Delving Into Ocean World Interiors

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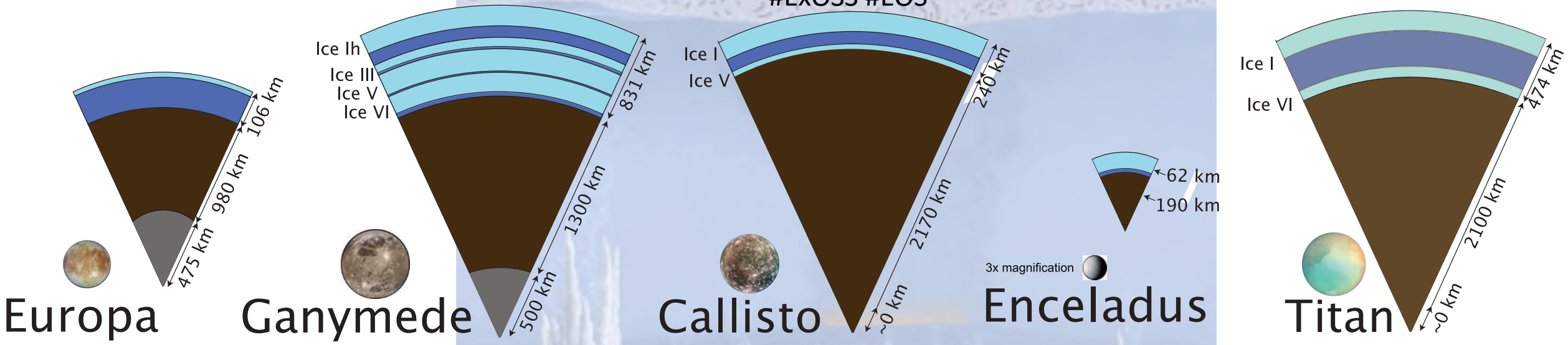
⊍Union College, Schenectady

Experimental Analysis of the Outer Solar System, Fayetteville, AR, August 15, 2018

#ExOSS #EOS



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Introduction

- Deep oceans 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…

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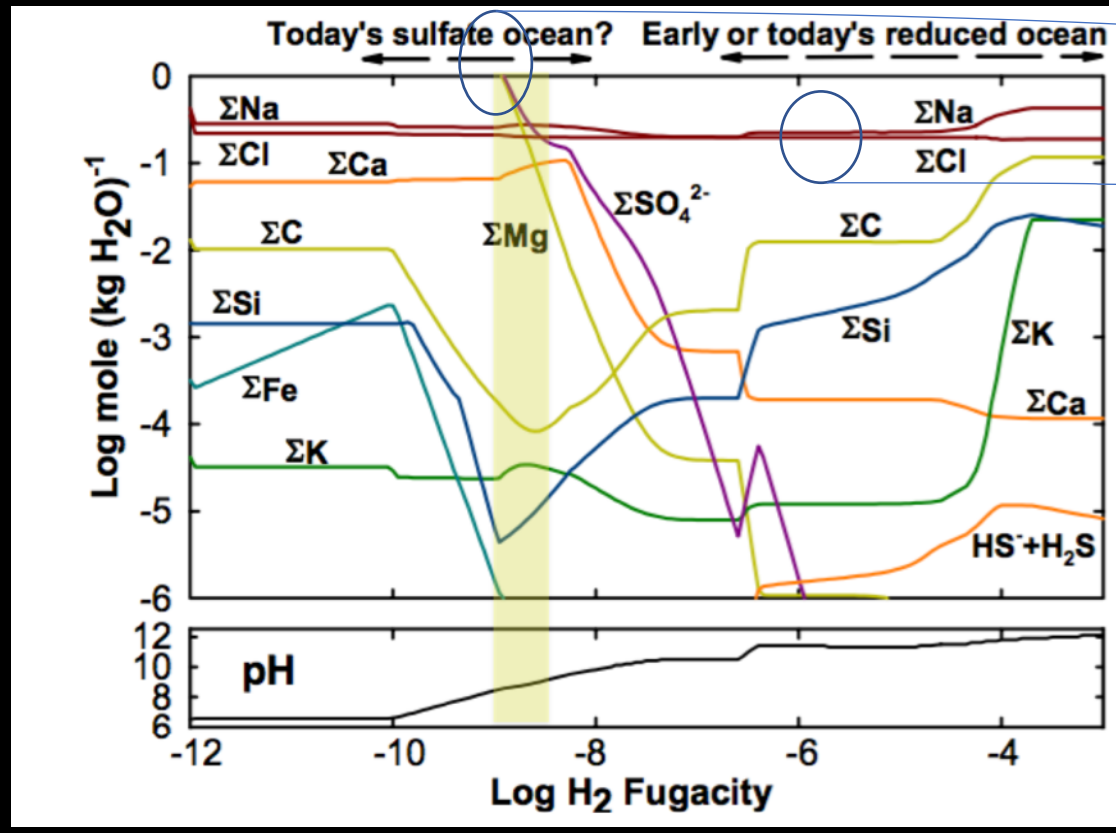
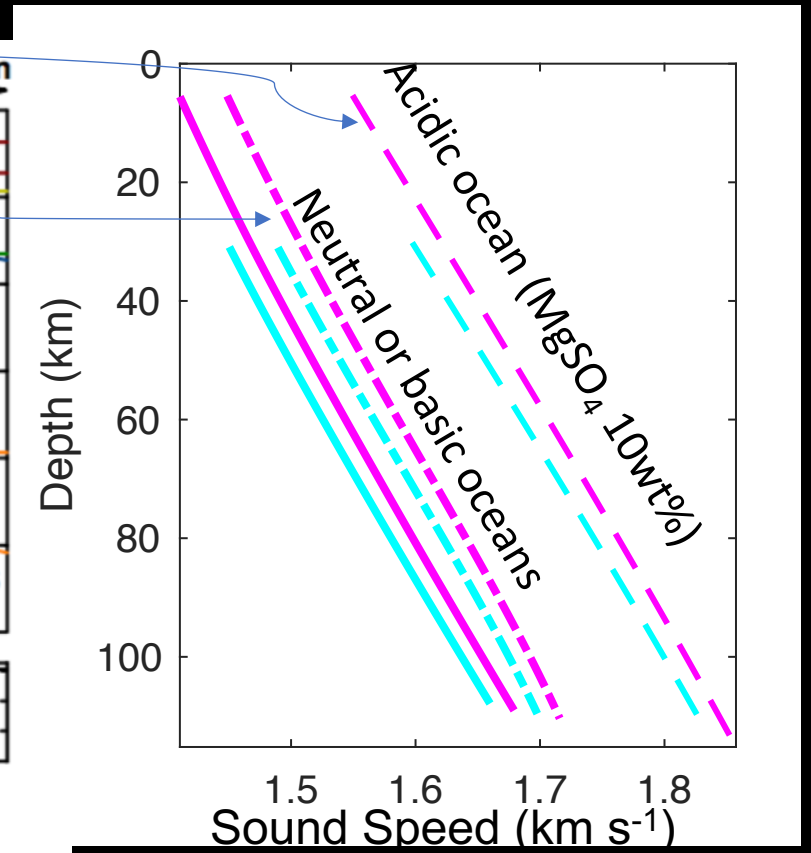
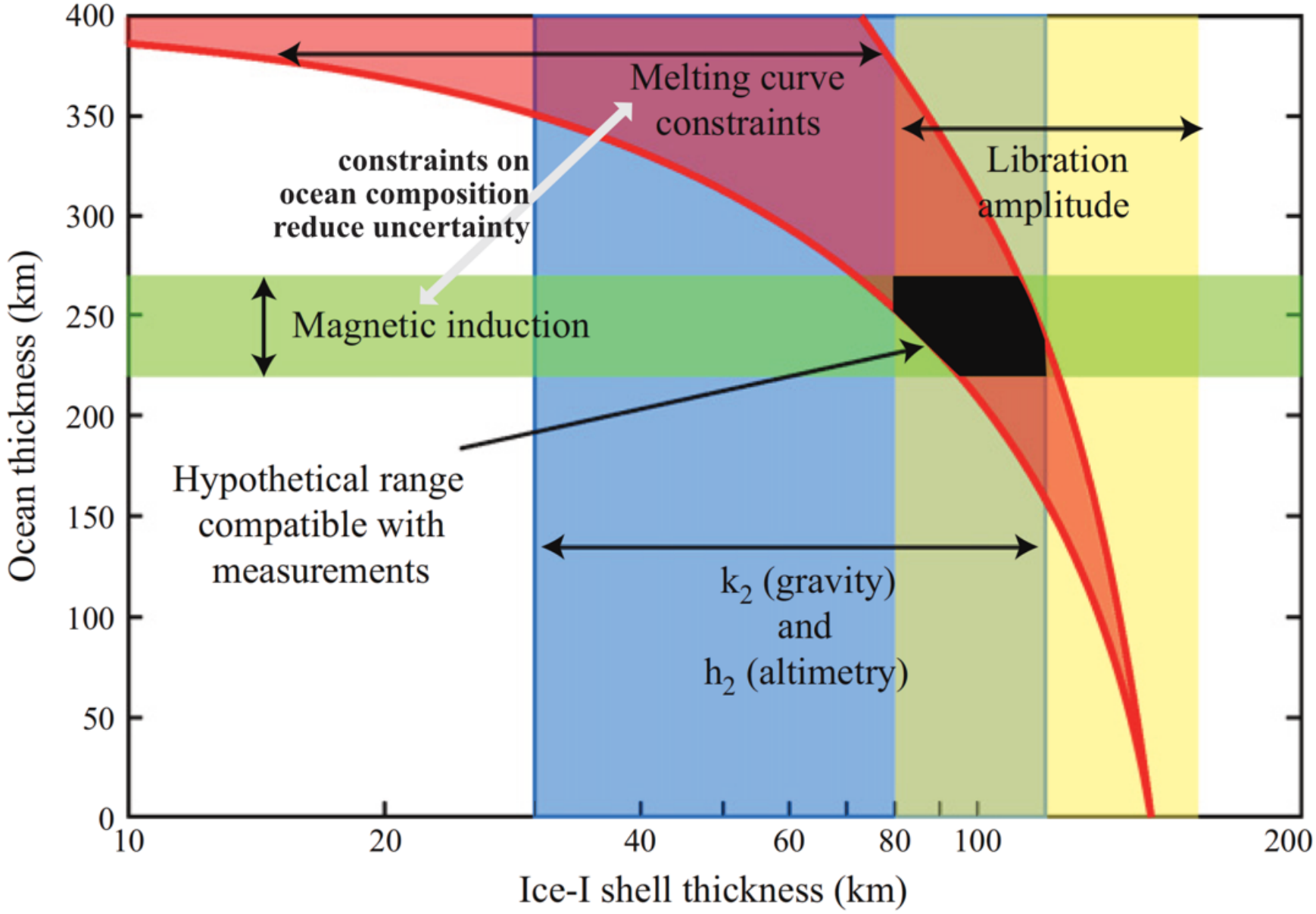
NaCl



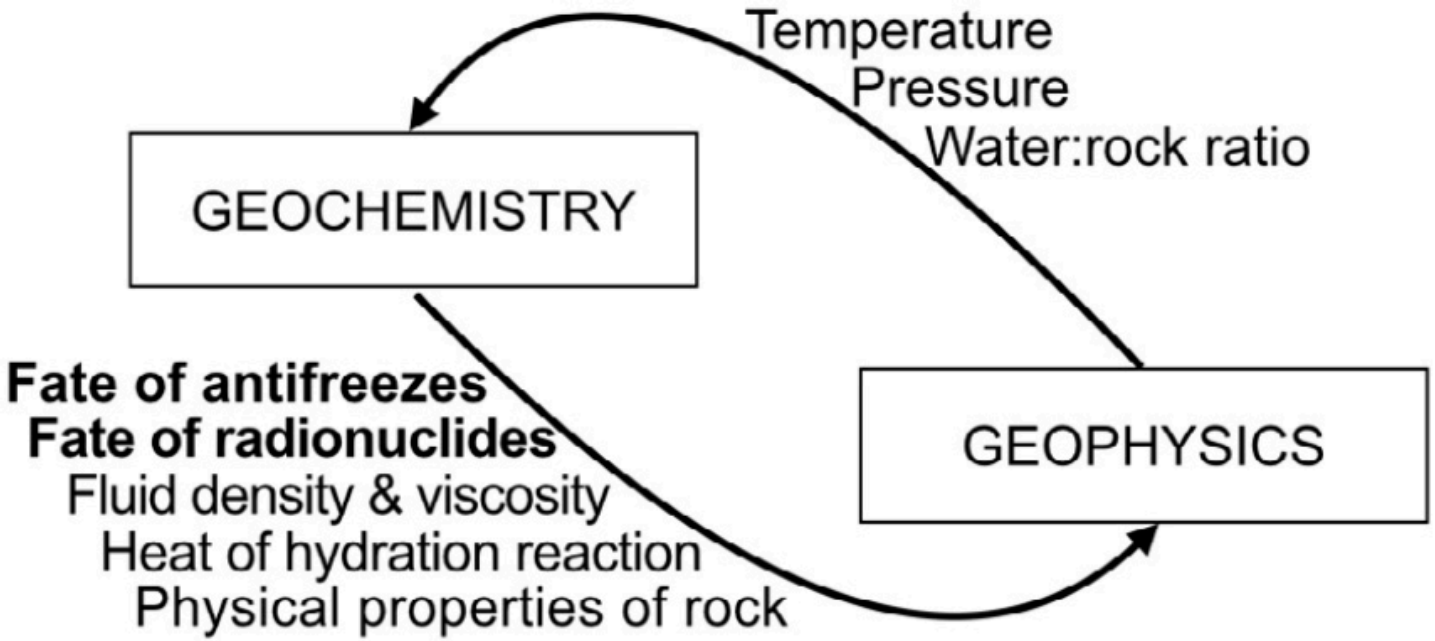
Modified from Zolotov 2008



Modified from Vance et al. 2017, JGR



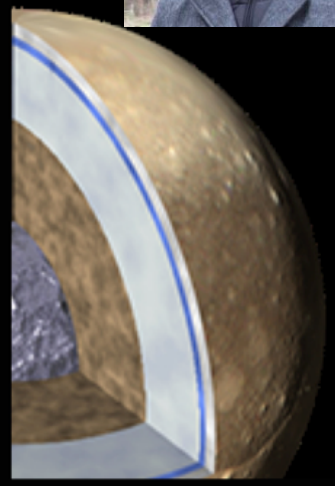
modified from Grasset et al. 2013, **JUpiter ICy moons Explorer**

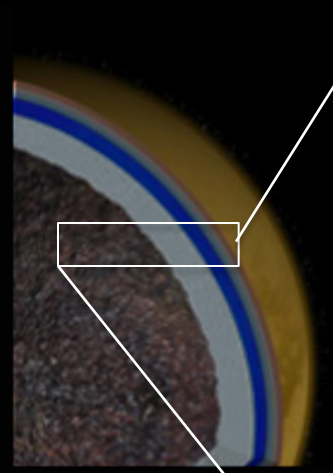


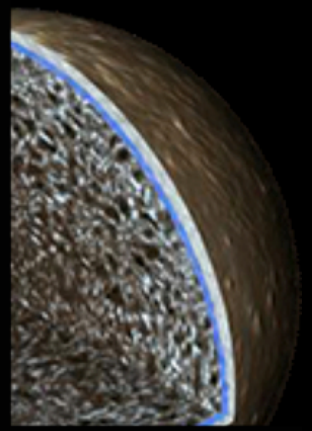
Neveu, Desch, and Castillo-Rogez 2017

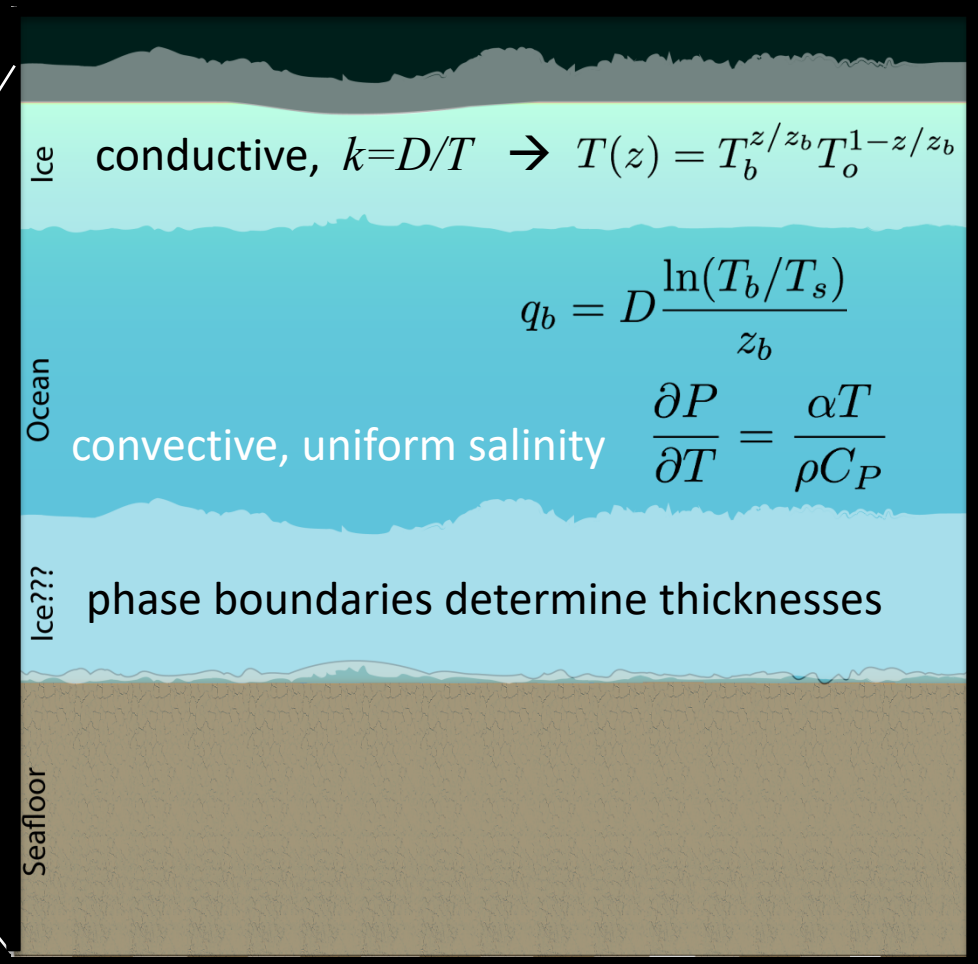
Geophysical Investigations of Habitability in Ice-Covered Ocean Worlds

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]



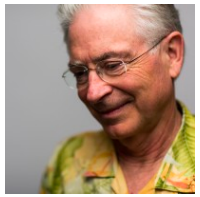






Vance et al. 2018; also Vance et al. 2014

Equations of State



J Michael Brown

Gibbs Energy Derivatives

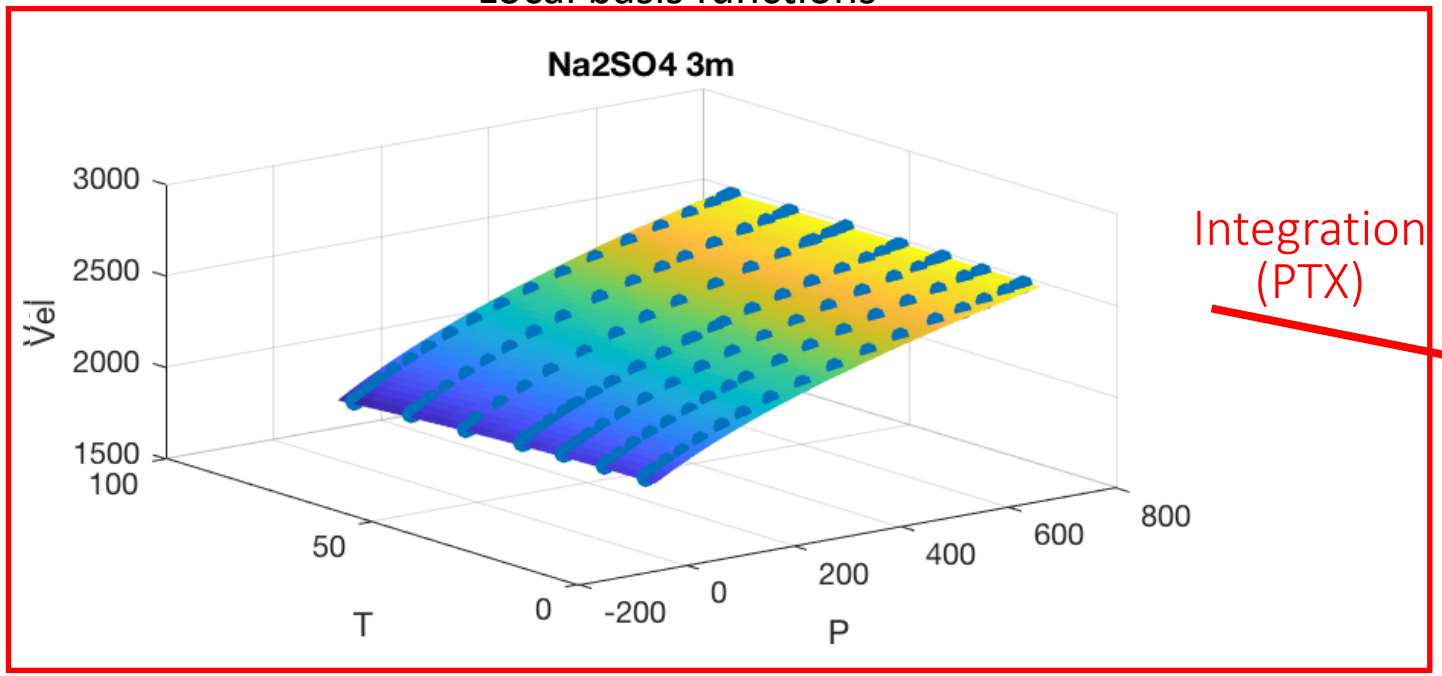
G is solution of an ODE

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	$\dfrac{G_P^2 G_{2T}}{G_{PT}^2 - G_{2T}G_{2P}}$

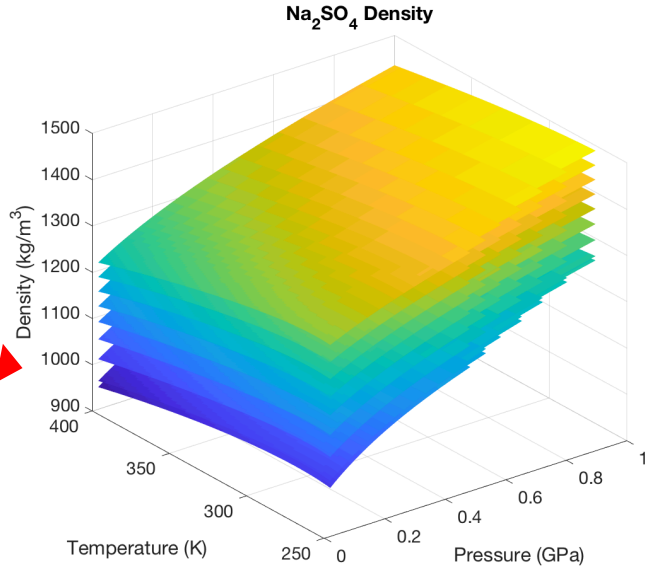
Gibbs energy at high pressure is determined from sound speeds vs P, T, and m

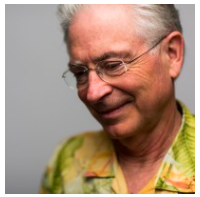
Speeds of sound in Na-Mg-Cl-SO_4-NH_3 brines

Local basis functions*



Integration (PTX)





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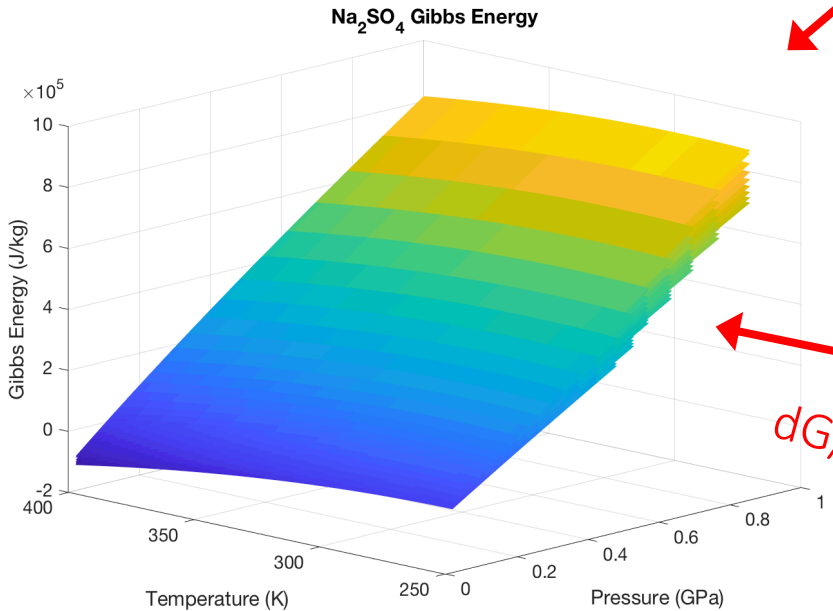
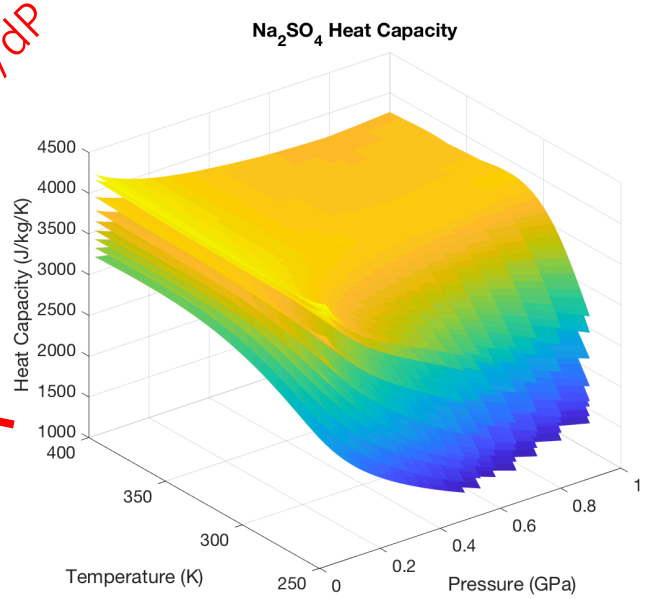
dG/dP



dG/dT

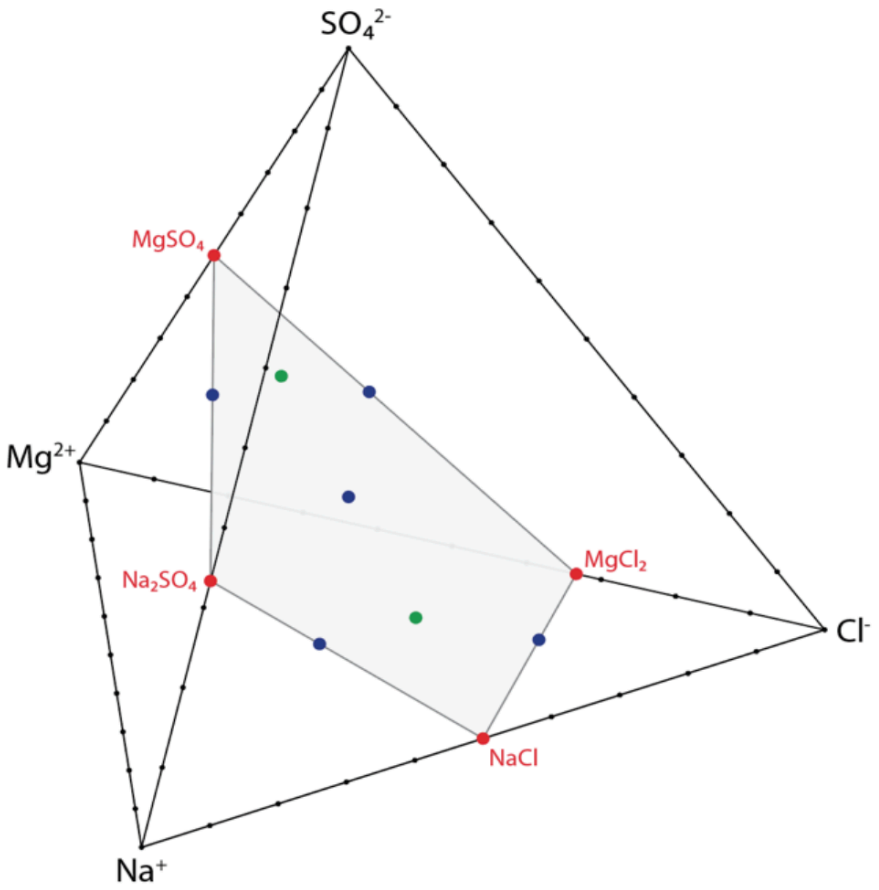


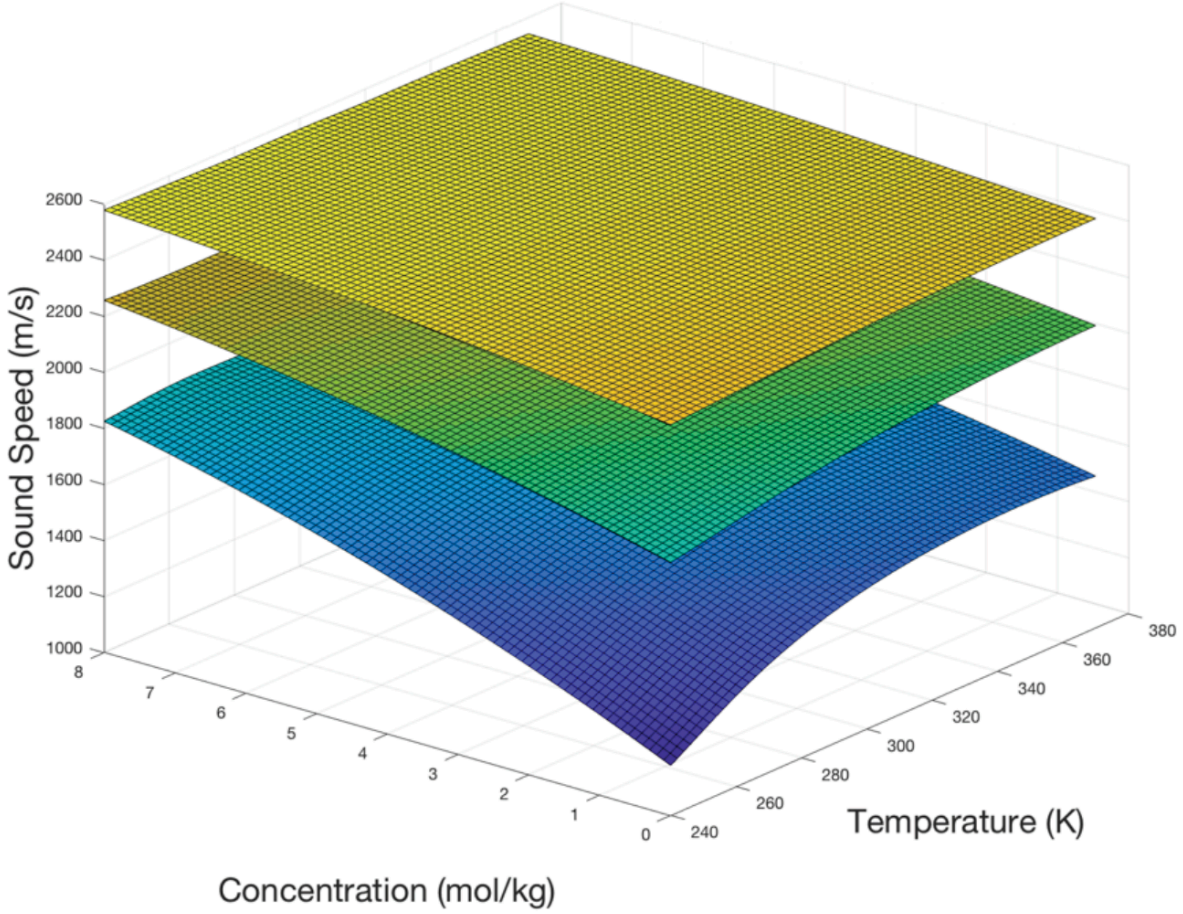
*Brown 2018, Fluid Phase Equilibria

Exploring material properties

Olivier Bollengier, Mineral Physics Lab, UW Seattle

NH_3


SO_4^{2-}
$MgSO_4$
Mg^{2+}
Na_2SO_4
$MgCl_2$
Cl^-
NaCl
Na^+


Sound Speed (m/s)
2600
2400
2200
2000
1800
1600
1400
1200
1000
8
7
6
5
4
3
2
1
0
240
260
280
300
320
340
360
380
Temperature (K)
Concentration (mol/kg)

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

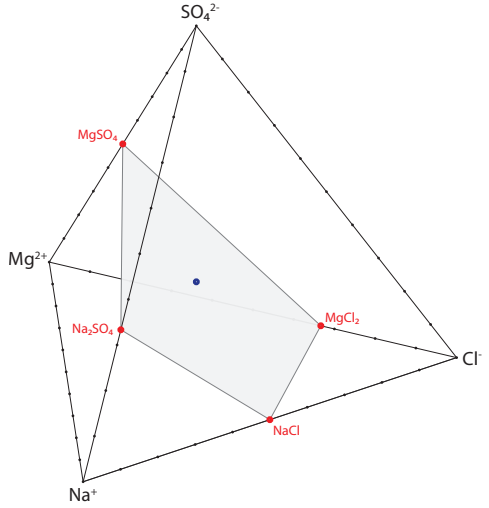
The Na-Mg-Cl-SO_4 brines

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

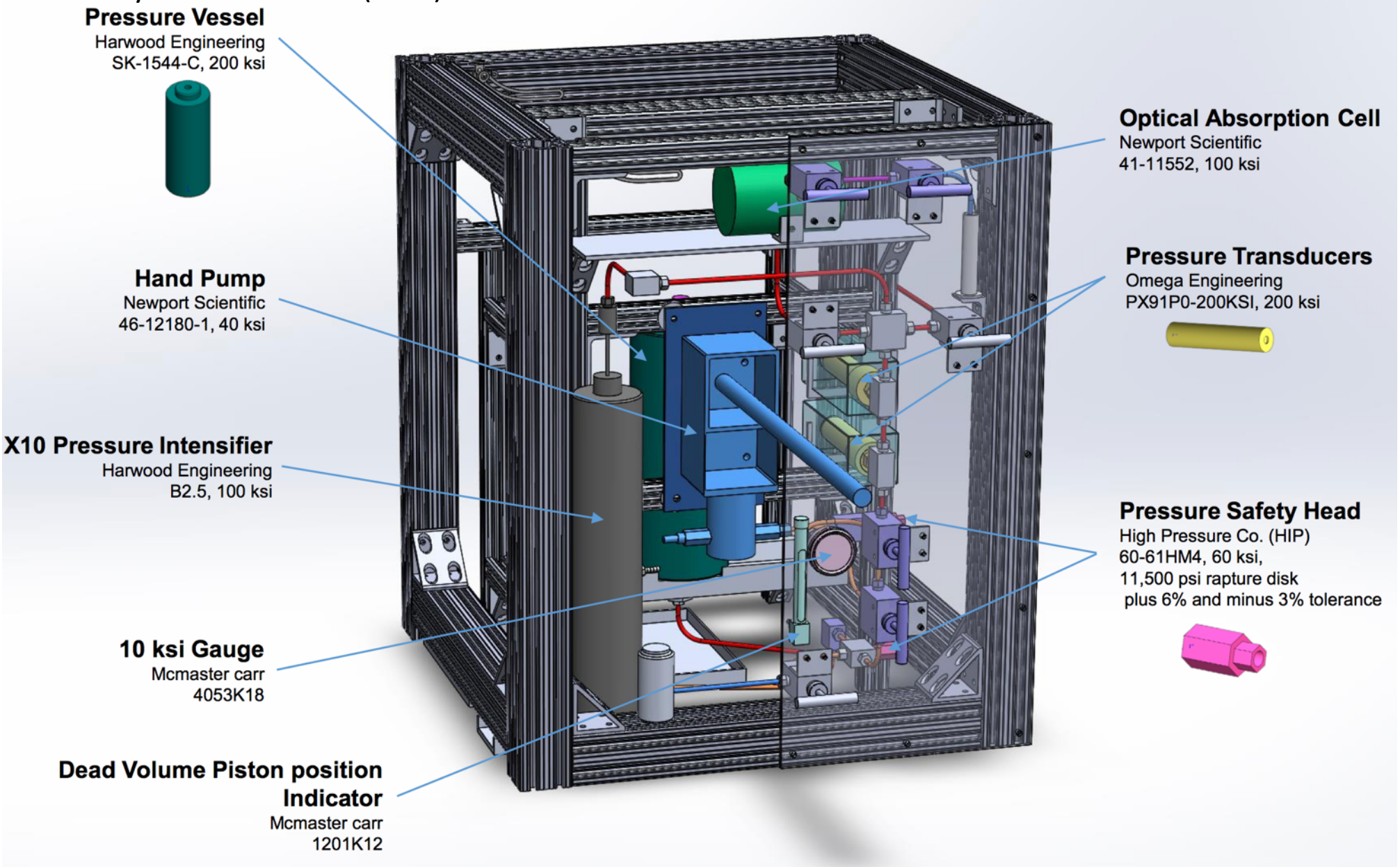
- NaCl, $NaSO_4$, $MgSO_4$, $MgCl_2$ @ 0.02%
- 0.1-700 MPa, 250-350 K
- 1/3, 1, 3 molal (+ 5 molal for Cl brines)
- 19 samples, 3300 sound speeds
- self-consistent pure water
- data collection recently completed



New JPL High-Pressure Facility

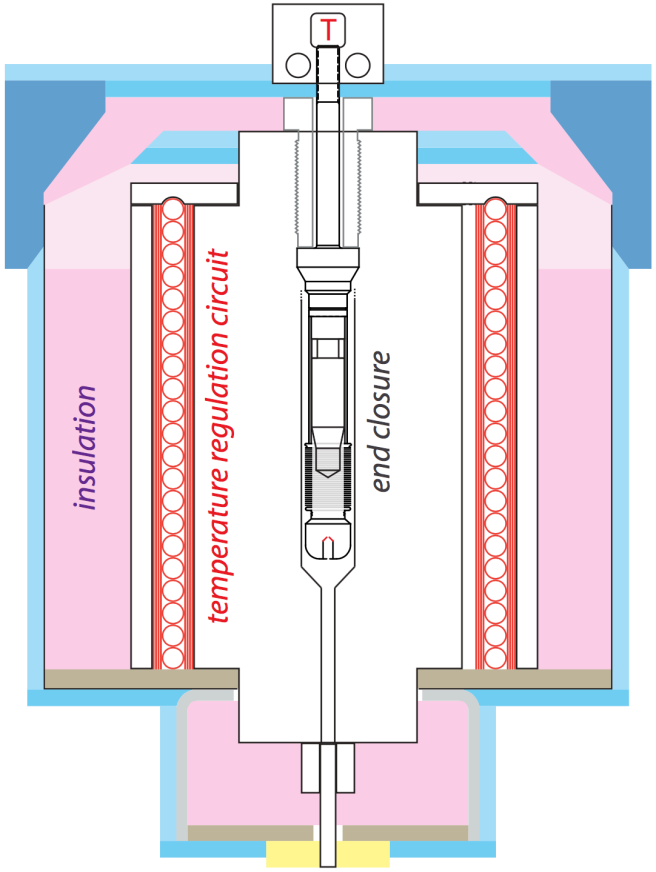
based on the UW simulator for icy world interiors (SIWI)

100,000 psi operating pressure

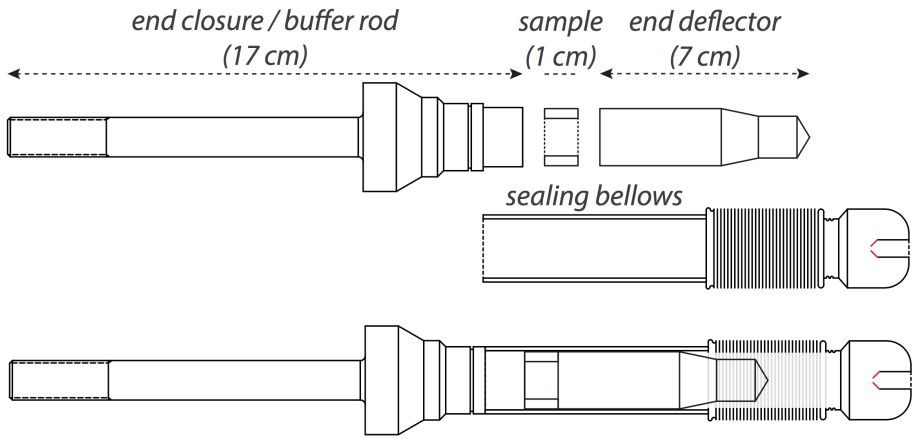


Speed of sound: the Na-Mg-Cl-SO_4-NH_3 brines

A high-pressure apparatus to measure sound speeds



Insulated high-pressure tank

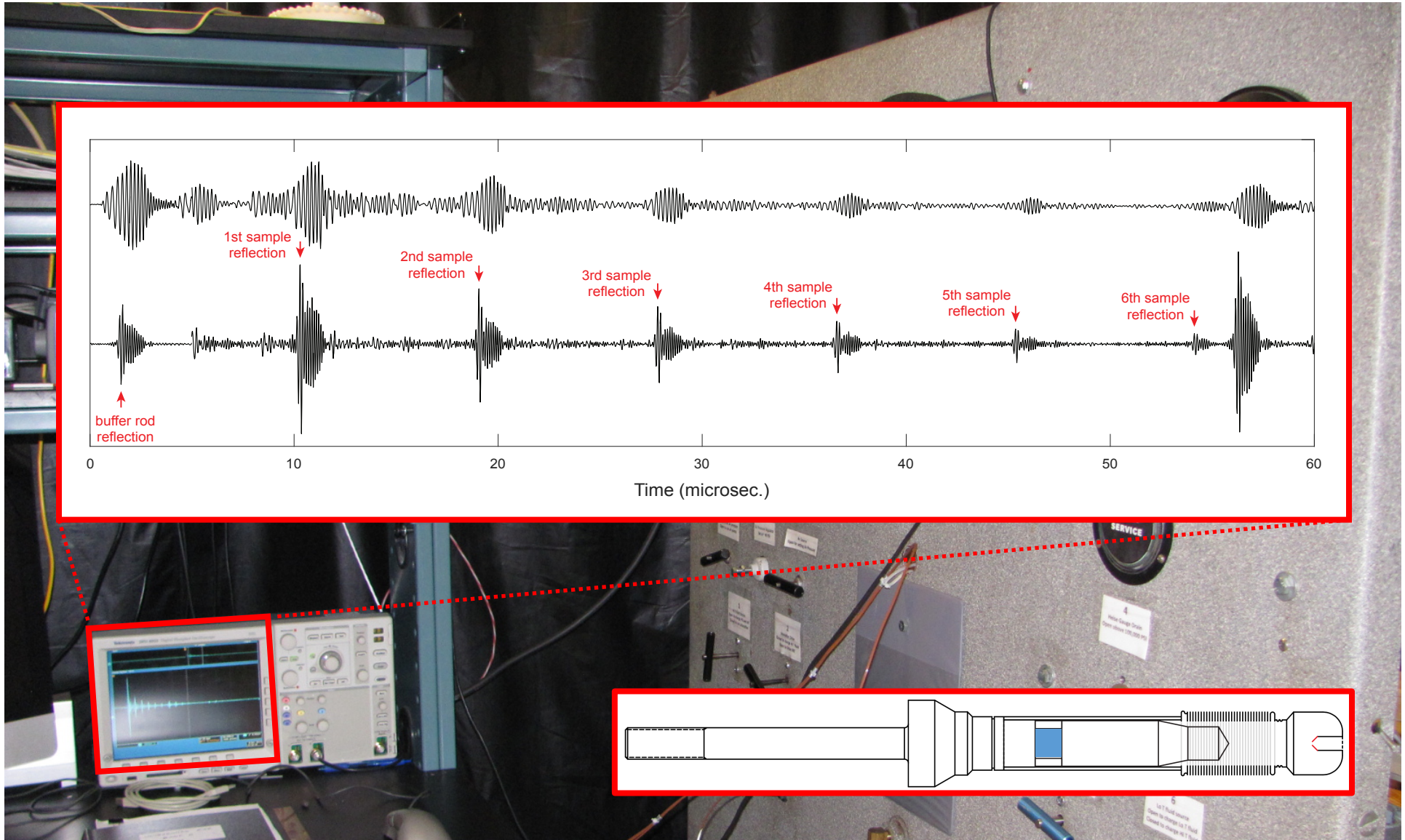


The end supports the sample chamber (inside the tank), and the ultrasonic transducer (outside the tank). The bellows adapt to change of sample volume (compressibility, expansivity) while keeping the sample pristine.

Maximum pressure: 800 MPa (Ti alloy).

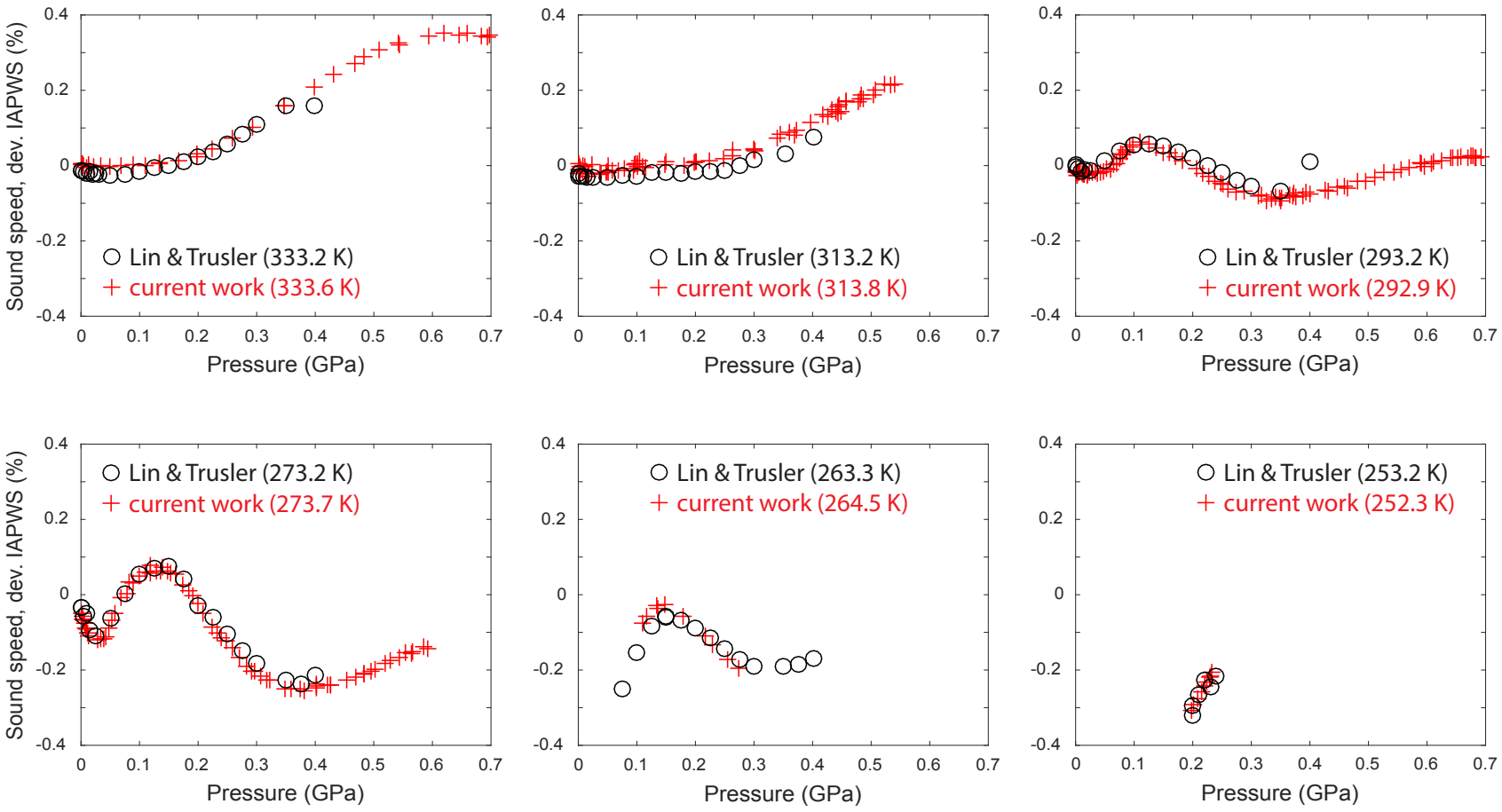
Speed of sound: the Na-Mg-Cl-SO_4 brines

Sound speed measurements



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

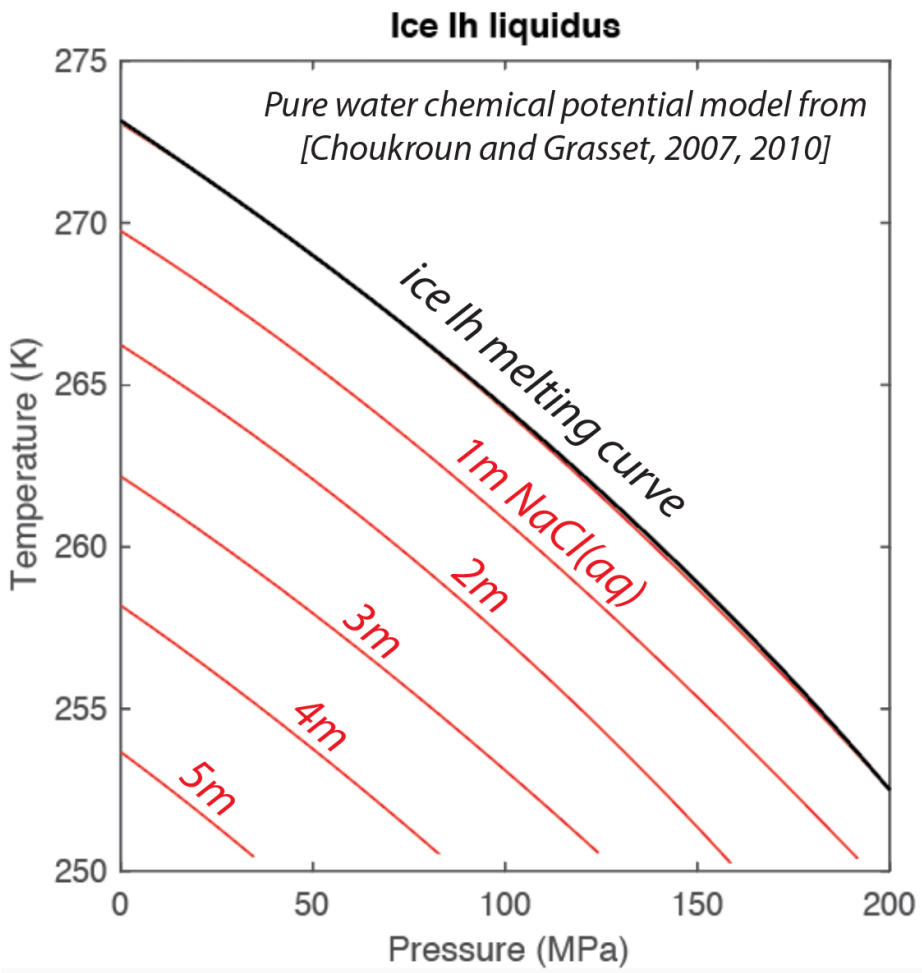
The pure water dataset

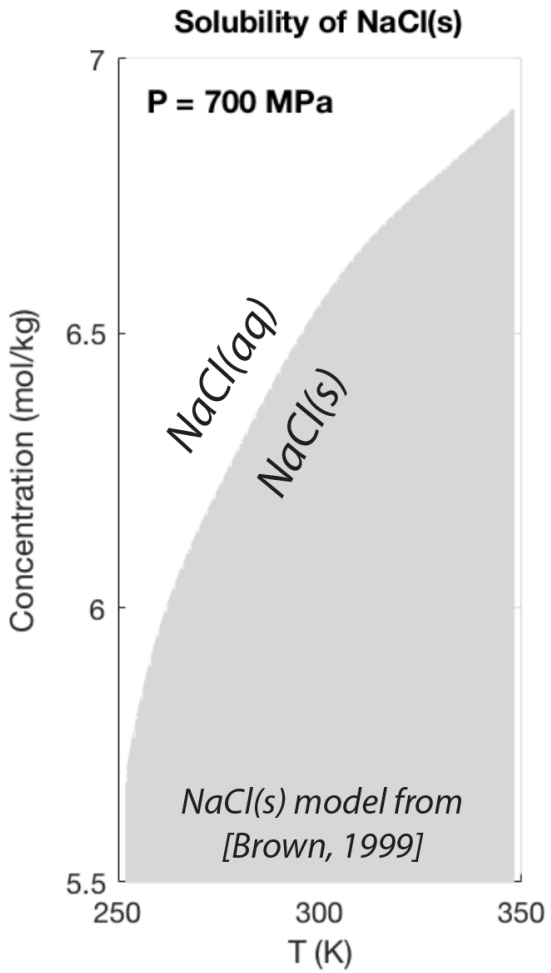


Comparison with Lin and Trusler 2012 (% deviation to IAPWS)

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

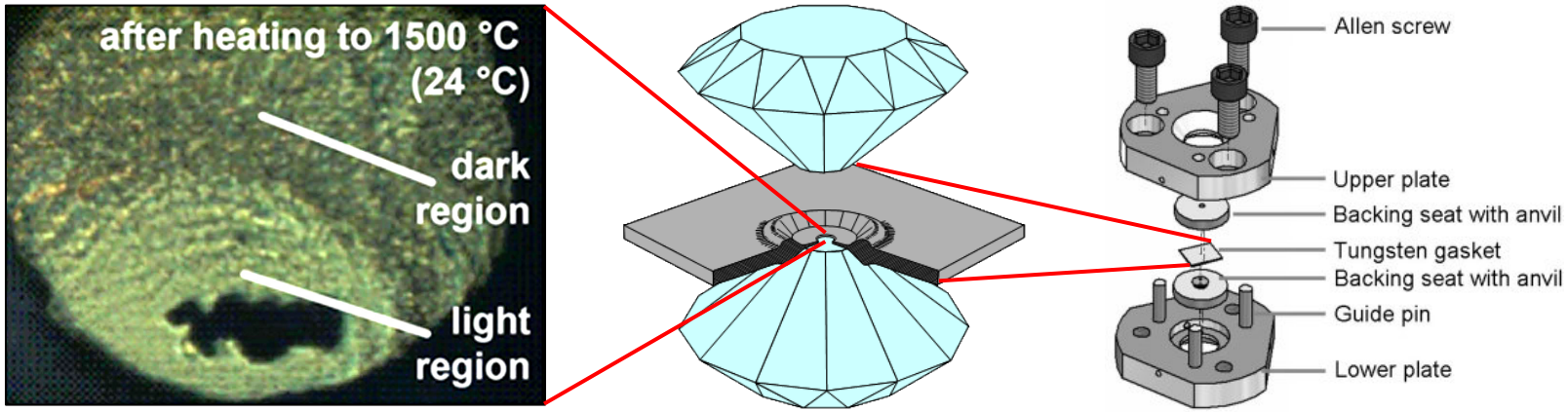
Examples of planetary science applications





Optical anvil cells: the H_2O-CO_2 system

Exploring phase diagram using optical anvil cells



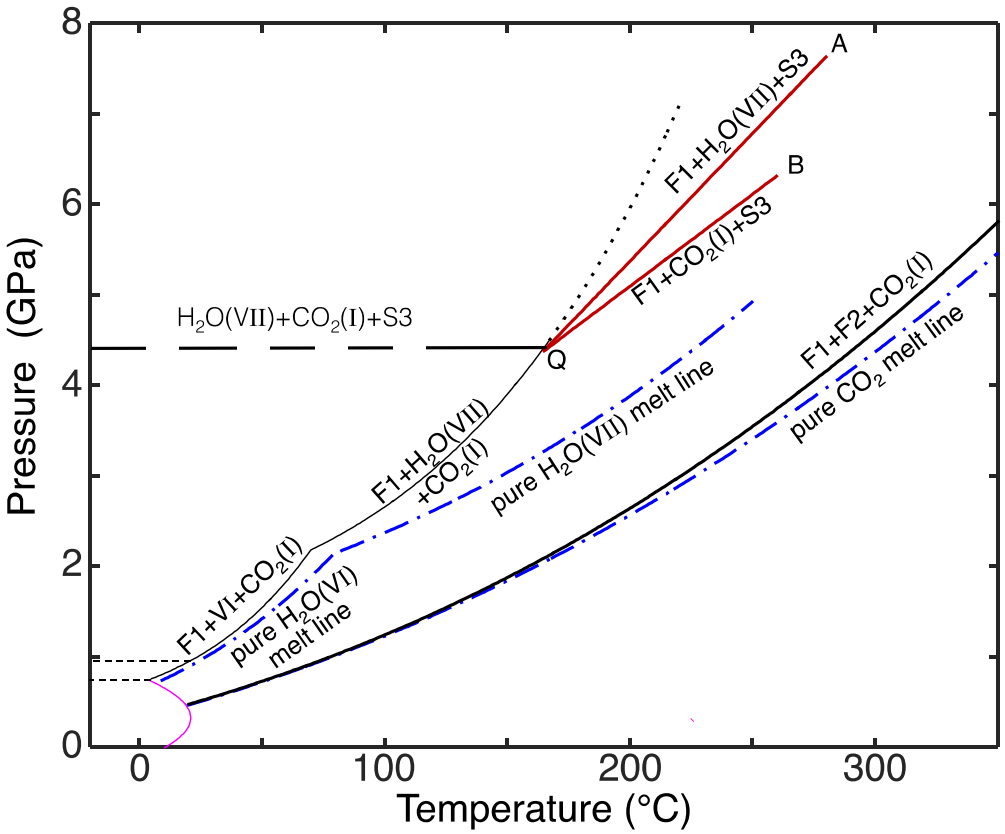
Microscopic sample Diamond anvils Anvil cell

OPTICAL ANVIL CELLS

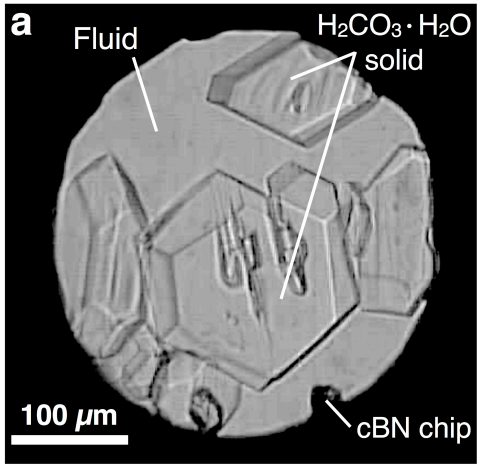
- access to multi-GPa pressures and high temperatures
- wide EM capabilities (visual monitoring, spectroscopy)
- nL (100 microns) loads: metastability, loading problems

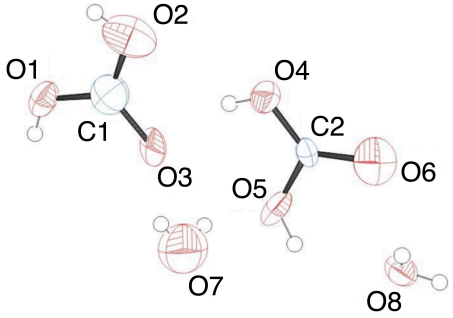
Optical anvil cells: the H_2O-CO_2 system

A new solid: the carbonic acid monohydrate



New melting curves in the H_2O-CO_2 system





H_2CO_3 monohydrate

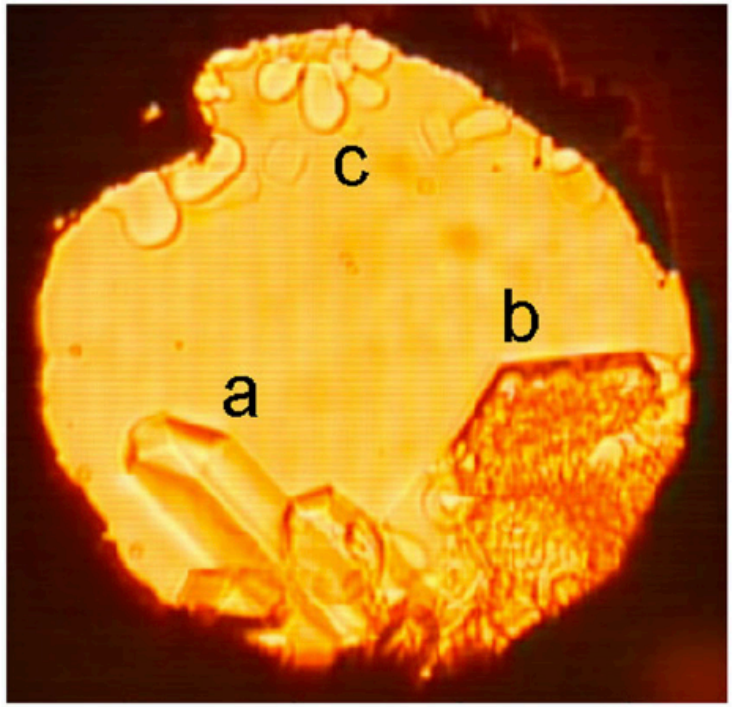


Figure 4. Photomicrograph of crystals growing from a water-CO_2 fluid at 240 °C and 6.5 GPa. Crystals "a" and "b" are both of phase S3 and were observed to fall through the fluid. At first "b" was clear, but then abruptly darkened, presumably as trapped fluid (non-stoichiometric relative to S3) precipitated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

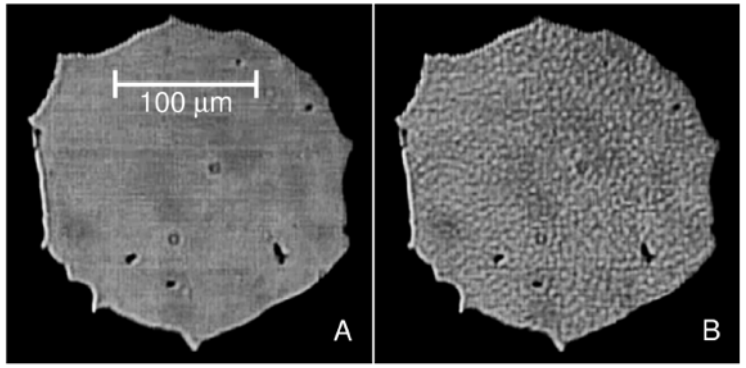
[American Journal of Science, Vol. 317, November, 2017, P. 967–989, DOI 10.2475/09.2017.01]

American Journal of Science

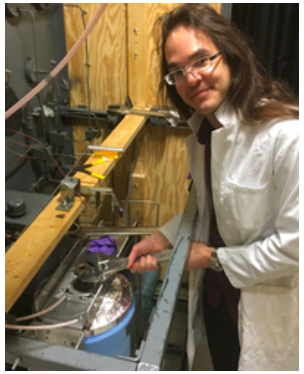
NOVEMBER 2017

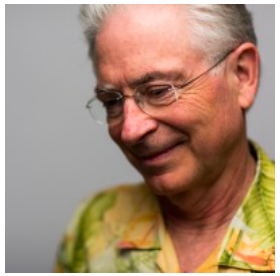
THE WATER-CARBON DIOXIDE MISCIBILITY SURFACE TO 450 °C AND 7 GPa

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

Optical anvil cells: the H_2O-CO_2 system
Summary

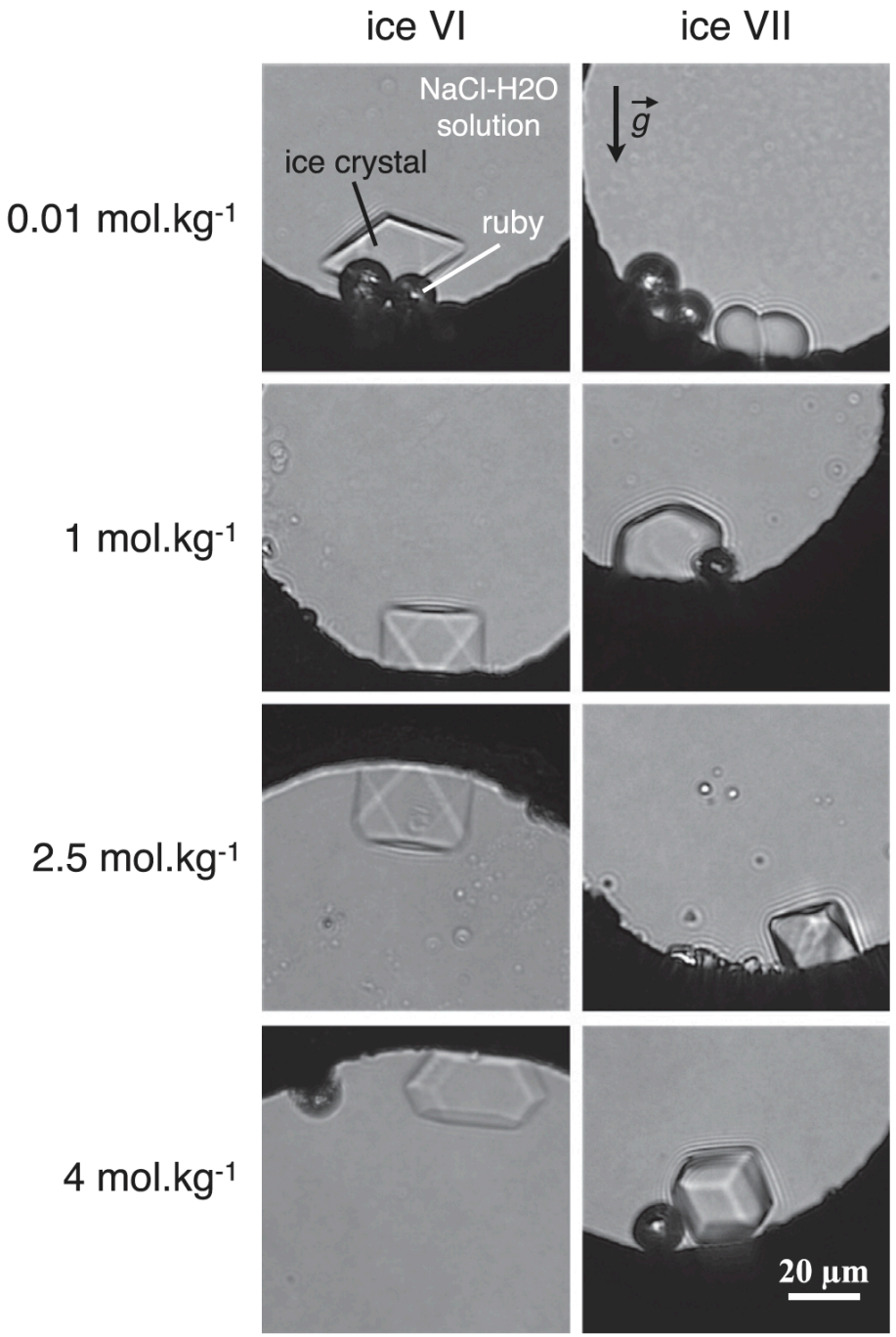
ANVIL CELL EXPERIMENTS

- access to large PT range
- phase equilibria and spectroscopy (X-ray, Raman…)
- new isotopic determination of loads

THE H_2O-CO_2 SYSTEM

- solubility surface: high antifreeze potential for water ices
- carbonic acid monohydrate: carbon storage above 4 GPa
- change of speciation: H_2CO_3 dominant at high pressures?

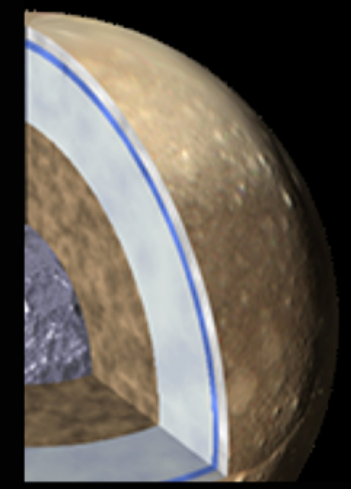
[Abramson et al. 2017a, 2017b, 2018]



Journaux et al. 2013

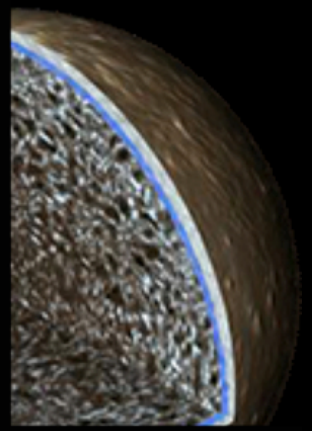
Applications of thermodynamics to deep oceans in large icy moons

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

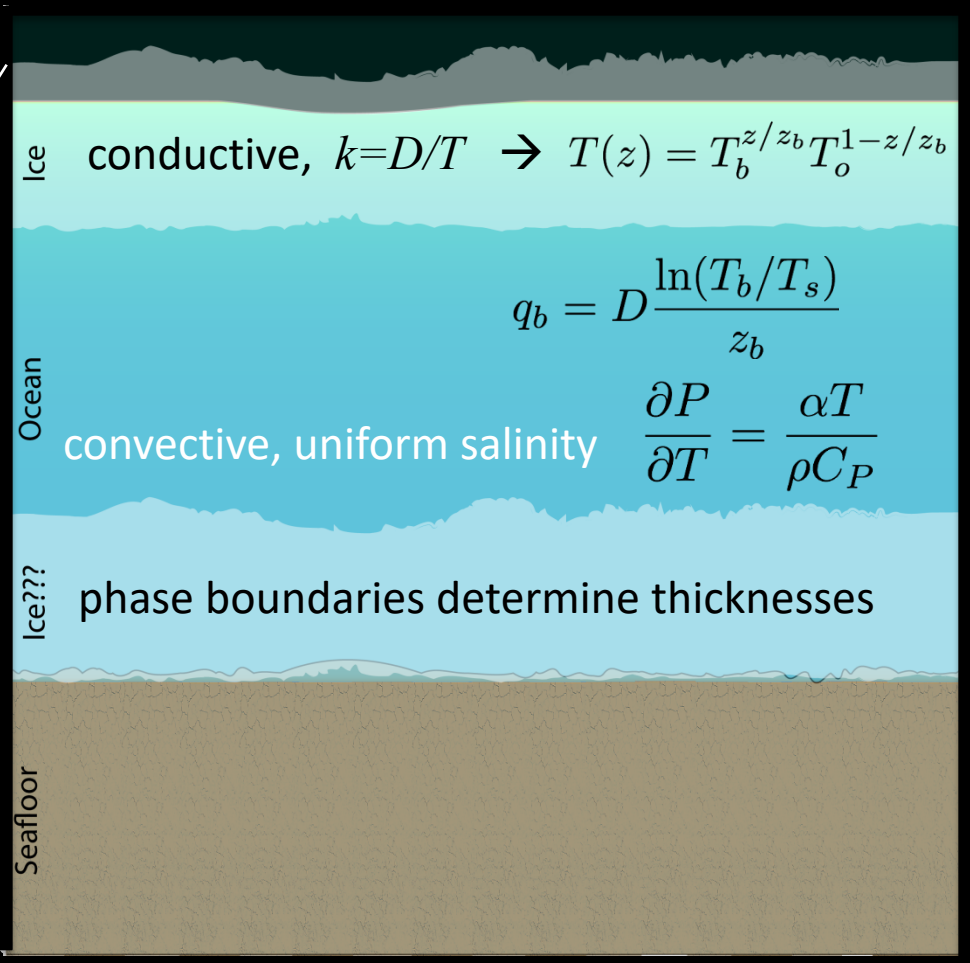


Ganymede

Titan



Callisto

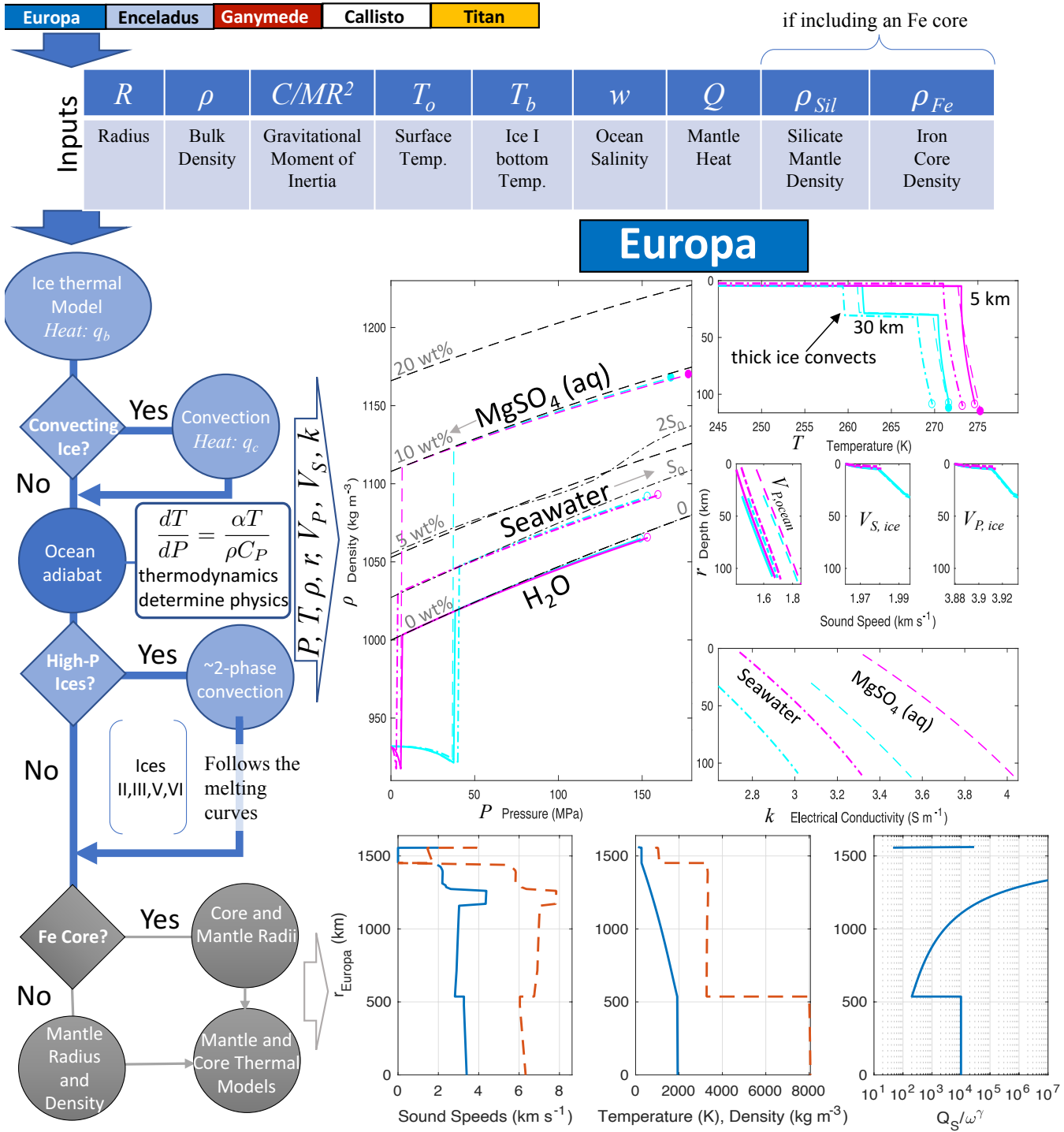


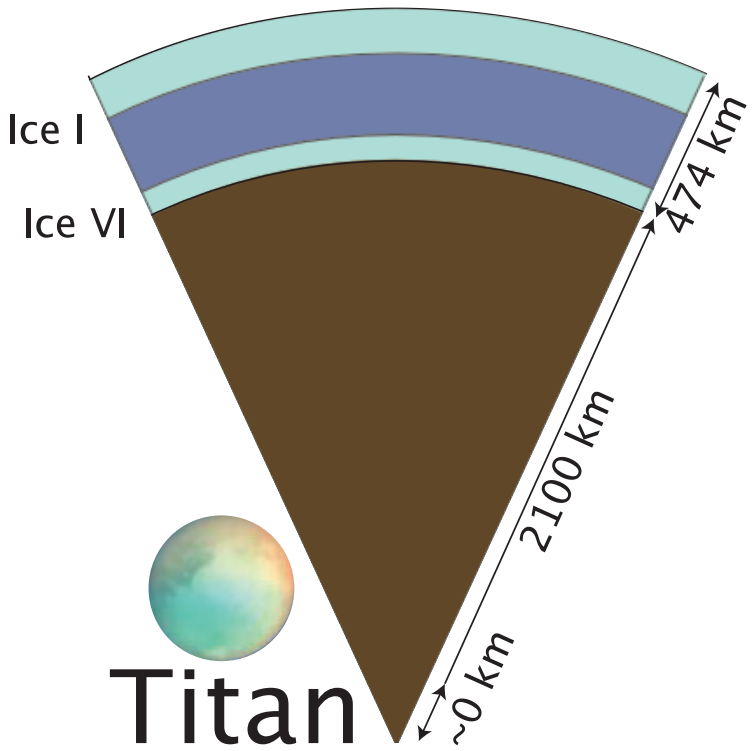
Vance et al. 2017; also Vance et al. 2014

PlanetProfile

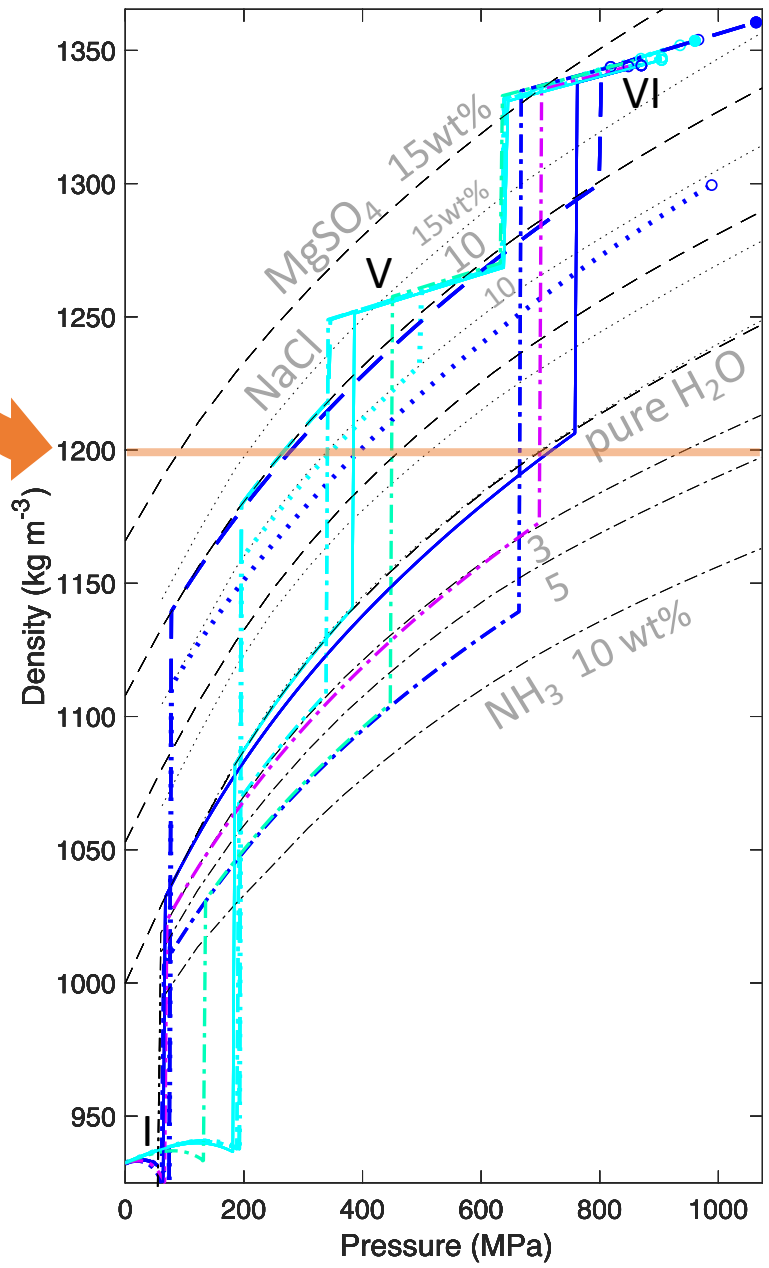
github.com/vancesteven/PlanetProfile

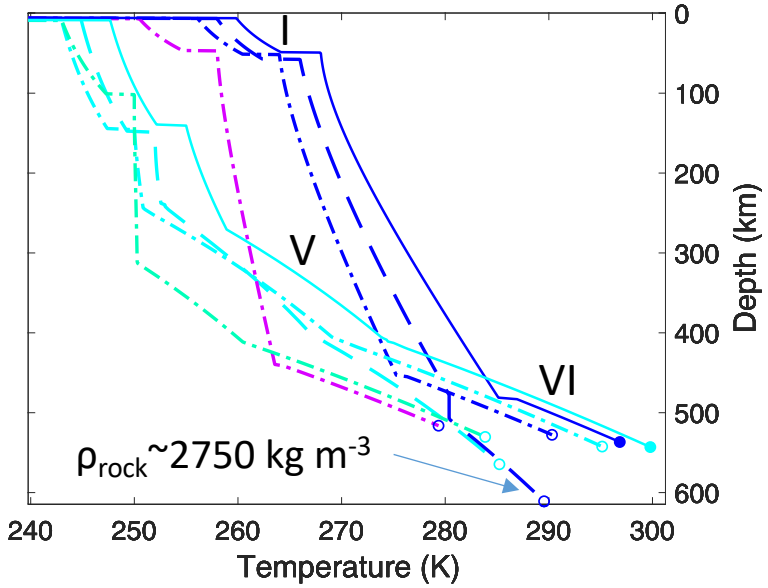
Vance et al. 2017, JGR.

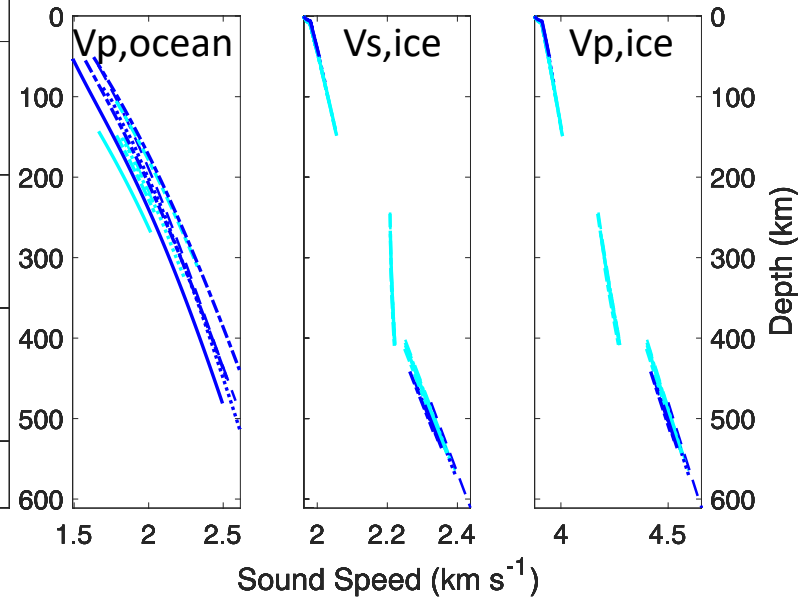




Mitri et al. 2014





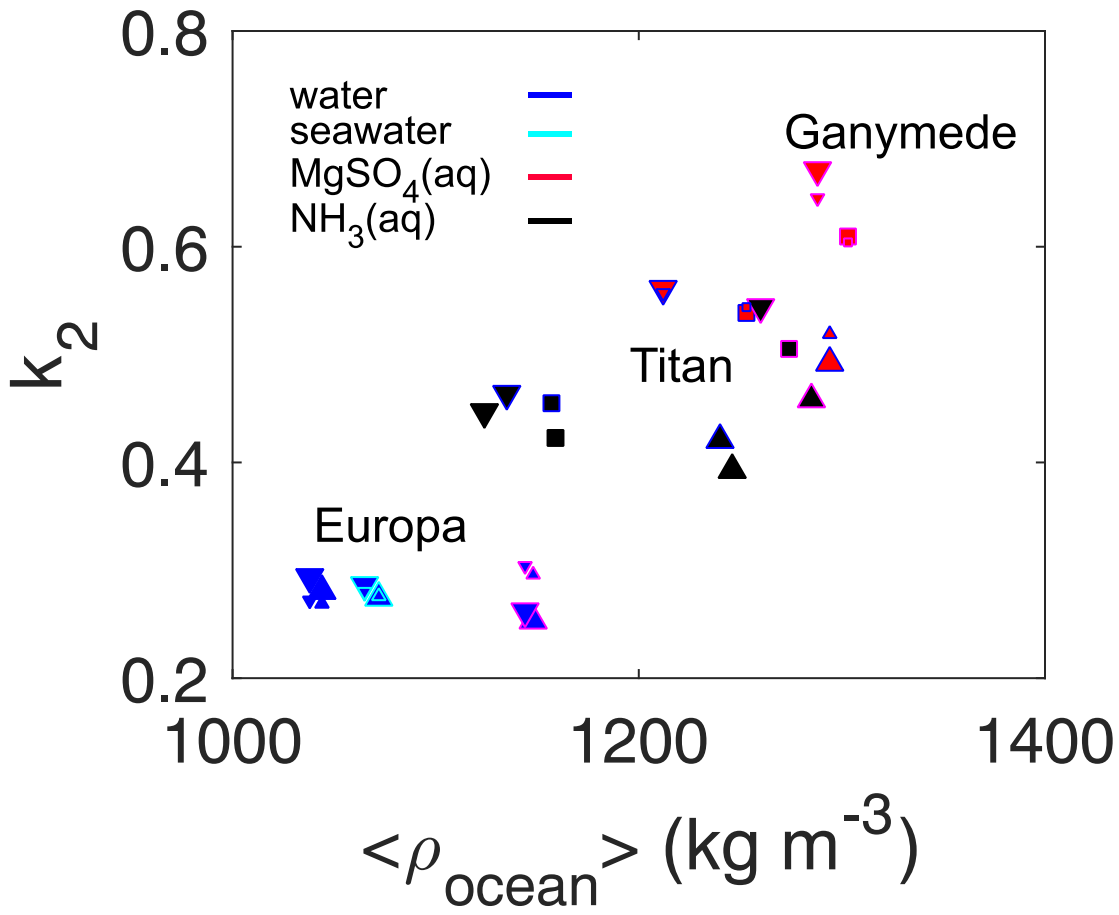


MoI* = 0.338 (*sic*)
(previous talk by Sotin showed 0.3318)
ρ_{rock}~2900 kg m^{-3}

Vance et al. 2017, JGR.

*moment of inertia

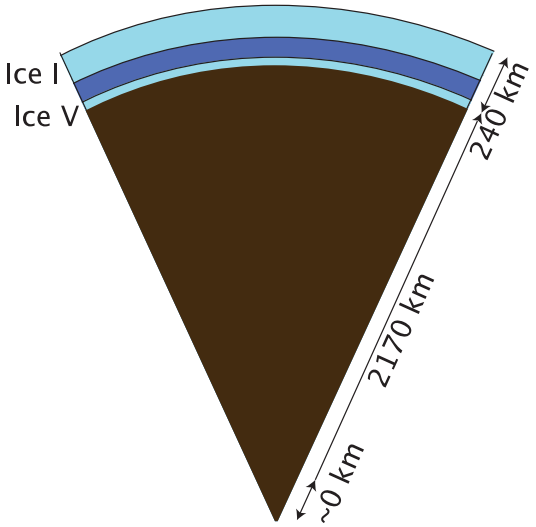
Tidal Dissipation

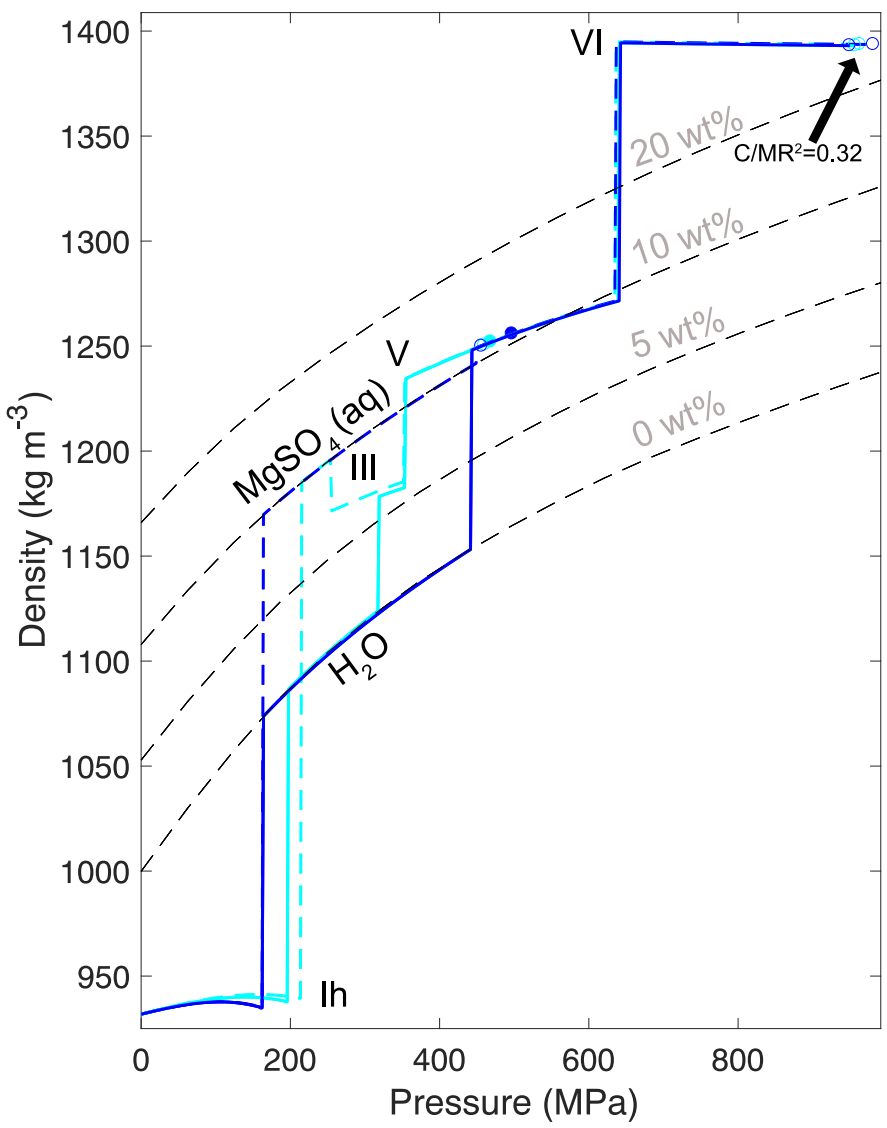


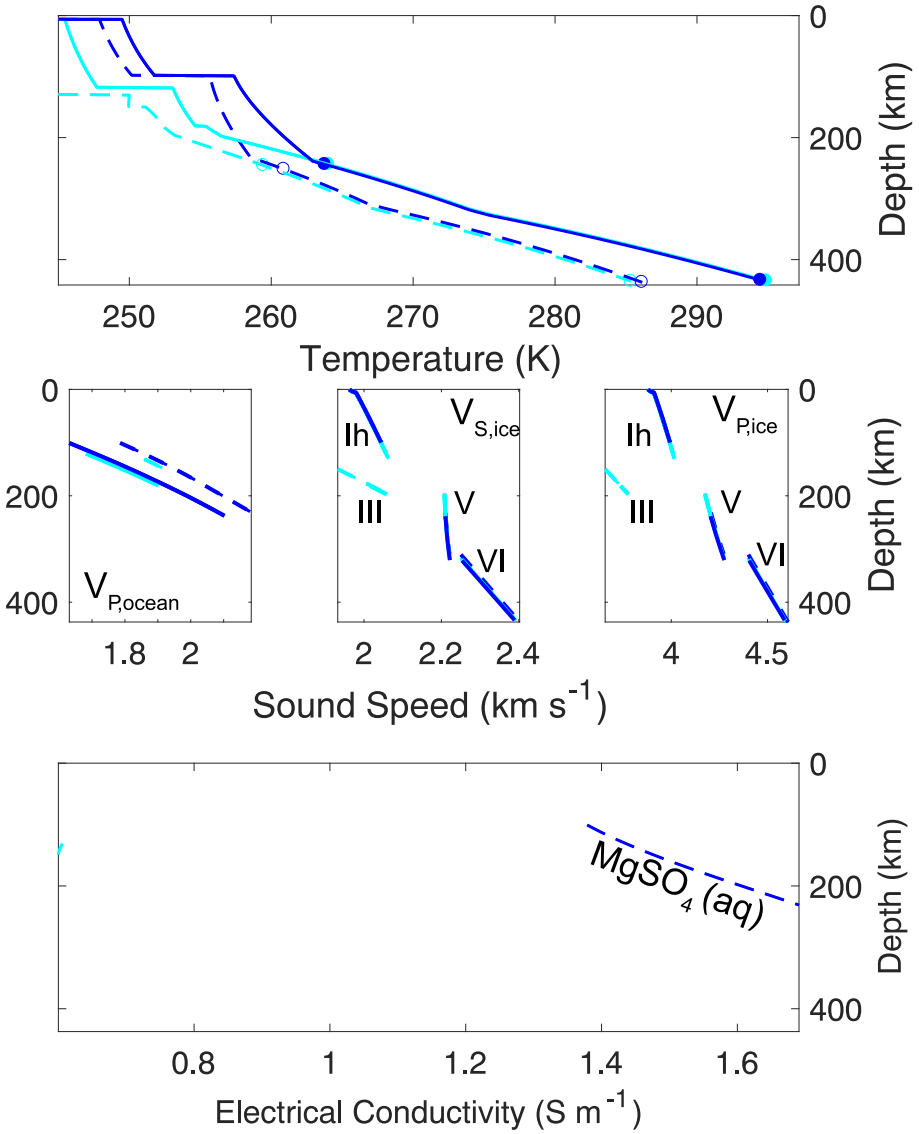
Contributed by
Gabriel Tobie and
Shunichi Kamata

Vance et al. 2017 JGR

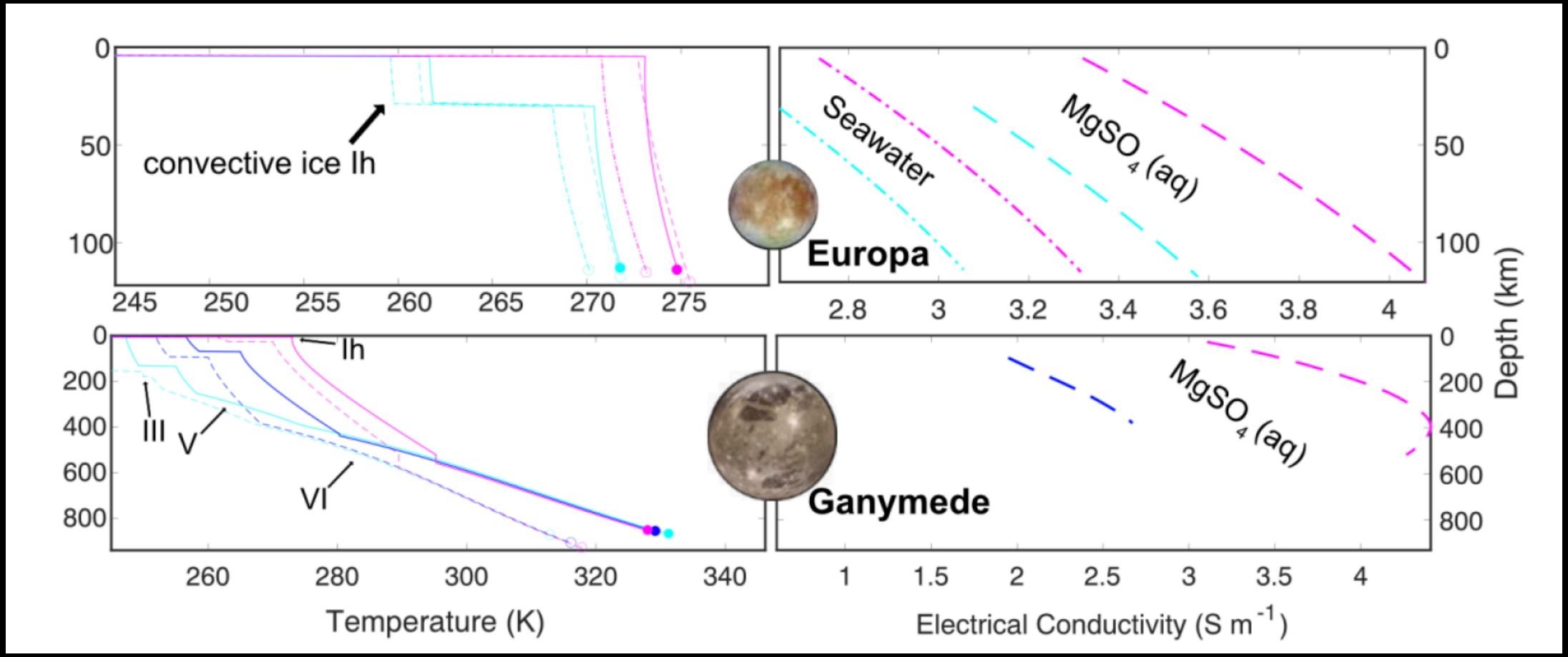
Callisto

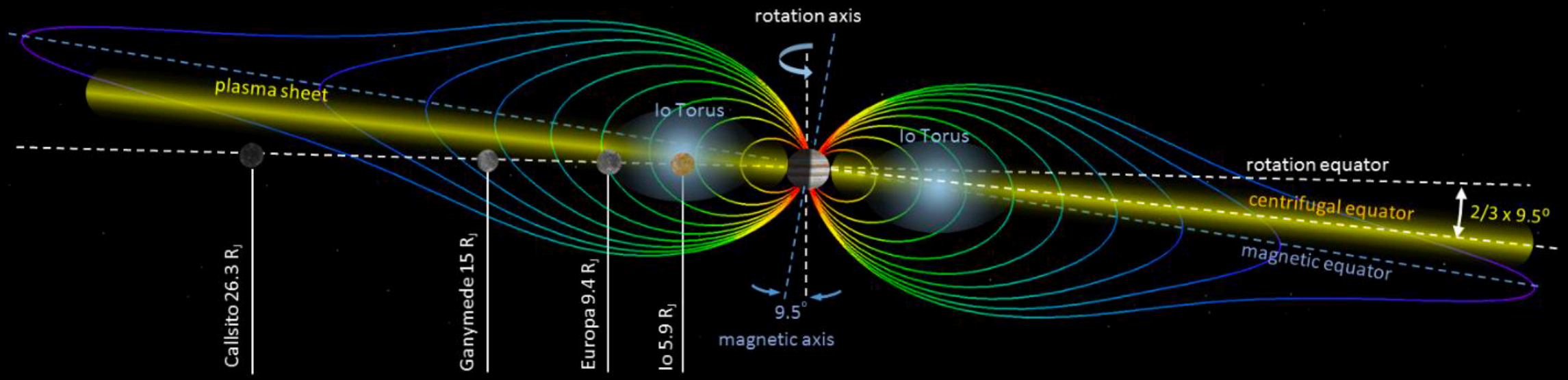


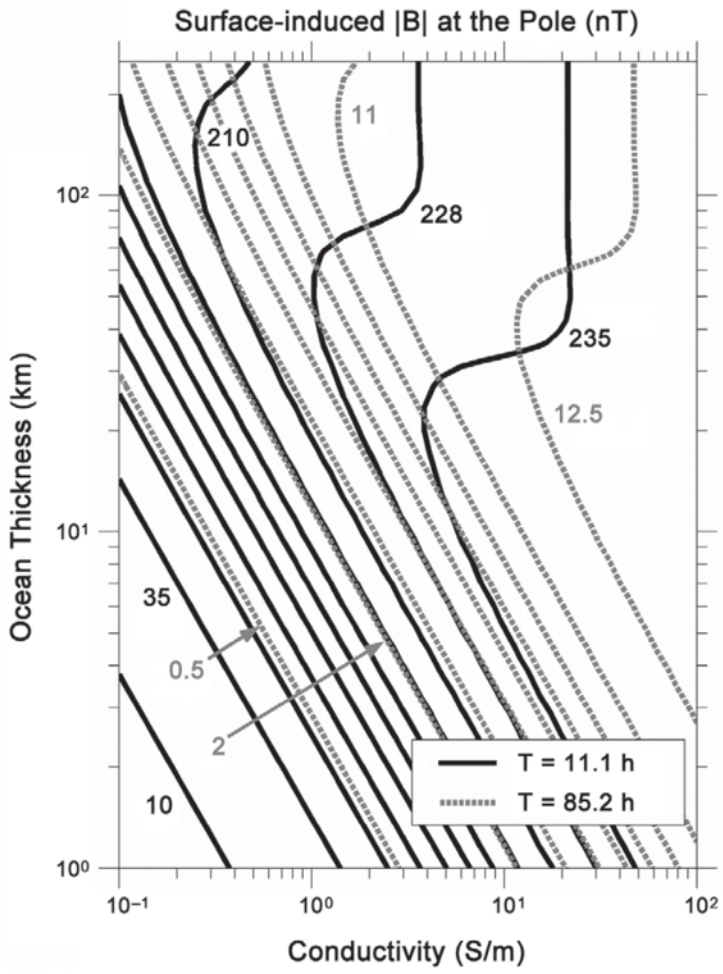




Vance et al. 2017, JGR.


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

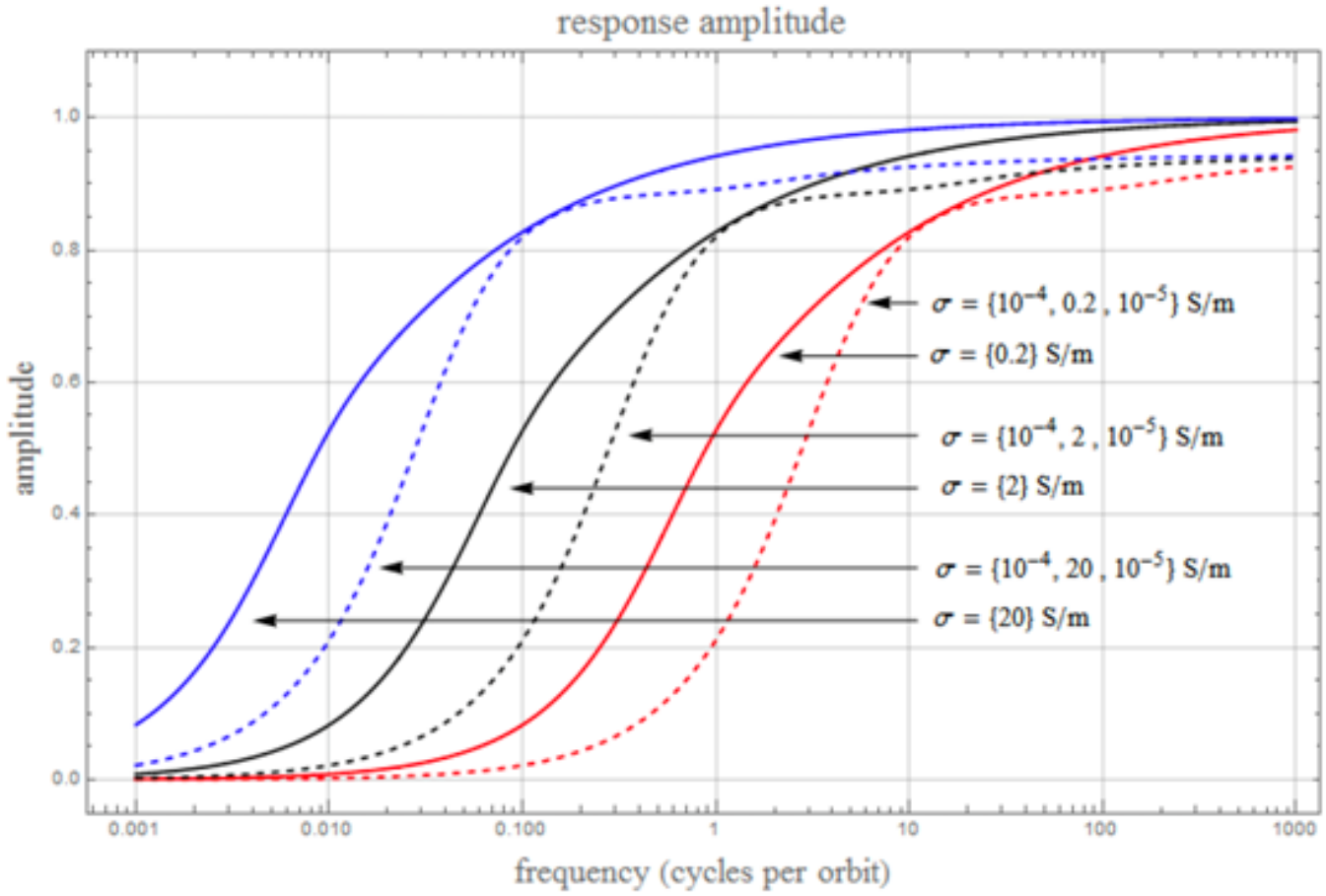


Khurana et al. 2009

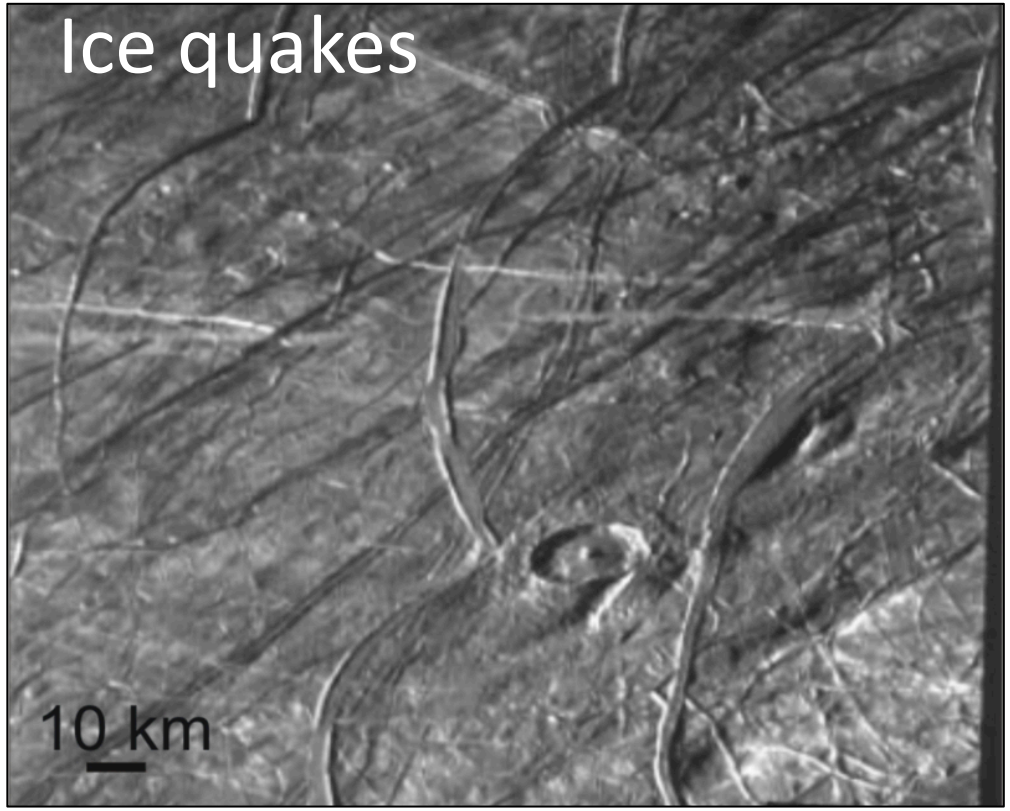
Bruce Bills

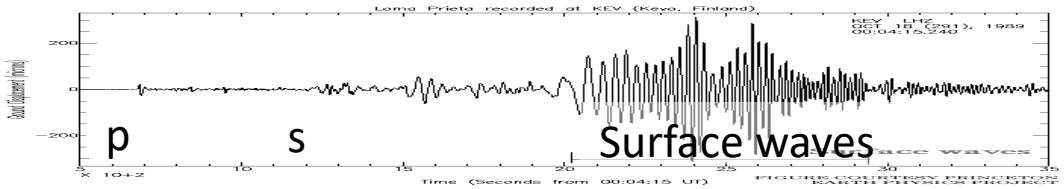
Corey Cochrane

Marshall Styczinski



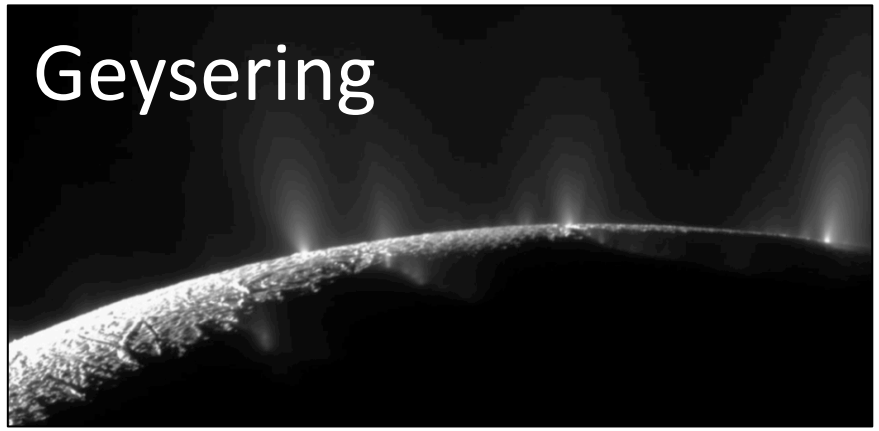
Seismology of Icy Ocean Worlds

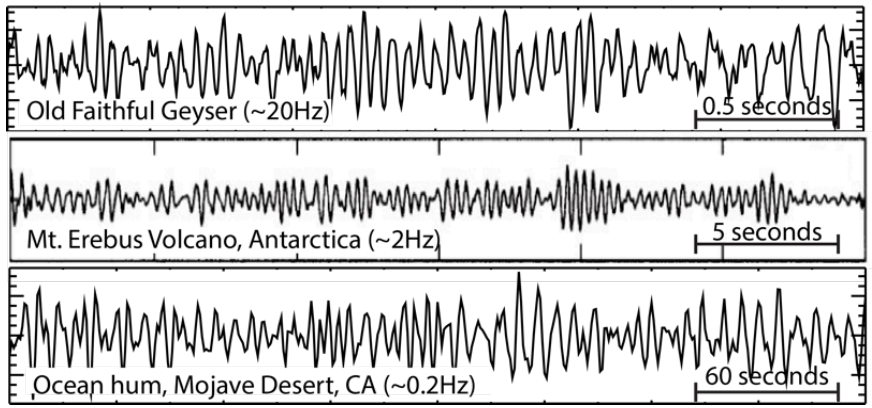


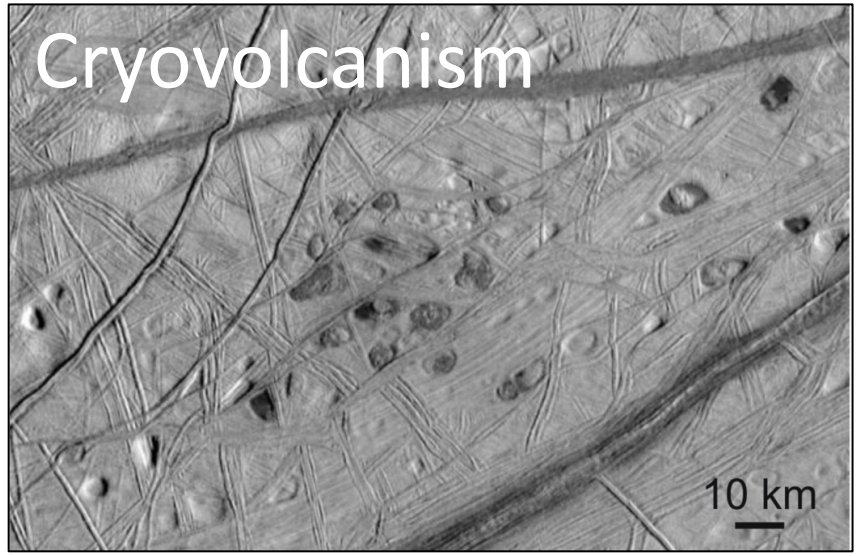


Europa's ice is young and geologically active

Fluid flow induced seismicity: continuous background "hum"





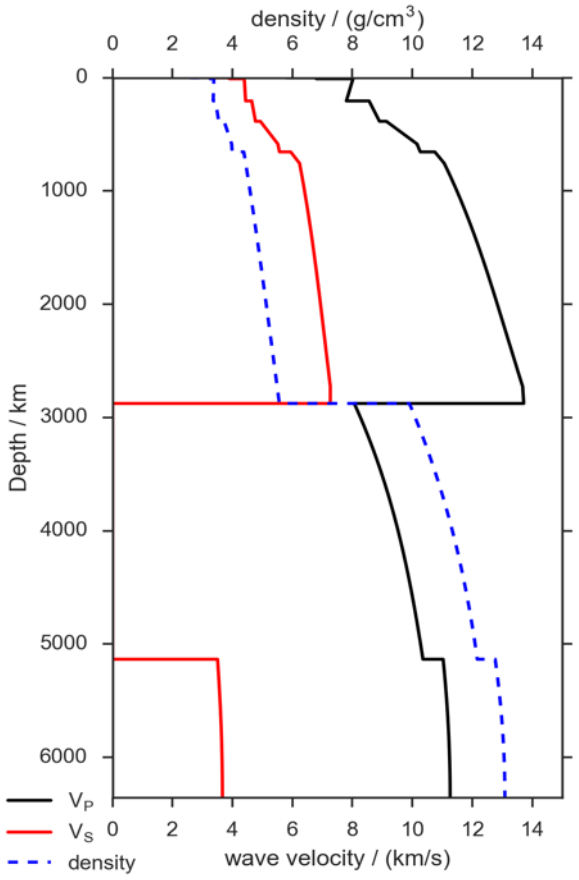


Vance et al. 2018 Astrobiology

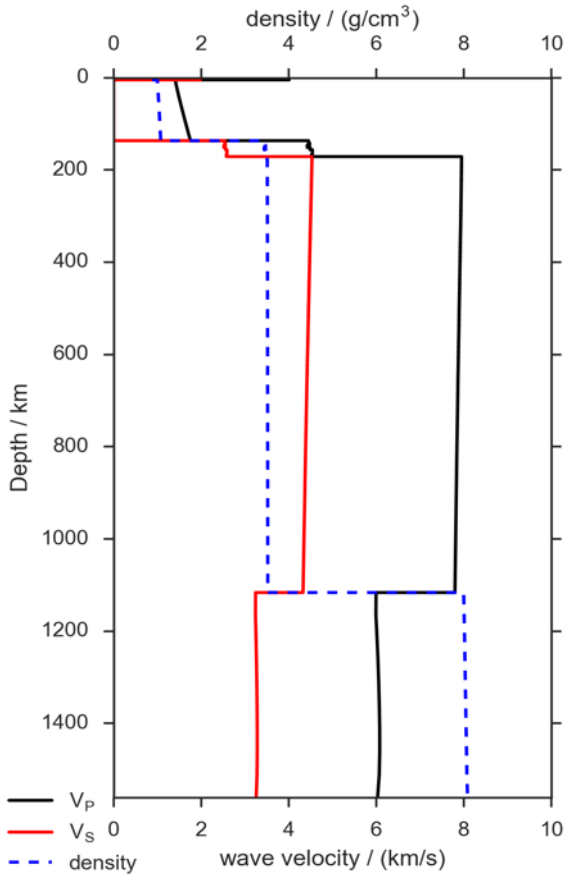
How might an ocean world sound?

Seismic Models

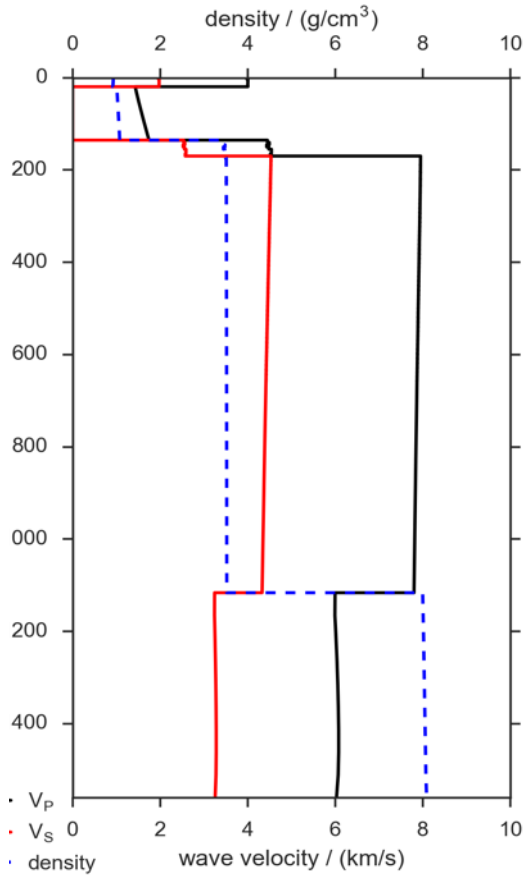
Earth



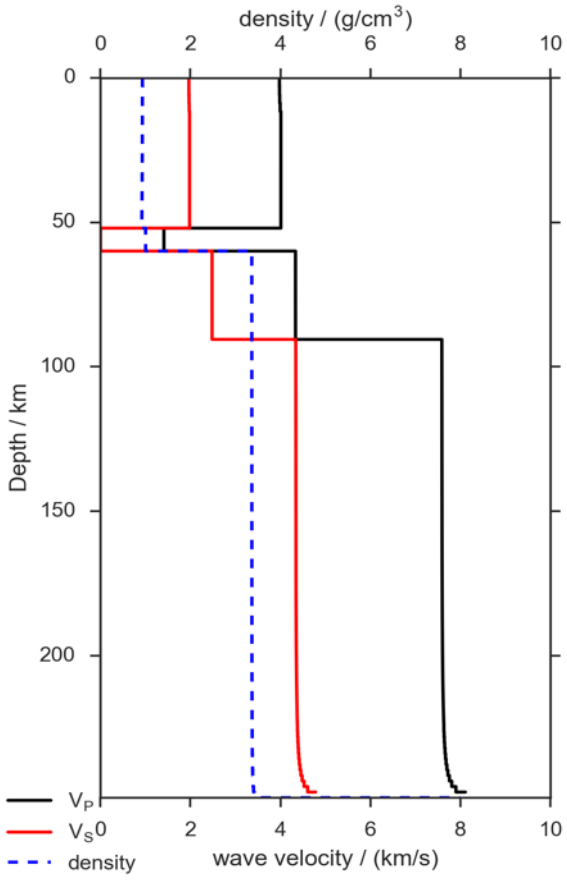
Europa (5km Ice)



Europa (20km Ice)

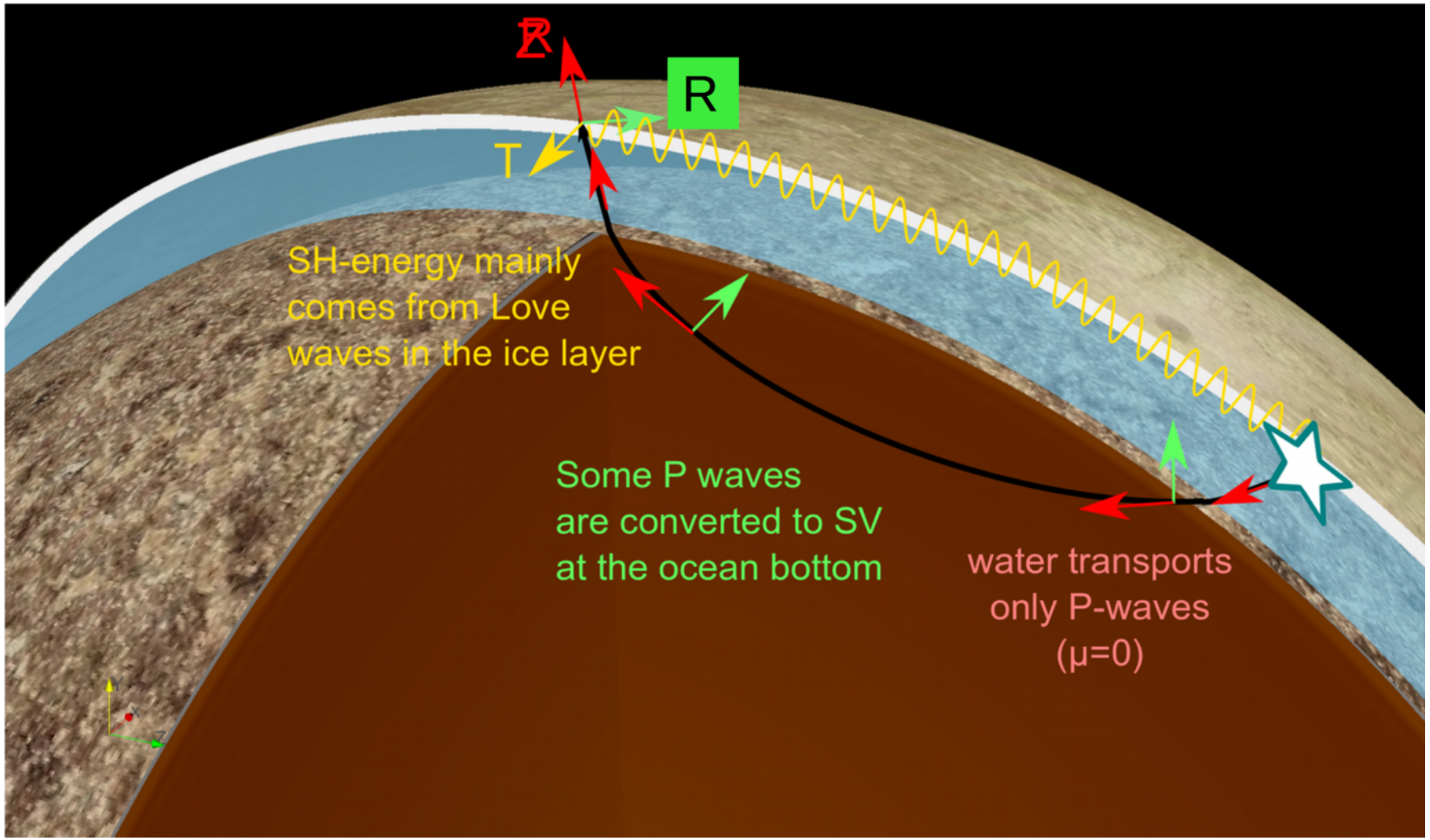


Enceladus

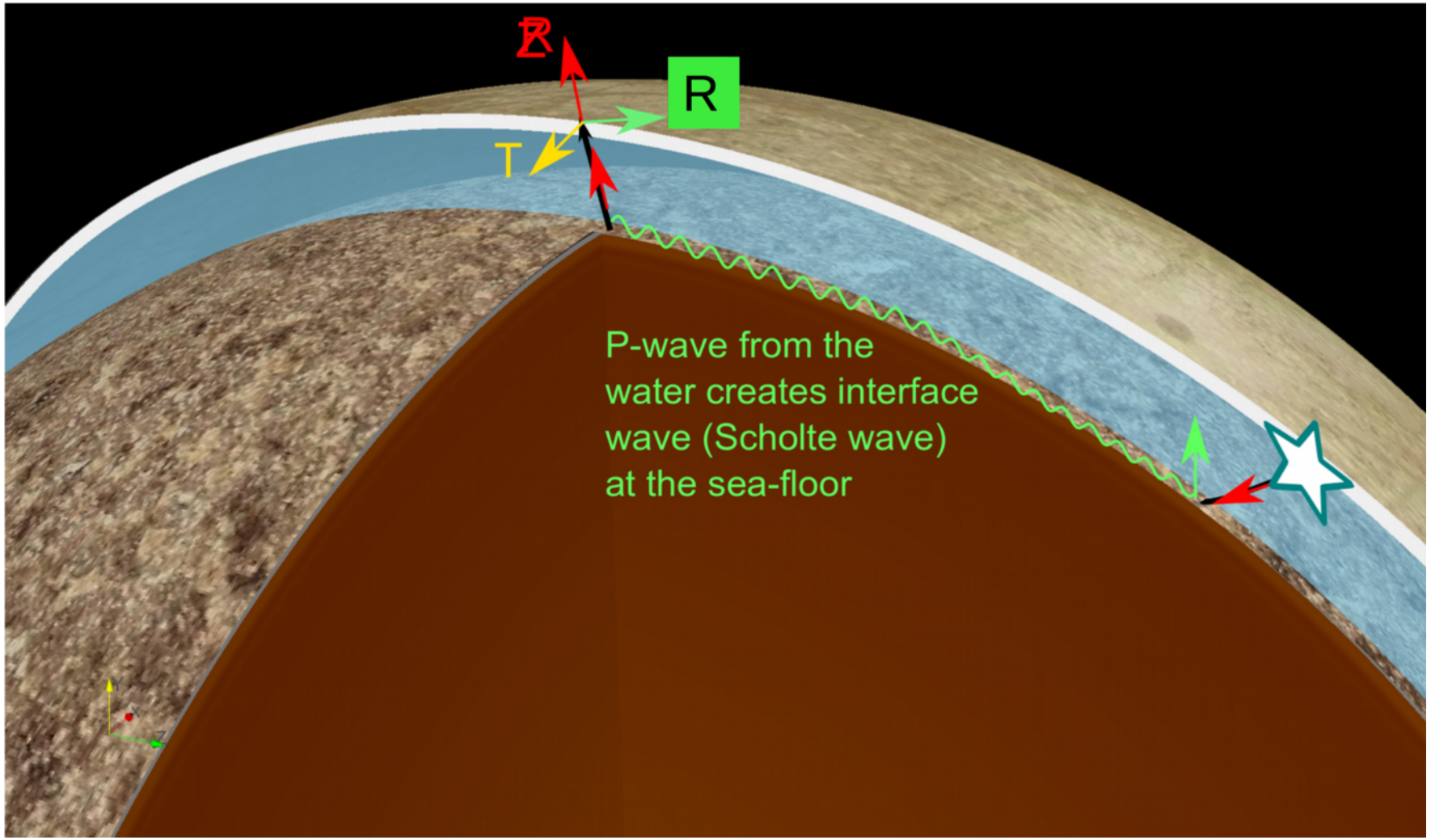


Stähler et al. 2018

Sensing the mantle and ice

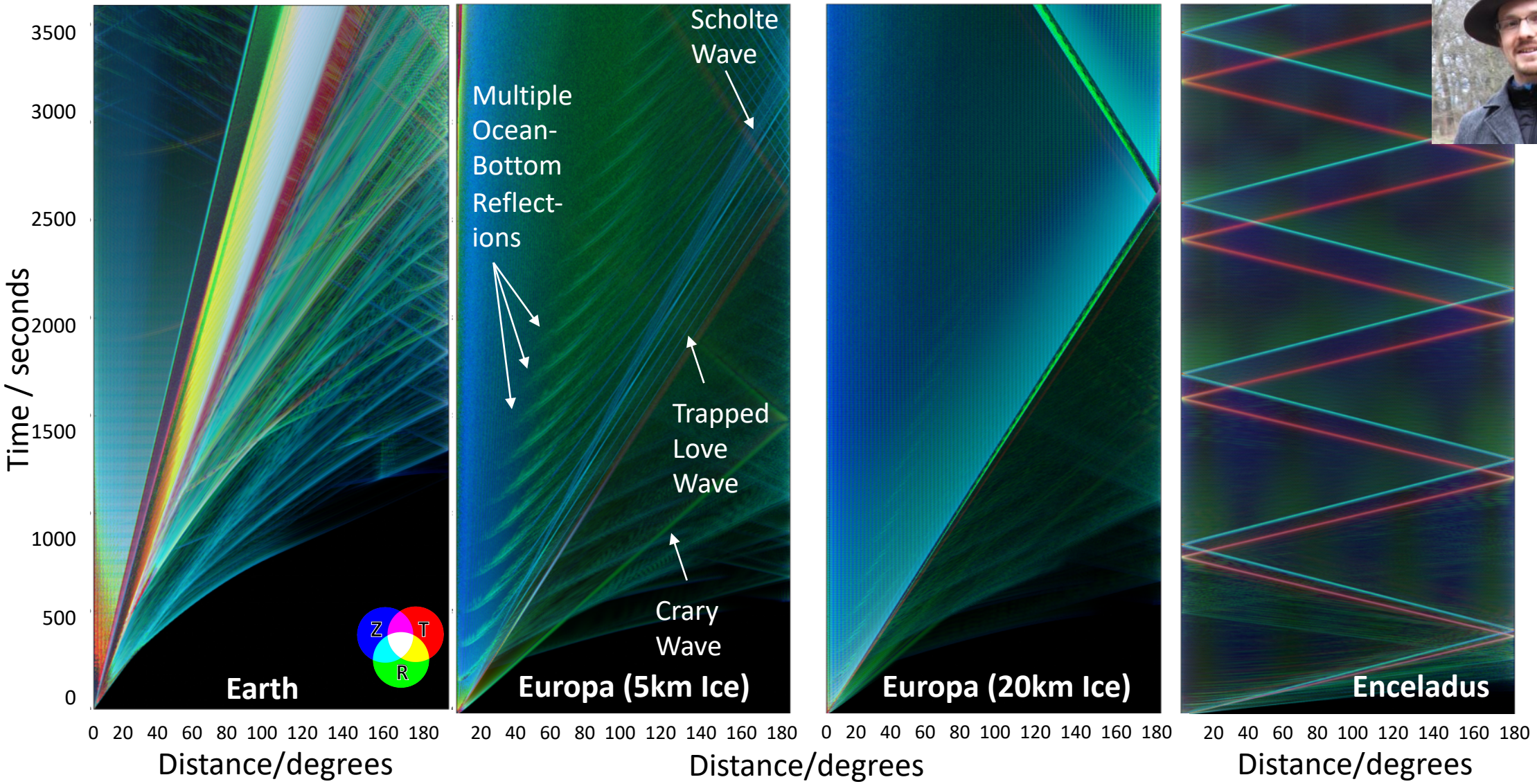


Sensing the mantle and ice



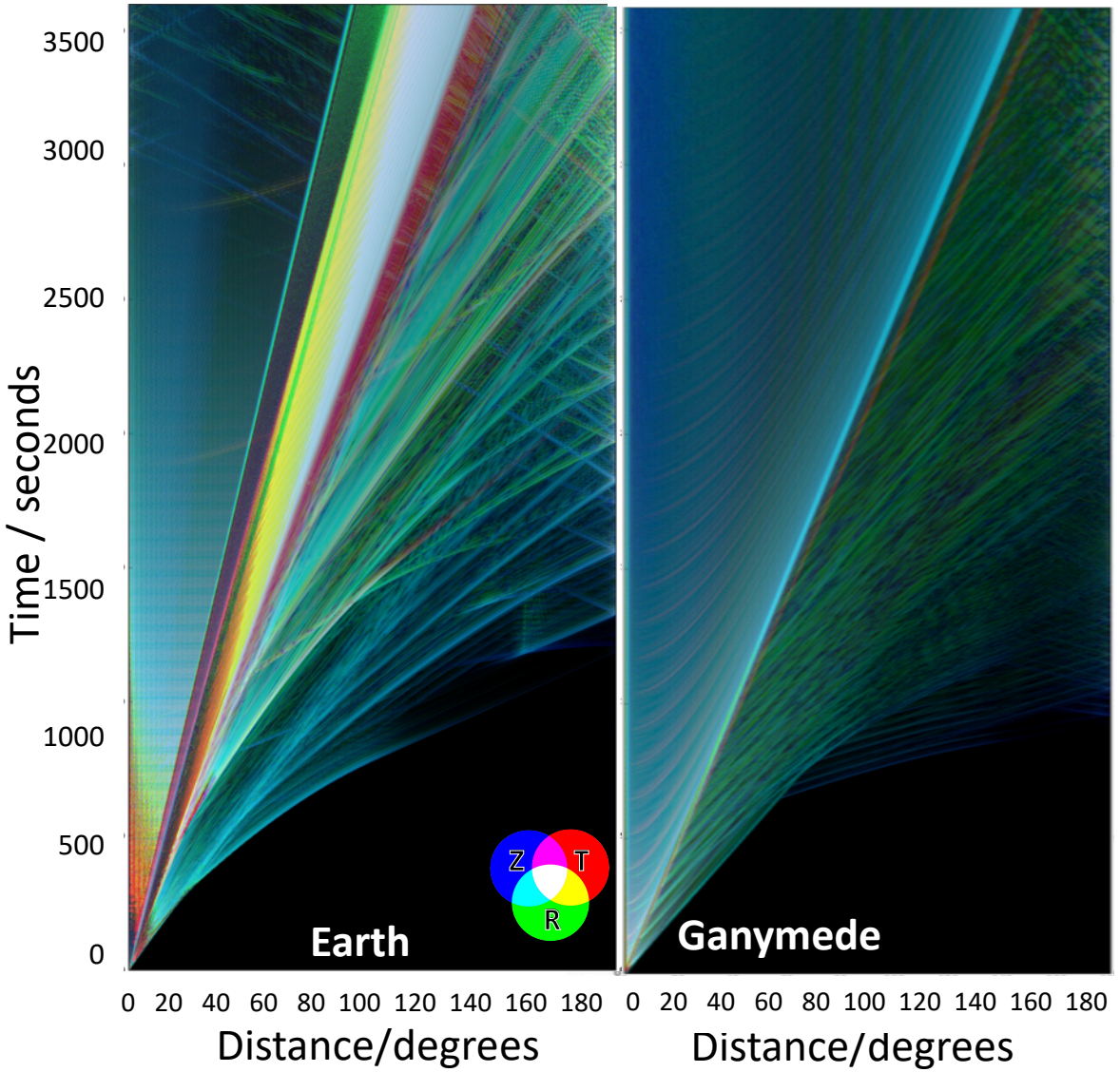
Each Ocean World Has a Unique Seismic Signature

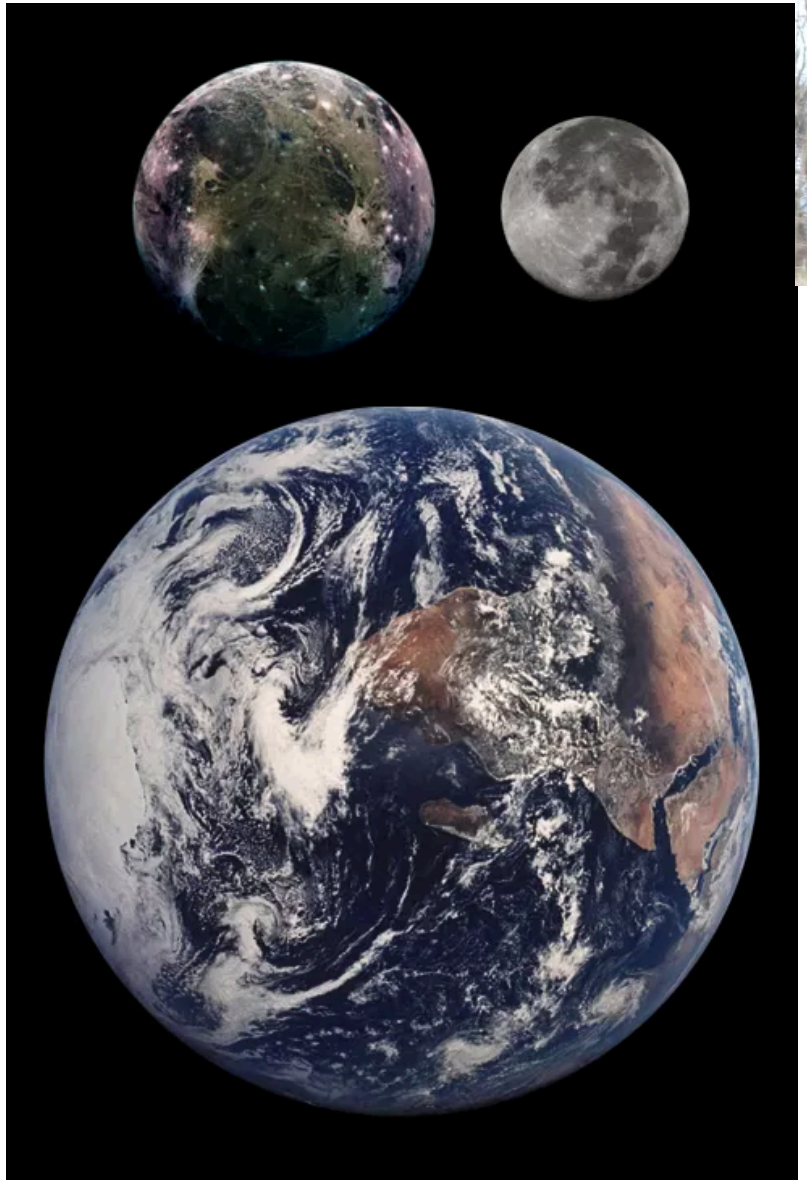
Stähler et al. 2018, JGR.



Each Ocean World Has a Unique Seismic Signature

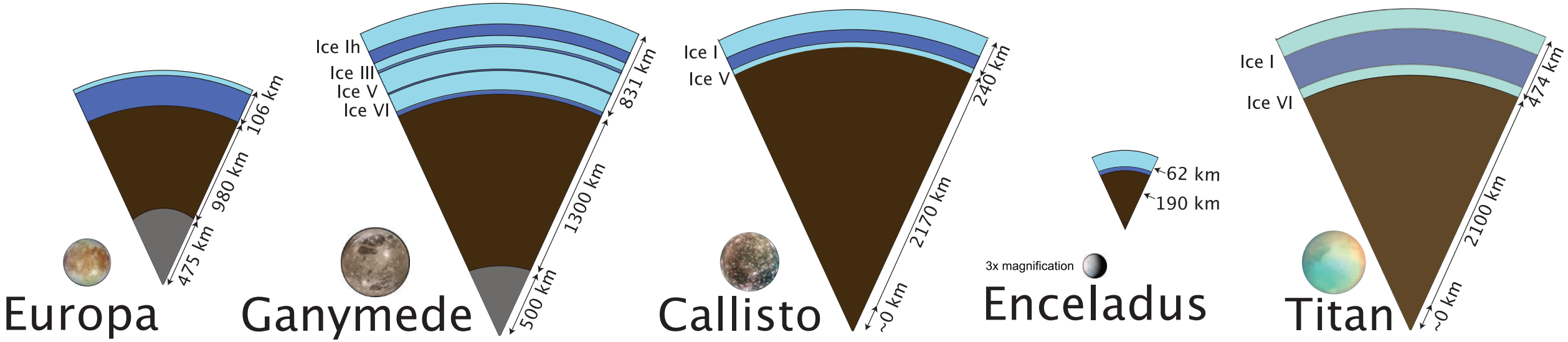
Stähler et al. 2018, JGR.

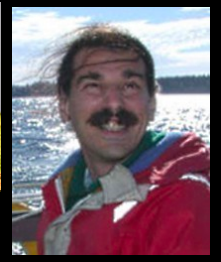
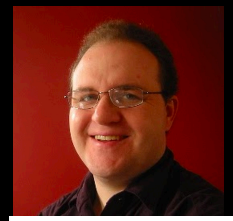




Conclusions

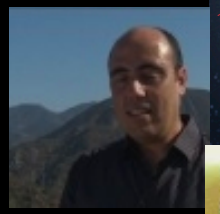
- Deep oceans expand the parameter space of possible ocean properties
- **Thermodynamics** and **forward models** enhance the science return from spacecraft missions

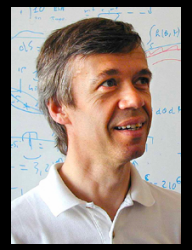


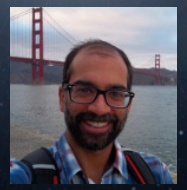
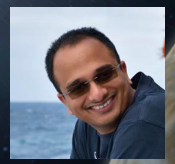



Support:

- 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

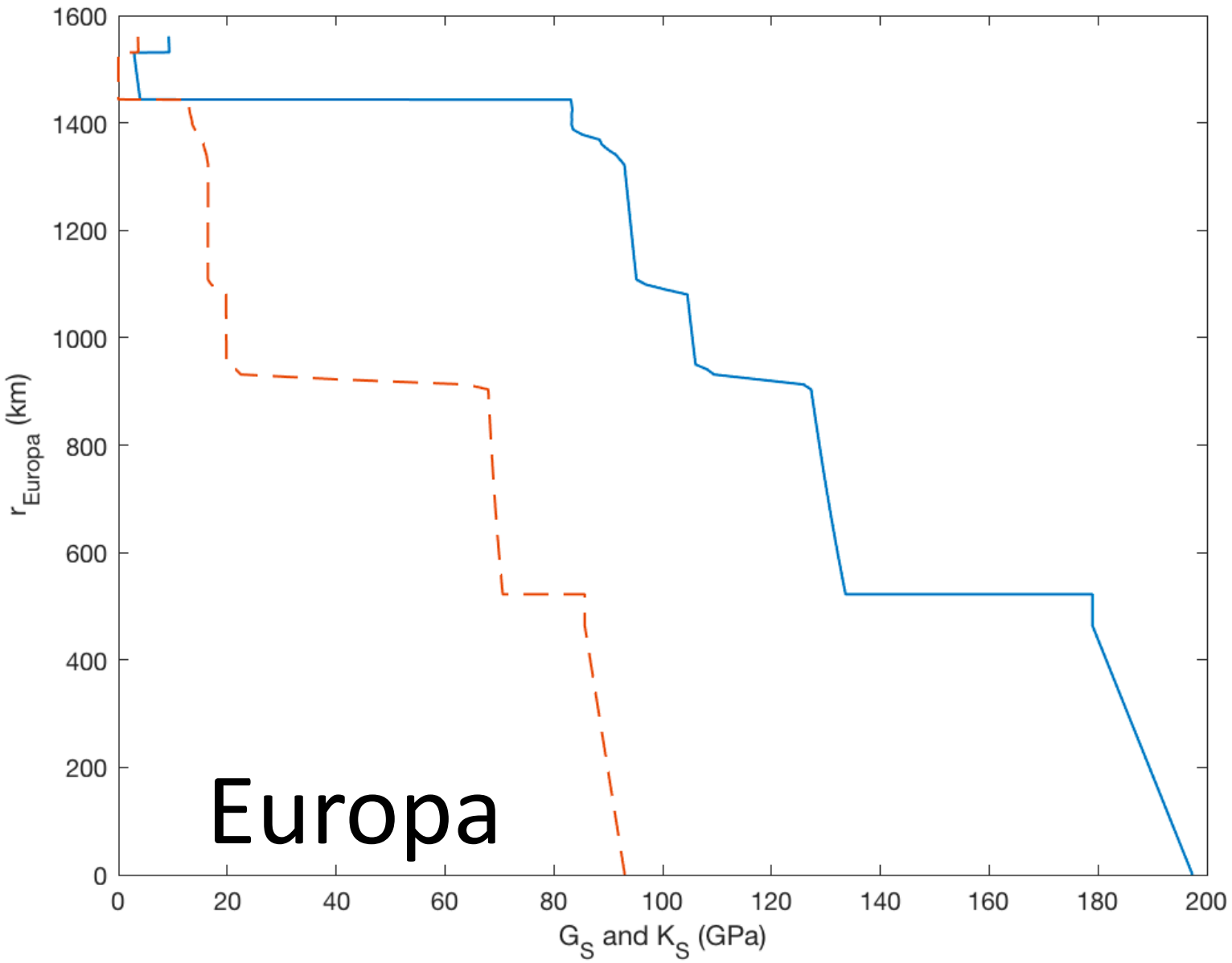
Tidal Dissipation

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

where

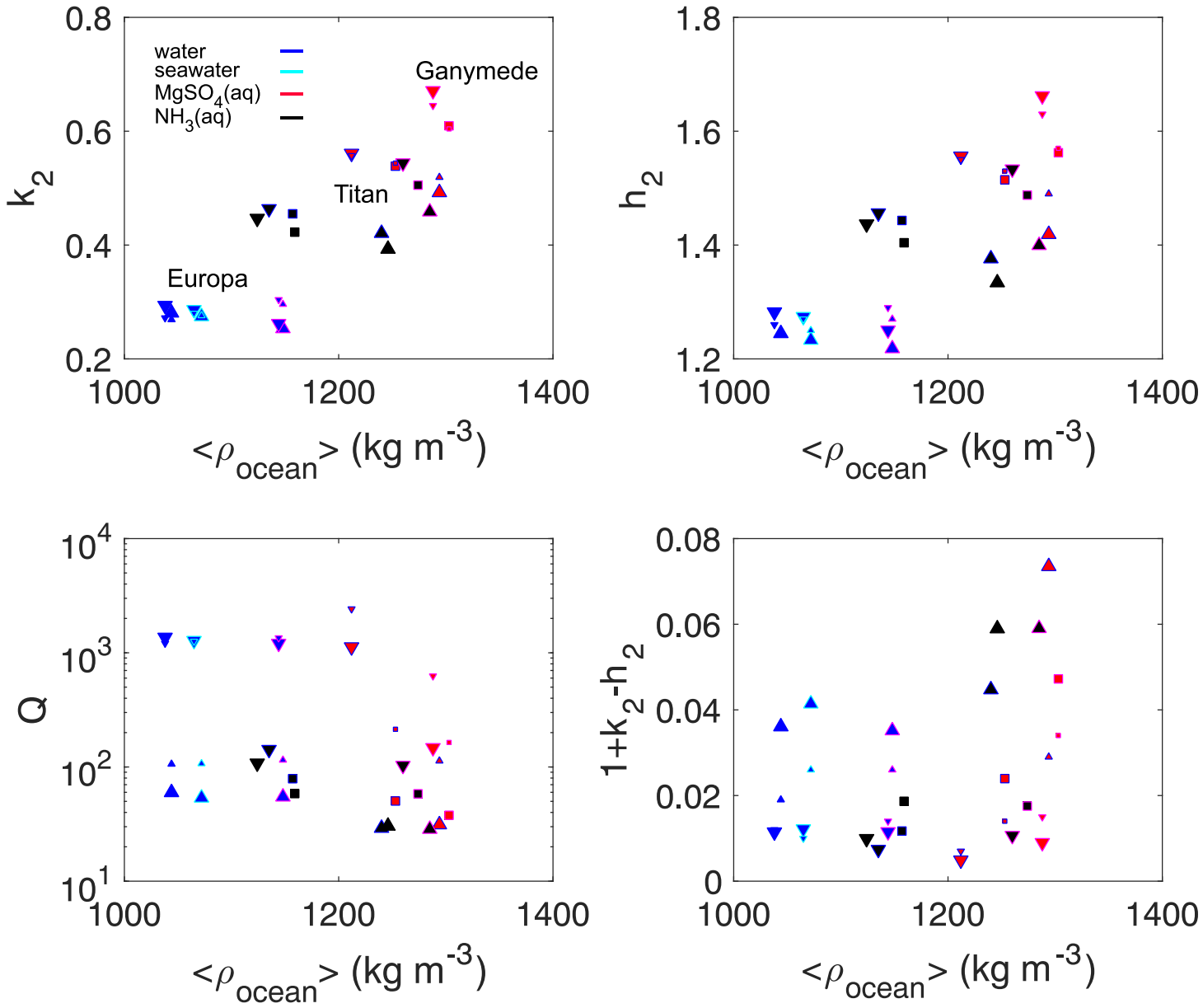
$$\tilde{\mu}(\omega) = \frac{\mu_{\mathrm{E}}\omega^2\eta^2}{\mu_{\mathrm{E}}^2 + \omega^2\eta^2} + i\frac{\mu_{\mathrm{E}}^2\omega\eta}{\mu_{\mathrm{E}}^2 + \omega^2\eta^2},$$

Tobie et al. 2006



Vance et al. 2017 JGR

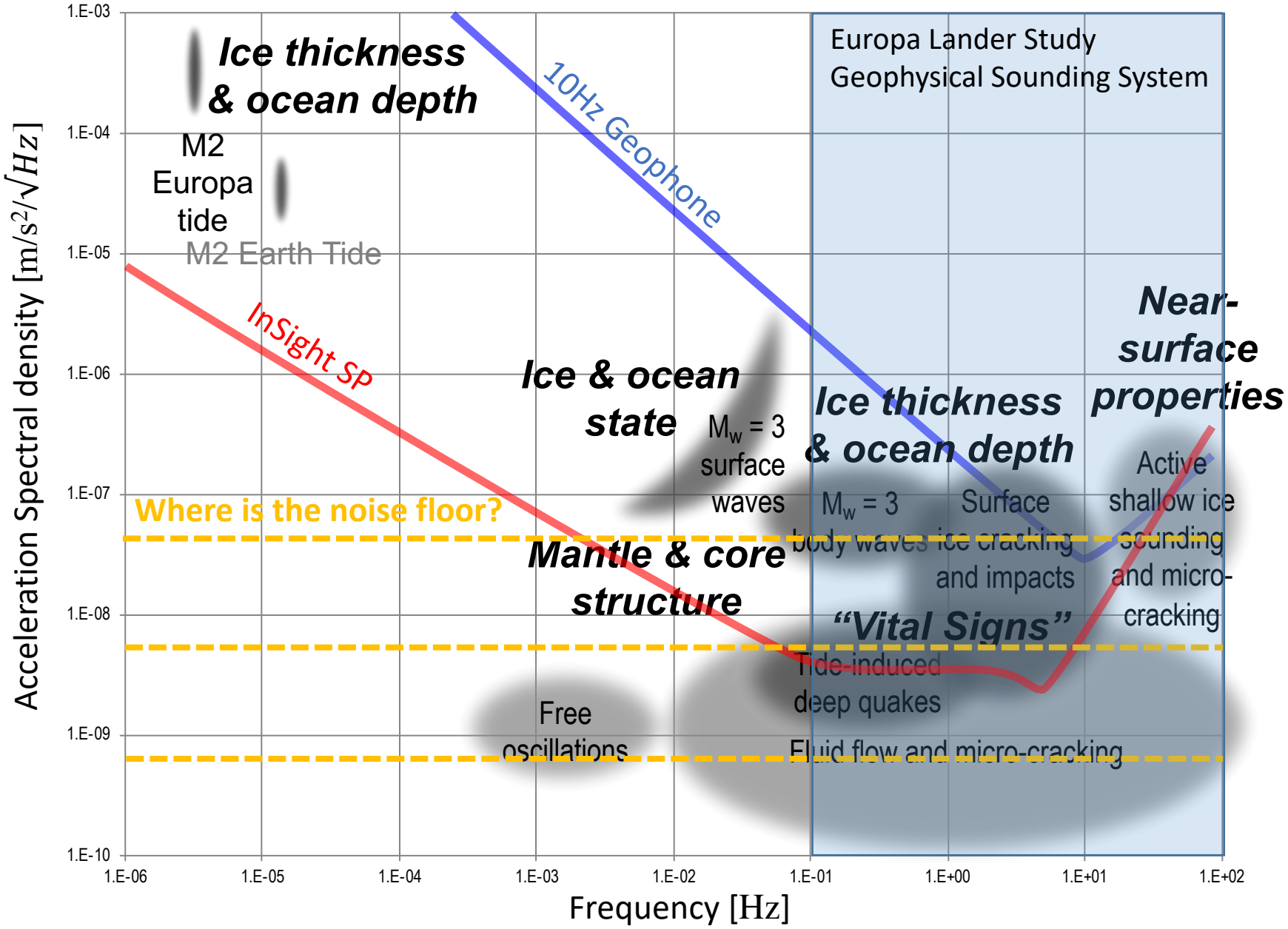
Tidal Dissipation

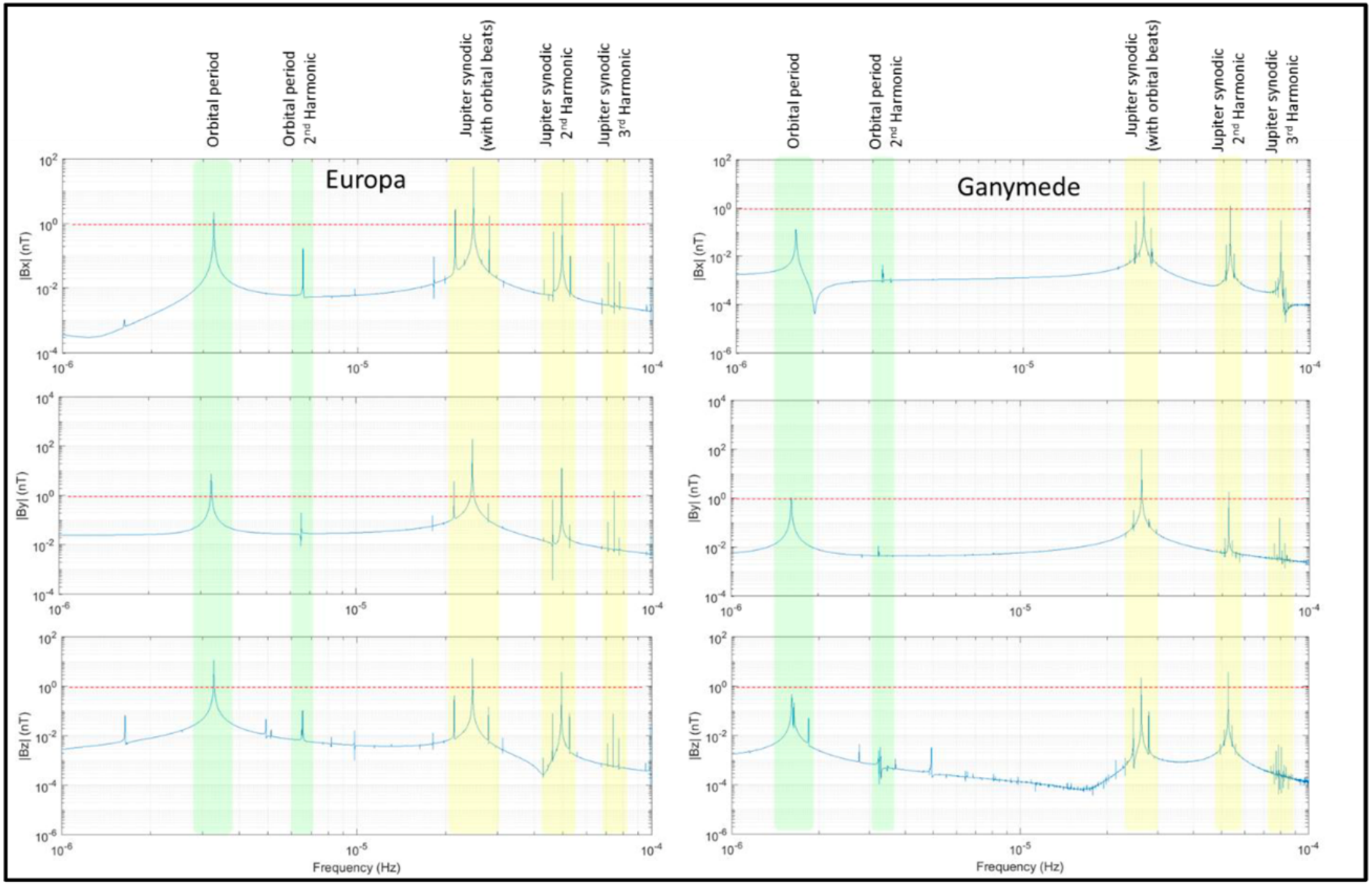


Contributed by
Gabriel Tobie and
Shunichi Kamata

Vance et al. 2017 JGR

Can we hear it?

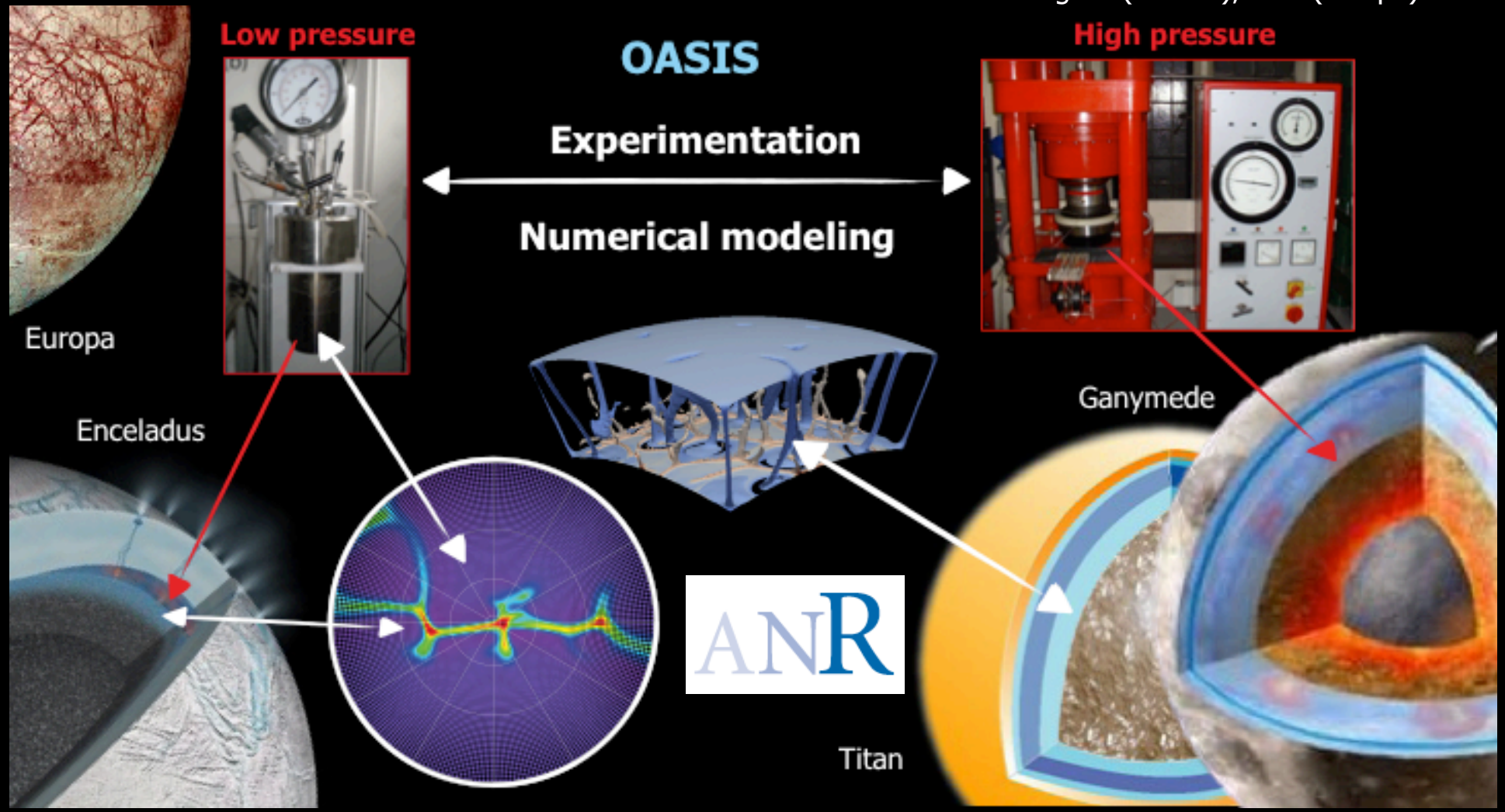



Orbital period
Orbital period 2nd Harmonic
Jupiter synodic (with orbital beats)
Jupiter synodic 2nd Harmonic
Jupiter synodic 3rd Harmonic
Europa
Ganymede
|Bx| (nT)
|By| (nT)
|Bz| (nT)
Frequency (Hz)

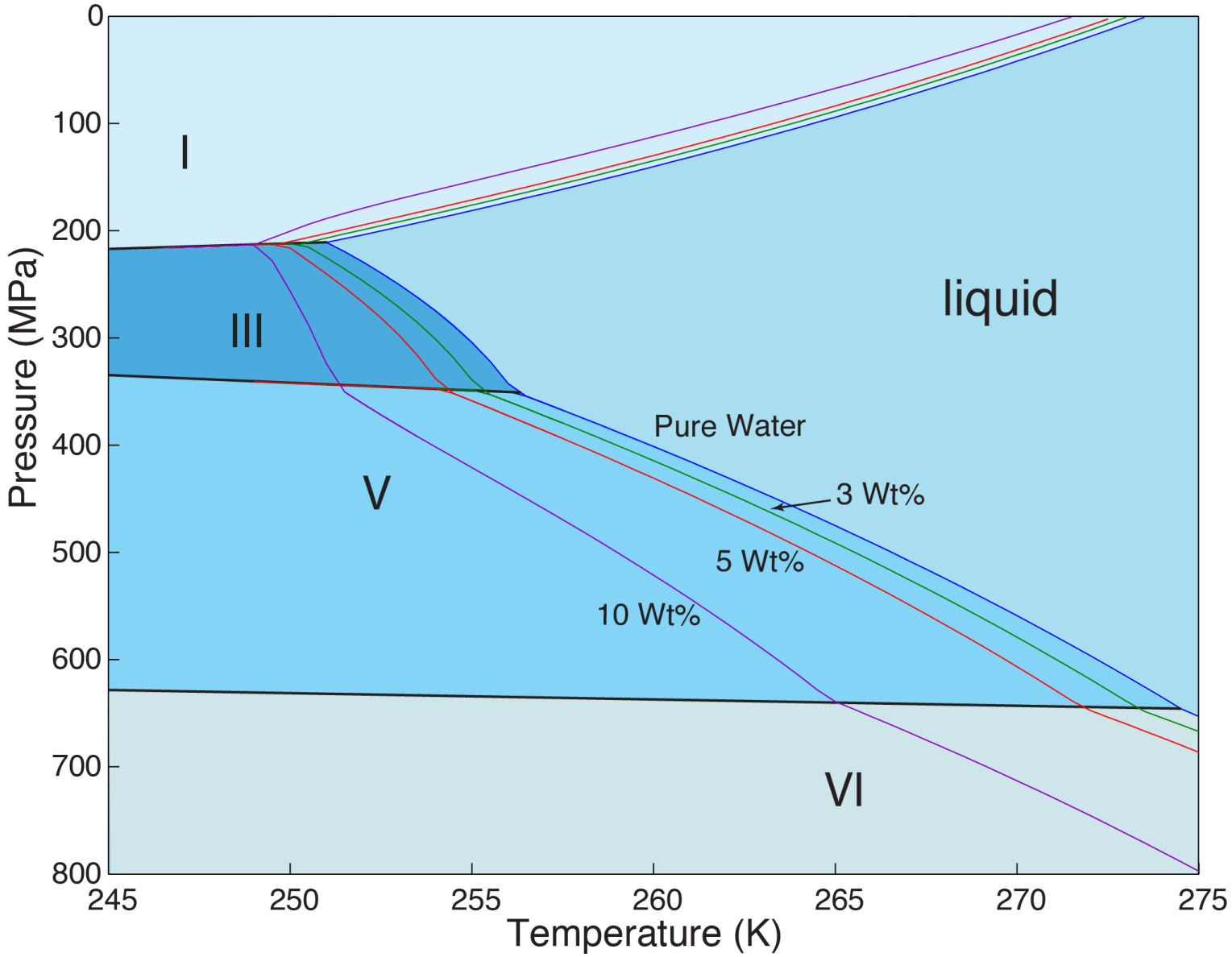
Project OASIS: Organic and Aqueous Systems in Icy Satellites

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)

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

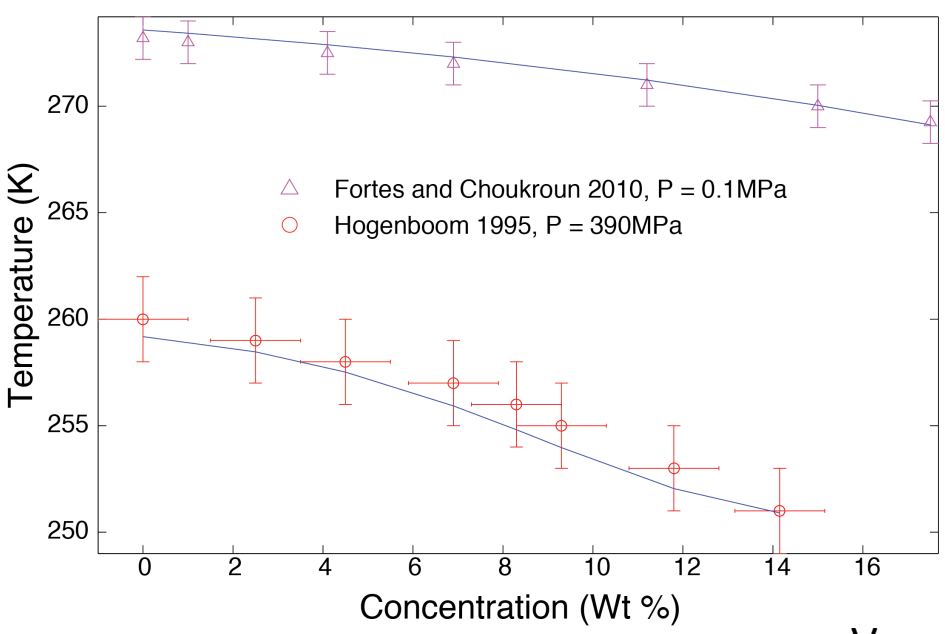
$\mu^S_{H_2O}$ from Choukroun and Grasset 2010

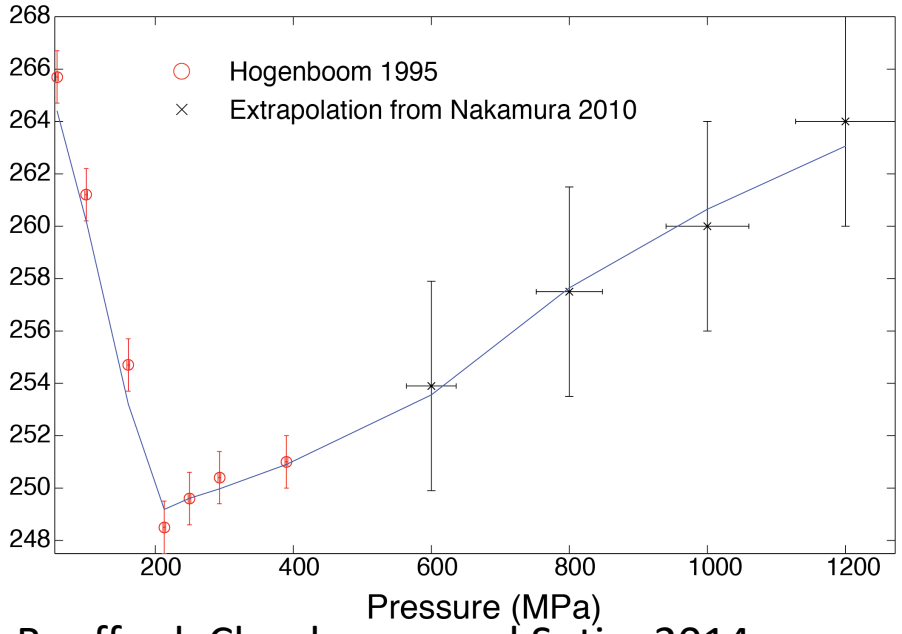
$$\mu^L_{H_2O}(P,T,X^L_{H_2O}) = \mu^L_{H_2O,pure} + RT\ln(\gamma^L_{H_2O} X^L_{H_2O})$$

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

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

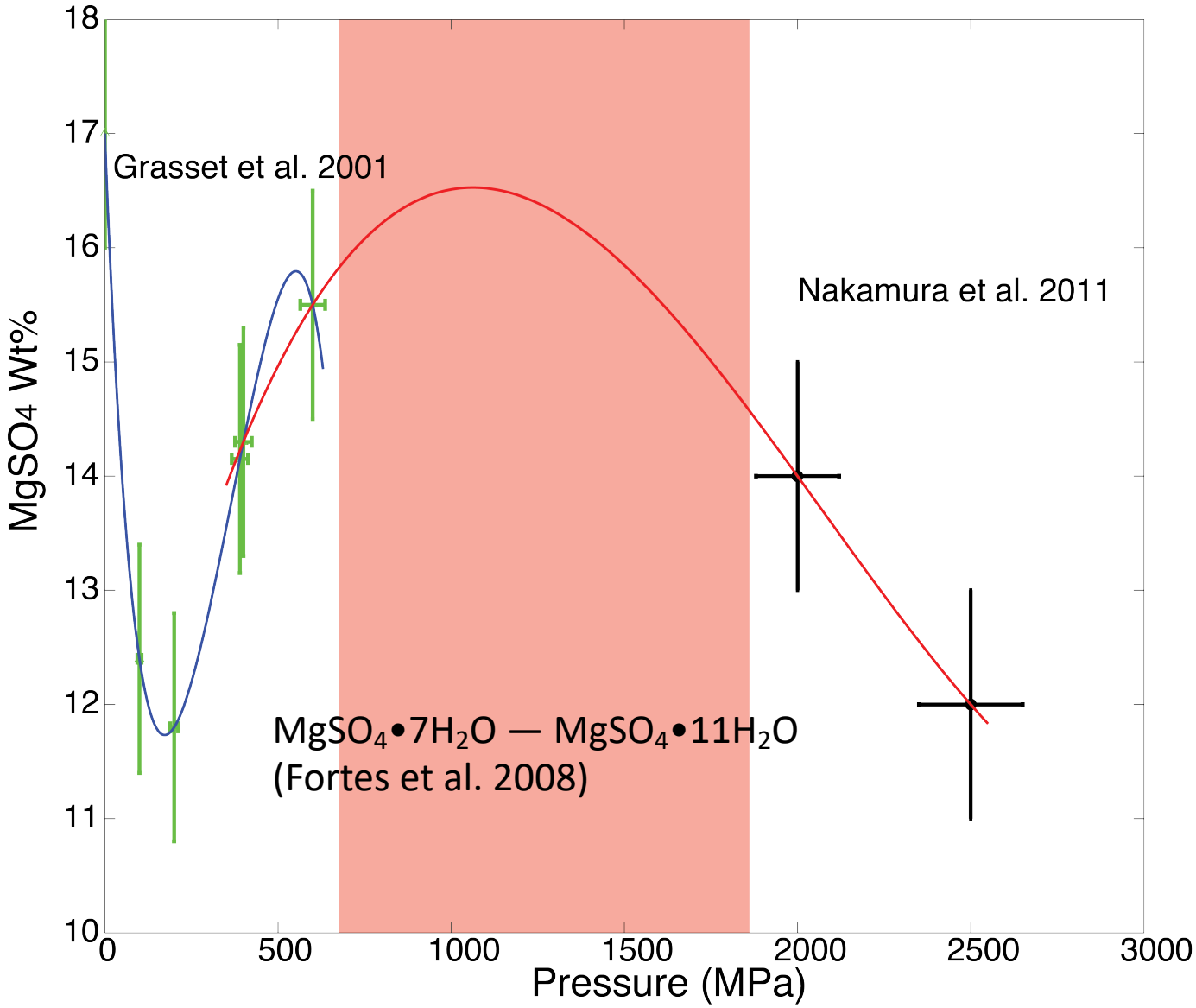
Eutectic Data

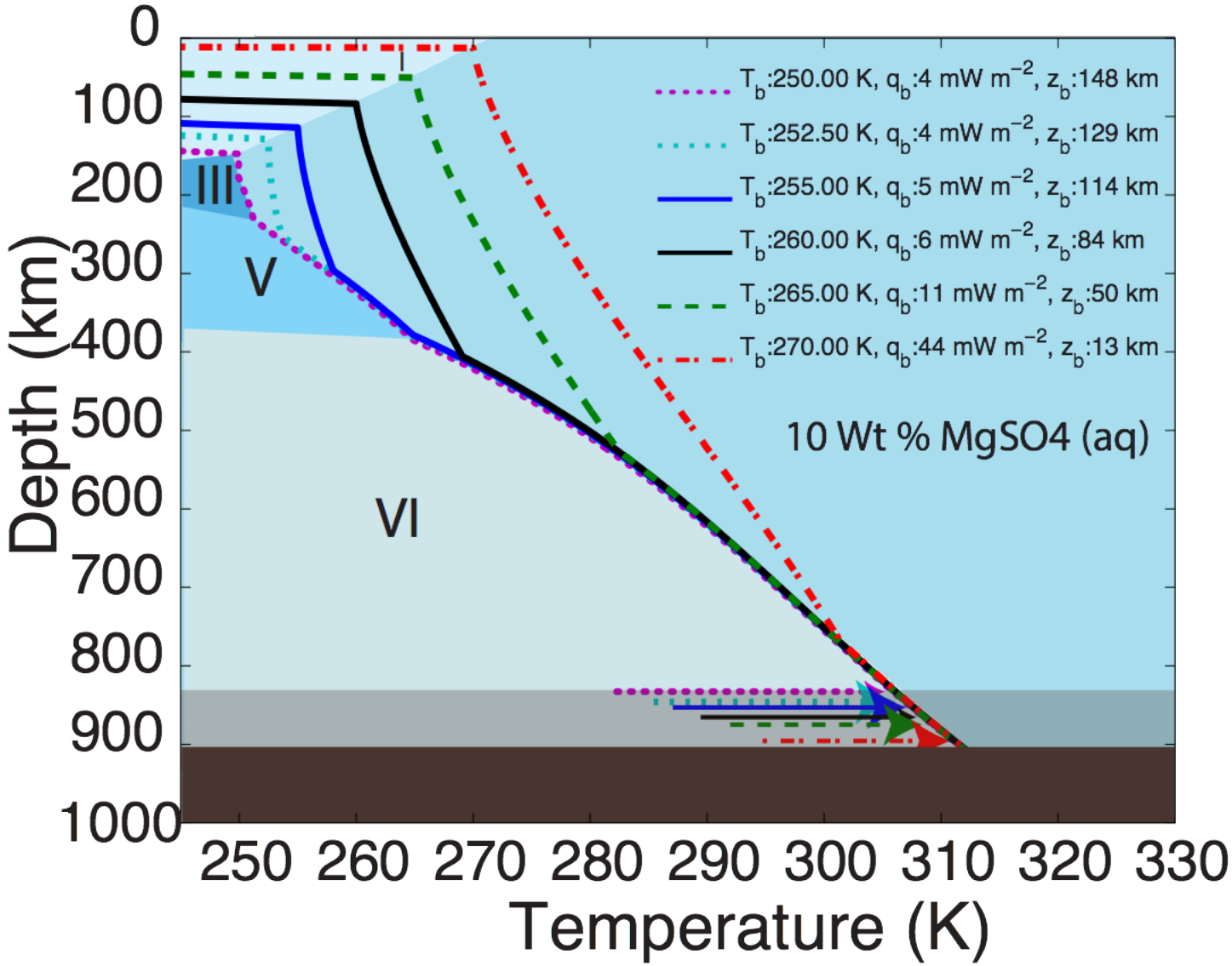


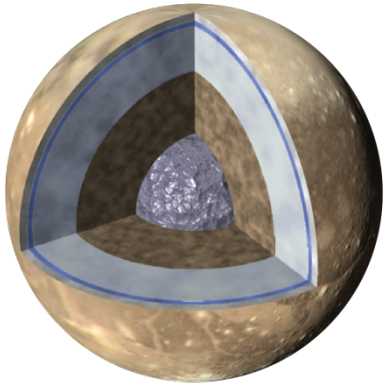


Vance, Bouffard, Choukroun, and Sotin, 2014.

Eutectic composition vs pressure



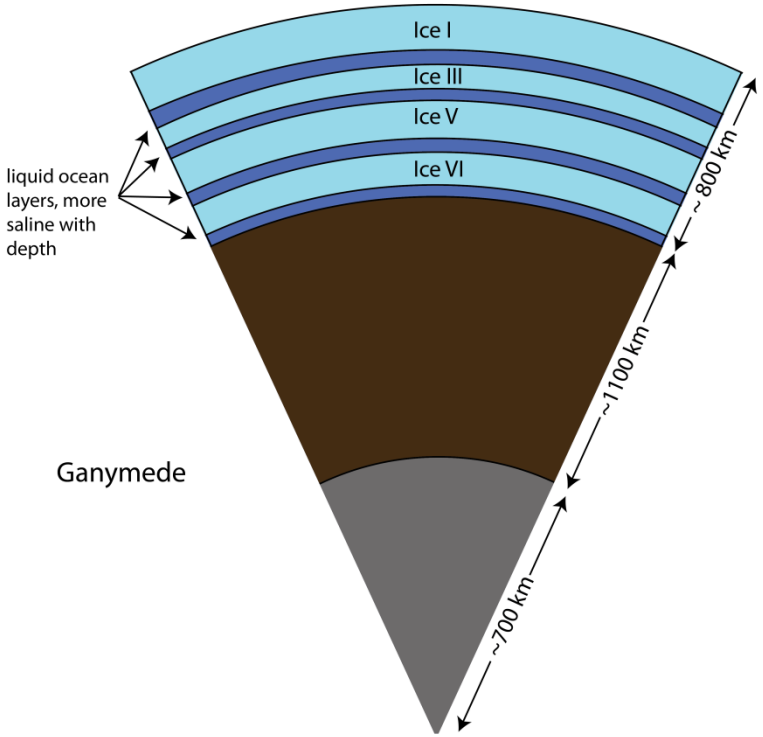




Modified from Vance, Bouffard, Choukroun, and Sotin, 2014, *PSS*

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



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

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

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

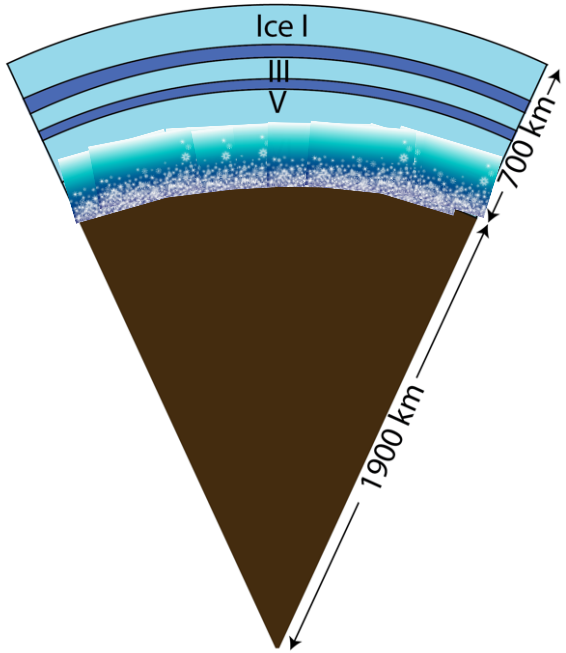
$$\rho_{iron} = \frac{\rho_{Fe}\rho_{FeS}}{X_{FeS}\left(\rho_{Fe} - \rho_{FeS}\right) + \rho_{FeS}} = 7,030$$

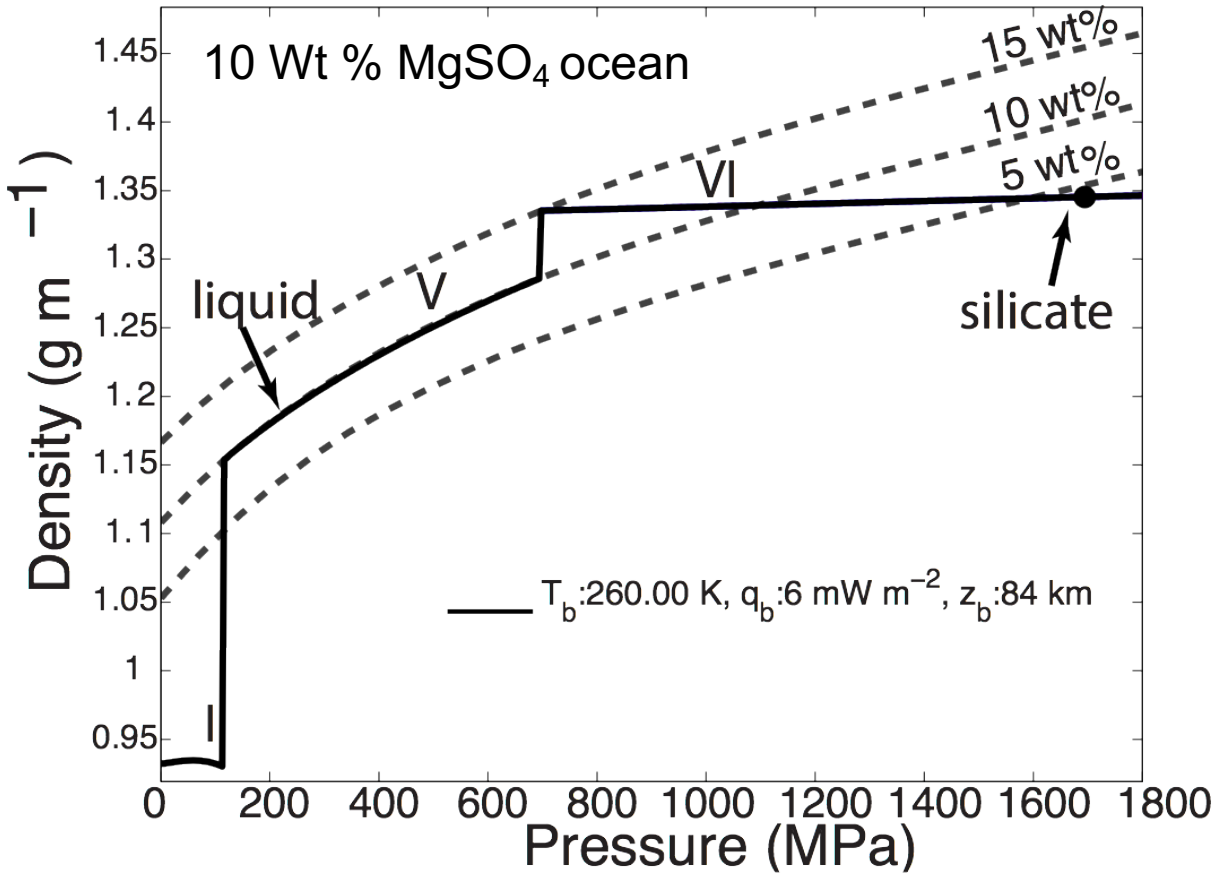
$$\rho_{silicate} = 3,125 \text{ kg m}^{-3}$$

Vance, Bouffard, Choukroun, and Sotin, 2014.

Thermal model constrains Ganymede's internal structure

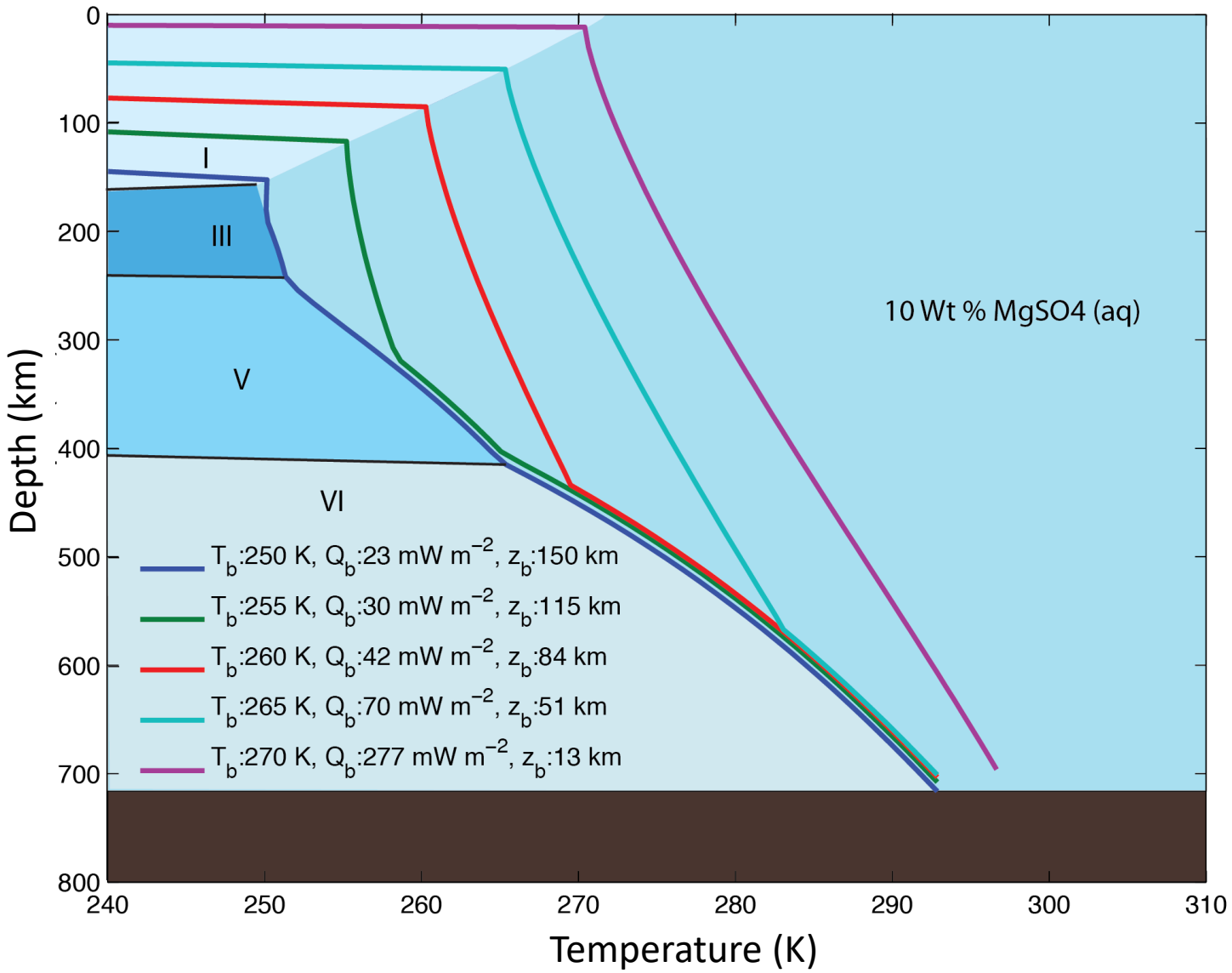
- ice I melting: T_b
- Follow melting curves in ice III, V, VI layers



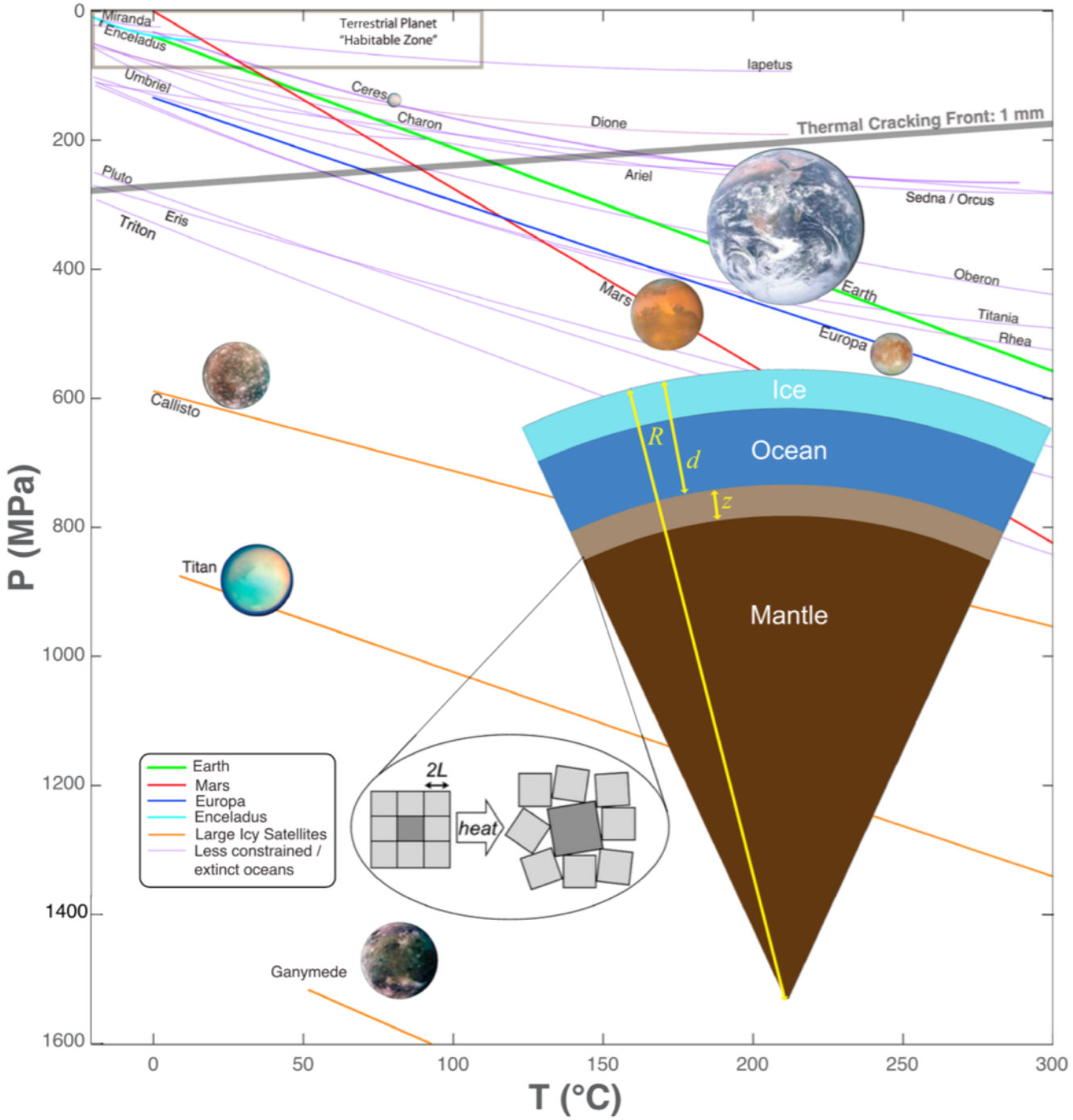


Modified from Vance, Bouffard, Choukroun, and Sotin, 2014, *PSS*

Salinity determines cryosphere structure



Vance, Bouffard, Choukroun, and Sotin, 2014.



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

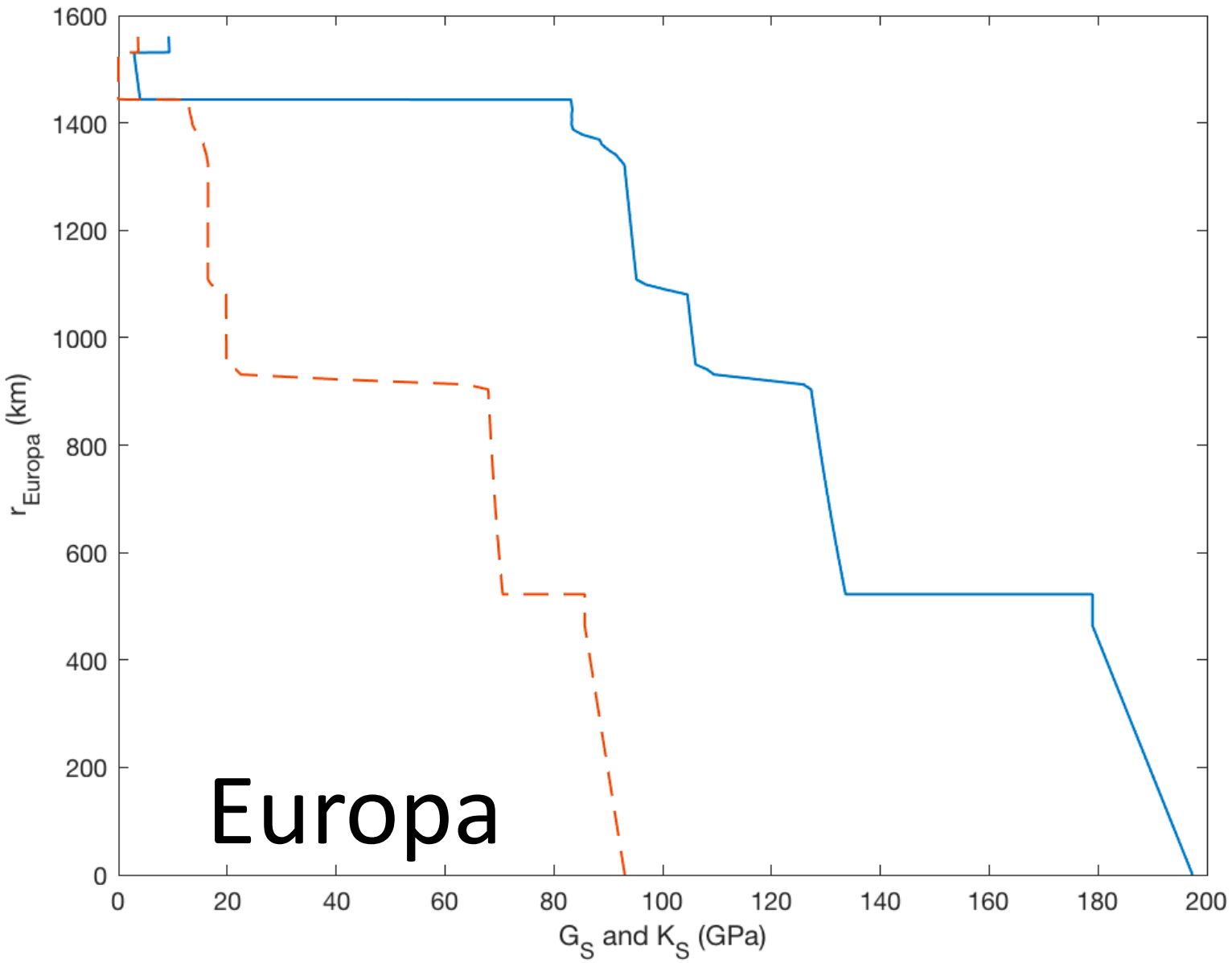
Tidal Dissipation

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

where

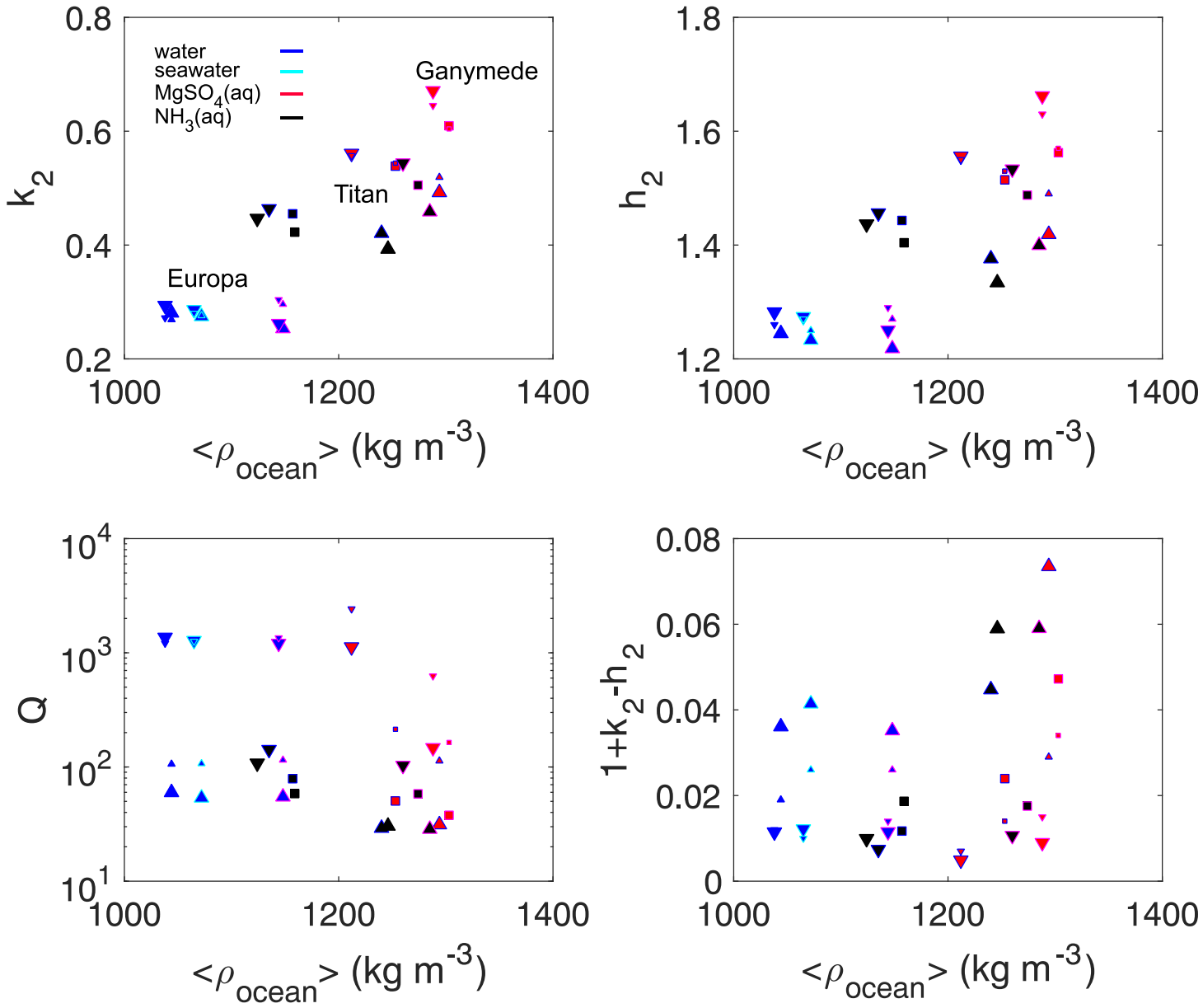
$$\tilde{\mu}(\omega) = \frac{\mu_{\mathrm{E}}\omega^2\eta^2}{\mu_{\mathrm{E}}^2 + \omega^2\eta^2} + i\frac{\mu_{\mathrm{E}}^2\omega\eta}{\mu_{\mathrm{E}}^2 + \omega^2\eta^2},$$

Tobie et al. 2006



Vance et al. 2017 JGR

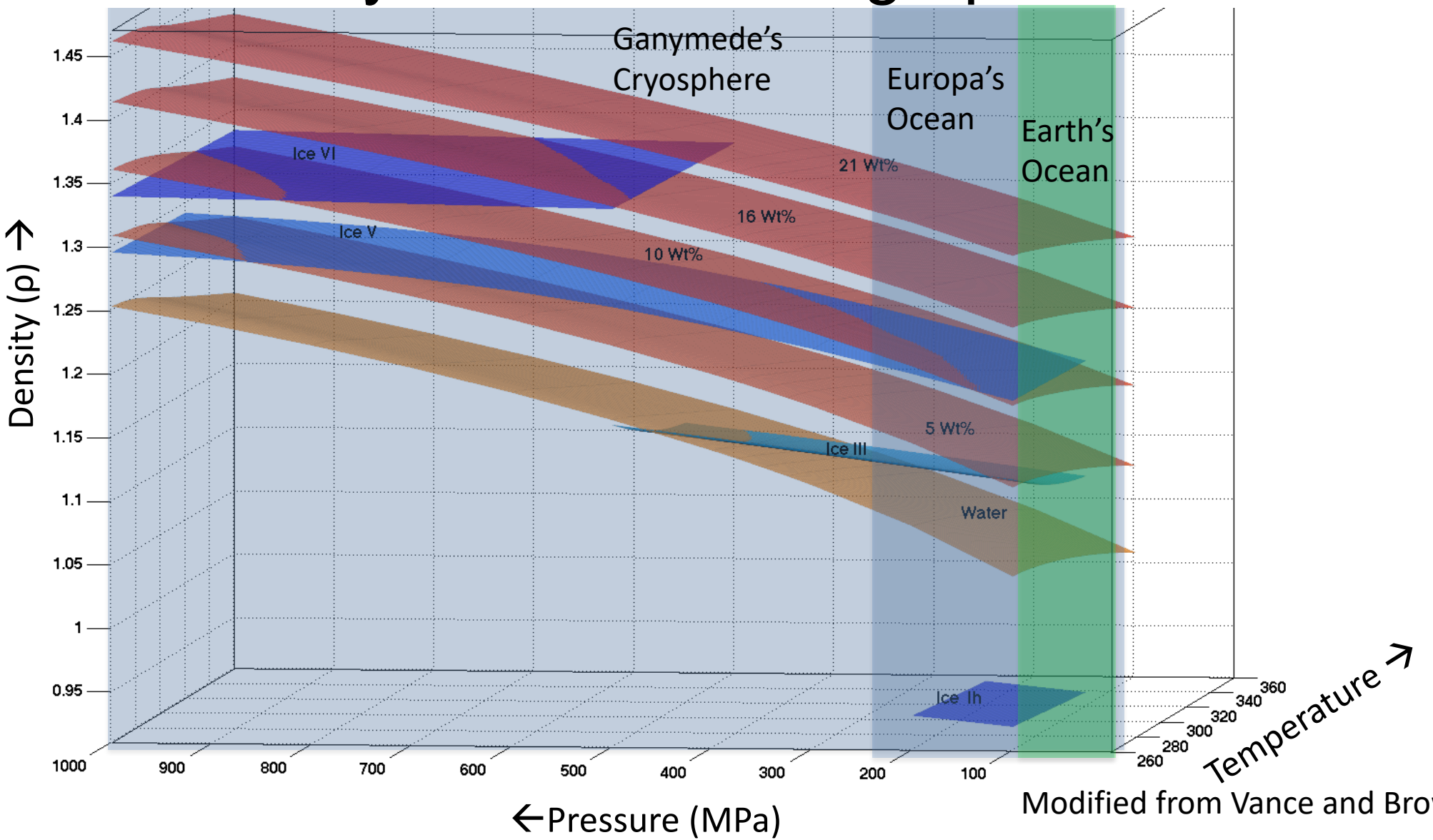
Tidal Dissipation



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.