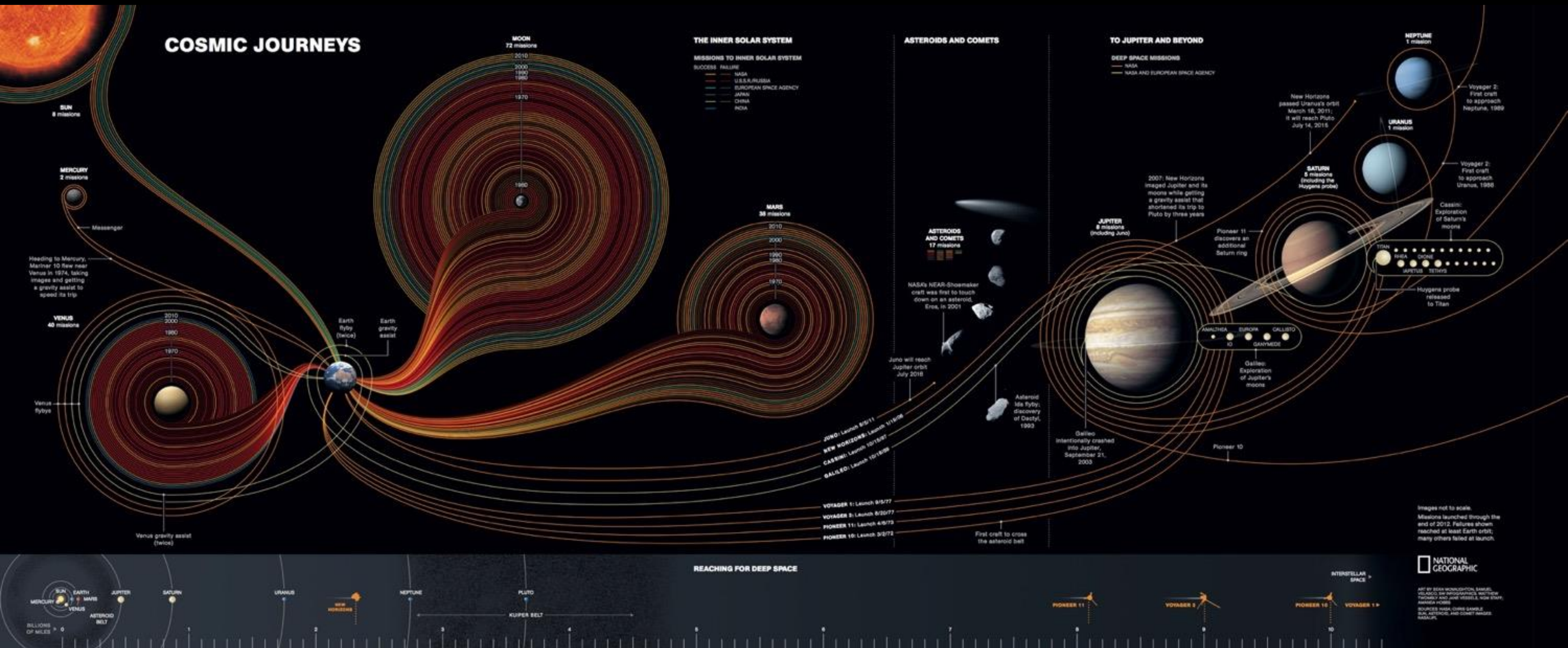
Jet Propulsion Laboratory
California Institute of Technology

On the Habitability of Ocean Worlds

Dr. Kevin Peter Hand
Jet Propulsion Laboratory

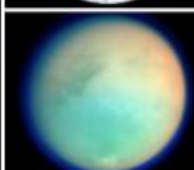


COSMIC JOURNEYS
SUN
8 missions
MERCURY
2 missions
Messenger
Heading to Mercury, Mariner 10 flew near Venus in 1974, taking images and getting a gravity assist to speed its trip
VENUS
40 missions
Venus flybys
Venus gravity assist (twice)
MOON
72 missions
MARS
38 missions
Earth flyby (twice)
Earth gravity assist
THE INNER SOLAR SYSTEM
MISSIONS TO INNER SOLAR SYSTEM
SUCCESS FAILURE
NASA
U.S.S.R./RUSSIA
EUROPEAN SPACE AGENCY
JAPAN
CHINA
INDIA
ASTEROIDS AND COMETS
ASTEROIDS AND COMETS
17 missions
NASA's NEAR-Shoemaker craft was first to touch down on an asteroid, Eros, in 2001
Juno will reach Jupiter orbit July 2016
Asteroid Ida flyby; discovery of Dactyl, 1993
First craft to cross the asteroid belt
TO JUPITER AND BEYOND
DEEP SPACE MISSIONS
NASA
NASA AND EUROPEAN SPACE AGENCY
JUPITER
8 missions
(including Juno)
2007: New Horizons imaged Jupiter and its moons while getting a gravity assist that shortened its trip to Pluto by three years
Galileo intentionally crashed into Jupiter, September 21, 2003
Galileo: Exploration of Jupiter's moons
AMALTHEA EUROPA CALLISTO
IO GANYMEDE
Pioneer 10
Pioneer 11 discovers an additional Saturn ring
SATURN
5 missions
(including the Huygens probe)
Cassini: Exploration of Saturn's moons
TITAN RHEA DIONE IAPETUS TETHYS
Huygens probe released to Titan
New Horizons passed Uranus's orbit March 18, 2011; it will reach Pluto July 14, 2015
URANUS
1 mission
Voyager 2: First craft to approach Uranus, 1986
NEPTUNE
1 mission
Voyager 2: First craft to approach Neptune, 1989
JUNO: Launch 8/5/11
NEW HORIZONS: Launch 1/19/06
CASSINI: Launch 10/15/97
GALILEO: Launch 10/18/89
VOYAGER 1: Launch 9/5/77
VOYAGER 2: Launch 8/20/77
PIONEER 11: Launch 4/6/73
PIONEER 10: Launch 3/2/72
Images not to scale.
Missions launched through the end of 2012. Failures shown reached at least Earth orbit; many others failed at launch.
REACHING FOR DEEP SPACE
SUN EARTH MARS MERCURY VENUS ASTEROID BELT JUPITER SATURN URANUS NEW HORIZONS NEPTUNE PLUTO KUIPER BELT
PIONEER 11 VOYAGER 2 PIONEER 10 VOYAGER 1
INTERSTELLAR SPACE
BILLIONS OF MILES 0 1 2 3 4 5 6 7 8 9 10
NATIONAL GEOGRAPHIC

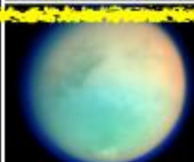
Ocean Worlds

Shown to scale

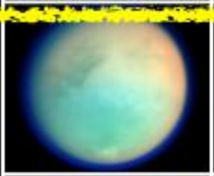
Ocean Worlds

Moon	Name, Planet	Geophysically & Geochemically Plausible?	Significant tidal energy to help maintain ocean?	Induced Magnetic Field?	Activity Observed?	Ocean in contact with rock?
	Europa, Jupiter	Yes	Yes	Yes	No (?)	Yes
	Ganymede, Jupiter	Yes	~Yes	Yes	No	No
	Callisto, Jupiter	Yes	No	Yes	No	No
	Enceladus, Saturn	???	???	???	Yes!	Yes!
	Titan, Saturn	Yes	No	???	???	No
	Triton, Neptune	Yes?	No	???	Yes	No

Ocean Worlds

Moon	Name, Planet	Geophysically & Geochemically Plausible?	Significant tidal energy to help maintain ocean?	Induced Magnetic Field?	Activity Observed?	Ocean in contact with rock?
	Europa, Jupiter	Yes	Yes	Yes	No (?)	Yes
	Ganymede, Jupiter	Yes	~Yes	Yes	No	No
	Callisto, Jupiter	Yes	No	Yes	No	No
	Enceladus, Saturn	???	???	???	Yes!	Yes!
	Titan, Saturn	Yes	No	???	???	No
	Triton, Neptune	Yes?	No	???	Yes	No

Ocean Worlds

Moon	Name, Planet	Geophysically & Geochemically Plausible?	Significant tidal energy to help maintain ocean?	Induced Magnetic Field?	Activity Observed?	Ocean in contact with rock?
	Europa, Jupiter	Time: Persistently Habitable? Yes.		Yes	No (?)	Yes
	Ganymede, Jupiter	Yes	~Yes	Yes	No	No
	Callisto, Jupiter	Yes	No	Yes	No	No
	Enceladu Saturn	Time: Persistently Habitable? TBD		??	Yes!	Yes
	Titan, Saturn	Yes	No	???	???	No
	Triton, Neptune	Yes?	No	???	Yes	No

Separate Origins in the Outer Solar System

5 My after launch from Earth:

Titan: ~3-20 rocks delivered

Europa: 30-100 rocks delivered

(out of 600 million)

Impact velocity

Titan: 10-15 km s^{-1} (atm)

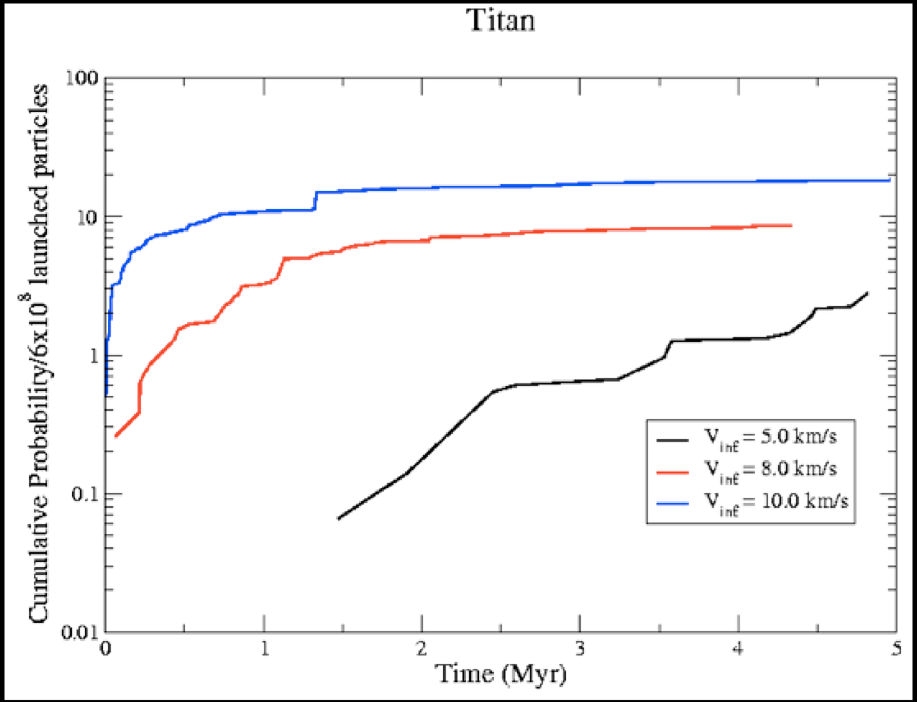
Europa: 20-30 km s^{-1}

Comparison: Earth to Mars during the first 0.5 Ga and arriving within 0.33 Ma of ‘launch’:

~ 10^8 ejecta (r = 0-2.67m)

~ 10^{11} kg total

Mileikowsky et al. 2000



Gladman et al. 2006

Prospect of extant life living in an environment that has not been exposed to Earth (or Martian) life.

Comparative Origins

Contingent vs Convergent *Chemical Evolution*

<u>Primordial Soup</u>
Continents
Sun
Tides
Hot Springs
...

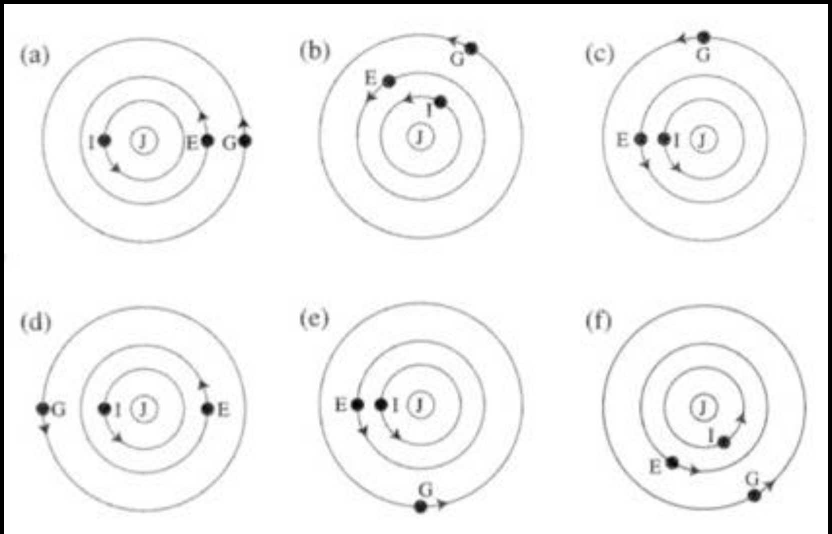
<u>Hydrothermal</u>
Deep Ocean
Fe-S
Alkaline
High/Low-T
...

Second data point

<u>Cold/Ice</u>
Faint young Sun
Sea ice
Subglacial Lakes
Snowball Earth
Much to be explored

<u>Transfer</u>
Little Utility

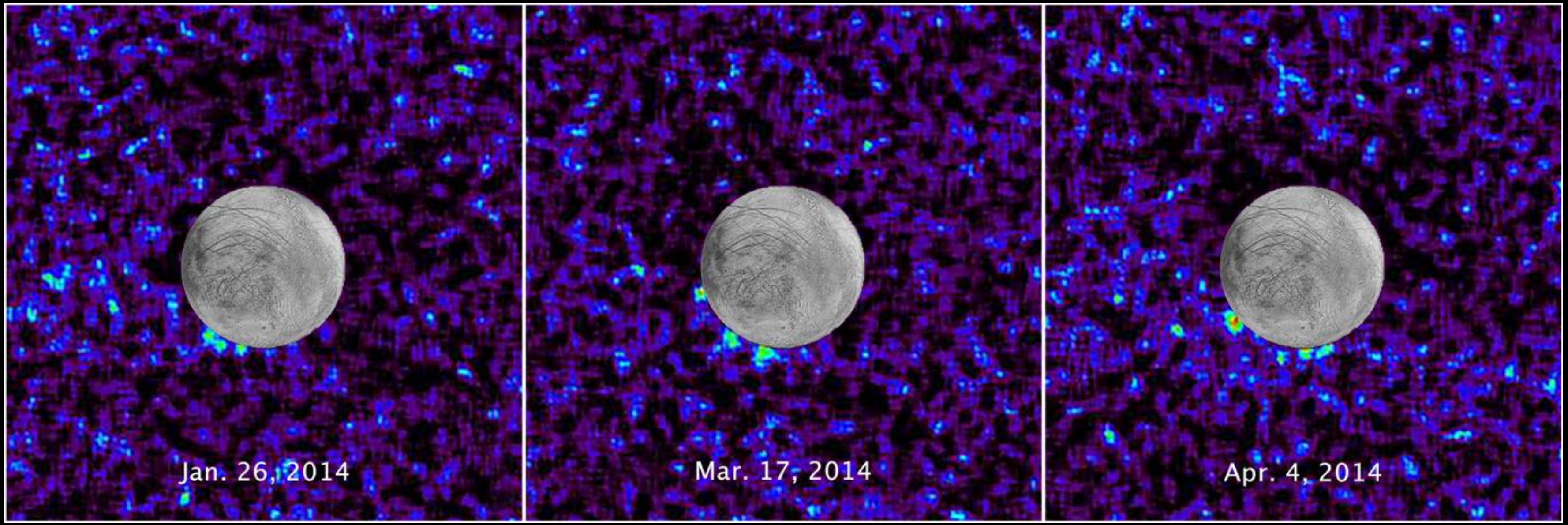
Liquid Water



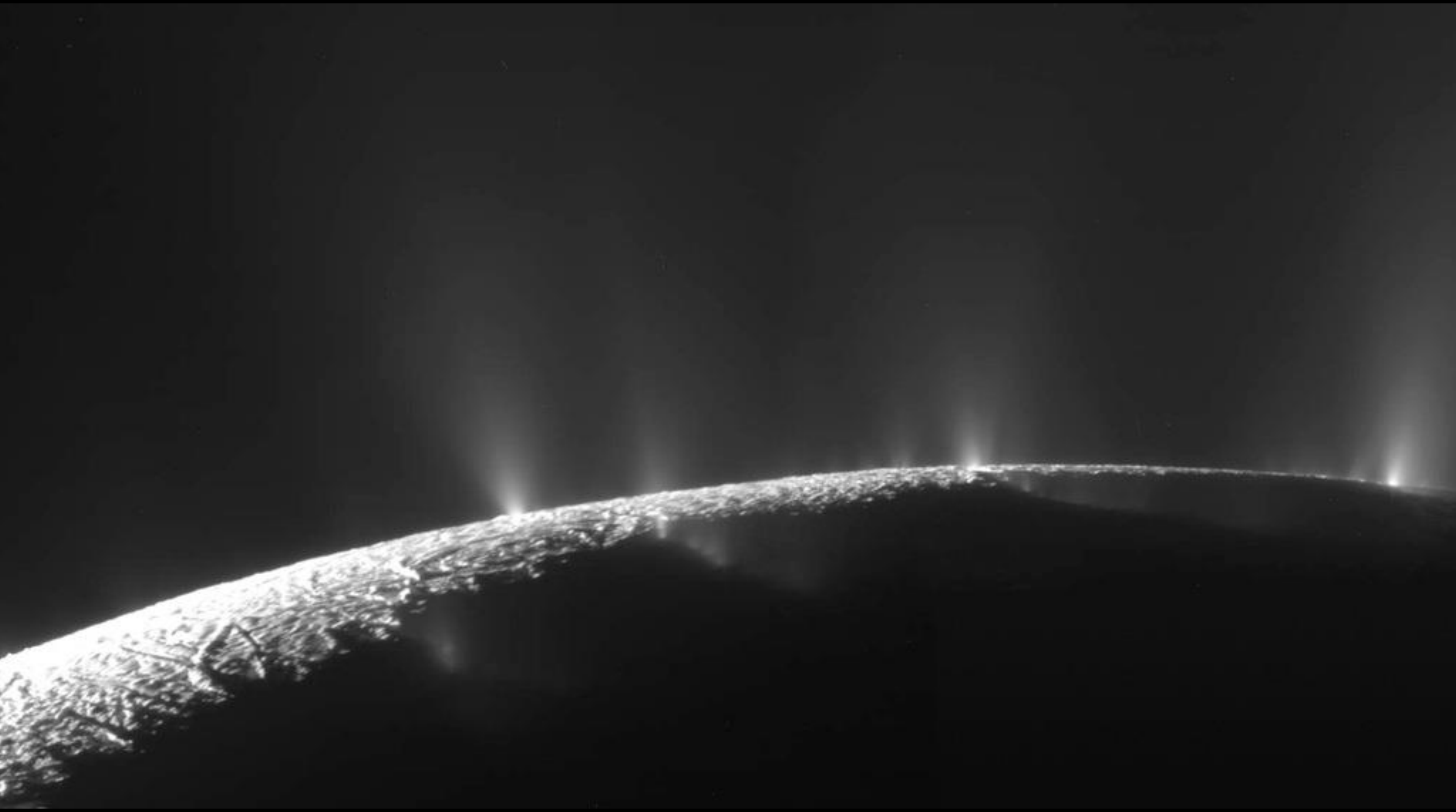
	Global heat production (W)	Average flux (mW m^{-2})	Comments	References
Earth	$3.2x10^{13}$	60-80	For Earth seafloor only. Approximately $1.1x10^{12}$ (34%) is concentrated around hydrothermal vents	Stein and Stein, 1994
Io	$2x10^{14}$	2500	Fresh lavas are estimated to reach temperatures of >1600 K	Veeder et al., 1994; Spencer et al., 2000; Geissler, 2003; Davies et al., 2001
Europa	10^{11}-10^{13}	10-800	Modeled range includes radiogenic only to full tidal dissipation in the ice shell and mantle	Moore & Hussman, 2009; Hussman et al., 2002
Moon	2.8-4.1 $x10^{11}$	9-13	Based on Apollo 15 & 17 in situ measurements	Siegler & Smrekar, 2014

Possible HST detection of water plumes on Europa

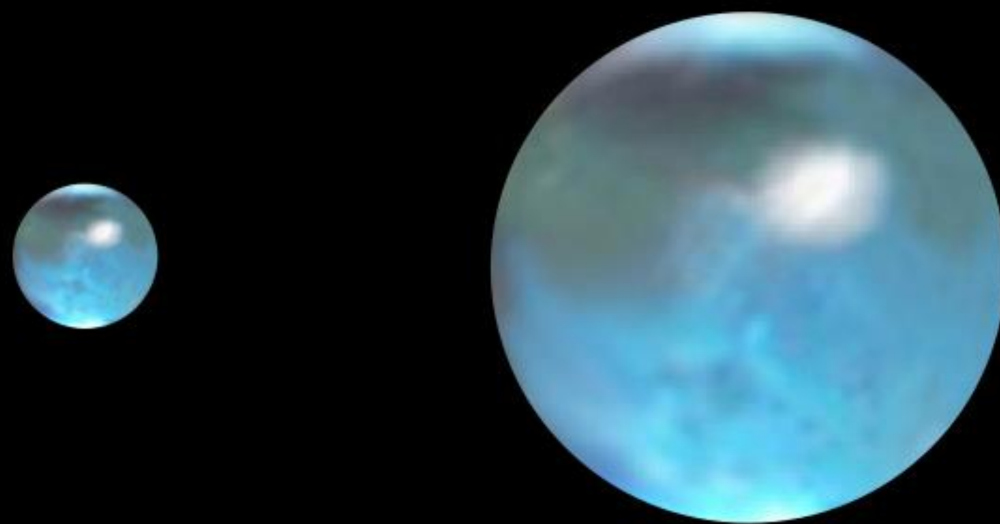
Anomalies on 3 of 10 transits



Sparks et al. 2016

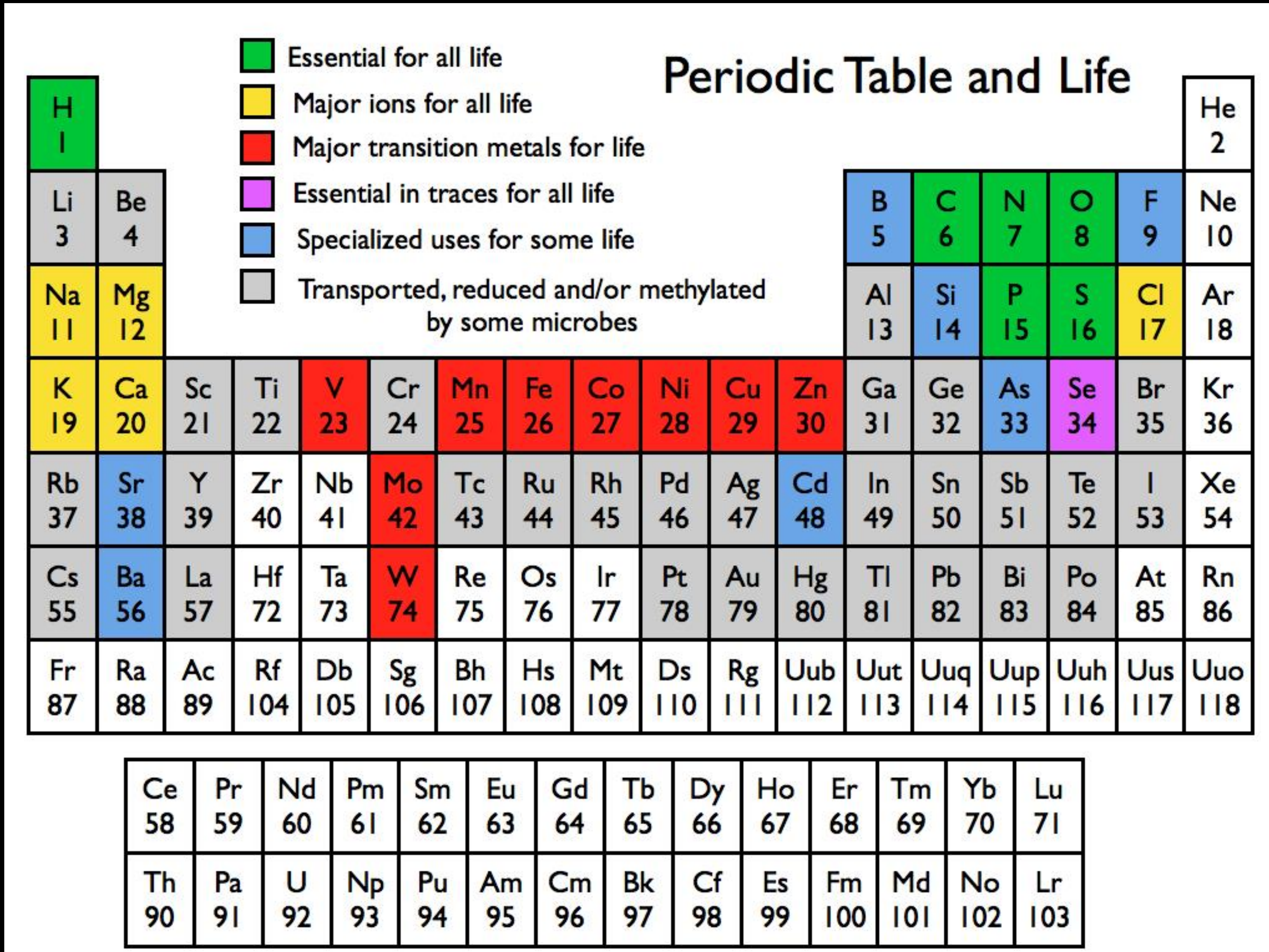



Janus
Epimetheus
Cassini Saturn Orbit Insertion
Ring Plane Crossing
Cassini
Division
Encke
Division
(Pan)
D
ring
C ring
B ring
A ring
(outer edge: Atlas)
F ring
(Prometheus,
Pandora)
G ring
Mimas
Enceladus
Tethys
Dione
Rhea
E ring
(to Titan)
Titan
Hyperion
Iapetus
Phoebe
NASA/JPL

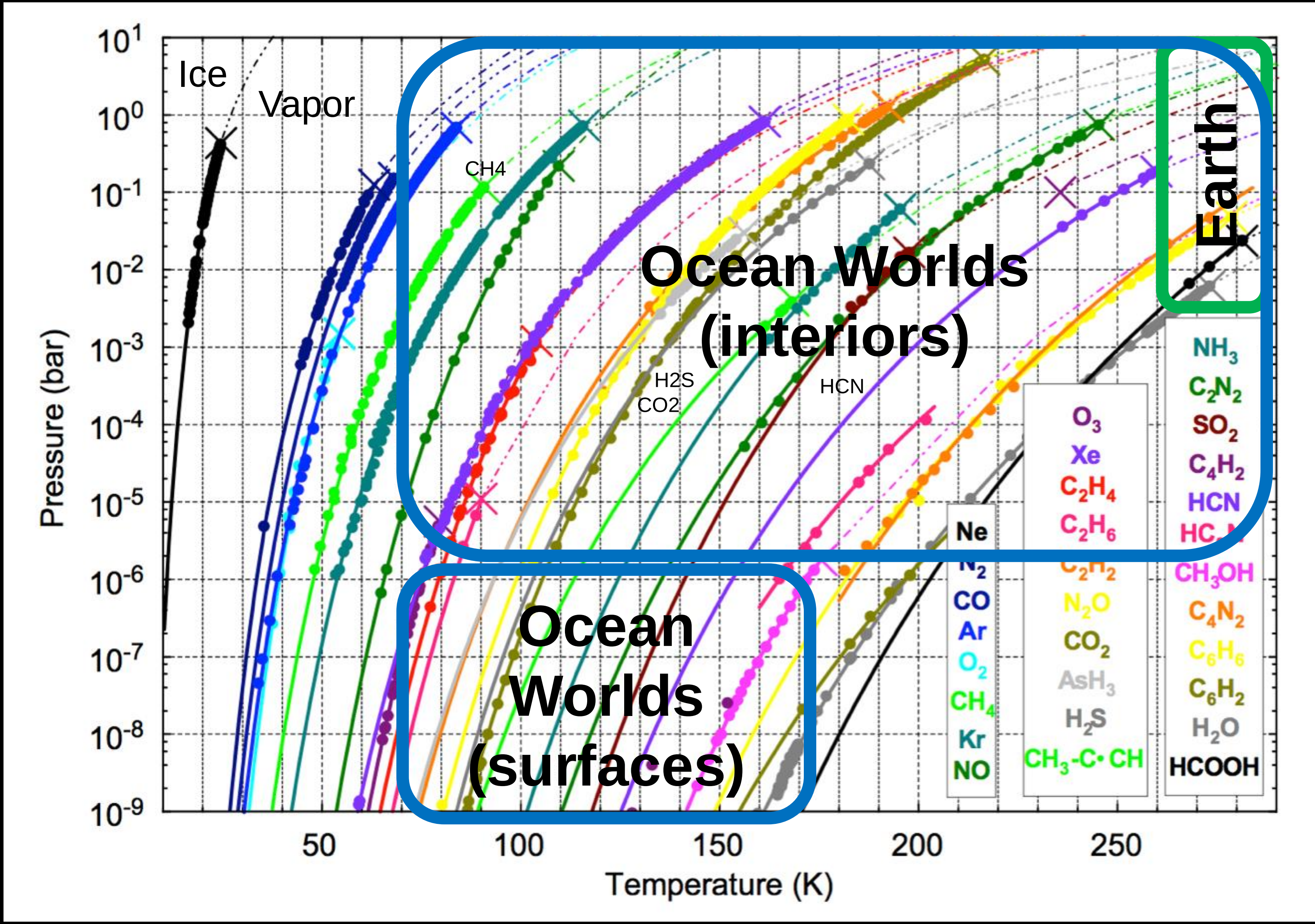


Ocean Worlds

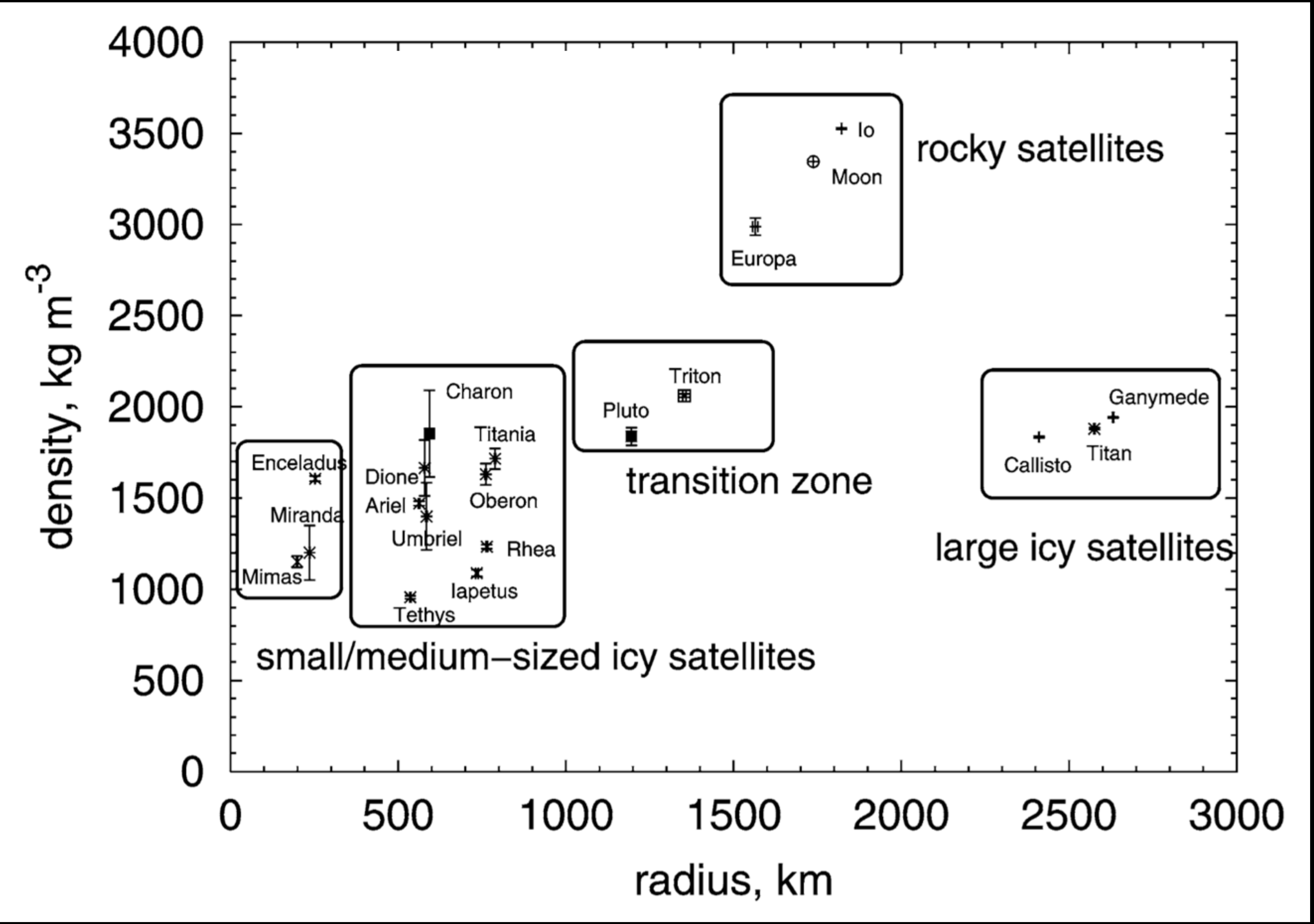
Elements



Adapted from Wackett et al. (2004)



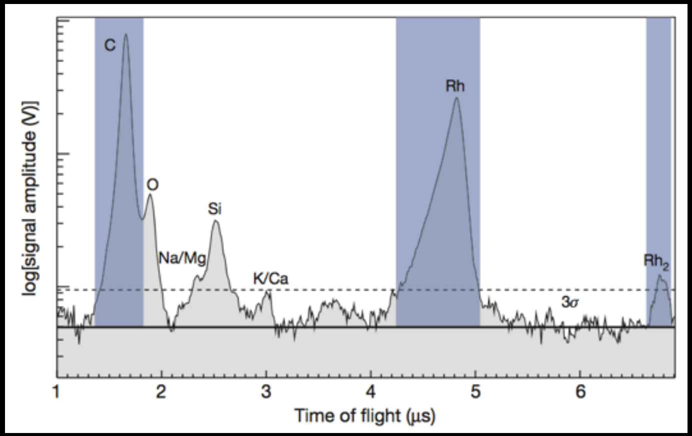
Fray & Schmitt (2009)

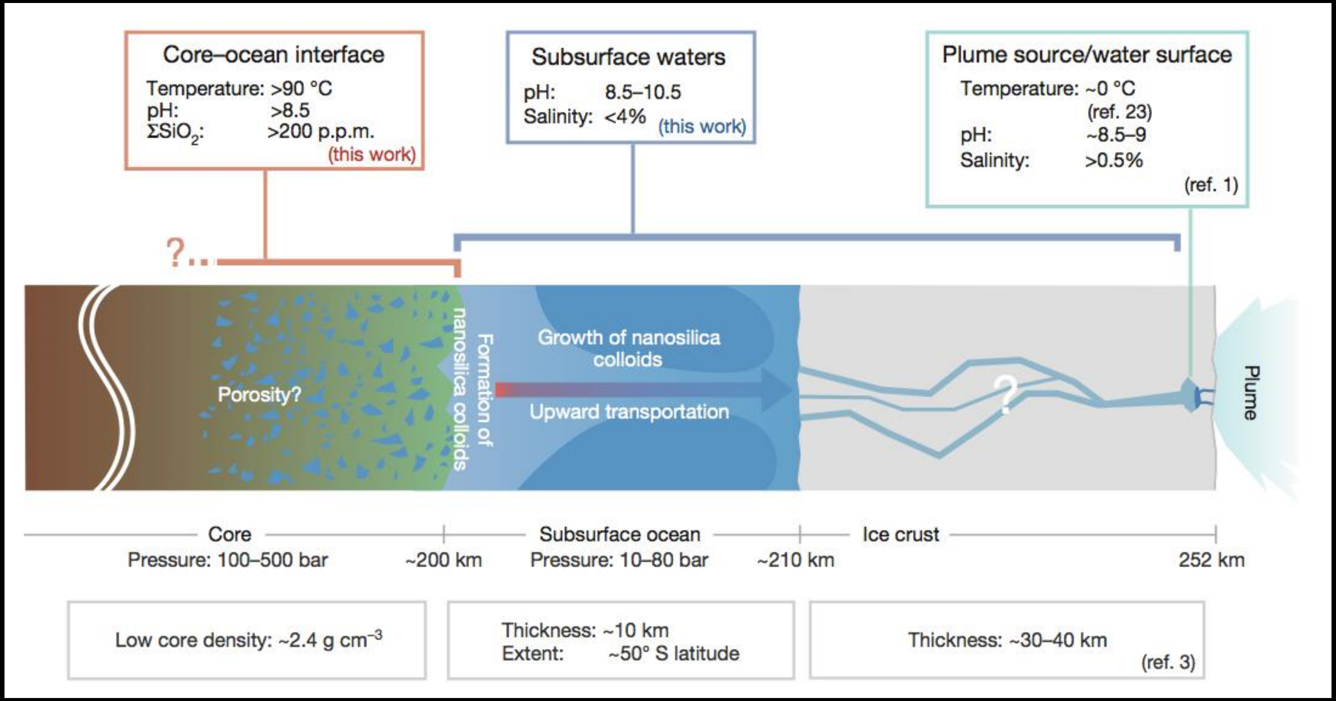


Hussmann et al. (2006)

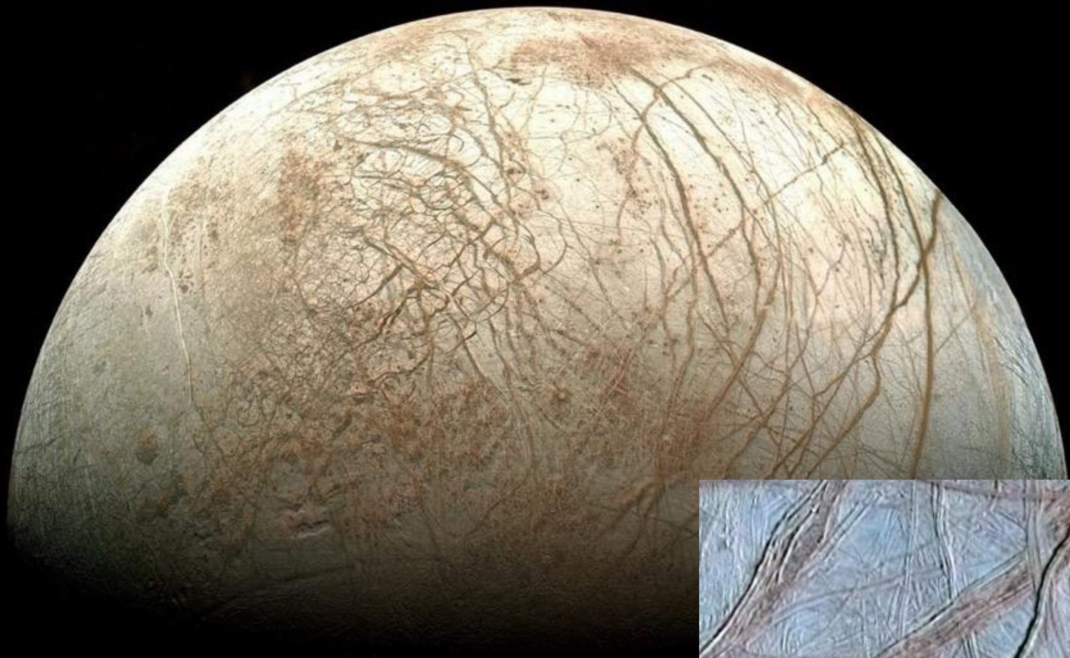
Water/Rock Interaction: SiO_2 in Enceladus' ice grains

Possibly resulting from low temperature, alkaline hydrothermalism.





Hsu et al., 2015

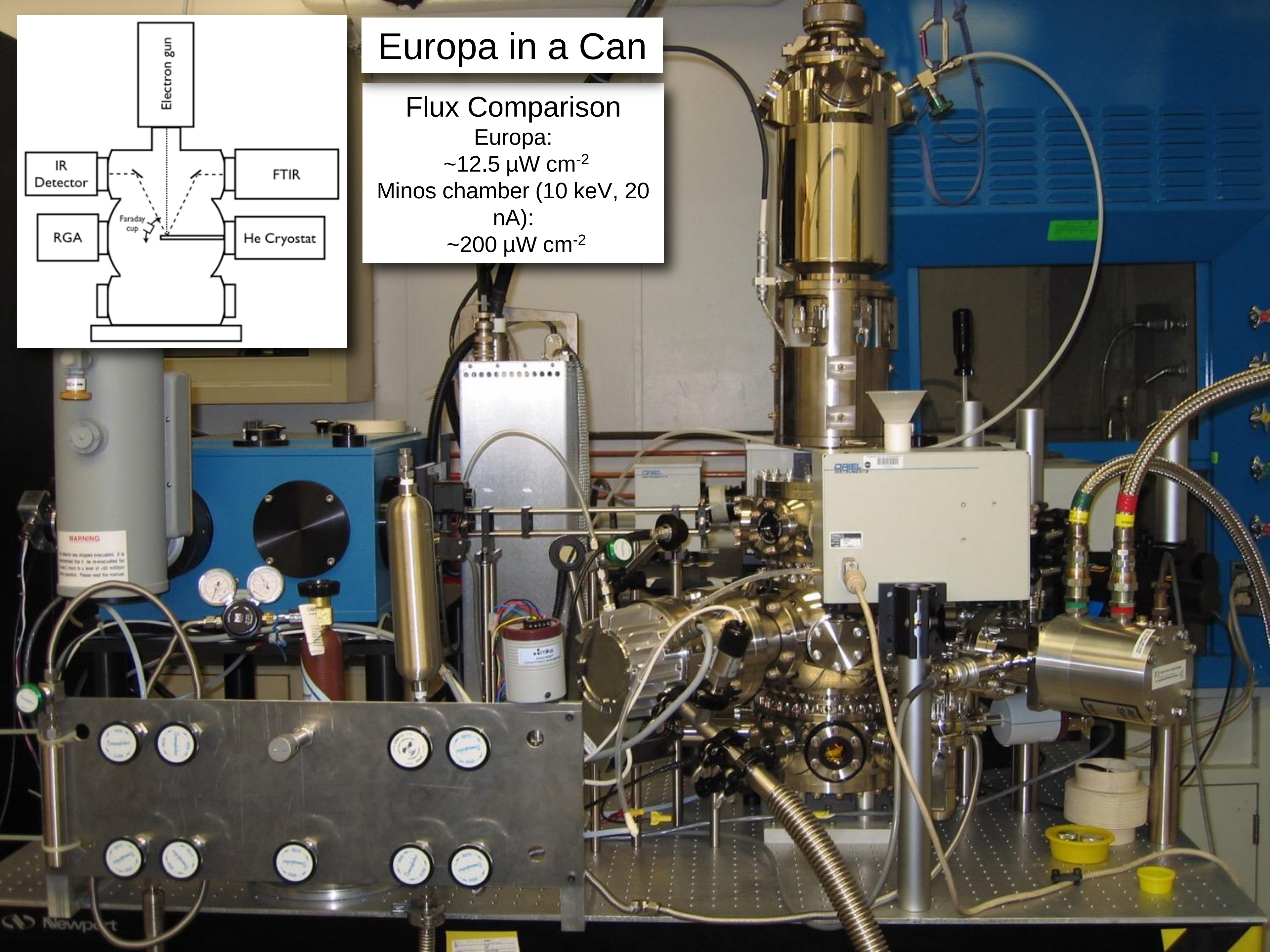


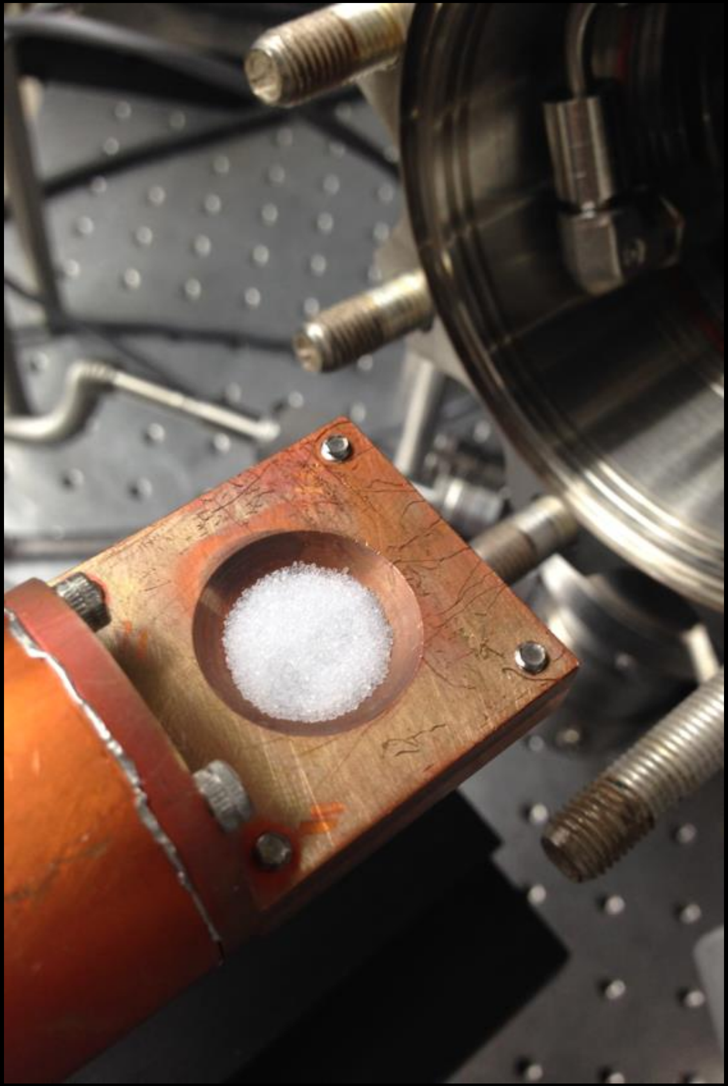
Europa

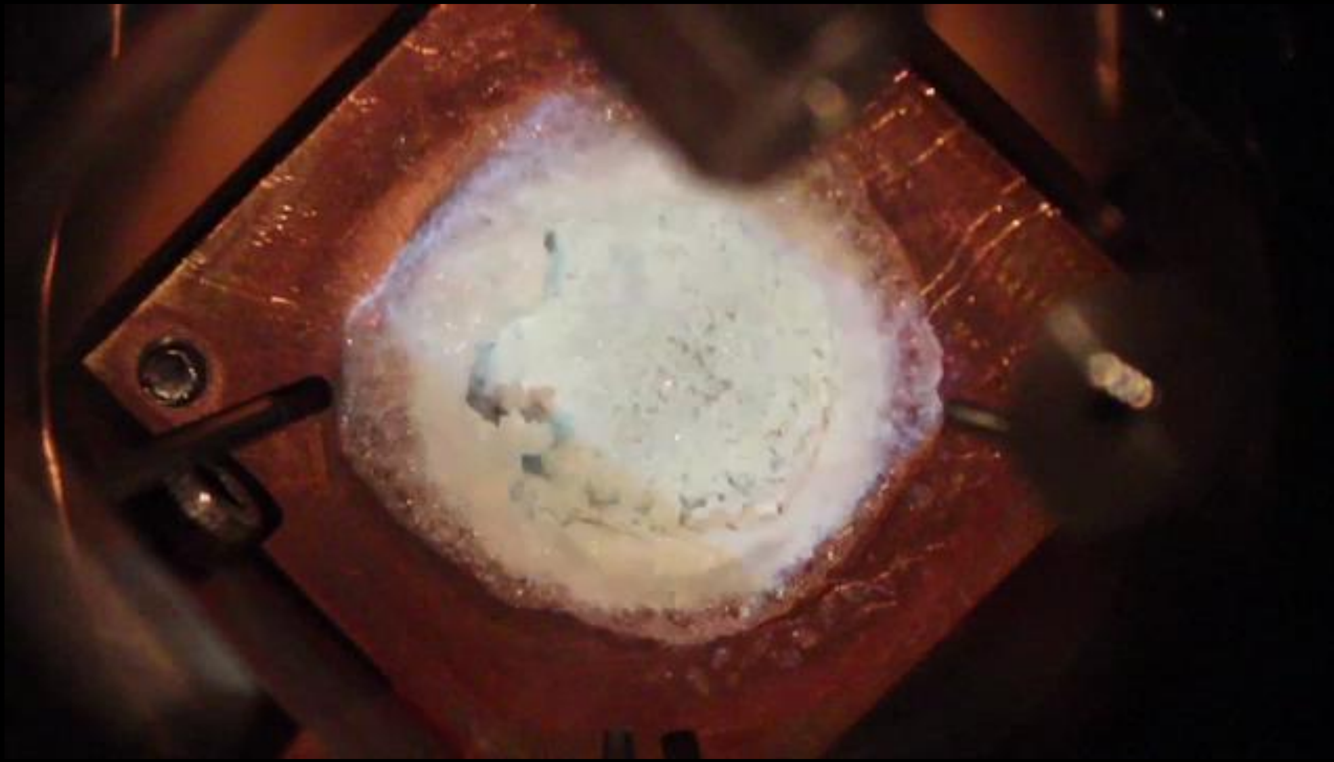
Europa in a Can

Flux Comparison

Europa:
~12.5 µW cm^{-2}
Minos chamber (10 keV, 20 nA):
~200 µW cm^{-2}





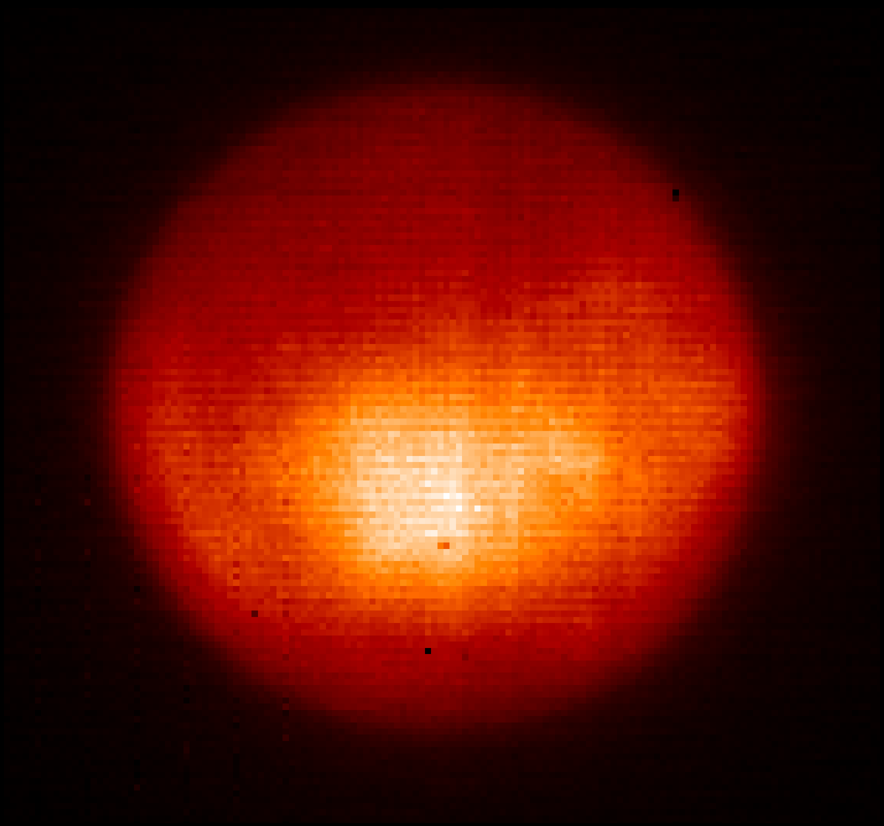


NaCl evaporite. T = 100 K, P = 1e-9 Torr, 10 keV electrons

Sodium chloride brine evaporite post-irradiation

Hand & Carlson, 2014

JPL



Fischer, Brown, & Hand, 2015

Energy

Energetic Limits on Life

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

$$\Delta G = -10.6 \pm 0.7 \; kJmol^{-1}$$

$$SO_4^{2-} + 4H_2 \rightarrow S^{2-} + 4H_2O$$

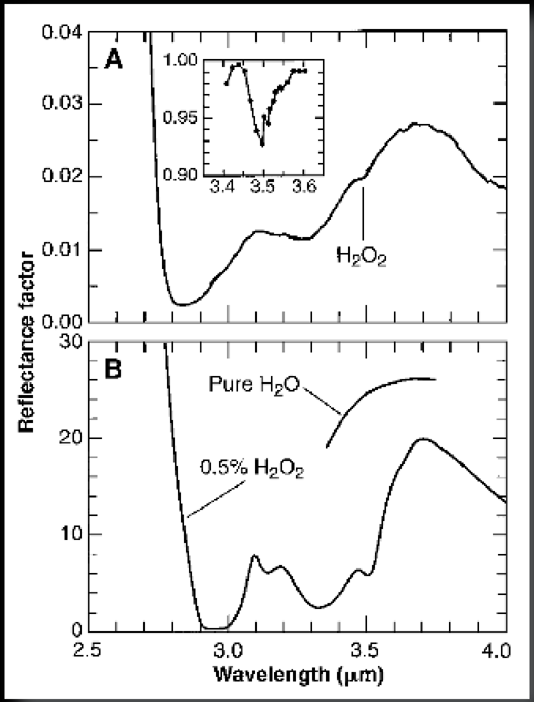
$$\Delta G = -19.1 \pm 1.7 \; kJmol^{-1}$$

1 bar, 22 °C

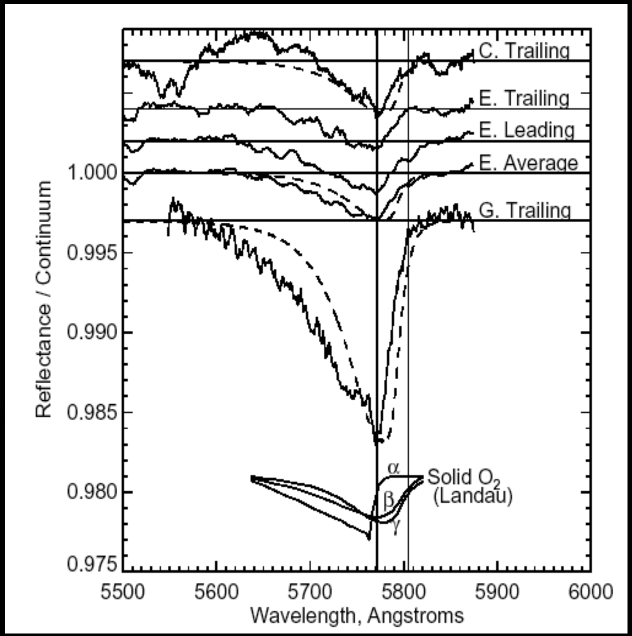
Hoehler et al. 2001

JPL

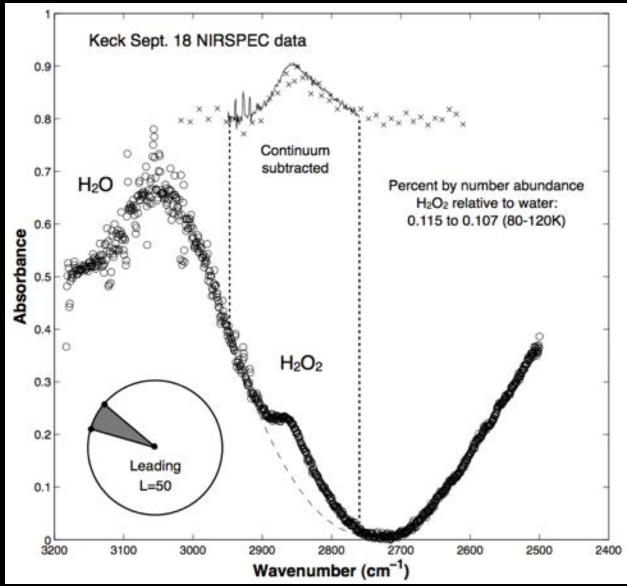
Oxidant production via Radiolysis



Carlson et al. 1999



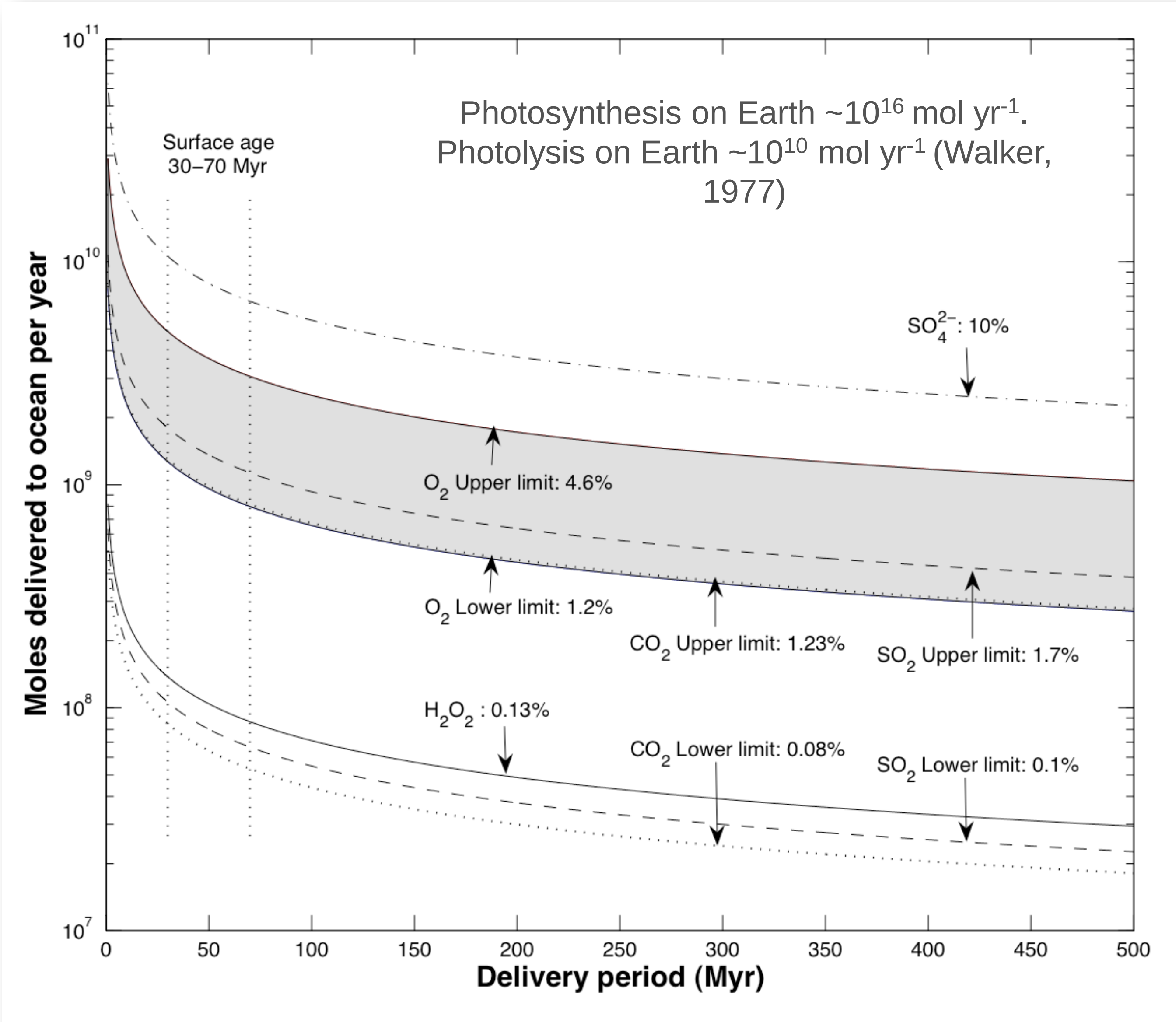
Spencer & Calvin 2002



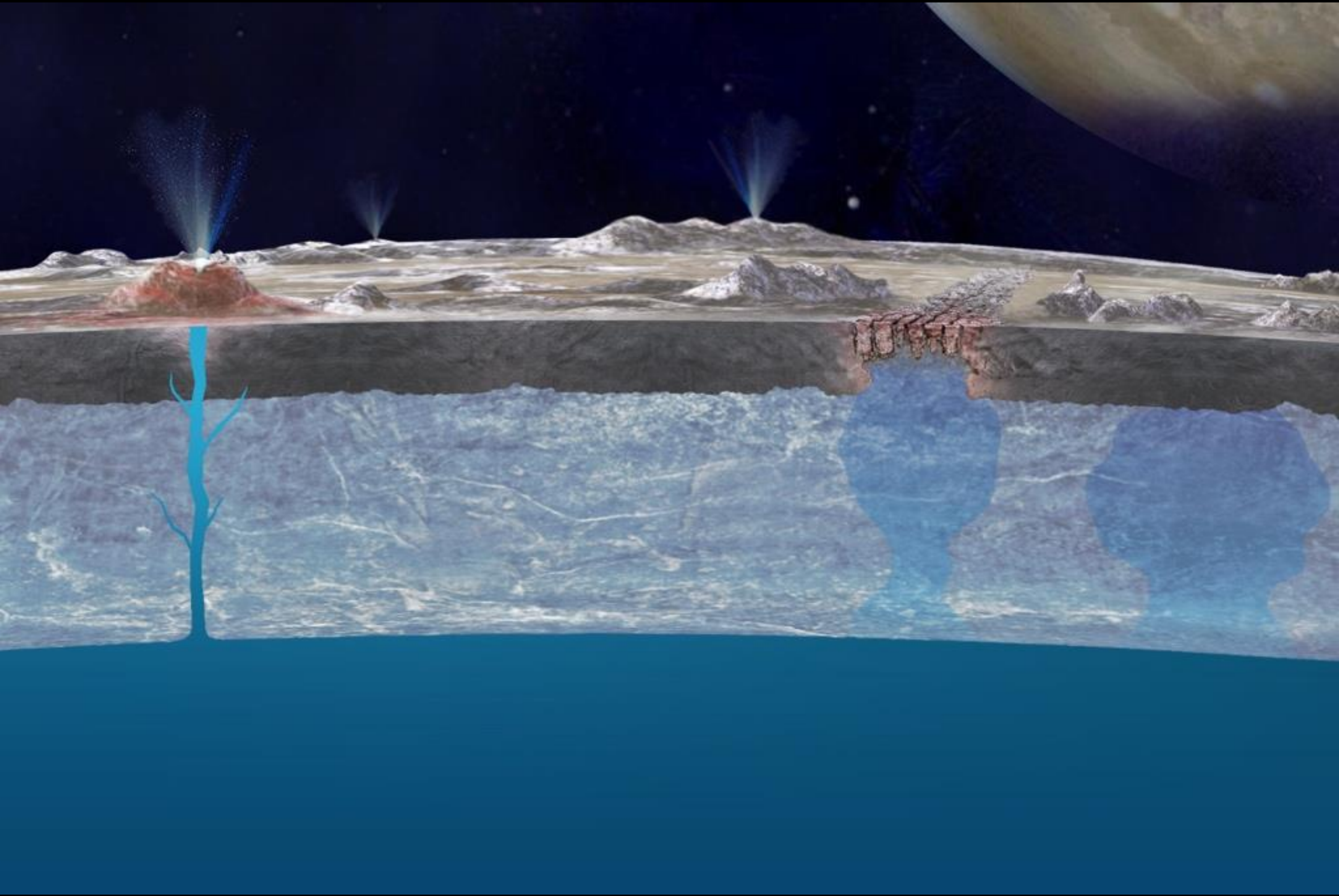
Hand & Brown 2013

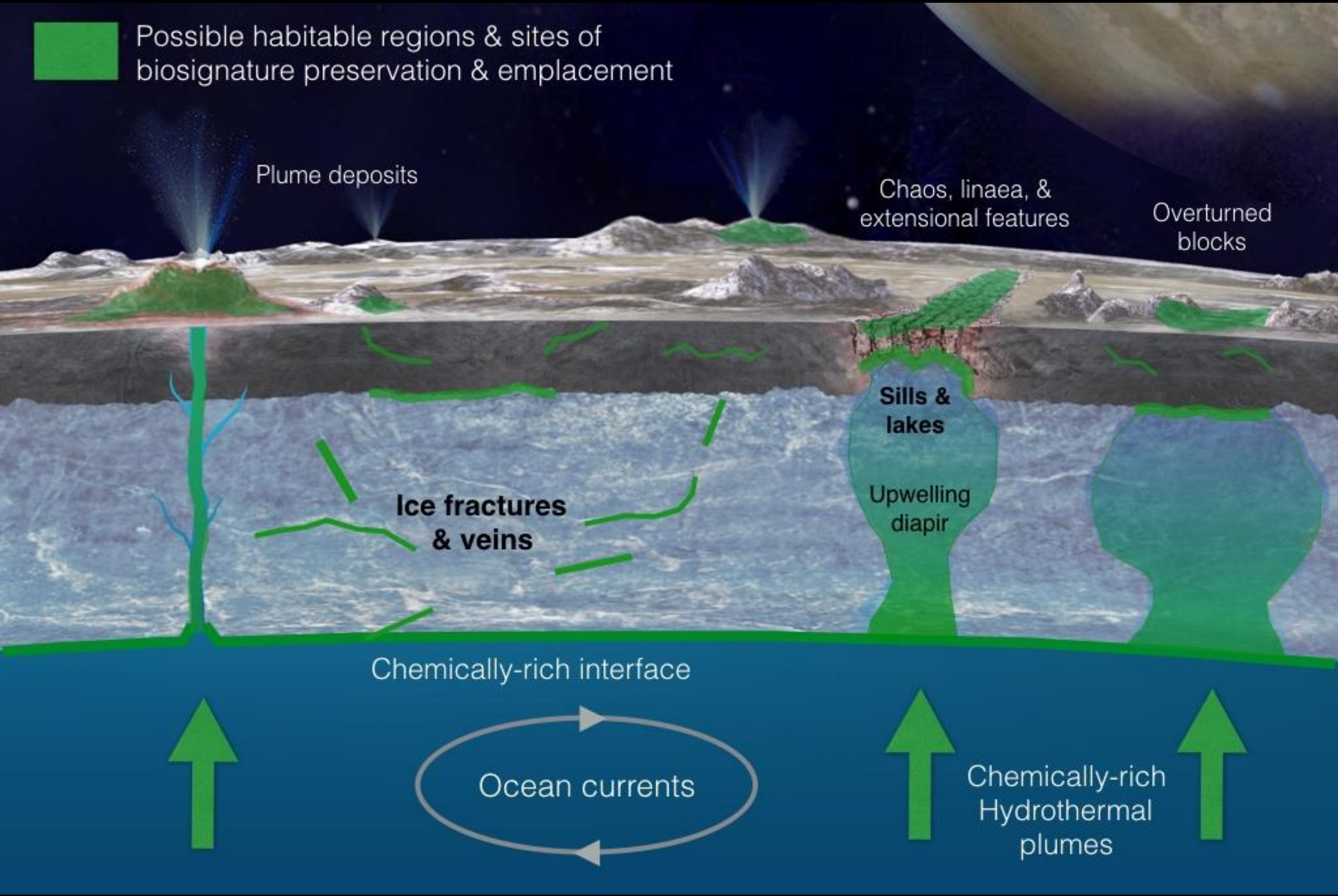
Observed oxidants on Europa: Oxygen, Peroxide, Ozone, Sulfate, Carbon dioxide, Sulfur dioxide.

Flux of radiolytically produced oxidants



Hand et al. (2007; 2009)




Possible habitable regions & sites of biosignature preservation & emplacement
Plume deposits
Chaos, linaea, & extensional features
Overturned blocks
Sills & lakes
Upwelling diapir
Ice fractures & veins
Chemically-rich interface
Ocean currents
Chemically-rich Hydrothermal plumes

Biosignatures across Space & Time

Target	Habitable environments	Investigation technique	Phase	Biosignature expression	Biosignature Age	Biosignature preservation considerations
Mars	Ancient lakes, seas, rivers; Possibly modern subsurface regions.	Remote + in situ	Solid (silicates) + Gas if modern	Sedimentary rock record; Atmosphere if modern component exists.	~3 Gya silicates and salts (though possible modern component).	~260-300 K depositional environments followed by highly variable lithification processes; Strong link to processes studied on Earth.
Ocean worlds	Subsurface oceans, sills, lakes, and ice veins.	Remote + in situ	Solid (water ice)	Surface emplacement of habitable liquid water regions (plumes, tectonics).	Modern to <100 My	~100 K surfaces provide strong preservation but subject to radiolytic modification.
Exoplanets	Surface oceans, continents, subsurface regions.	Remote	Gas	Biological modification of atmospheric and surface composition.	Modern	Highly variable depending on balance between biological and geological activity of planet.

Ocean Worlds

- Science
  - Ocean worlds are possibly the best place to search for extant (living) life and a second, independent origin.
  - We are on the brink of revolutionizing biology.
  - Comparative oceanography (Earth, Europa, Enceladus, Titan) will spark new discoveries and insights regardless of habitability.
- Technology
  - Convergence of launch vehicle, propulsion, landing, and instrumentation needs.
  - Diversity of mission options: some low-cost missions (Titan lake landers, Enceladus plume fly-through) and some larger mission (Europa melt-probes).
  - Win-win of exploring Earth as a bridge to exploring ocean moons.

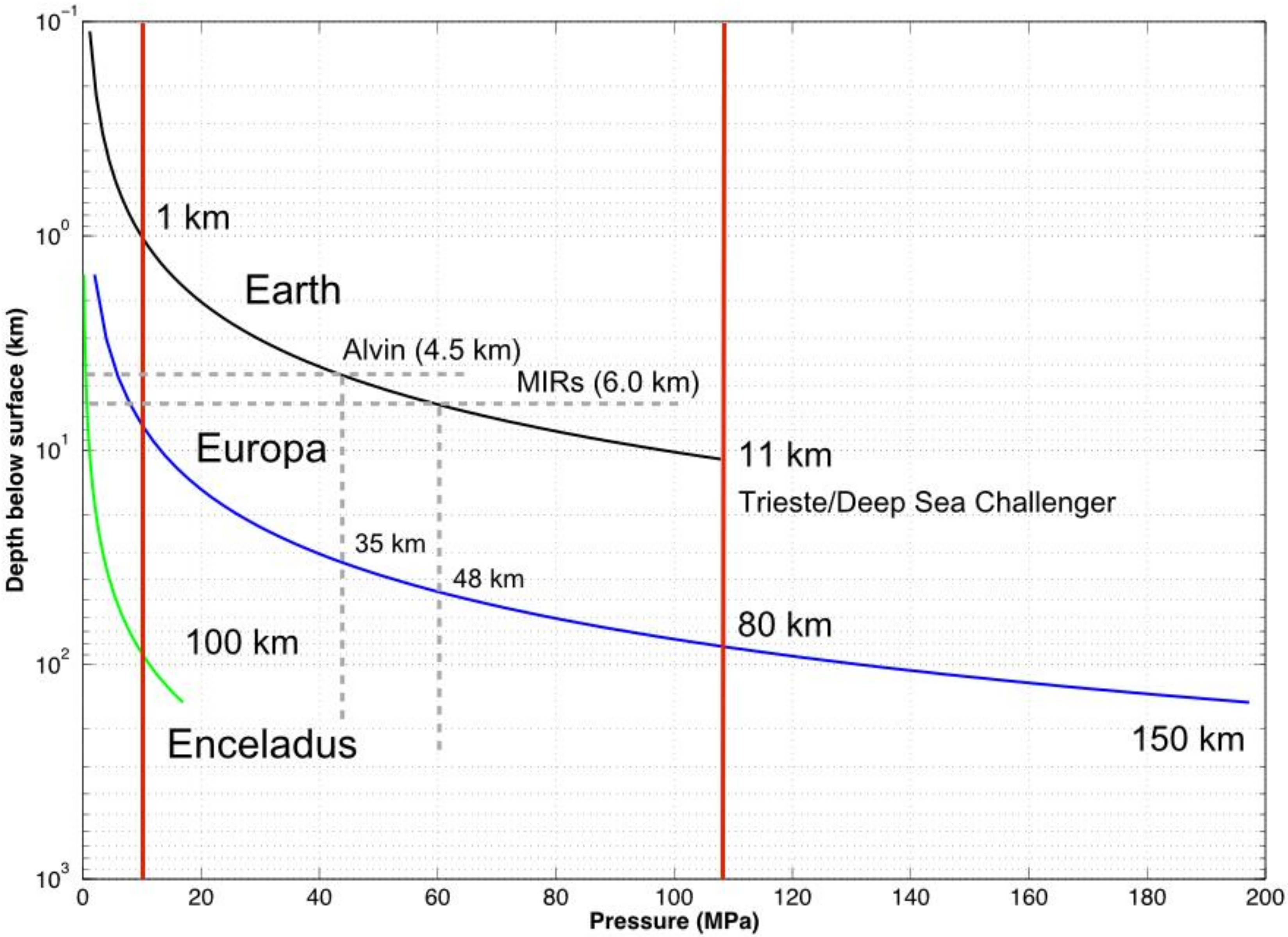
Jet Propulsion Laboratory
California Institute of Technology

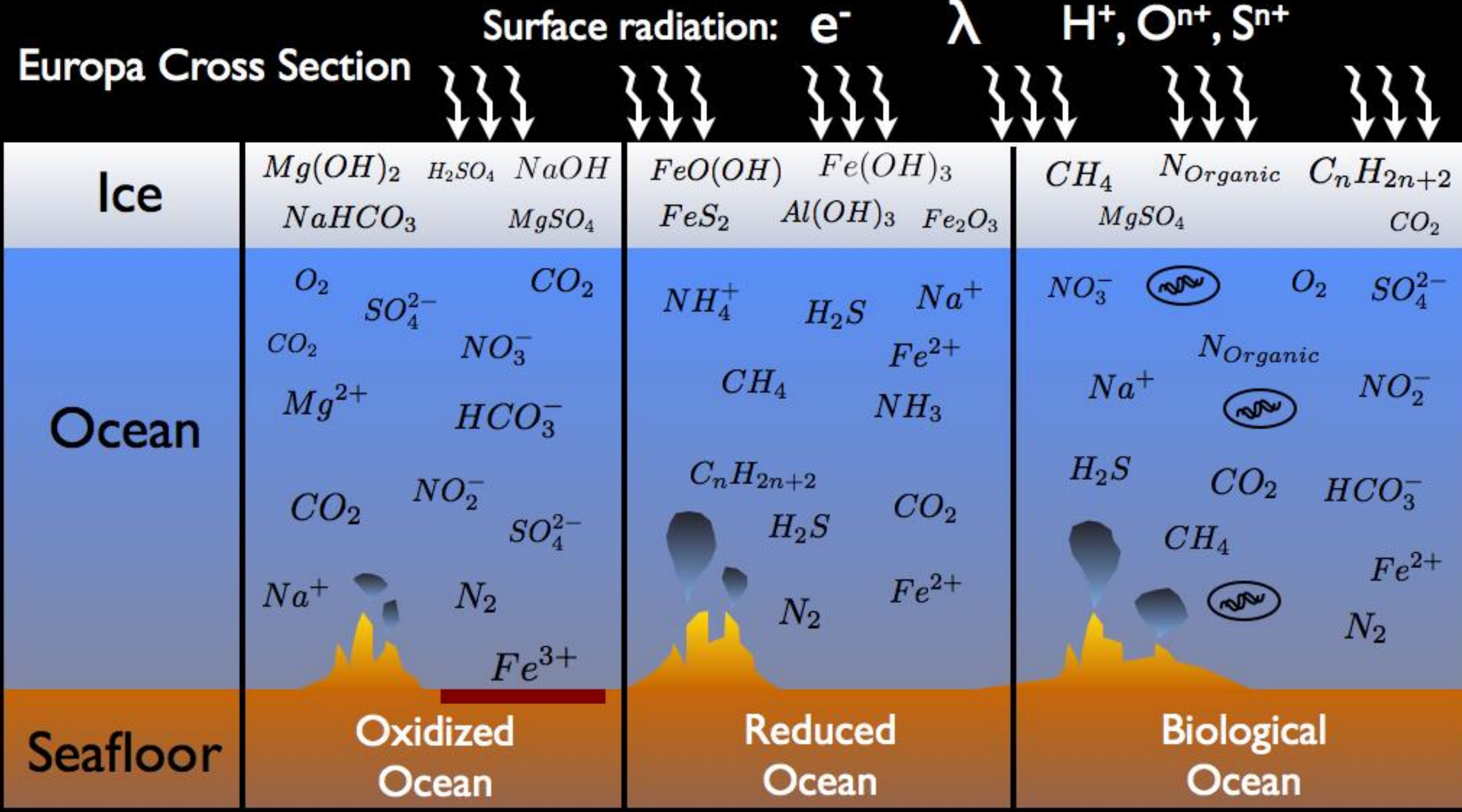
jpl.nasa.gov

Signs of Life: Statement of Task

- What is our current understanding of the limits of life and life's interactions with the environments of planets and moons?
- Are we today positioned to design, build and conduct experiments or observations capable of life detection remotely or in situ in our own solar system and from afar on extrasolar worlds?
- How could targeted research help advance the state of the art for life detection, including instrumentation and precursor research, to successfully address these challenges?

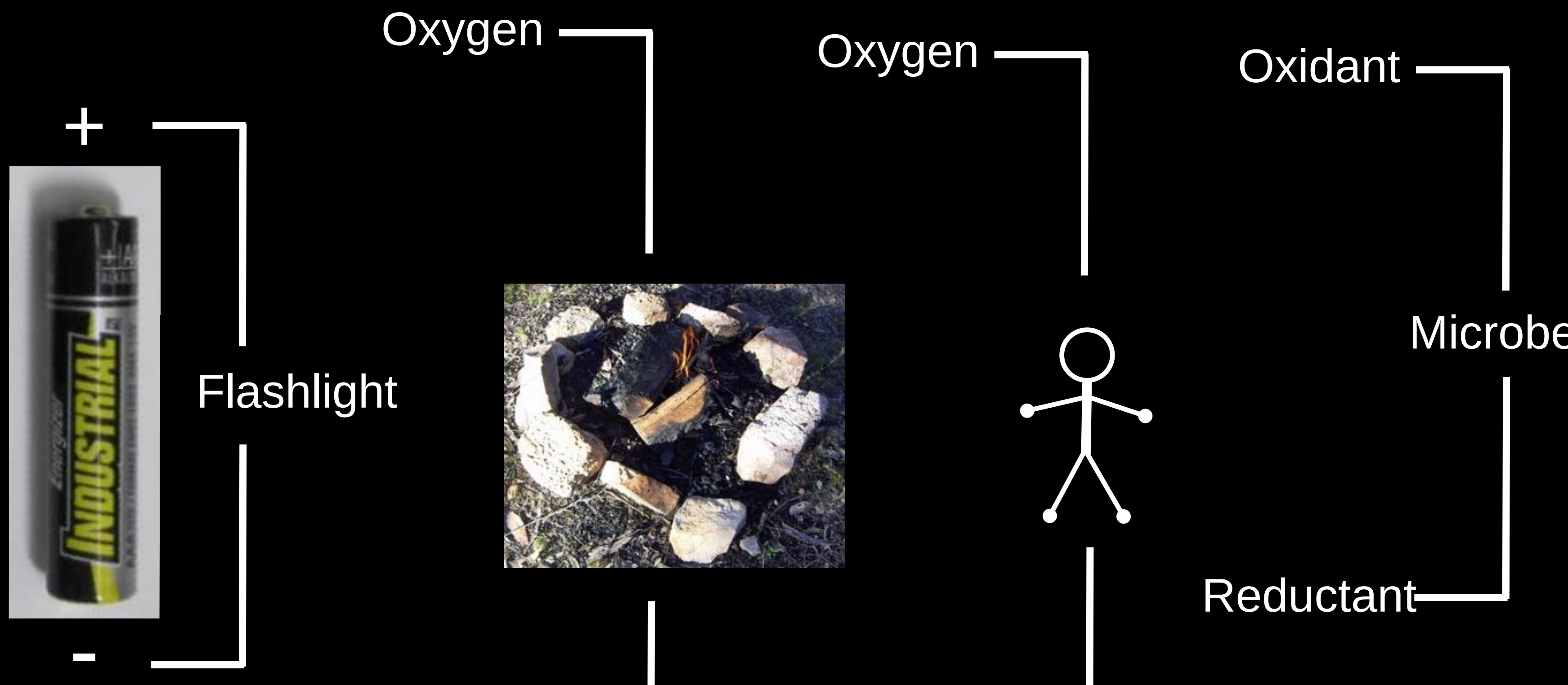
Pressure-Depth Comparison





Europa Cross Section
Surface radiation: e⁻ λ H⁺, Oⁿ⁺, Sⁿ⁺
Ice
Ocean
Seafloor
$Mg(OH)_2$ H_2SO_4 $NaOH$
$NaHCO_3$ $MgSO_4$
O_2 CO_2 SO_4^{2-} CO_2 NO_3^- Mg^{2+} HCO_3^- CO_2 NO_2^- SO_4^{2-} Na^+ N_2 Fe^{3+}
Oxidized Ocean
$FeO(OH)$ $Fe(OH)_3$
FeS_2 $Al(OH)_3$ Fe_2O_3
NH_4^+ H_2S Na^+ Fe^{2+} CH_4 NH_3 C_nH_{2n+2} CO_2 H_2S Fe^{2+} N_2
Reduced Ocean
CH_4 $N_{Organic}$ C_nH_{2n+2}
$MgSO_4$ CO_2
NO_3^- O_2 SO_4^{2-} $N_{Organic}$ Na^+ NO_2^- H_2S CO_2 HCO_3^- CH_4 Fe^{2+} N_2
Biological Ocean

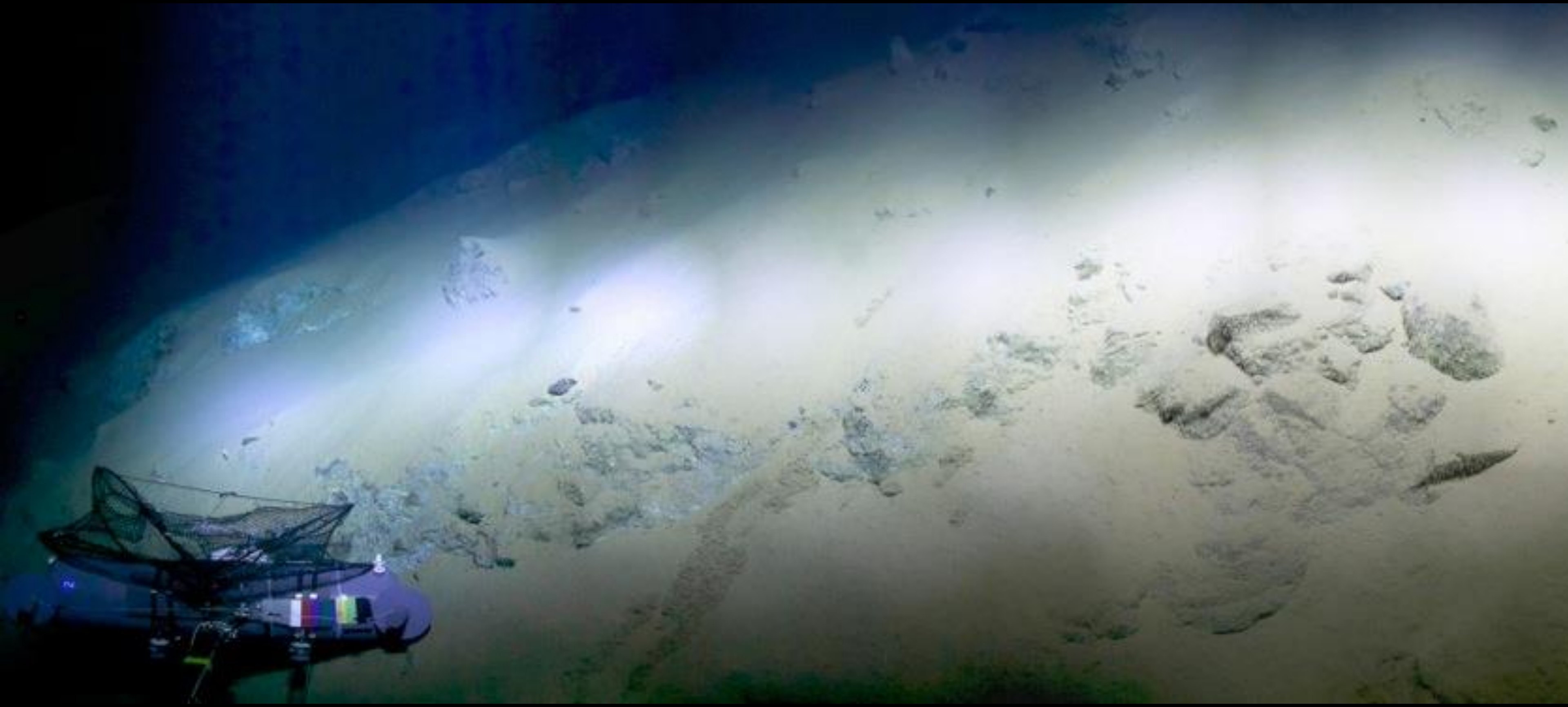
Life alleviates chemical disequilibrium in the environment

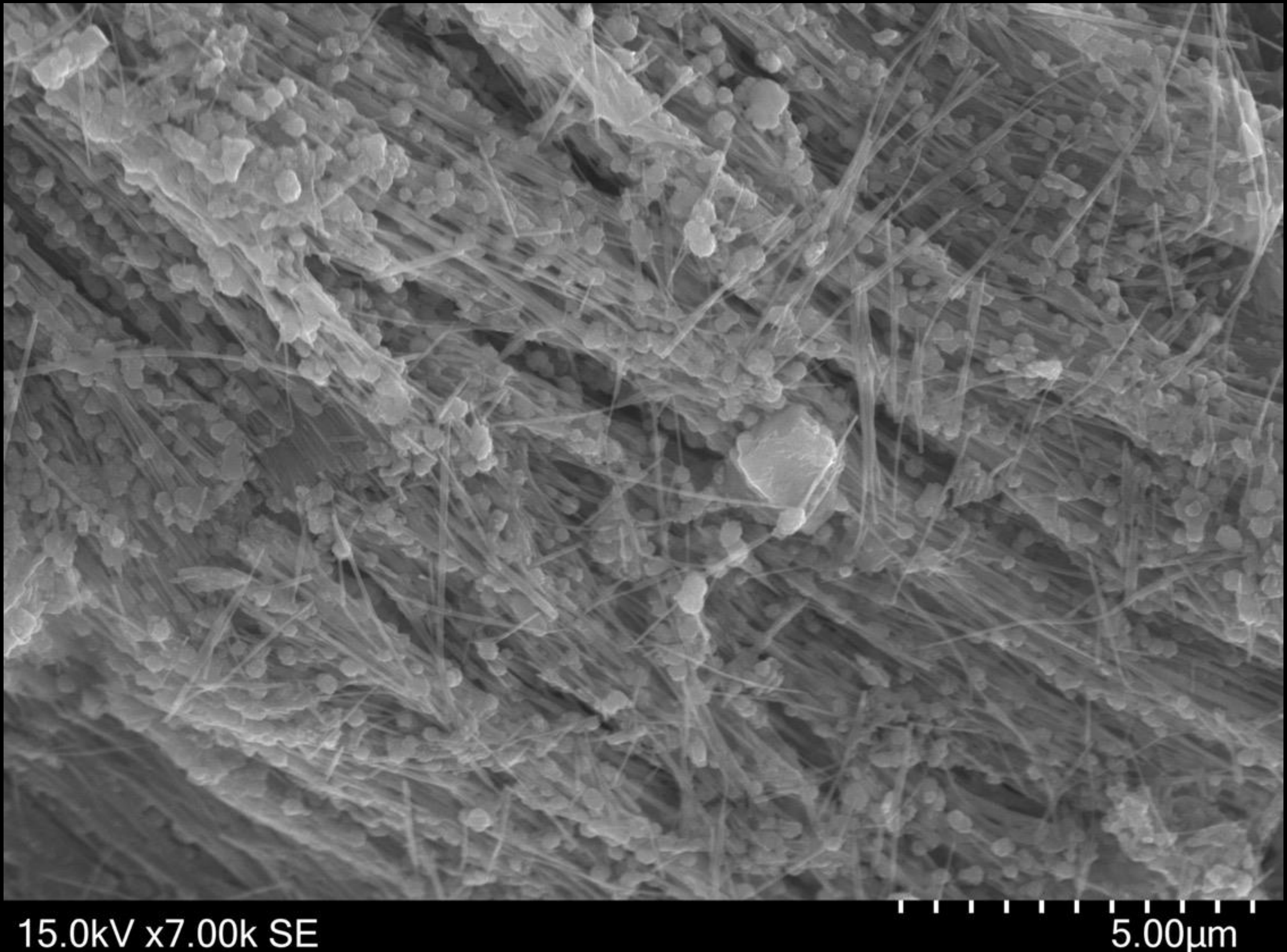


Earth is a dynamic planet with many niches of chemical disequilibrium

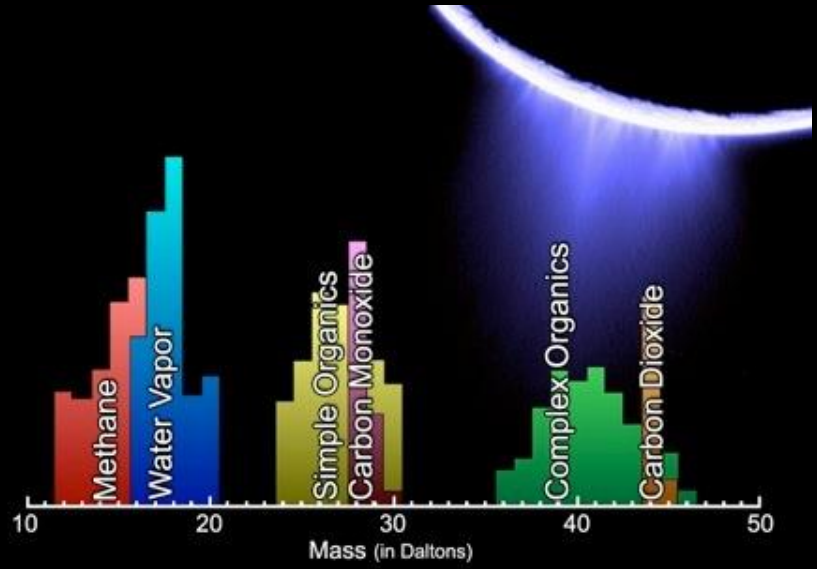
JPL

Sirena Deep: 10,700 m

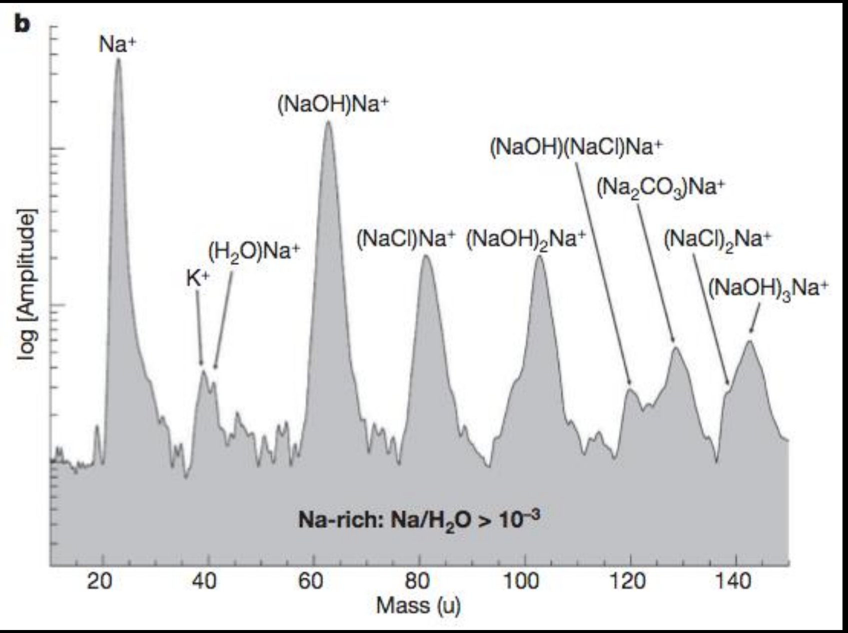




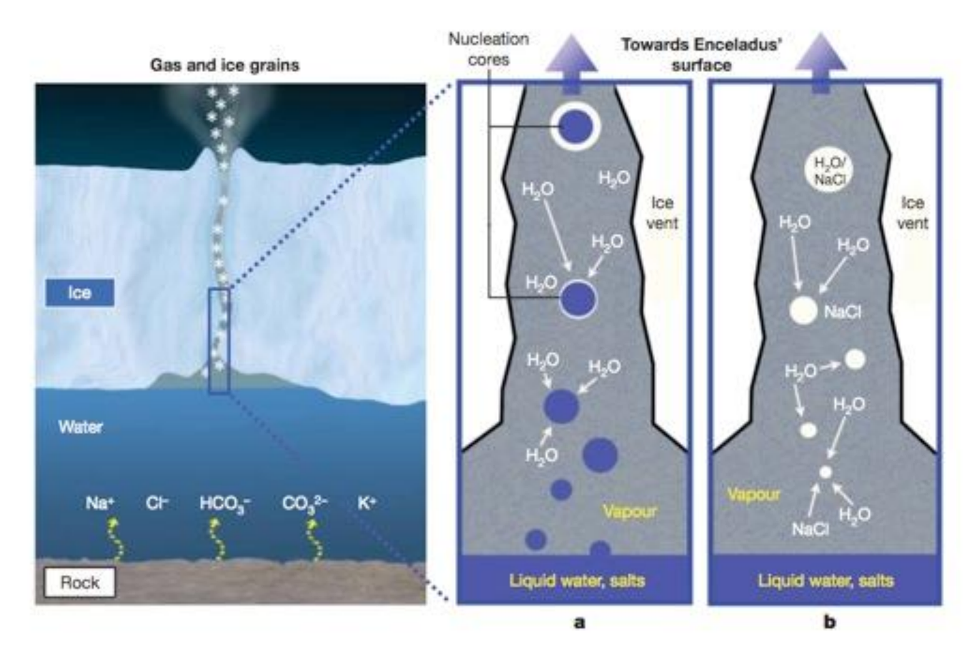
Hand et al. (in prep)



Waite et al. 2006; 2009



Postberg et al. 2009



Postberg et al. 2009

The Icy Advantage

Stability of biologically important molecules

Miller and Orgel (1974)

1. Alanine decomposition via decarboxylation (-COOH to CO_2): Half-life is Ga for <25°C but ~10 yr at 150°C

2. Many amino acids have half-lives of thousands of years at 25°C but for T approaching 0°C half-lives extend to 10^7-10^9 yrs

3. Many purines and pyrimidines show an order of magnitude increase in half-life as T goes from 25°C to 0°C

4. Peptides, DNA, and RNA have a hydrolysis half-life of 30 yr at 25°C vs 900 yrs at 0°C

Miller's Foresight: Eutectics in freezer from 1972-1997

Yields (in %) of Adenine and Amino Acids, Based on the Carbon in the Starting Amount of HCN[a], Produced from the Various Frozen Samples

	0.1 M NH_4CN −78°C, 25 yr	0.1 M NH_4CN −20°C, 25 yr	0.1 M NH_4CN −20°C, 2 months	Spark discharge −20°C, 5 yr
Adenine	0.040	0.038	5×10^{-4}	6×10^{-4}
Glycine	1.5	1.3	0.57	0.16
Alanine	0.009	0.008	0.001	0.4
Aspartic acid	~0.02	~0.02	5×10^{-5}	$<4 \times 10^{-6}$

Note. The values have uncertainties of about ±10%.

[a] In the spark discharge experiment, yields are based on the starting moles of CH_4.

Levy et al. 2000

Stability of HCN and formamide on early Earth

Estimated steady state concentrations (mol L^{-1}) of HCN and formamide in the primitive ocean

	pH	200 °	100 °	0 °
[HCN]	7	2×10^{-15}	4×10^{-12}	2×10^{-5}
[HCN]	8	6×10^{-16}	7×10^{-13}	2×10^{-6}
[Formamide]	7	2×10^{-17}	1×10^{-14}	1×10^{-8}
[Formamide]	8	2×10^{-18}	1×10^{-15}	1×10^{-9}

A HCN production rate of 100 nmol cm^{-2} yr^{-1} and an ocean volume of 300 L cm^{-2} were used.

Miyakawa et al. 2002

See also: Trinks et al. (2005), Attwater et al. (2010)

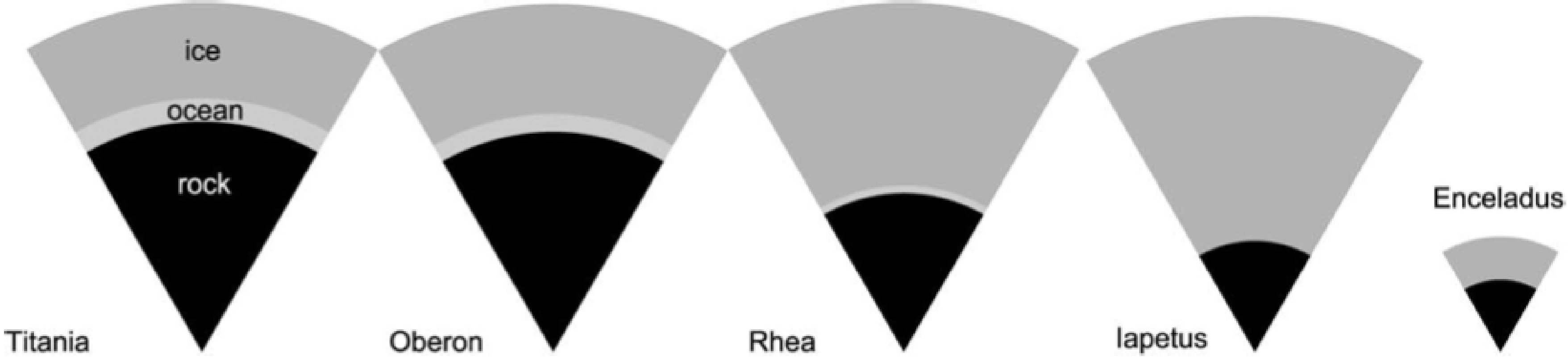


Fig. 6. Examples of interior structures according to the results shown in Tables 3 and 6. For the satellites containing a liquid layer, the models with the following initial NH_3-concentrations are shown: Titania, $X_0 = 4.3\%$; Oberon, $X_0 = 2.9\%$, and Rhea, $X_0 = 0.5\%$. The latter values imply present-day liquid layers close to the peritectic composition (see Table 6). Sizes are shown to scale.

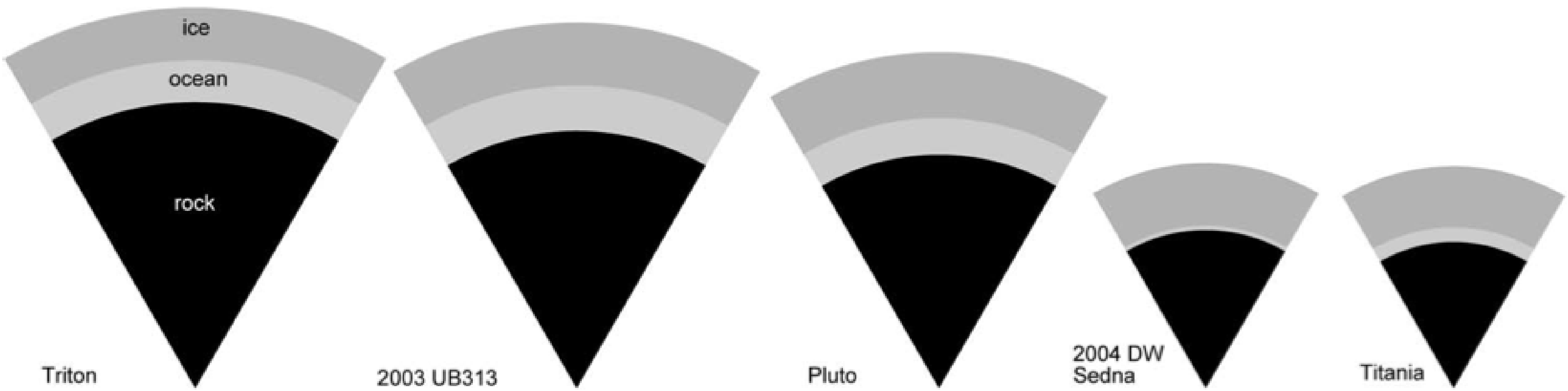
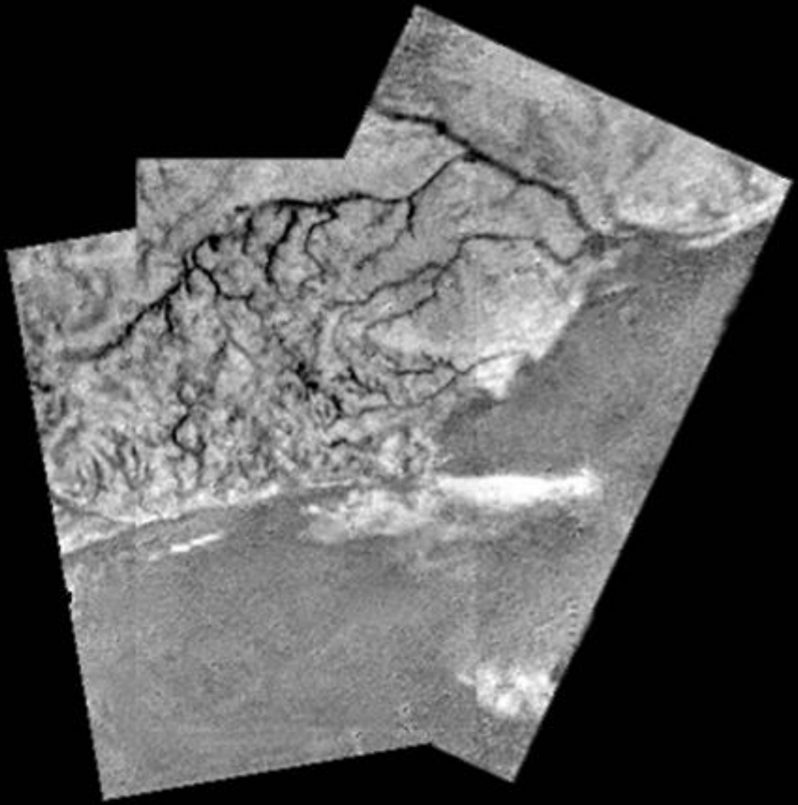
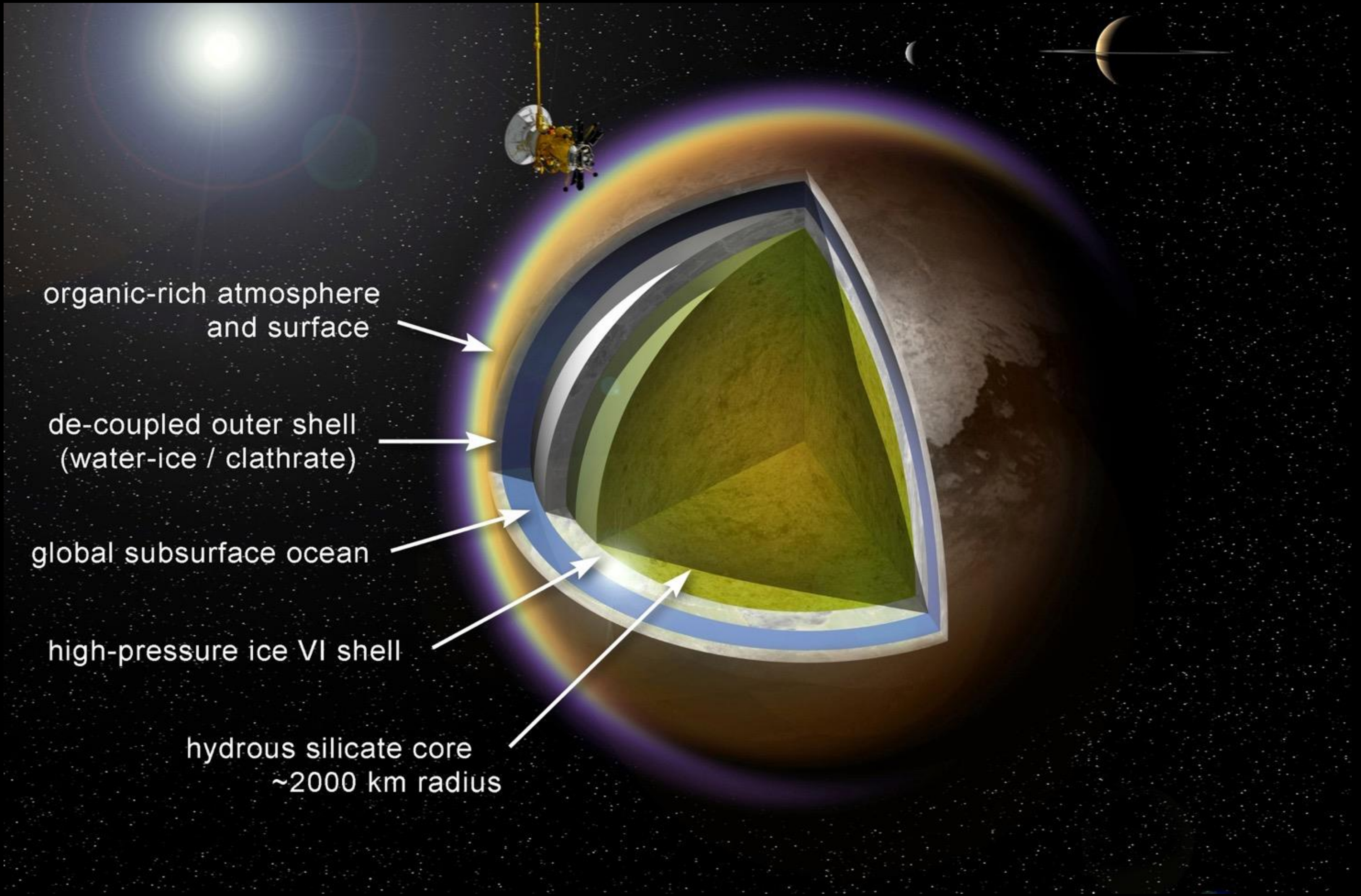


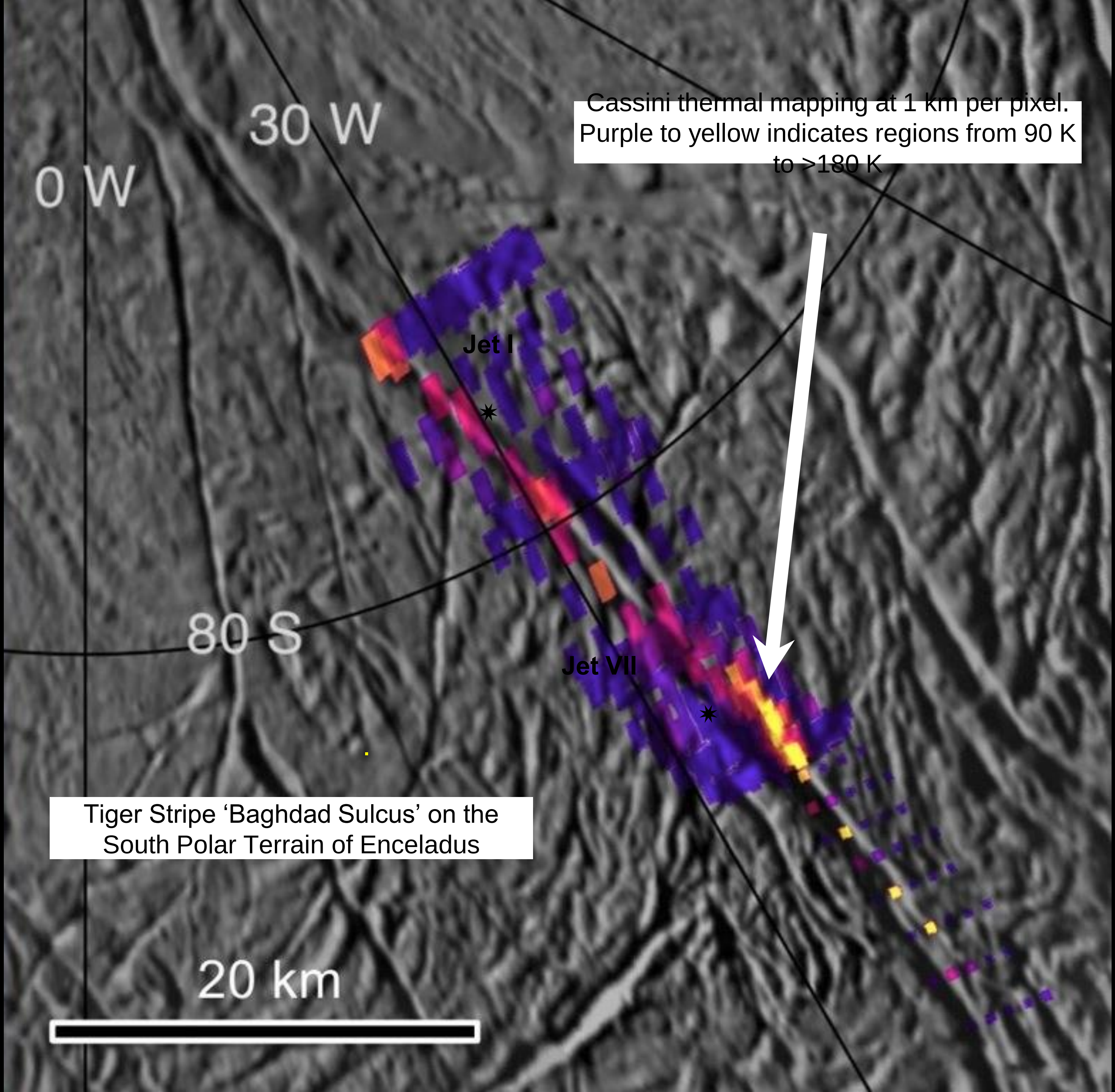
Fig. 7. Interior structure models according to Tables 6 and 8. The following initial NH_3-concentrations were used (see Tables 6 and 8): Triton, $X_0 = 5\%$; 2003 UB_{313}, $X_0 = 5\%$; Pluto $X_0 = 5\%$; 2004 DW/Sedna, $X_0 = 1.4\%$. Titania is included on the right for size comparison with Fig. 6. Sizes are shown to scale. For UB_{313} we used a radius of 1300 km, which is the lower bound of the value determined by Bertoldi et al. (2006).

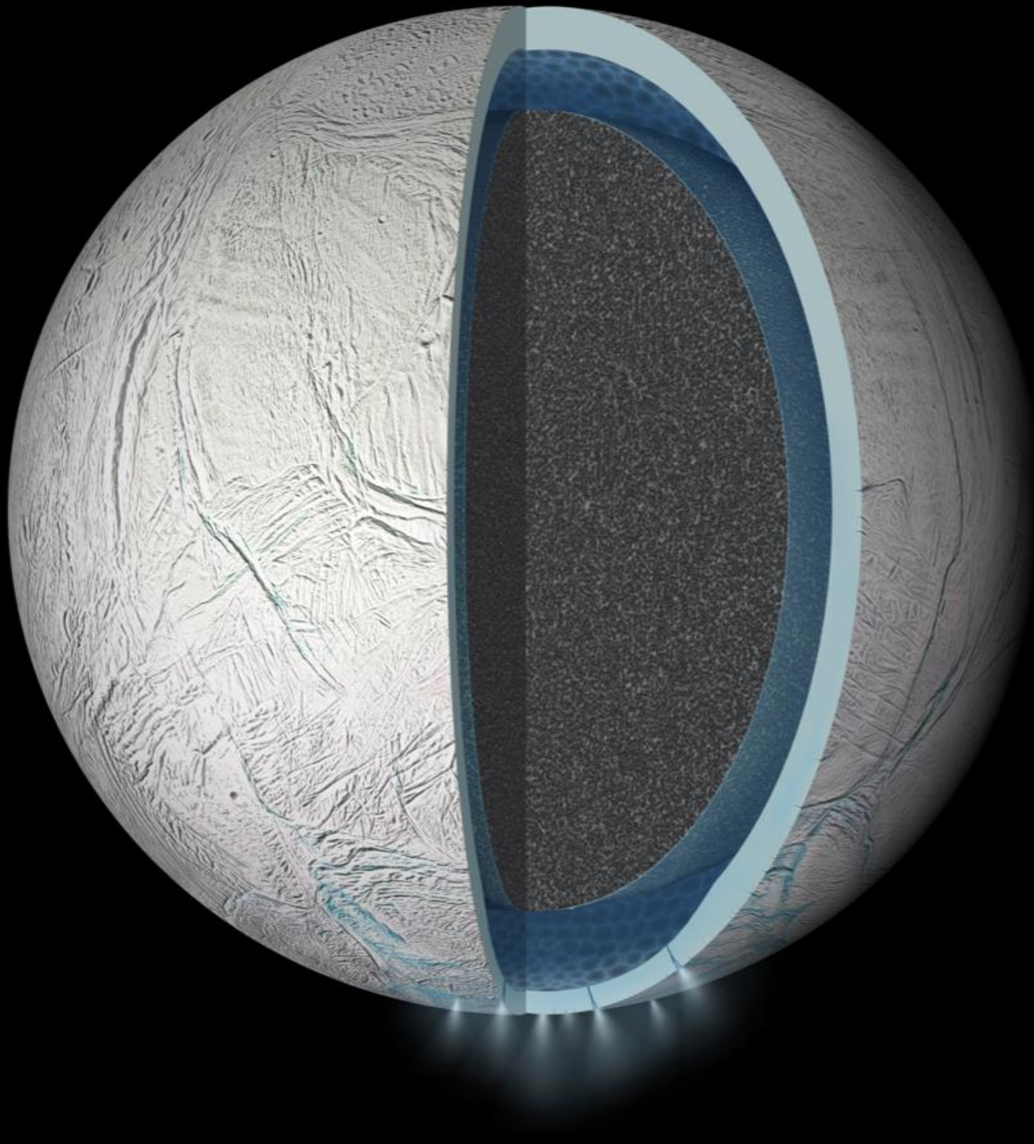
Hussmann et al., 2006



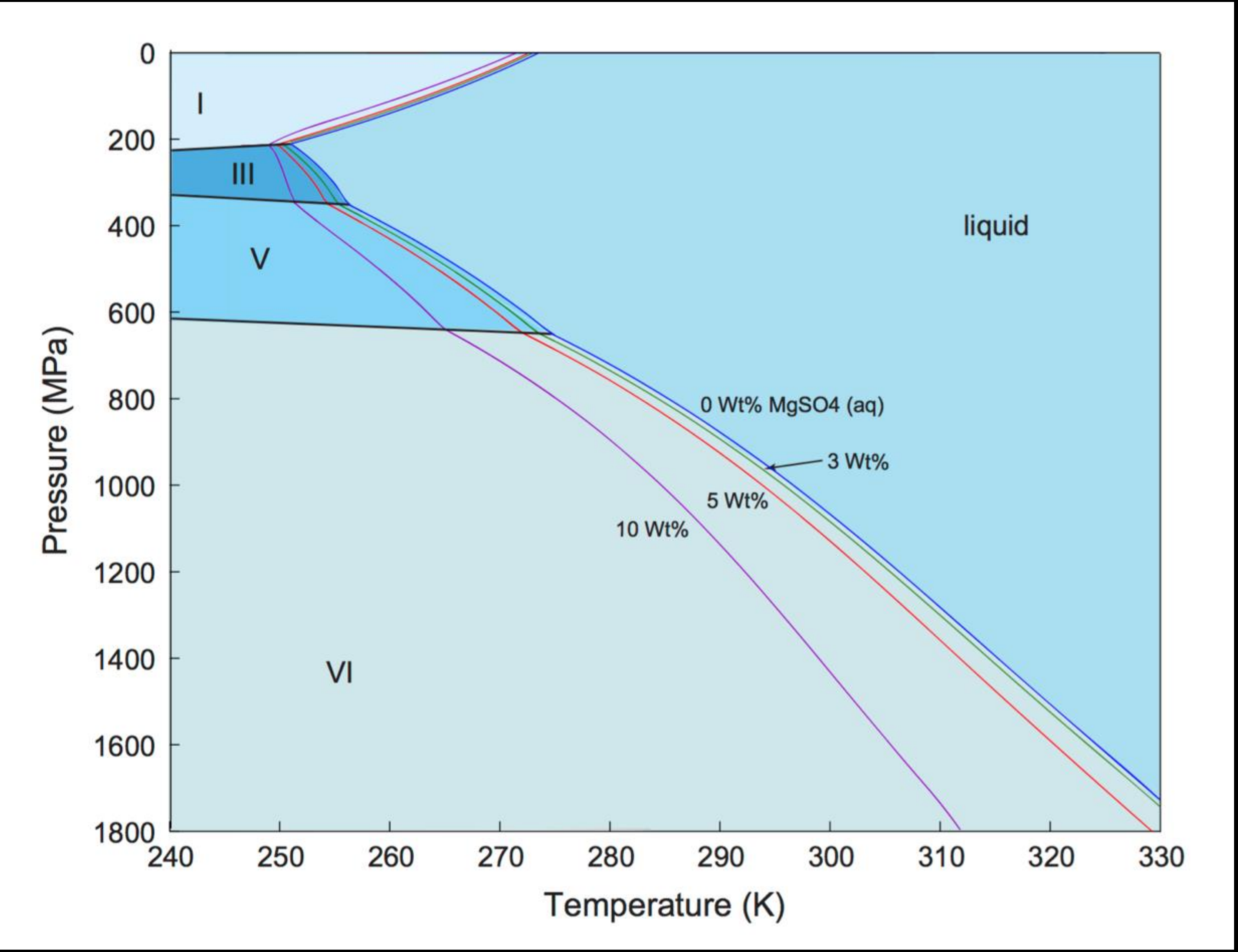


organic-rich atmosphere
and surface
de-coupled outer shell
(water-ice / clathrate)
global subsurface ocean
high-pressure ice VI shell
hydrous silicate core
~2000 km radius


Cassini thermal mapping at 1 km per pixel. Purple to yellow indicates regions from 90 K to >180 K
30 W
0 W
Jet I
80 S
Jet VII
Tiger Stripe 'Baghdad Sulcus' on the South Polar Terrain of Enceladus
20 km



JPL



Vance et al. (2014)