off Earth



An Enceladus program in three steps

Direct access to material known to originate in a habitable ocean

- Plume transects
- Sensitive and agnostic compositional analyzers

Wet-chemistry and microscopy of grain material

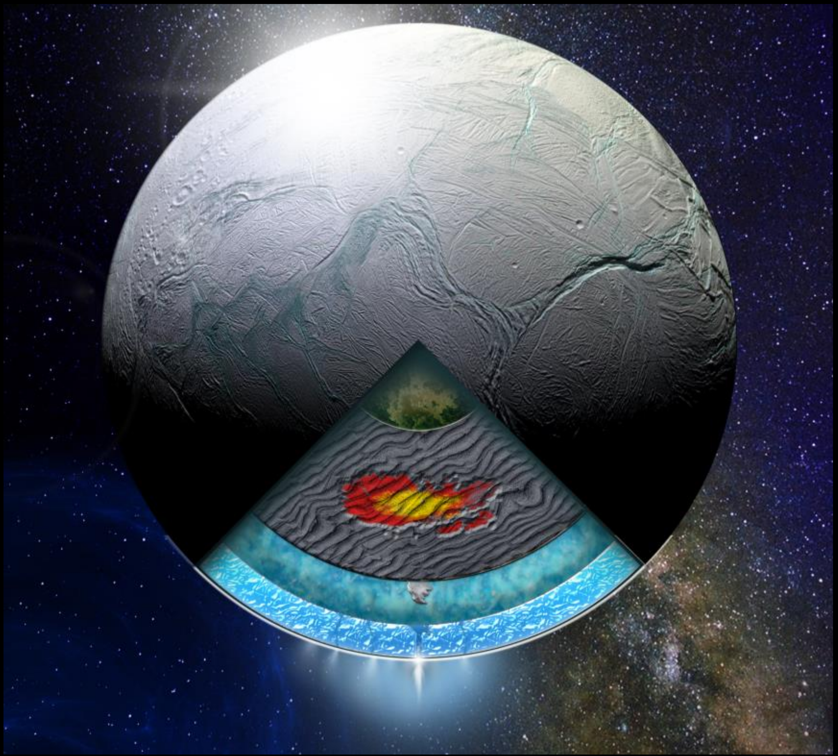
Collection, preservation, and return of samples

Surface collection of large amounts of material

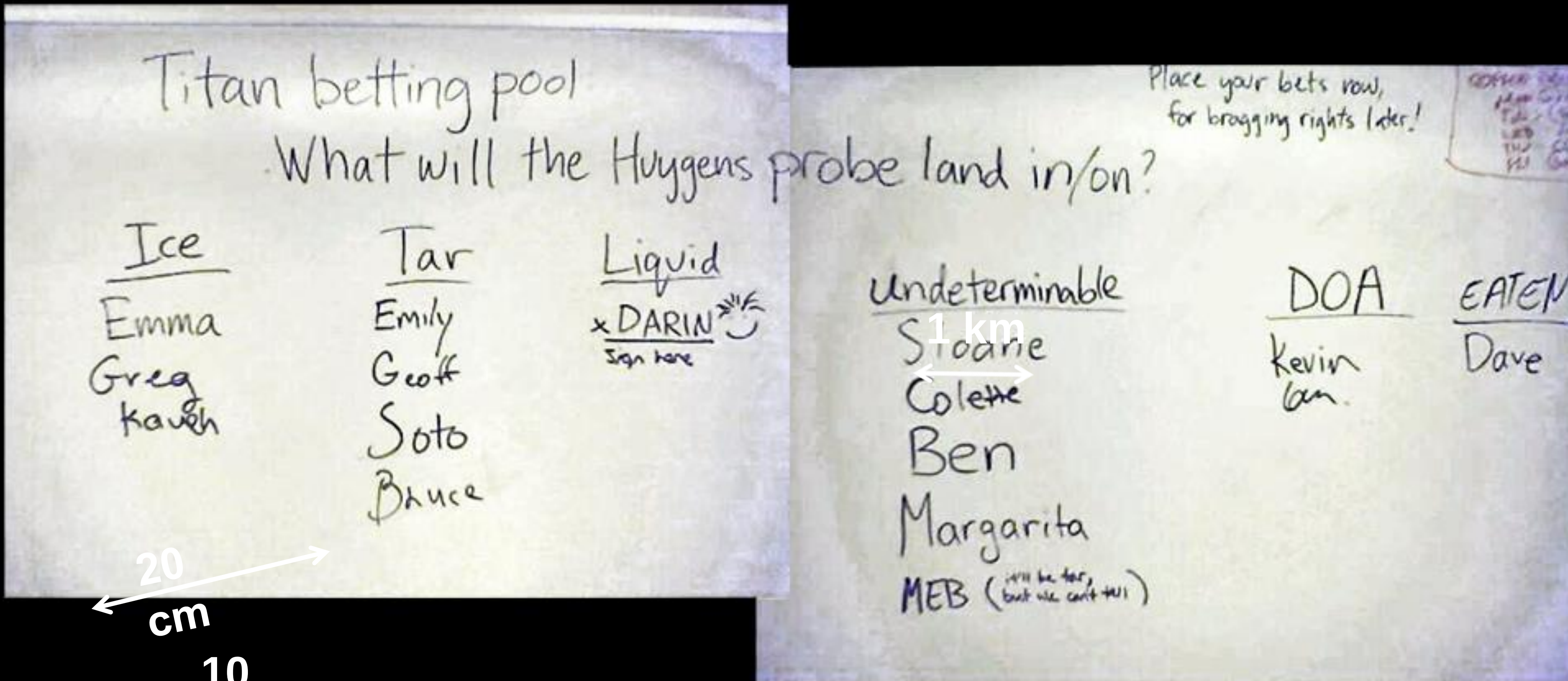
'Downhole' access to the foaming interface

Under-ice exploration of ocean ceiling

Open ocean exploration, including seafloor hydrothermal systems known to exist



Sherwood, B et al. Program options to explore ocean worlds, GLEX 2017



1 km

20 cm

10 cm

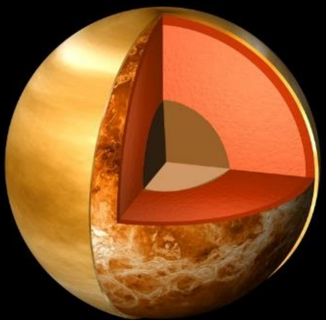
10 cm

atmospheric density at the surface

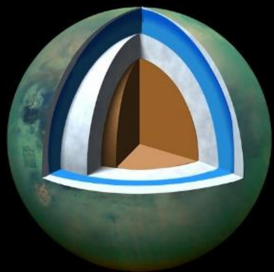
What the right model for the emergence of life?

- **Darwin's warm little ponds**
- **Sea floor hydrothermal vents**

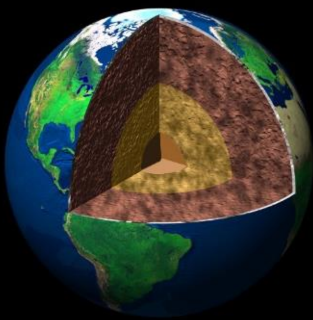
GANYMEDE



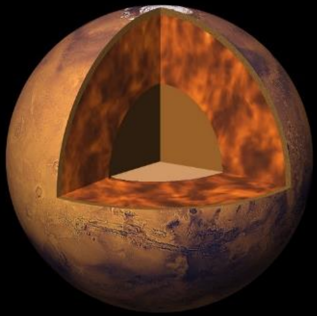
VENUS



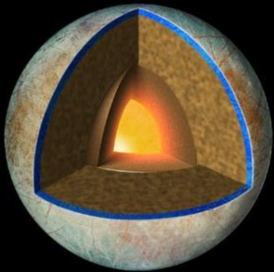
TITAN



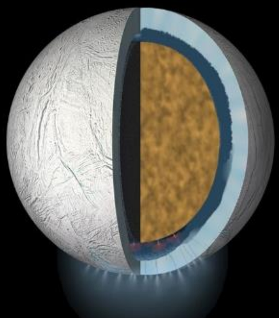
EARTH



MARS



EUROPA



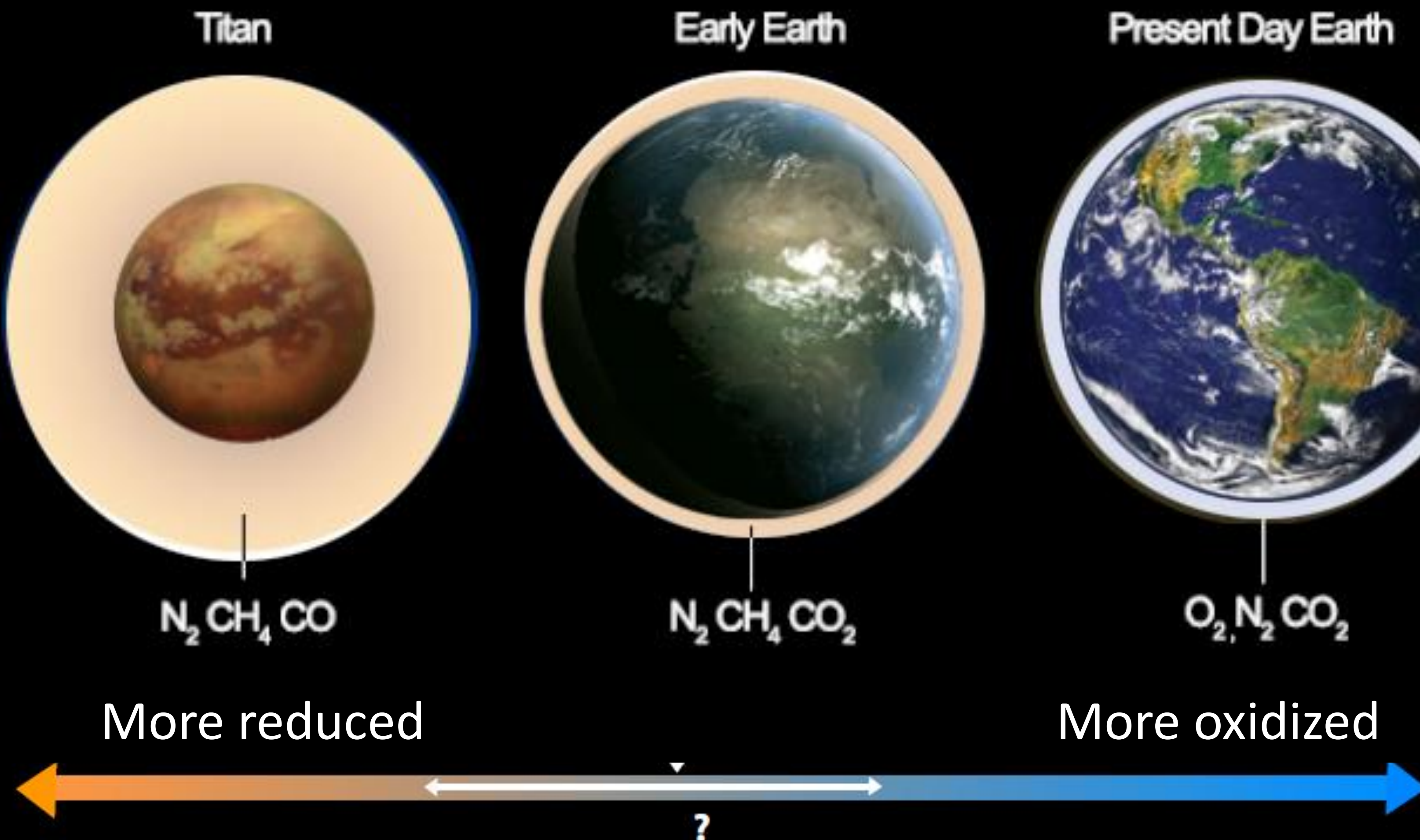
ENCELADUS

Has life emerged at the rock/ocean interface of icy moons?

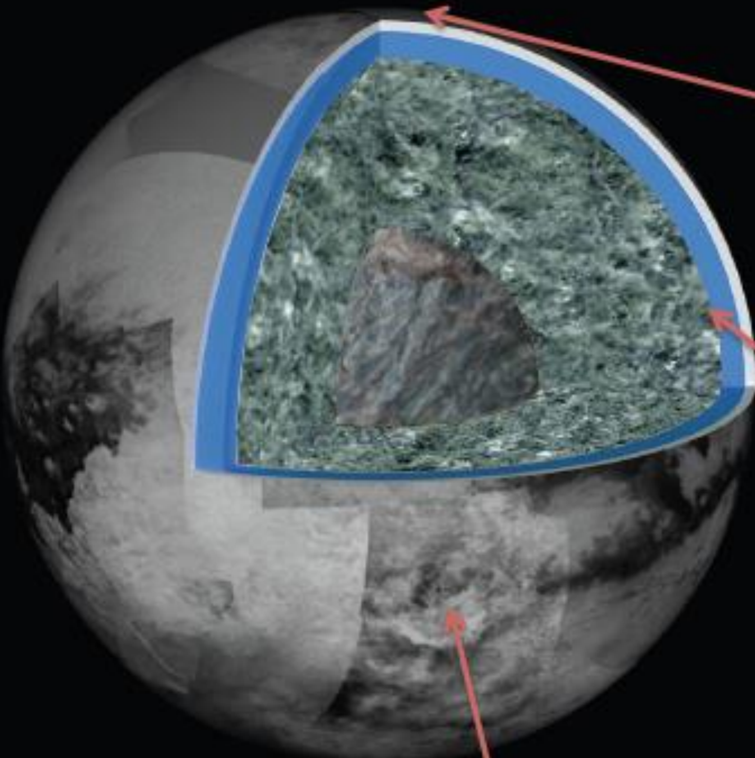
Enceladus - Europa - Titan

ocean/rock exchange

Similar organic chemistry between early Earth and Titan



Titan: Life today; life's origins



Life in the methane-ethane lakes and seas of Titan:

- --totally alien biology
- --does not violate physics
- --strict test of life's cosmic commonality

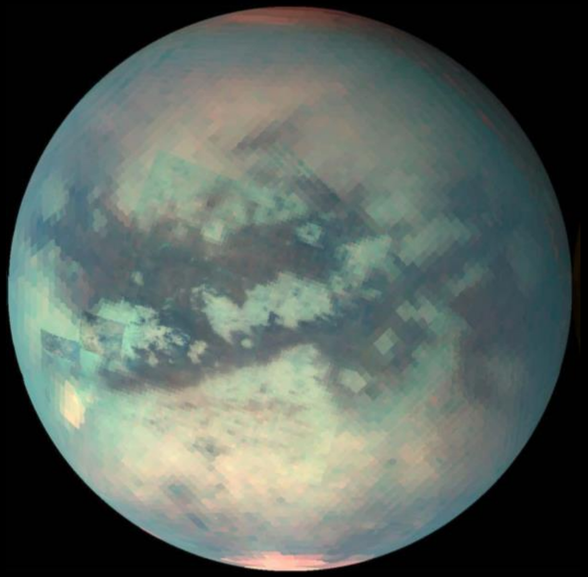
Base of the liquid water ocean: life as we know it in hydrothermal vents?

Impact craters:
Comet/asteroid impacts melt crust for hundreds to thousands of years.

- --organics evolve in water then freeze
- --experiments in origin of life preserved for study

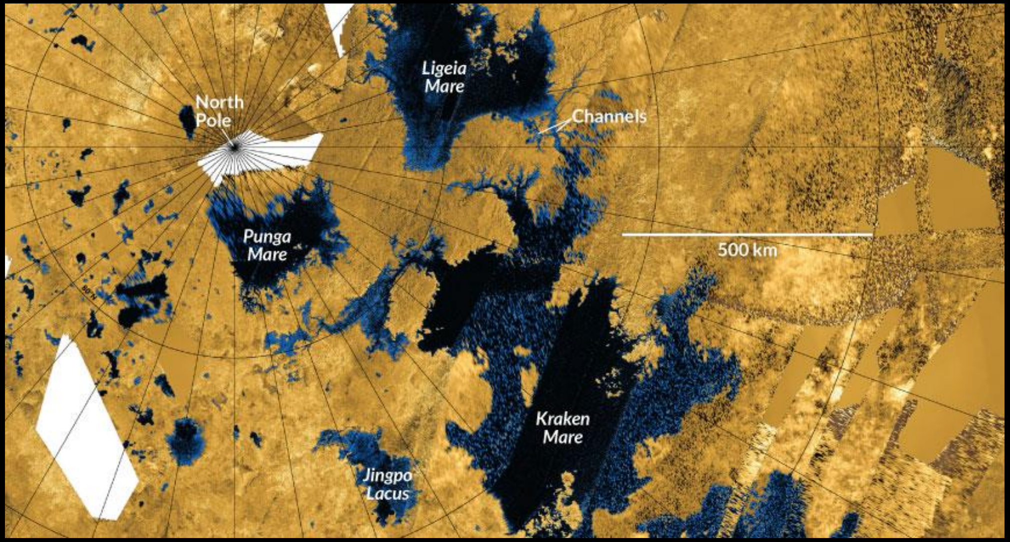
Titan is the once and future Earth

- Before Earth was a “pale blue dot” was it a pale orange dot?

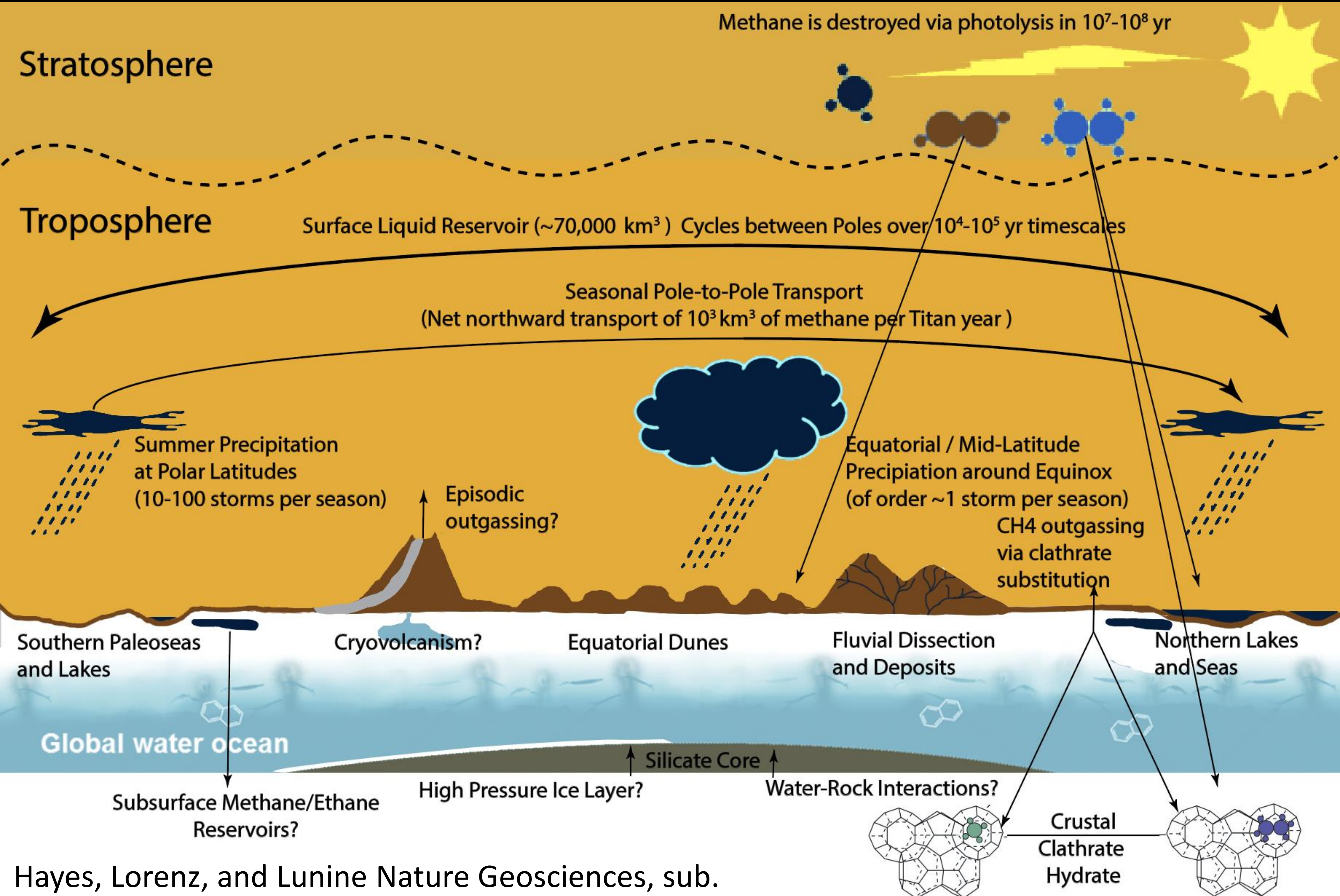


- Titan may play out in methane the post-ocean hydrologic cycle of Earth’s far future.

- A world with a subsurface ocean of (salty) water and surface seas of methane, ethane…



Titan: best place to look for weird biochemistry?



Hayes, Lorenz, and Lunine Nature Geosciences, sub.

A Titan program in three steps

Comprehensive reconnaissance of a complex world

- Atmospheric organics factory
- Global hi-res surface mapping
- Remote sense subsurface

→ Aerial exploration

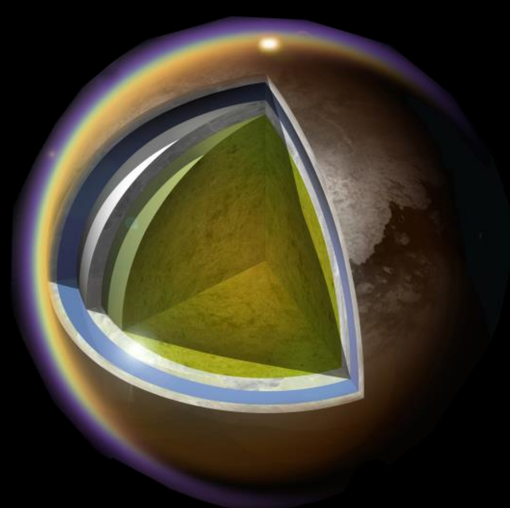
→ Buoyant sea exploration

→ Mobile surface exploration

→ In situ analysis of weathered organics

→ Sample return

→ Through-crust ocean access



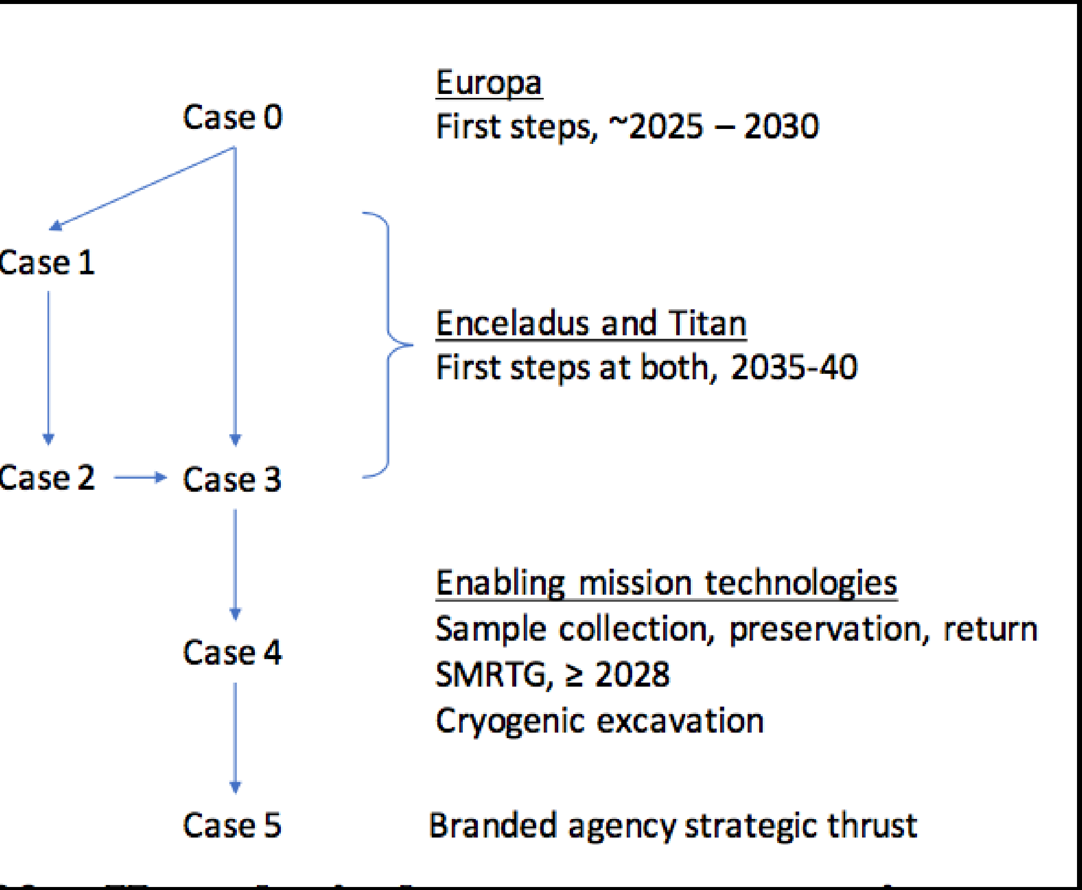
Sherwood, B et al. Program options to explore ocean worlds, GLEX 2017

Key technologies are common to all the targets (some of these not needed in early steps)

- Planetary protection of and from ocean-world material
- “Life-detection” measurement techniques and instruments
- Sample acquisition, handling, preservation
- Cryogenic mechanisms and electronics
- Modular radioisotope power systems
- Autonomous exploration that conducts science investigations

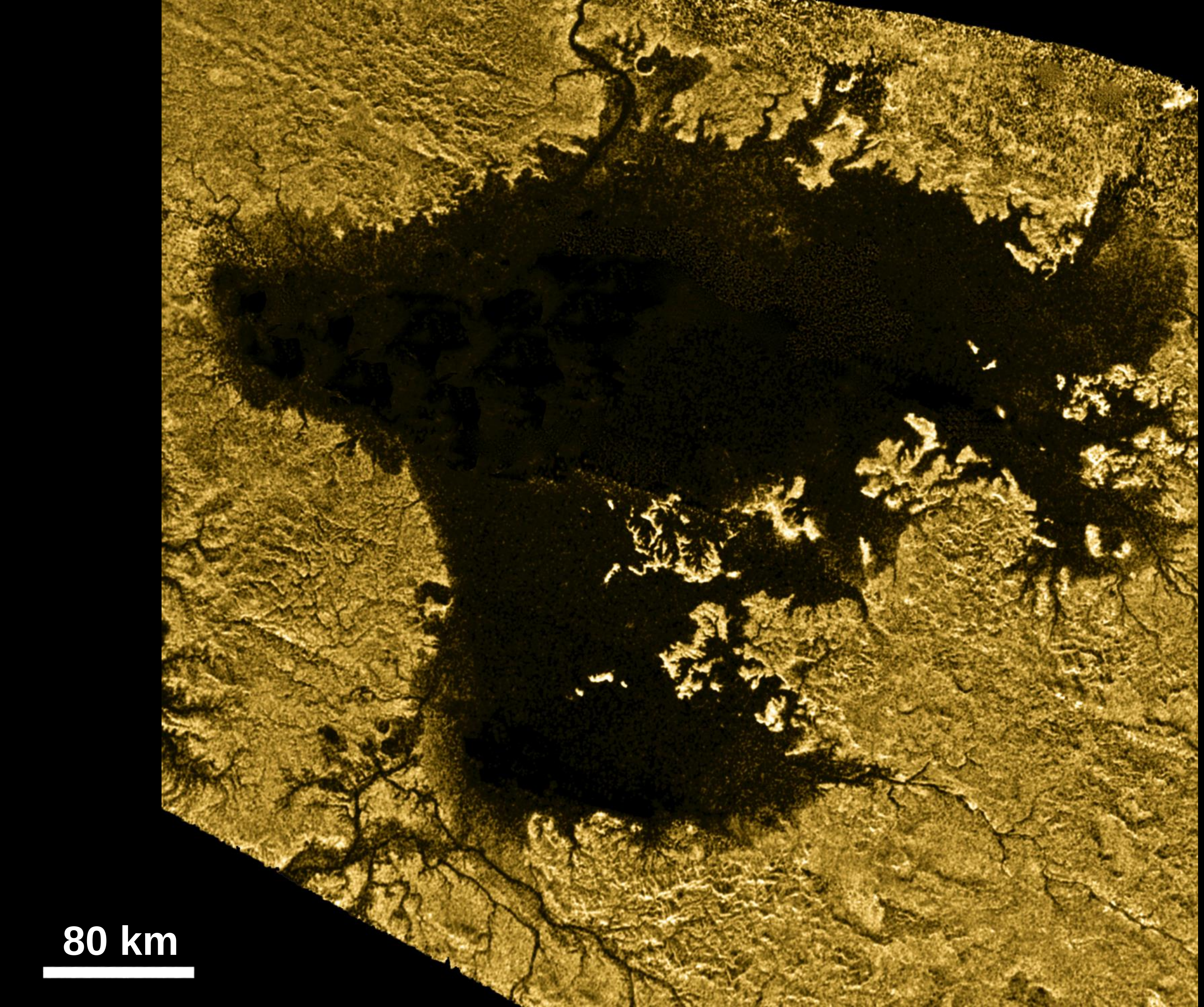
Sherwood, B et al. Program options to explore ocean worlds, GLEX 2017

Programmatic options for an OWEP



Case 0 – Status quo today
Case 1 – Select two New Frontiers missions in 2019
Case 2 – Select two New Frontiers missions every 5 years
Case 3 – Create $1B directed-purpose mission class for OW
Case 4 – Add strategically managed OW Technology Program
Case 5 – Establish a formal Ocean Worlds Exploration Program

Sherwood, B et al. Program options to explore ocean worlds, GLEX 2017



80 km