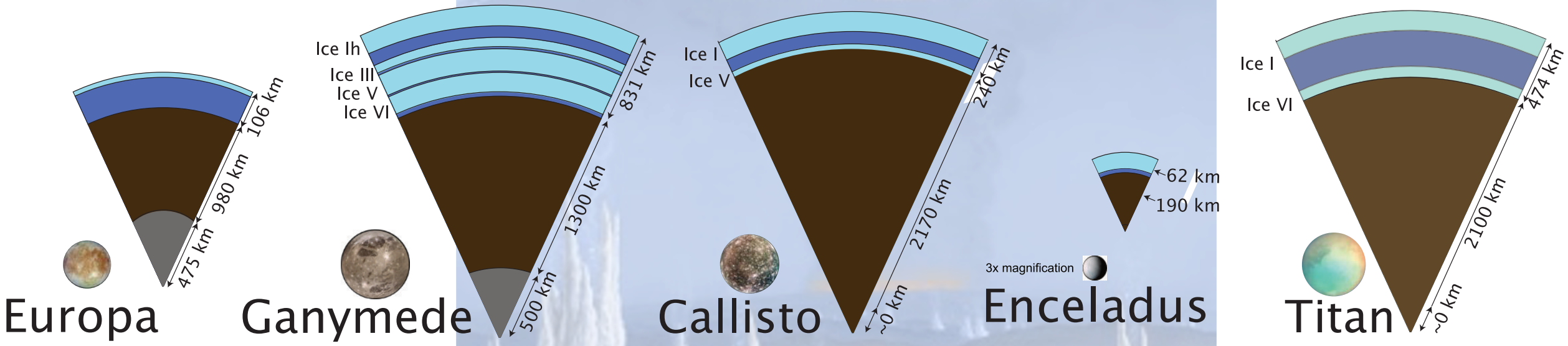
Exploring Icy Ocean Worlds in the Solar System and Beyond

Steve Vance (svance@jpl.caltech.edu)

Jet Propulsion Laboratory, California Institute of Technology, Pasadena

University of Calgary, October 12, 2018



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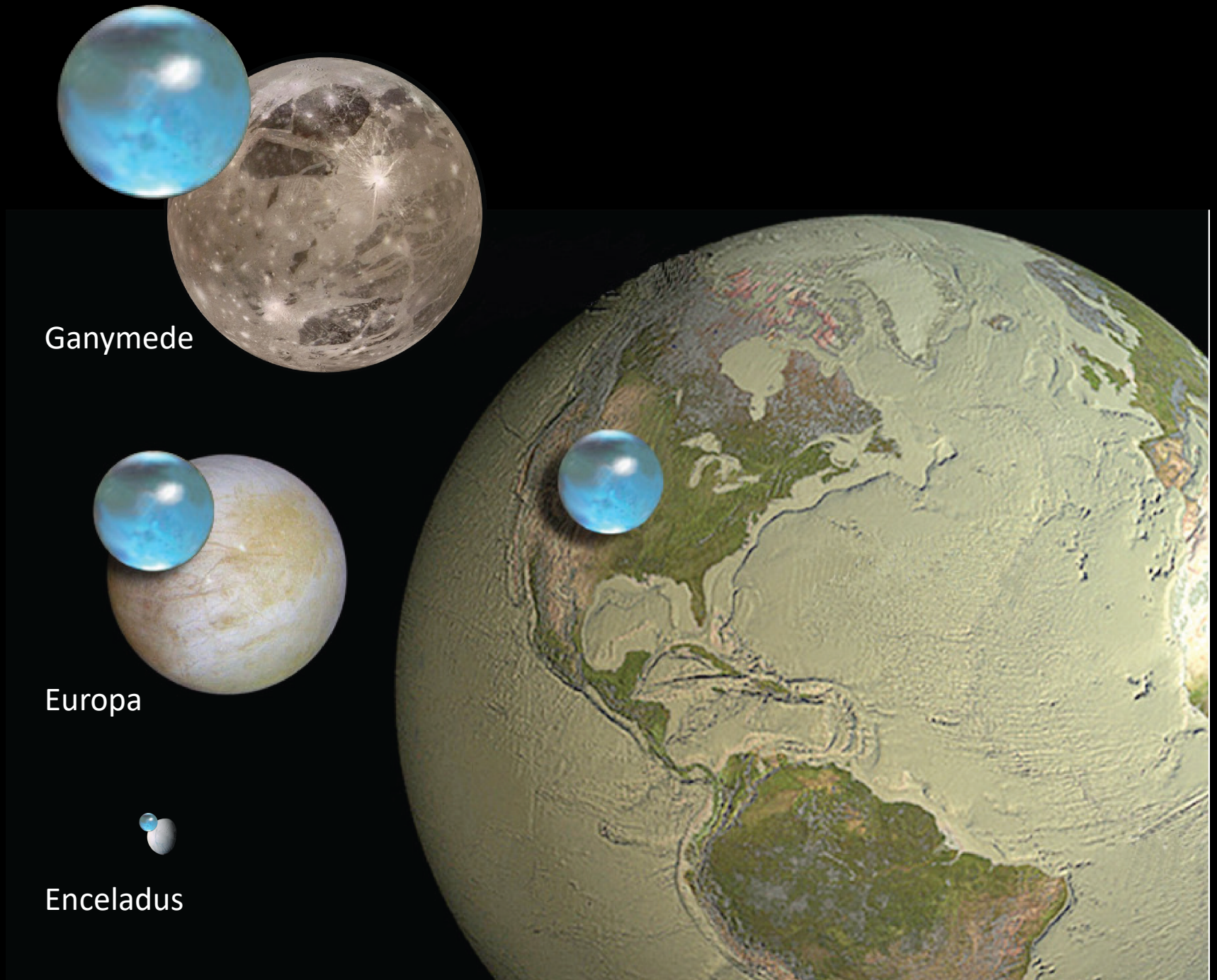
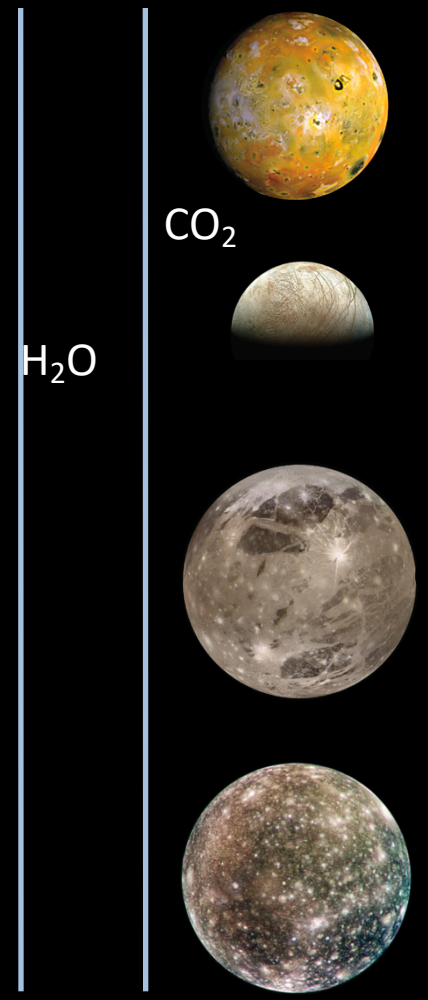
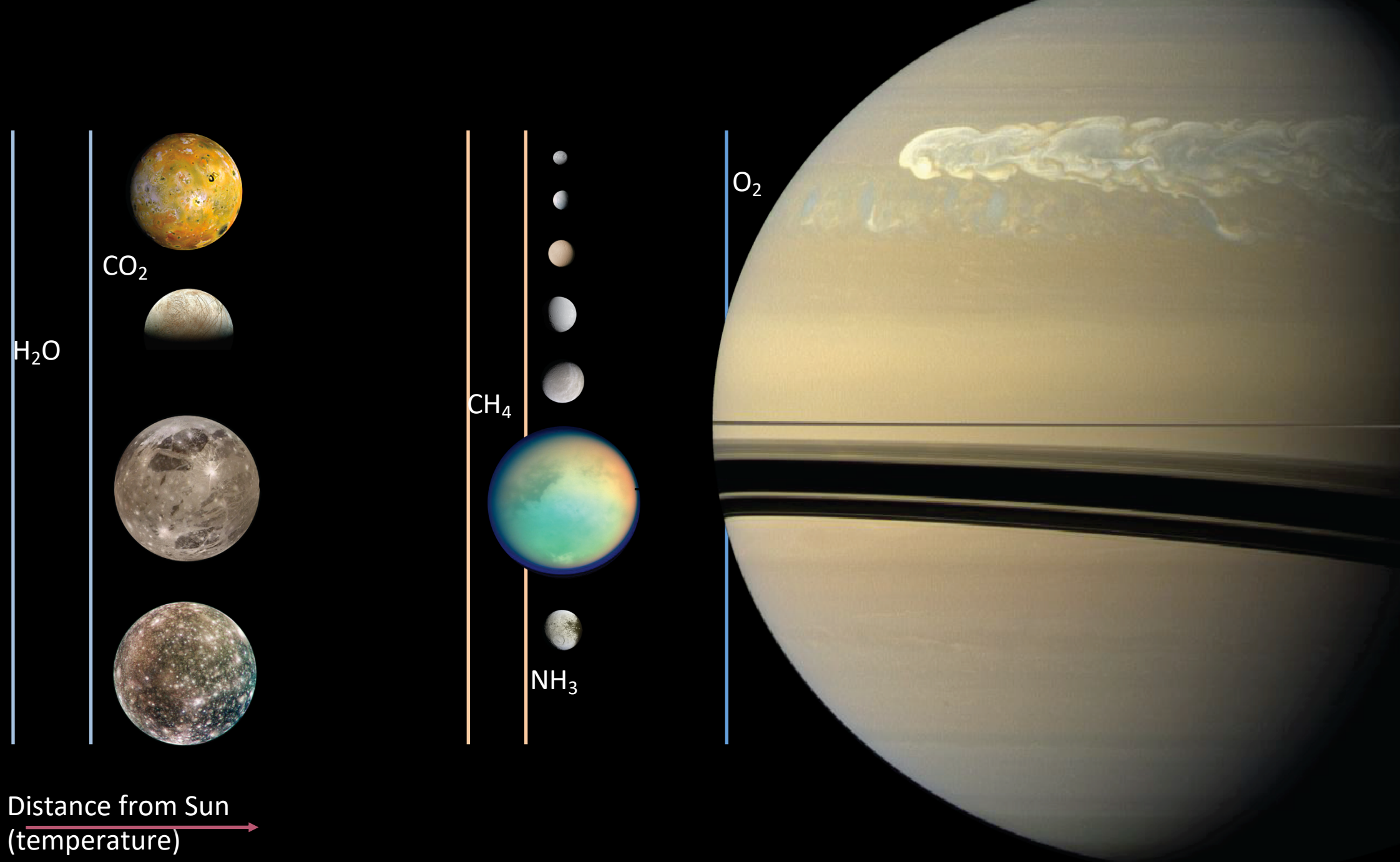
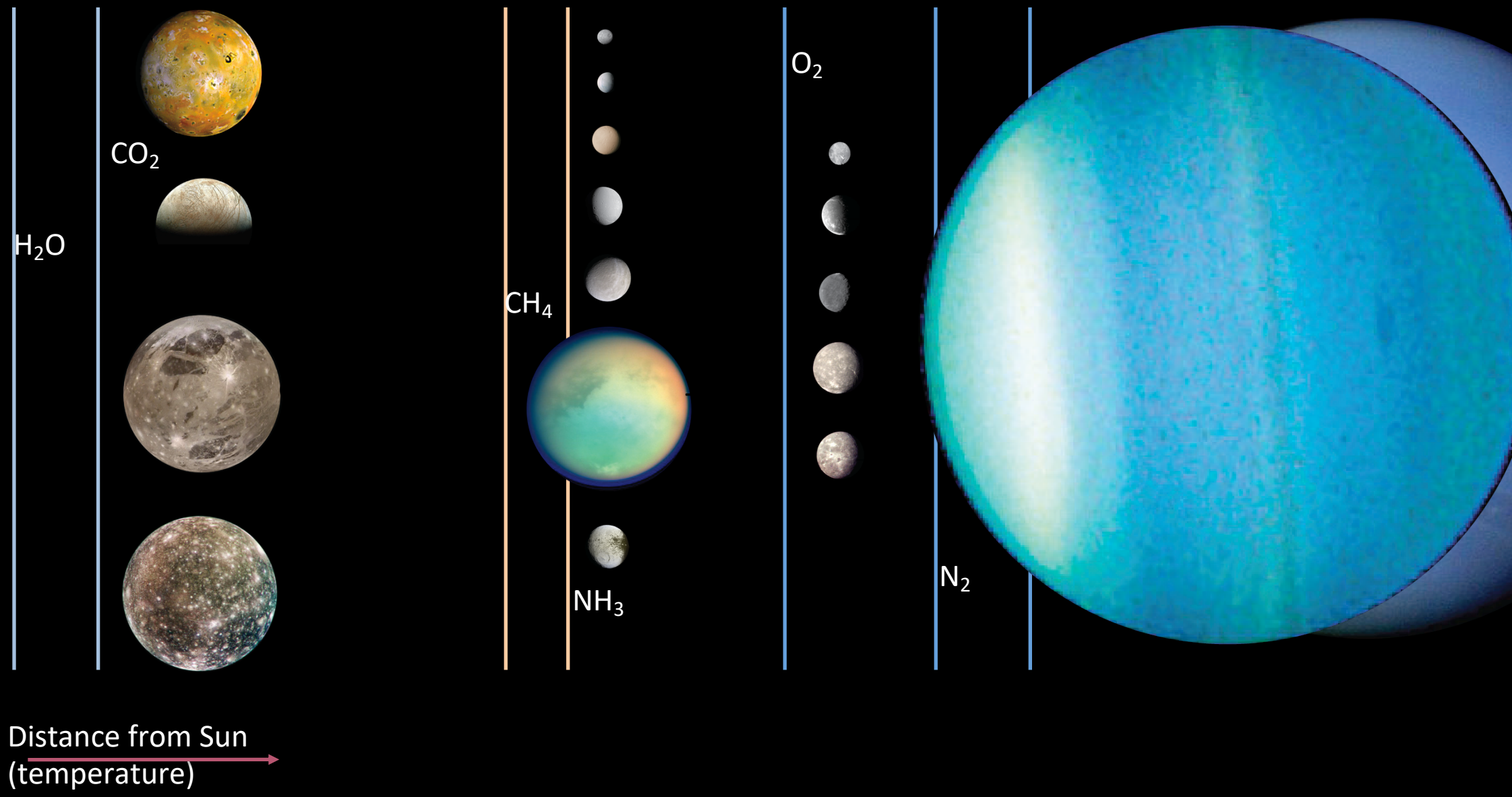
How icy moons may differ from Earth


Ganymede
Europa
Enceladus



Distance from Sun
(temperature)


H_2O
CO_2
CH_4
NH_3
O_2
Distance from Sun
(temperature)


H_2O
CO_2
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N_2
Distance from Sun
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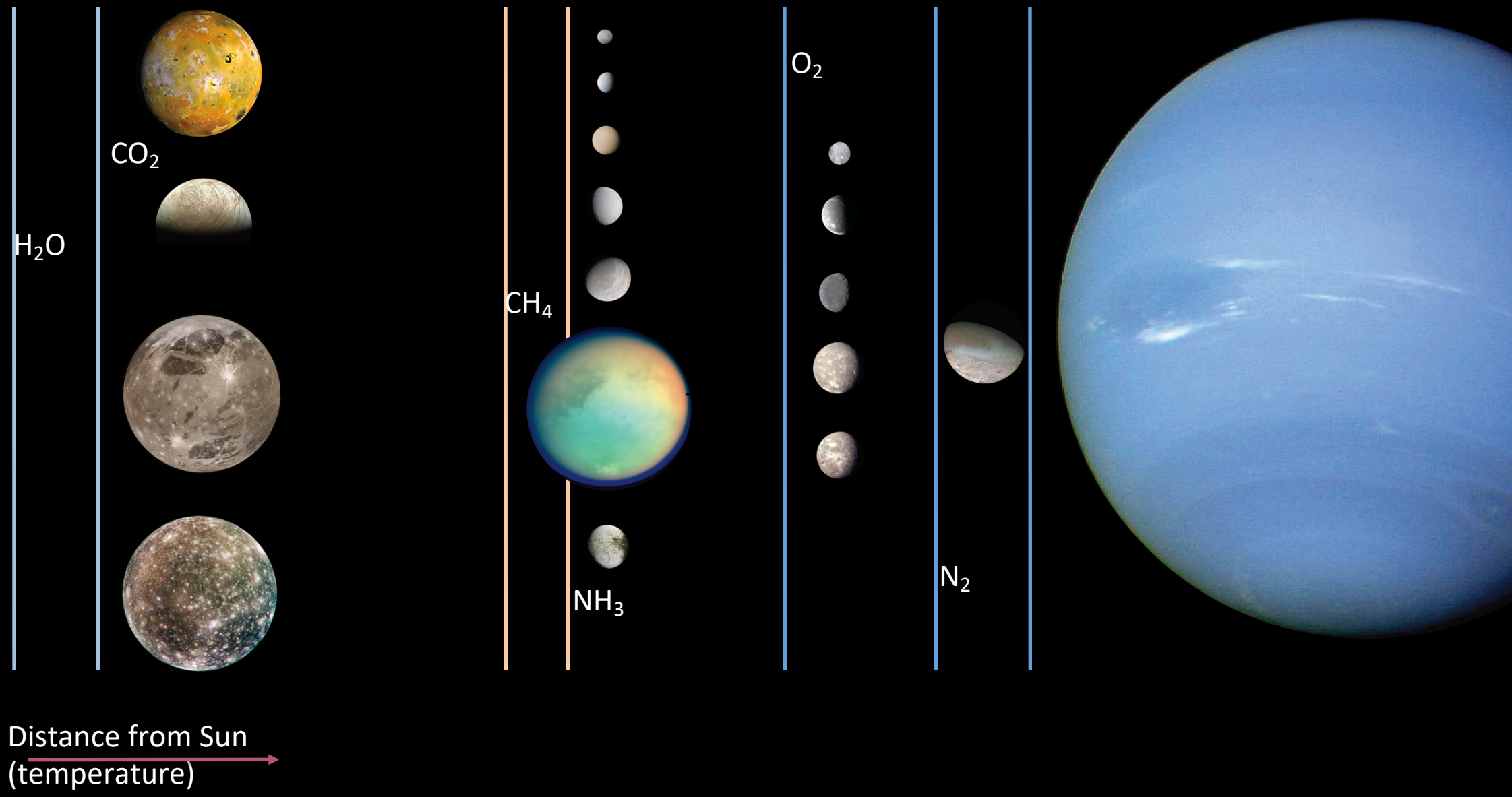
H_2O
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Distance from Sun
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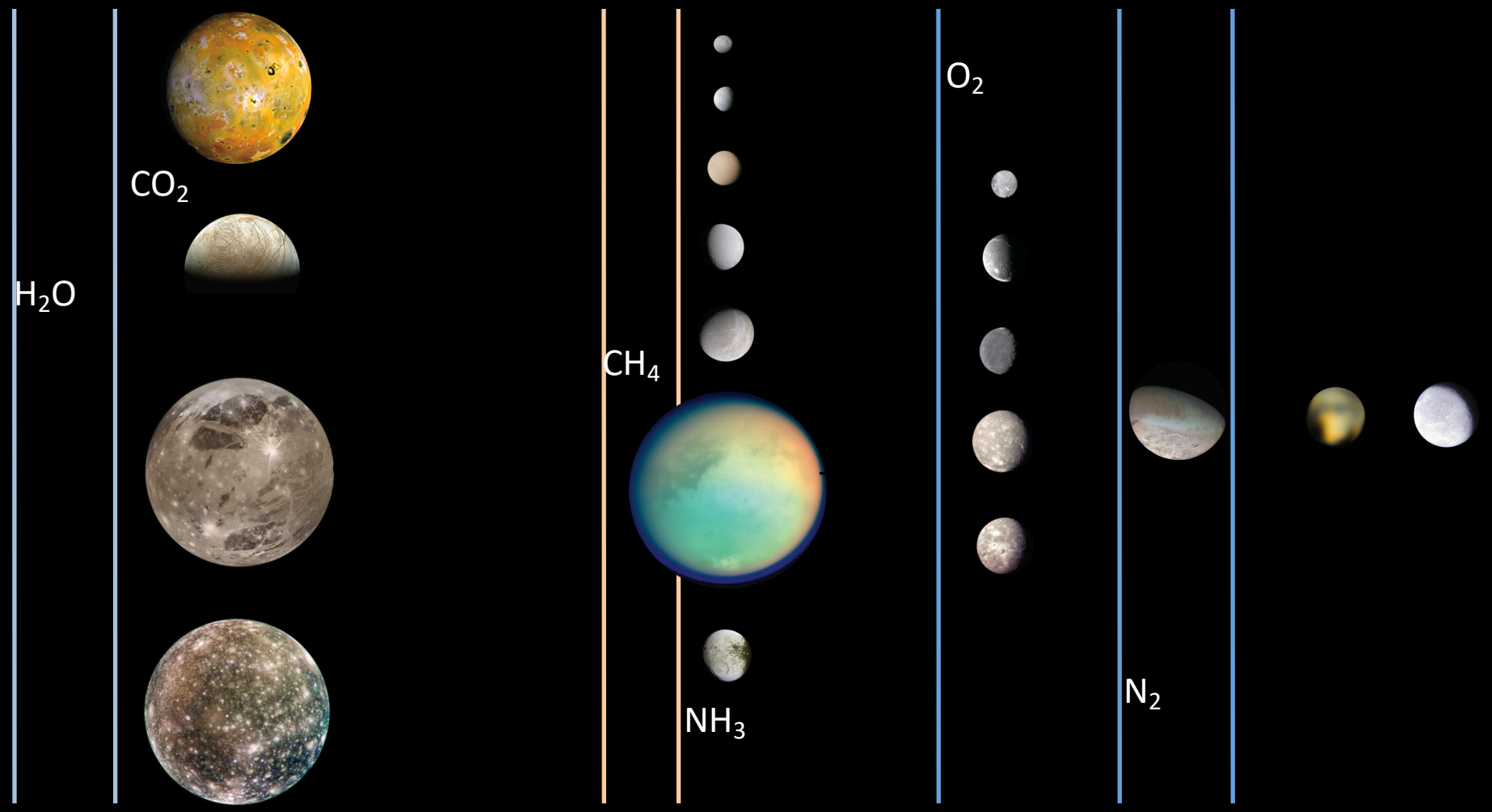
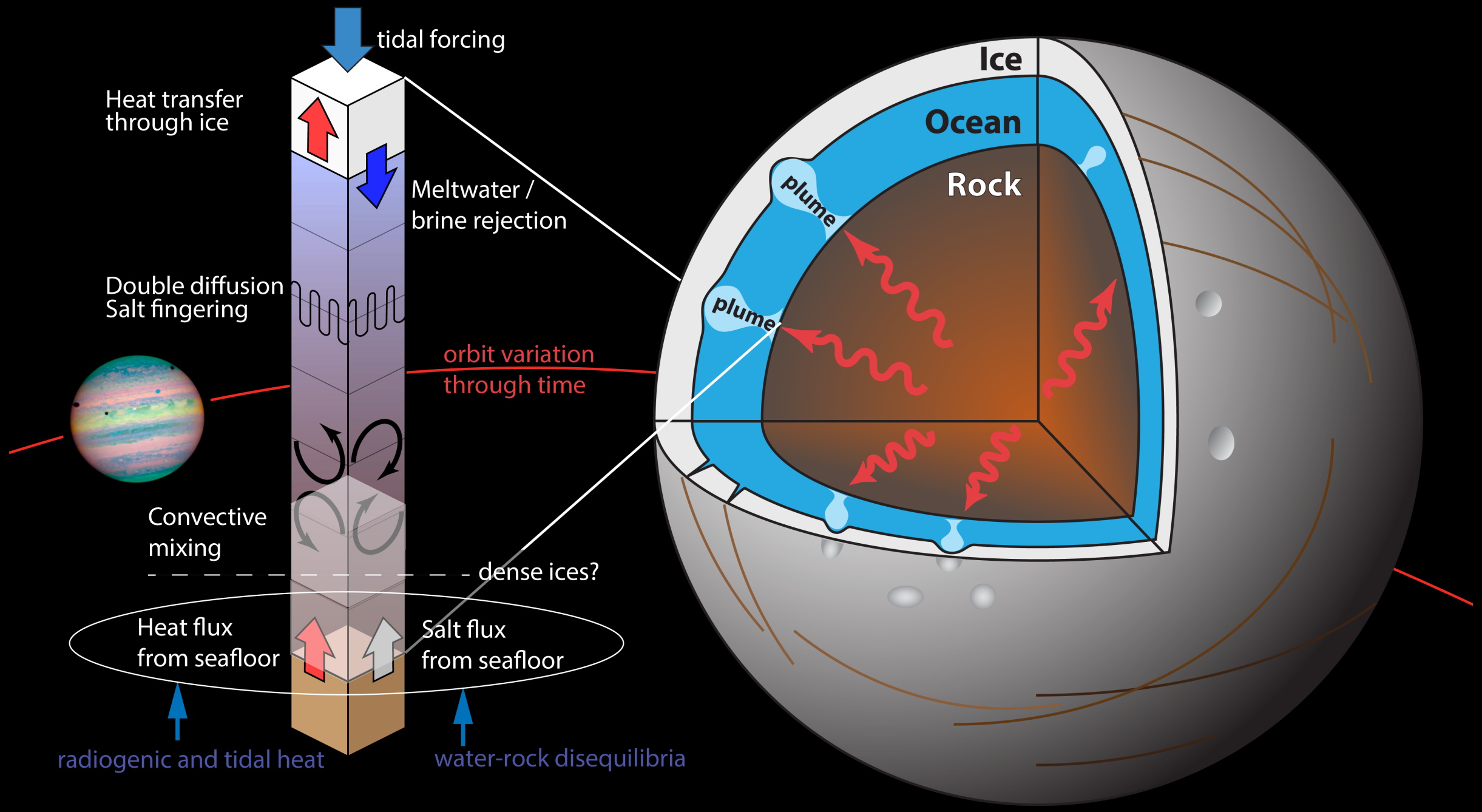
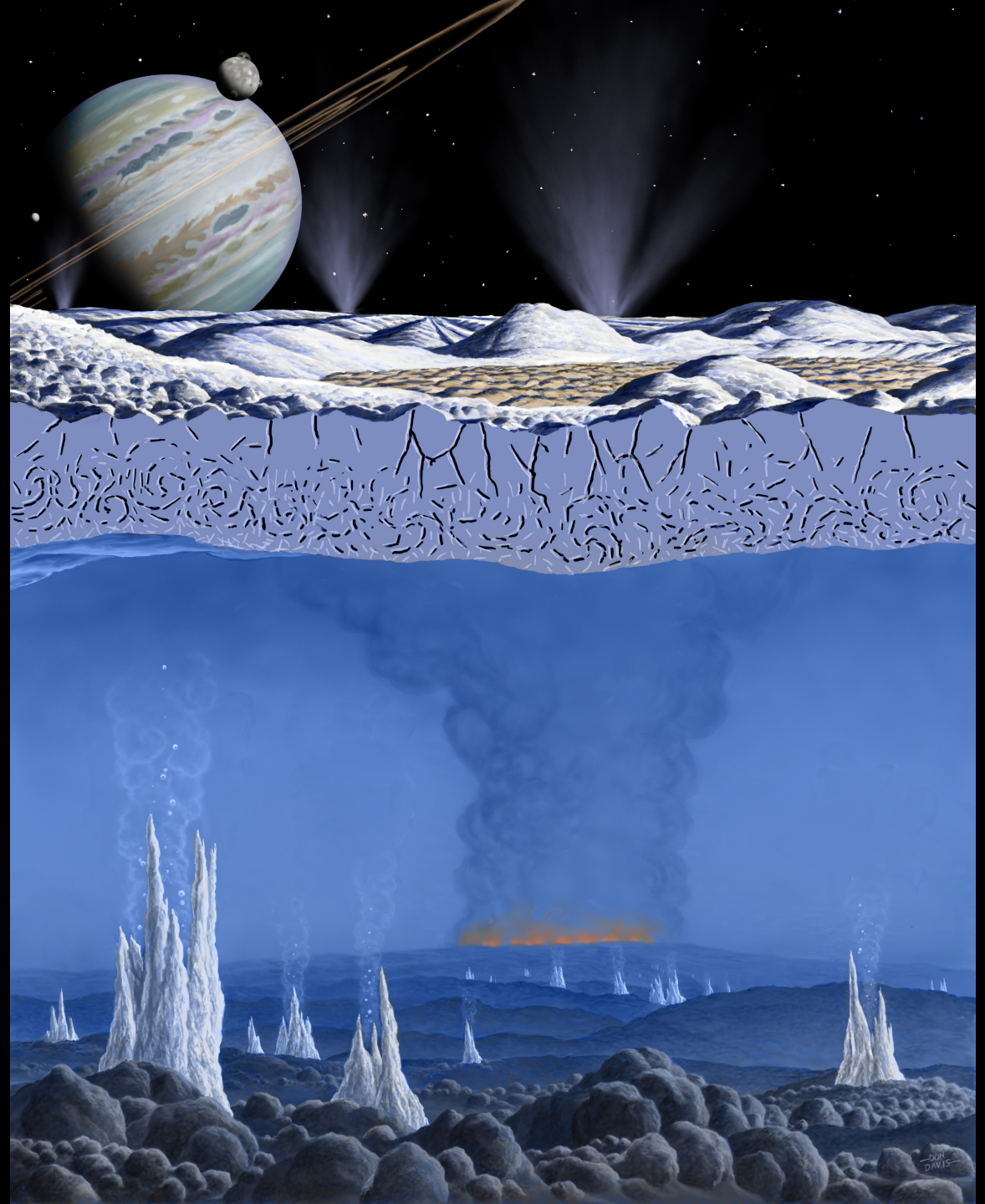


Distance from Sun
(temperature) →

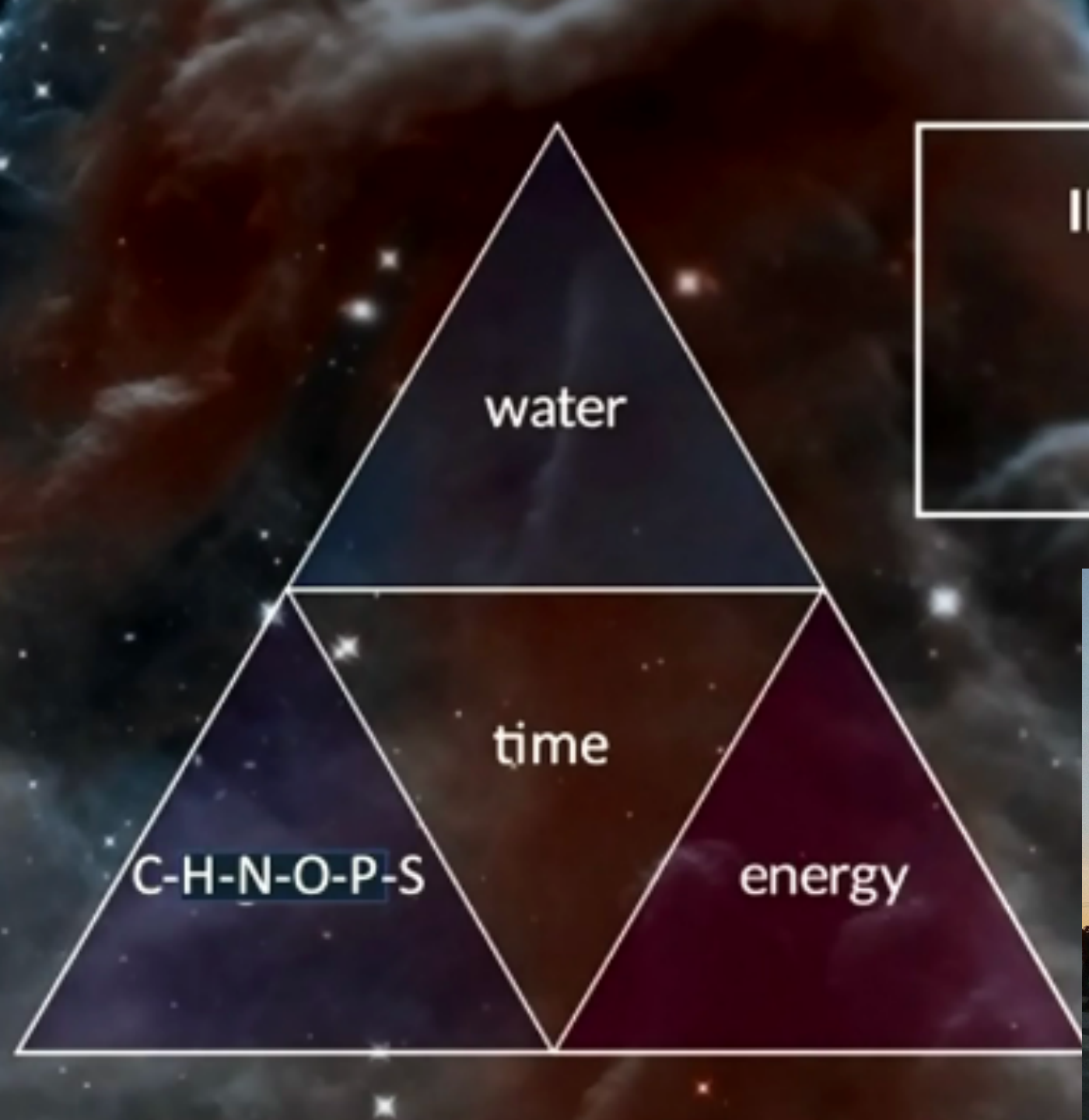
more Kuiper Belt and Oort Cloud objects,
and exomoons!


tidal forcing
Heat transfer through ice
Meltwater / brine rejection
Double diffusion Salt fingering
orbit variation through time
Convective mixing
dense ices?
Heat flux from seafloor
Salt flux from seafloor
radiogenic and tidal heat
water-rock disequilibria
Ice
Ocean
Rock
plume
plume



Don Davis

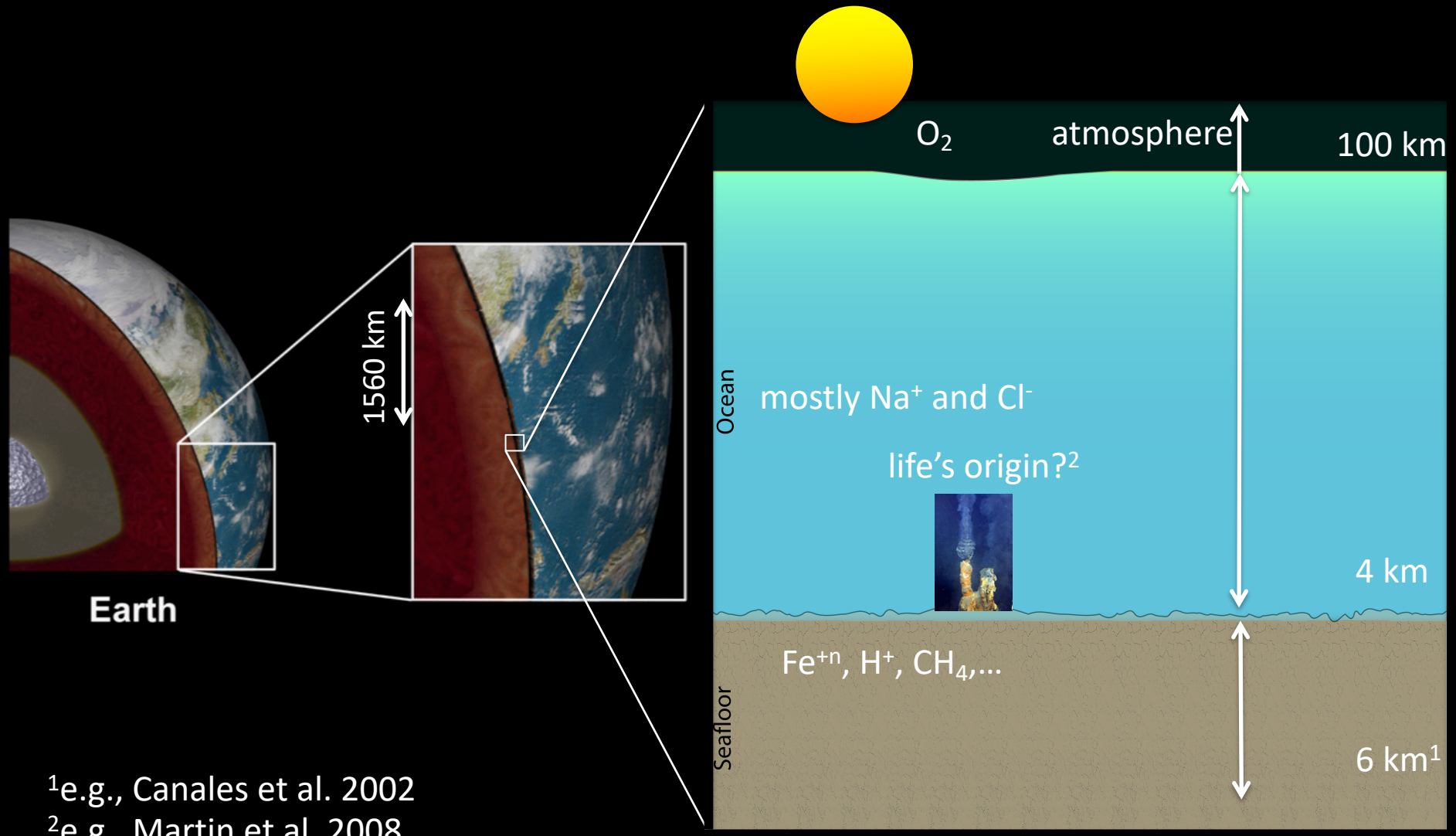
Habitability


water
time
C-H-N-O-P-S
energy

NASA
INGREDIENTS
FOR LIFE

VONS
Ingredients for life.
life

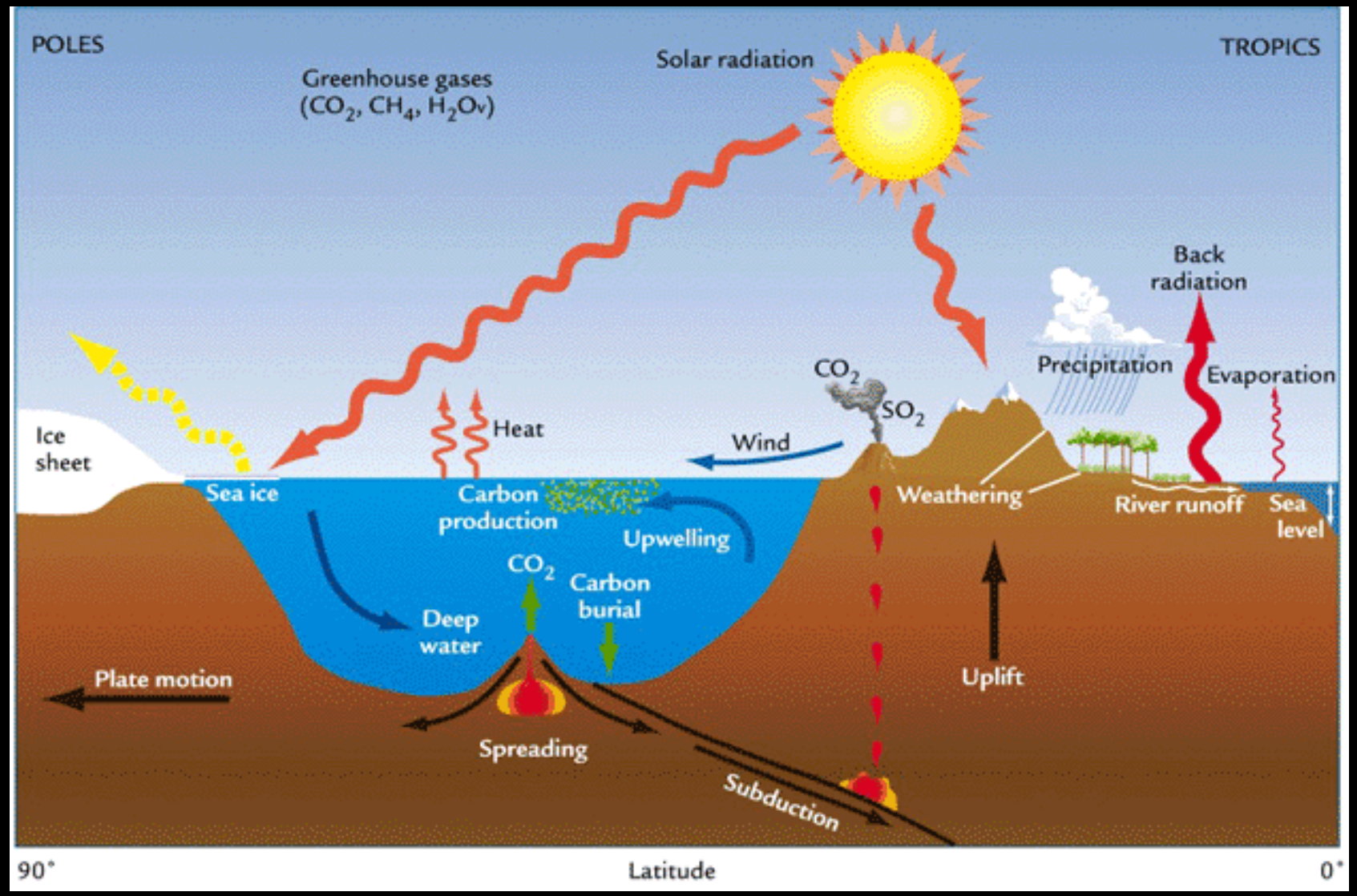
The Earth System



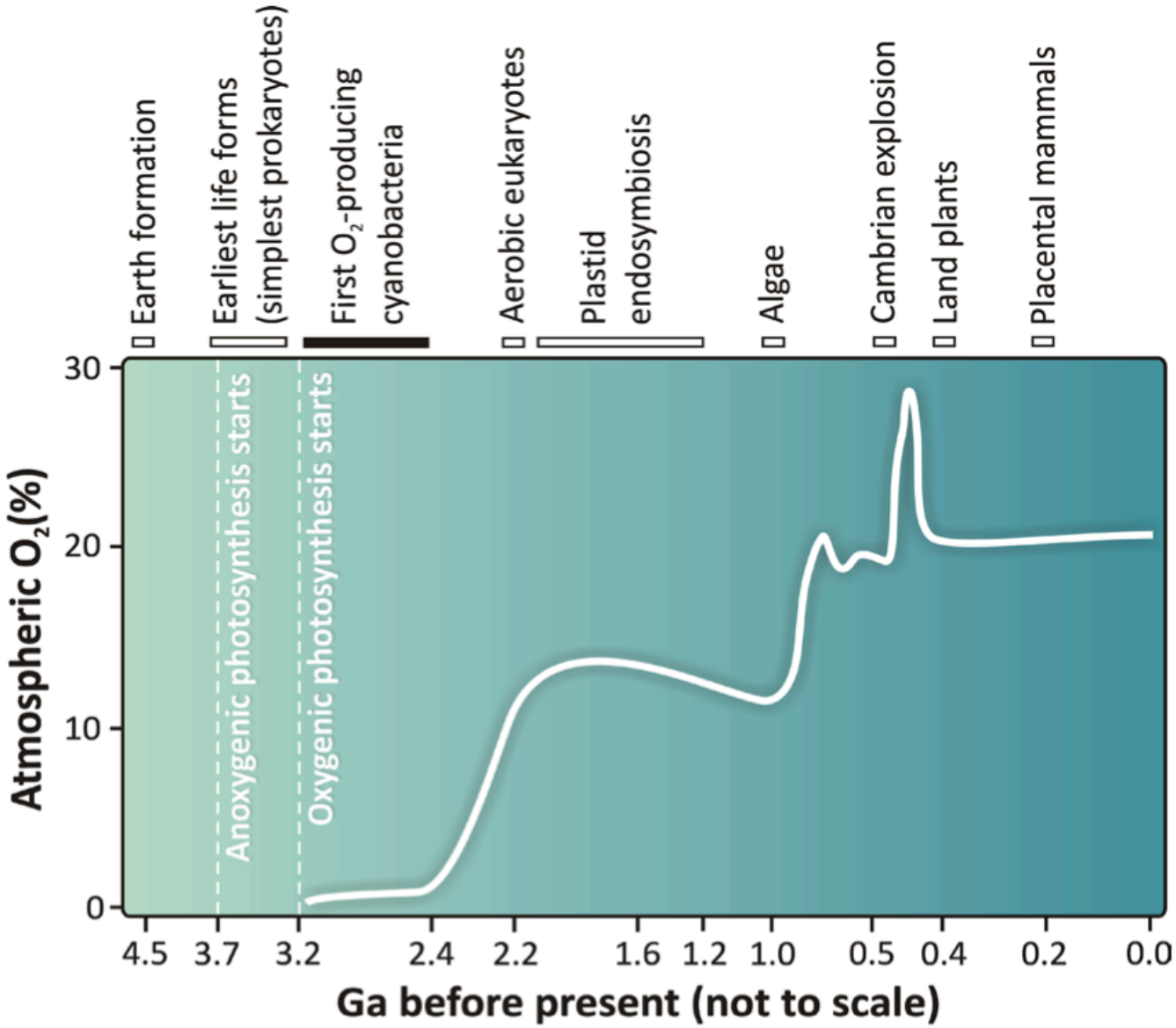
[1]e.g., Canales et al. 2002
[2]e.g., Martin et al. 2008

Earth Images: NASA

The Earth System

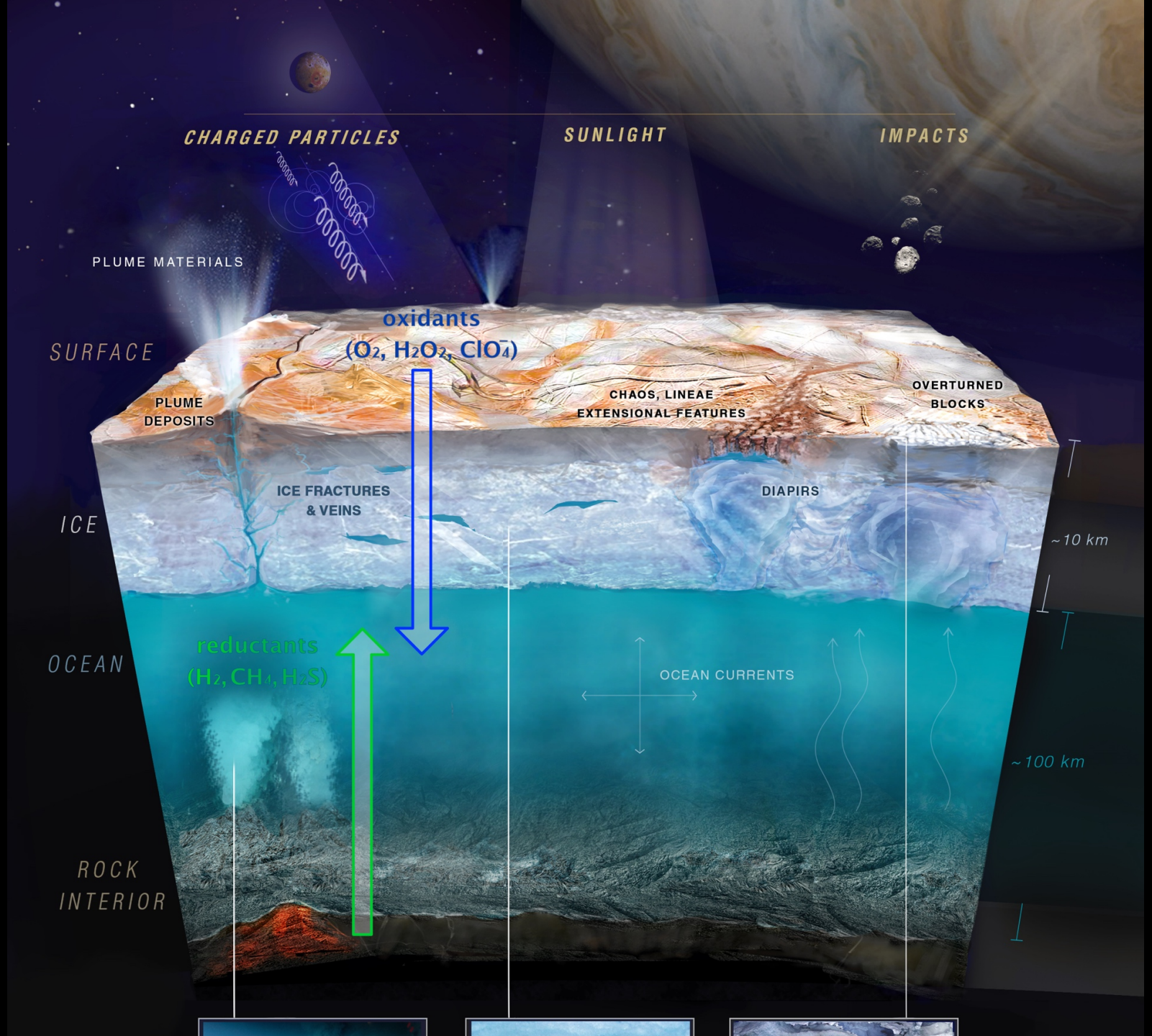


http://wiki.fis-ski.com/index.php/Earth_Systems

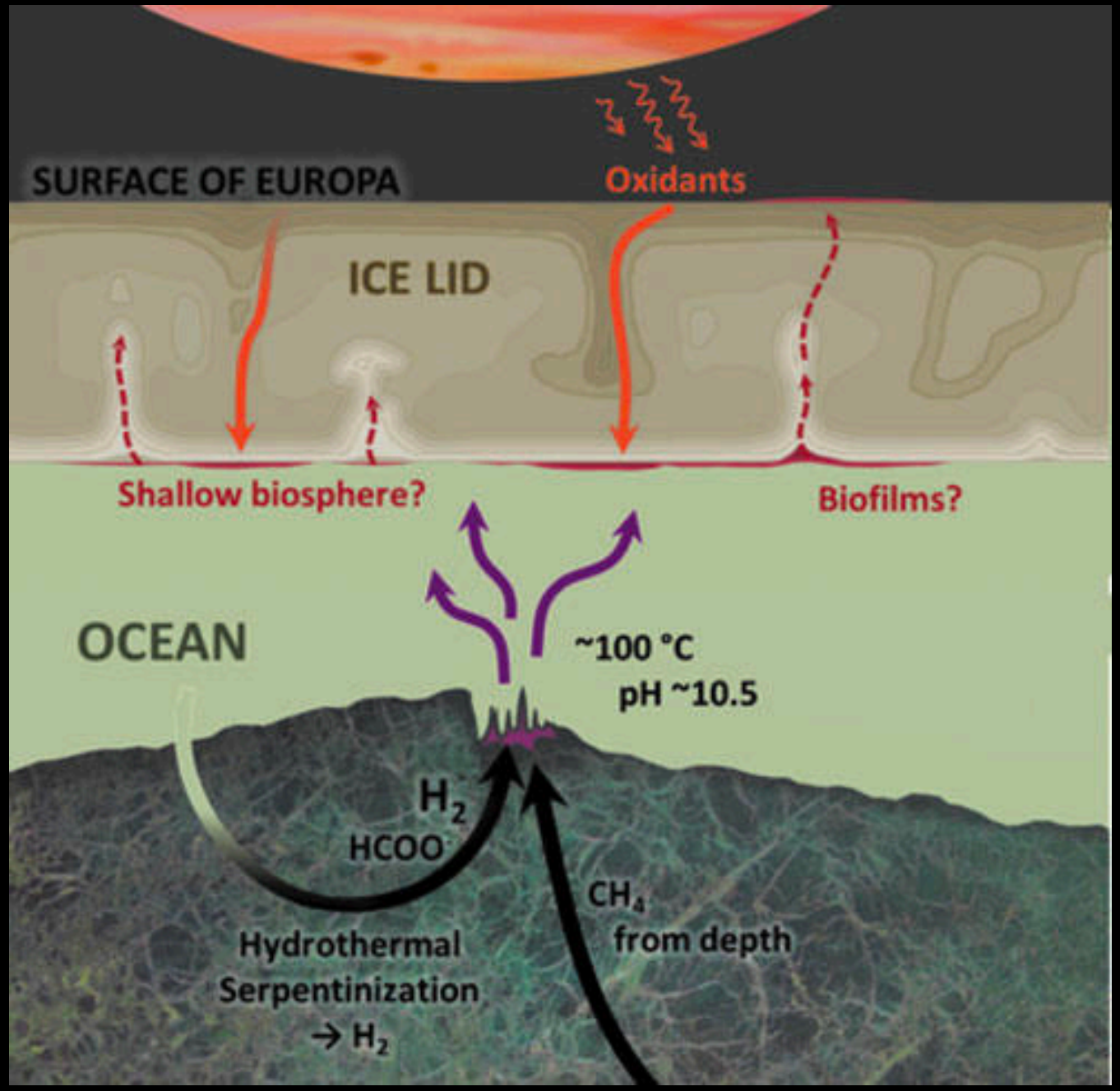


From “Adventures with cyanobacteria: a personal perspective,“ Govindjee et al. 2011

Europa

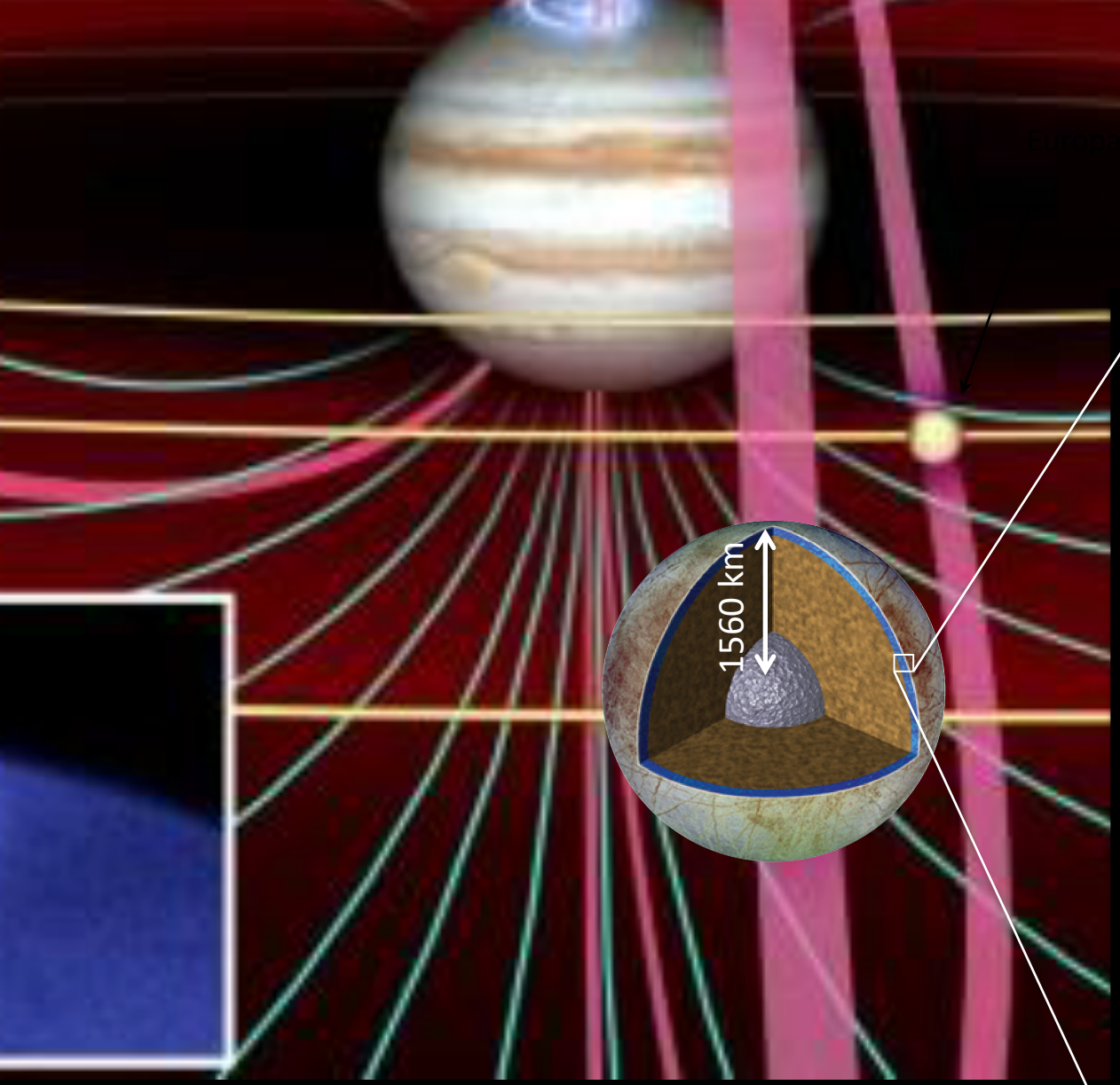


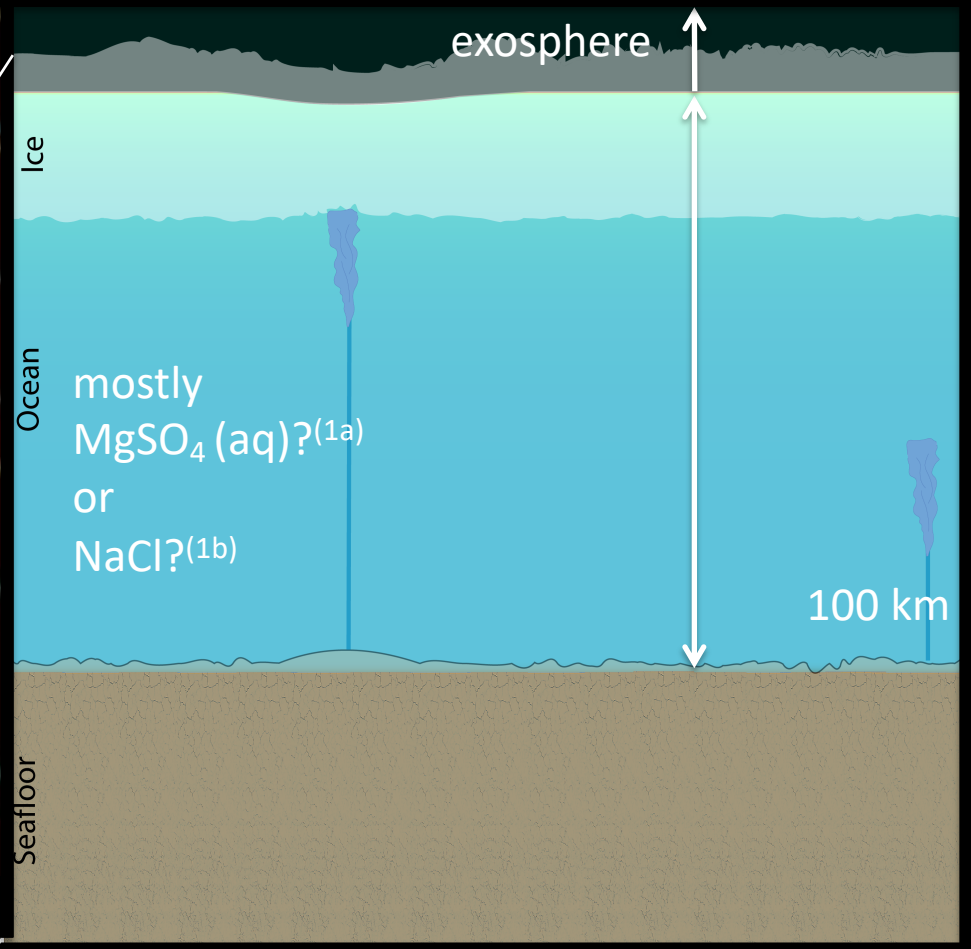
Modified from the 2016 Lander SDT Report



Russell et al. 2017

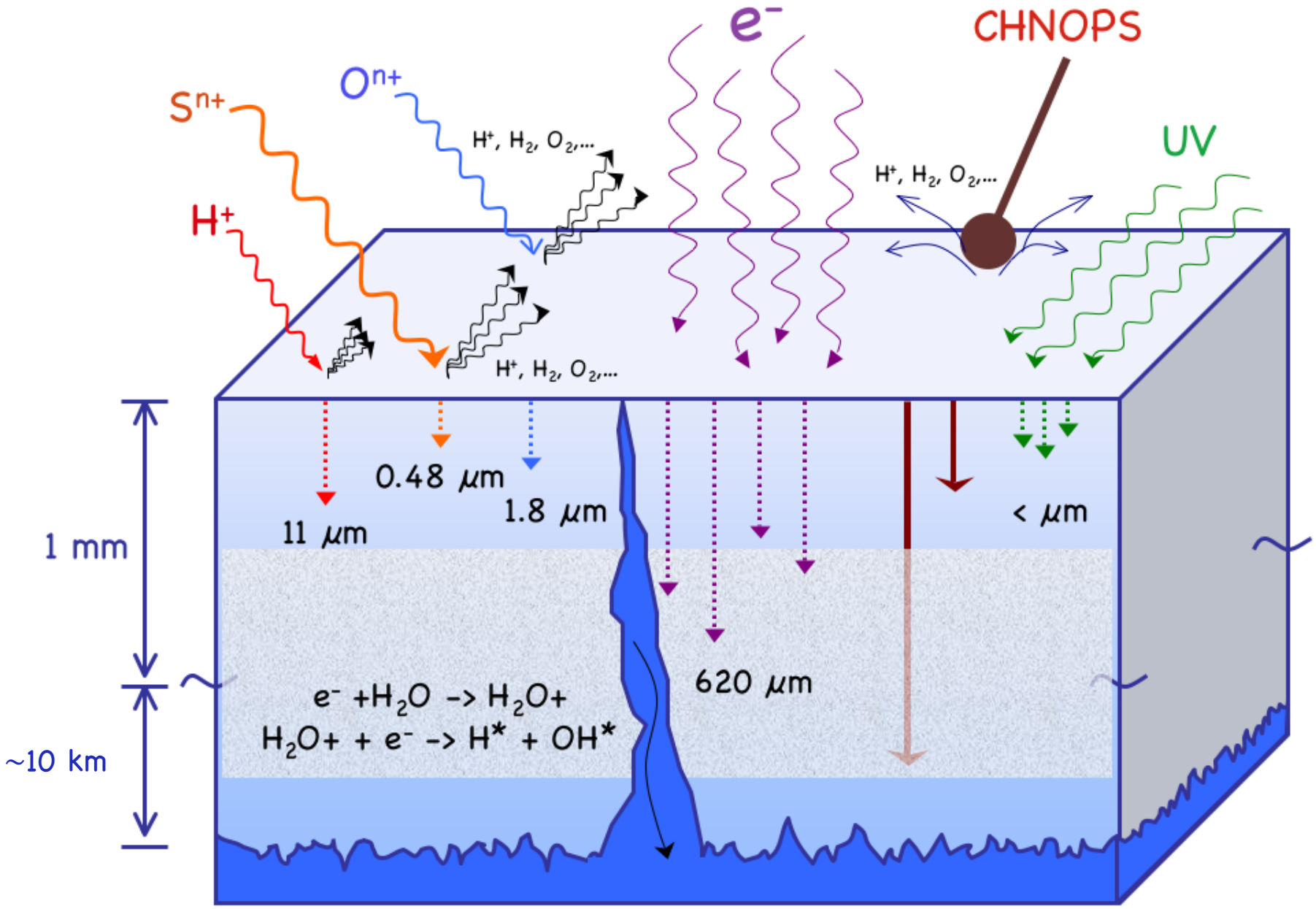
Europa





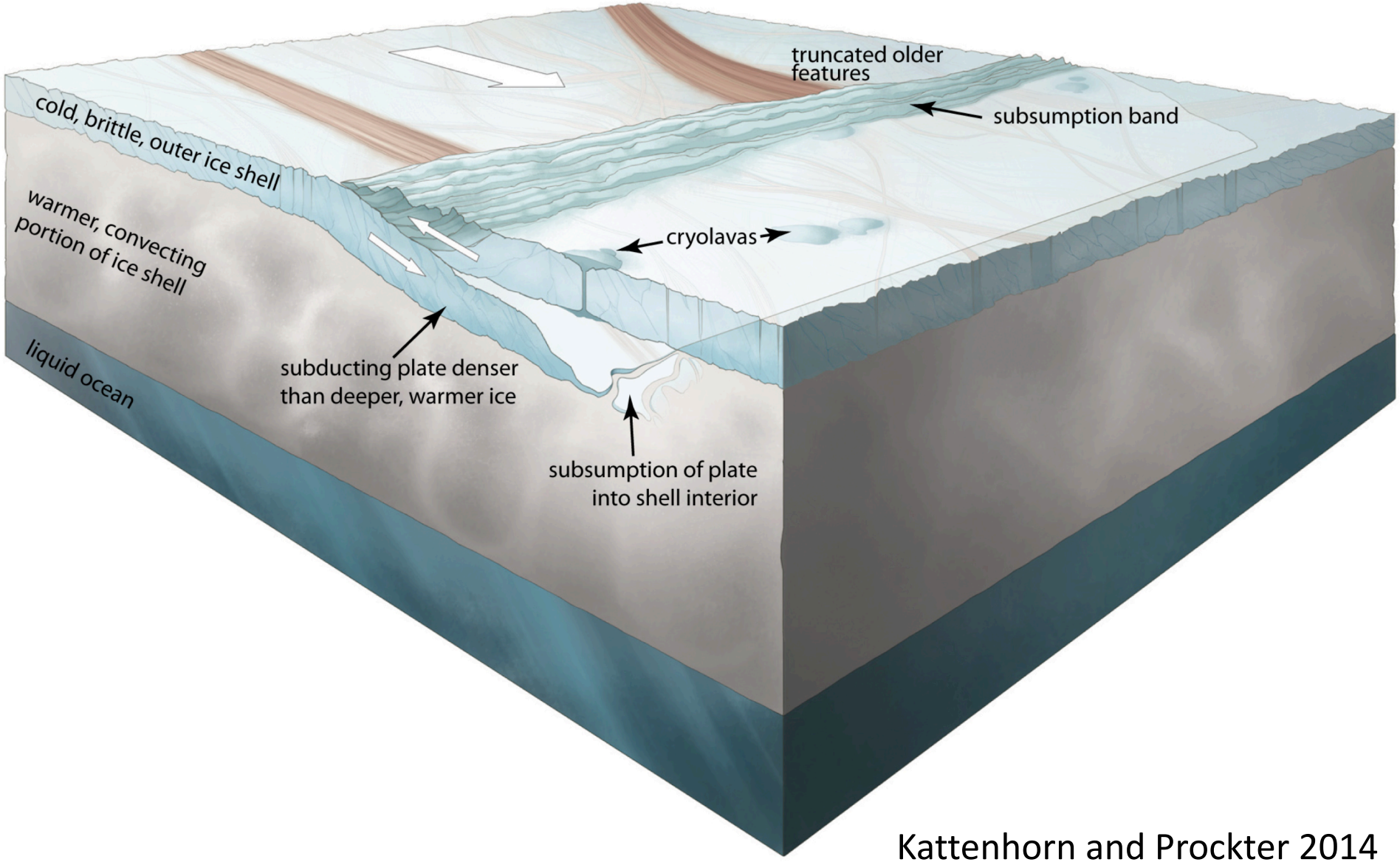
[1a]e.g., Zolotov and Kargel 2009
[1b] Brown and Hand 2013

The Surface Radiation Environment of Europa



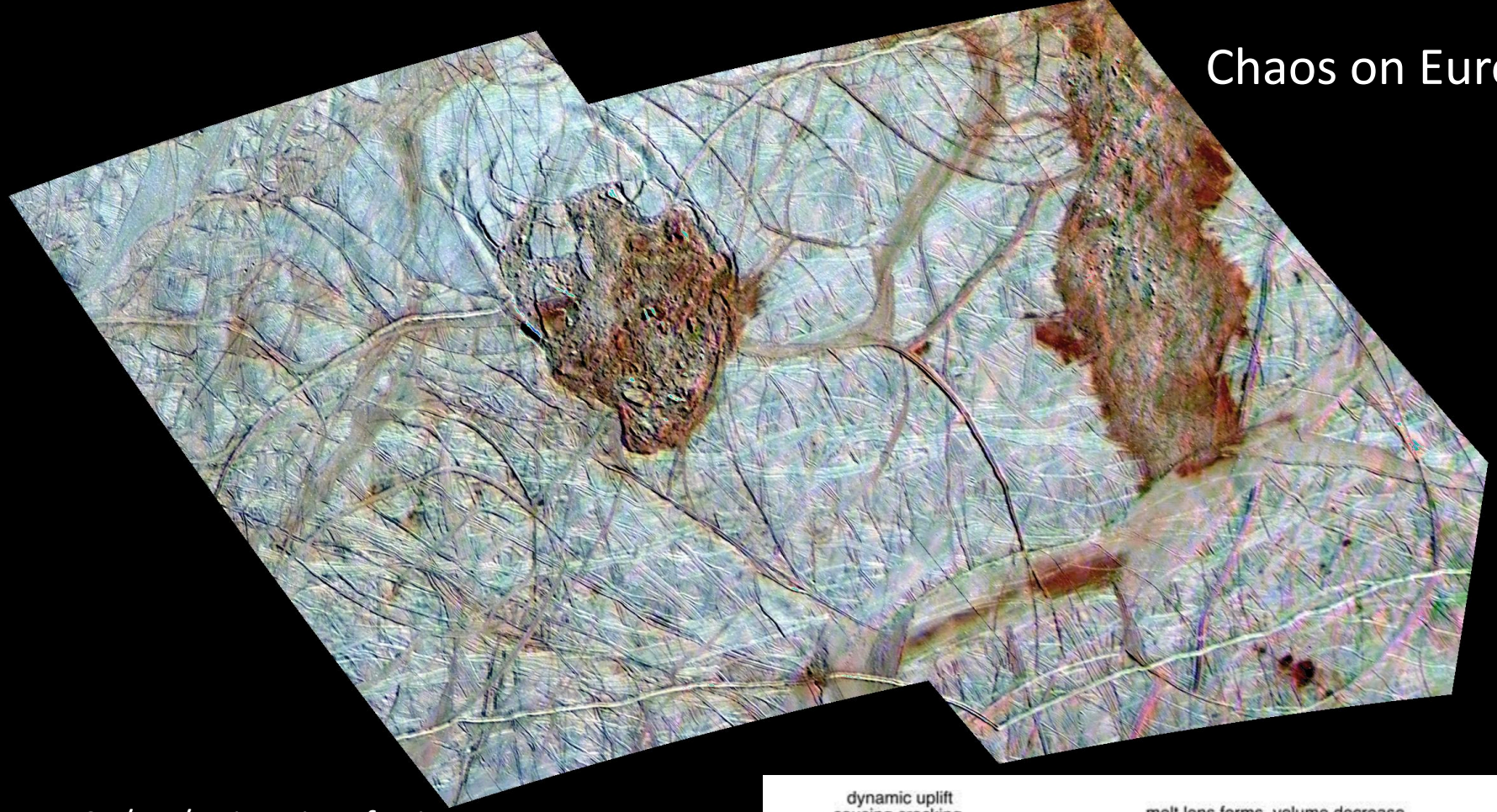
Graphic: Kevin Hand

“Plate Tectonics” on Europa

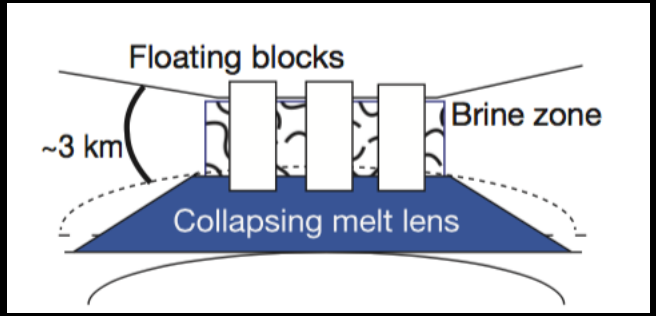


Kattenhorn and Prockter 2014

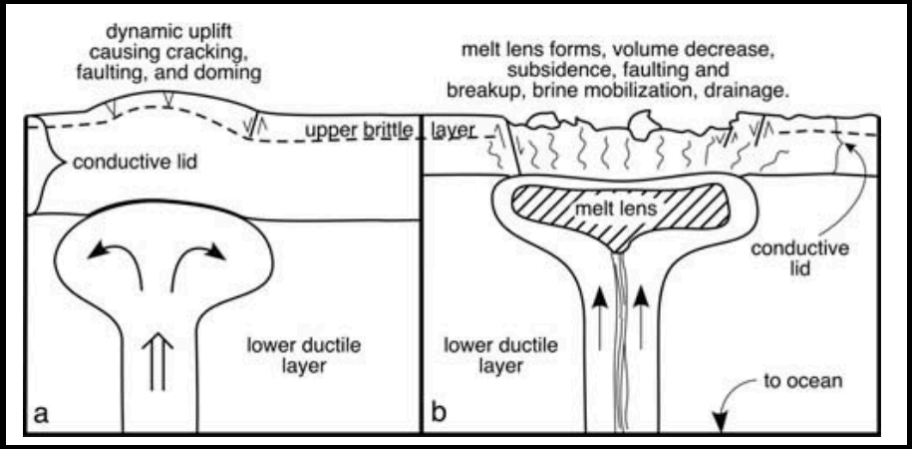
Chaos on Europa



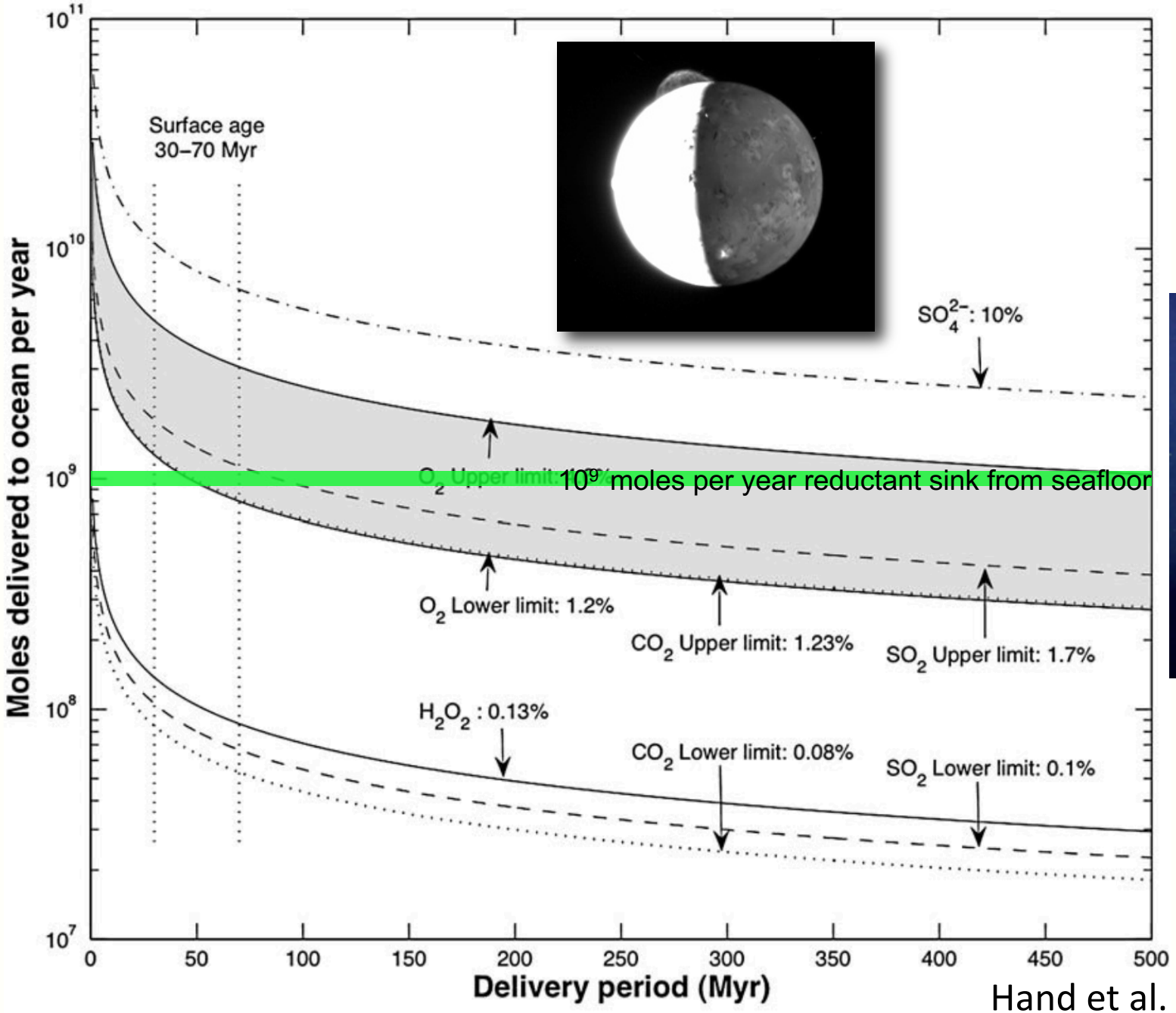
NASA/JPL/University of Arizona



Schmidt et al. 2011



Sotin et al. 2002



Hand et al. 2007, 2009

High-T Hydrothermal Reductants

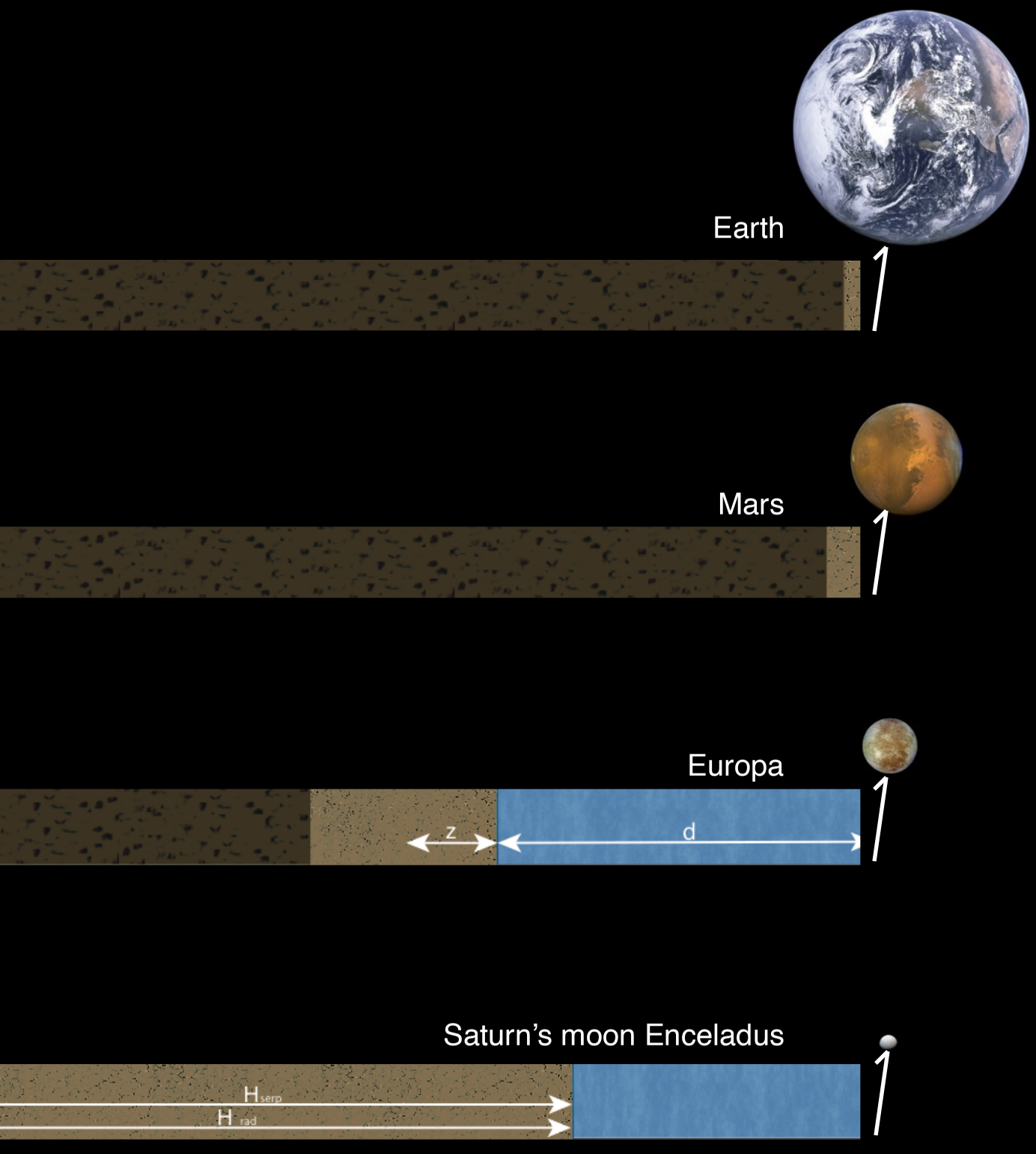
Volcanic hydrothermal flux should scale with Europa's heat:

$Q = H/c_w \Delta T$ (Lowell and Dubose 2004)

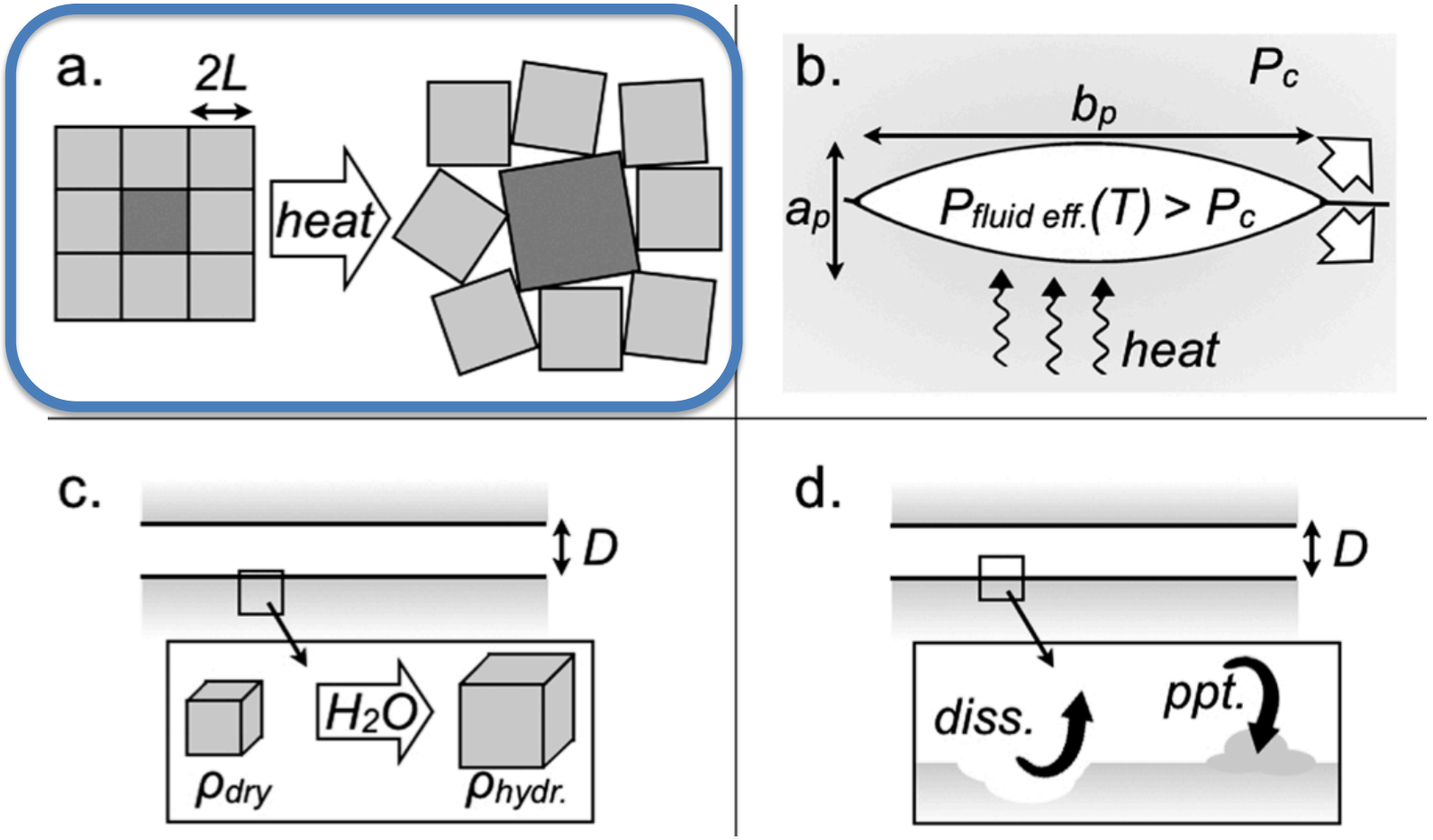
assume ΔT=350°C and 2-6 m*m* H_2 (Holland 2002)

Low-T Hydrothermal Reductants

A reducing mantle interface without tides heating the rock

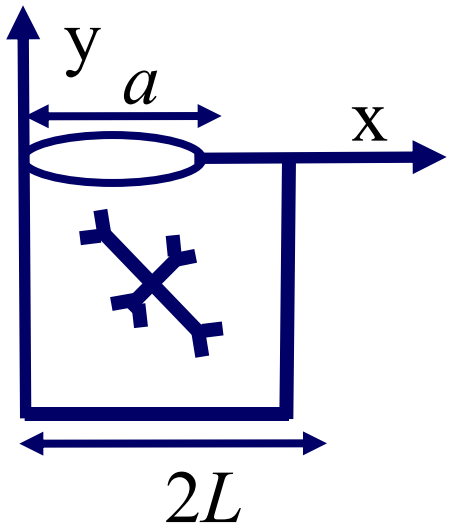

Earth
Mars
Europa
z
d
Saturn's moon Enceladus
H serp
H rad

Vance et al. 2007, Vance and Goodman 2009



Neveu et al. 2014

A cracking model is applied to a cooling mantle



$$K_I = \sqrt{\frac{2}{\pi a}} \int_0^a \frac{\sigma_{yy}(x)\sqrt{x}}{\sqrt{a-x}} dx - P_c\sqrt{\pi a}$$

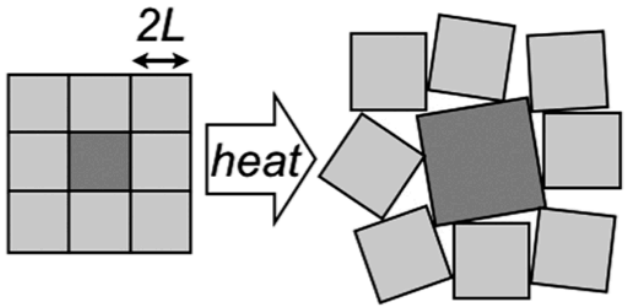
$$\sigma_{yy}(x) = \frac{E\Delta\alpha(T'-T)}{2\pi(1-\nu^2)} \left(\frac{4L^2}{4L^2+(2L-x)^2} - \frac{4L^2}{4L^2+x^2} + \ln\left[\frac{2L-x}{x}\right] - \frac{1}{2}\ln\left[\frac{4L^2+(2L-x)^2}{4L^2+x^2}\right] \right)$$

<u>olivine</u>

Grain size = 2*L*

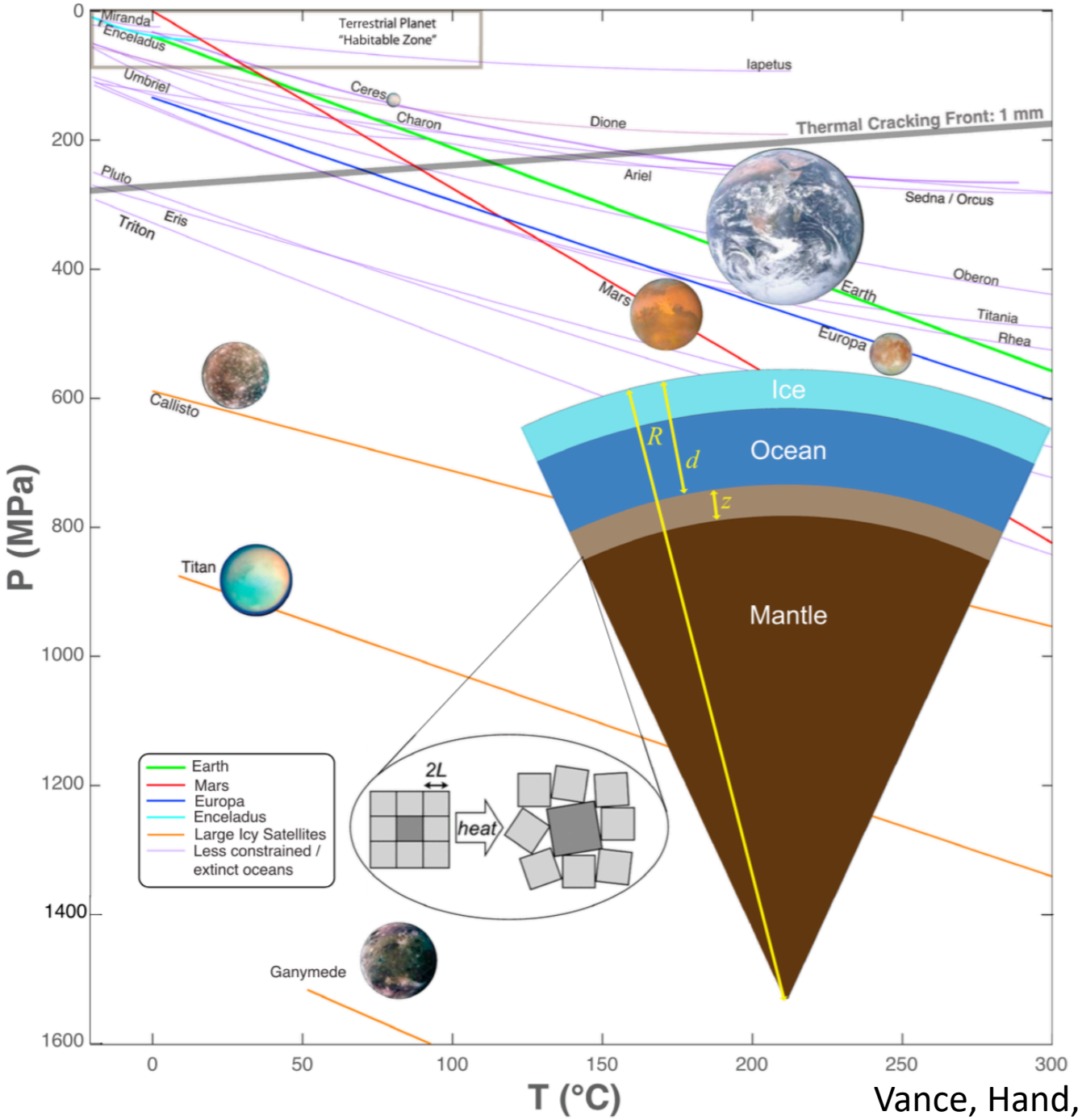
Max flaw size = *a*

$$\frac{d\langle\sigma\rangle}{dT} = \frac{12\Omega\dot{\delta}_b D_o E}{\sqrt{3}k_b L^3 \dot{T}} \frac{e^{-Q/RT}}{T}\langle\sigma\rangle - \frac{\beta E\Delta\alpha}{(1+\nu)} \Rightarrow T' \approx \frac{Q/R}{\ln\left[\frac{\sqrt{3}nk_b L^3\dot{T}}{12\Omega\delta_b D_o E}\right]}$$



Neveu et al. 2014

Vance et al. 2007, Vance and Goodman 2009



Vance, Hand, and Pappalardo, 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.

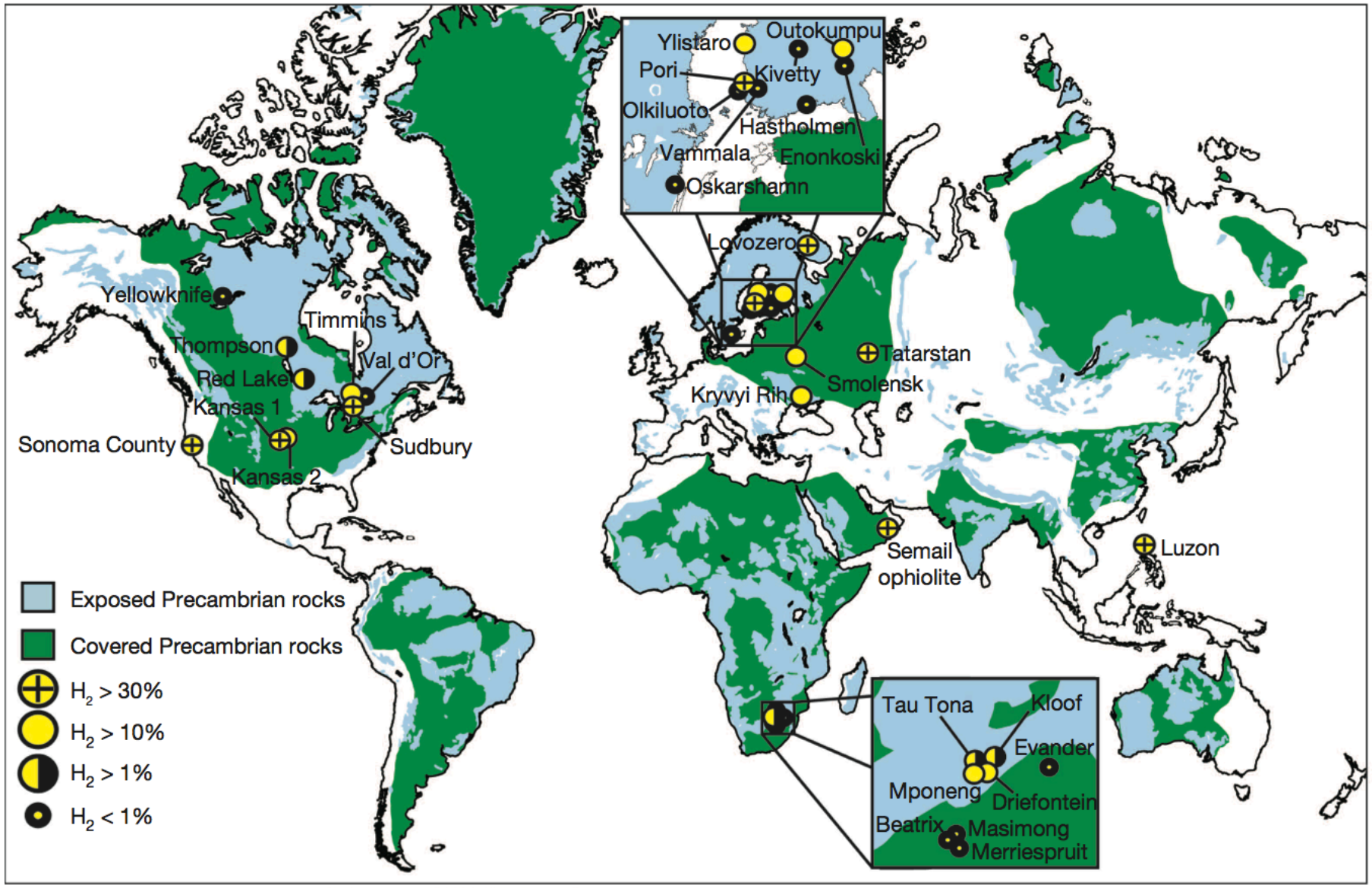
H_2

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

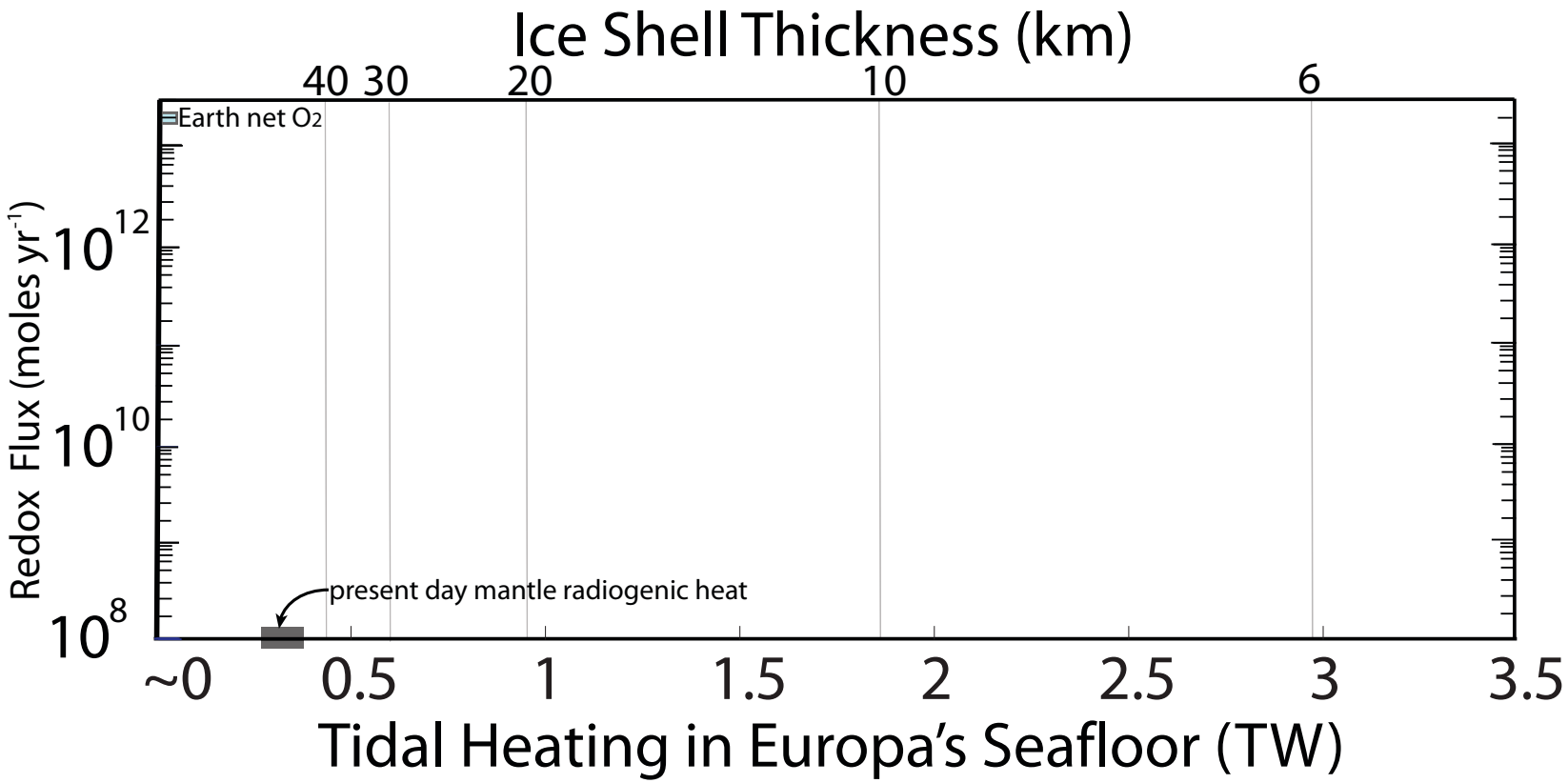
forsterite + water = brucite + serpentine.

Heat
41 kJ/mol olivine

Now accounting for estimates of H_2 and O_2 from the Earth System



Sherwood-Lollar et al. 2014

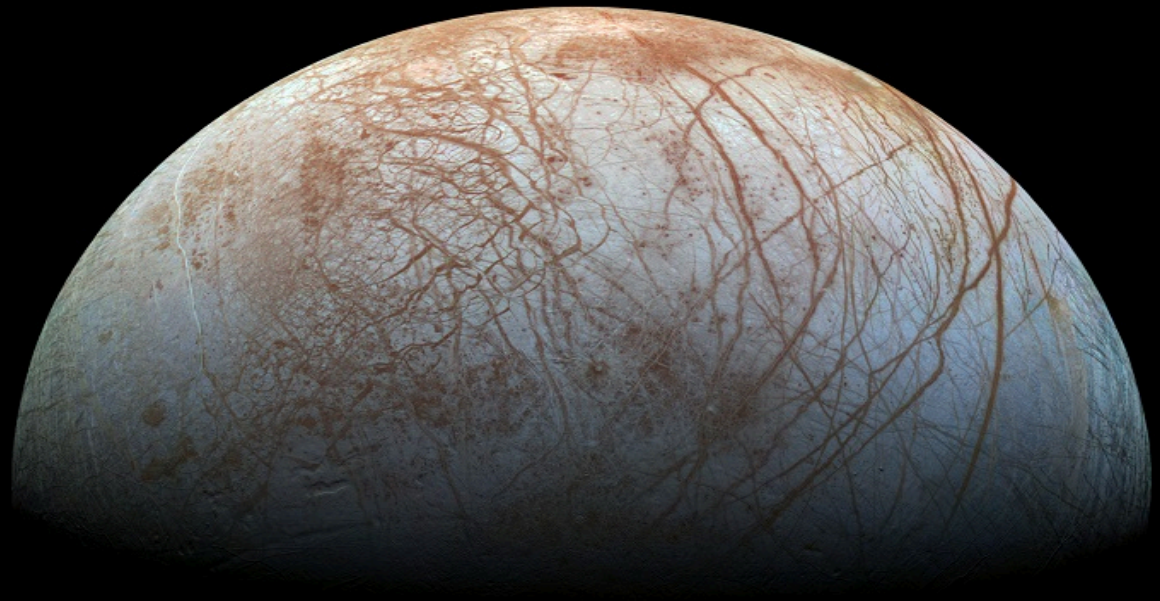


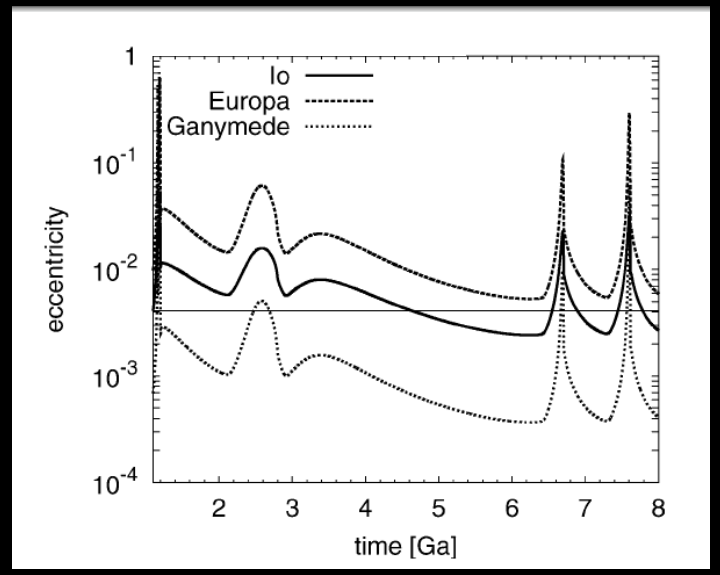
Vance, Hand, and Pappalardo, 2016

EUROPA

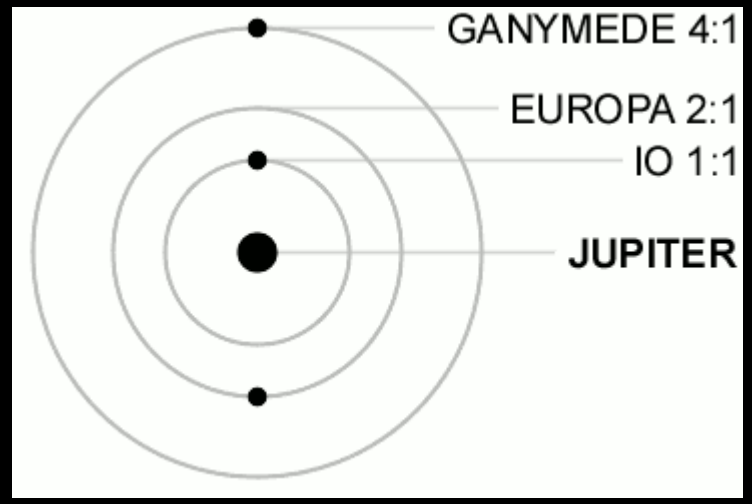
SYSTEM SCIENCE

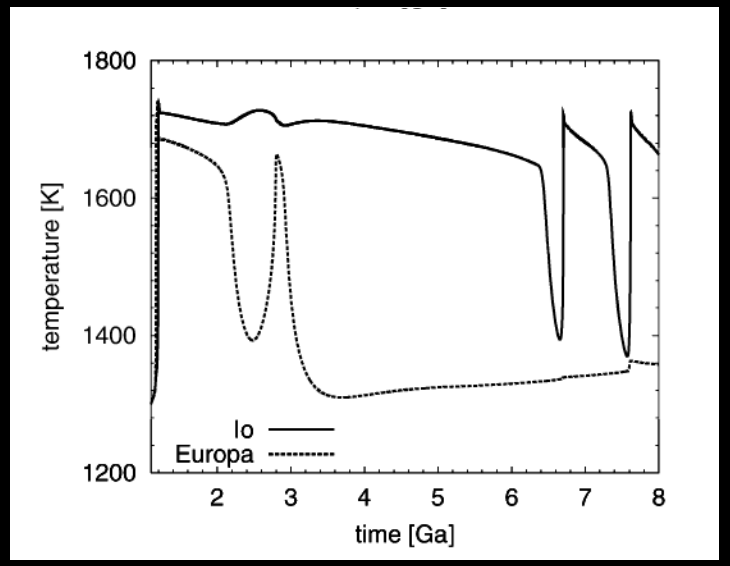
FROM BIOGEOCHEMICAL CYCLES TO GLOBAL CHANGE





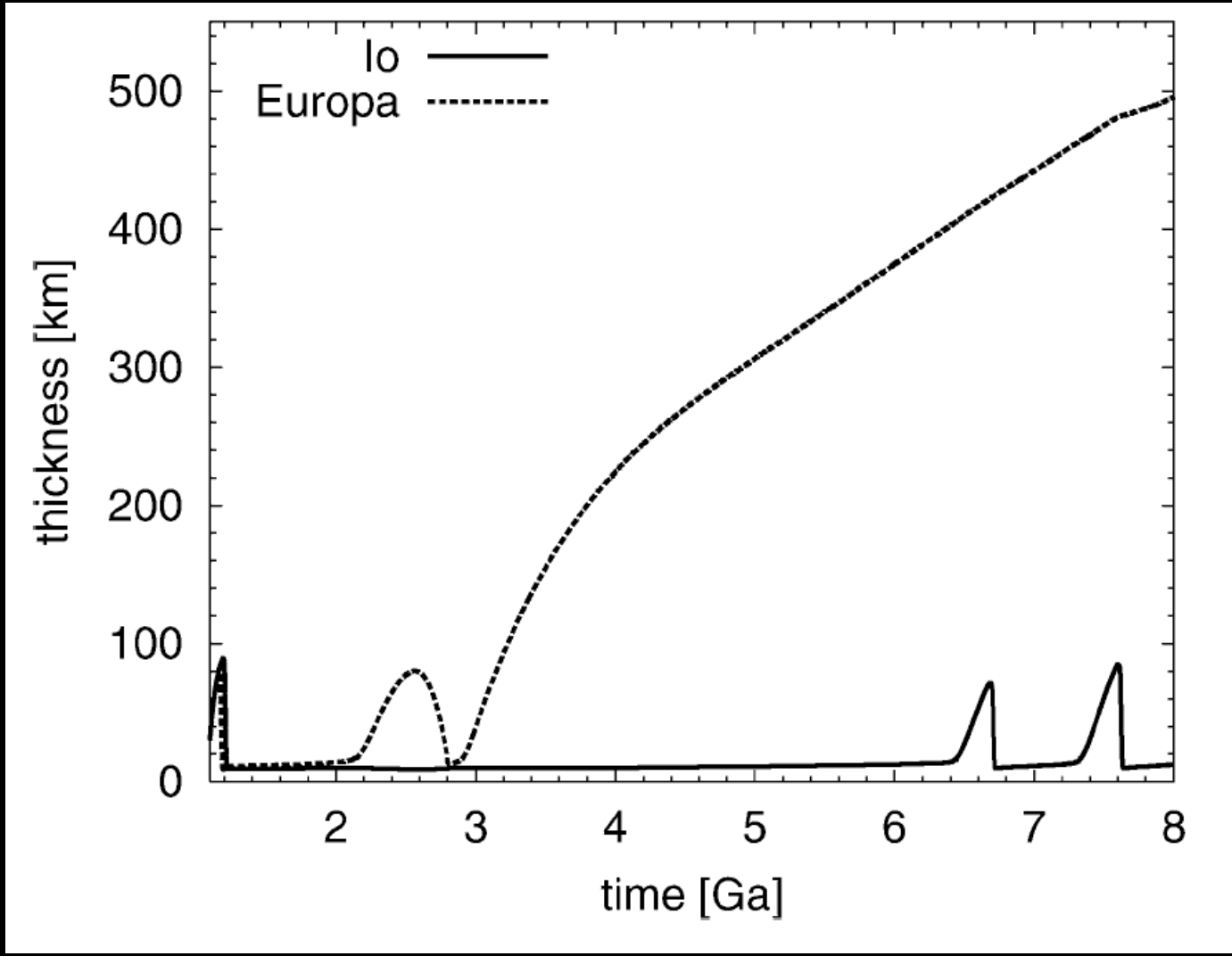
eccentricities evolved through time



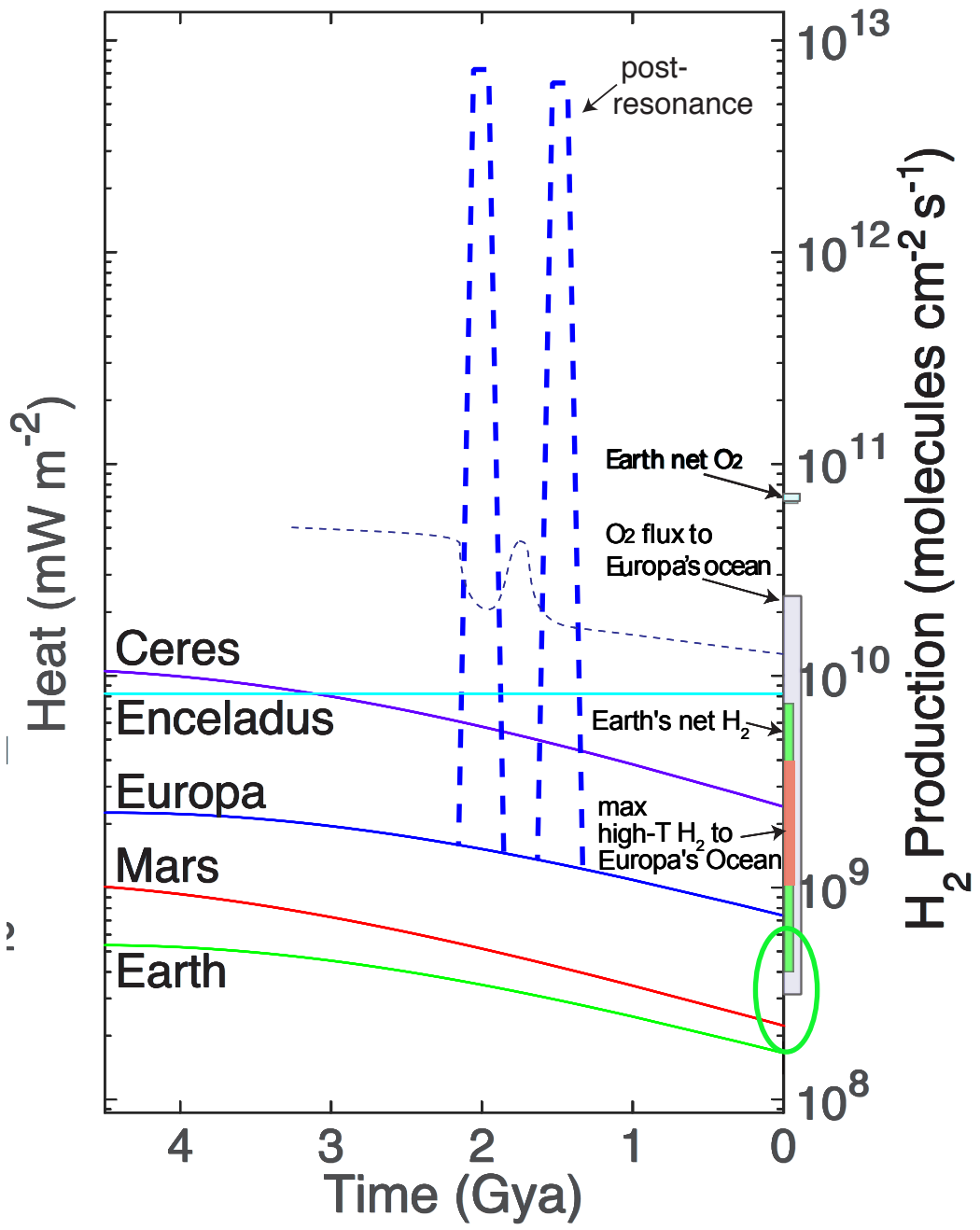


(average) mantle temperature changes in response to changes in tidal forcing.

Hussmann *et al*. 2004



Hussmann *et al.* 2004



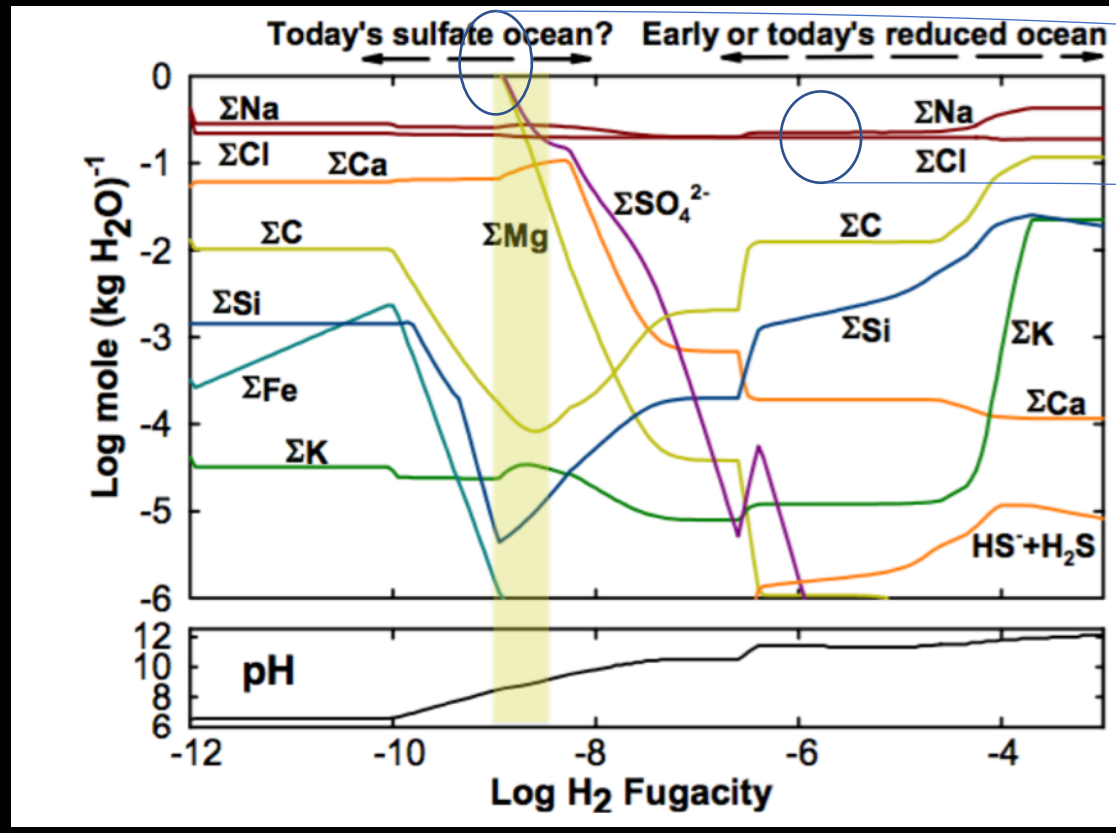
Vance, Hand, and Pappalardo, 2016

Introduction

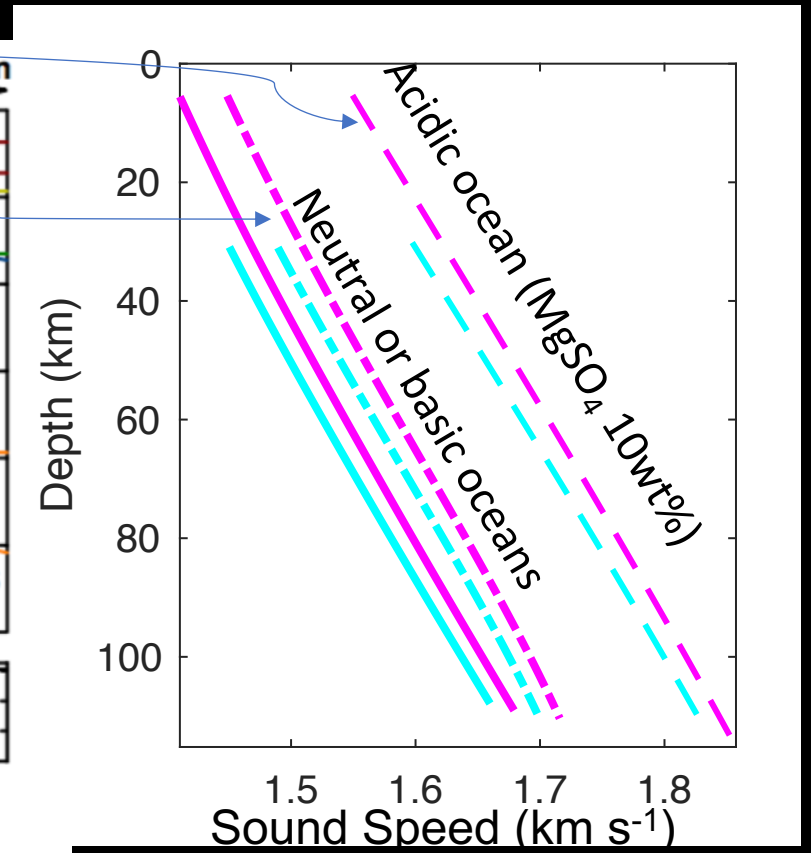
- Deep oceans on other worlds!
- Expand the parameter space of possible ocean properties
  - A broad range of **P, T**, and **undetermined composition**
  - Ocean and ice composition affect thermal properties, melting points.
  - These are being explored in the lab
- This will be important as **new spacecraft measurements** improve constraints on
  - composition, heat flow, density structure, etc…

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

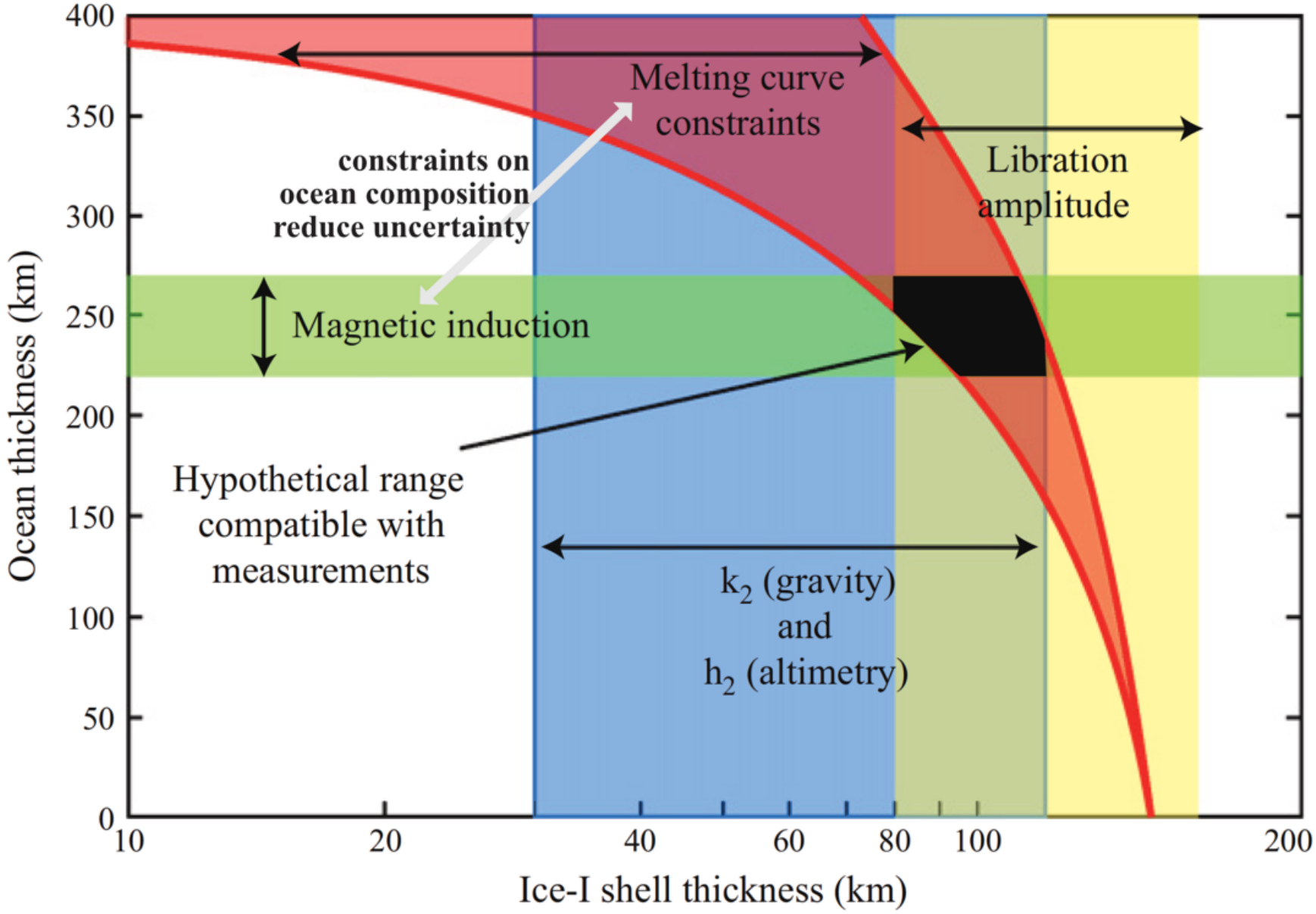
NaCl



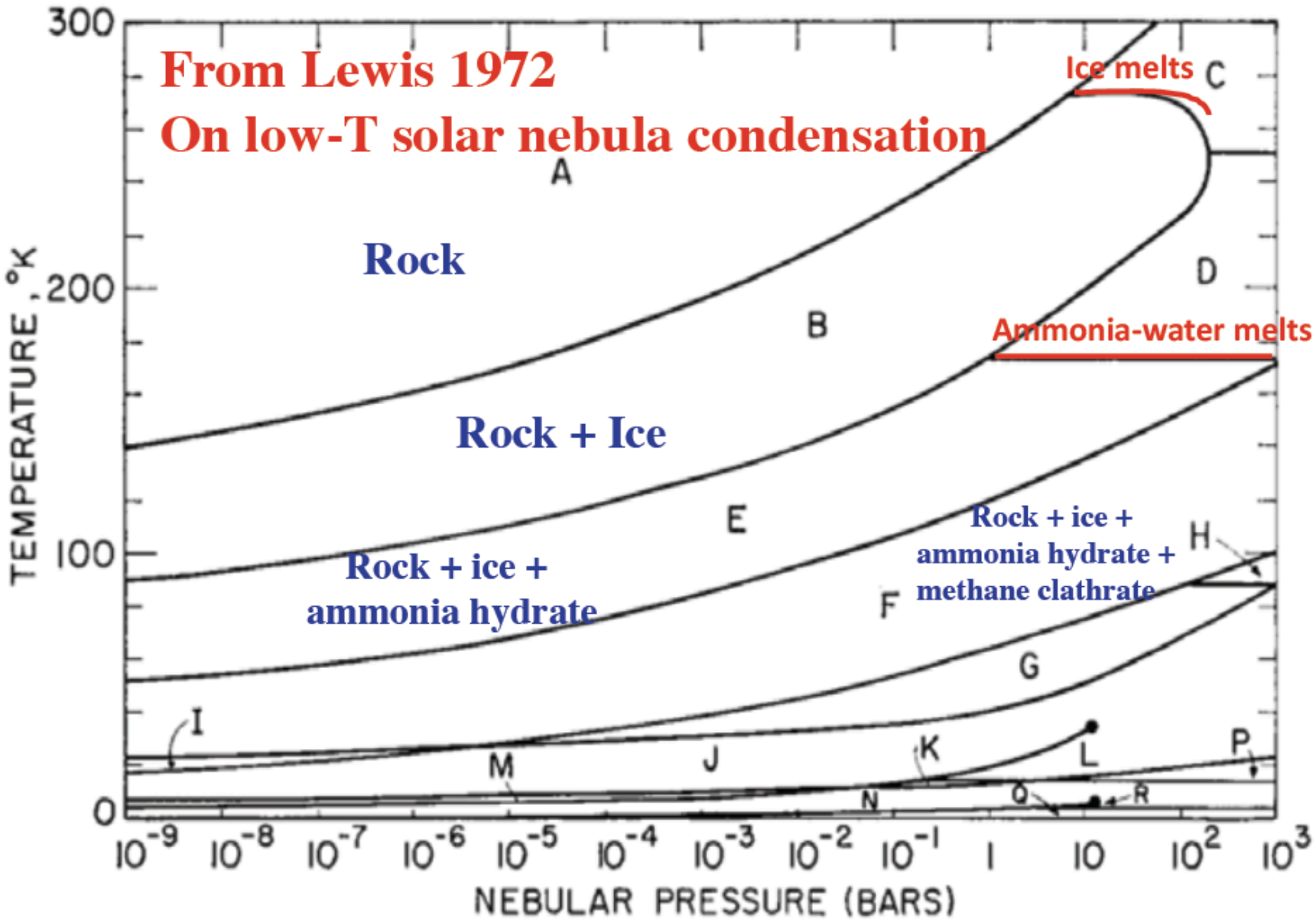
Modified from Zolotov 2008



Modified from Vance et al. 2017, JGR



modified from Grasset et al. 2013, **JUpiter ICy moons Explorer**



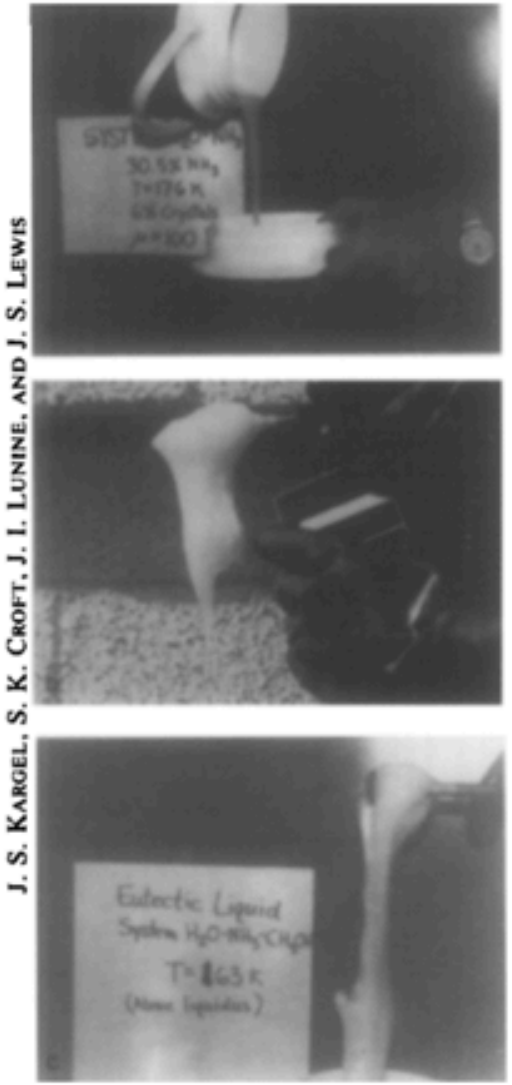
Slide courtesy of Jeff Kargel

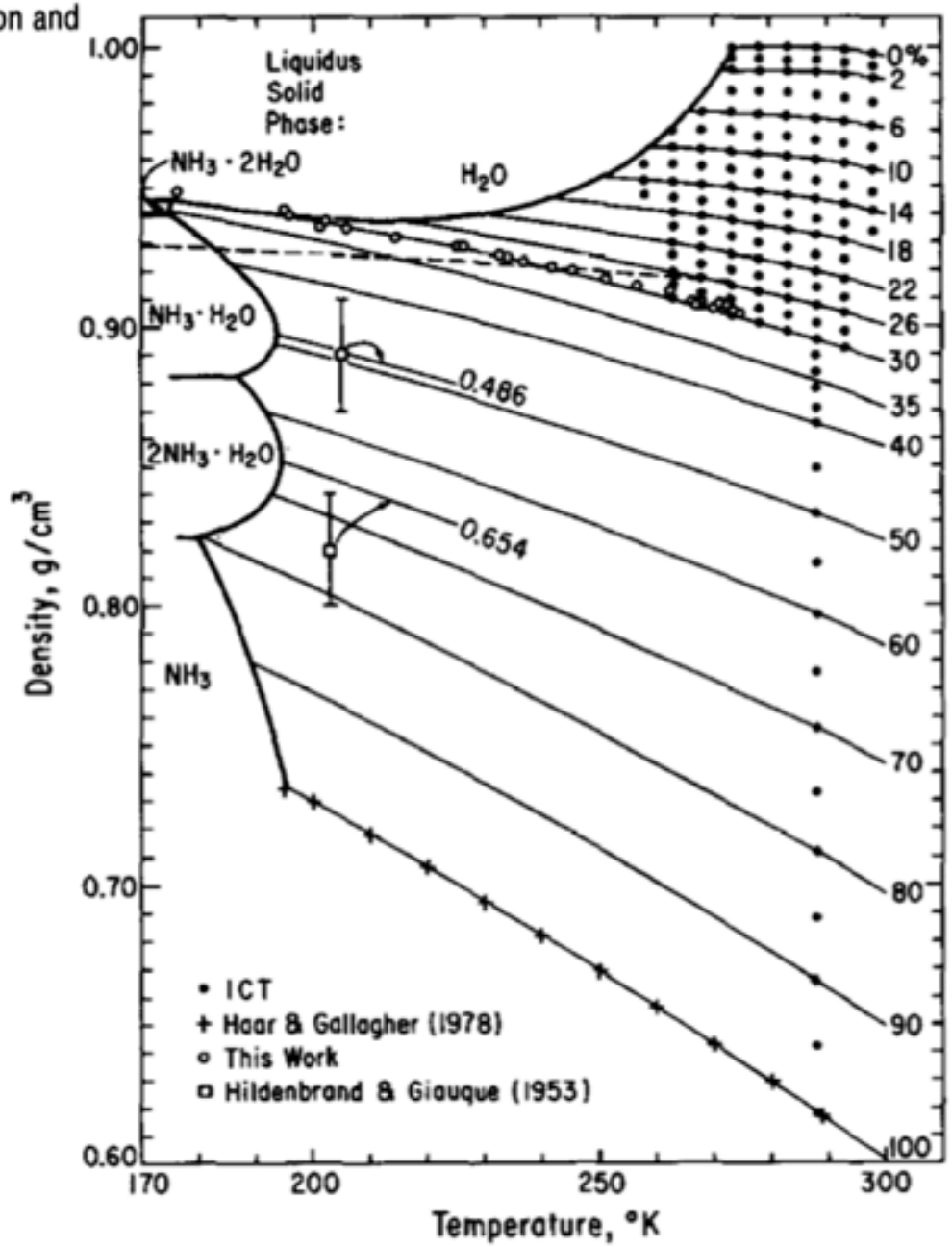
Equation of State of Ammonia–Water Liquid: Derivation and Planetological Applications[1]

S. K. CROFT, J. I. LUNINE, AND J. KARGEL

Rheological Properties of Ammonia–Water Liquids and Crystal–Liquid Slurries: Planetological Applications

J. S. KARGEL, S. K. CROFT, J. I. LUNINE, AND J. S. LEWIS

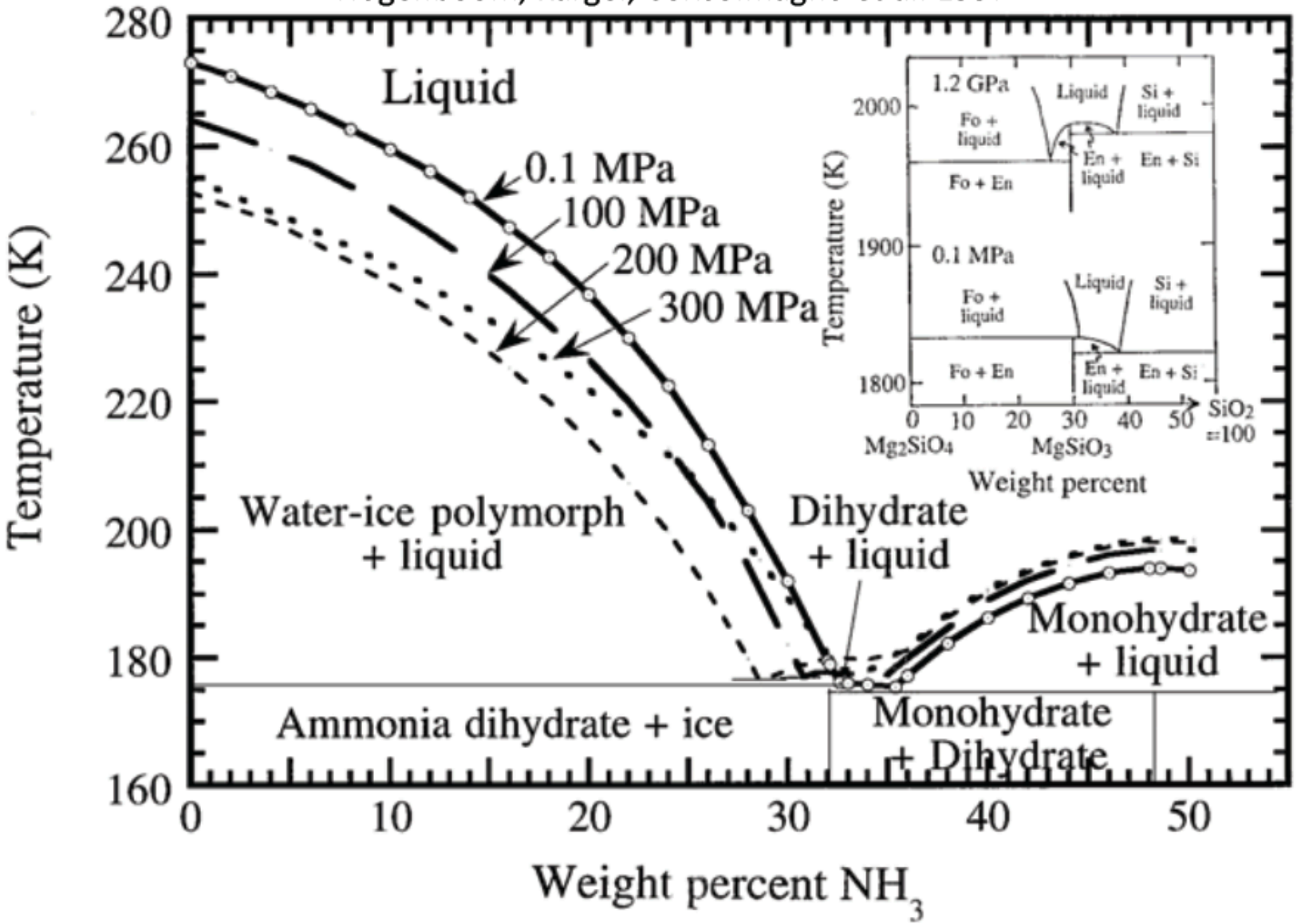




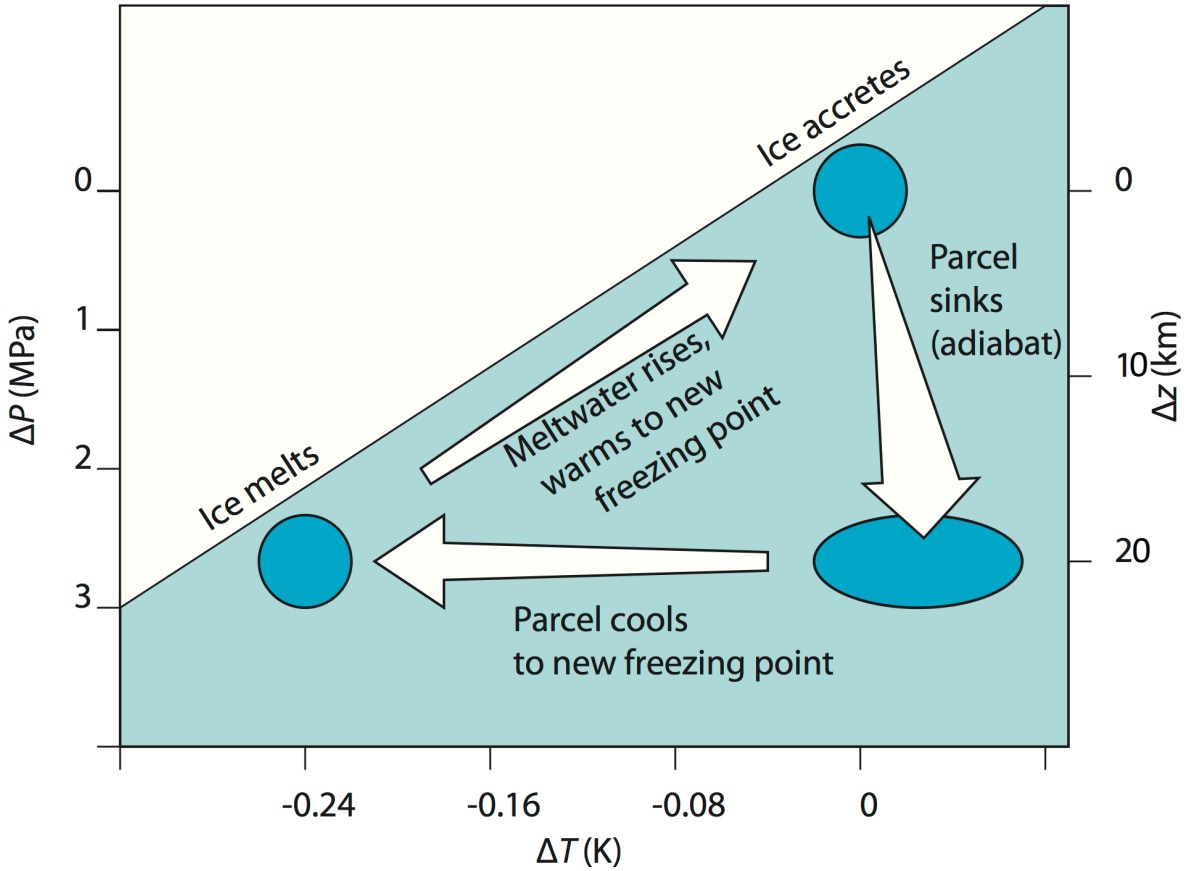
Slide courtesy of Jeff Kargel

The Ammonia–Water System and the Chemical Differentiation of Icy Satellites

Hogenboom, Kargel, Consolmagno et al. 1997

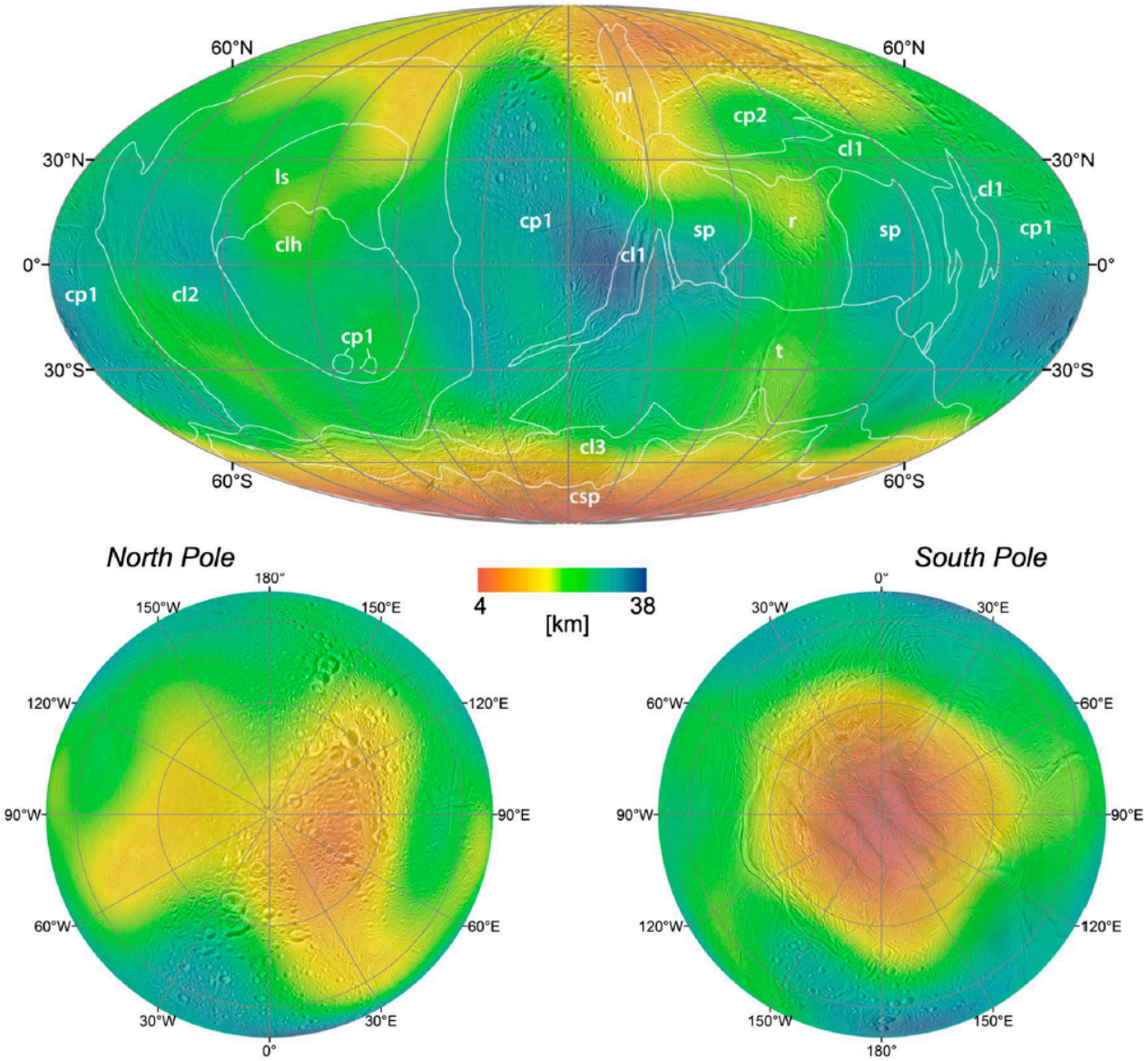


Slide courtesy of Jeff Kargel

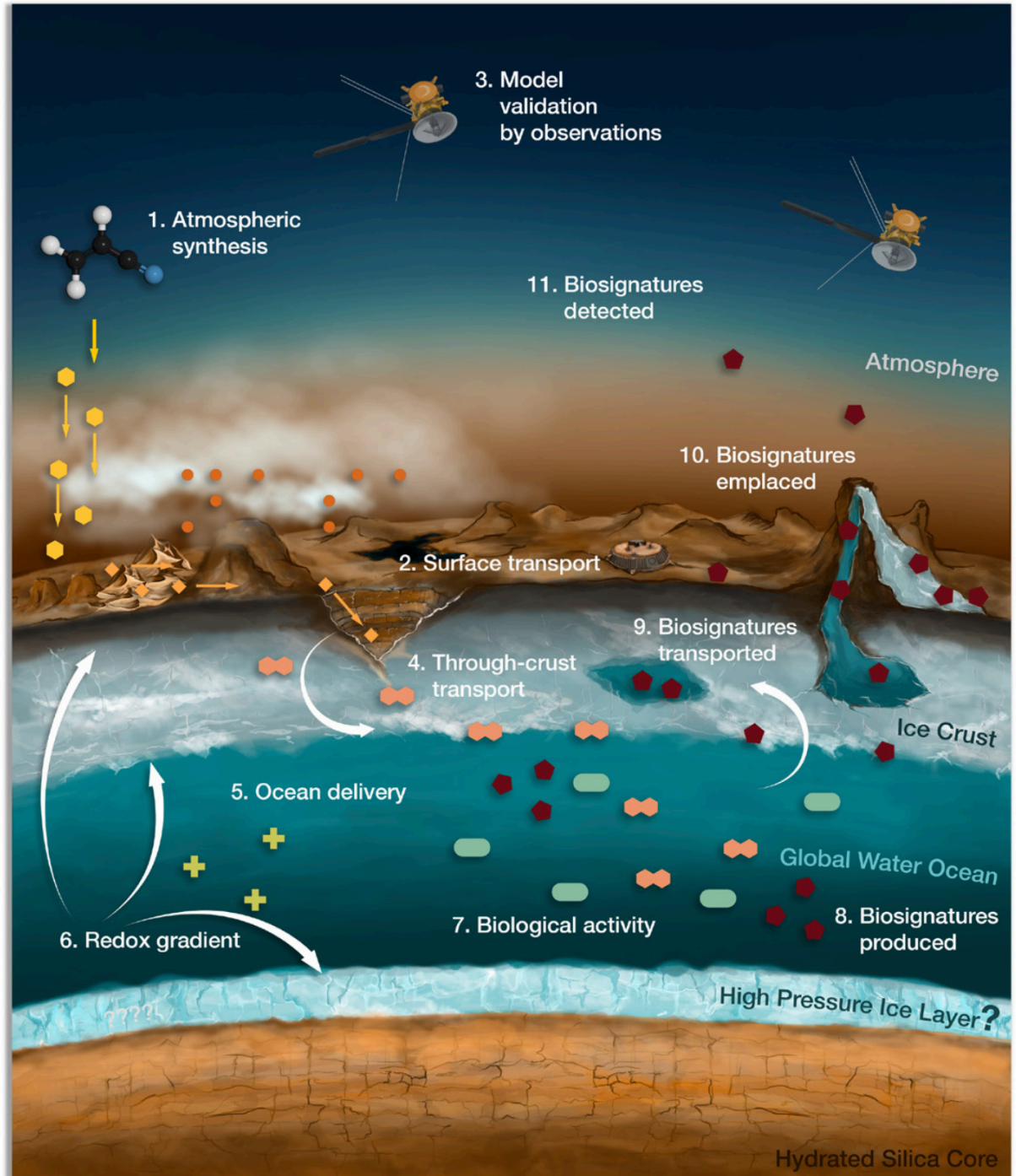


Modified from Vance and Goodman 2009

Enceladus Ice shell thickness



Cadek et al. 2016



- Surface Sediments
- Atmospheric Fallout
- Potential Life
- Inorganic Ions
- Delivered Organics
- Volatile Methane
- Potential Chemical Biosignatures

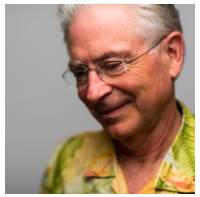
HABITABILITY OF HYDROCARBON WORLDS

TITAN AND BEYOND

Exploring material properties

Olivier Bollengier, Mineral Physics Lab, UW Seattle

Equations of State
(here come some thermodynamics)



J Michael Brown

Gibbs Energy Derivatives

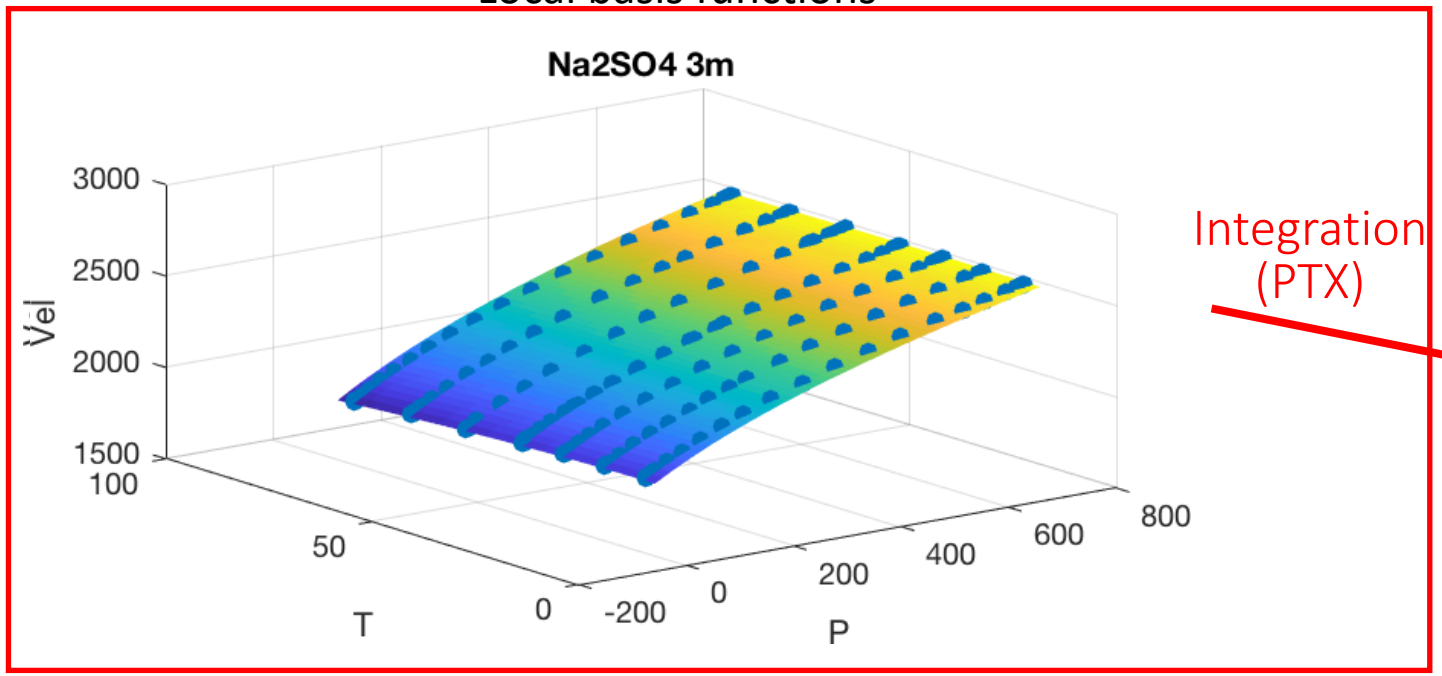
G is solution of an ODE

Volume (1/Density)	$V = dG/dP$	G_P
Measure These →		Determine G
Specific Heat (constant pressure)	$-C_p/T$	G_{2T}
Predict These ←		Know G
Chemical Potential	μ	G_x
Thermal Expansivity	α	G_{PT}/G_P
Sound Speed	u^2	$\dfrac{G_P^2 G_{2T}}{G_{PT}^2 - G_{2T}G_{2P}}$

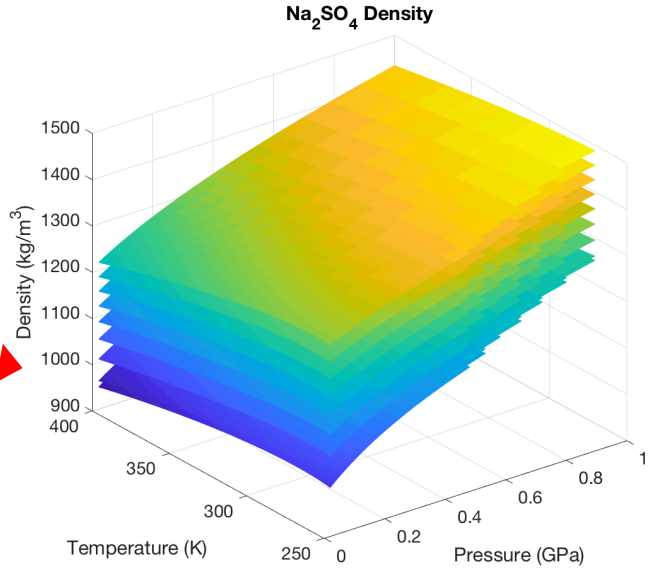
Gibbs energy at high pressure is determined from sound speeds vs P, T, and m

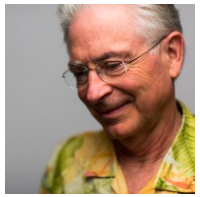
Speeds of sound in Na-Mg-Cl-SO_4-NH_3 brines

Local basis functions*



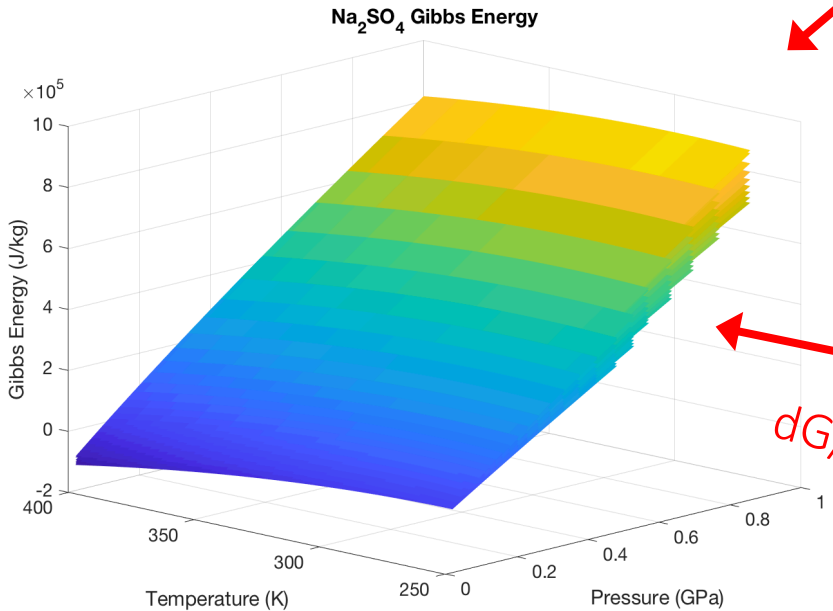
Integration (PTX)



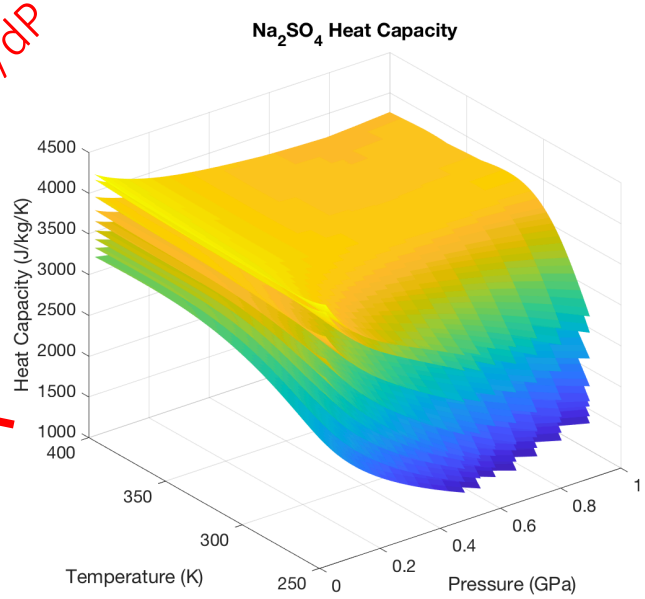


J Michael Brown

dG/dP



dG/dT



*Brown 2018, Fluid Phase Equilibria

Speed of sound: the Na-Mg-Cl-SO_4 brines

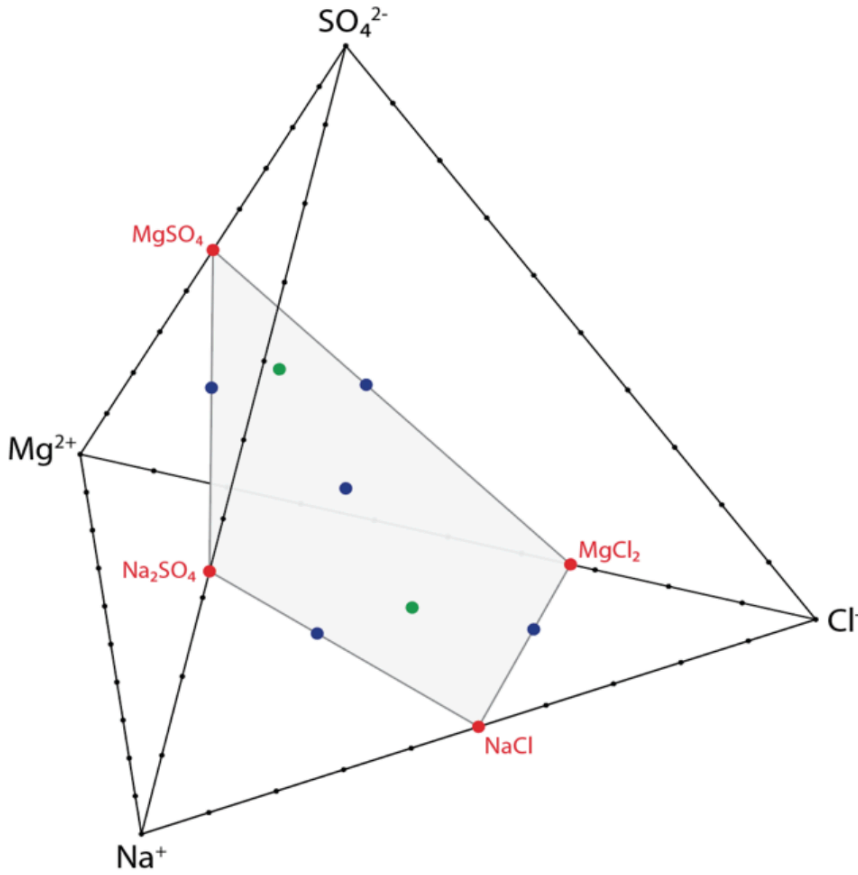
The Na-Mg-Cl-SO_4 brines

SCARCE LITERATURE

- all salts to 100 MPa [Chen et al. 1977]
- $MgSO_4$ to 700 MPa @ 0.25% [Vance and Brown 2013]
- 1 m Na_2SO_4 to 3 GPa @ 2% [Mantegazzi et al. 2012]
- 1, 3 m NaCl to 4.5 GPa @ 2% [Mantegazzi et al. 2013]

UW BRINES DATABASE

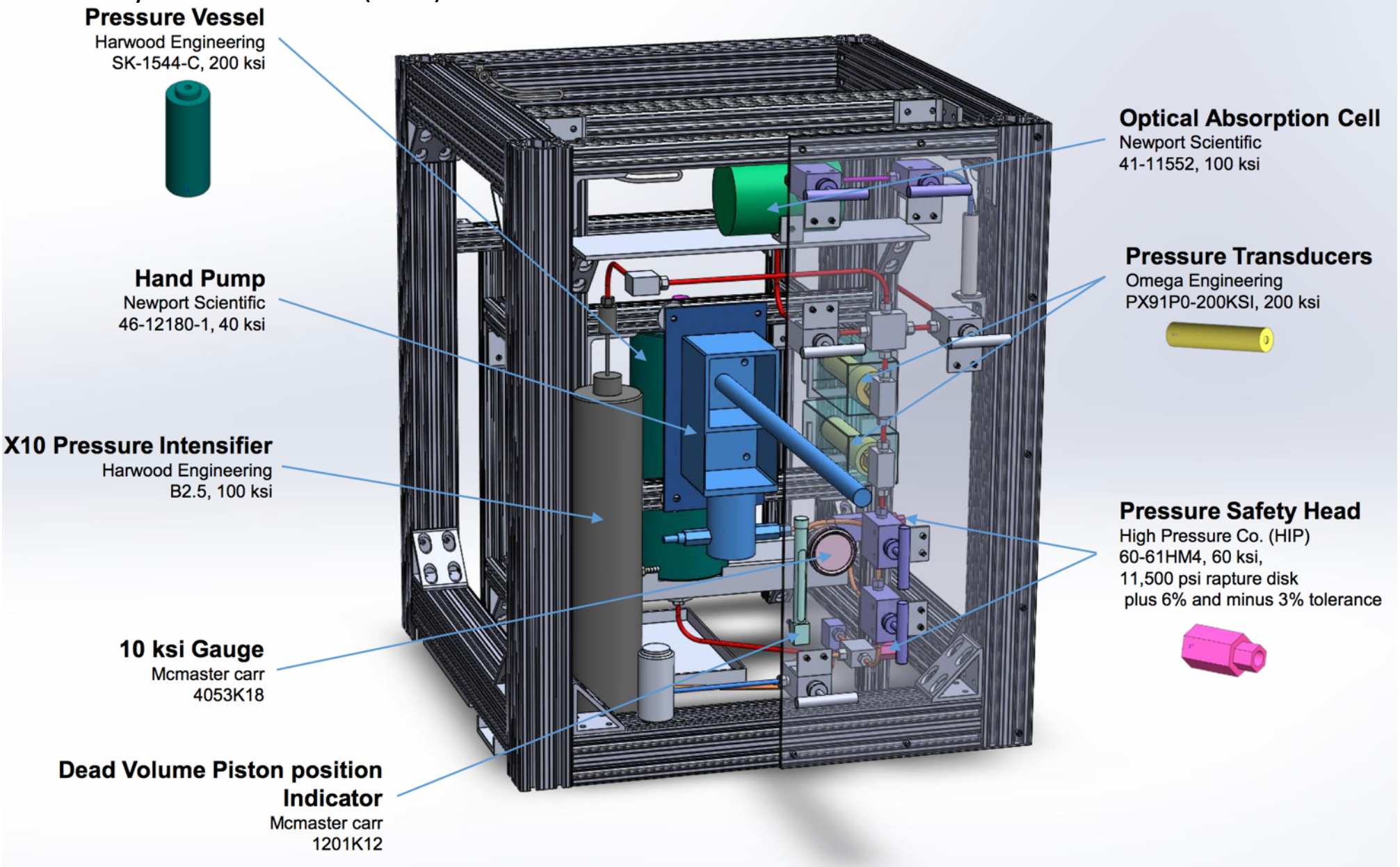
- NaCl, $NaSO_4$, $MgSO_4$, $MgCl_2$ @ 0.02%
- 0.1-700 MPa, 250-350 K
- 1/3, 1, 3 molal (+ 5 molal for Cl brines)
- 19 samples, 3300 sound speeds
- self-consistent pure water
- data collection recently completed
- beginning mixed solutions
- beginning the addition of NH3
- building additional experiment at JPL



New JPL High-Pressure Facility

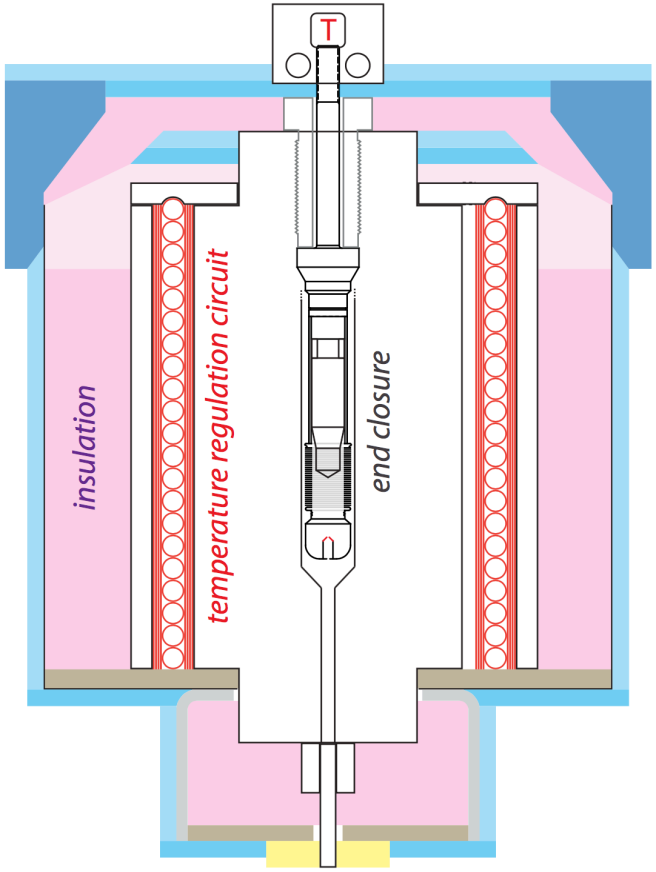
based on the UW simulator for icy world interiors (SIWI)

100,000 psi operating pressure

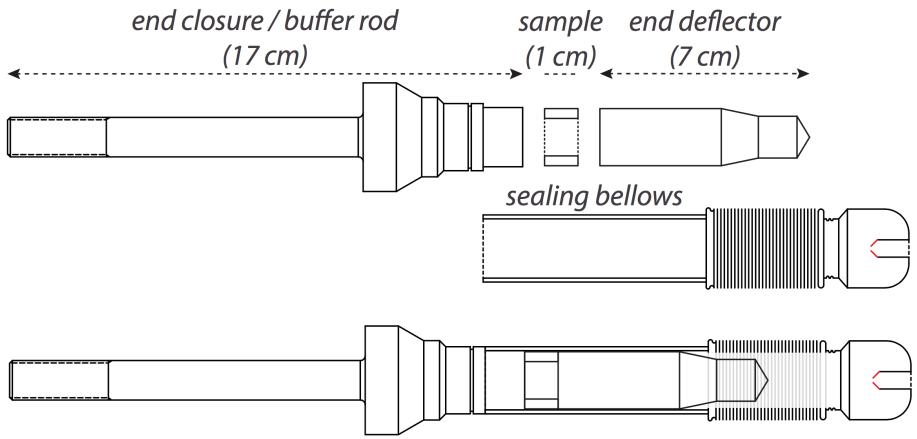


Speed of sound: the Na-Mg-Cl-SO_4-NH_3 brines

A high-pressure apparatus to measure sound speeds



Insulated high-pressure tank

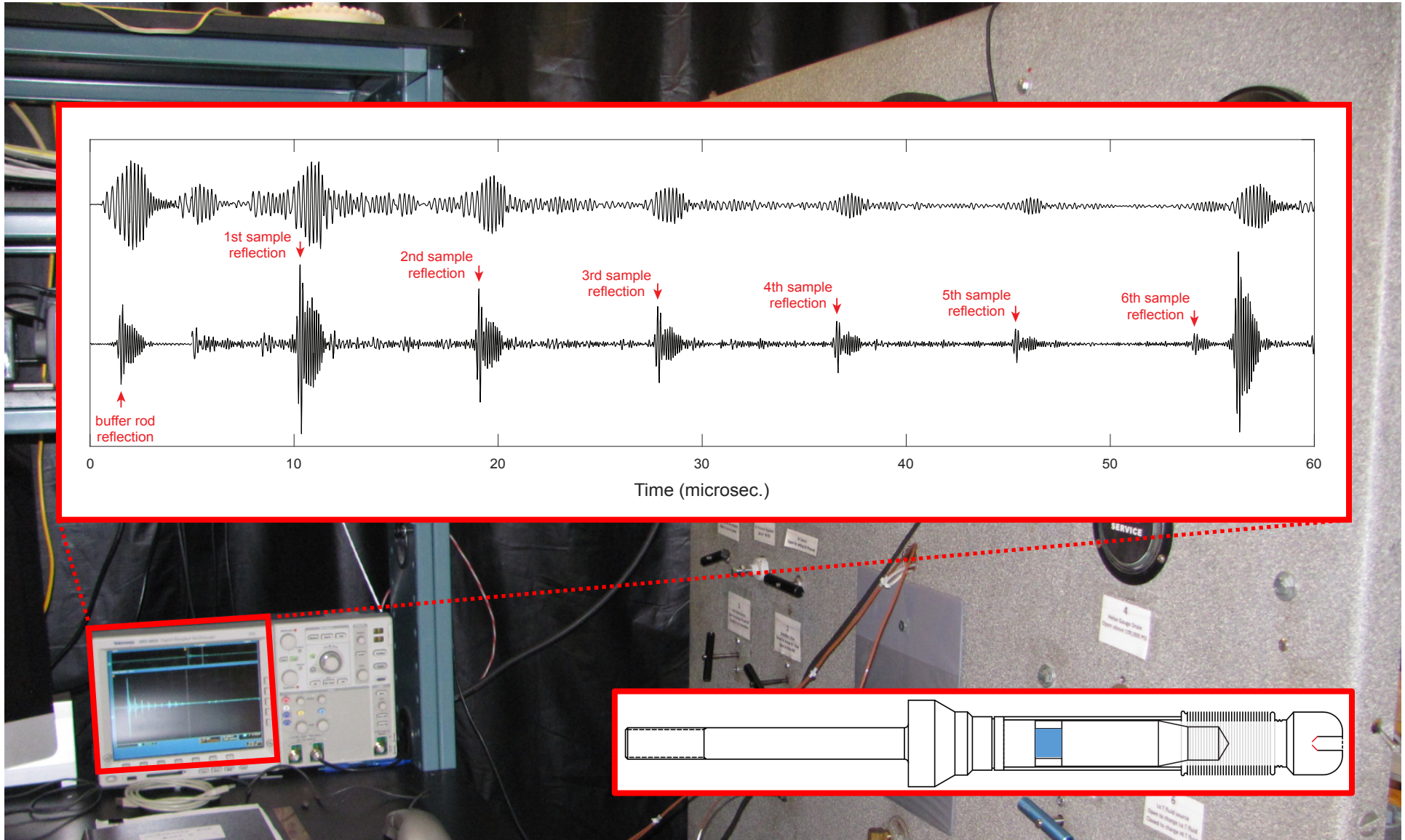


The end supports the sample chamber (inside the tank), and the ultrasonic transducer (outside the tank). The bellows adapt to change of sample volume (compressibility, expansivity) while keeping the sample pristine.

Maximum pressure: 800 MPa (Ti alloy).

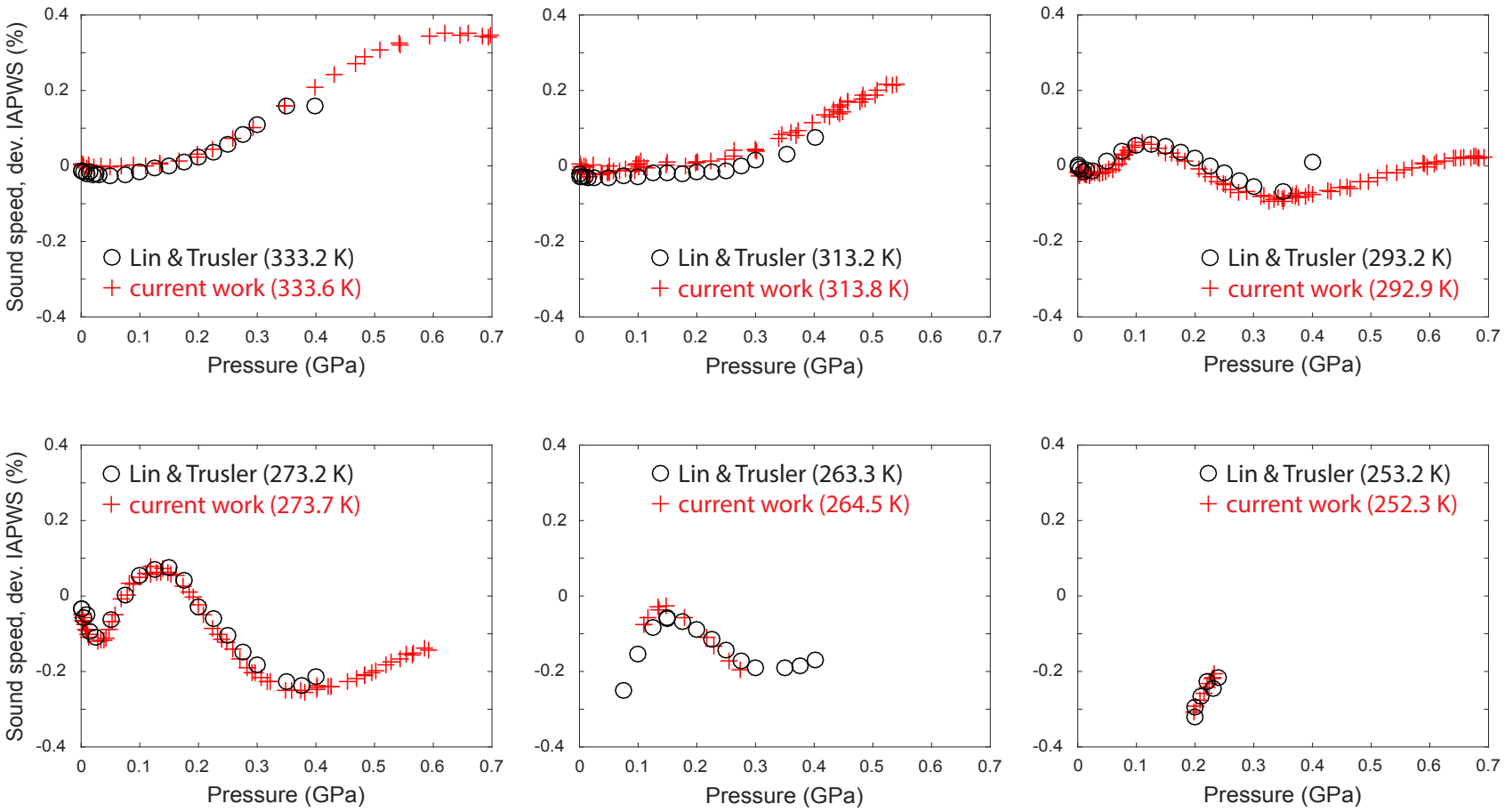
Speed of sound: the Na-Mg-Cl-SO_4 brines

Sound speed measurements



Speed of sound: the Na-Mg-Cl-SO_4 brines

The pure water dataset



Comparison with Lin and Trusler 2012 (% deviation to IAPWS)

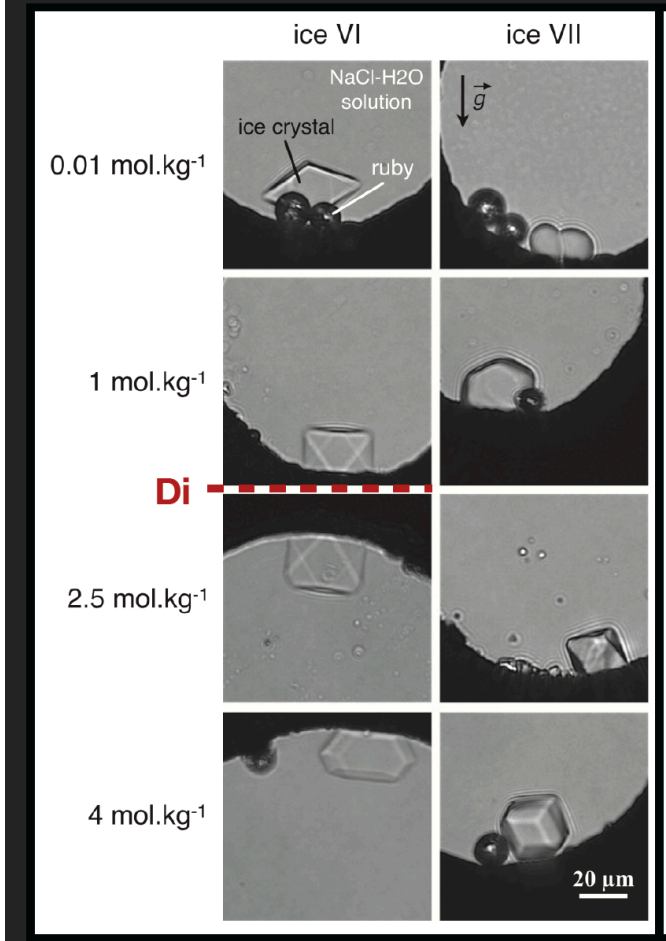
Bollengier et al, in prep.

Liquid-Ice Interactions
(beware more thermodynamics toward the end)

Phase equilibria

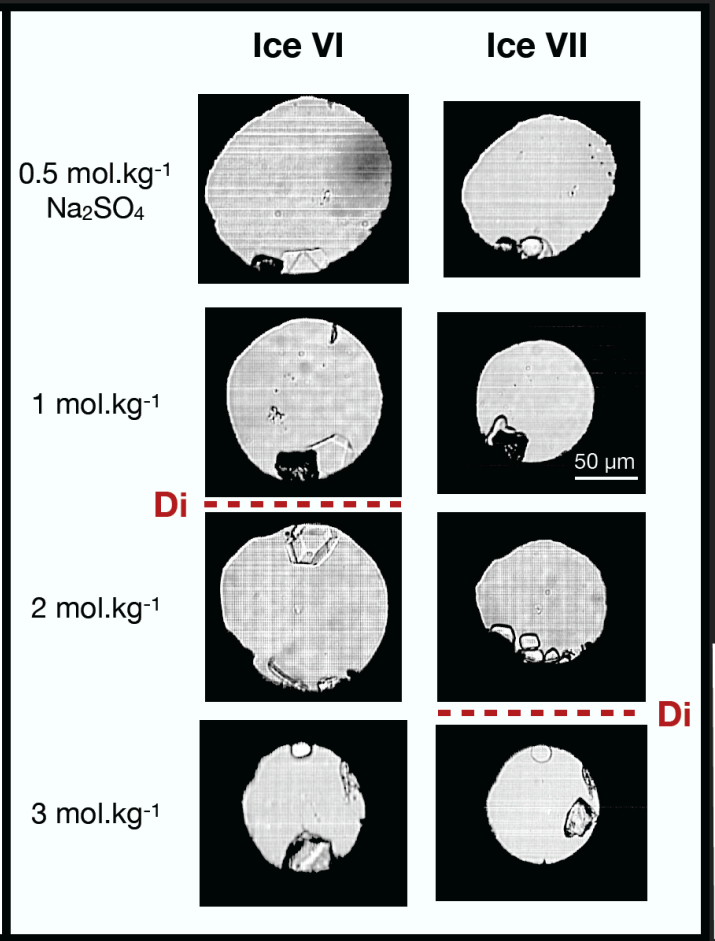
Density inversion

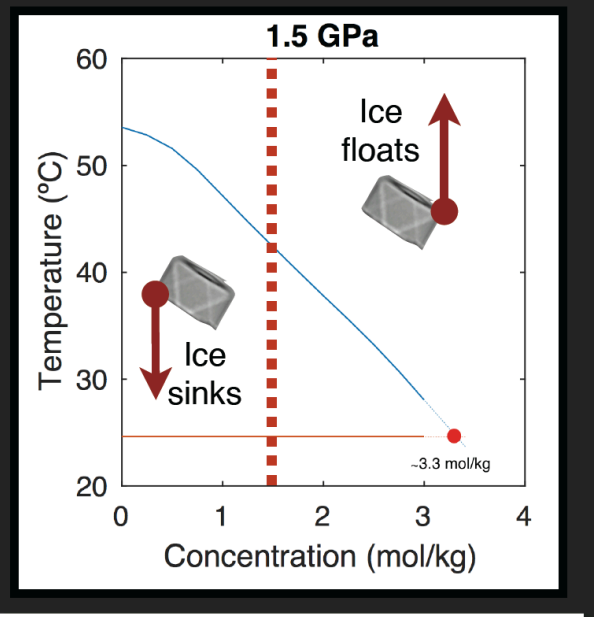
H_2O-NaCl

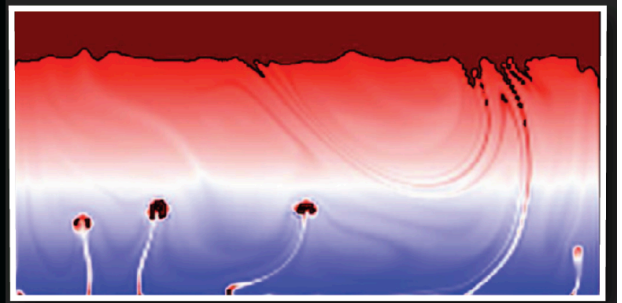


Journaux et al. (2013)

H_2O-Na_2SO_4





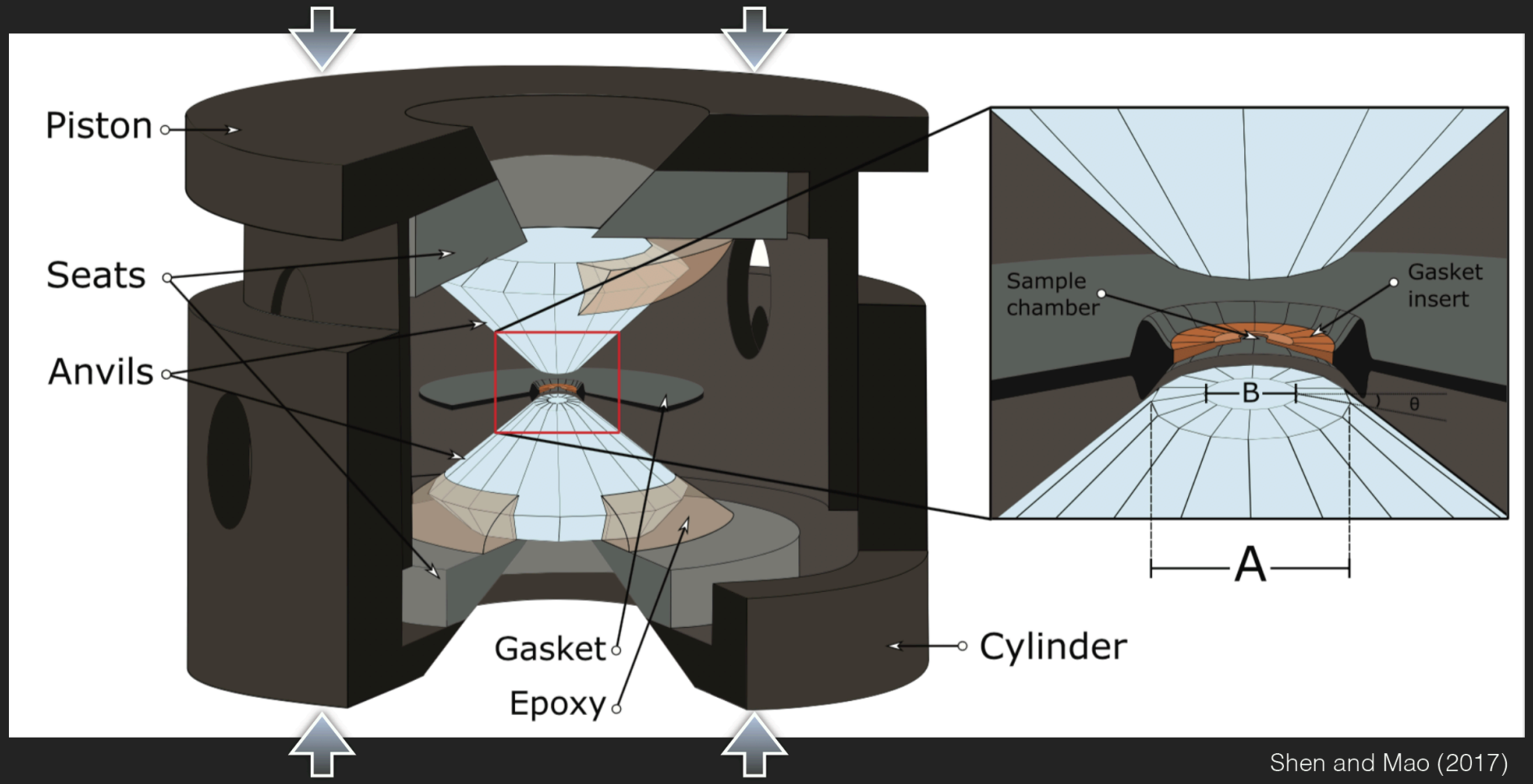


Kalousová, K., et al., Icarus 299 (2018) 133–147

Complex thermodynamical evolution as ocean freezes

Methods

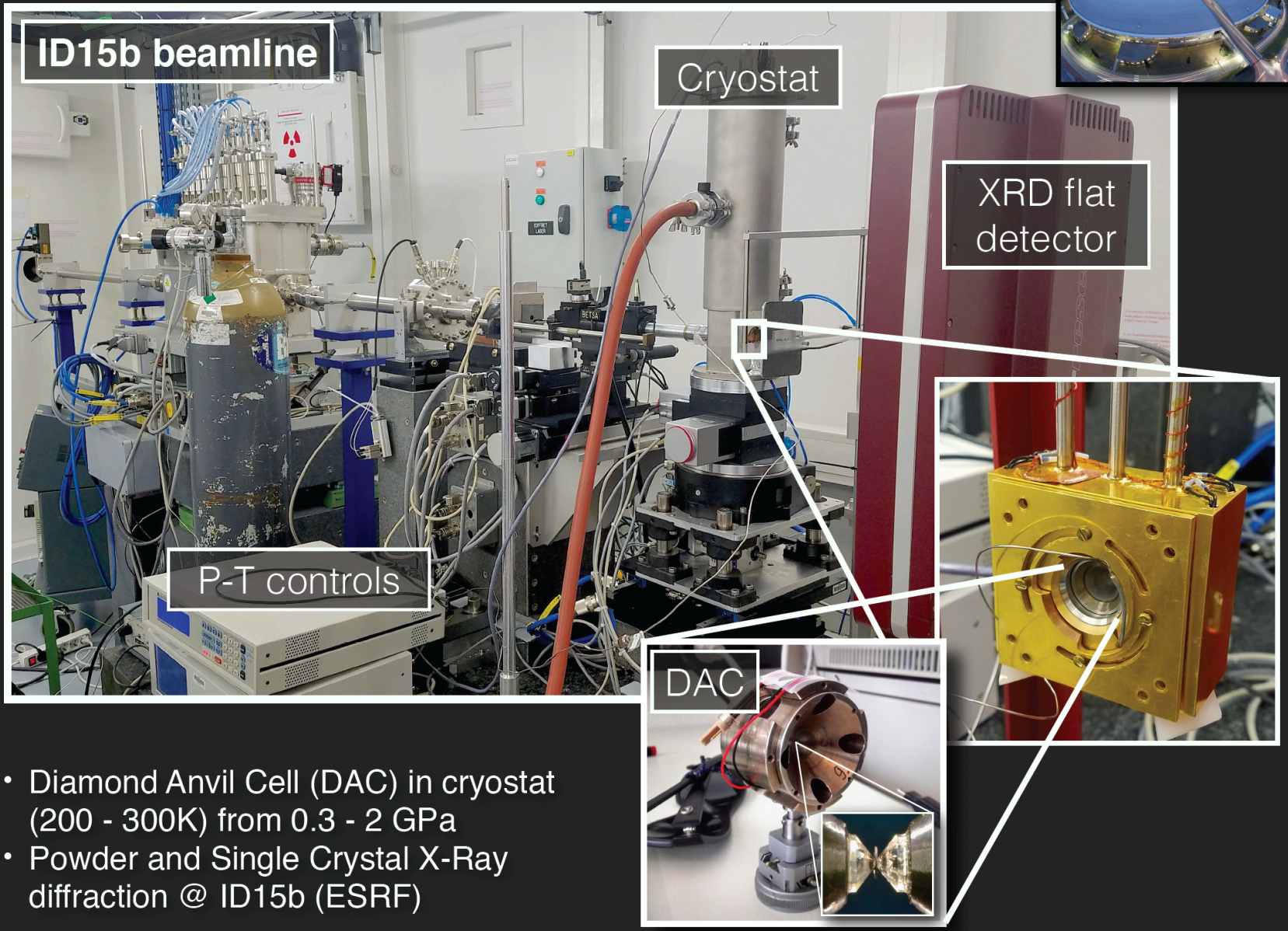
Diamond anvil cell (DAC)



Shen and Mao (2017)

Methods

HP experiment



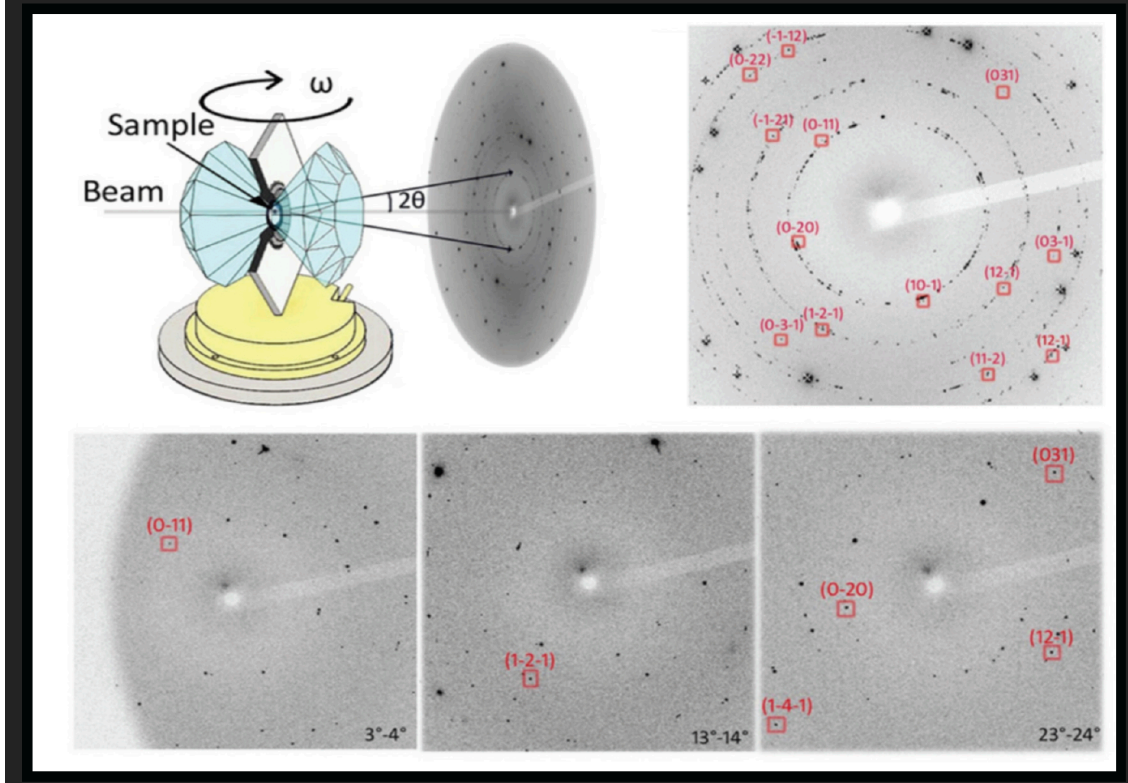
- Diamond Anvil Cell (DAC) in cryostat (200 - 300K) from 0.3 - 2 GPa
- Powder and Single Crystal X-Ray diffraction @ ID15b (ESRF)

Methods

HP experiment

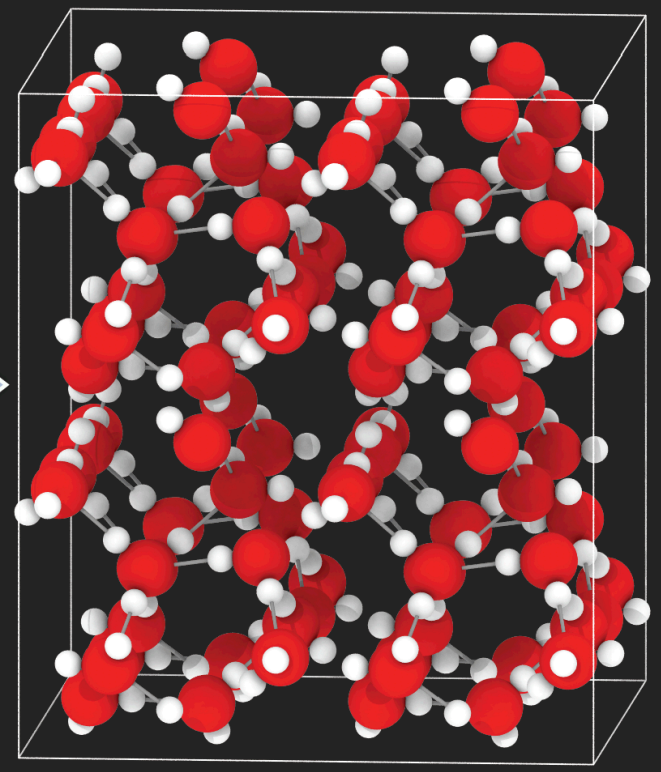
Structure and volume from powder and Single Crystal X-Ray diffraction

Measurement



Shen and Mao (2017)

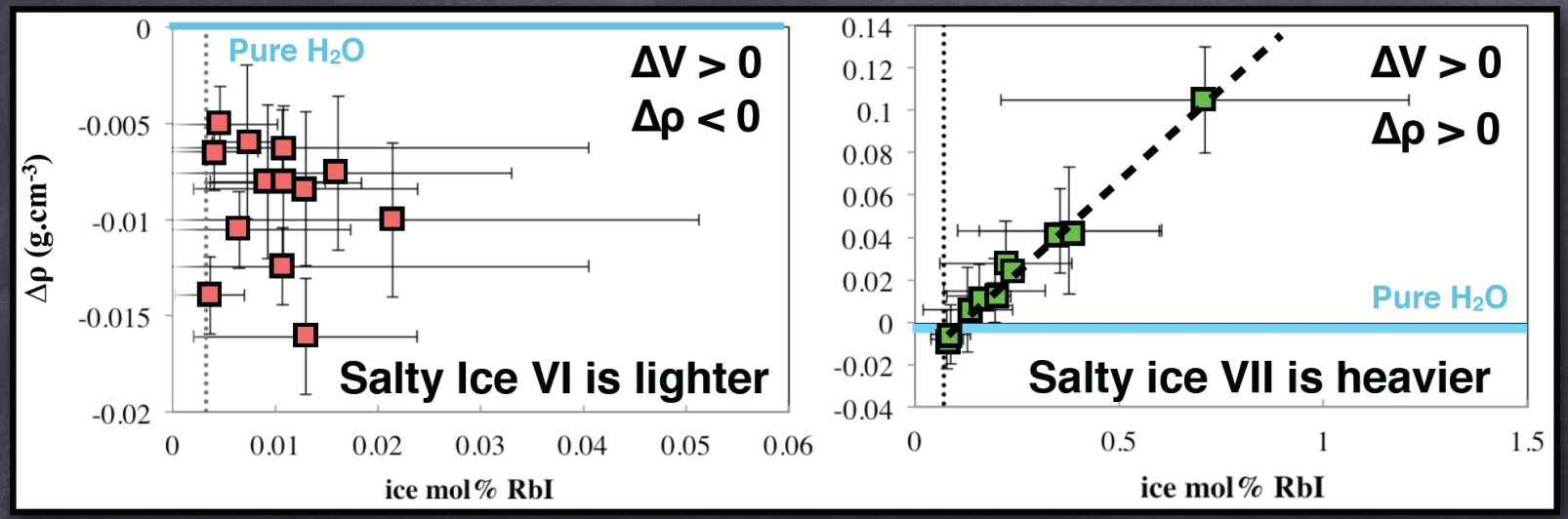
Electron density
-> Structure (ice III)



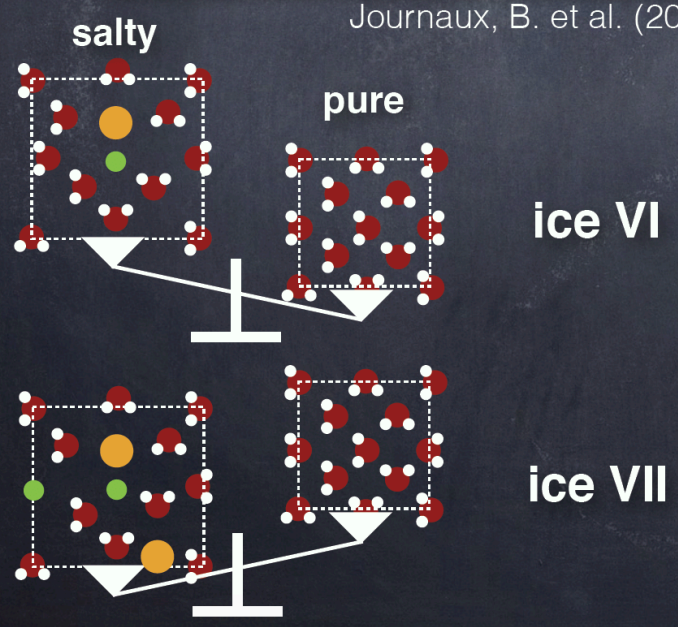
HP ices

Combination with XRD results

Volume determined with X-Ray diffraction and combined with chemistry from XRF to obtain density



Journaux, B. et al. (2017) . Earth and Planetary Science Letters 463, 36–47



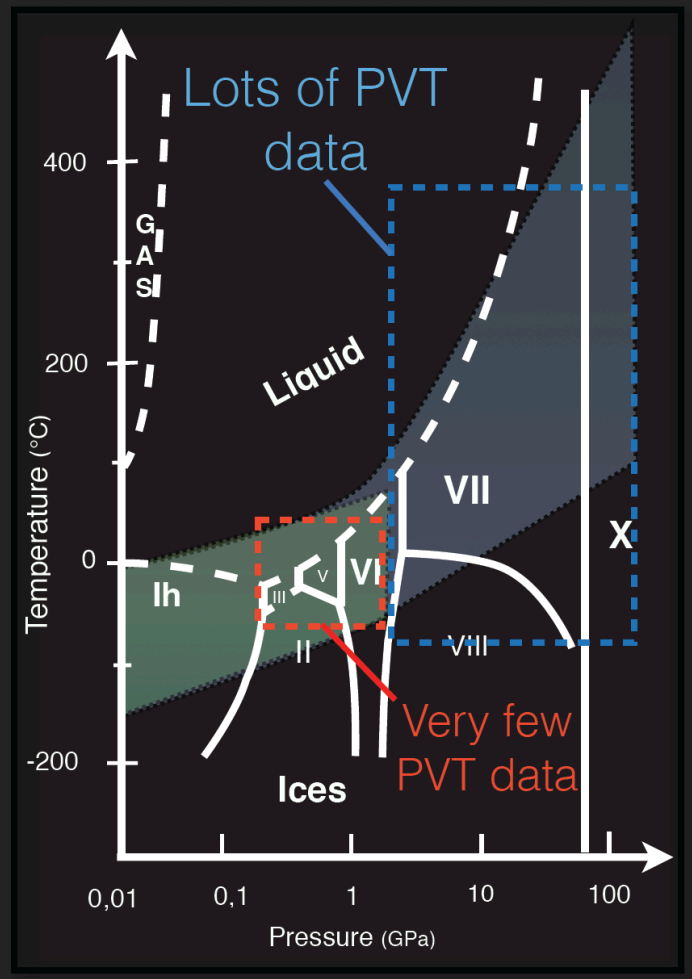
- Crystal volume increases for ice VI & VII
- But for ice VII the larger amount of salt incorporated makes the salty ice denser
- **Similar effects on ice VI for NaCl and $MgSO_4$ (new synchrotron results - feb 2017)**
- More experiments to come for other HP ices (UW, synchrotron)

Phase equilibria (DAC measurements)

Current knowledge on HP ices Thermodynamics

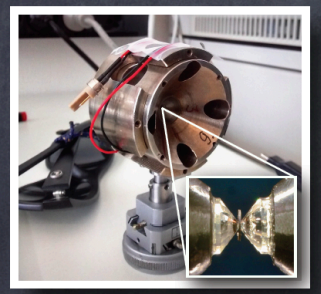
Ice polymorph	PVT data	EOS
Ih	Many	Yes
II	< 10*	No
III	< 15*	No
V	< 15*	No
VI	> 50 at T > 300 K	Yes > 300K
VII	> 200	Yes
Liquid	> 1000	Yes

* no or low consistency between volumes and methods



Need for new PVT data taken *in-situ* < 300 K and between 0.3 - 2 GPa

Phase equilibria (DAC measurements)

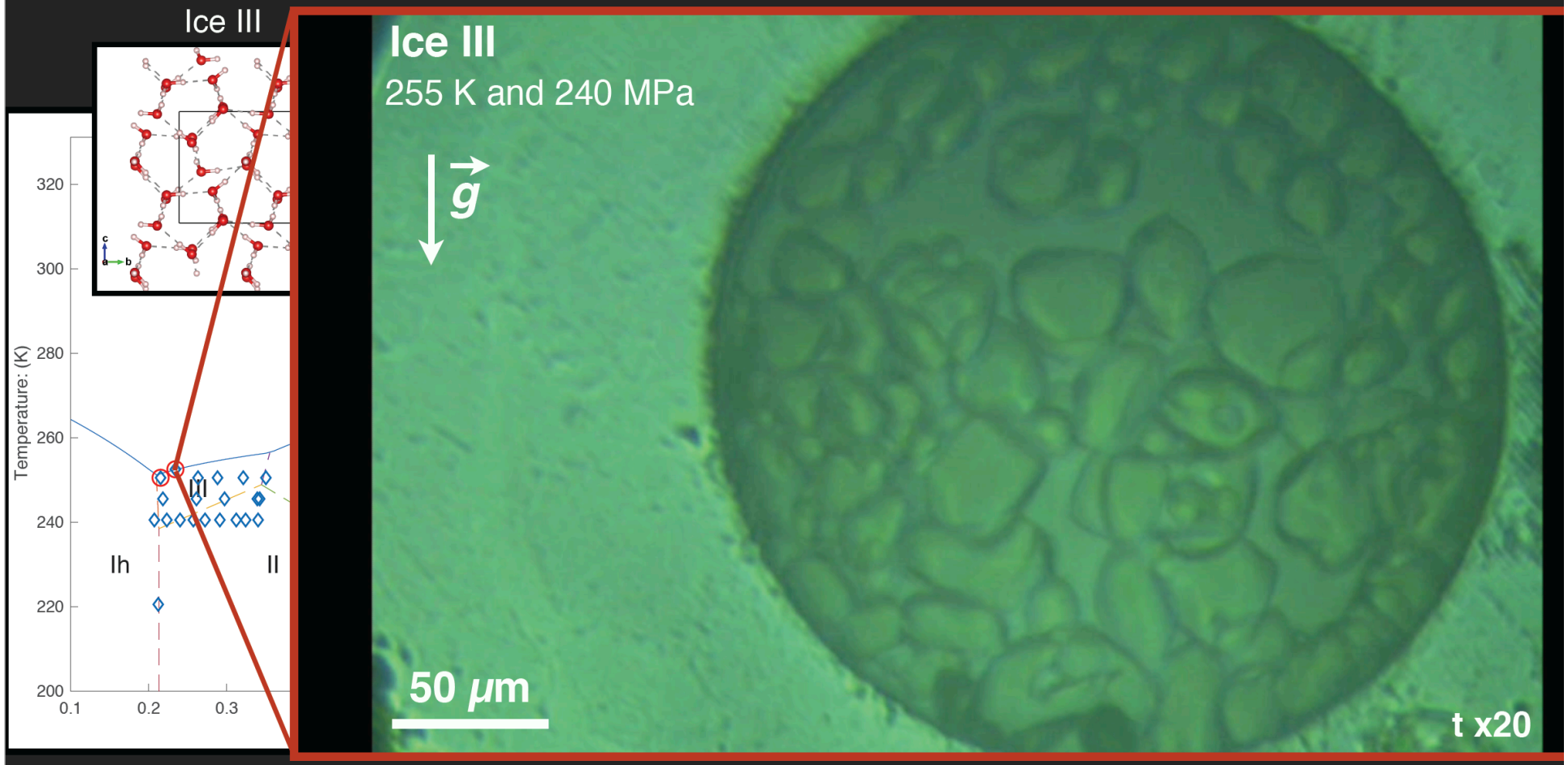


Study of the (Na-Cl-Mg-SO_4) + H_2O systems
in the 50 MPa - 10GPa ; 200 - 600 K range

Solutes	NaCl	$MgSO_4$	Na_2SO_4	$MgCl_2$	Mix
Melting curve	✓	🔬	✓	⌛	⌛
Eutectic	🔬	🔬	✓	⌛	⌛
Relative density	✓	✓	✓	⌛	⌛

Results

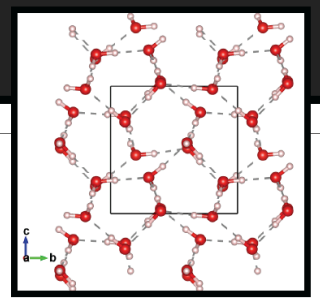
HP Data

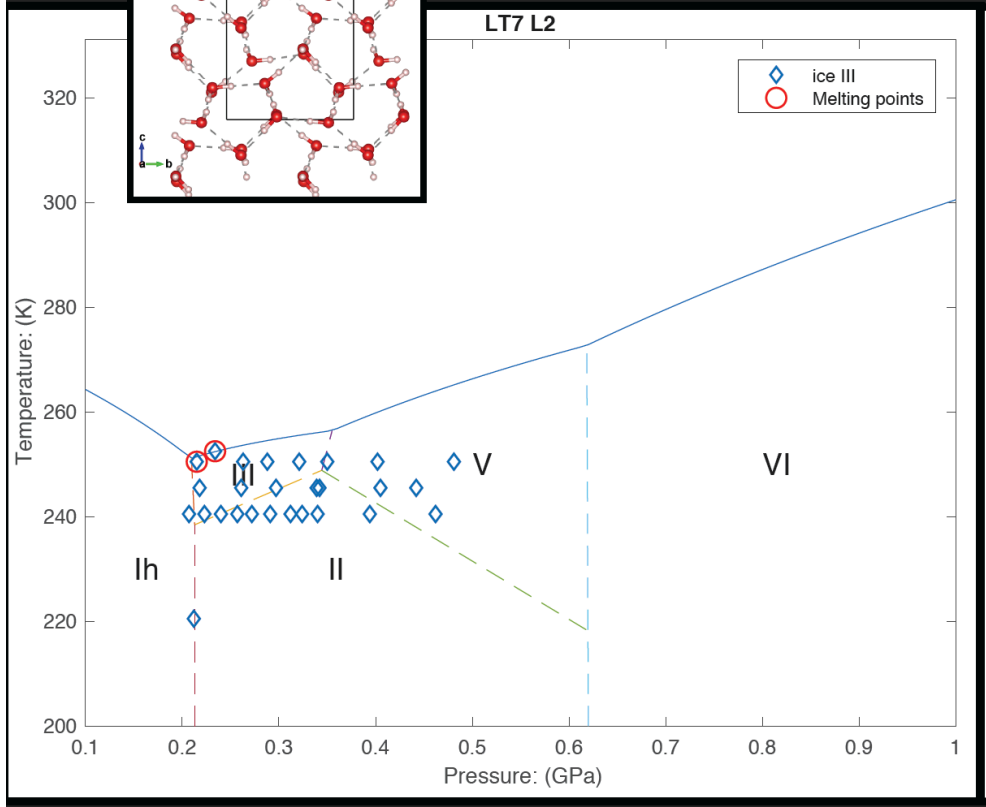


Results

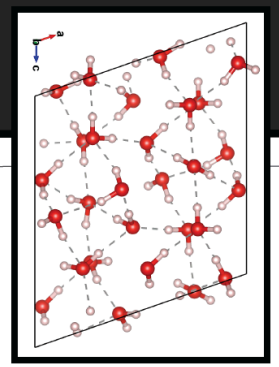
HP Data

Ice III

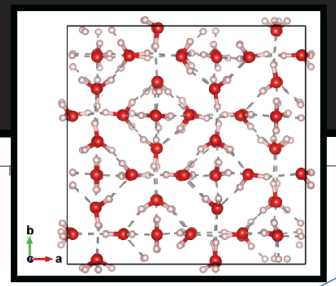


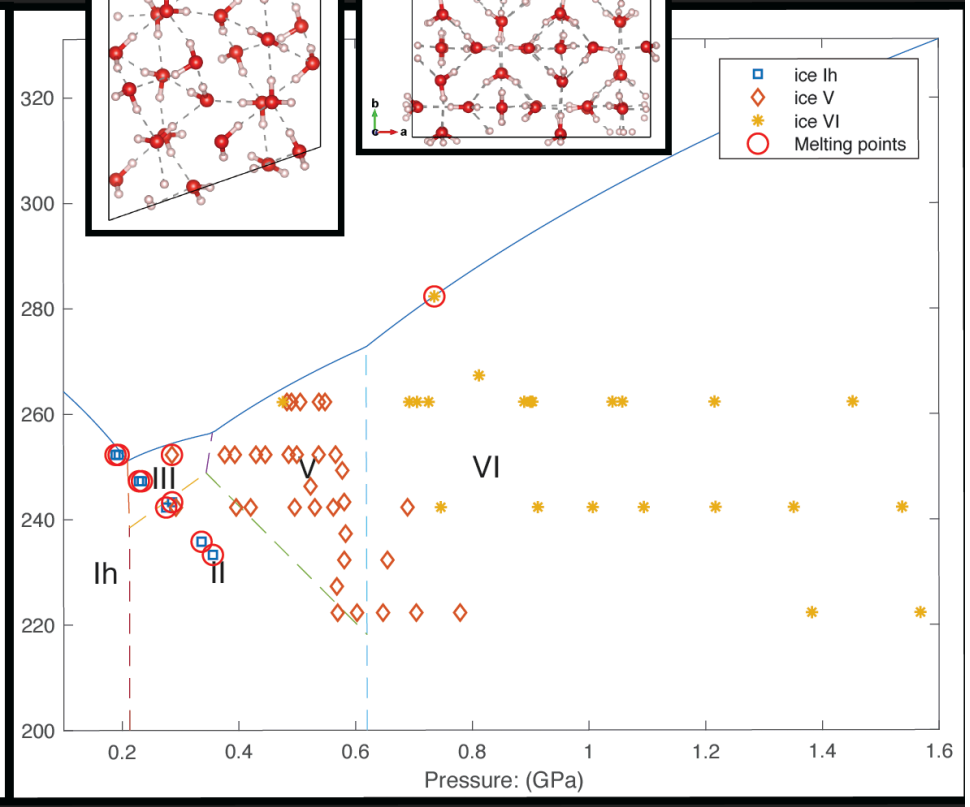


Ice V



Ice VI





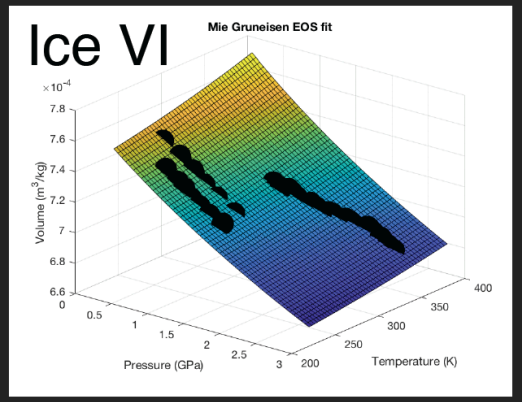
In-situ single crystal and powder XRD
PVT data also far into metastable domain

Results

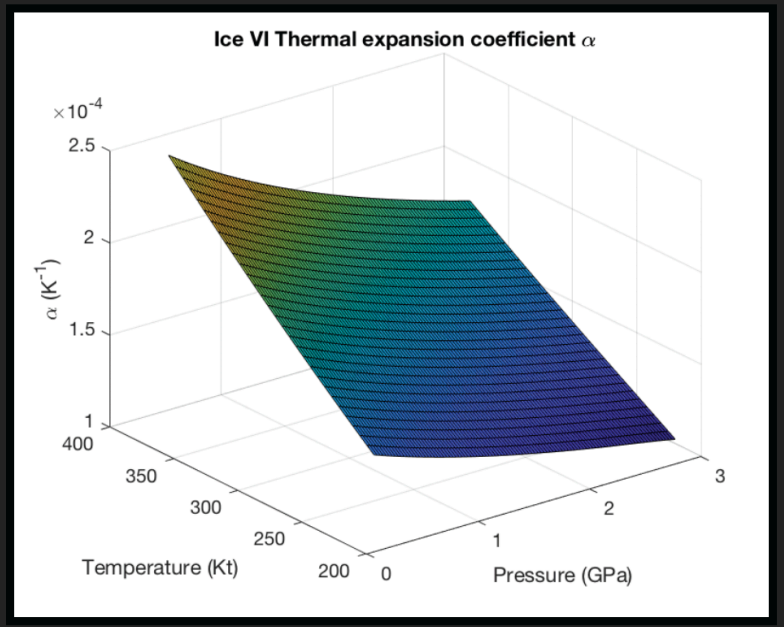
Equation of state + LBF

$$P(V,T) = P_0(V) + P_{thermal}(V,T)$$

Ice VI

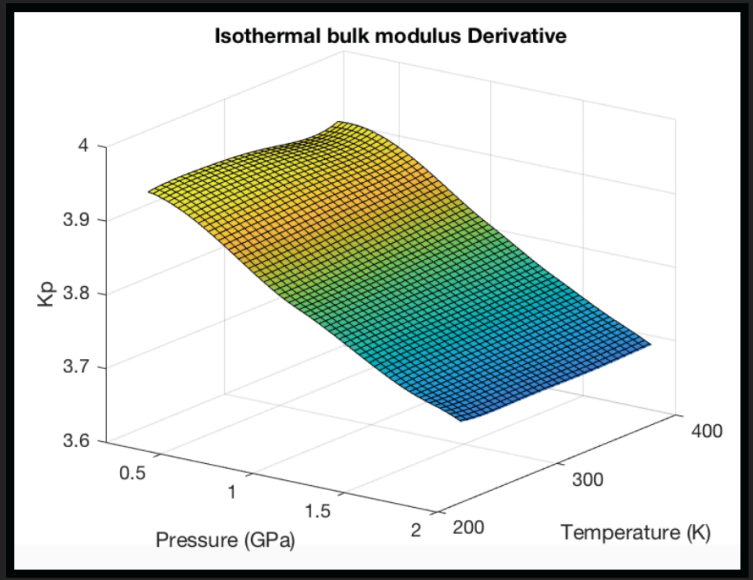


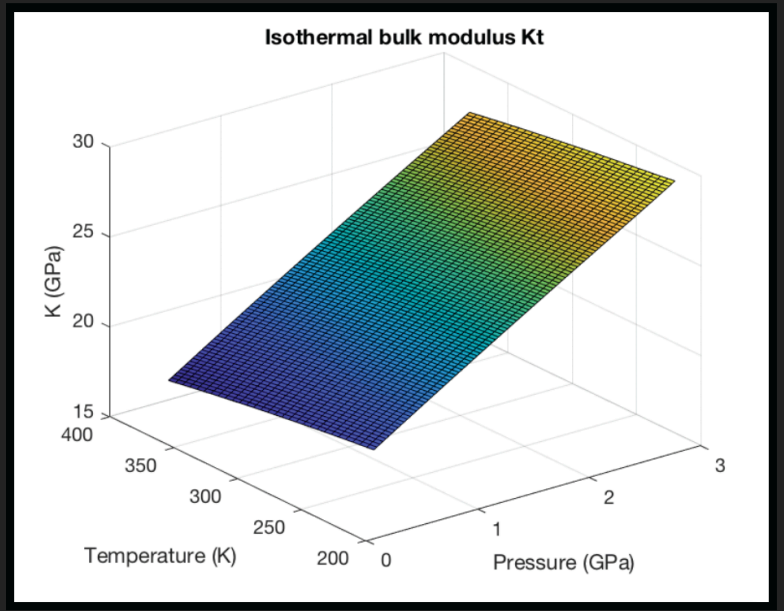
$$\alpha = \left[\frac{dV}{dT}\right]_P \cdot \frac{1}{V}$$



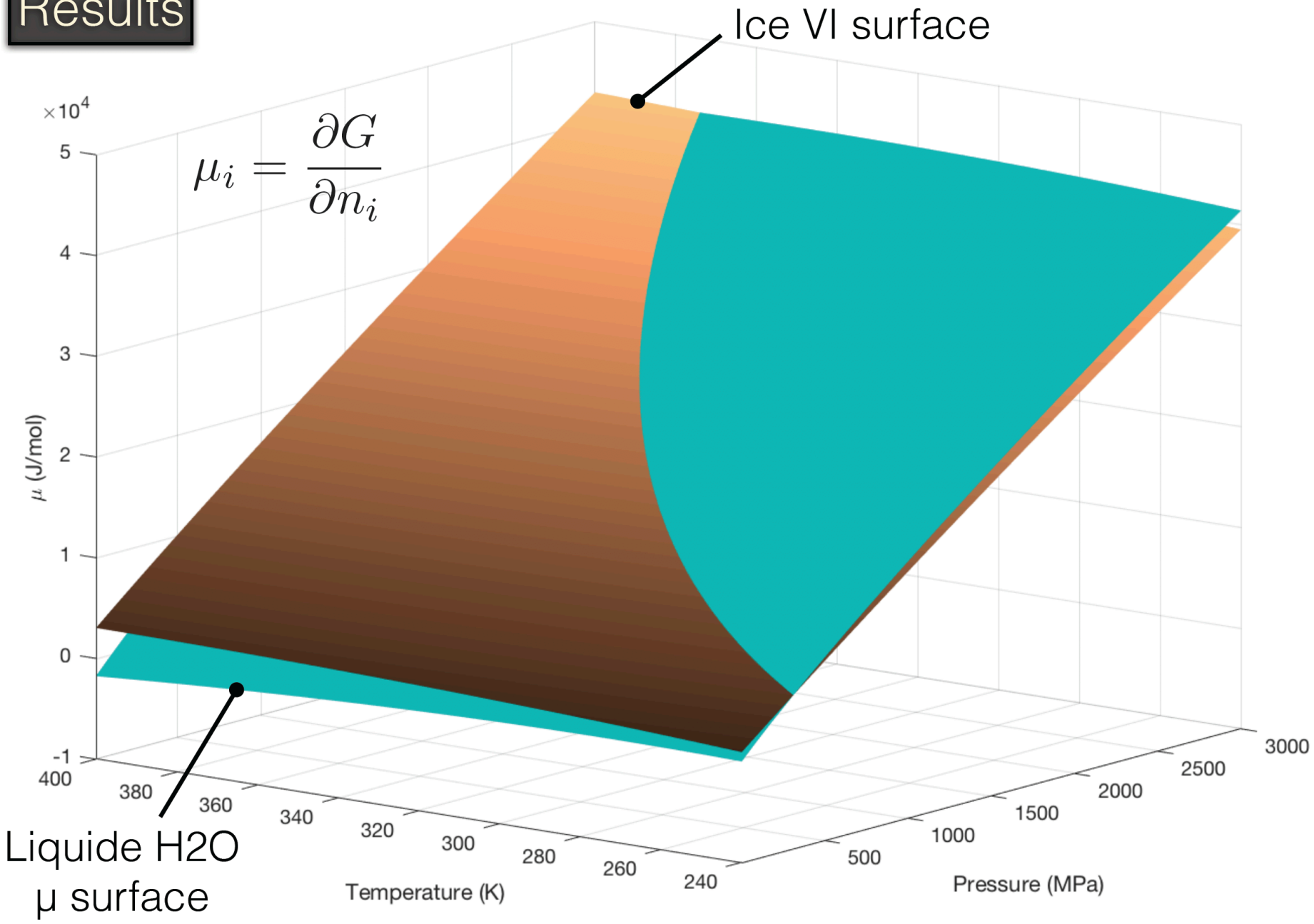
$$K_T = -V \cdot \left[\frac{dP}{dV}\right]_T$$

$$Kp = \left[\frac{dK_T}{dP}\right]_T$$



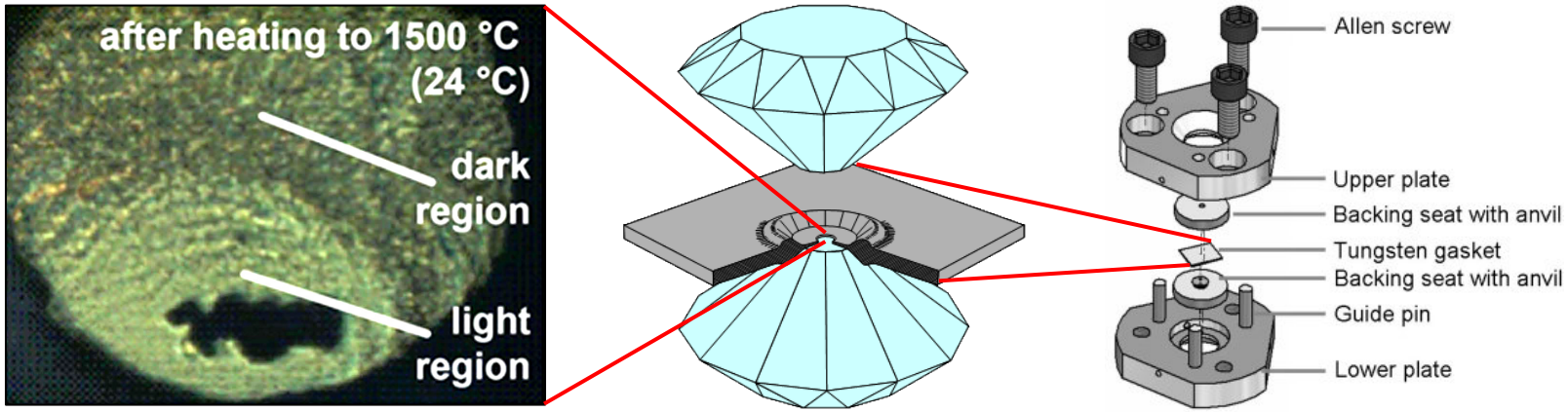


Results


Ice VI surface
$\mu_i = \frac{\partial G}{\partial n_i}$
×10^4
5
4
3
2
1
0
-1
μ (J/mol)
400
380
360
340
320
300
280
260
240
Temperature (K)
500
1000
1500
2000
2500
3000
Pressure (MPa)
Liquide H2O
μ surface

Optical anvil cells: the H_2O-CO_2 system

Exploring phase diagram using optical anvil cells



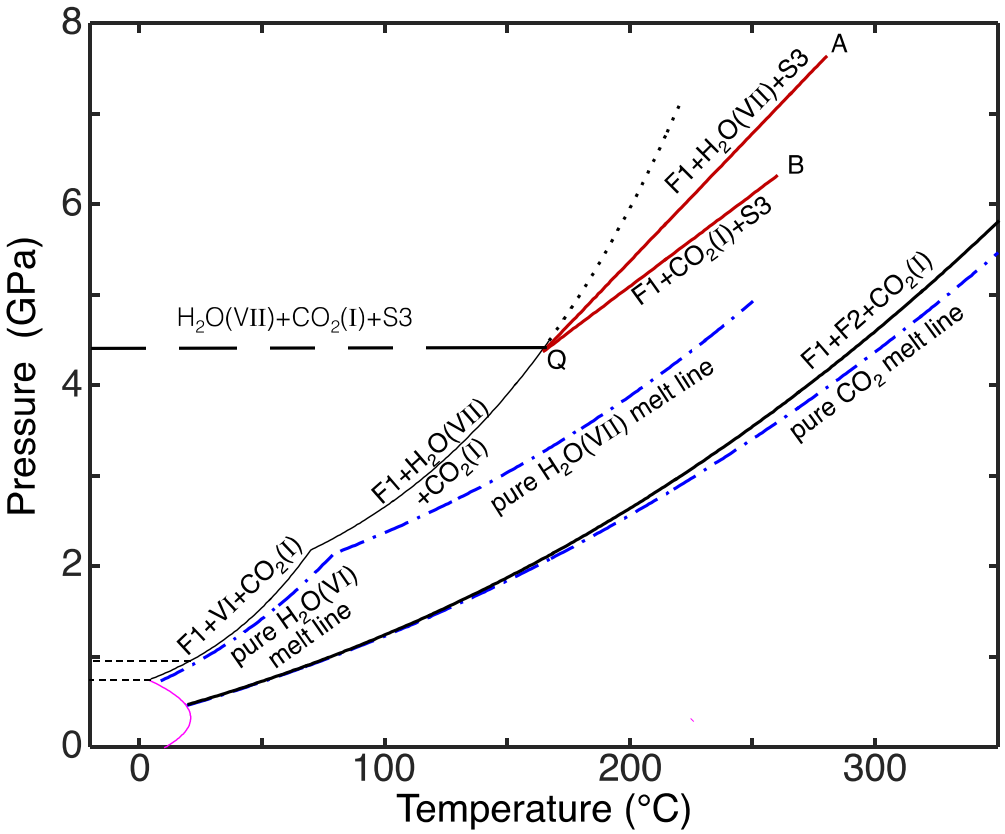
Microscopic sample Diamond anvils Anvil cell

OPTICAL ANVIL CELLS

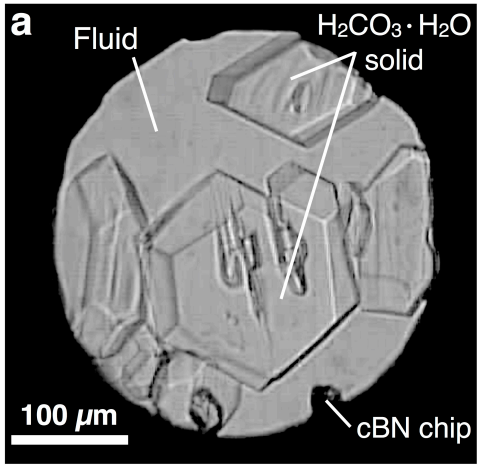
- access to multi-GPa pressures and high temperatures
- wide EM capabilities (visual monitoring, spectroscopy)
- nL (100 microns) loads: metastability, loading problems

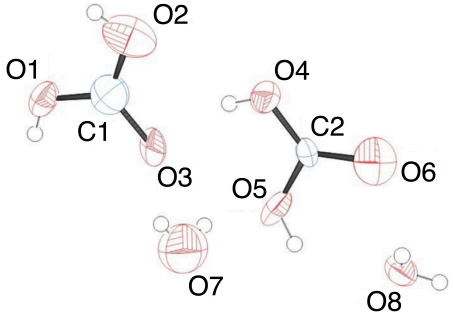
Optical anvil cells: the H_2O-CO_2 system

A new solid: the carbonic acid monohydrate



New melting curves in the H_2O-CO_2 system





H_2CO_3 monohydrate

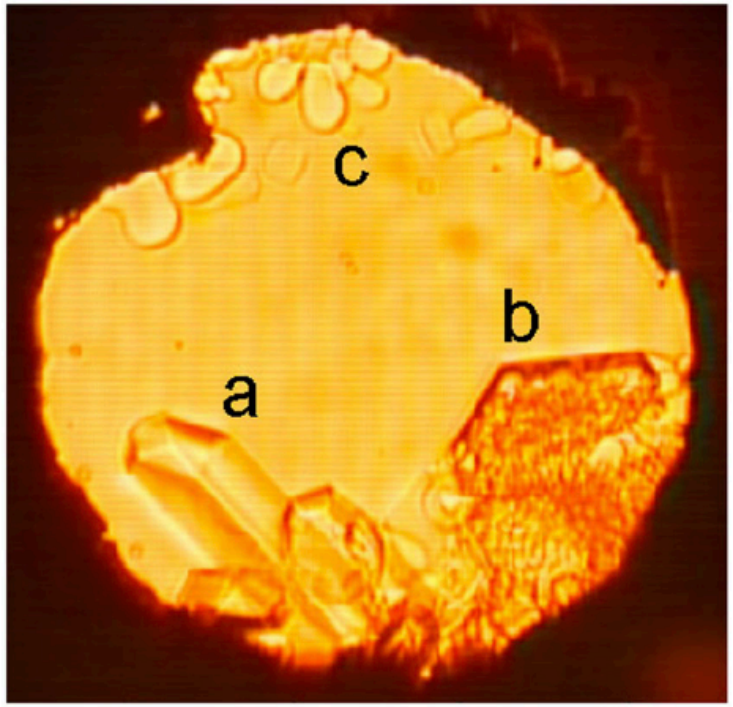


Figure 4. Photomicrograph of crystals growing from a water-CO_2 fluid at 240 °C and 6.5 GPa. Crystals "a" and "b" are both of phase S3 and were observed to fall through the fluid. At first "b" was clear, but then abruptly darkened, presumably as trapped fluid (non-stoichiometric relative to S3) precipitated crystallites of the H_2O(VII)-S3 eutectic. Crystals "c" are H_2O(VII) which floated up through the fluid.

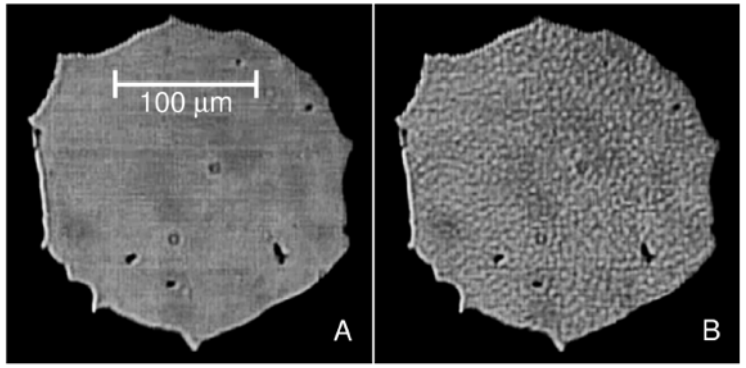
[American Journal of Science, Vol. 317, November, 2017, P. 967–989, DOI 10.2475/09.2017.01]

American Journal of Science

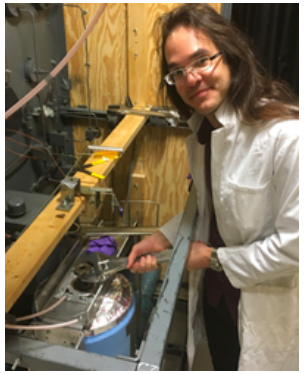
NOVEMBER 2017

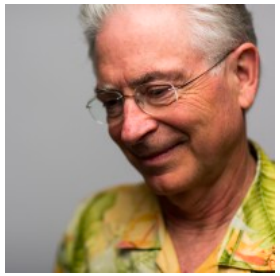
THE WATER-CARBON DIOXIDE MISCIBILITY SURFACE TO 450 °C AND 7 GPa

EVAN H. ABRAMSON†, OLIVIER BOLLENGIER, and J. MICHAEL BROWN



SCIENTIFIC REPORTS





OPEN

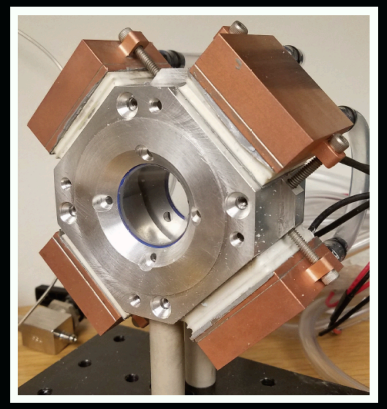
Water-carbon dioxide solid phase equilibria at pressures above 4 GPa

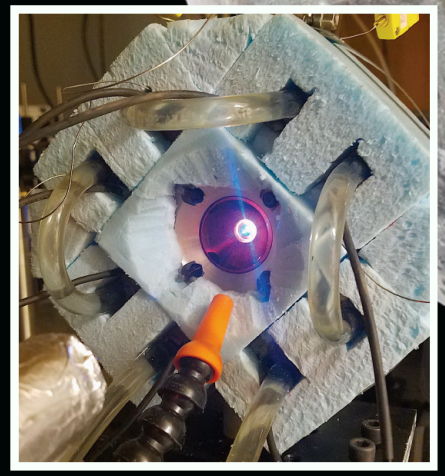
E. H. Abramson, O. Bollengier & J. M. Brown

Upcoming work :

- Ice Ih and ice VII Gibbs surfaces
- Solid - solid phase transition
- Salts melting point depression measurements at T < 300K
- Combine effects of NaCl and $MgSO_4$ (density, incorporation, equilibriums)
- Combine effects of volatiles (CO_2, NH_3, CH_4, etc.)
- Implementation in Planetary interior simulation ongoing in Nantes (Tobie) and JPL (Vance)
- Ice II PVT data (ESRF beam time granted!)
- Study the influence of salt incorporation
- Open source Python Package

New DAC cryostat (220-300 K) :



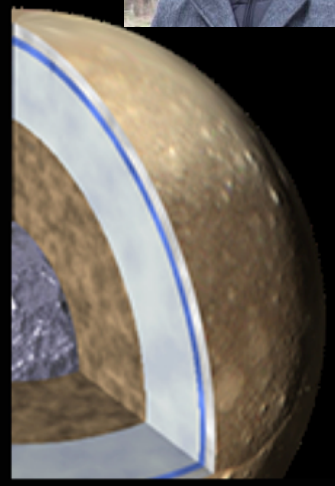


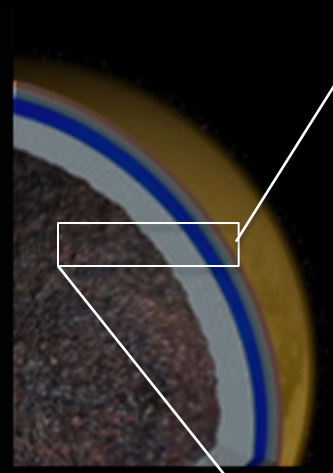
Applications of thermodynamics to deep oceans in large icy moons

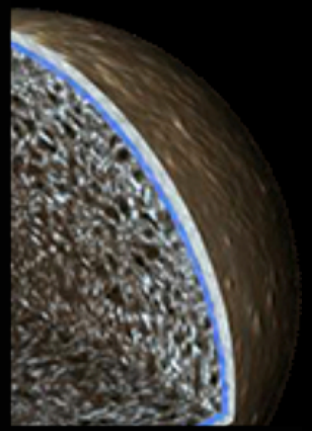
- Density
- Temperature
- Tidal dissipation
- Magnetic induction
- Seismic propagation

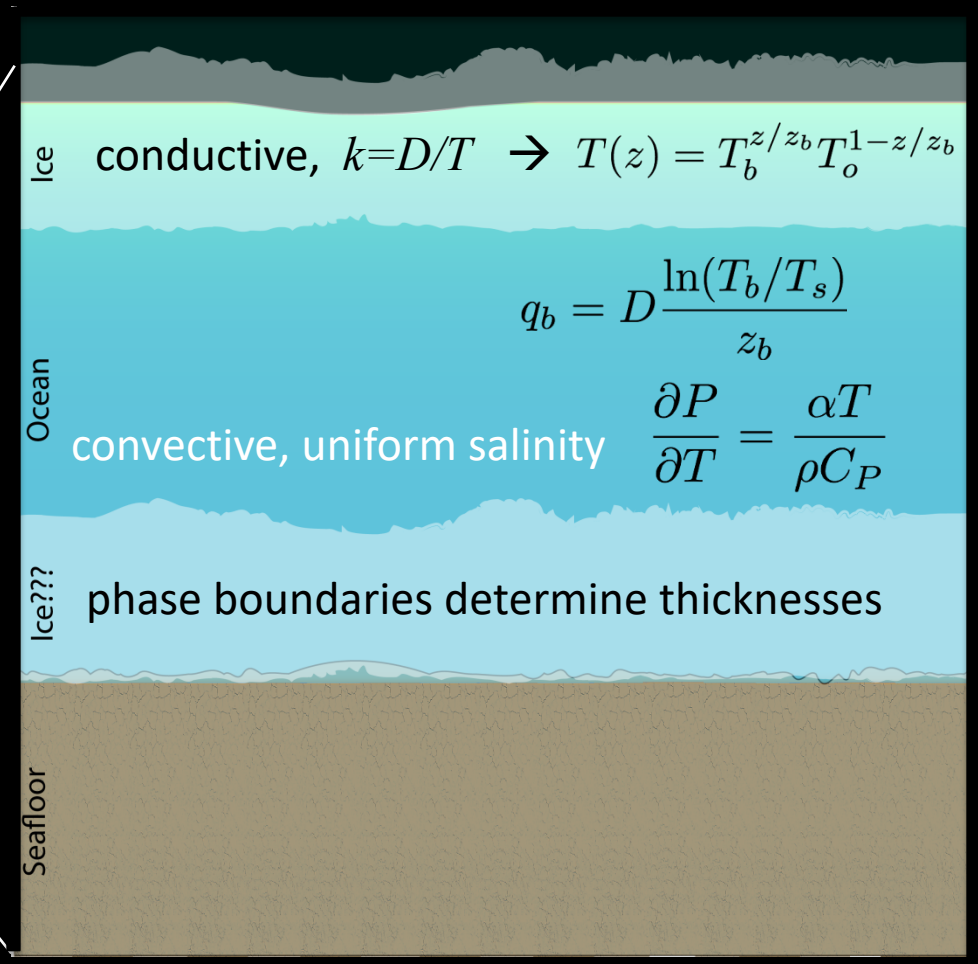
Geophysical Investigations of Habitability in Ice-Covered Ocean Worlds

Steven D. Vance[1], Mark P. Panning[1], Simon Stähler[2,3], Fabio Cammarano[4], Bruce G. Bills[1], Gabriel Tobie[5,6], Shunichi Kamata[7], Sharon Kedar[1], Christophe Sotin[1], William T. Pike[8], Ralph Lorenz[9], Hsin-Hua Huang[10,11], Jennifer M. Jackson[10], and Bruce Banerdt[1]







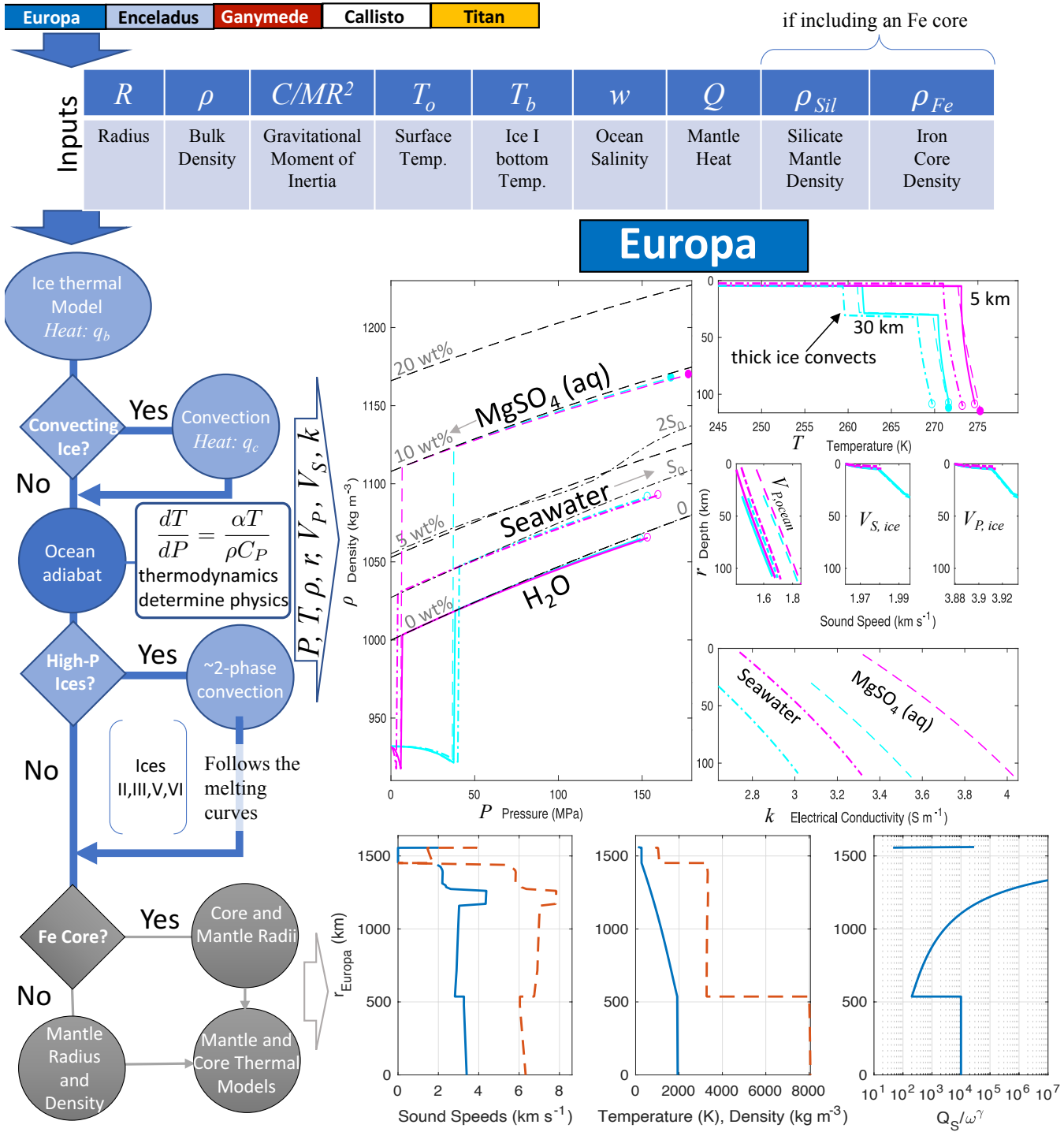


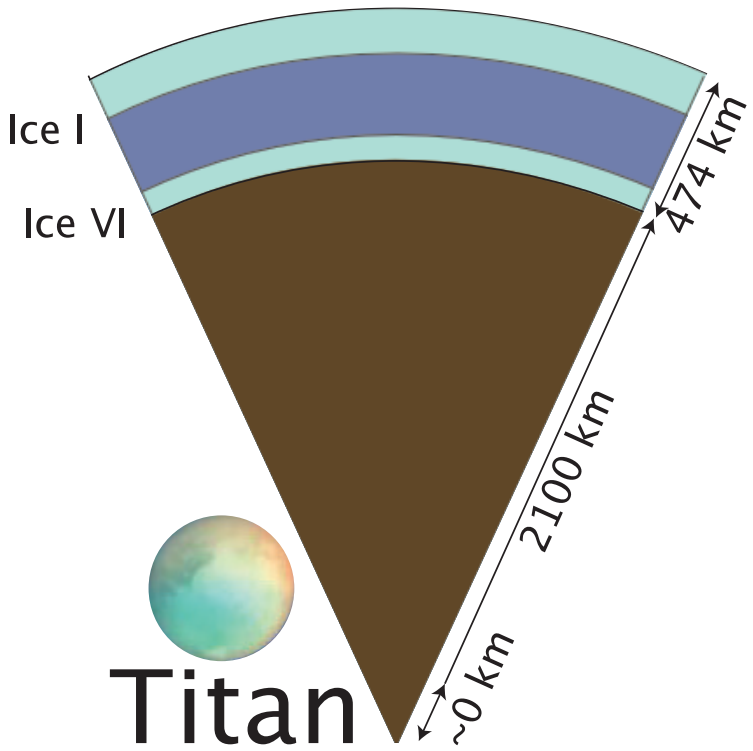
Vance et al. 2018; also Vance et al. 2014

PlanetProfile

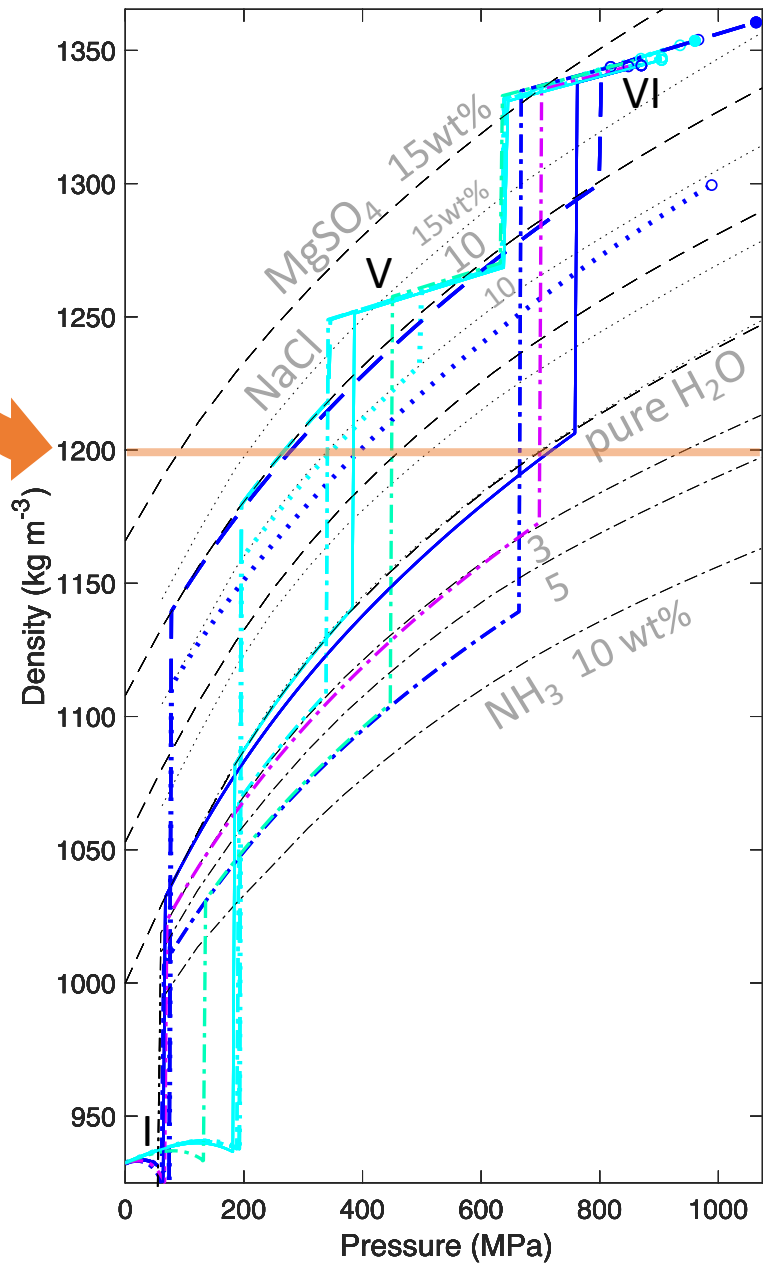
github.com/vancesteven/PlanetProfile

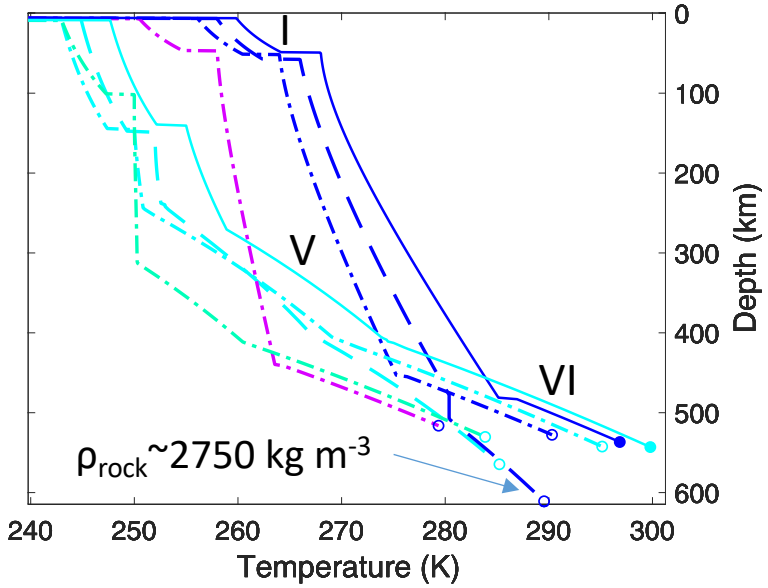
Vance et al. 2017, JGR.

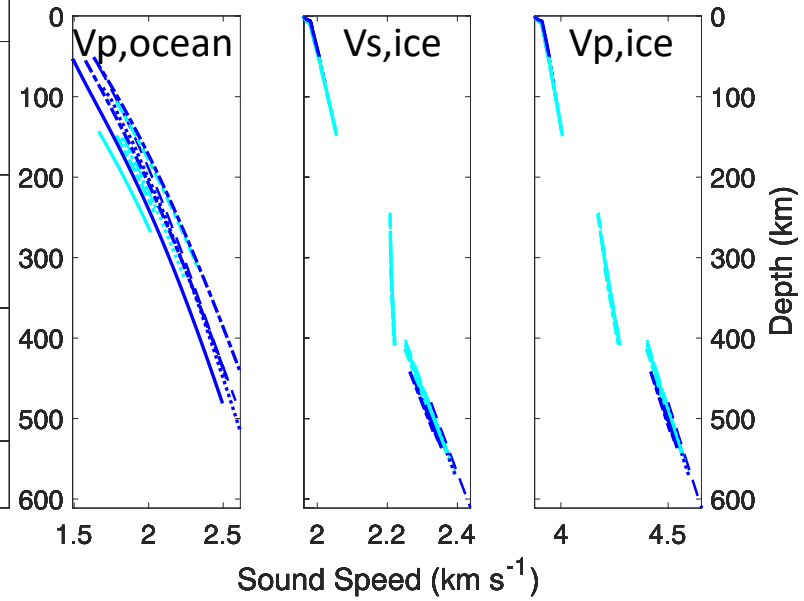




Mitri et al. 2014





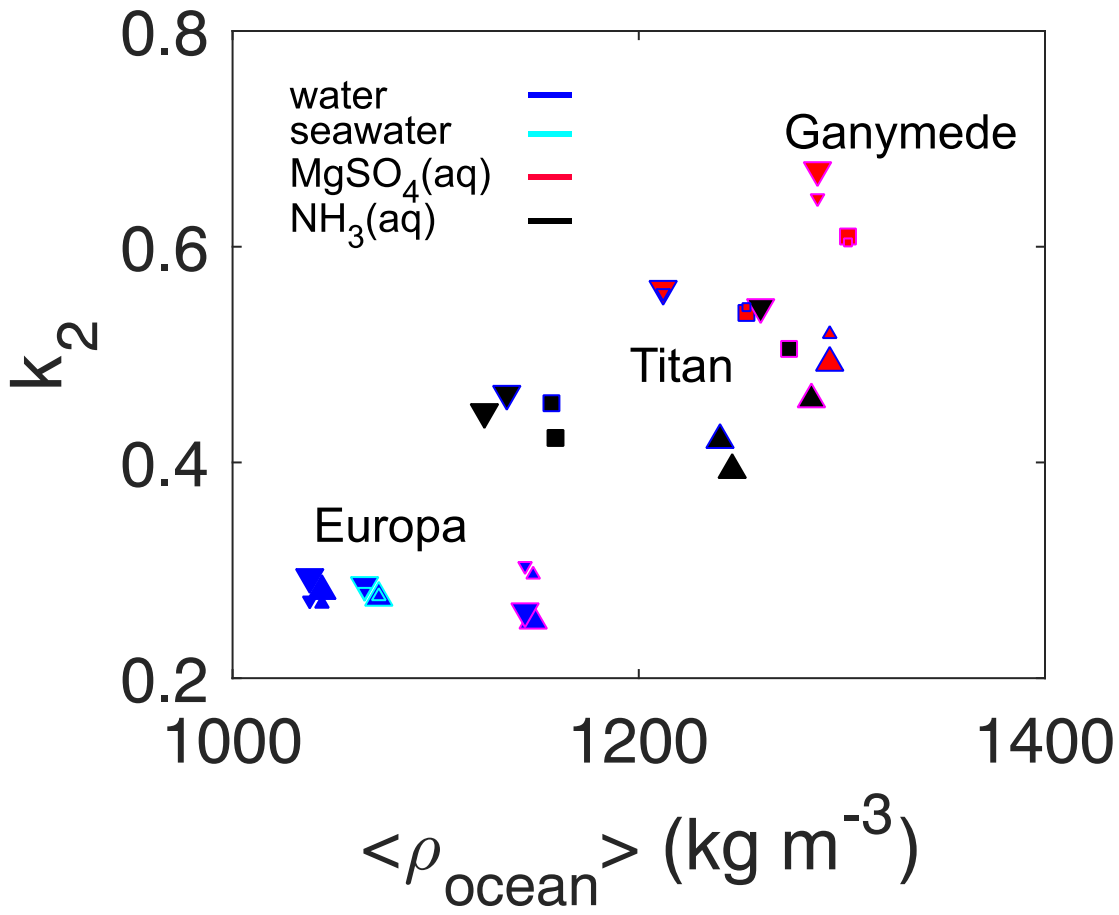


MoI* = 0.338 (*sic*)
(previous talk by Sotin showed 0.3318)
ρ_{rock}~2900 kg m^{-3}

Vance et al. 2017, JGR.

*moment of inertia

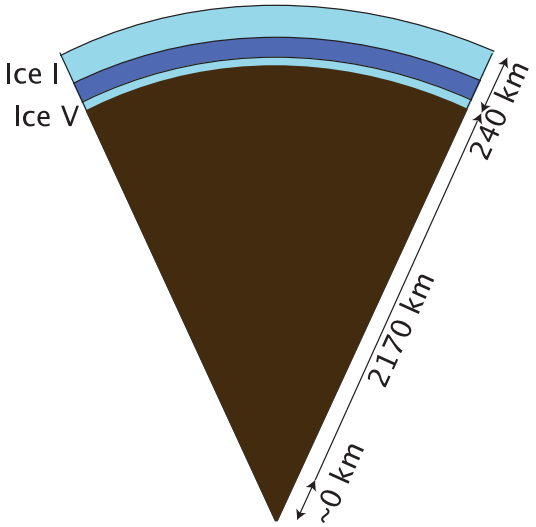
Tidal Dissipation

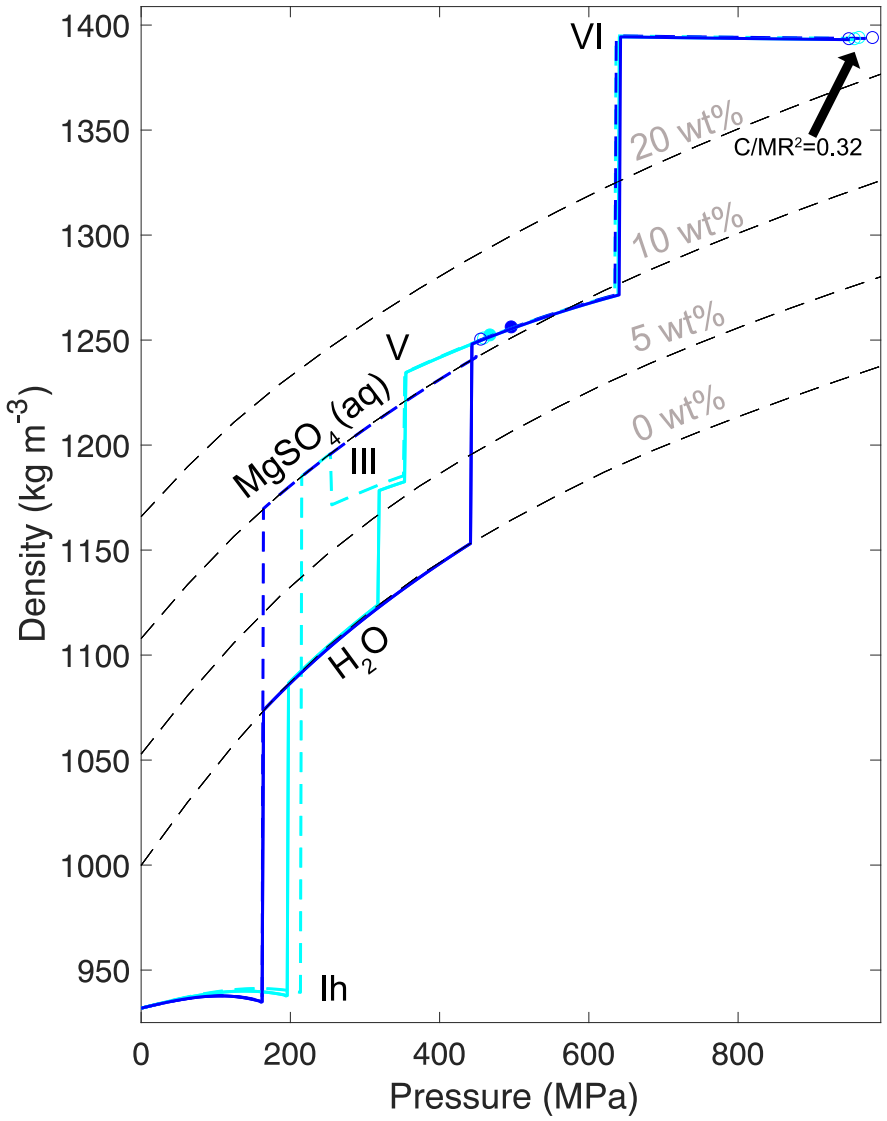


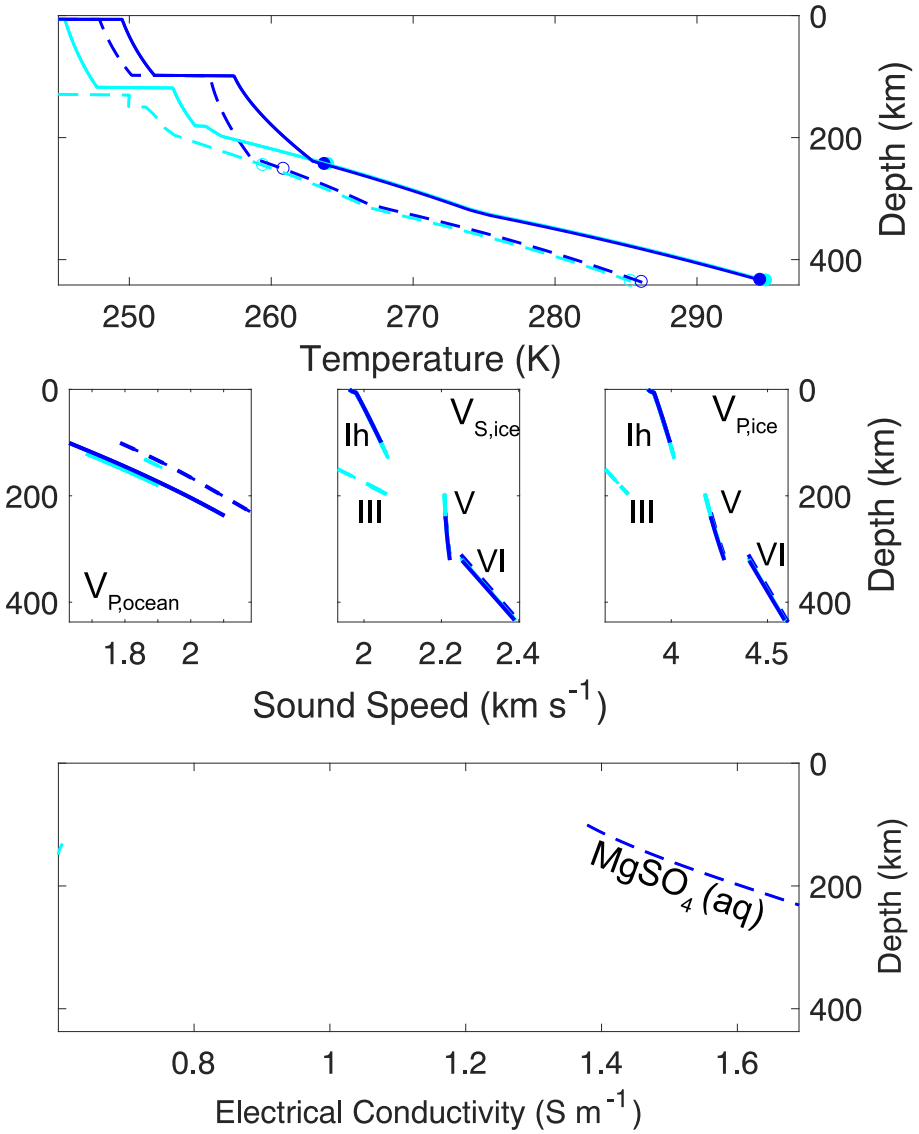
Contributed by
Gabriel Tobie and
Shunichi Kamata

Vance et al. 2017 JGR

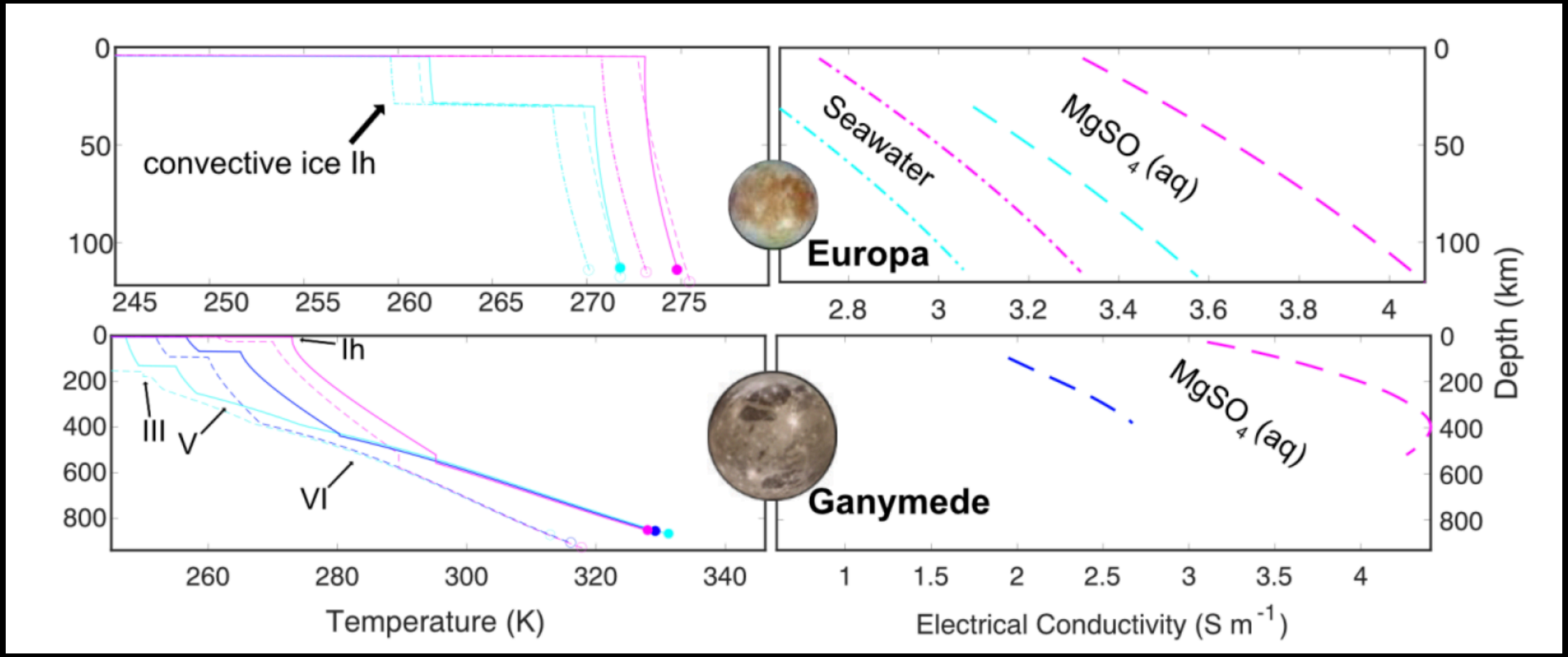
Callisto

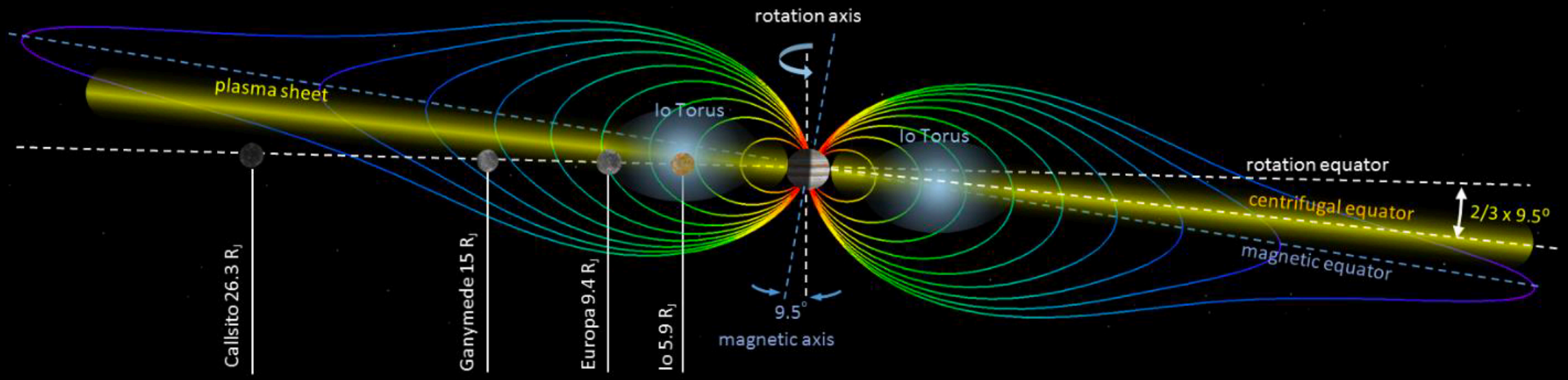


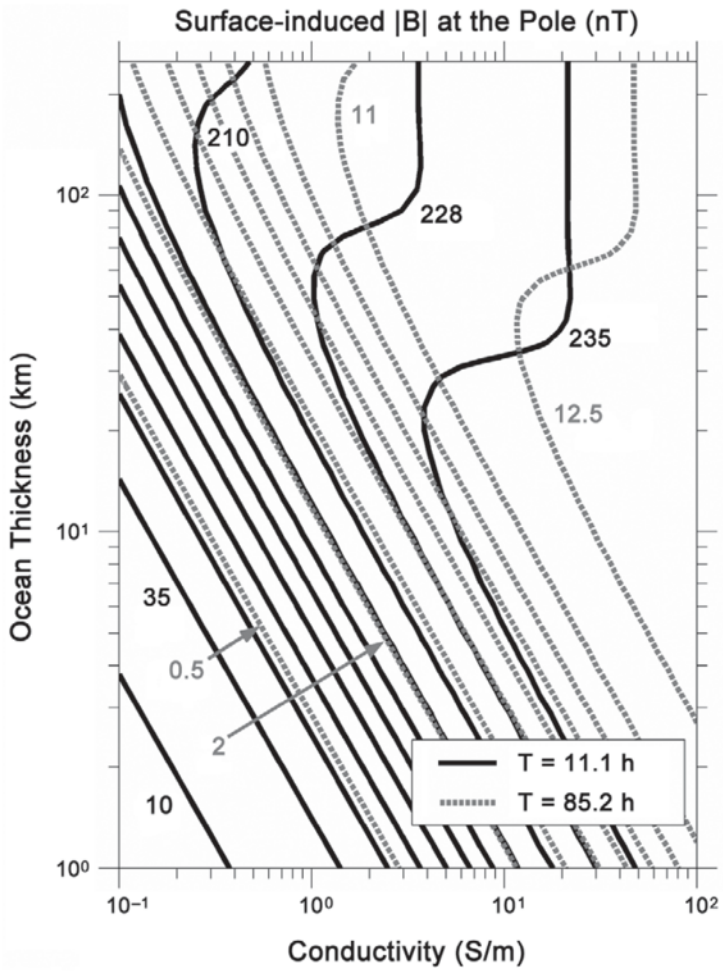




Vance et al. 2017, JGR.


convective ice Ih
Seawater
MgSO4 (aq)
Europa
Ih
III
V
VI
MgSO4 (aq)
Ganymede
Depth (km)
Temperature (K)
Electrical Conductivity (S m-1)


rotation axis
plasma sheet
Io Torus
Io Torus
rotation equator
centrifugal equator
2/3 x 9.5°
magnetic equator
Callsito 26.3 R_J
Ganymede 15 R_J
Europa 9.4 R_J
Io 5.9 R_J
9.5°
magnetic axis

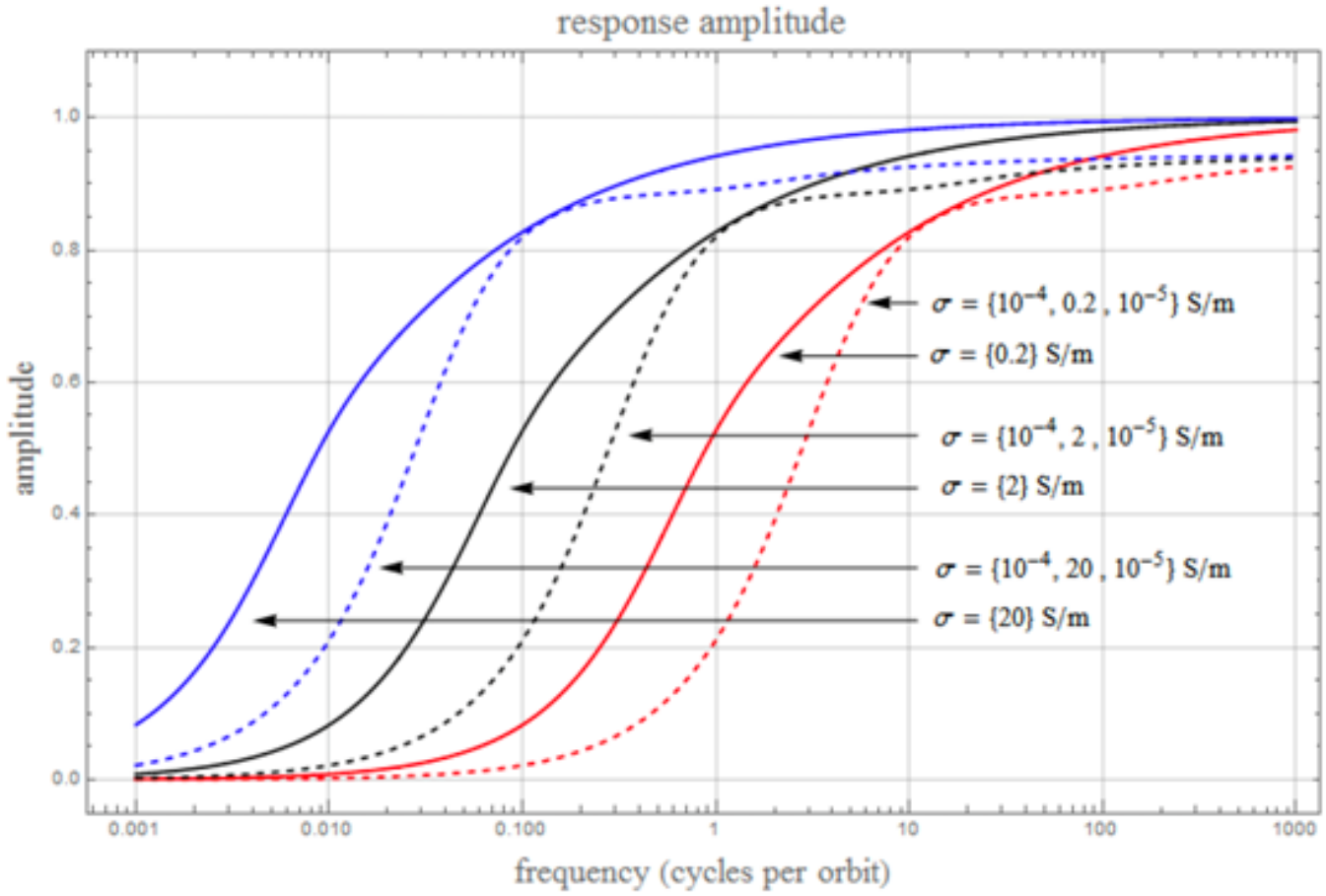


Khurana et al. 2009

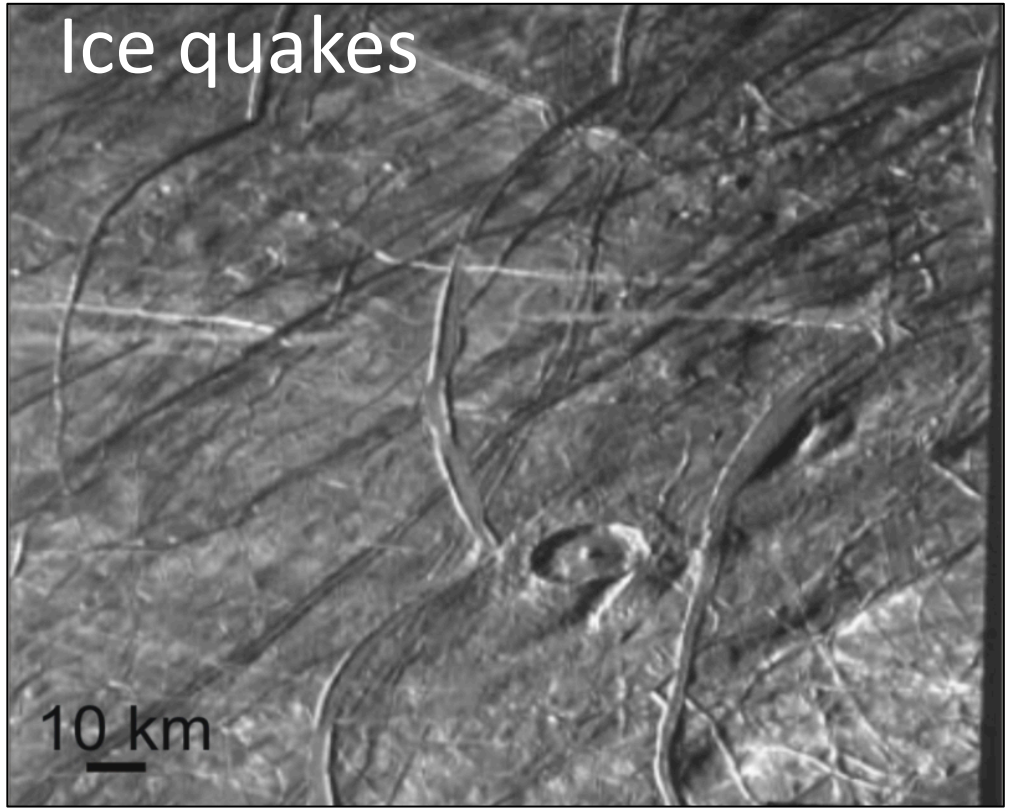
Bruce Bills

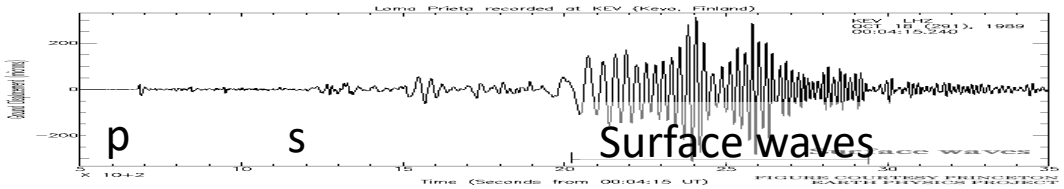
Corey Cochrane

Marshall Styczinski



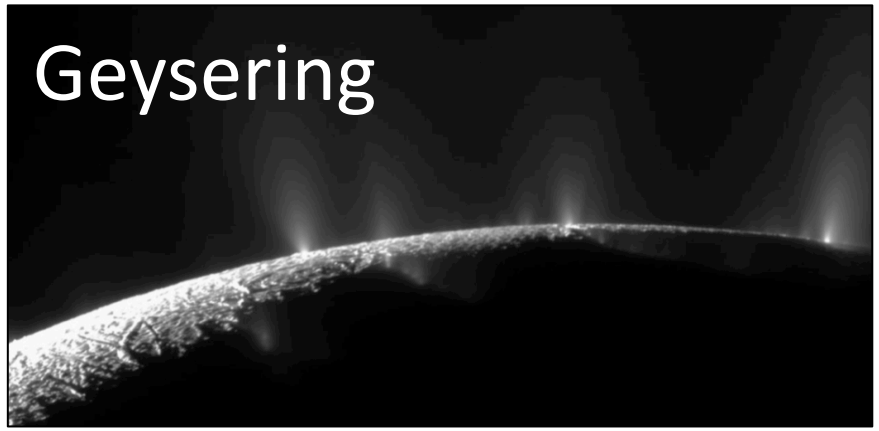
Seismology of Icy Ocean Worlds

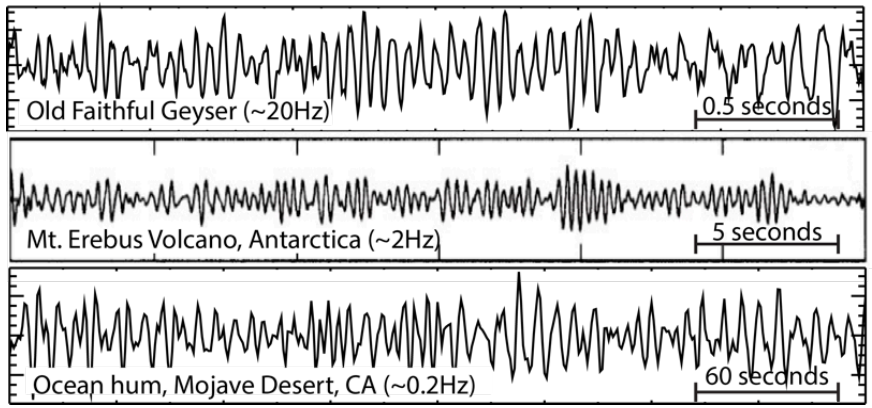


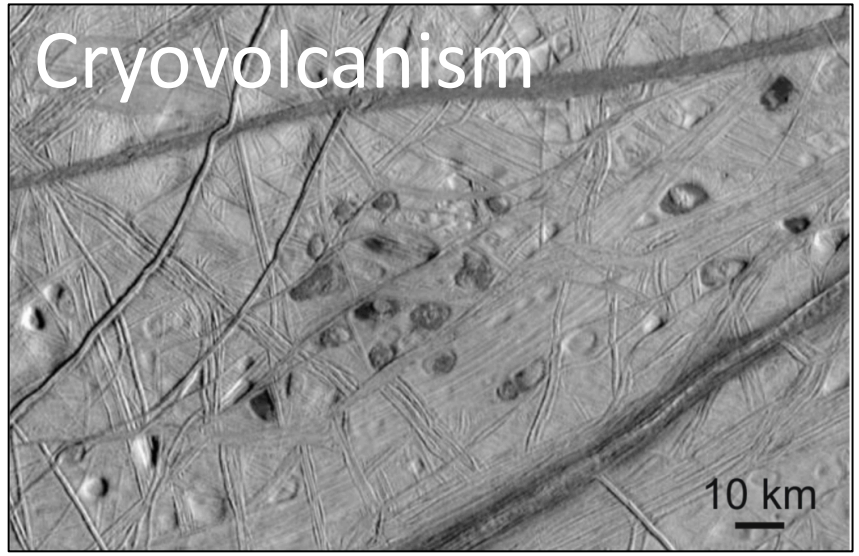


Europa's ice is young and geologically active

Fluid flow induced seismicity: continuous background "hum"





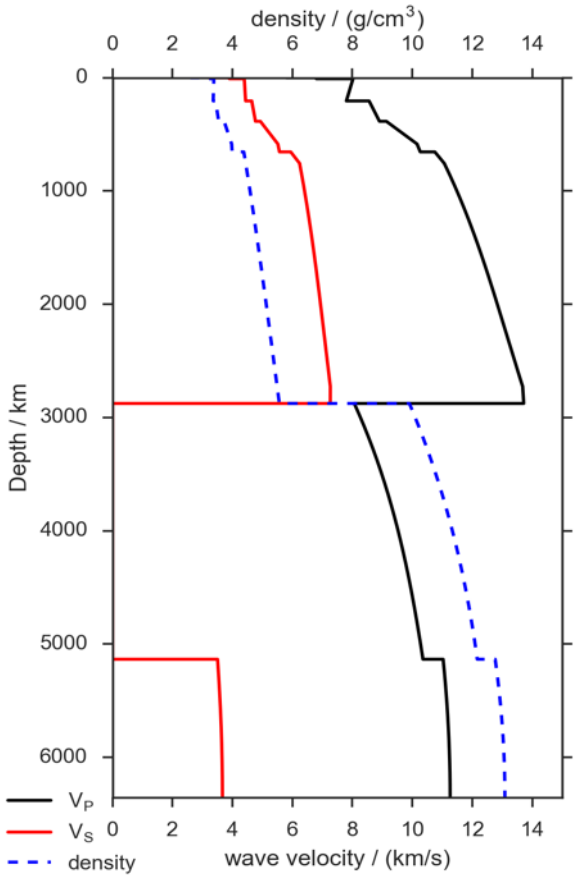


Vance et al. 2018 Astrobiology

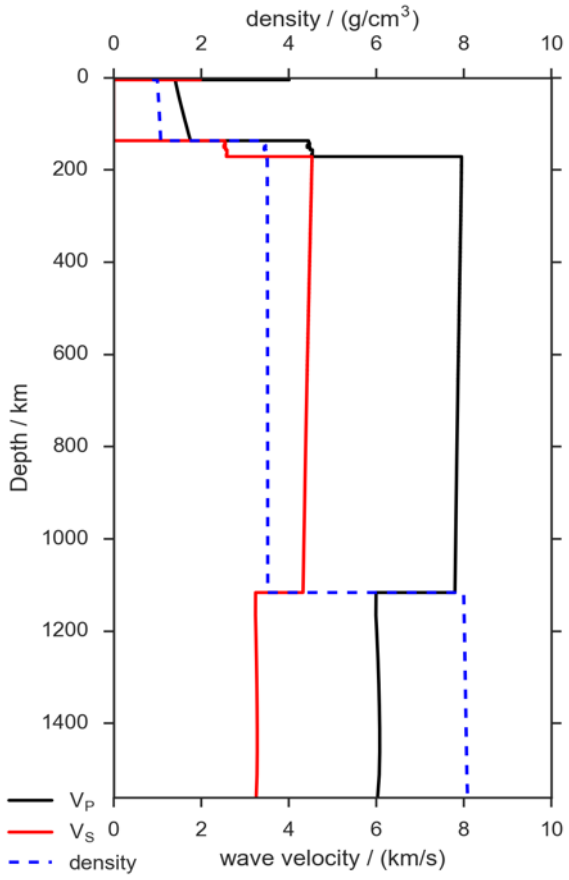
How might an ocean world sound?

Seismic Models

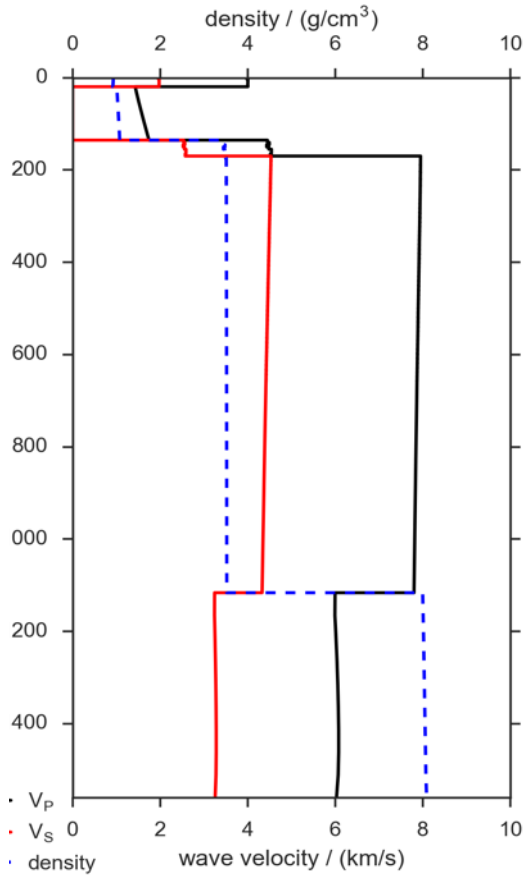
Earth



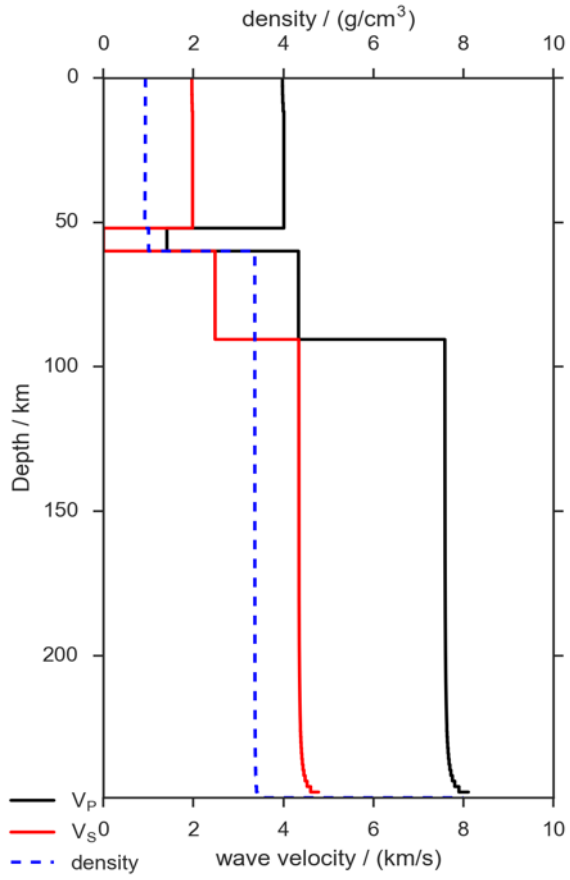
Europa (5km Ice)



Europa (20km Ice)

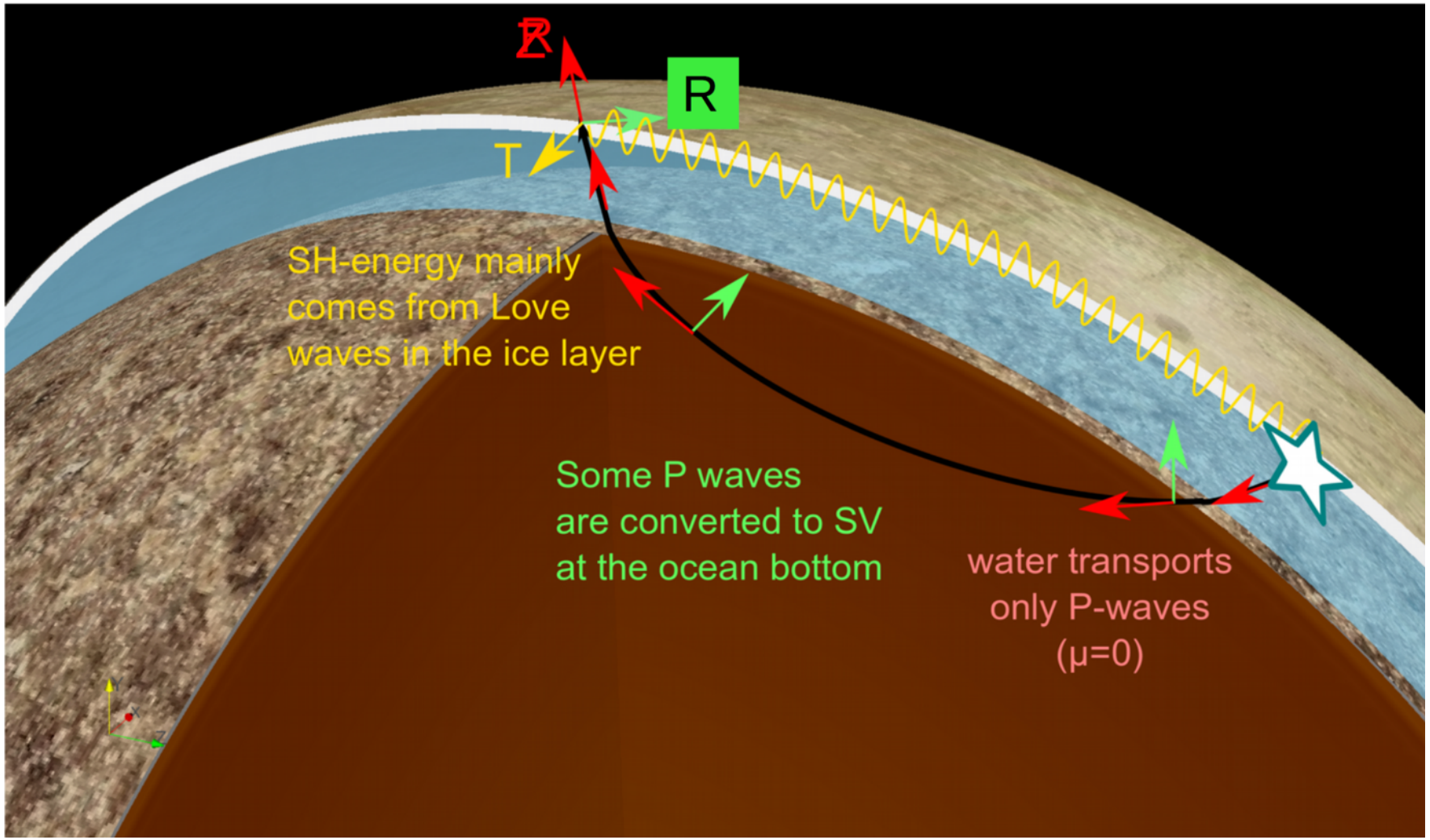


Enceladus

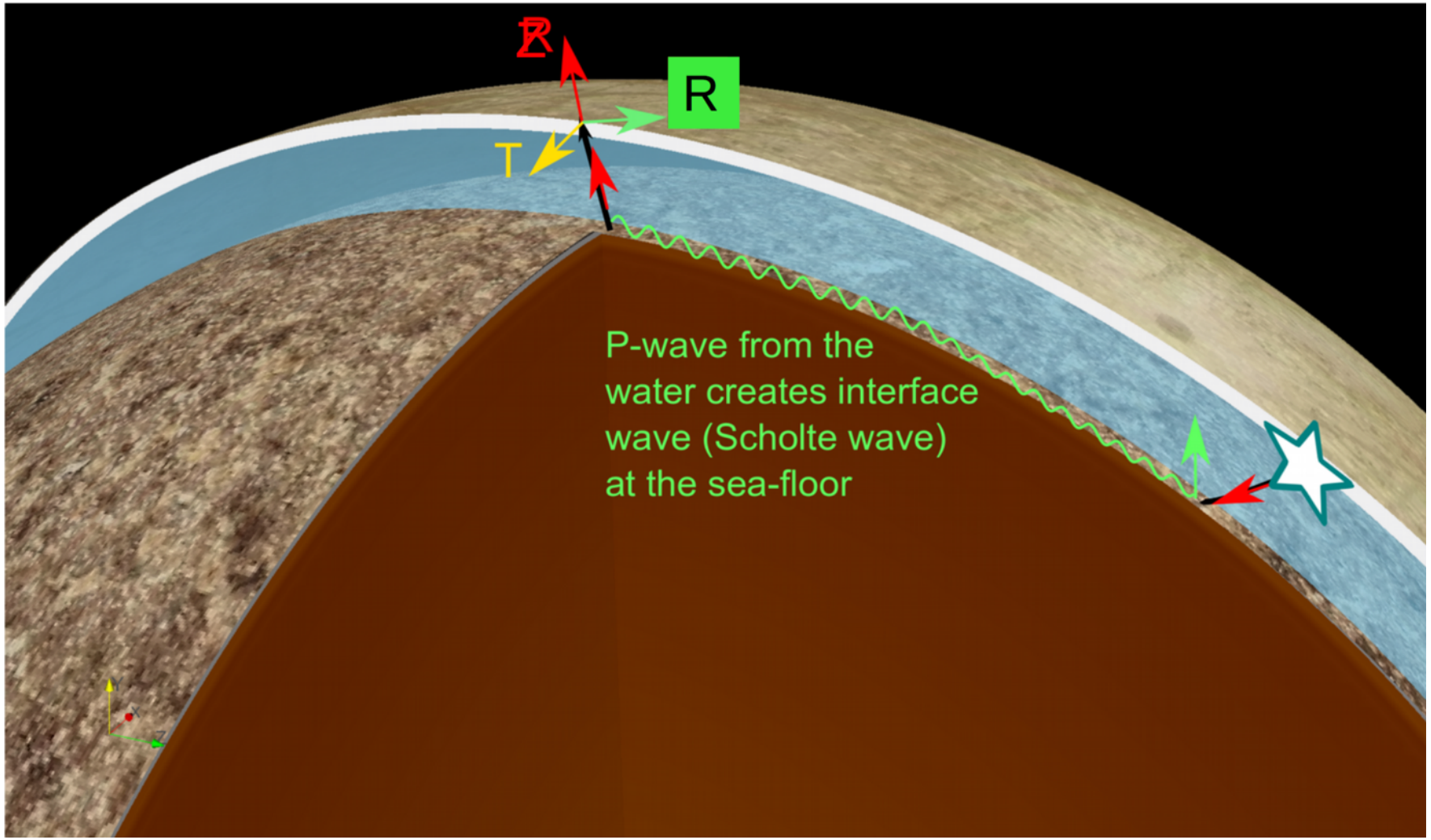


Stähler et al. 2018

Sensing the mantle and ice

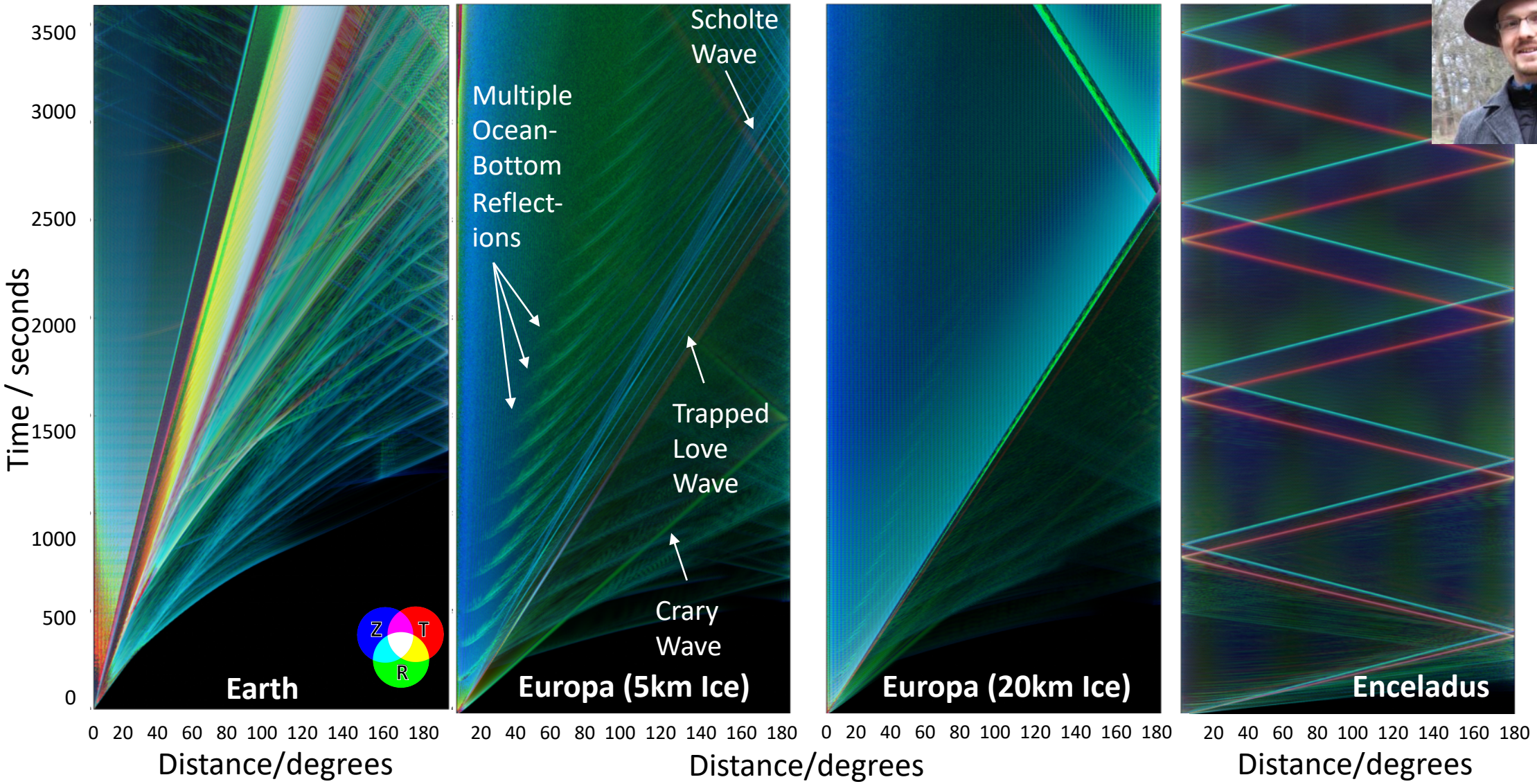


Sensing the mantle and ice



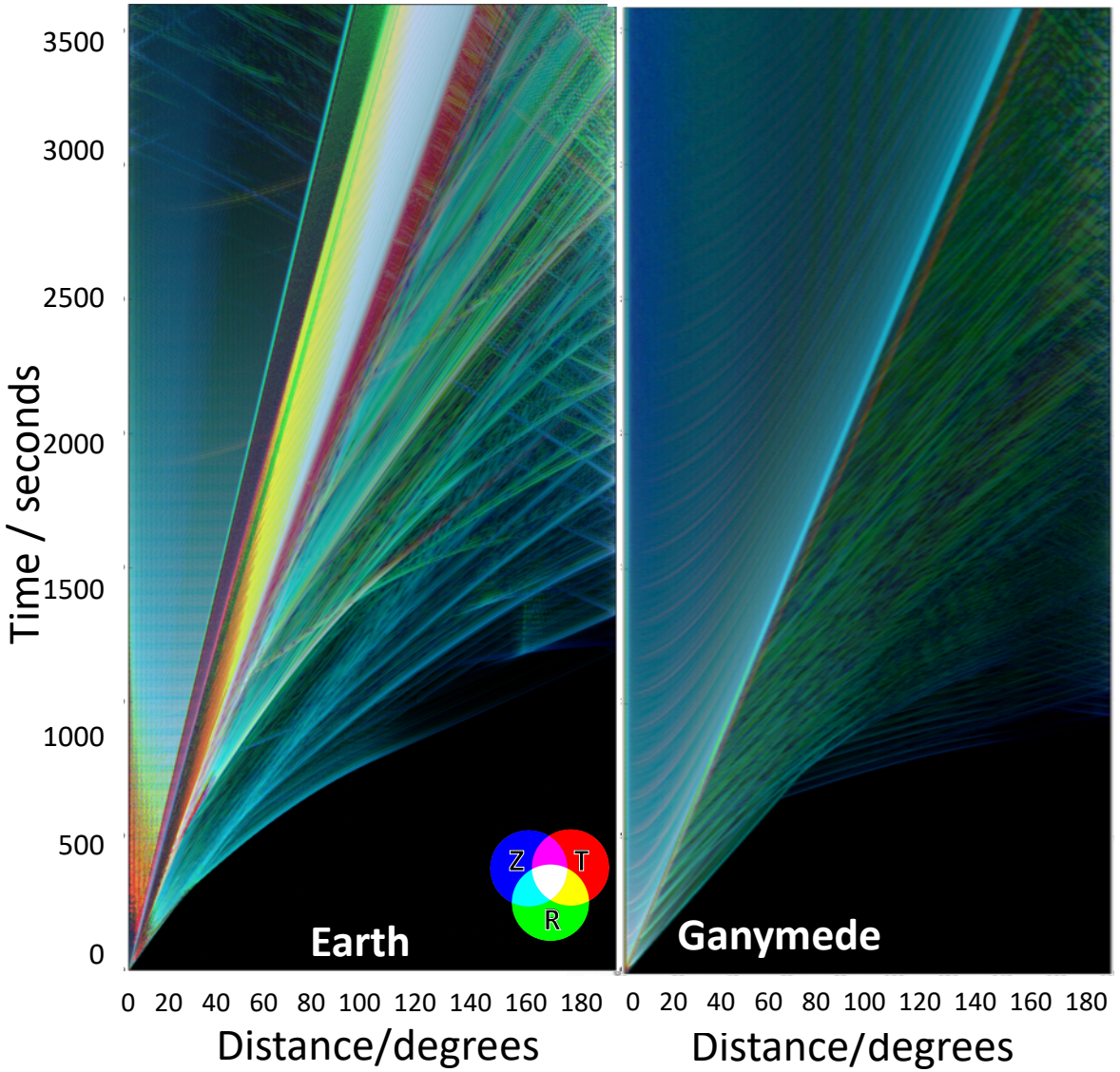
Each Ocean World Has a Unique Seismic Signature

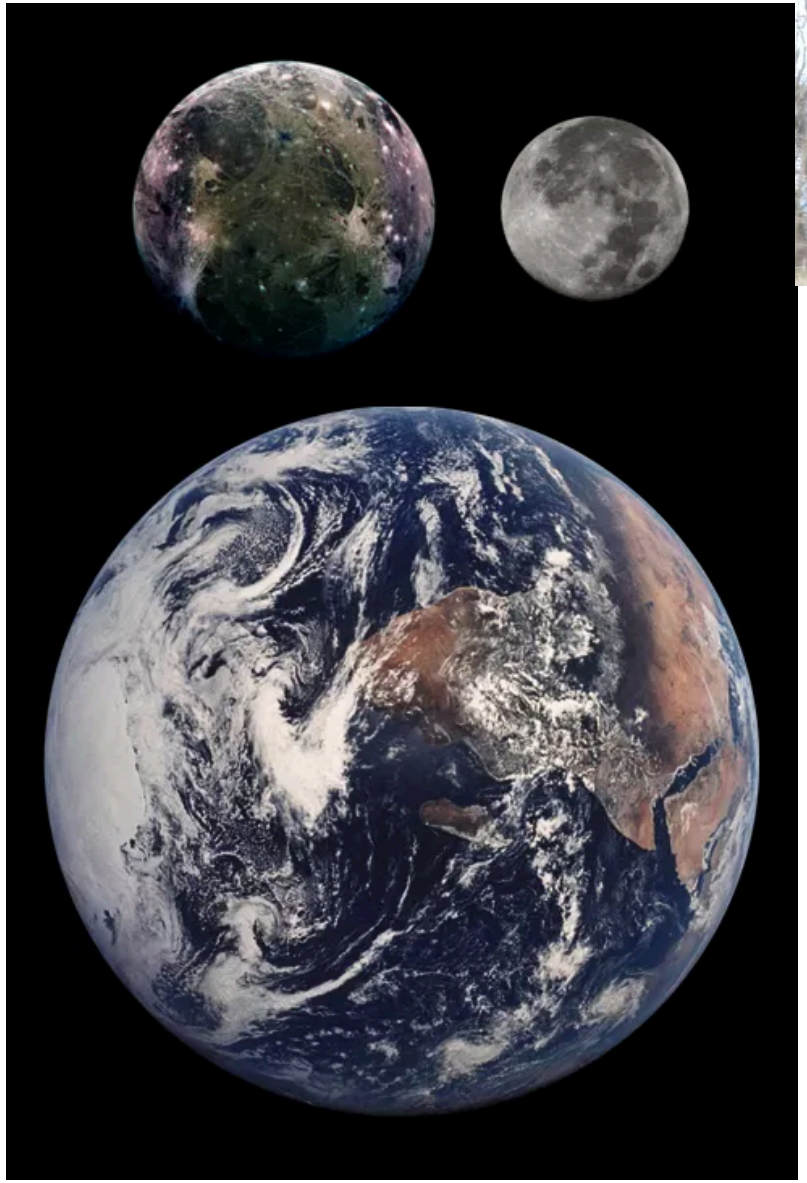
Stähler et al. 2018, JGR.



Each Ocean World Has a Unique Seismic Signature

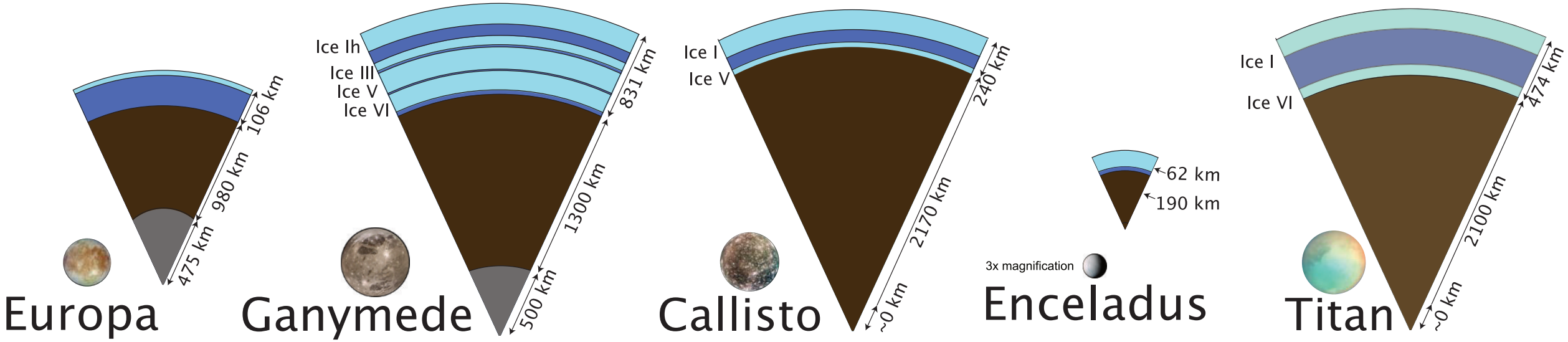
Stähler et al. 2018, JGR.





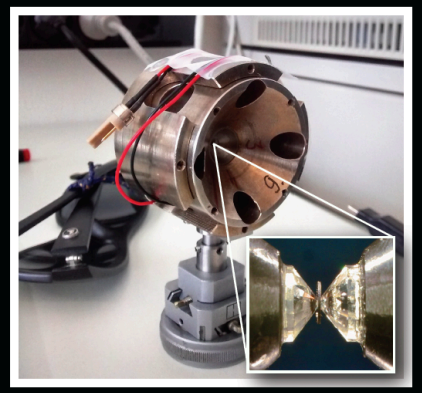
Conclusions

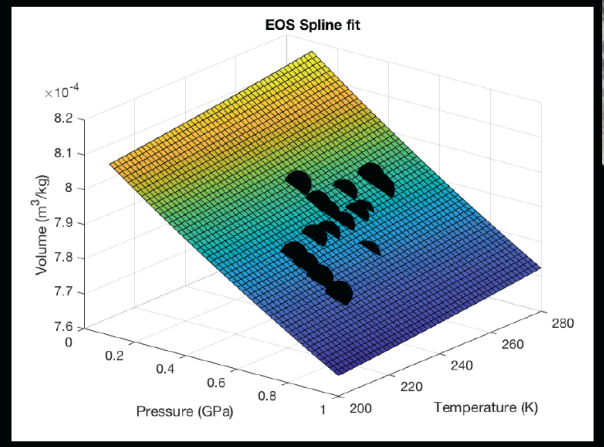
- Deep oceans expand the parameter space of possible ocean properties
- **Thermodynamics** and **forward models** enhance the science return from spacecraft missions

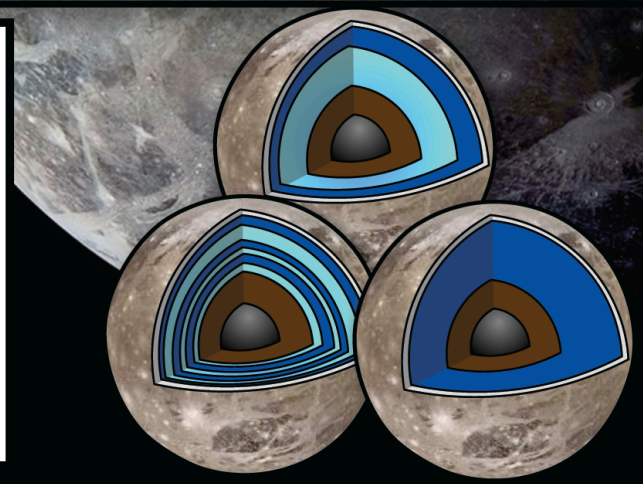


Conclusions

- Comprehensive experimental coverage of ices/solution equilibriums at T > 300K (melting, eutectic and relative density)
- EOS framework (Mie Gruneisen + Gibbs LBF) that enable realistic and comprehensive thermodynamic properties description over large PT range for each ice polymorphs
- Combination with aqueous solution LBF allow phase boundary predictions for H_2O-(Mg,Na,Cl,SO_4) systems
- Representation easily sharable (1 file 50 Ko) and updatable with new data. (http://earthweb.ess.washington.edu/brown/)
- **New behavior to play with in simulations (density inversions, melting point depression)**







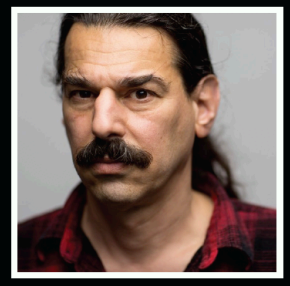
The team "face diagram":

UW team :

B. Journaux

J. M. Brown

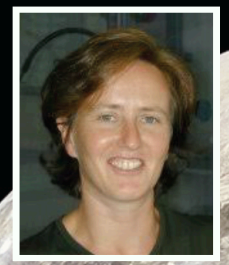
O. Bollengier

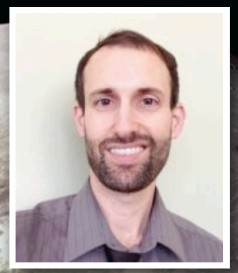

E. Abramson

Beyond :

Anya Pakhomova (DESY)

Ines Collins (ESRF)


Tiziana Boffa-Ballaran (BGI)


Steve Vance (JPL)

Sylvain Petitgirard (BGI)

Gabriel Tobie (LPGN)

Icy Worlds
Astrobiology at the Water-Rock Interface

NASA Astrobiology Institute

NASA POSTDOCTORAL PROGRAM

LPG

UWastrobiology

JPL

BGI Bayerisches Geoinstitut

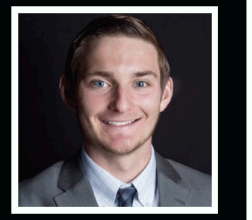
ESRF

@MinPhysUW
@B_jour

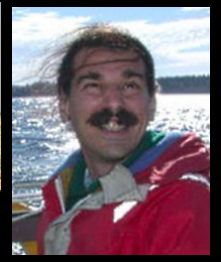
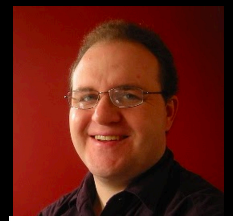
UW undergrads :

Jason Ott

Penny Espinoza

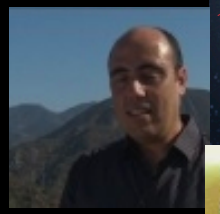

Nathan Reinsdorf

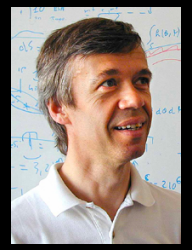
Fred Bradley

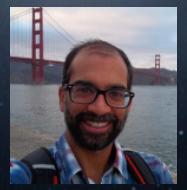
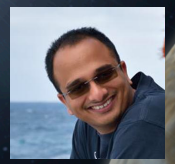



Support:

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





Jet Propulsion Laboratory
California Institute of Technology

Icy Worlds

Astrobiology at the Water-Rock Interface

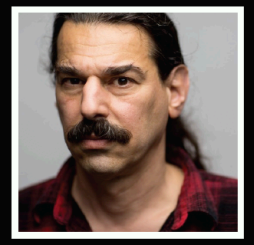
Summary

High pressure physical chemistry have permitted to suggests that :

- **Aqueous salty solution can be stable to much greater depth than predicted with just pure water**
- **Salt solutes can be transported by high pressure ices**
- Large water-rich planetary bodies should not be ruled out as potential habitable worlds!
- Experimental high pressure physical chemistry has a major role to play in constraining the habitability of deep extraterrestrial environments

Thanks to :

J. M. Brown (UW)


E. Abramson (UW)

O. Bollengie (UW)

S. Vance (JPL)

And also ;
Sylvain Petitgirard (BGI), Tiziana Boffa-Ballaran (BGI), Anya Pakhomova (DESY),
I. Collins (ESRF)
I. Daniel (ENS-Lyon)

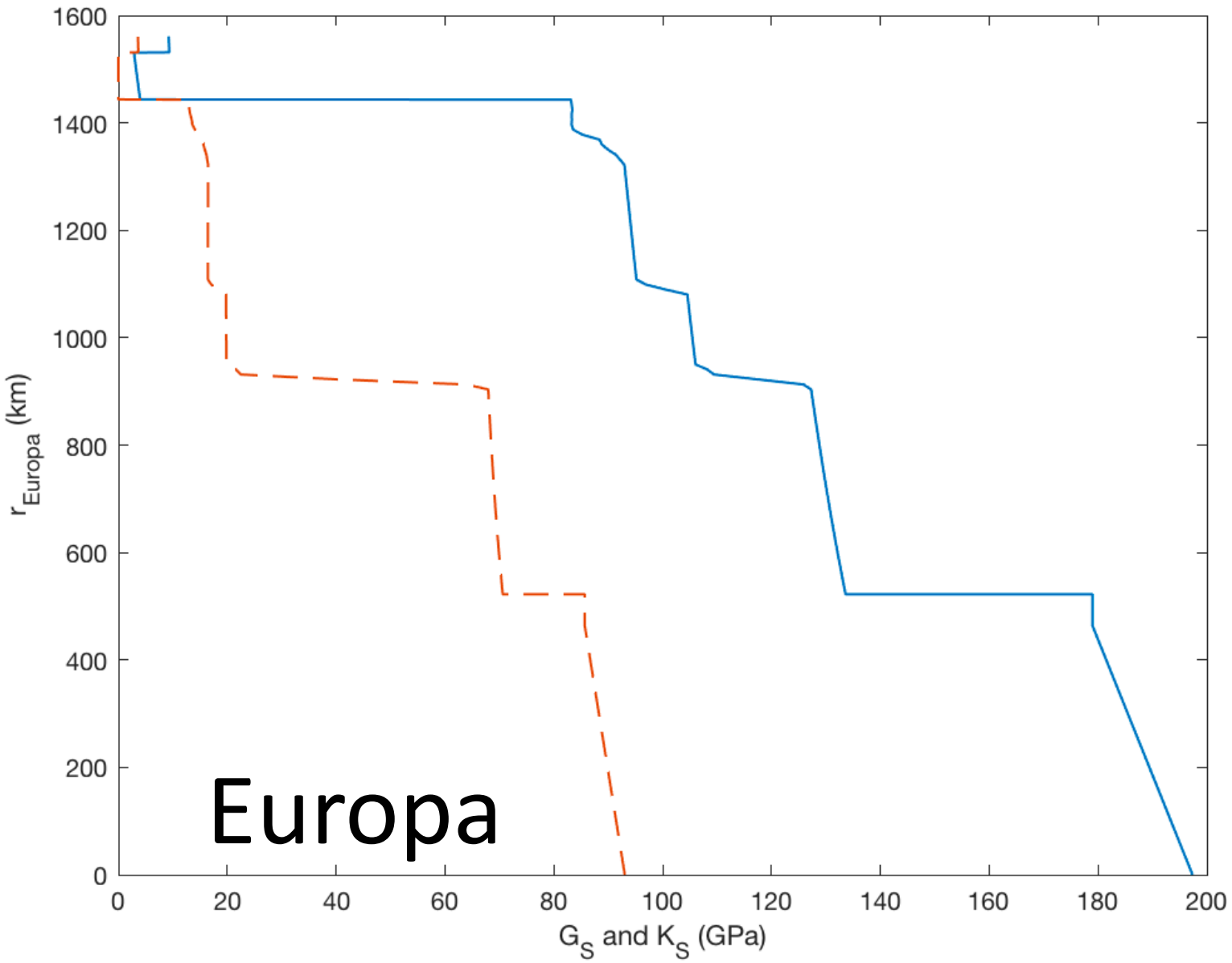
Tidal Dissipation

$$\tilde{\sigma}_{ij} = 2\tilde{\mu}(\omega)\tilde{\varepsilon}_{ij} + \left[K_{\mathrm{E}} - \frac{2}{3}\tilde{\mu}(\omega)\right]\tilde{\varepsilon}_{kk}\delta_{ij},$$

where

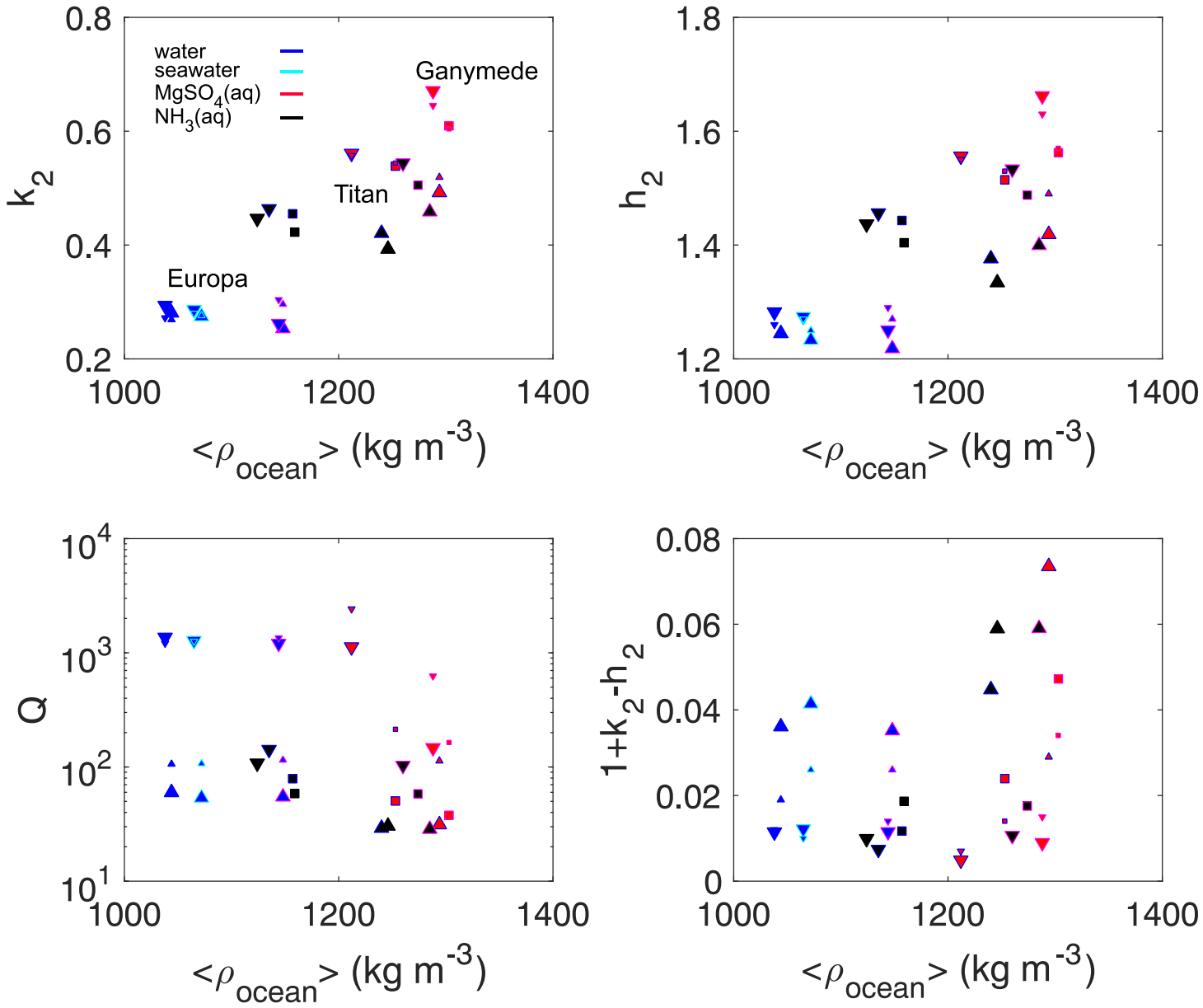
$$\tilde{\mu}(\omega) = \frac{\mu_{\mathrm{E}}\omega^2\eta^2}{\mu_{\mathrm{E}}^2 + \omega^2\eta^2} + i\frac{\mu_{\mathrm{E}}^2\omega\eta}{\mu_{\mathrm{E}}^2 + \omega^2\eta^2},$$

Tobie et al. 2006



Vance et al. 2017 JGR

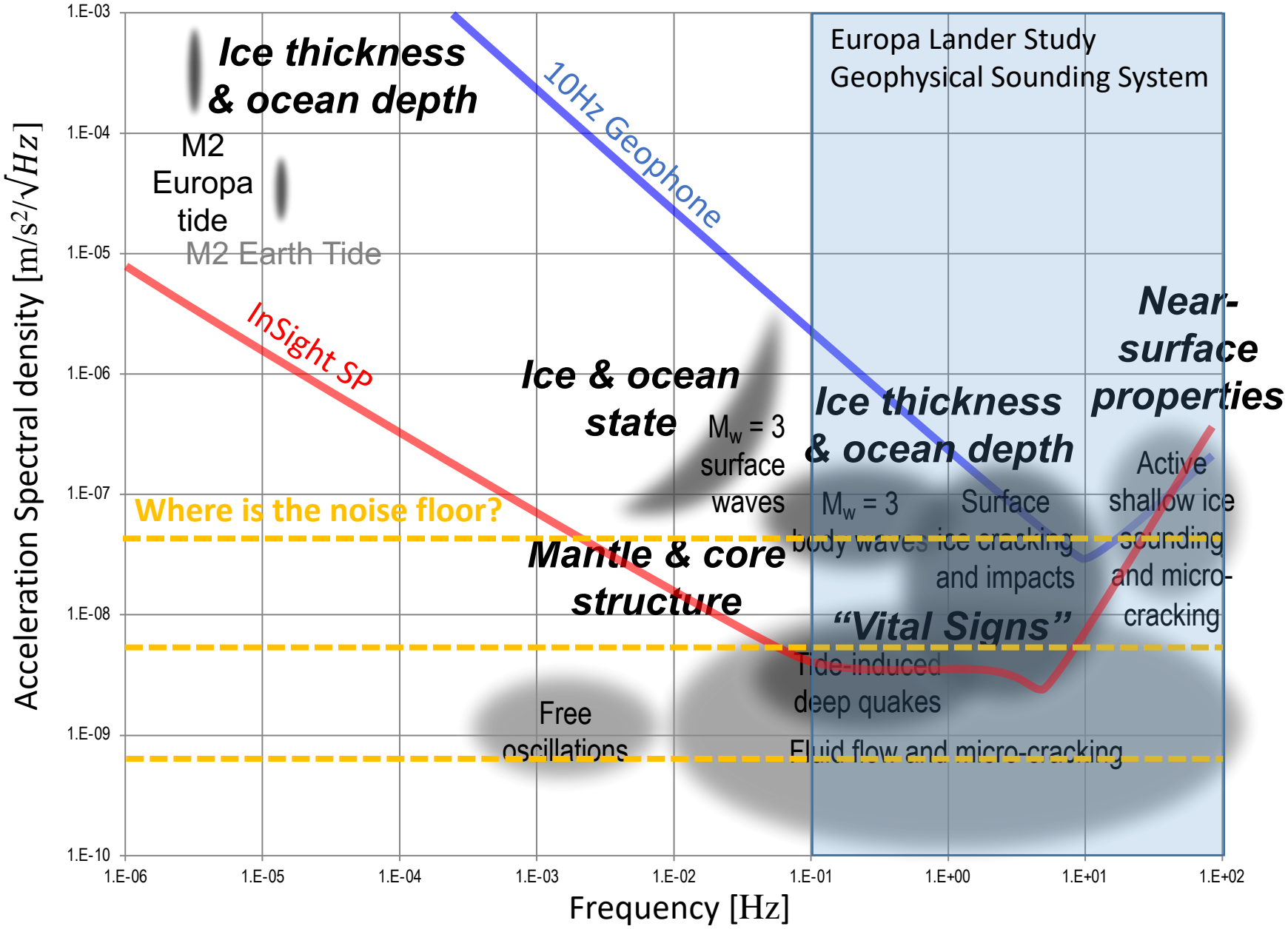
Tidal Dissipation

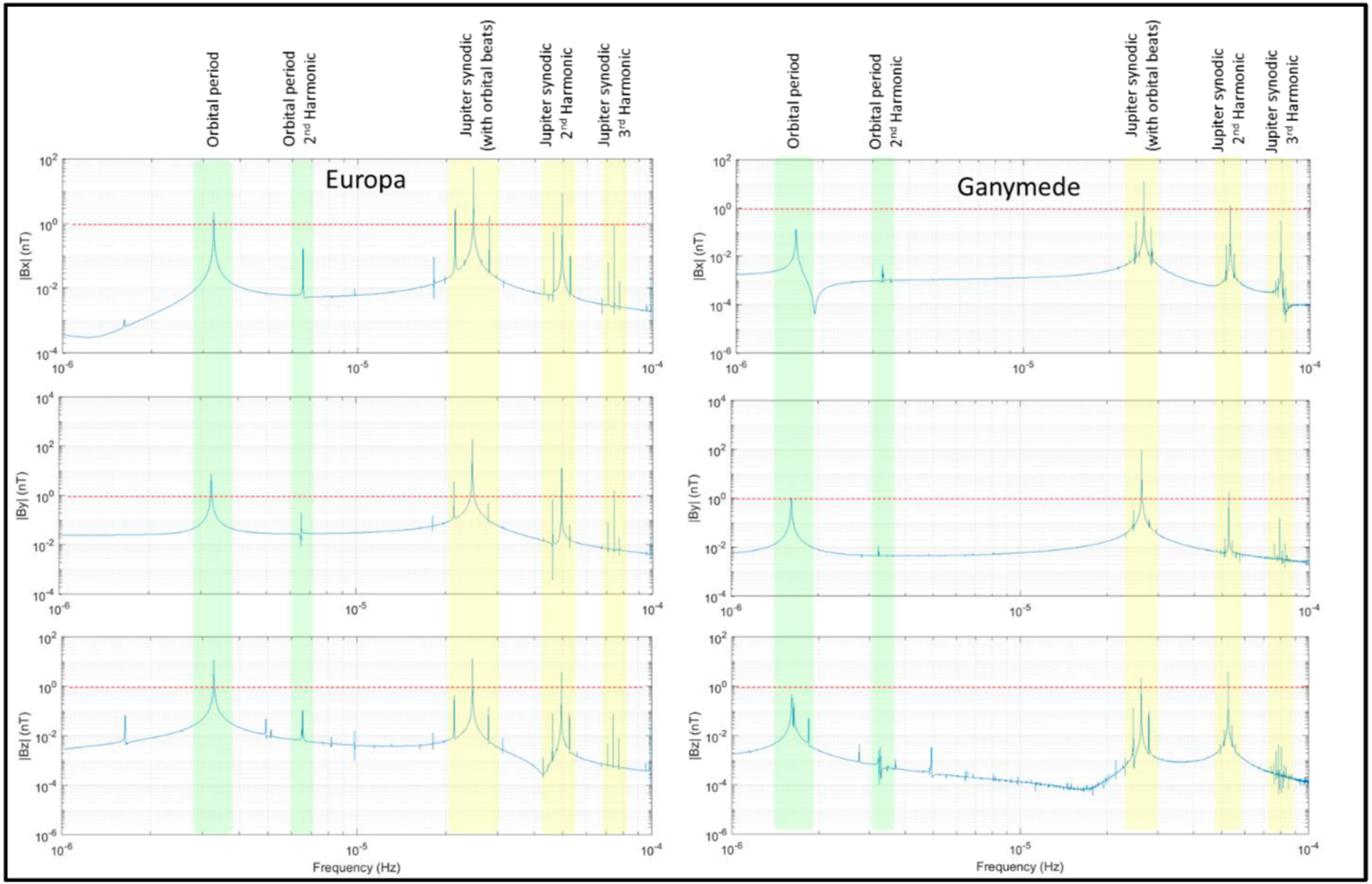


Contributed by
Gabriel Tobie and
Shunichi Kamata

Vance et al. 2017 JGR

Can we hear it?

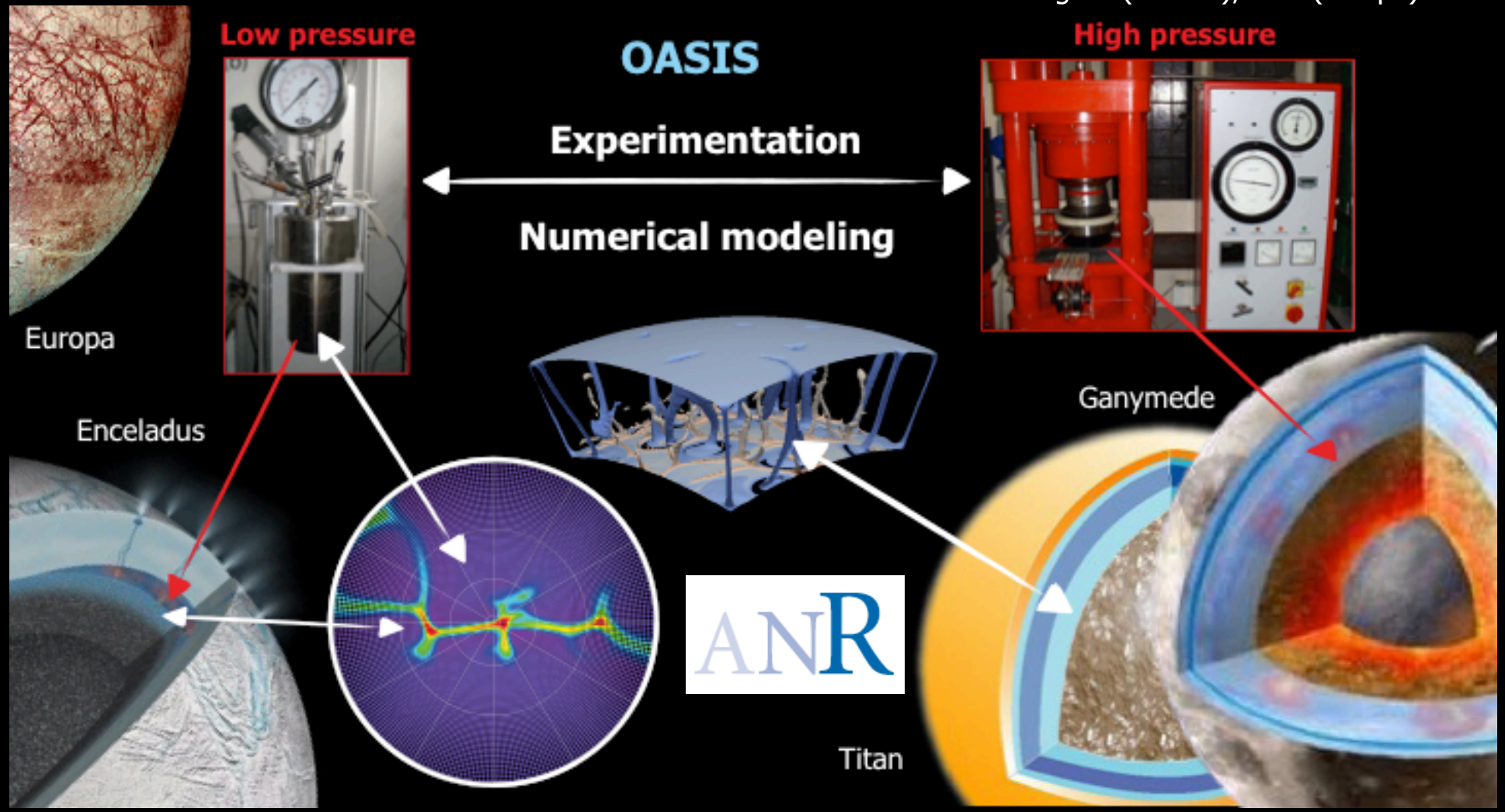



Orbital period
Orbital period 2nd Harmonic
Jupiter synodic (with orbital beats)
Jupiter synodic 2nd Harmonic
Jupiter synodic 3rd Harmonic
Europa
Ganymede
|Bx| (nT)
|By| (nT)
|Bz| (nT)
Frequency (Hz)

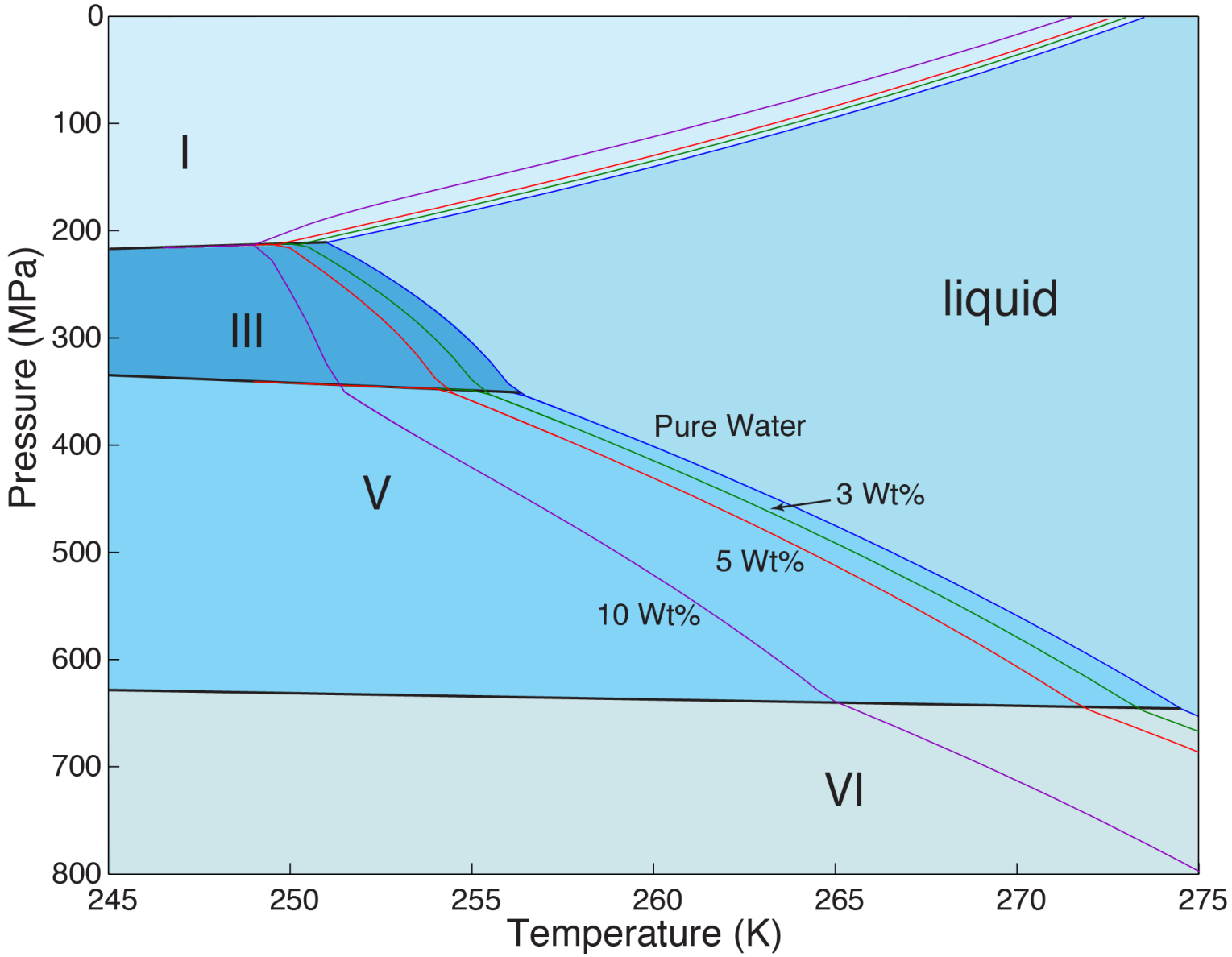
Project OASIS: Organic and Aqueous Systems in Icy Satellites

OASIS strategy: Combining experimental and modeling approaches to provide constraints on the aqueous alteration processes occurring inside icy worlds from their accretion to present.

OASIS consortium (P.I. G. Tobie) France: LPG (Nantes), ISTerre (Grenoble), CRPG (Nancy); Czech Rep.: Charles Univ. (Prague); Germany: Univ. Heidelberg; US: JPL-Caltech (Pasadena), Univ. Washington (Seattle), ASU (Tempe)



Phase diagram for aqueous magnesium sulfate ($MgSO_4$)



Vance, Bouffard, Choukroun, and Sotin, 2014.

Thermochemistry of H_2O(s)-MgSO4(aq)

$$\mu^L_{H_2O} = \mu^S_{H_2O} \text{ in equilibrium}$$

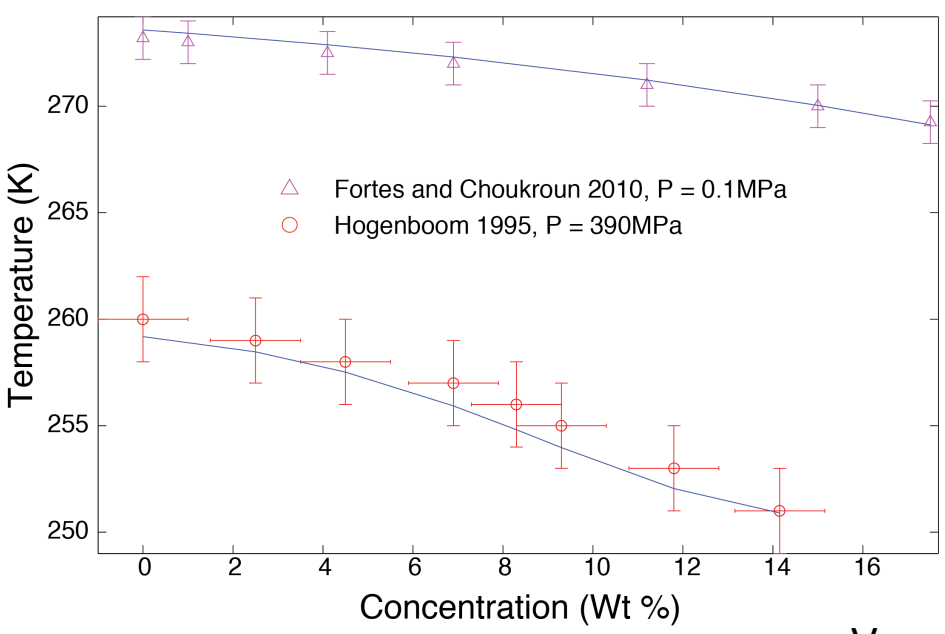
$\mu^S_{H_2O}$ from Choukroun and Grasset 2010

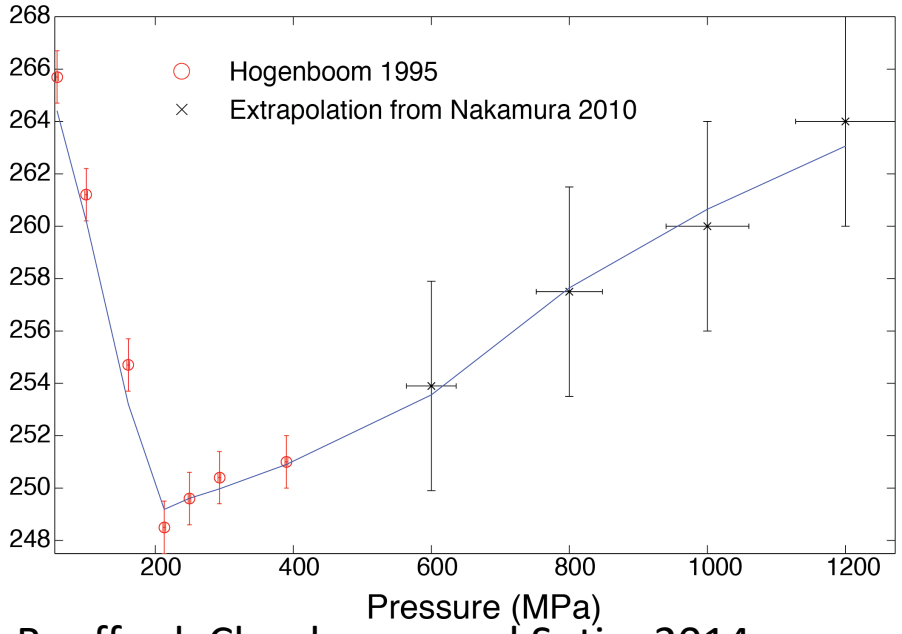
$$\mu^L_{H_2O}(P,T,X^L_{H_2O}) = \mu^L_{H_2O,pure} + RT\ln(\gamma^L_{H_2O} X^L_{H_2O})$$

$$RT\ln\gamma = W(1 - X^L_{H_2O})^2$$

$$W = w_0\left(1 + w_1 \tanh(w_2 P)\right)\left(1 + \frac{w_3}{(T - T_o)^2}\right)$$

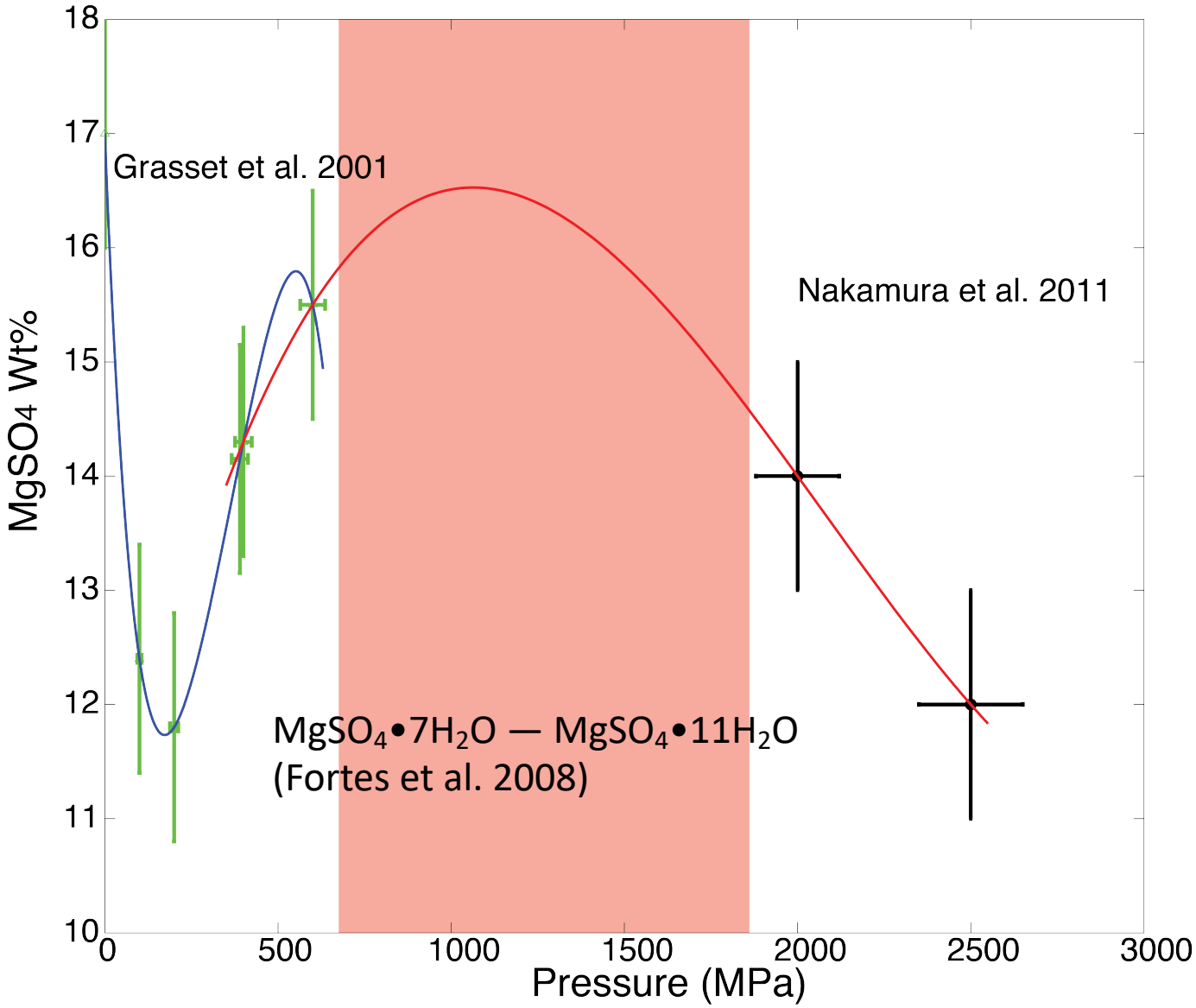
Eutectic Data

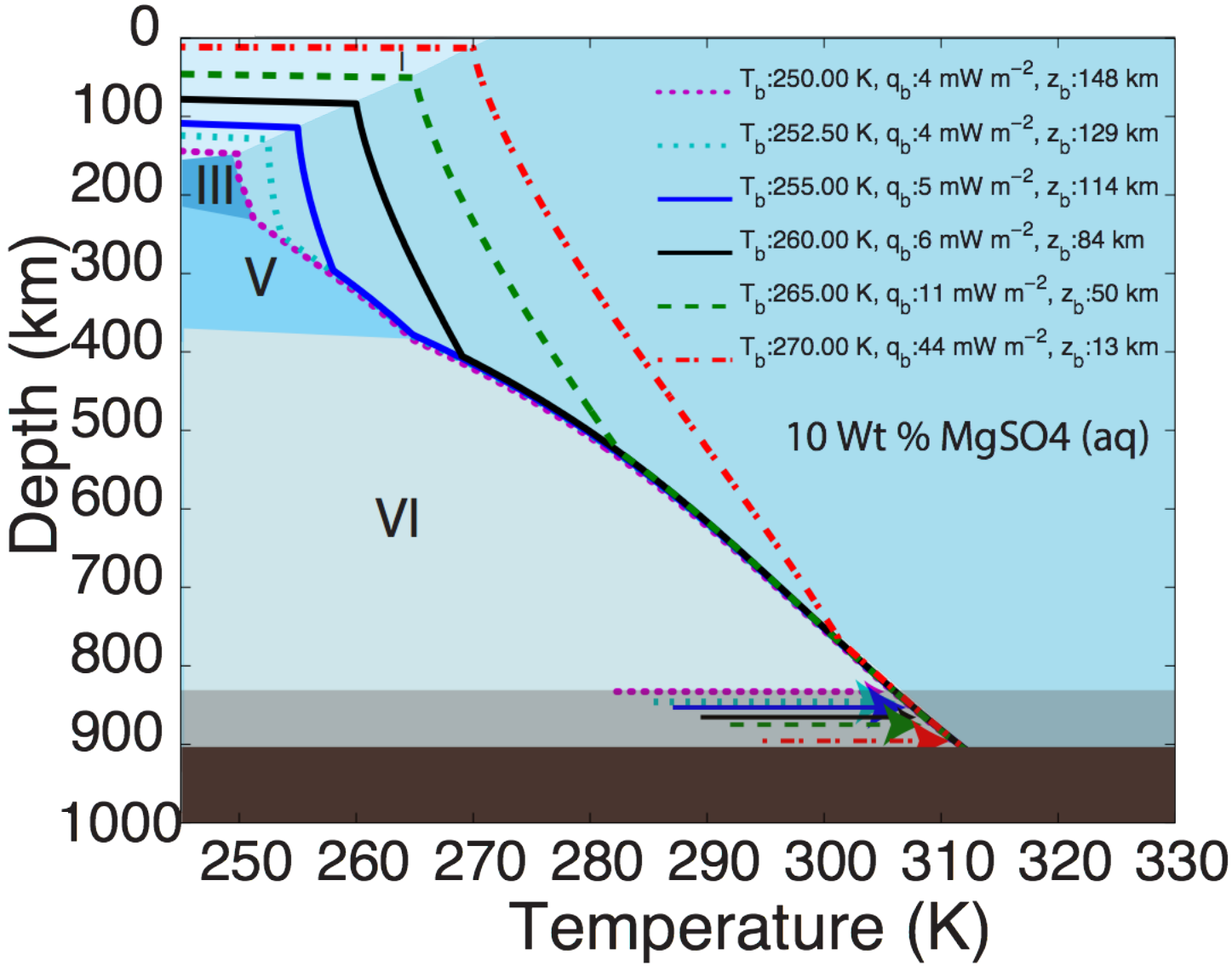


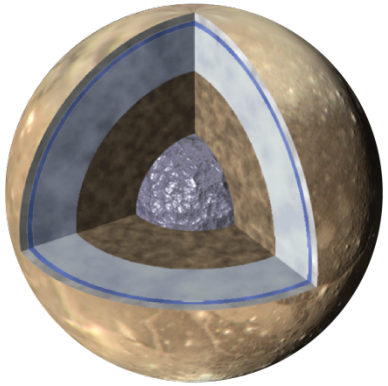


Vance, Bouffard, Choukroun, and Sotin, 2014.

Eutectic composition vs pressure



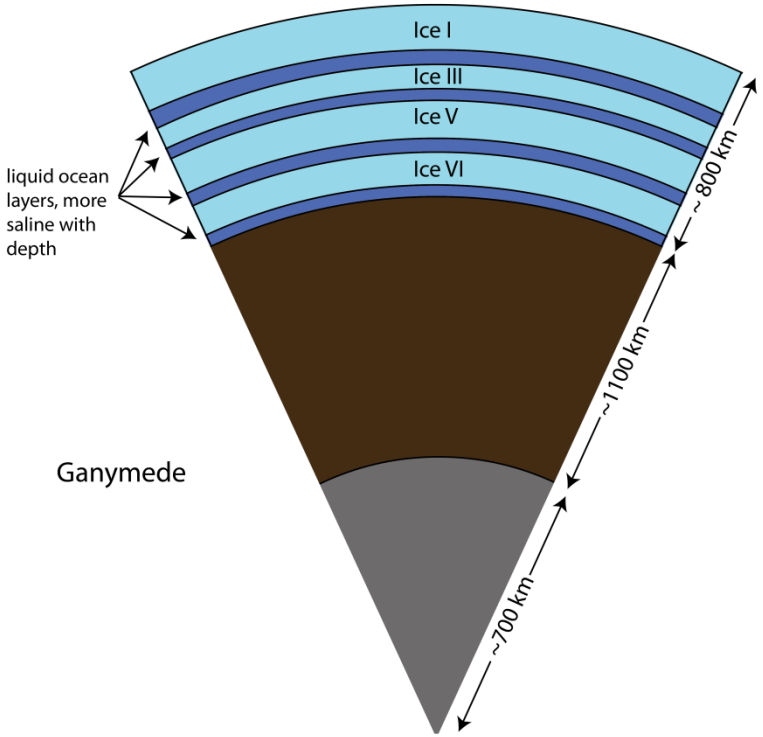




Modified from Vance, Bouffard, Choukroun, and Sotin, 2014, *PSS*

Constraint on depth to silicate mantle, size of Fe-FeS core

Calculate radii from Galileo constraints on Ganymede's density (1,942±4.8 kg/m3) and gravitational moment of inertia (C/MR^2 = 0.3105±0.028) Schubert+ 2004



$$M_{iron} = M - M_{H_2O} - \frac{4\pi}{3}\rho_{sil}\left(R_{sil}^3 - R_{iron}^3\right)$$

$$R_{iron} = \left(\frac{M - M_{H_2O} - \frac{4\pi}{3}\rho_{sil}R_{sil}^3}{\frac{4\pi}{3}\left(\rho_{iron} - \rho_{sil}\right)}\right)^{1/3}$$

$$C = C_{H_2O} + \frac{8\pi}{15}\left(\rho_{sil}\left(R_{sil}^5 - R_{iron}^5\right) + \rho_{iron}R_{iron}^5\right)$$

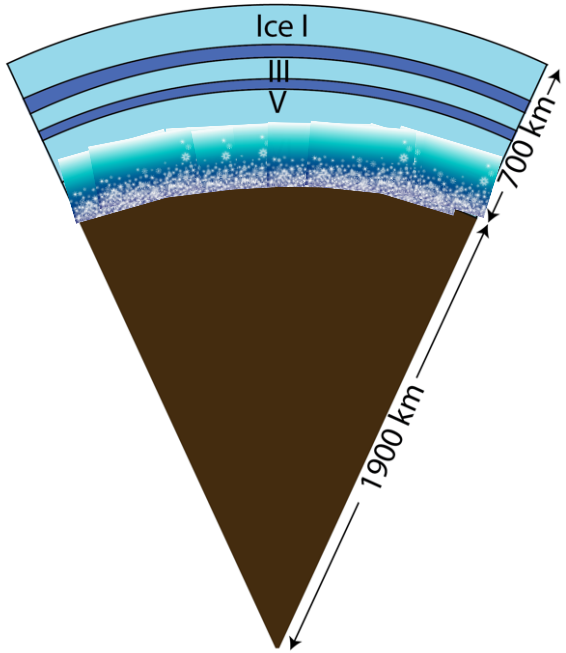
$$\rho_{iron} = \frac{\rho_{Fe}\rho_{FeS}}{X_{FeS}\left(\rho_{Fe} - \rho_{FeS}\right) + \rho_{FeS}} = 7,030$$

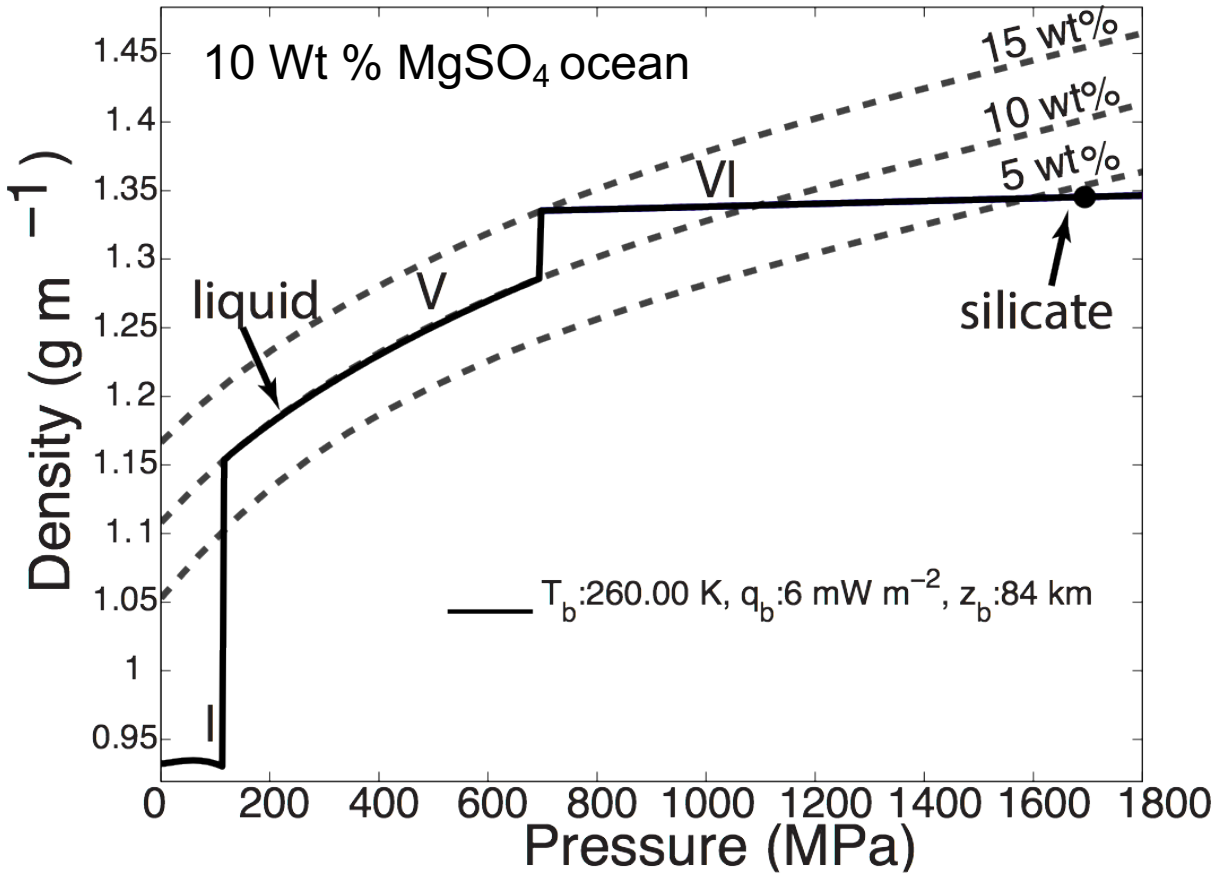
$$\rho_{silicate} = 3,125 \text{ kg m}^{-3}$$

Vance, Bouffard, Choukroun, and Sotin, 2014.

Thermal model constrains Ganymede's internal structure

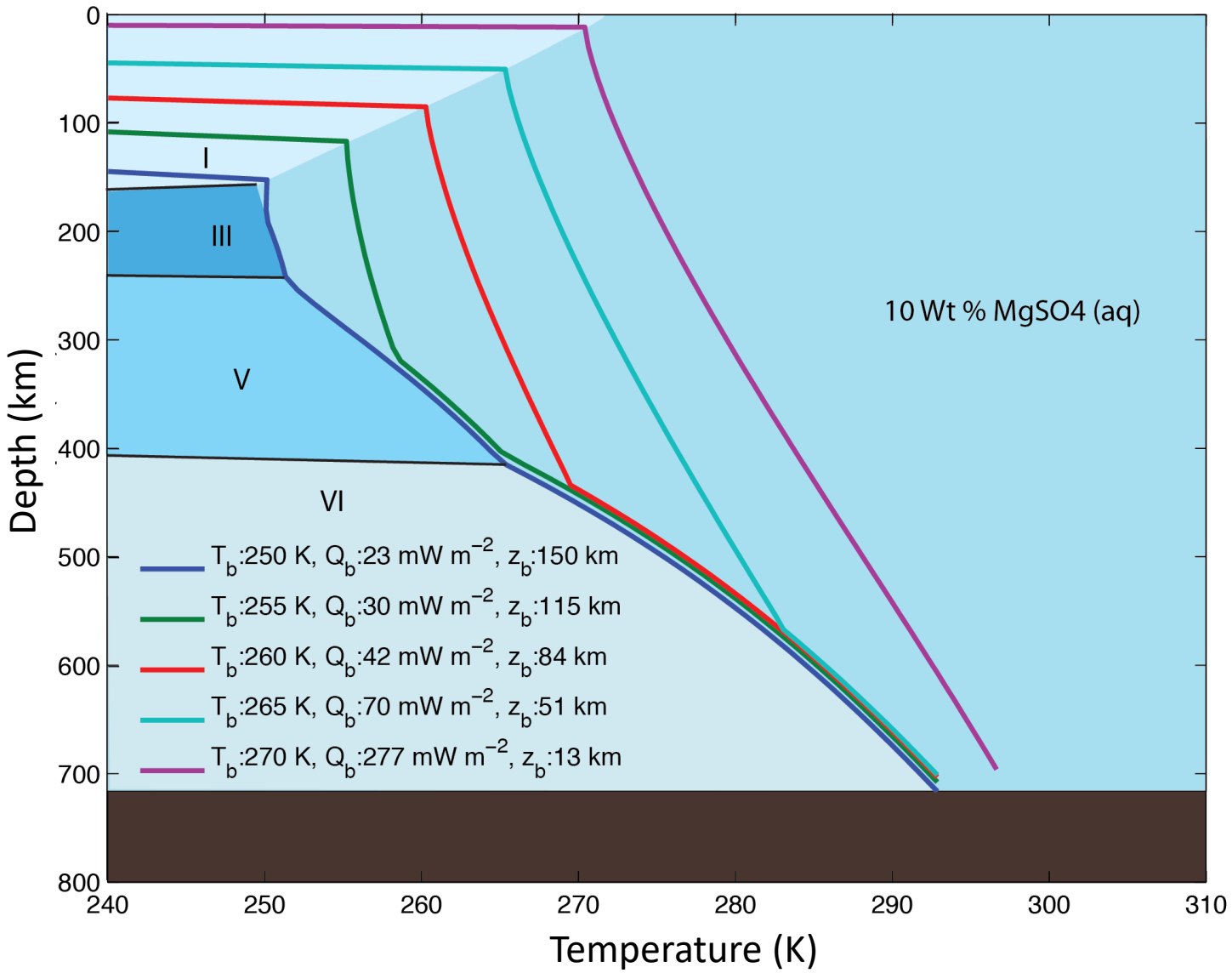
- ice I melting: T_b
- Follow melting curves in ice III, V, VI layers



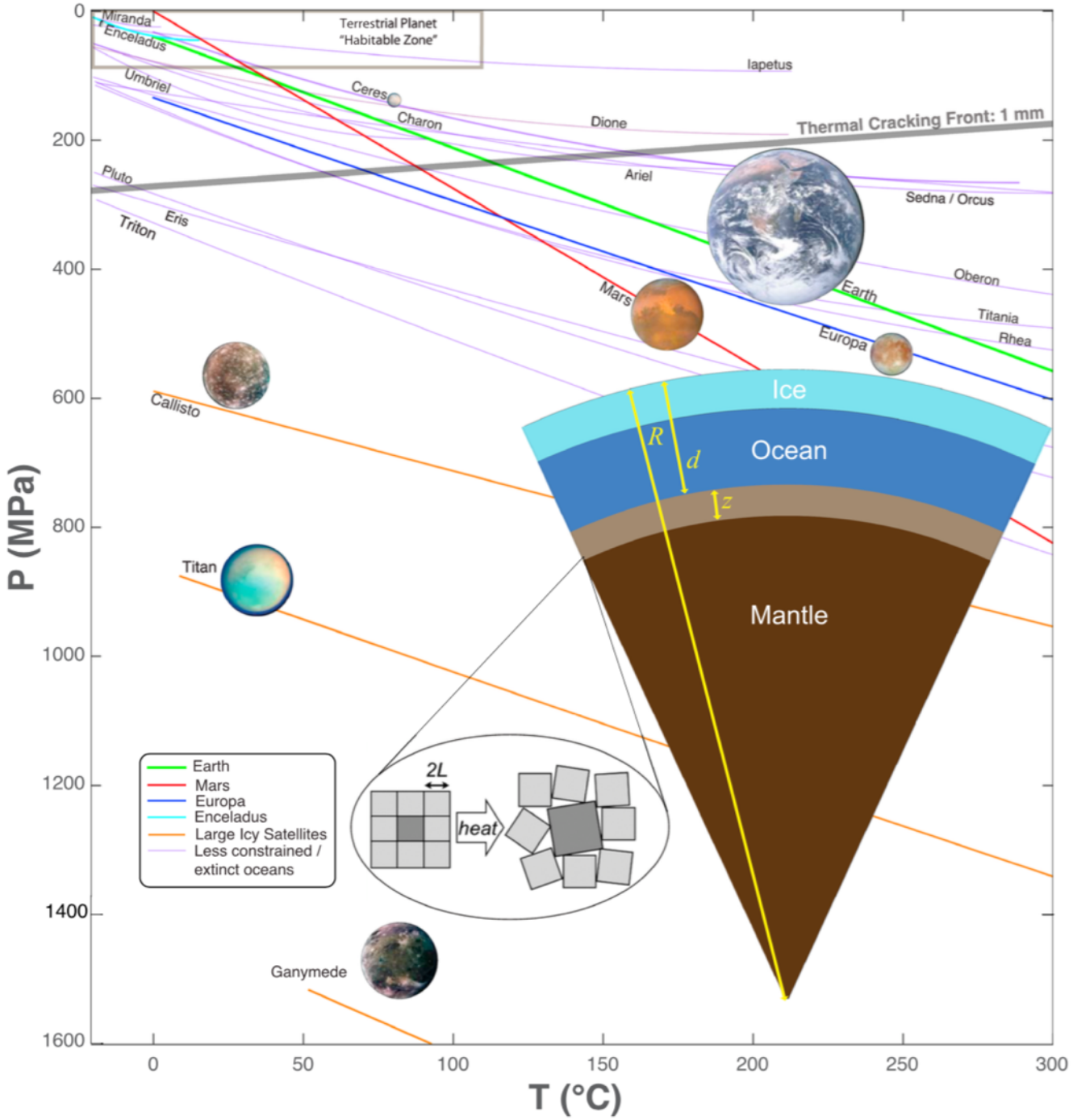


Modified from Vance, Bouffard, Choukroun, and Sotin, 2014, *PSS*

Salinity determines cryosphere structure



Vance, Bouffard, Choukroun, and Sotin, 2014.



Vance, Hand, and Pappalardo 2016
Also Vance et al. 2007
→"small ocean planets" (SOPs!)

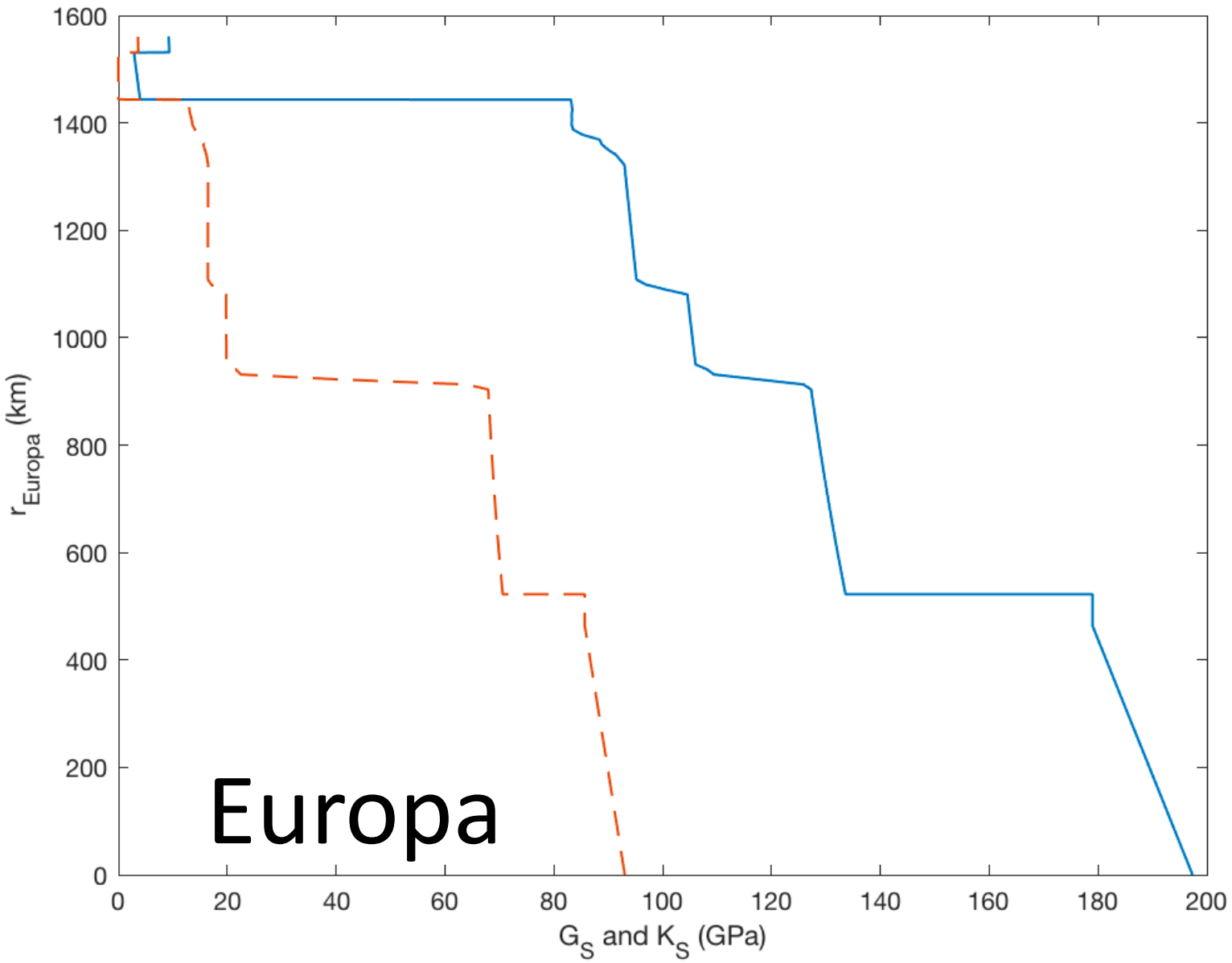
Tidal Dissipation

$$\tilde{\sigma}_{ij} = 2\tilde{\mu}(\omega)\tilde{\varepsilon}_{ij} + \left[K_{\mathrm{E}} - \frac{2}{3}\tilde{\mu}(\omega)\right]\tilde{\varepsilon}_{kk}\delta_{ij},$$

where

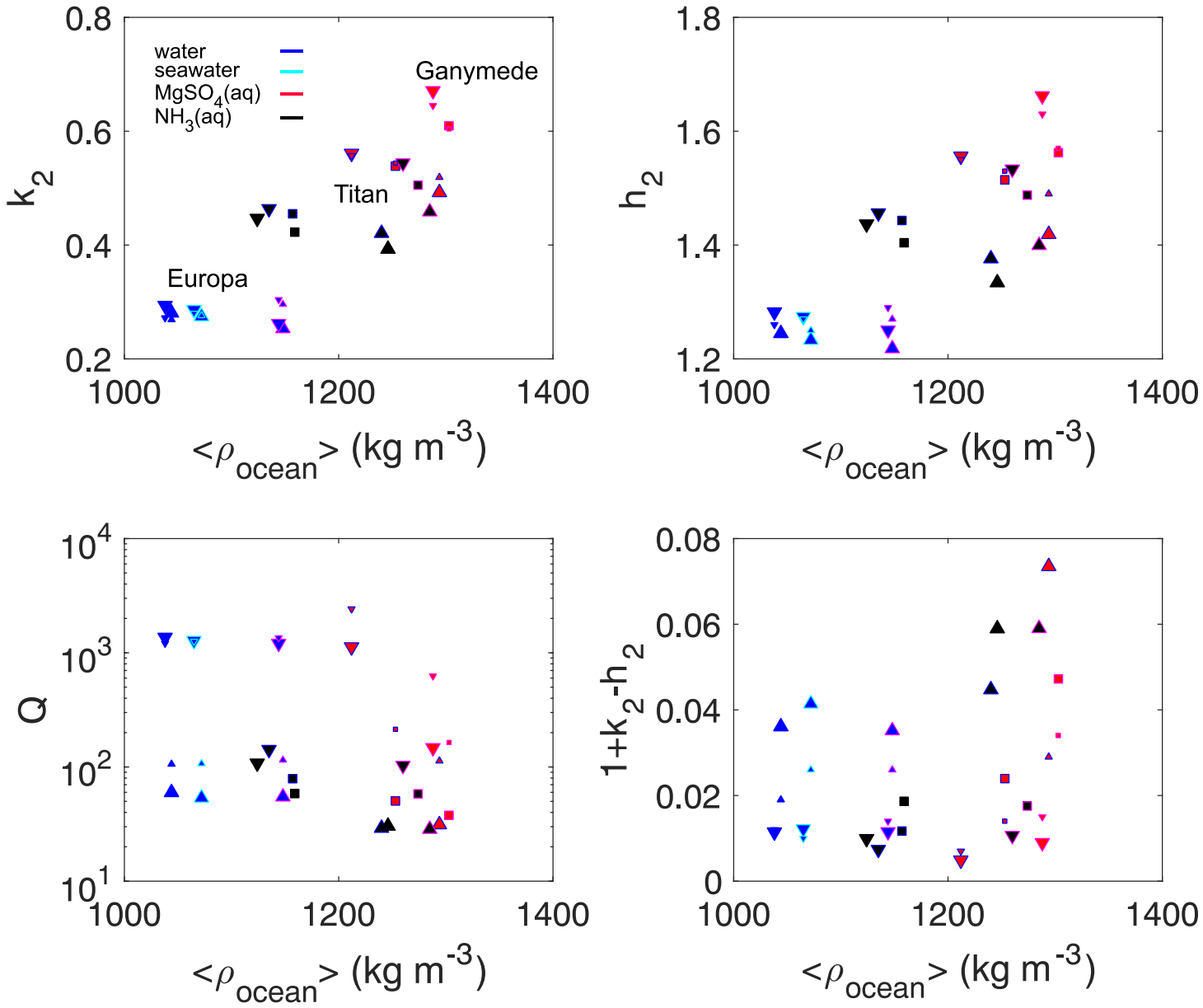
$$\tilde{\mu}(\omega) = \frac{\mu_{\mathrm{E}}\omega^2\eta^2}{\mu_{\mathrm{E}}^2 + \omega^2\eta^2} + i\frac{\mu_{\mathrm{E}}^2\omega\eta}{\mu_{\mathrm{E}}^2 + \omega^2\eta^2},$$

Tobie et al. 2006



Vance et al. 2017 JGR

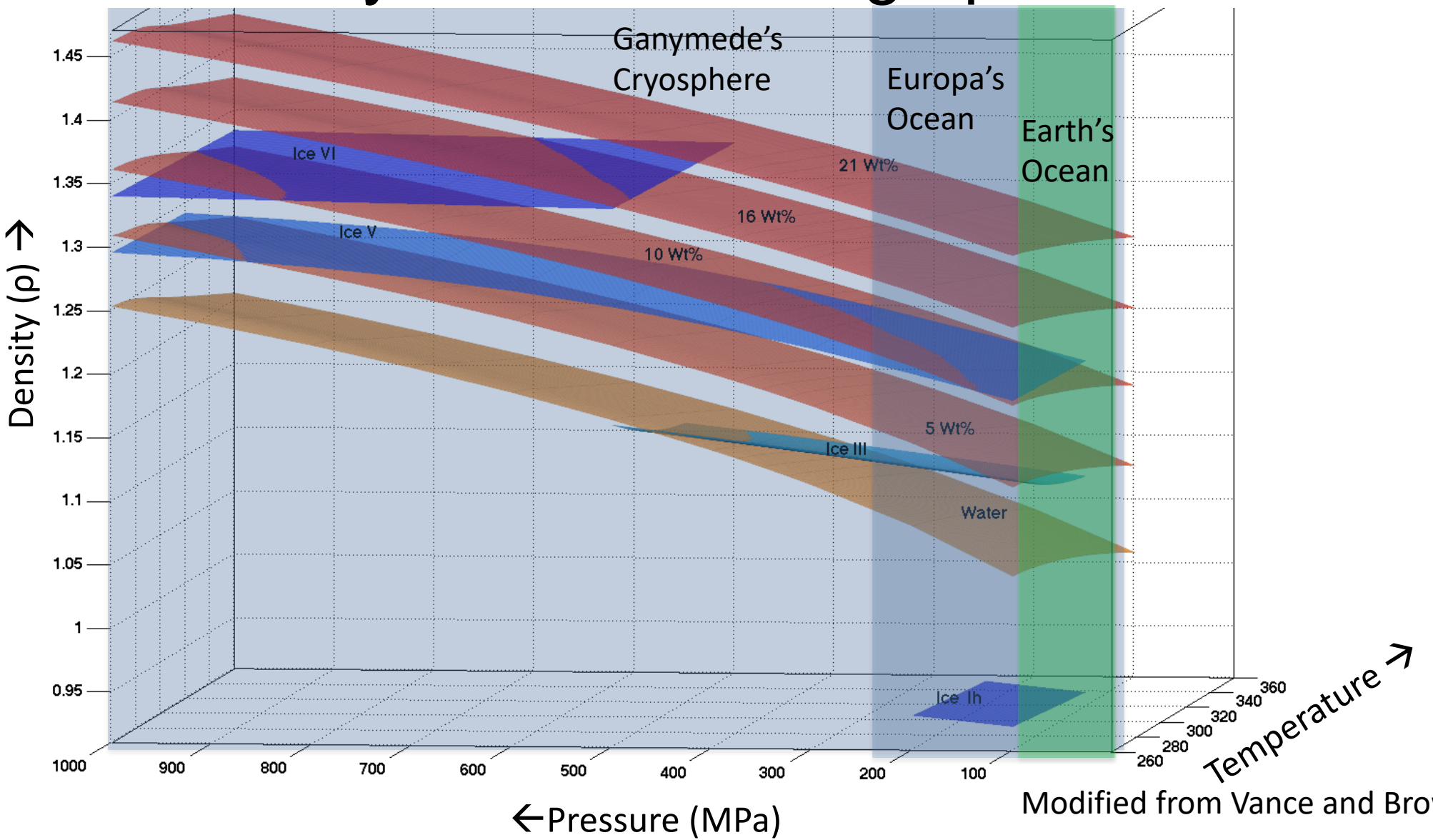
Tidal Dissipation



Contributed by
Gabriel Tobie and
Shunichi Kamata

Vance et al. 2017 JGR

Concentrated $MgSO_4$ solutions are convectively stable under high-pressure ices



Modified from Vance and Brown 2013.