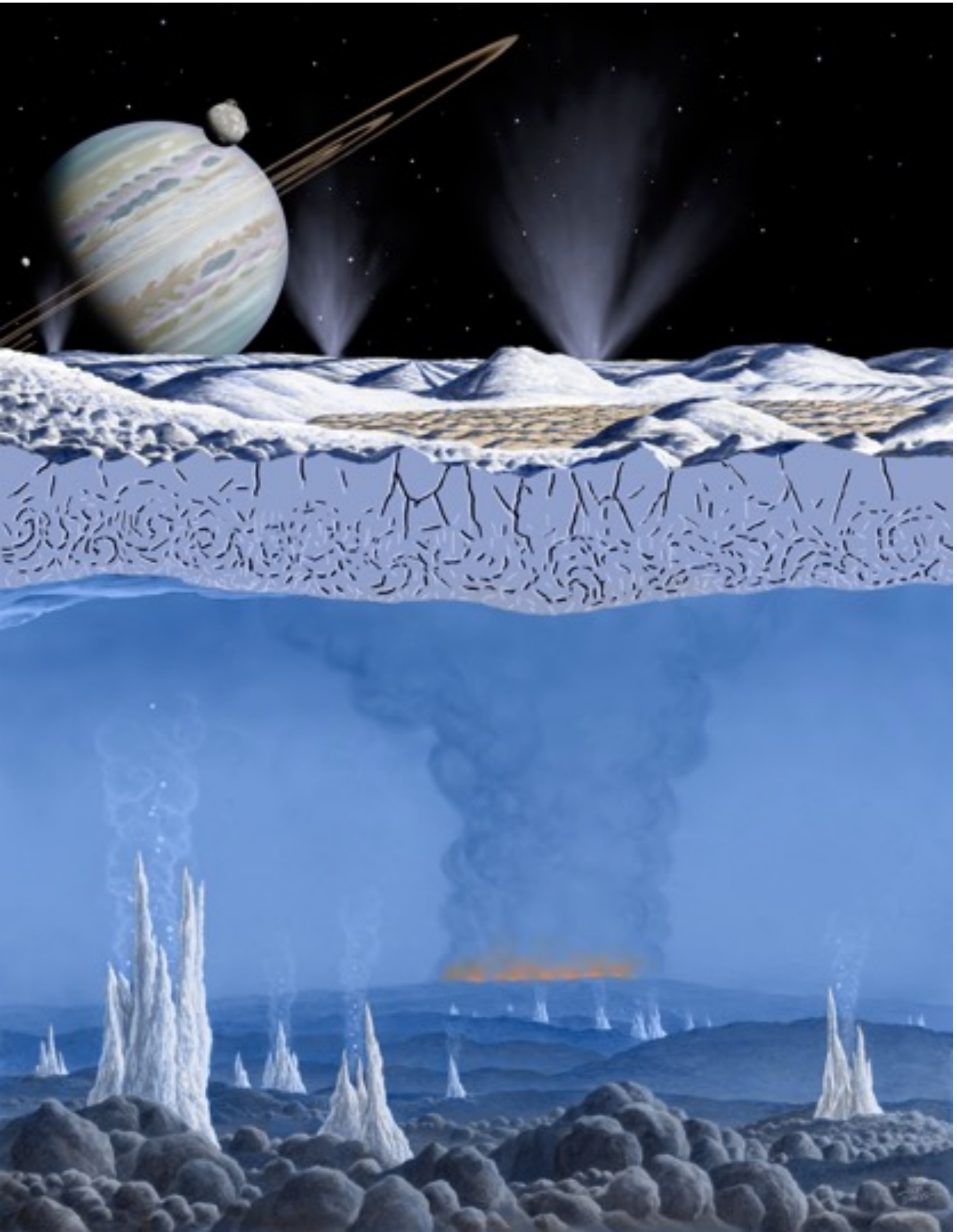


Don Davis

Geophysical Tests for Habitability in Icy Ocean Worlds

Steve Vance

5/23/17

Confidential manuscript submitted to *JGR Planets*

Geophysical tests for habitability in ice-covered ocean worlds

Steven D. Vance[1], Mark P. Panning[1*], Simon Stähler [2†] Fabio Cammarano[3], Bruce G. Bills[1], Sharon Kedar[1], Christophe Sotin[1], William T. Pike[4], Ralph Lorenz[5], Victor Tsai[6], Hsin-Hua Huang[6,7], Jennifer M. Jackson[6], Bruce Banerdt [1]

Vance et al., *in submitted*.

Icy and Exo Ocean Worlds

Advances in computational capabilities enable **new equations of state** based on experiments

Requiring self-consistent thermodynamics and accounting for ocean salinity affects **how extraterrestrial oceans work**:

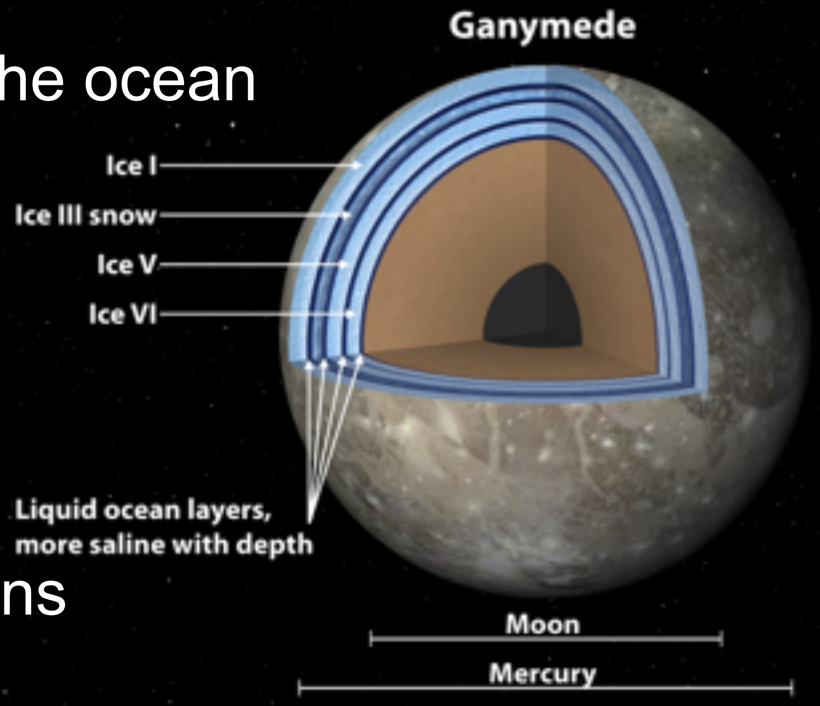
-alters **temperature structure** of the ocean

-reduces **presence of ices**

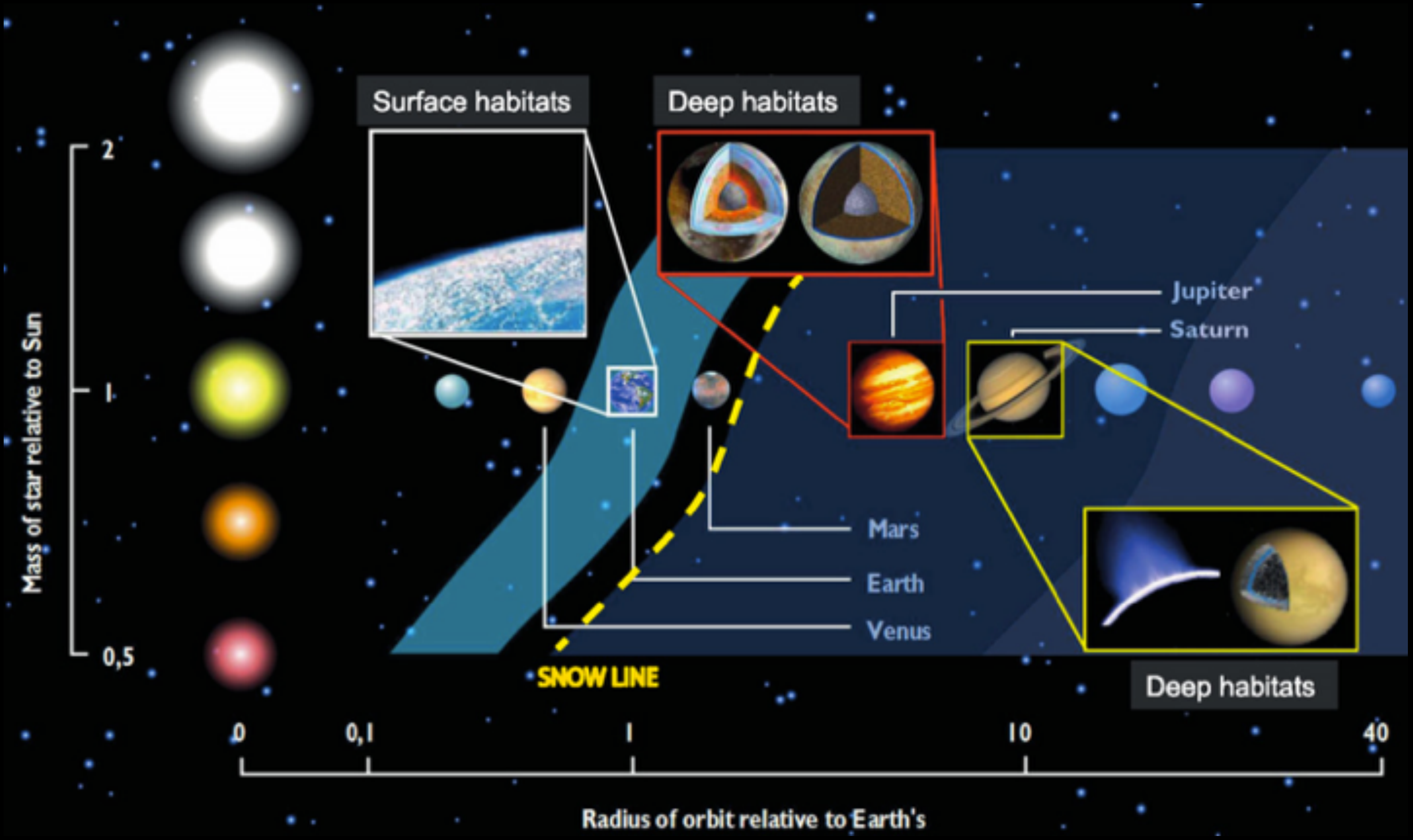
-lead to layered oceans-ices

—> when does ice float or sink?

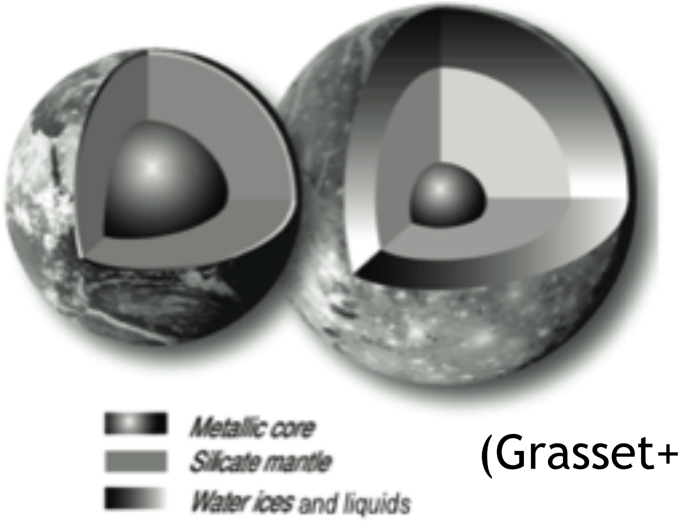
—> how might water-rock reactions create food for life



Icy worlds expand the "habitable zone".



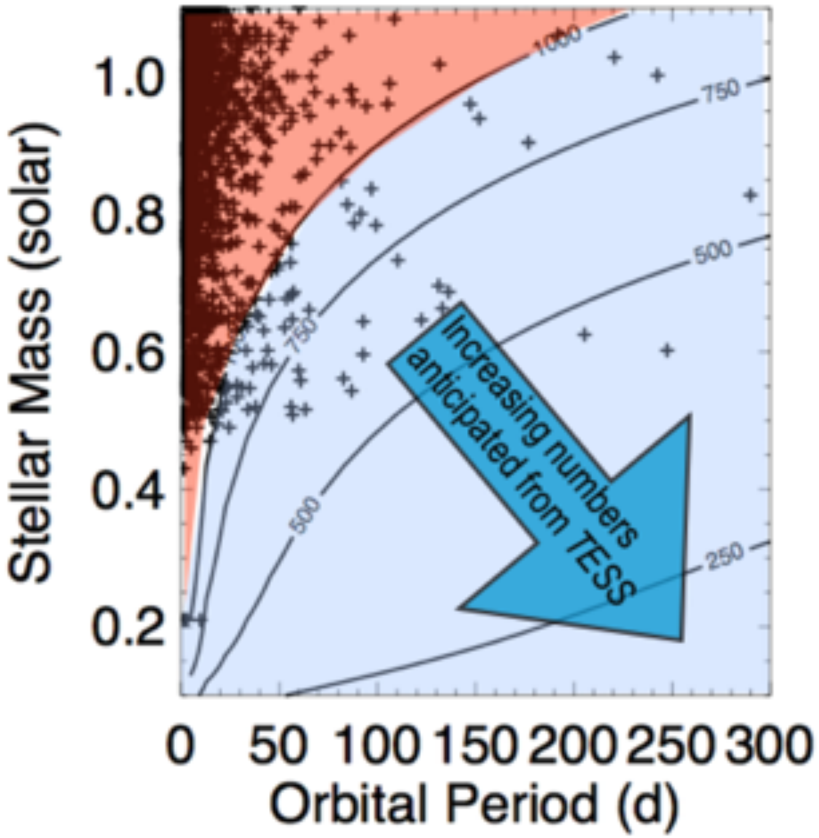
Super-Ganymedes
Super-Earths
Super-Europas?



(Grasset+ 2009)

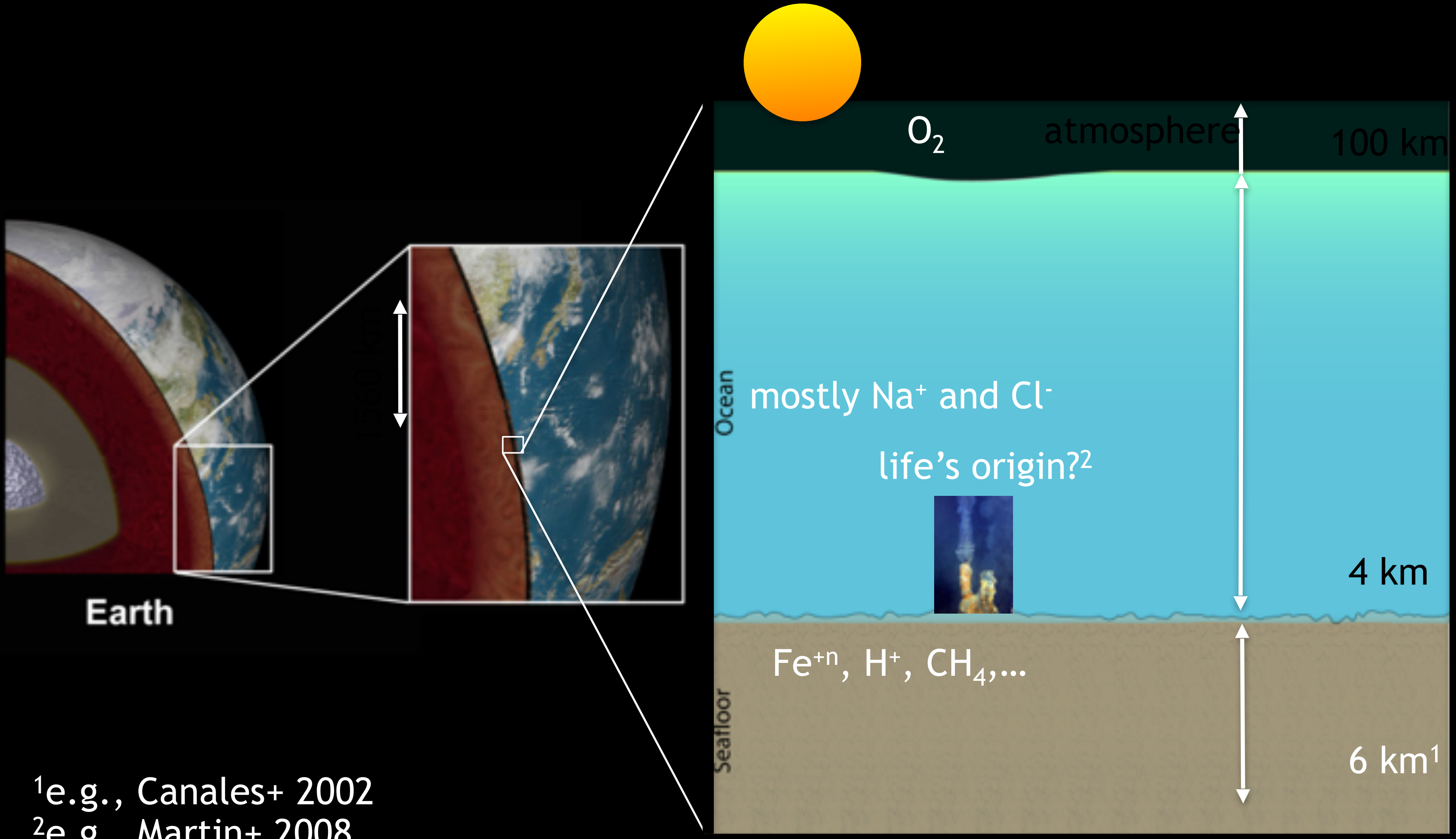
Kepler planets $R<2.5R_{Earth}$

contours: $T_{surface}$ (K)



TESS: Transiting Exoplanet Survey Satellite
(Ricker+2014)

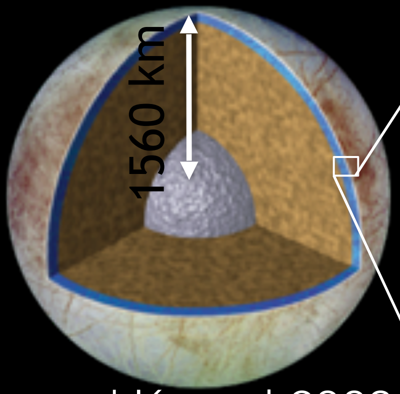
How do extraterrestrial oceans compare with Earth’s?

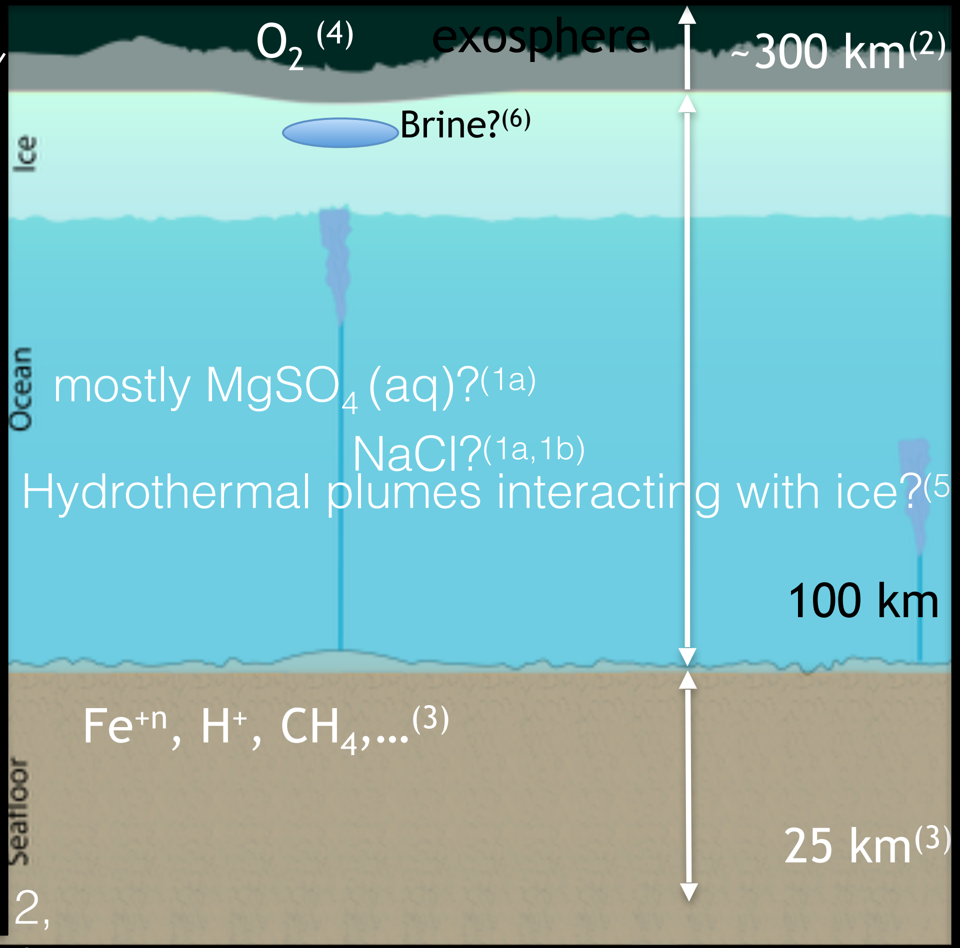


[1]e.g., Canales+ 2002
[2]e.g., Martin+ 2008

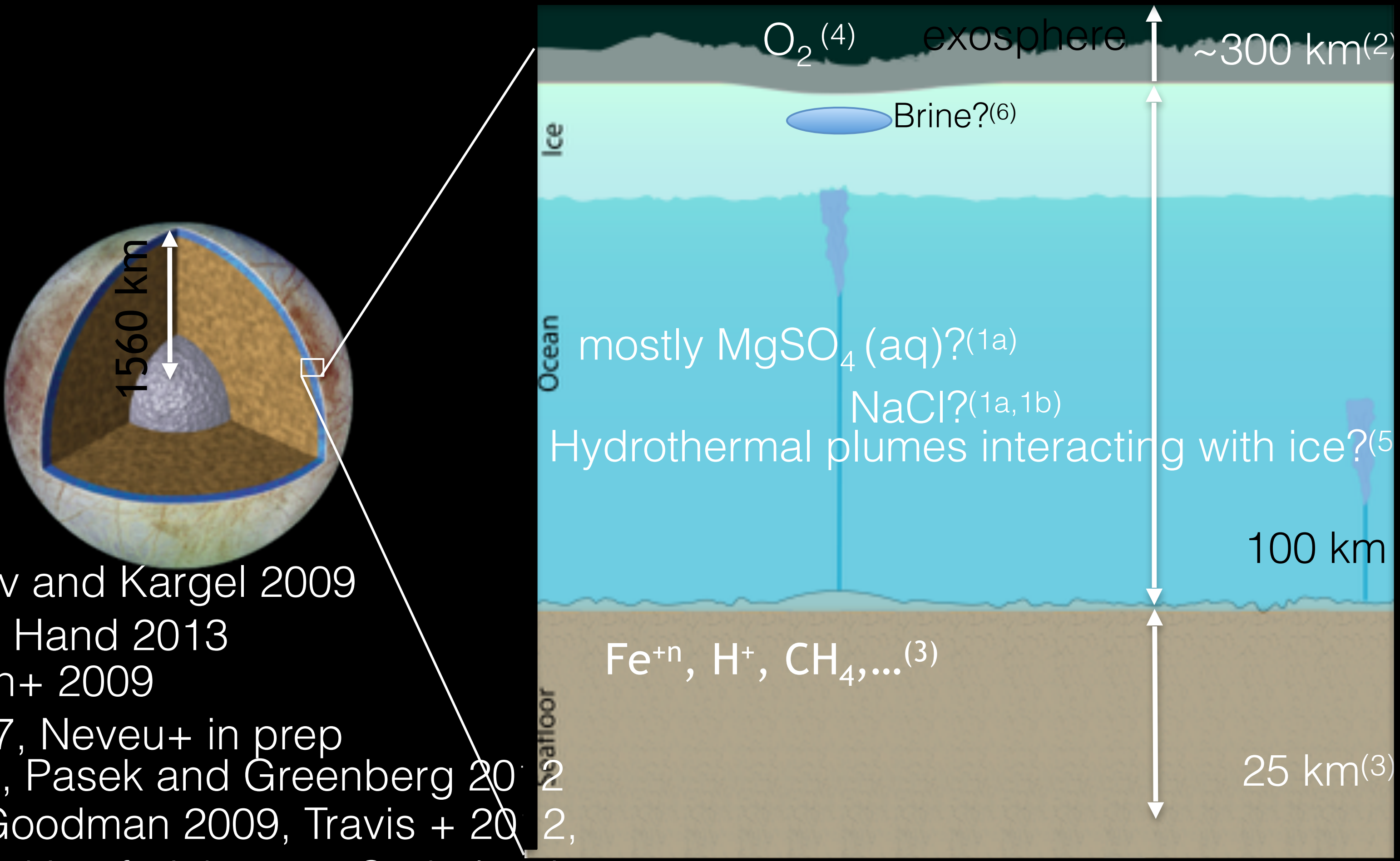
Enceladus

Europa



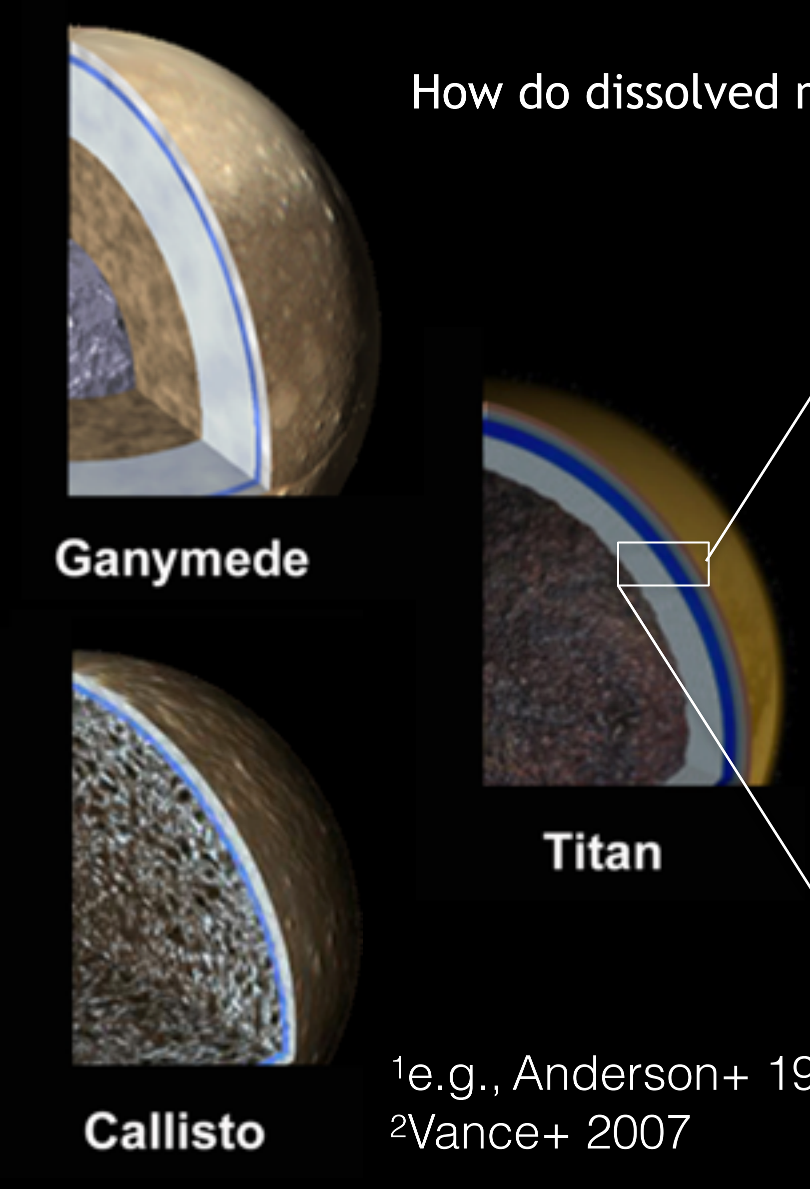


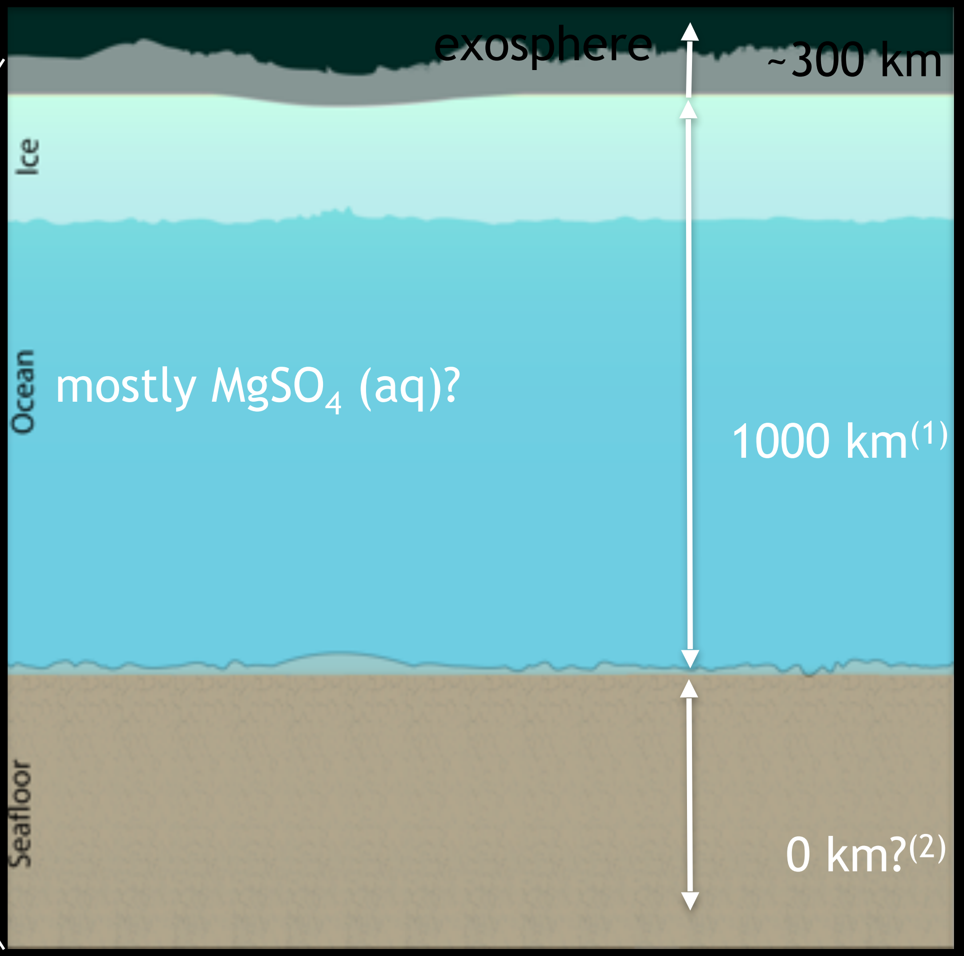
[1a]e.g., Zolotov and Kargel 2009
[1b] Brown and Hand 2013
[2]e.g., Johnson+ 2009
[3]Vance+ 2007, Neveu+ *in prep*
[4]Hand+ 2009, Pasek and Greenberg 2012
[5]Vance and Goodman 2009, Travis + 20 2, Goodman and Lenferink 2012, Soderlund+ 2014
[6]Schmidt+ 2011



[1a]e.g., Zolotov and Kargel 2009
[1b] Brown and Hand 2013
[2]e.g., Johnson+ 2009
[3]Vance+ 2007, Neveu+ in prep
[4]Hand+ 2009, Pasek and Greenberg 2012
[5]Vance and Goodman 2009, Travis + 2012, Goodman and Lenferink 2012, Soderlund+ 2014
[6]Schmidt+ 2011

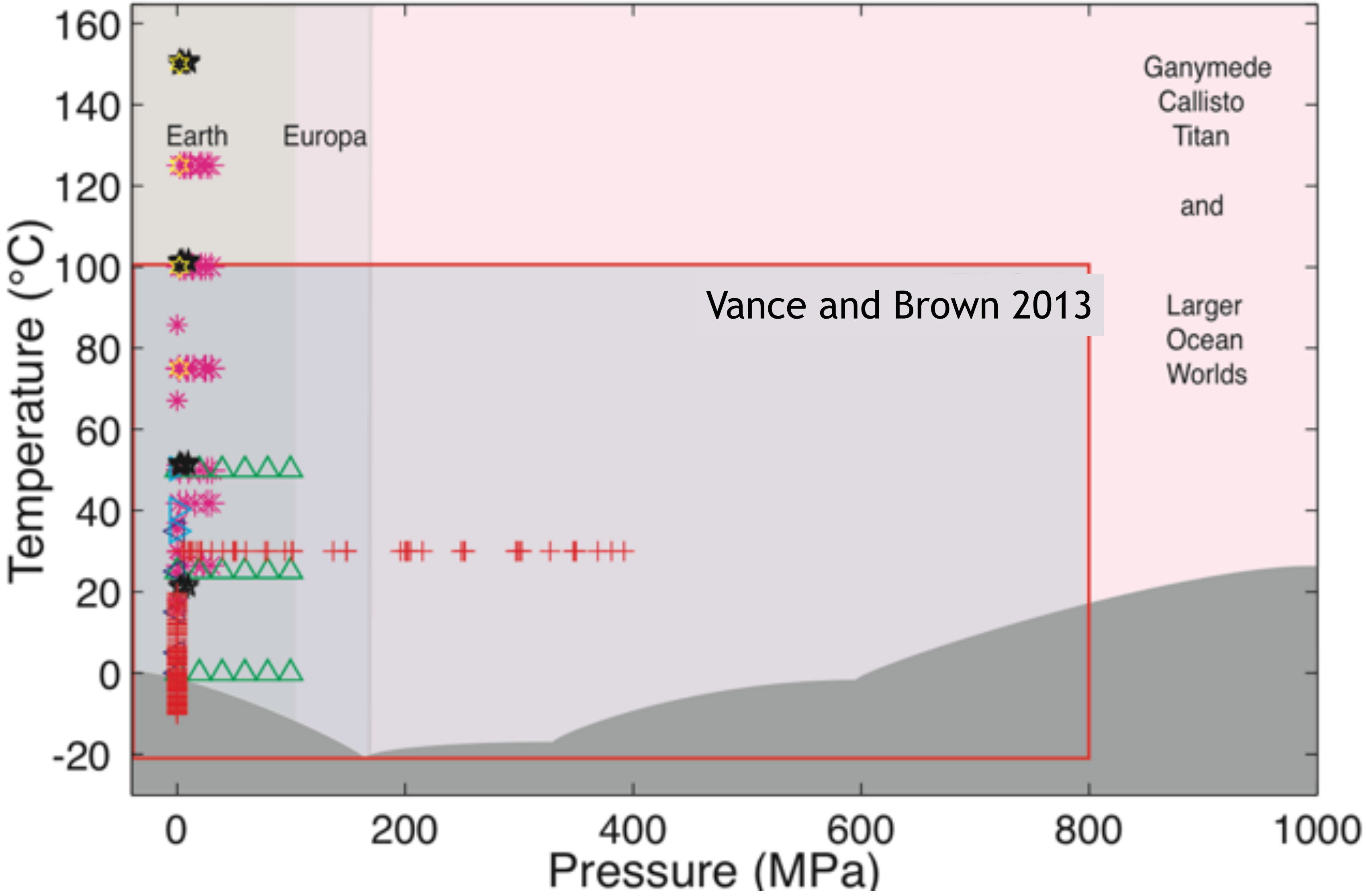
How do dissolved materials affect ocean structure and habitability?

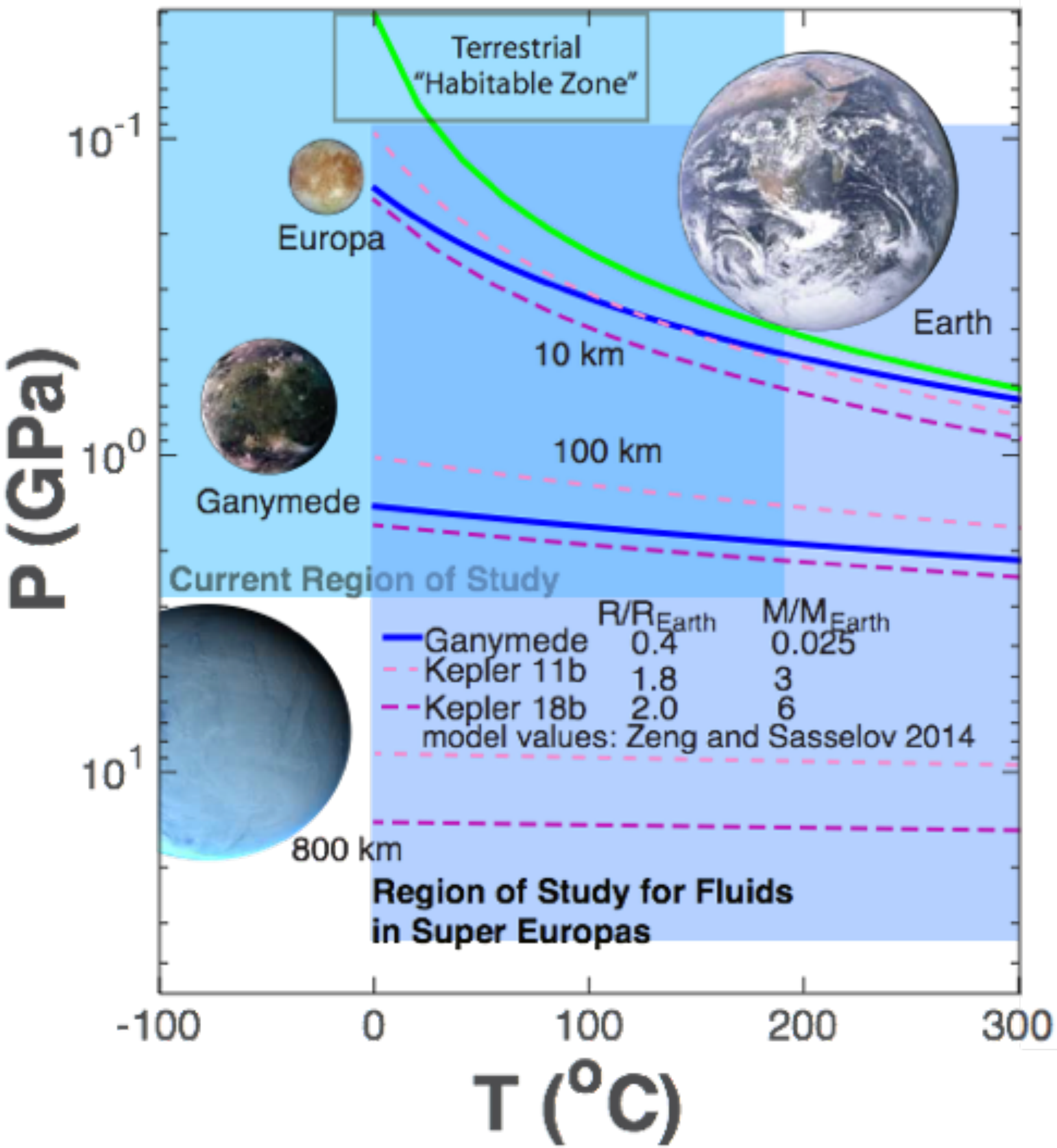




[1]e.g., Anderson+ 1996
[2]Vance+ 2007

Knowledge of $MgSO_4$(aq) fluid properties

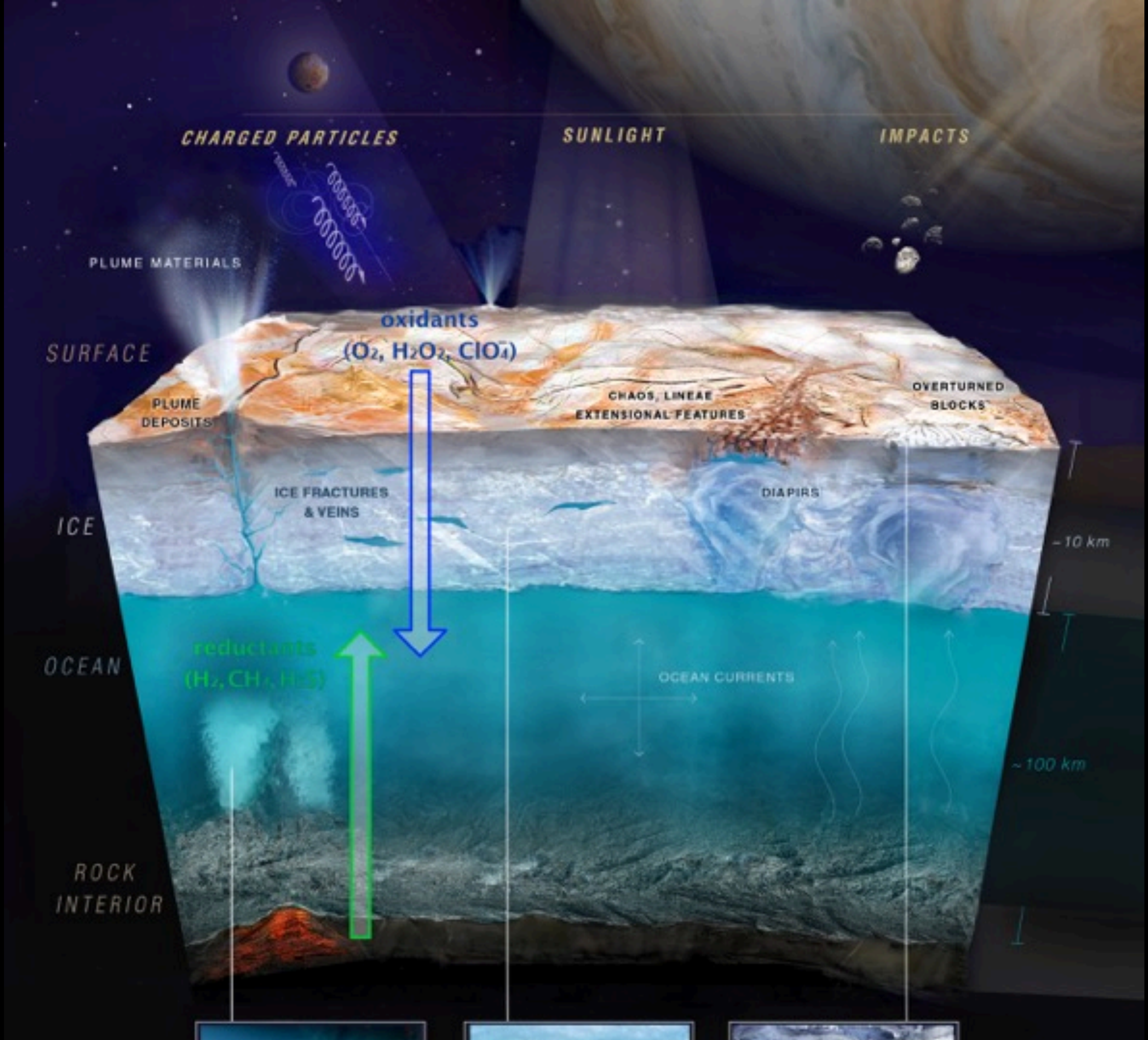




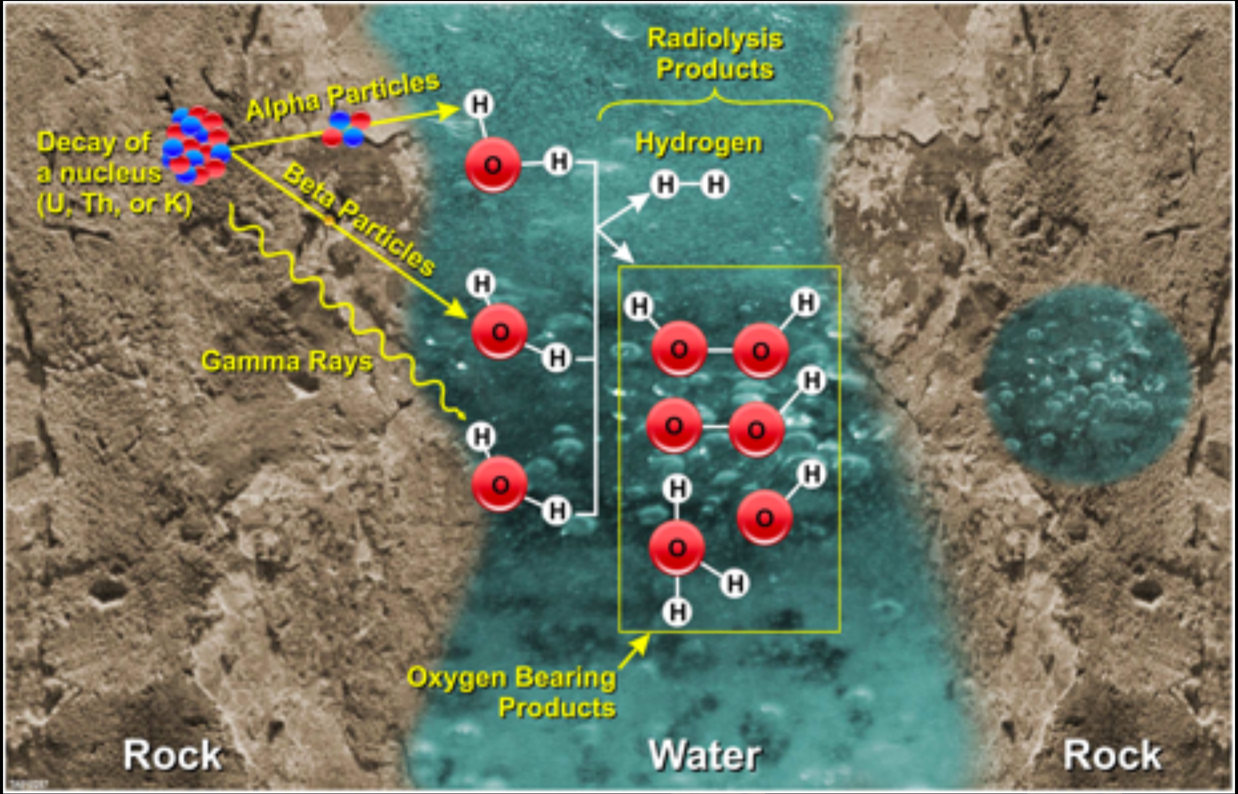
Terrestrial
"Habitable Zone"
Europa
Earth
Ganymede
10 km
100 km
800 km
Current Region of Study
R/R$_{Earth}$
M/M$_{Earth}$
Ganymede 0.4 0.025
Kepler 11b 1.8 3
Kepler 18b 2.0 6
model values: Zeng and Sasselov 2014
Region of Study for Fluids
in Super Europas
P (GPa)
10^{-1}
10^{0}
10^{1}
T (^{o}C)
-100
0
100
200
300

How can we use geophysical measurements to test habitability?

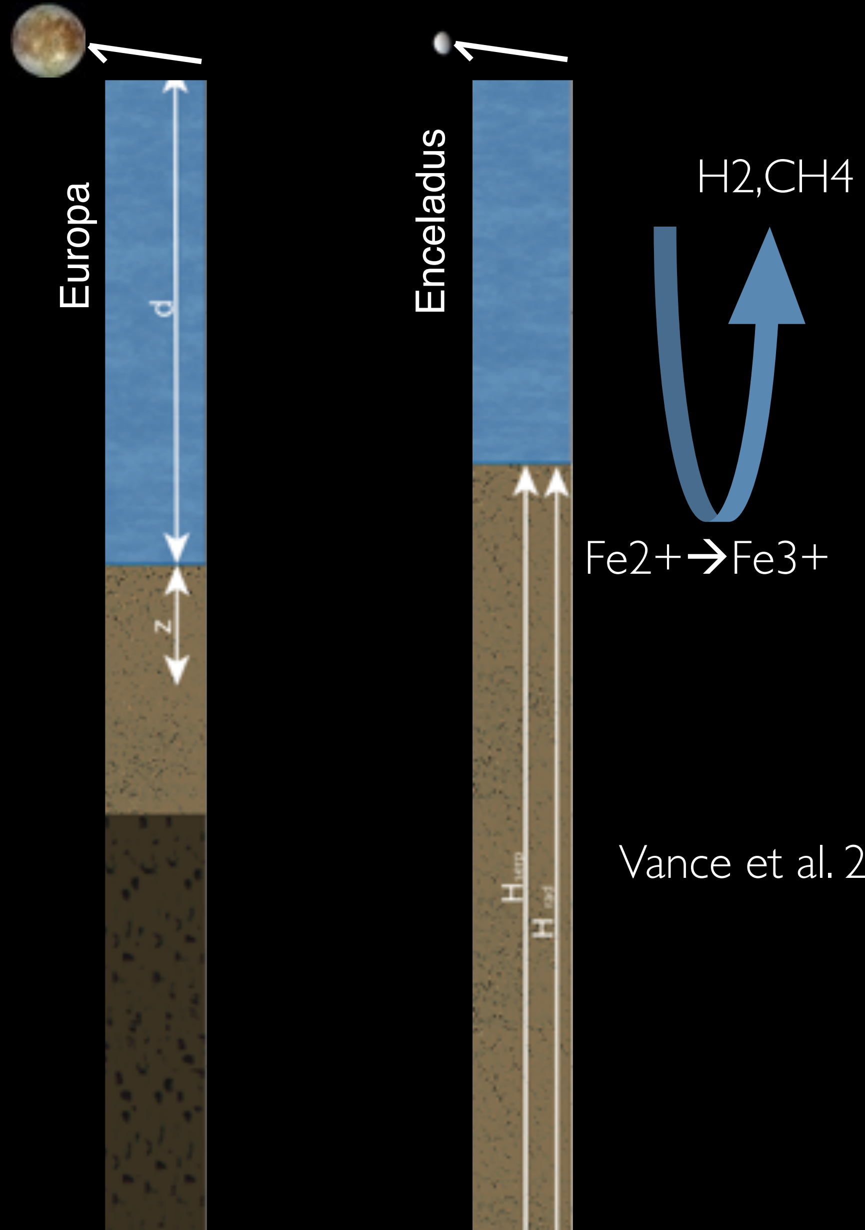
Europa



Modified from the 2016 Lander SDT Report



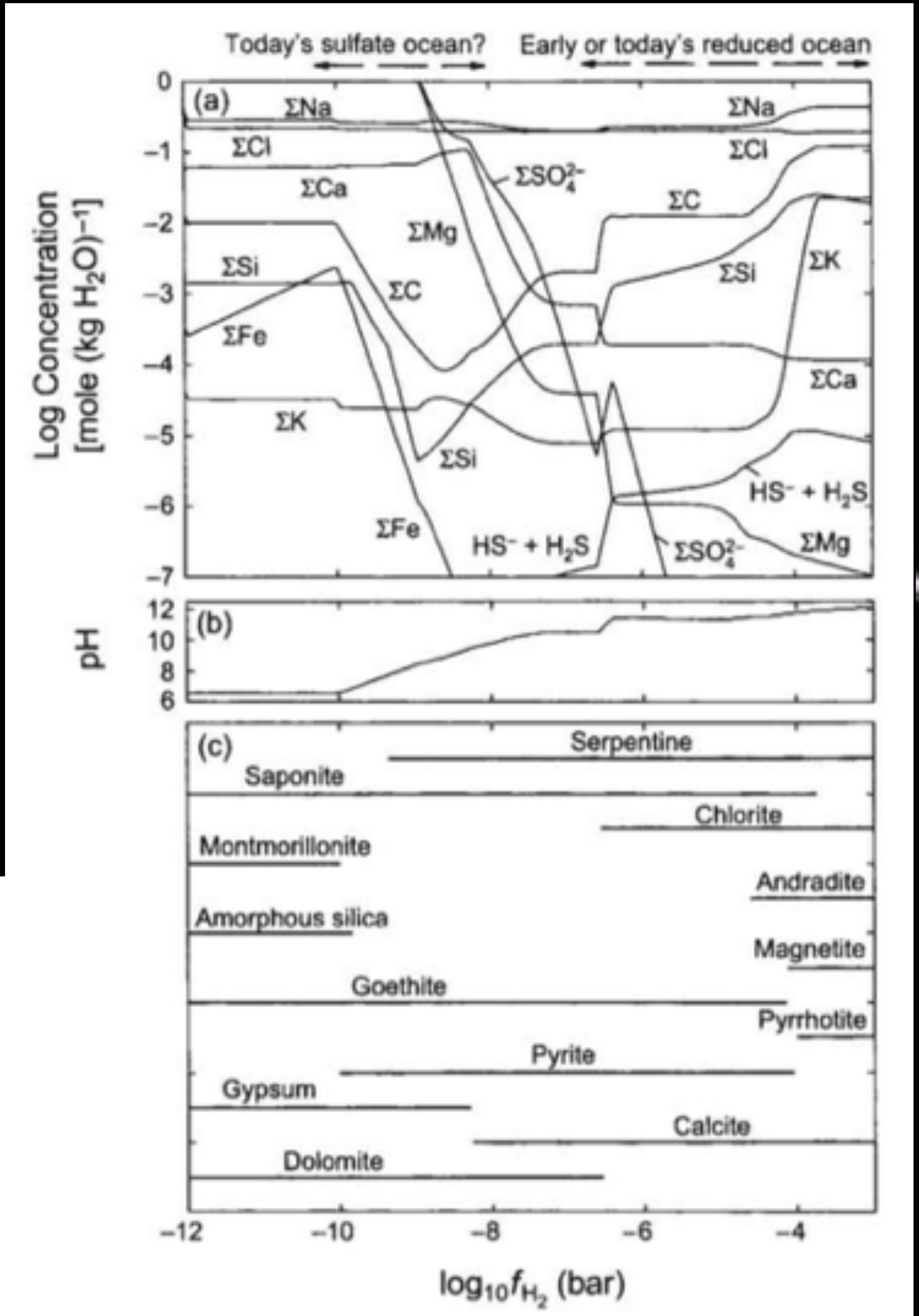
Bouquet et al. 2017



Vance et al. 2007, 2016

$MgSO_4$

?

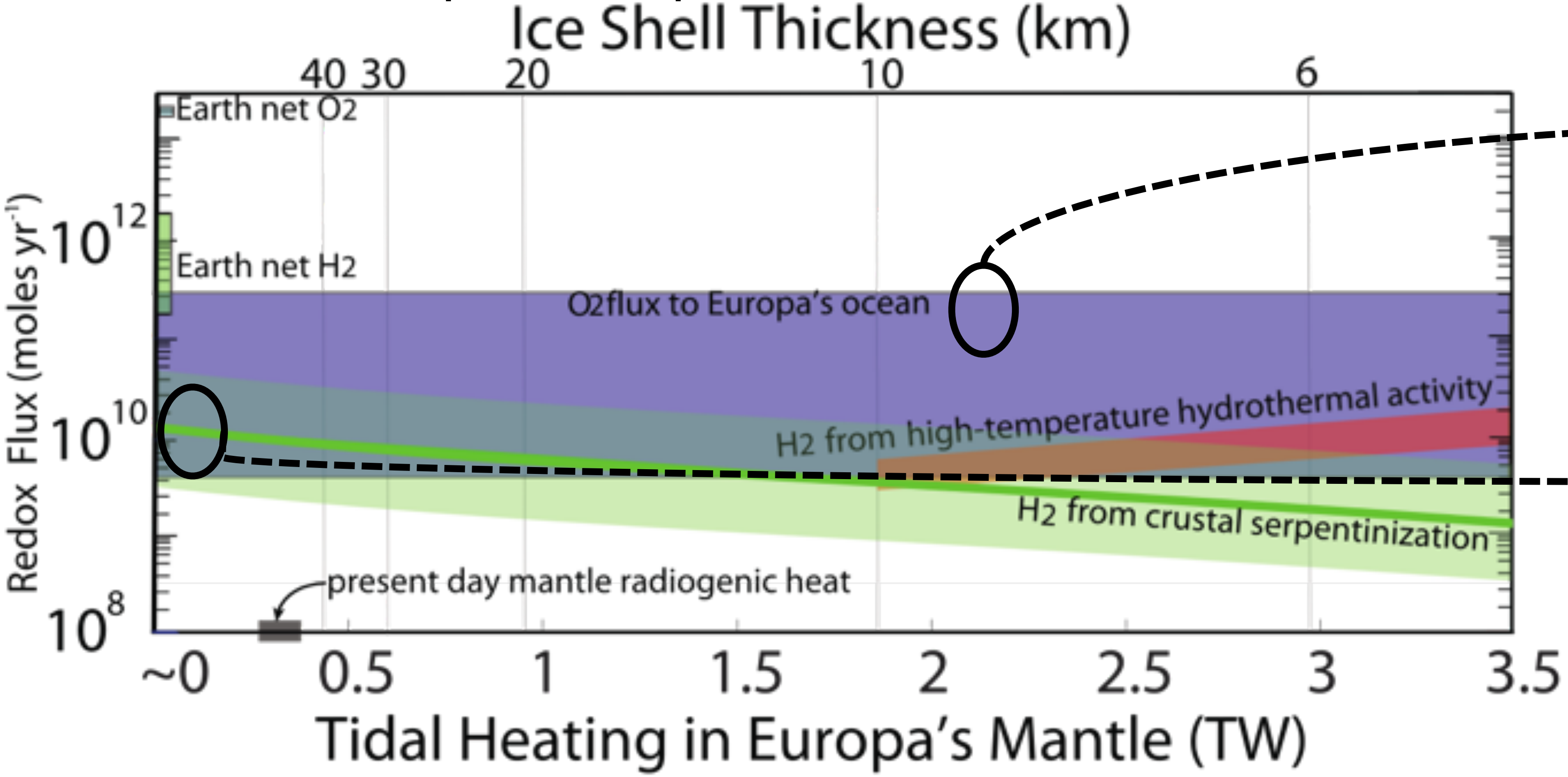


NaCl

Zolotov and Kargel 2009

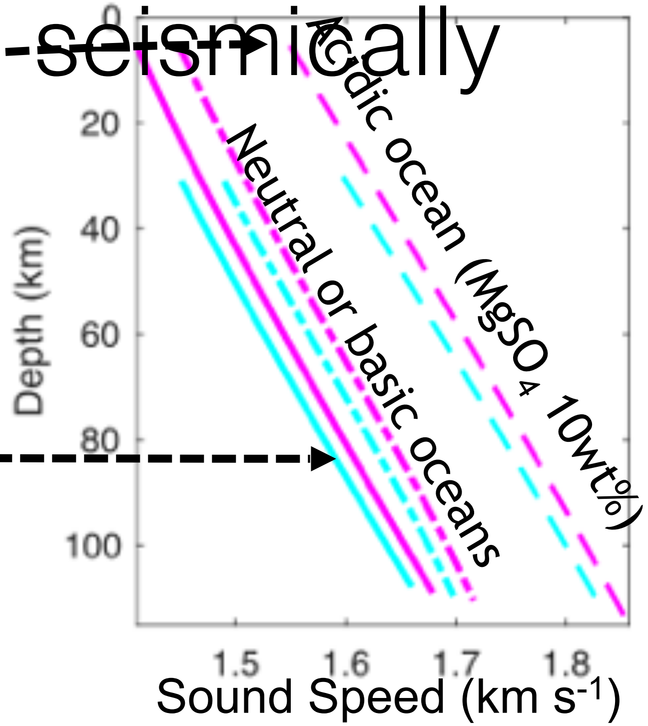
Seismological Constraints on Habitability

Ocean pH dependent on redox fluxes



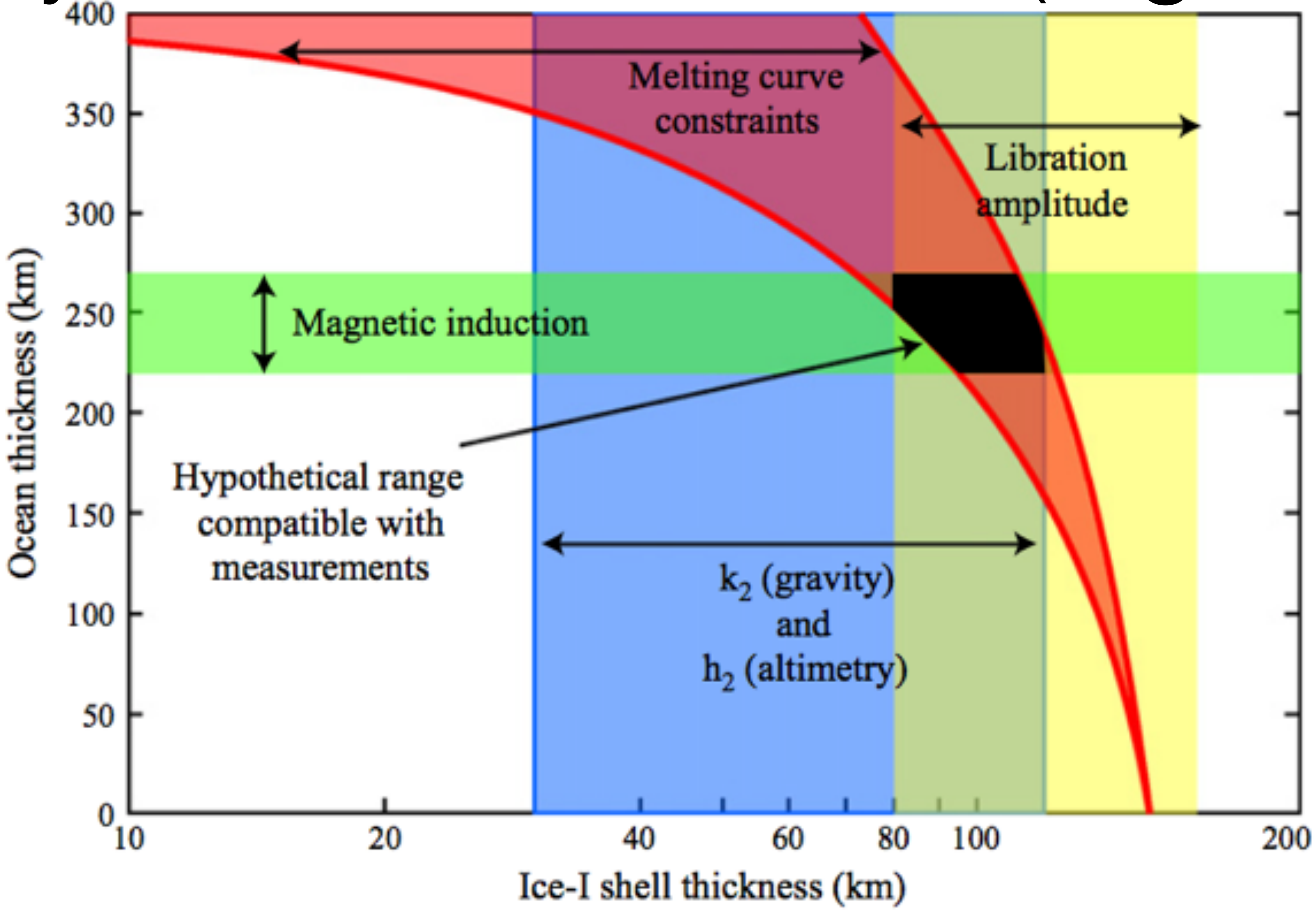
Vance et al. 2016

High vs low pH differ seismically



Vance et al. *submitted*

Geophysical measurements (e.g. at Ganymed



Grasset et al. 2013, JUpiter ICy moons Explorer

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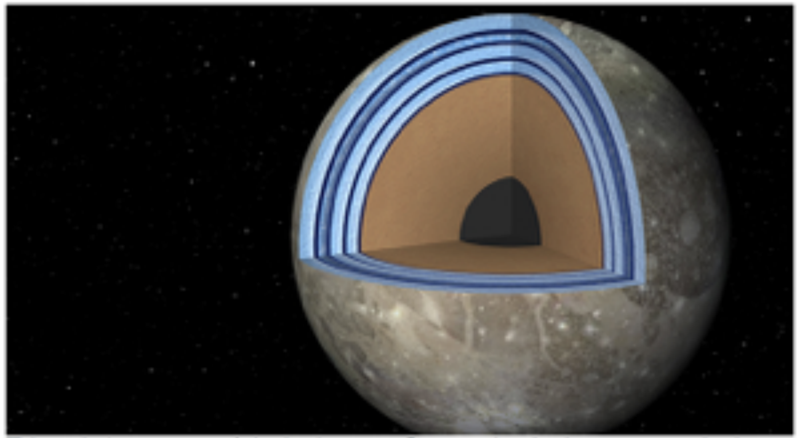
Ganymede May Harbor 'Club Sandwich' of Oceans and Ice



This artist's concept of Jupiter's moon Ganymede, the largest moon in the solar system, illustrates the "club sandwich" model of its interior oceans.
Image credit: NASA/JPL-Caltech
› Full image and caption

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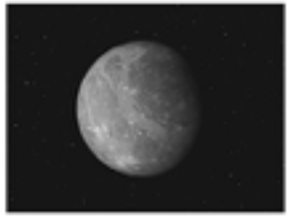
May 01, 2014

The largest moon in our solar system, a companion to Jupiter named Ganymede, might have ice and oceans stacked up in several layers like a club sandwich, according to new NASA-funded research that models the moon's makeup.

Previously, the moon was thought to harbor a thick ocean sandwiched between just two layers of ice, one on top and one on bottom.

"Ganymede's ocean might be organized like a Dagwood sandwich," said Steve Vance of NASA's Jet Propulsion Laboratory in Pasadena, Calif., explaining the moon's resemblance to the "Blondie" cartoon character's multi-tiered sandwiches. The study, led by Vance, provides new theoretical evidence for the team's "club sandwich" model, first proposed last year. The research appears in the journal Planetary and Space Science.

Animation



Jupiter's 'Club Sandwich' Moon

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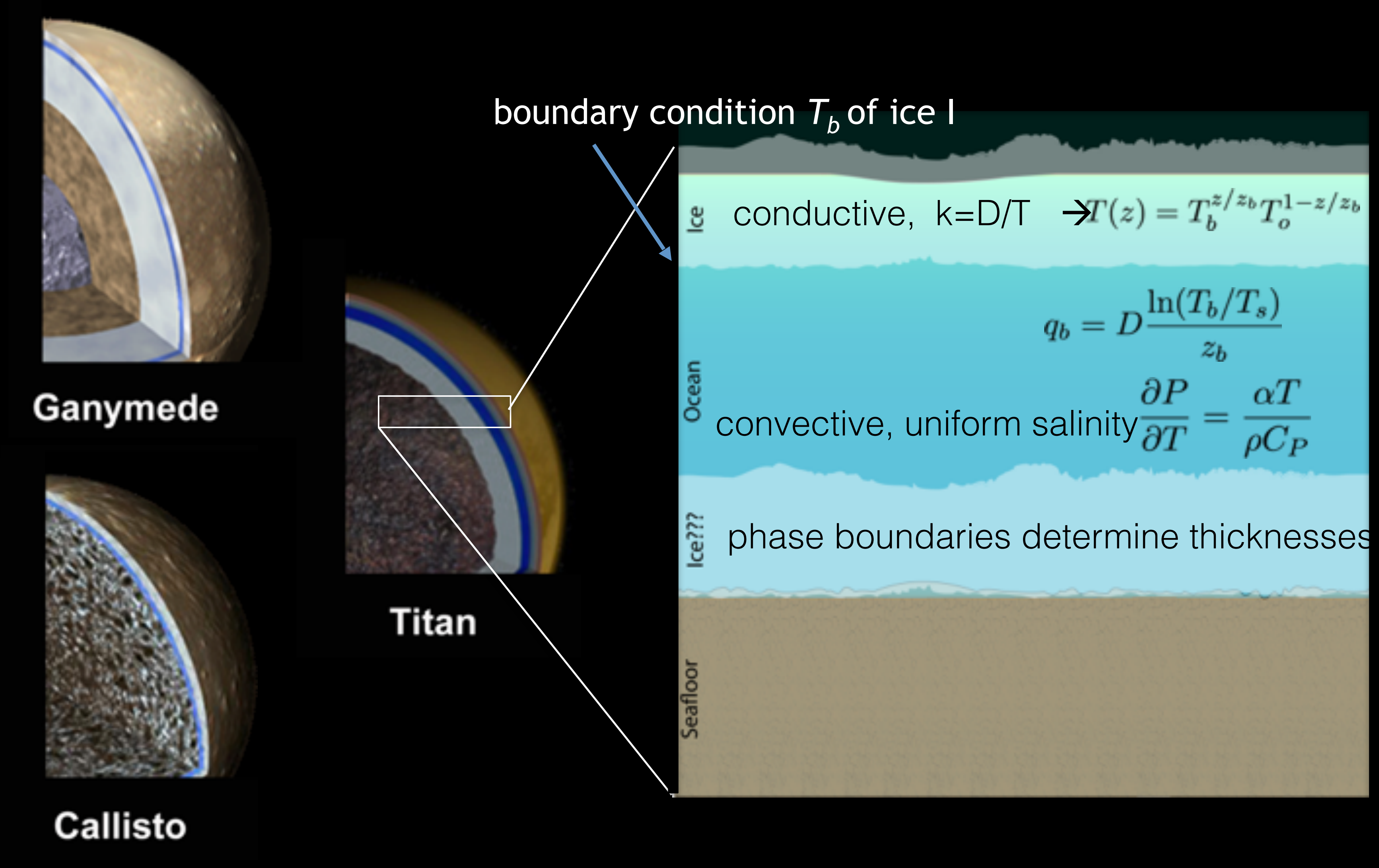
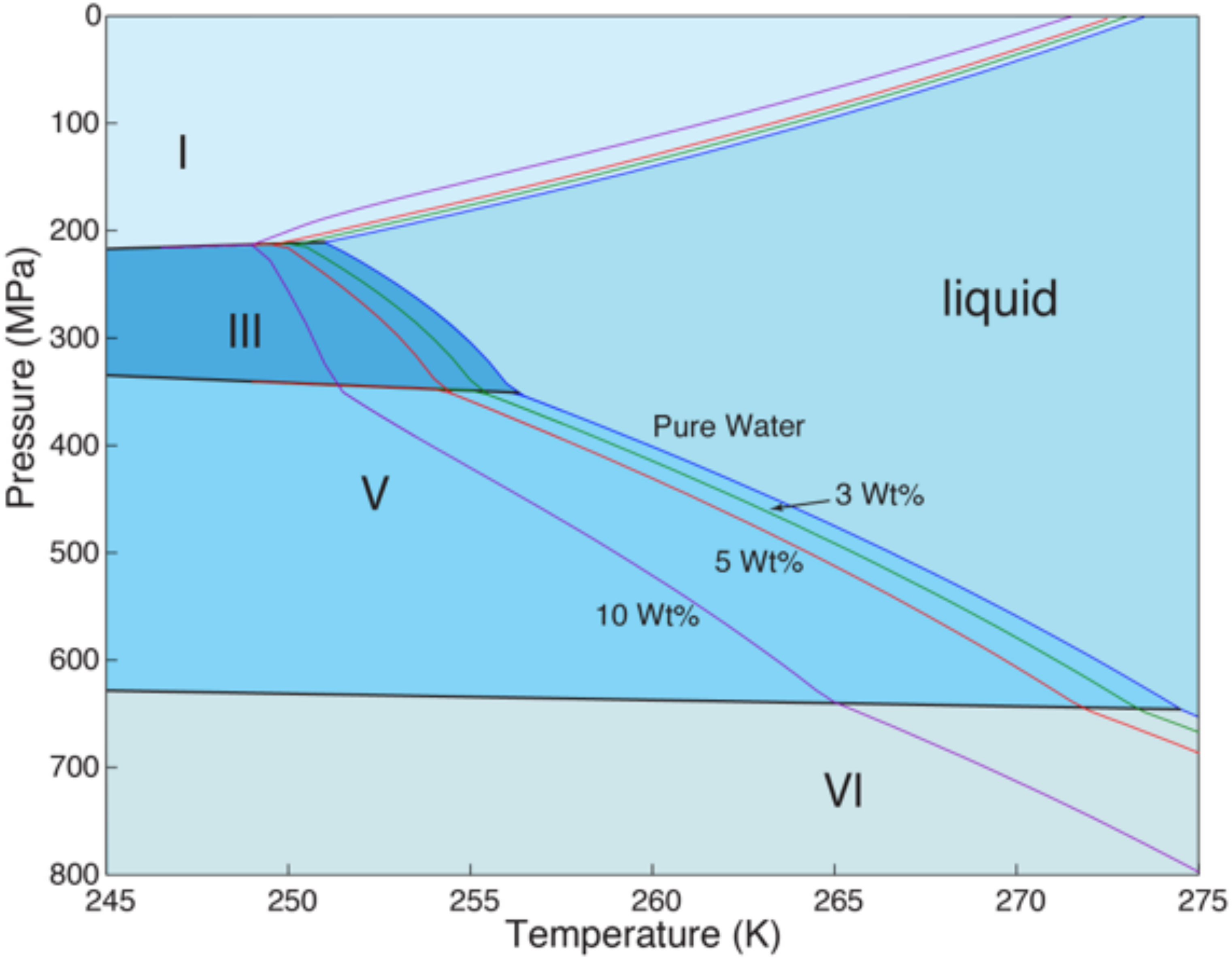
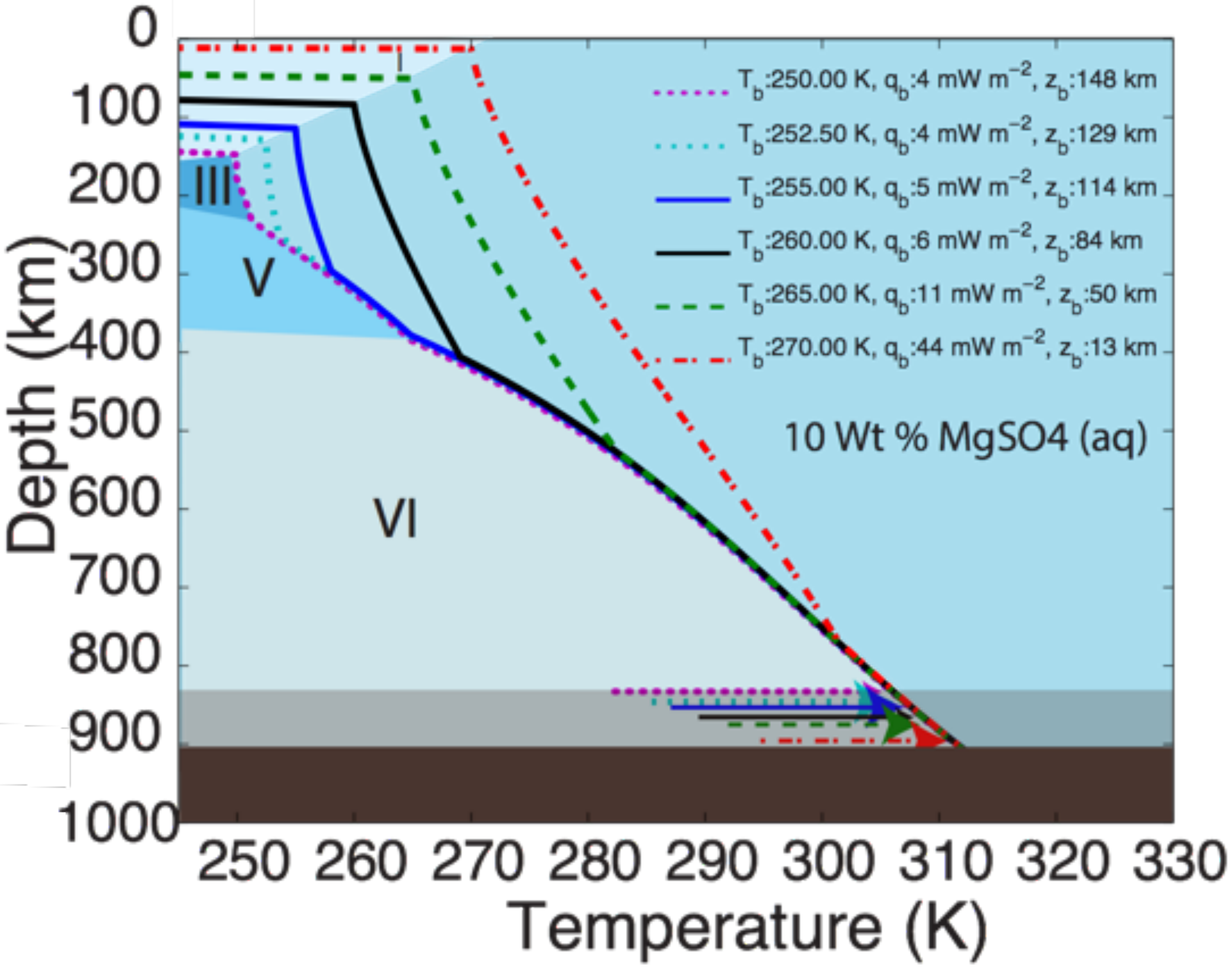


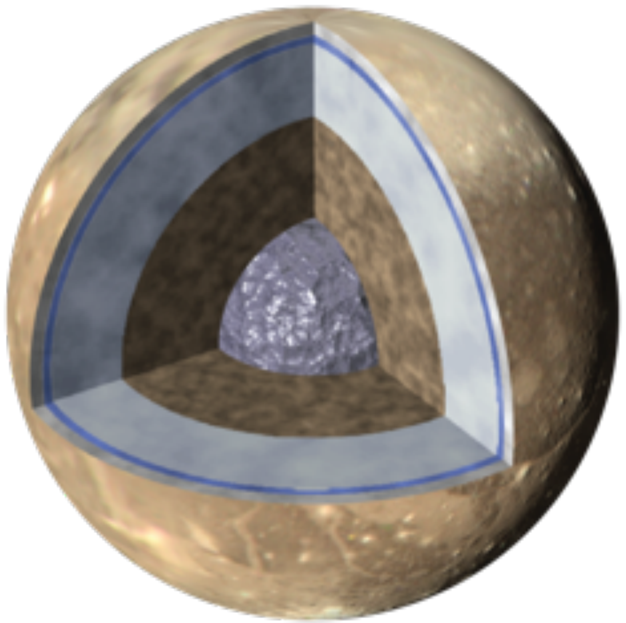
Ganymede
Callisto
Titan
boundary condition T_b of ice I
Ice
conductive, k=D/T → $T(z) = T_b^{z/z_b} T_o^{1-z/z_b}$
Ocean
$q_b = D \frac{\ln(T_b/T_s)}{z_b}$
convective, uniform salinity $\frac{\partial P}{\partial T} = \frac{\alpha T}{\rho C_P}$
Ice???
phase boundaries determine thicknesses
Seafloor

Phase diagram for aqueous magnesium sulfate ($MgSO_4$)



Vance, Bouffard, Choukroun, and Sotin, 2014, PSS

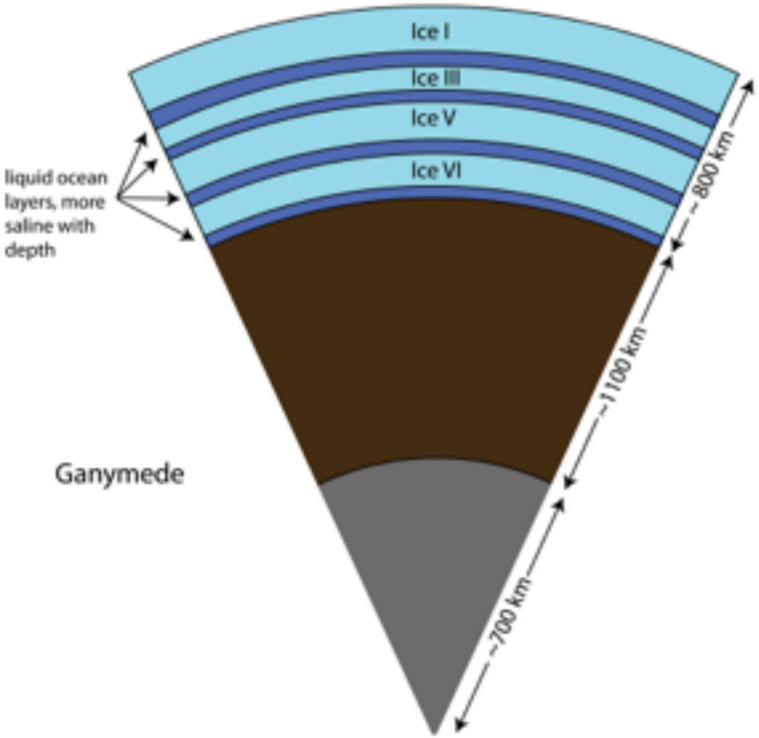




Modified from Vance, Bouffard, Choukroun, and Sotin, 2014,

Thermal model constrains Ganymede's internal structure

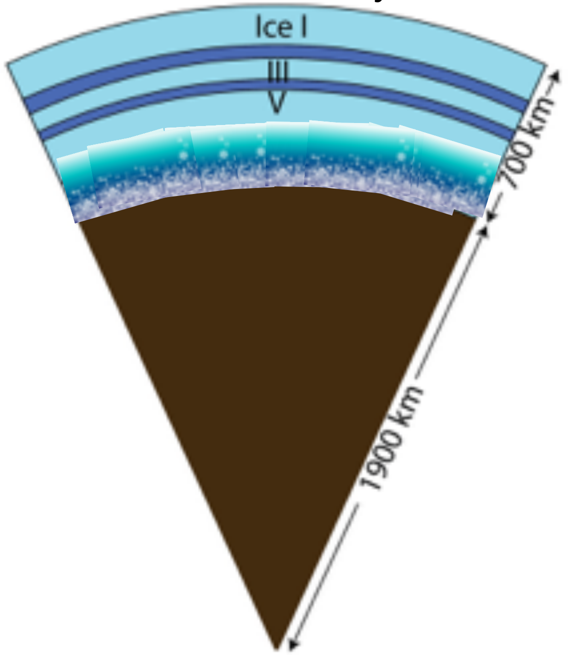
Calculate radii from Galileo constraints on Ganymede's density (1,942±4.8 kg/m3) and gravitational moment of inertia (C/MR^2 = 0.3105±0.028) Schubert+ 2004

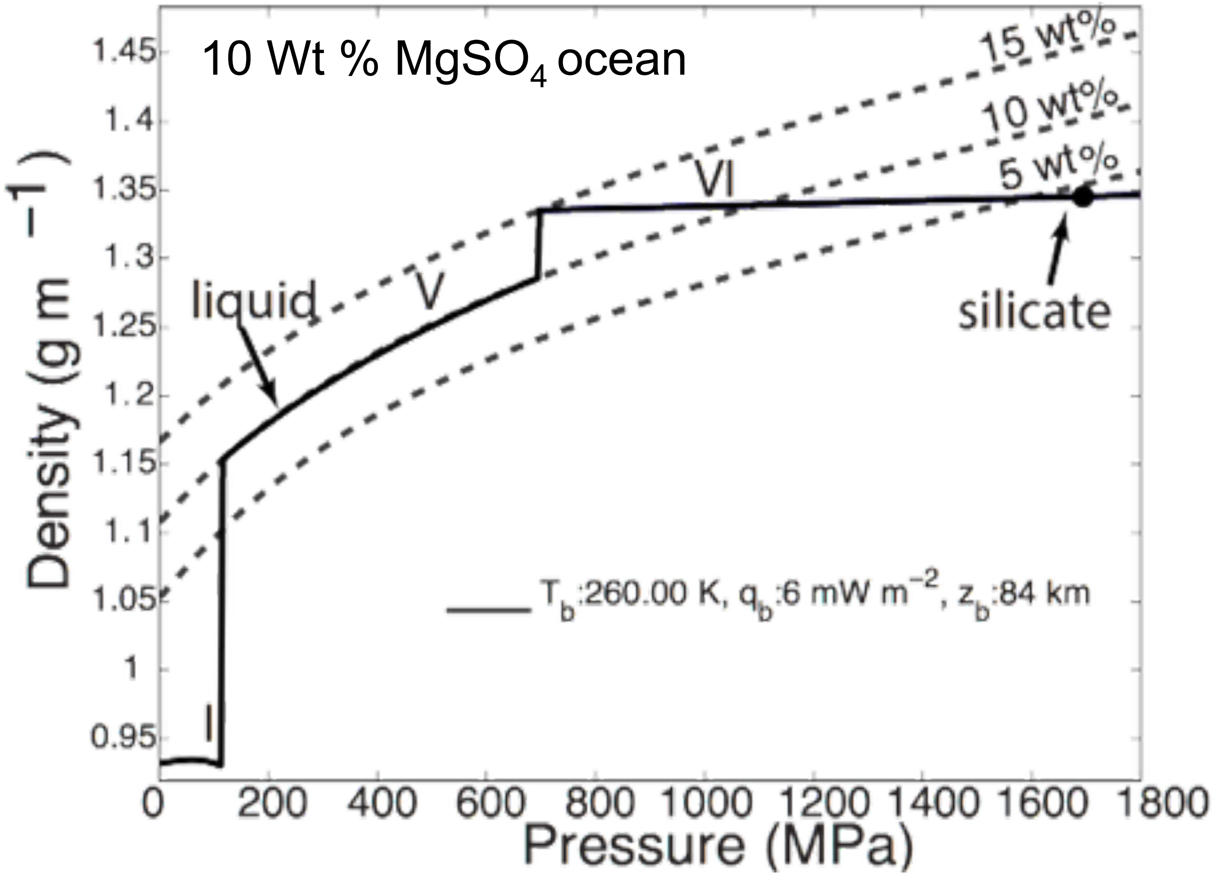


Vance, Bouffard, Choukroun, and Sotin, 2014, PSS

Thermal model constrains Ganymede's internal structure

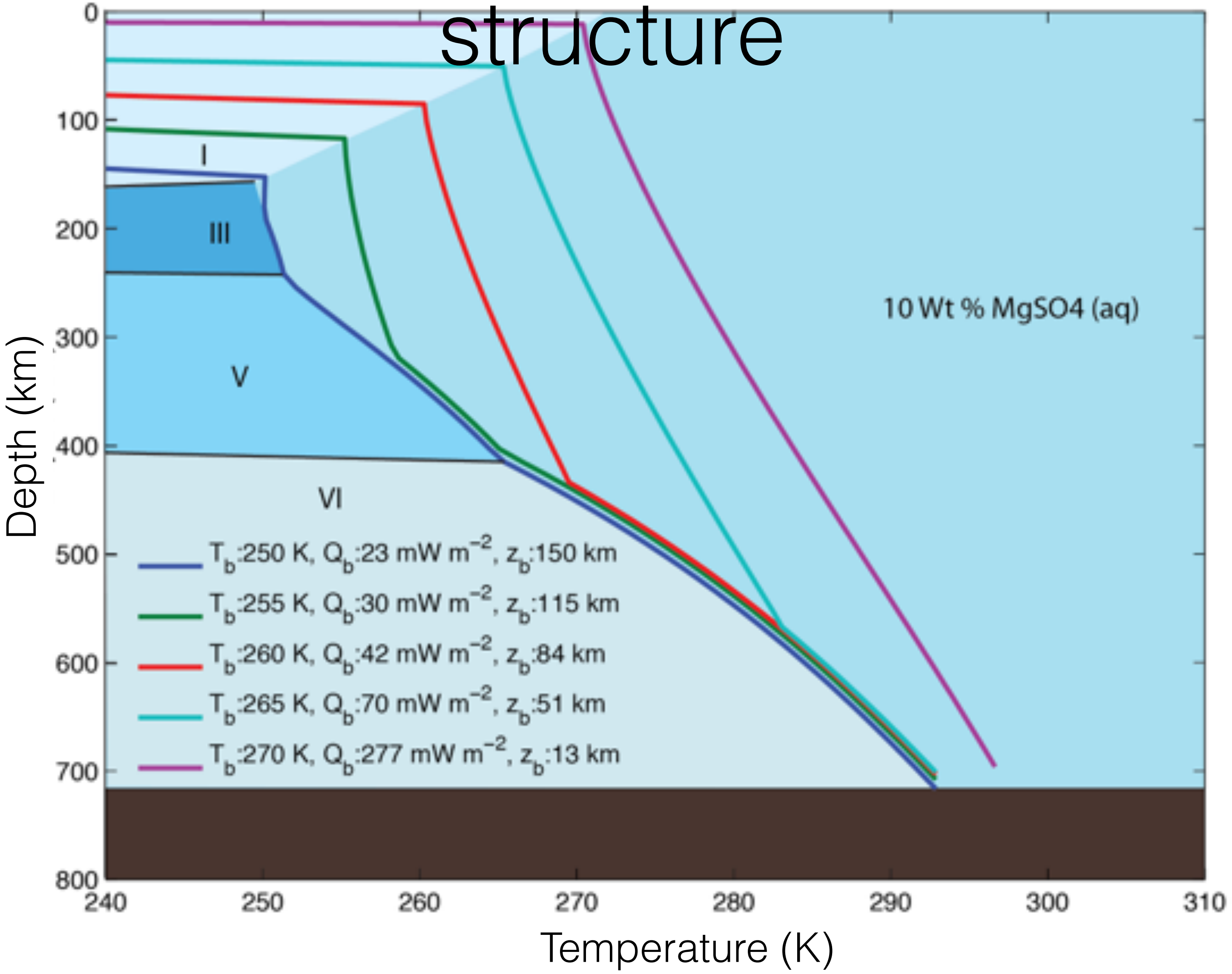
- ice I melting: T_b
- Follow melting curves in ice III, V, VI layers





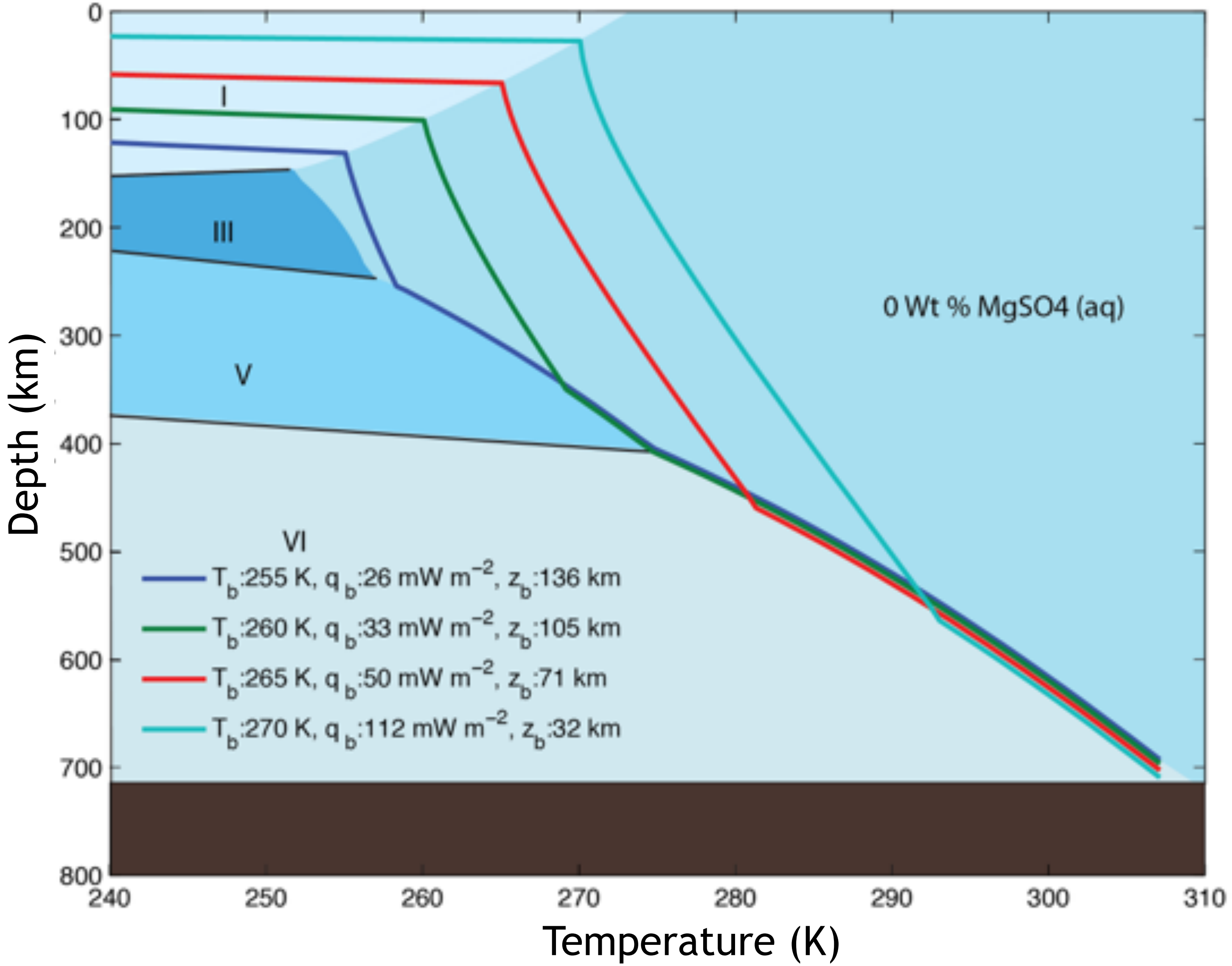
Modified from Vance, Bouffard, Choukroun, and Sotin, 2014,

Salinity determines cryosphere structure

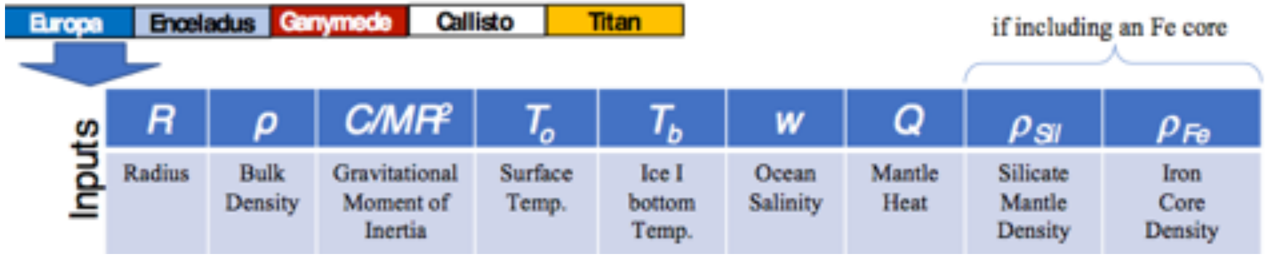


Vance, Bouffard, Choukroun, and Sotin, PSS 2014.

Salinity determines cryosphere



Vance, Bouffard, Choukroun, and Sotin, PSS 2014.



PlanetProfile

github.com/vancesteven/PlanetProfile
Vance et al. *submitted.*

	Radius (km)	Density (kg m^{-3})	Moment of Inertia
Europa	1565.0±8.0	2989±46	0.346±0.005
Ganymede	2631±1.7	1942.0±4.8	0.3115±0.0028
Callisto	2410.3±1.5	1834.4±3.4	0.3549±0.0042
Enceladus	252.1±0.2	1609±5	0.335
Titan	2574.73±0.09	1879.8±0.004	0.3438±0.0005

Schubert et al. 2004; Iess et al. 2010, 2012 phase equilibria, $\alpha, \rho, C_P, v, G_S, K_S$

Fluid

- $MgSO_4$ (aq) (Vance and Brown 2013, Vance et al. 2014)
  - 0-2 molal; 250-400 K; 0-2 GPa
- Seawater (NaCl) — Gibbs Seawater (McDougall 2011)
  - 0-2S0; 250-400 K; 0-0.1 GPa
- NH_3 (aq) (Tillner-Roth and Friend 1998, Choukroun et al. 2010)
  - 0-10 wt%; 250-400 K; 0-2 Gpa

Ice

Ice Ih, II, III, V, VI (Choukroun et al. 2010)

Margules activity model for melting can be replaced with chemical potentials for ice and water being developed by the NAI Icy Worlds team (Brown et al….)

Rock

Perple_X (Connolly et al. 2009)

using databases from Holland and Powell (2011),

Stixrude and Lithgow-Bertollini (2011)

Melting curves for (aq) $MgSO_4$

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

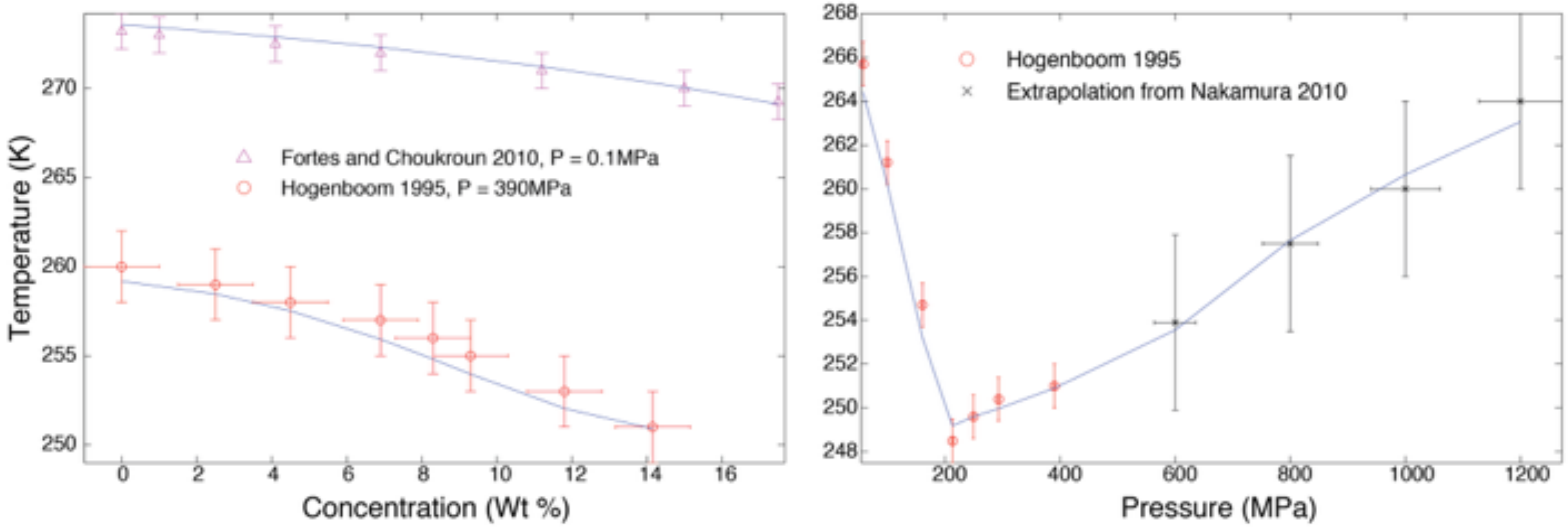
$\mu^S_{H_2O}$ from Choukroun and Grasset 2010

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

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

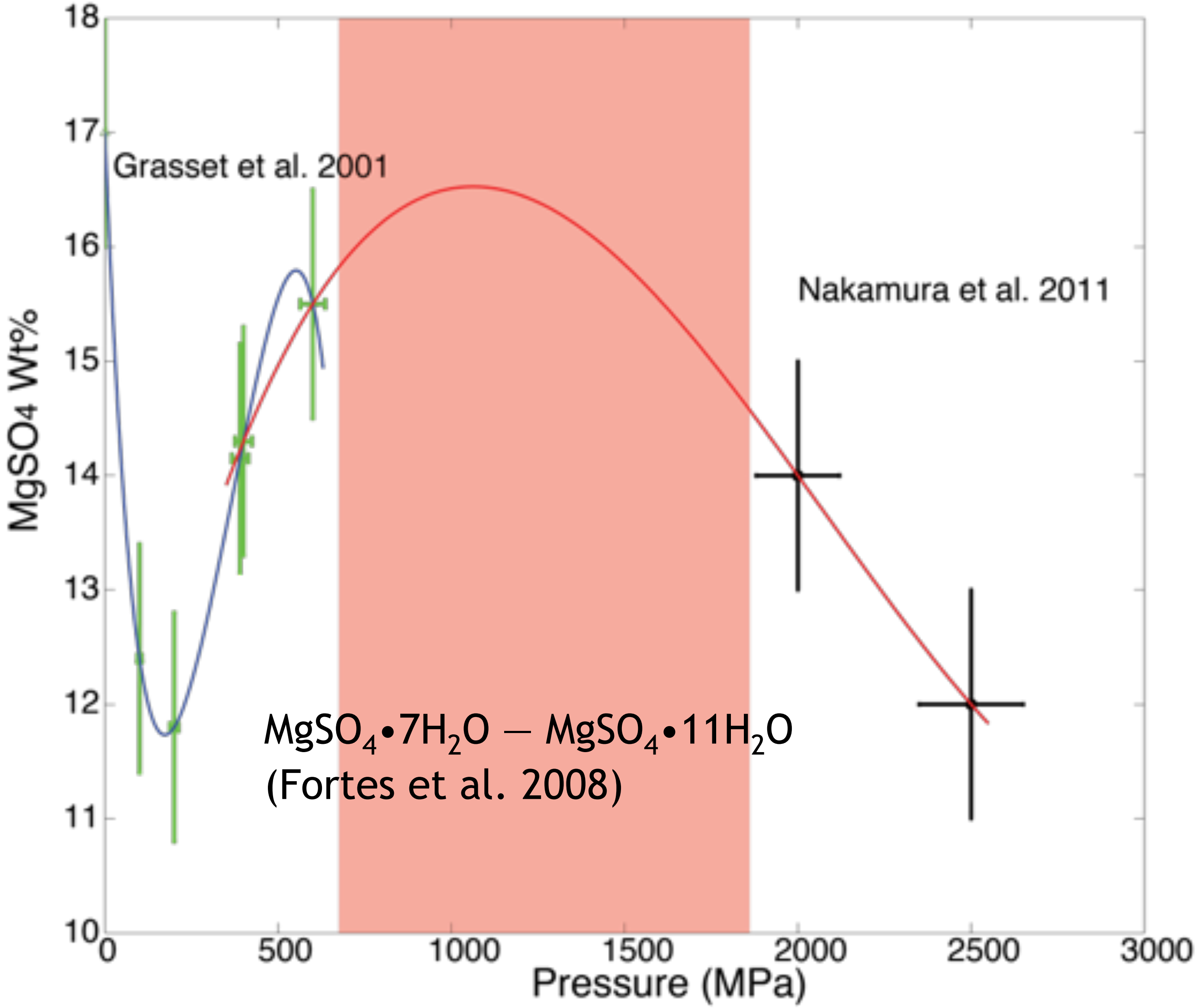
$$W = w_0\left(1 + w_1\tanh(w_2P)\right)\left(1 + \frac{w_3}{(T-T_0)^2}\right)$$

Freezing and Eutectic Data



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

Eutectic composition vs pressure



Melting curves for (aq) NH_3

- Activity model for solid-liquid stability:

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

$$W = w_0\left(1 + w_1 \tanh(w_2 P)\right)\left(1 + w_3 T + \frac{w_4}{T}\right)$$

Choukroun and Grasset 2010

Gibbs Energy Derivatives

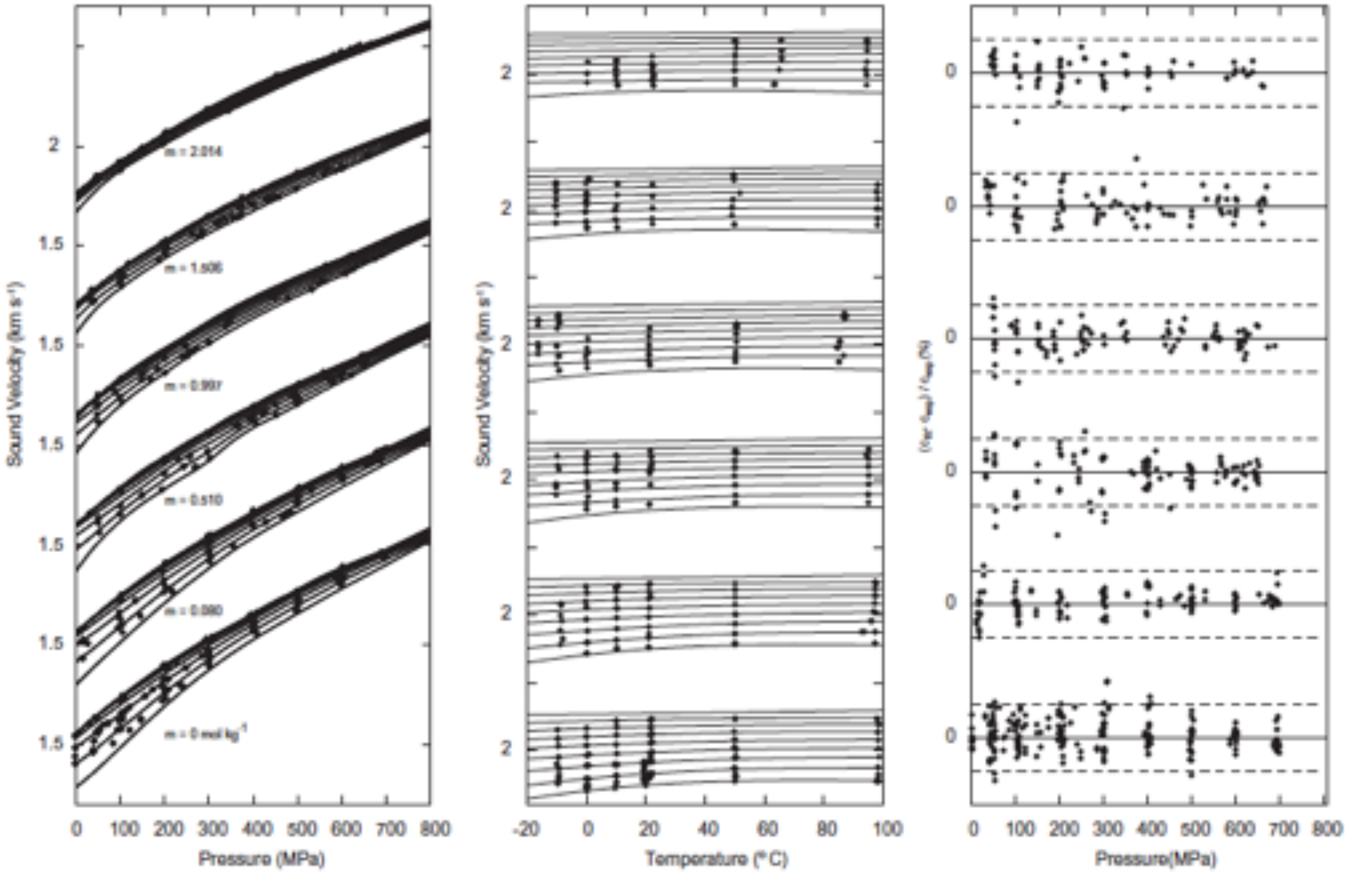
G is solution of an ODE

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	m	G_x
Thermal Expansivity	a	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 accurately determined from sound speeds vs P, T, and X

Workflow for EOS measurements

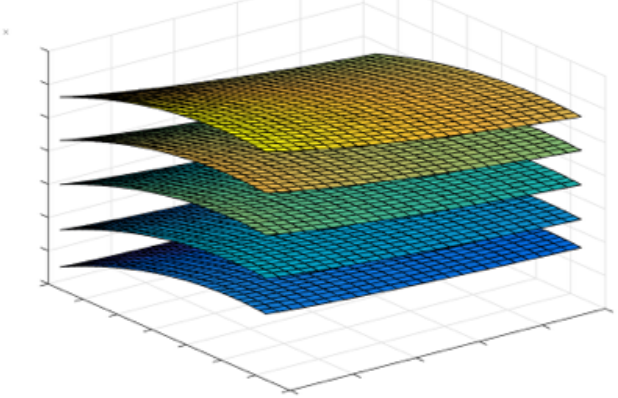
Collect lab measurements in fluids and fit sound speeds



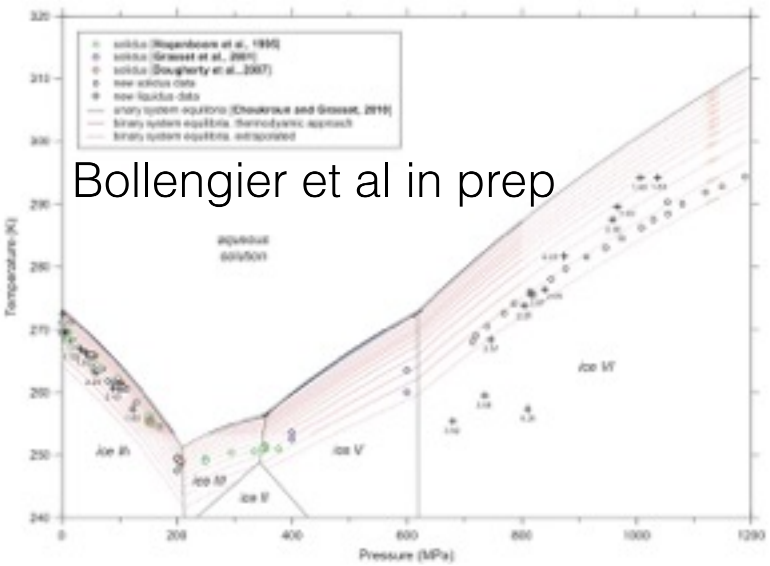
Vance and Brown 2013

Create G representation and then predict thermodynamic properties

G vs P, T, and m

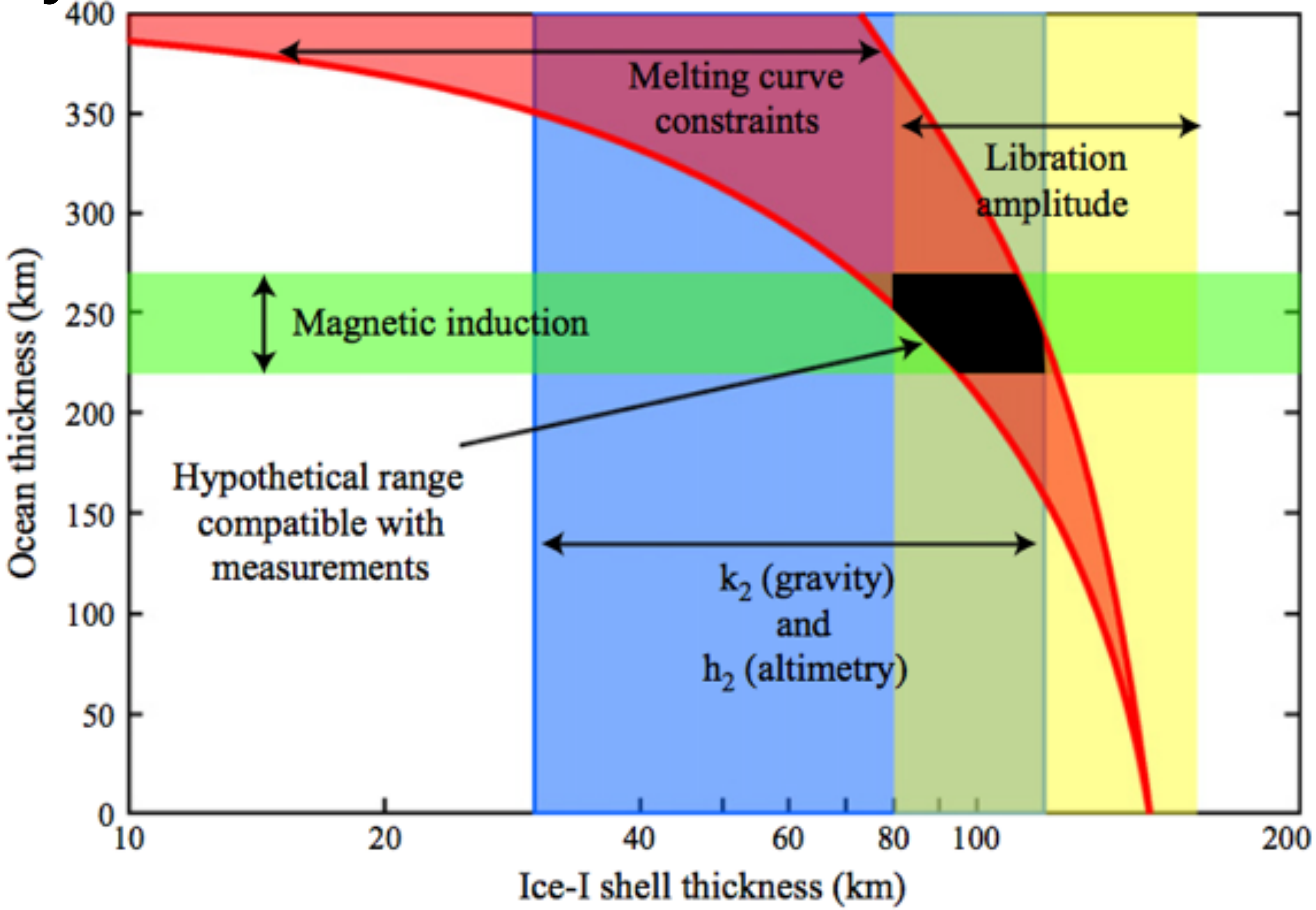


Predict phase equilibria



Bollengier et al in prep

Geophysical measurements

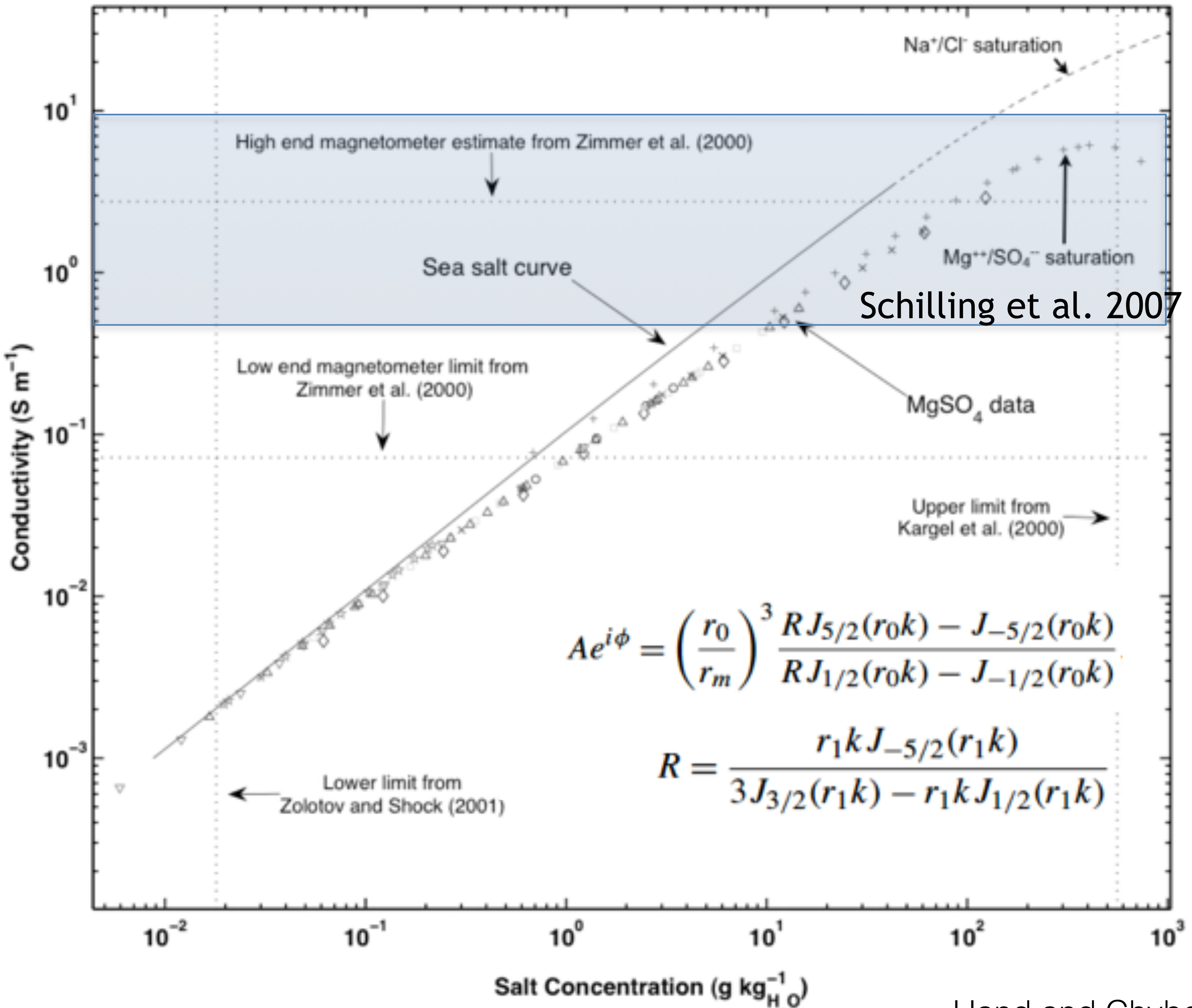


Grasset et al. 2013, **JUpiter ICy moons Explorer**

Salinity

Salinity
High pH - NaCl

Seawater salinity, mostly NaCl,
Available from TEOS-10
0 to 42 psu (~g/kg)
-35 to 2 °C
 0 to 100 MPa
Hill 1986



Hand and Chyba, 2007

Salinity
Low pH - $MgSO_4$

$$k = \frac{\Lambda m}{\rho}$$

Available for $MgSO_4$:

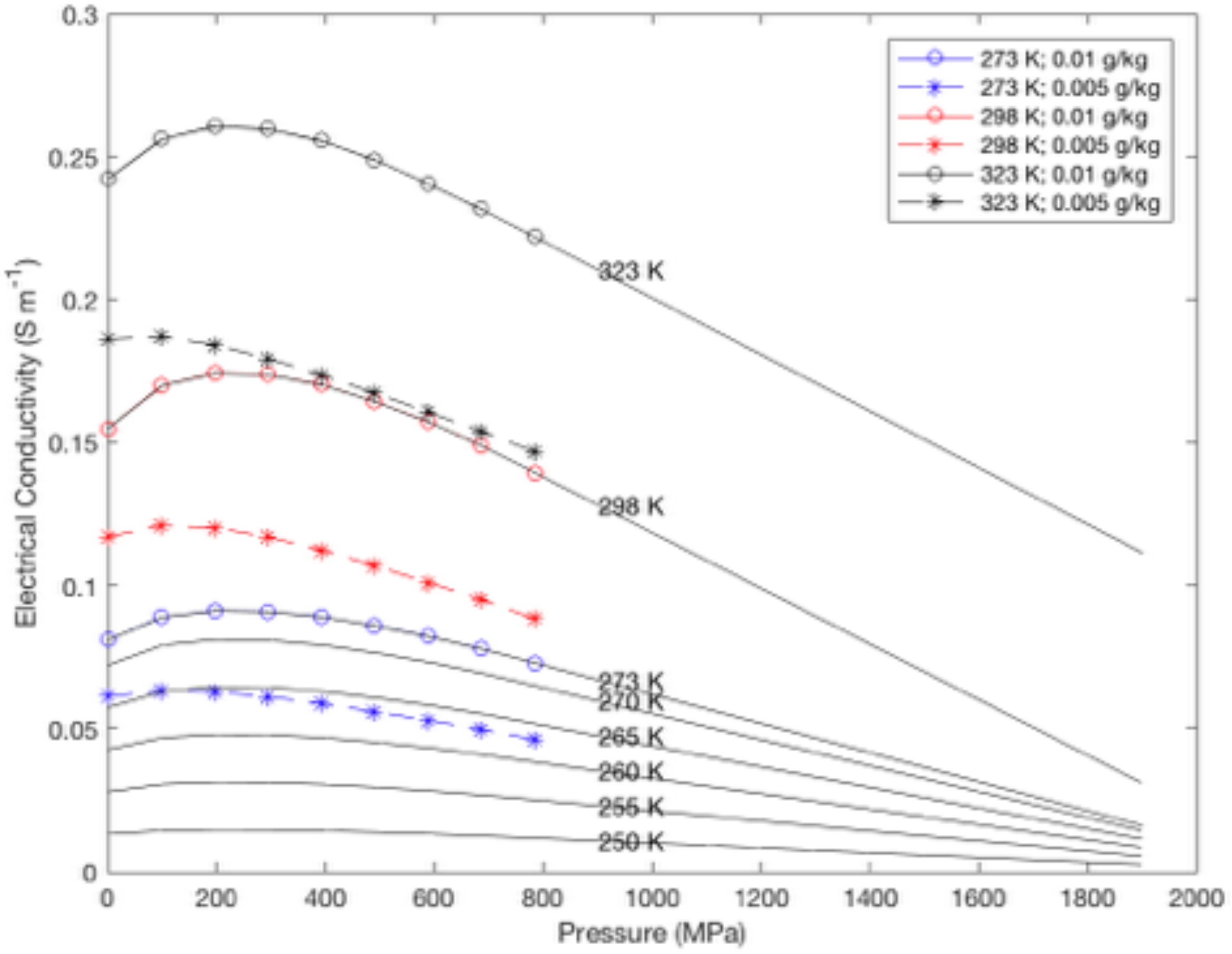
0.005 and 0.01 moles / kgH_2O

0.1 to 800 MPa

298 to 423 K

Larionov and Kryukov (1984)

Extrapolated to high concentration and low temperature



Vance et al., *in submitted.*

Submitted work
Considers historical “pyrolite” and “chondrite” compositions
as per Kuskov and Kronrod (2001)
Adds Na_2O 1wt% and saturated hydration

Core is either gamma iron or variable FeS

Future work can explore variable mineralogy.
e.g.:
mantle iron, MgO/(MgO+FeO)
sulfur partitioning into core and ocean

Rocky component (mol%)

	Pyrolite[a]	L-LL Chondrite[b]	Pyrolite[b]	L-LL Chondrite[b]
SiO_2	38.71	38.73	38.66	42.78
MgO	49.85	38.73	48.53	39.68
FeO	6.17	14.98	5.72	13.98
CaO	2.94	2.12	3.50	2.13
Al_2O_3	2.22	1.36	3.59	1.43
Na_2O	0.11	1.02	–	–

[a] *Cammarano et al.* [2011]; [b] modified from *Cammarano et al.* [2006]

Core composition and properties

	fcc-γ-Iron[a]	Fe-S (5% < X_{FeS} < 20%)[b]
ρ	8000	5150-(%S-10)×50
α, 10^{-5} K^{-1}	5	9.2
K_S, GPa	156	53.2-(%S-10)×2
$\partial K_S/\partial P$	5.0	4.66
$\partial K_S/\partial T$, Pa K^{-1}	-0.040	–
G, GPA	76.5	–
$\partial G/\partial P$	2	–
$\partial G/\partial T$, Pa K^{-1}	-0.023	–

[a] *Cammarano et al.* [2006]; [b] *Sanloup et al.* [2000]

Elastic Properties

Elastic Properties - Ices

Crystalline Phase	K_S GPa	K'_S	K''_S GPa^{-1}	μ GPa	μ'	μ'' GPa^{-1}
I_h	9.5	0.33	-0.026	3.3	0.537	-.025
II	13.89	1.6	—	5.15	3.5	—
III	8.9	3.65	—	2.7	6.55	—
V	11.8	4.8	—	5.7	0.9	—
VI	14.6	4.1	—	5.0	3.0	—

$$V_S = \left[\frac{\mu}{\rho}\right]^{1/2}$$

$$V_P = \left[\frac{K_S}{\rho} + \frac{4}{3}V_S^2\right]^{1/2}$$

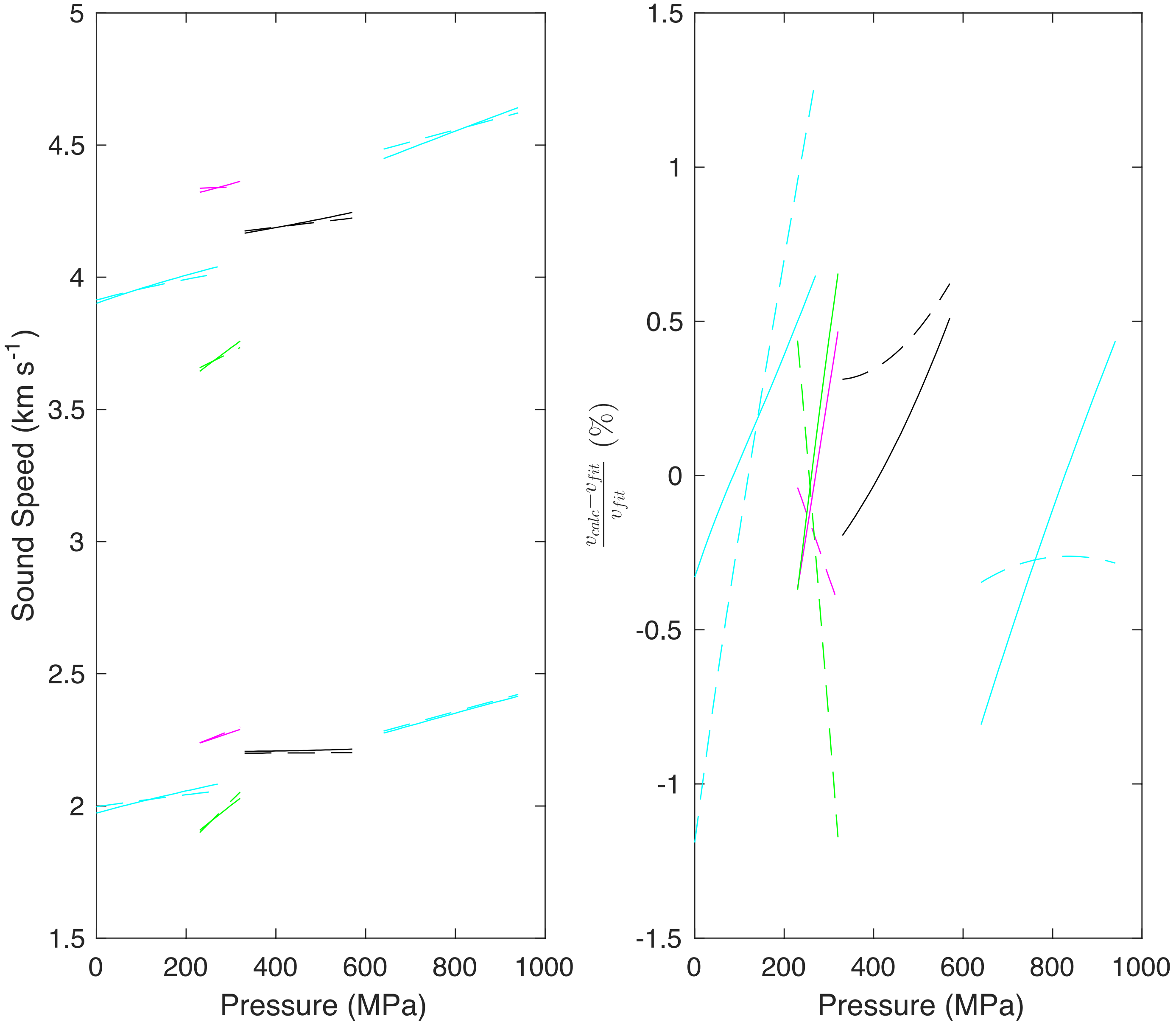
Sound speed in ice
based on Shaw 1986 and Gagnon et al. 1988, 1990
from fits to measurements around -35°C

forward model for bulk sound speed from ice equations of state based on density and phase boundaries

$$\frac{\partial \rho}{\partial P}_T = \frac{1}{v_c^2}$$

Choukroun et al. 2010

Vance et al., *in submitted.*



Vance et al., *in submitted.*

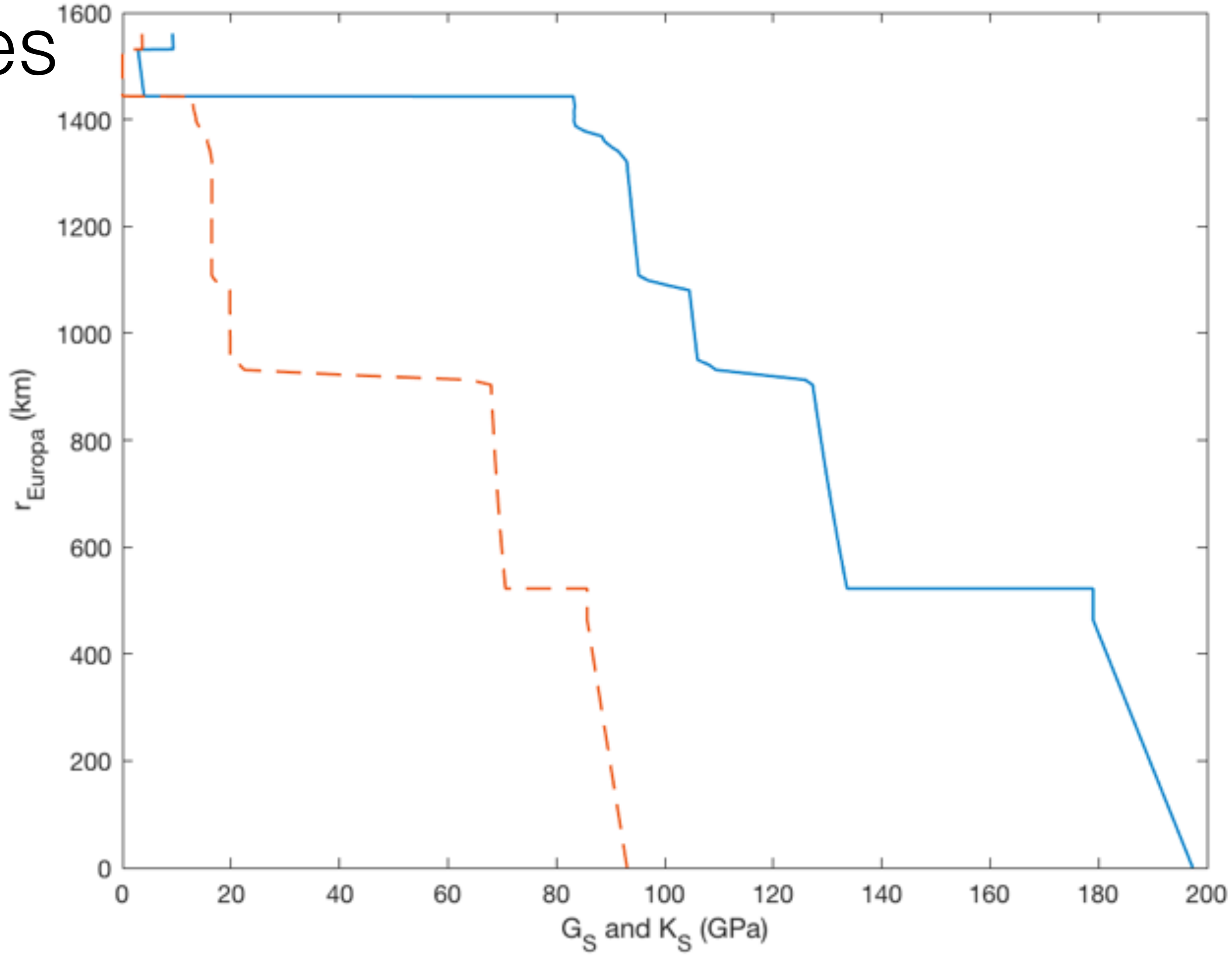
Elastic Properties → Tides

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

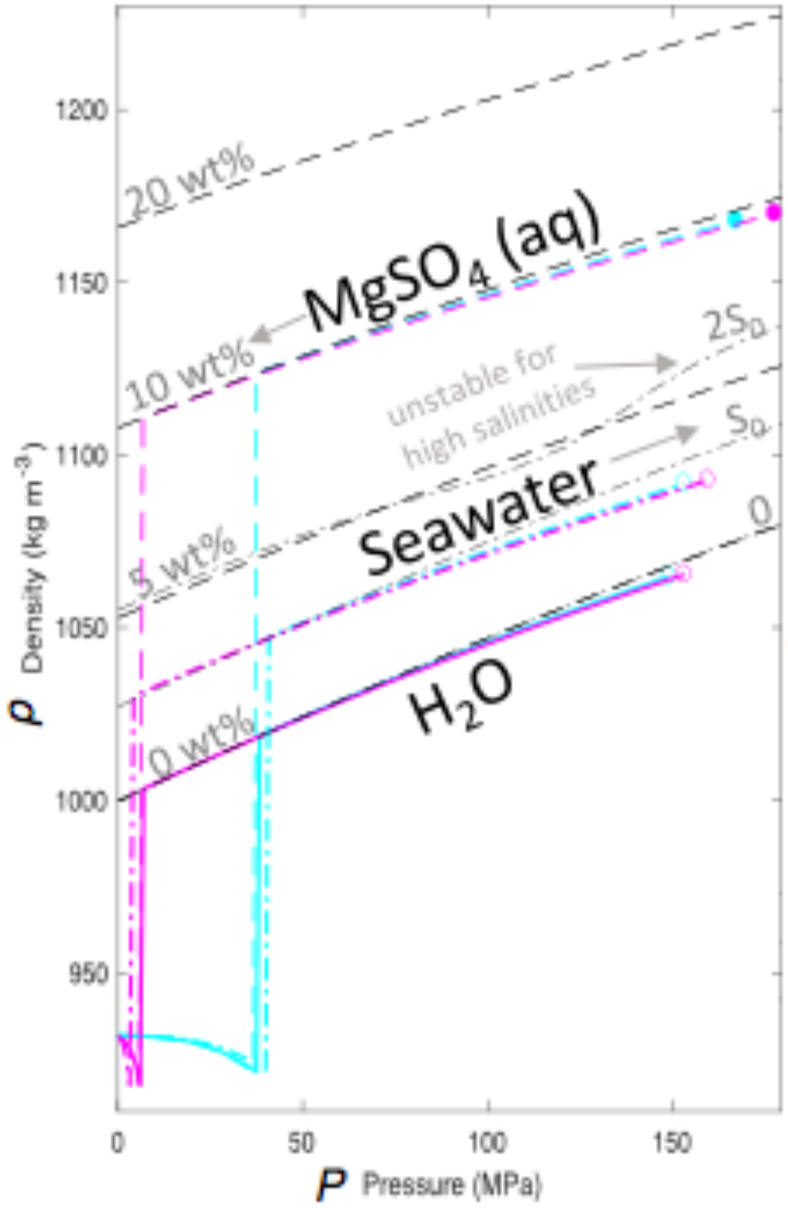
where

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

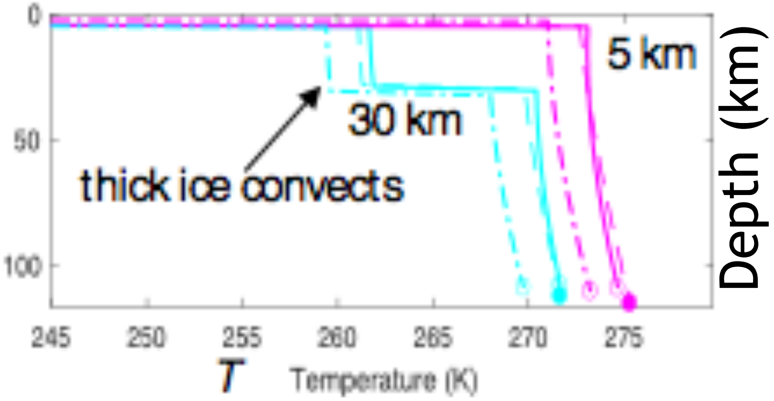
Tobie et al. 2006



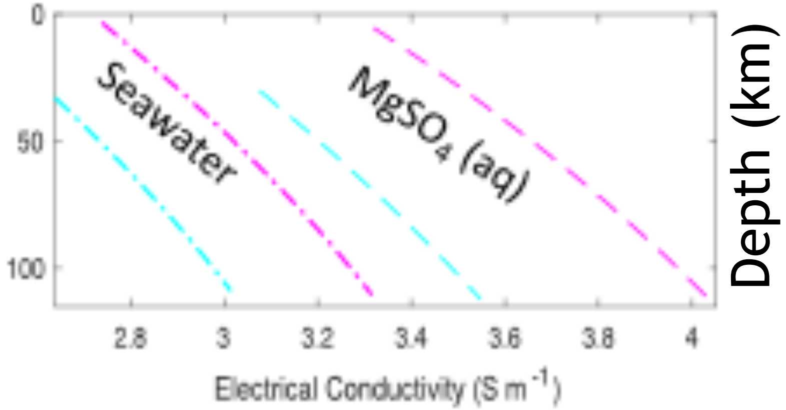
Europa



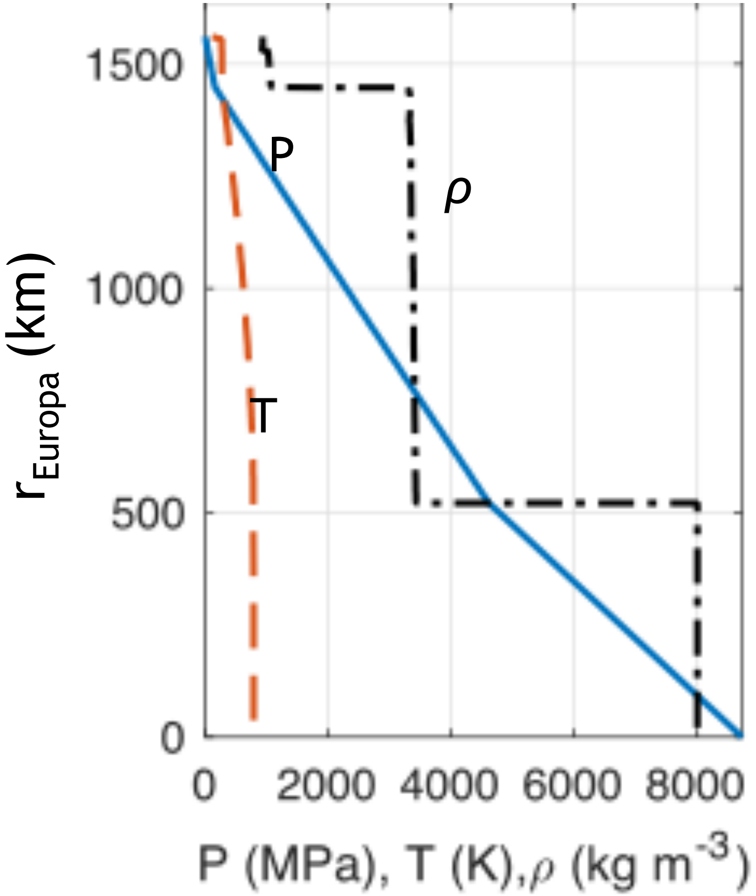
20 wt%
MgSO4 (aq)
10 wt%
unstable for high salinities
2S0
S0
5 wt%
Seawater
0
0 wt%
H2O
1200
1150
1100
1050
1000
950
ρ Density (kg m-3)
0
50
100
150
P Pressure (MPa)



5 km
30 km
thick ice convects
0
50
100
245
250
255
260
265
270
275
T Temperature (K)
Depth (km)

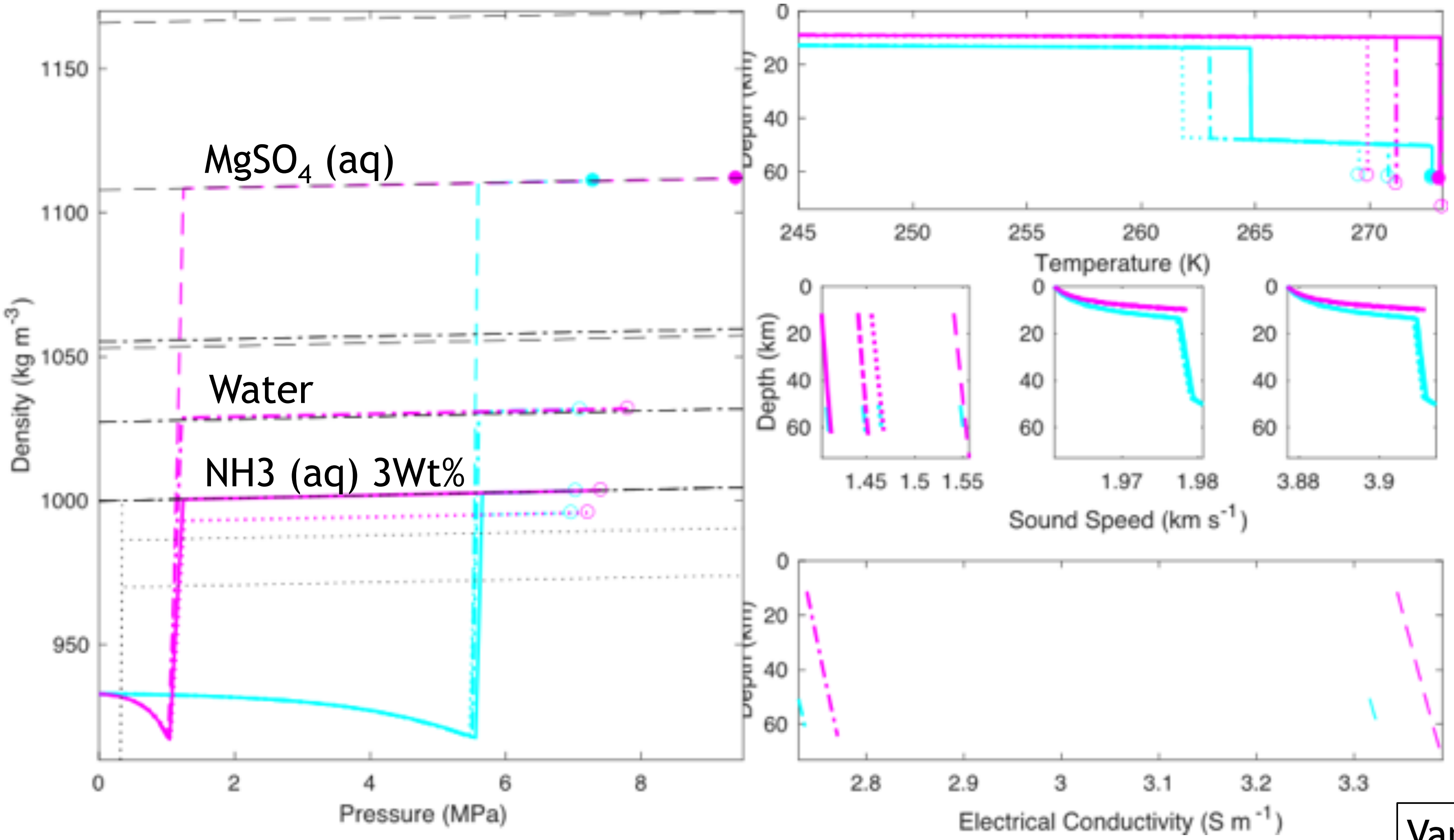


Seawater
MgSO4 (aq)
0
50
100
2.8
3
3.2
3.4
3.6
3.8
4
Electrical Conductivity (S m-1)
Depth (km)



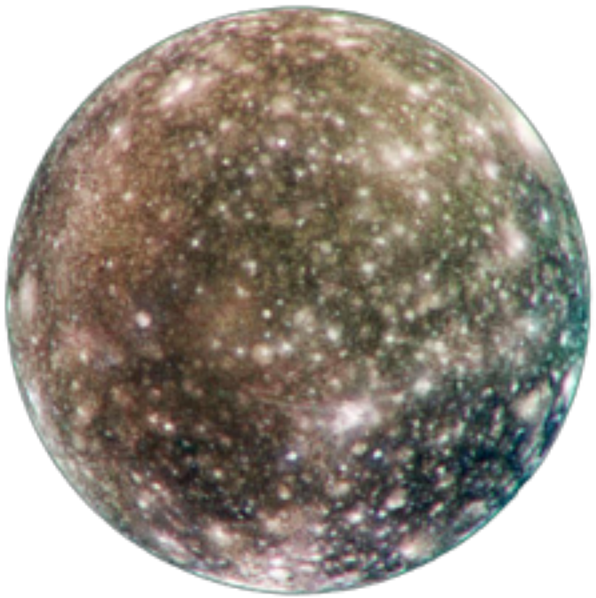
1500
1000
500
0
P
ρ
T
r Europa (km)
0
2000
4000
6000
8000
P (MPa), T (K), ρ (kg m-3)

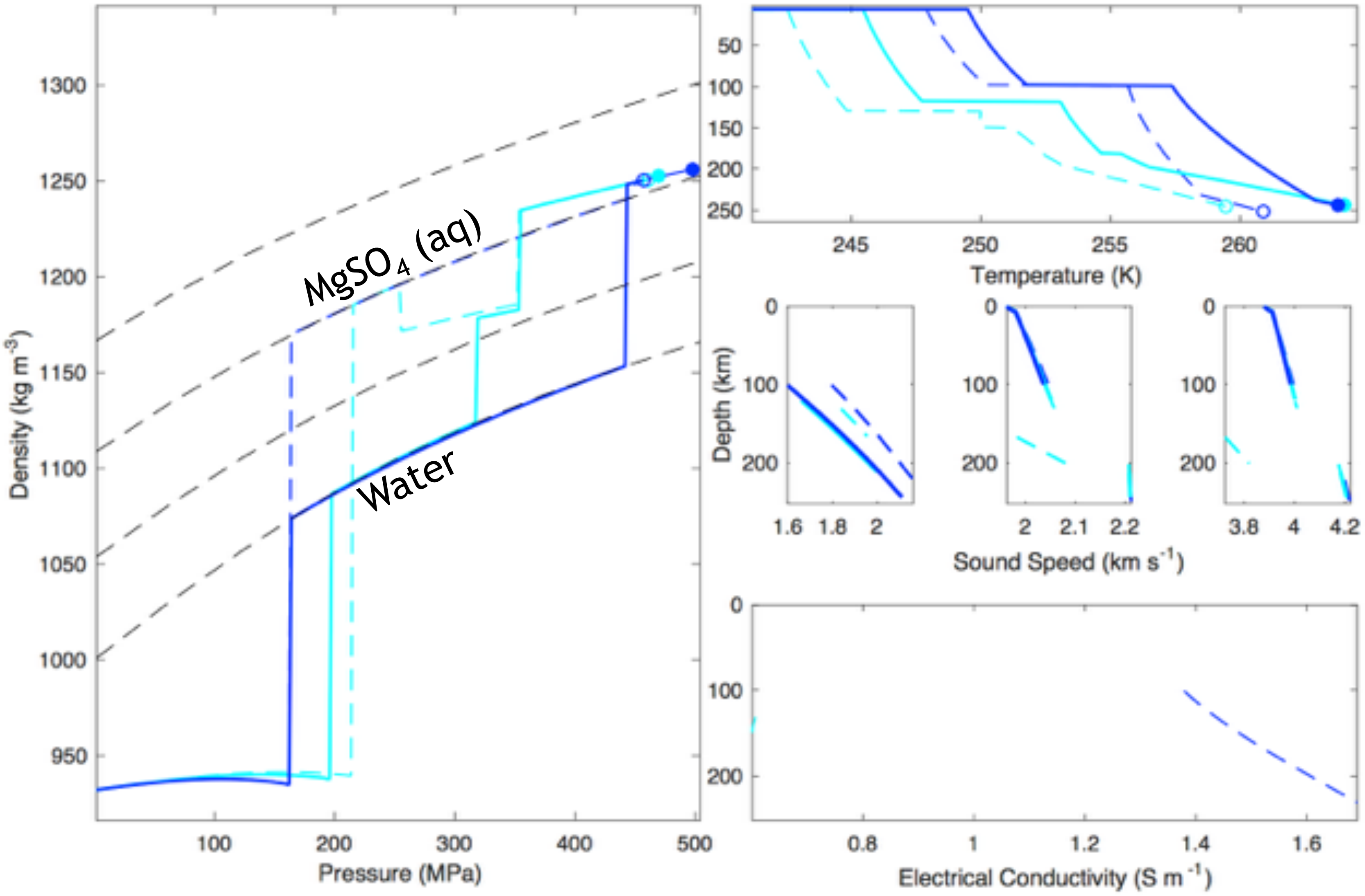
Enceladus



Vance et al., *in submitted*.

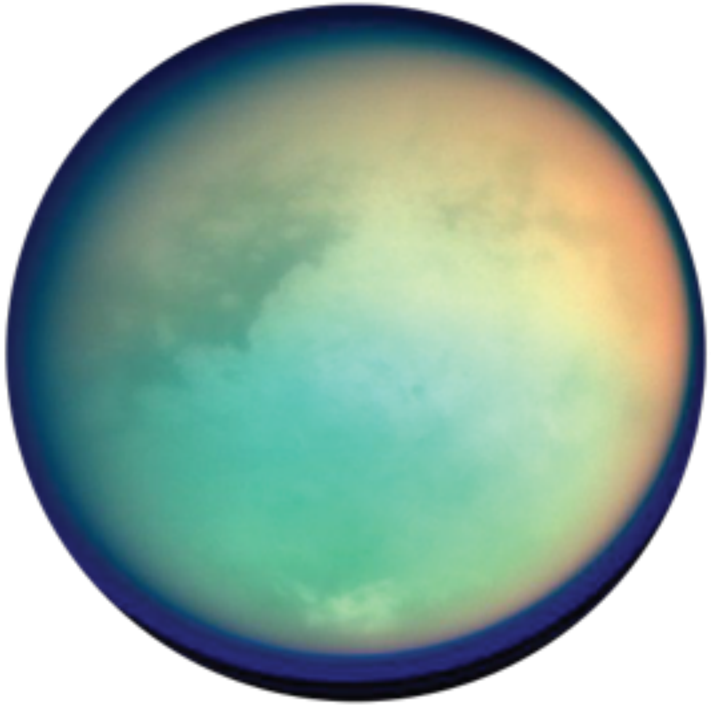
Callisto

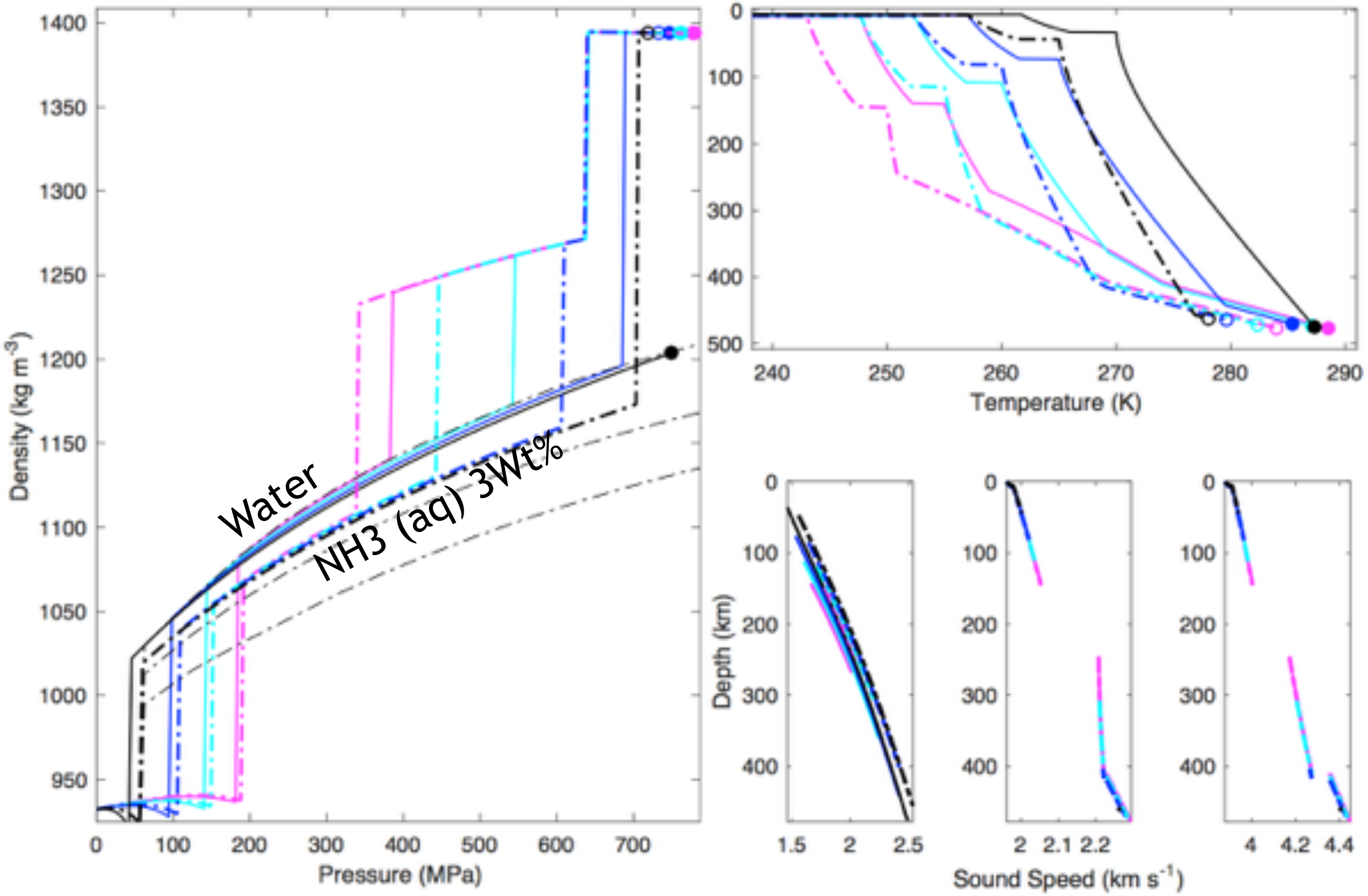




Vance et al., *in submitted*.

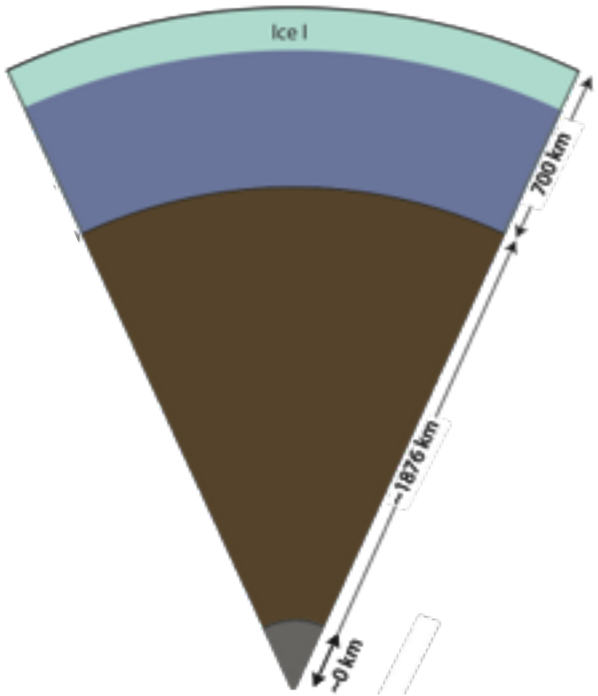
Titan

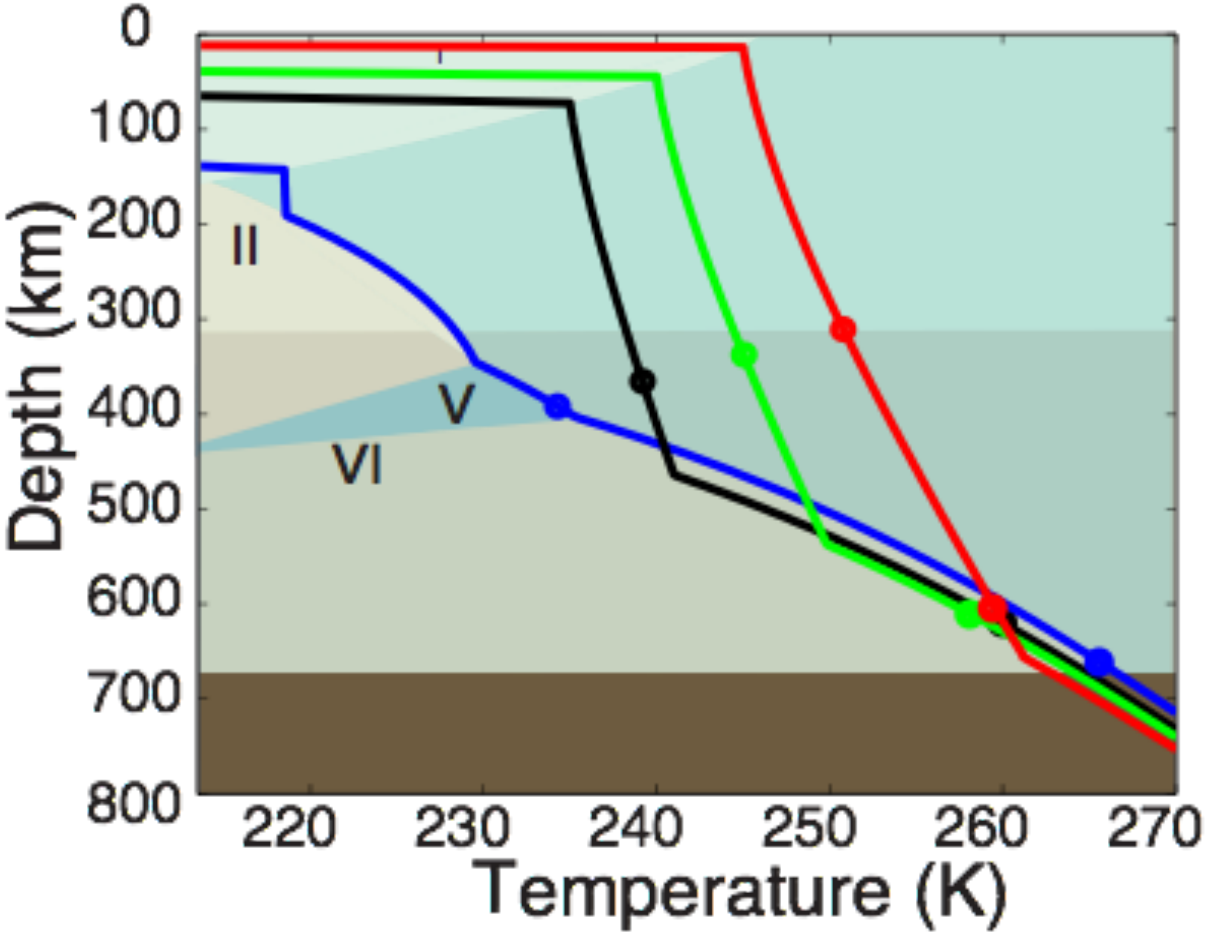




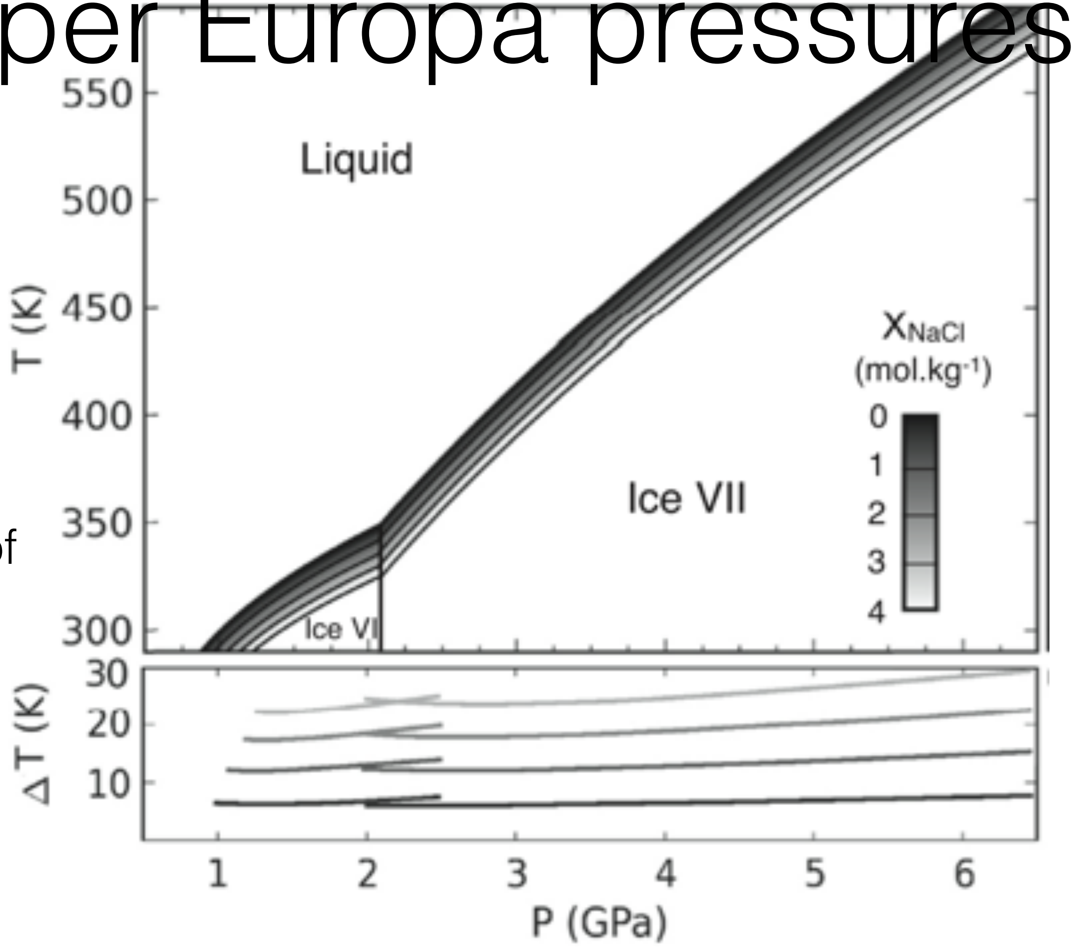
Vance et al., *in submitted*.

Titan: 15 wt% NH_3 ocean





Buoyant ices are also predicted in NaCl(aq), studied at super Europa pressures



Stronger melting point suppression documented for NaCl

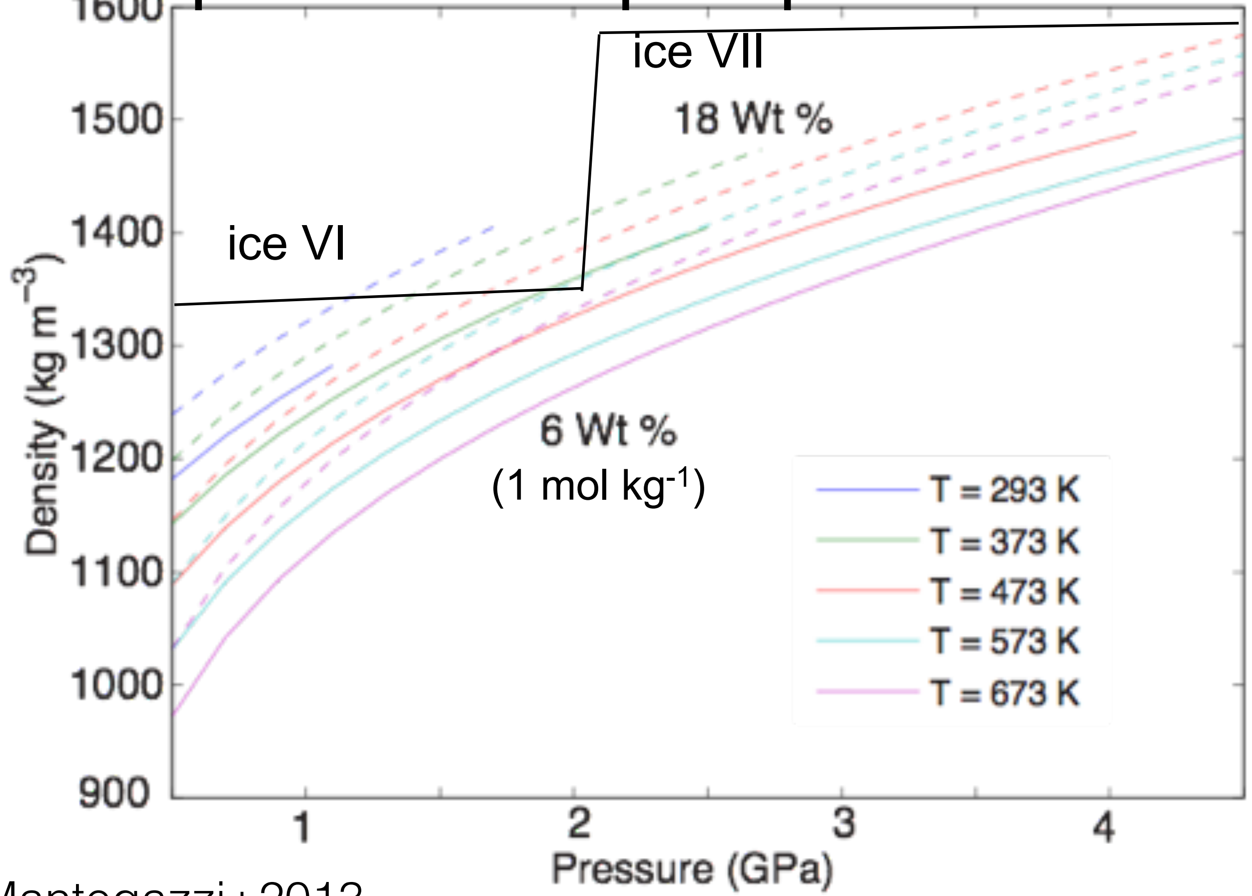
Phase measurements not available in 0.1 to 1 GPa range of pressures

Journaux+ 2013

Buoyant ices are also predicted in NaCl(aq), studied at super Europa pressures

High density at low temperature

Thermodynamics not available near freezing point (T<293 K)



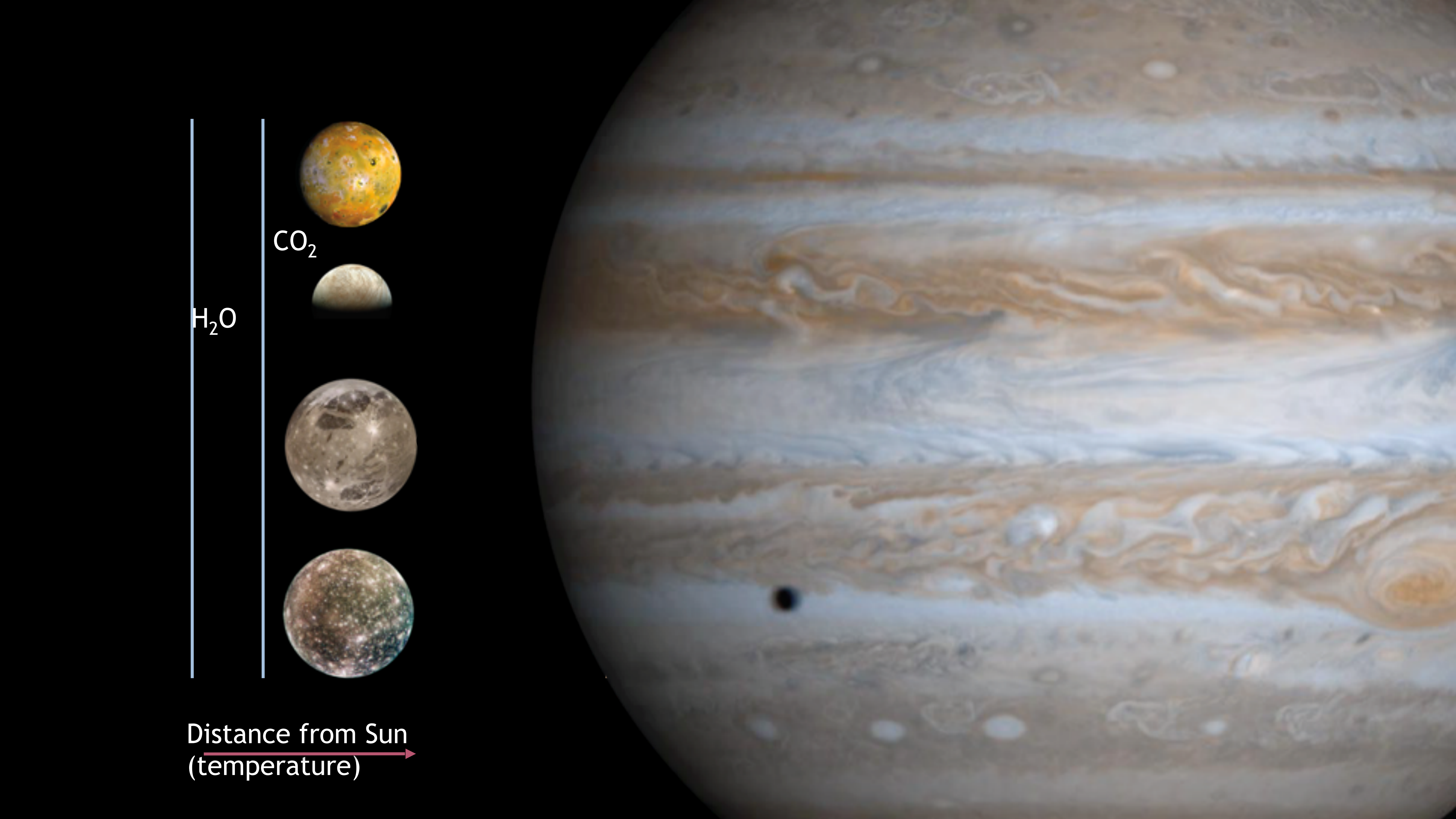
NaCl data from Mantegazzi+2013

Ice densities from Reimers and Watts 1984, Vega+ 2005, Choukroun+ 2010

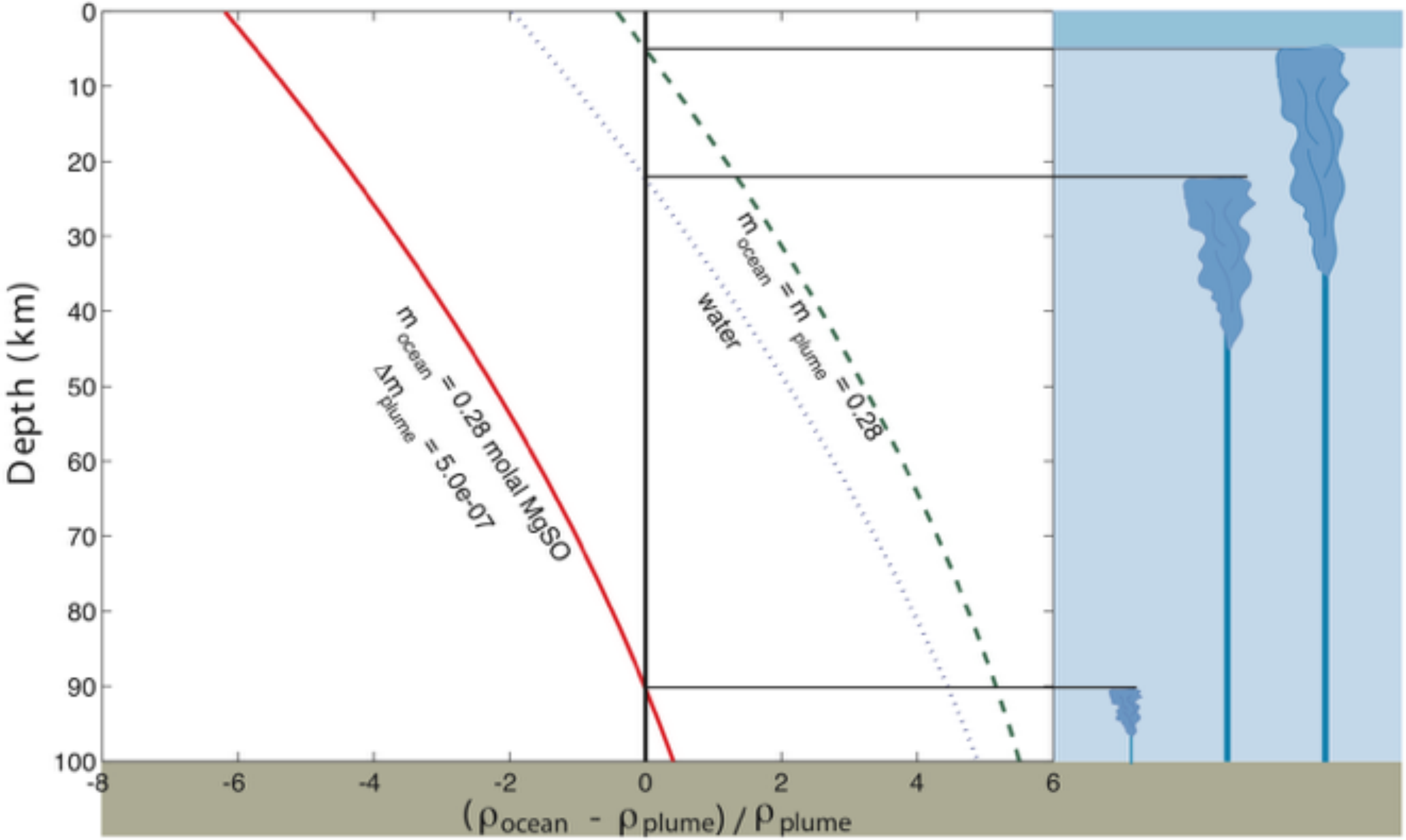
Geophysical tests for habitability

- Requiring thermodynamic consistency helps to distinguish among solutions to geophysical datasets
- This could enable measurements of ocean pH
- Titan and Callisto may lack high pressure ices
- Thermodynamic consistency requires further development of EOS for ices fluids, and rocks

Backup

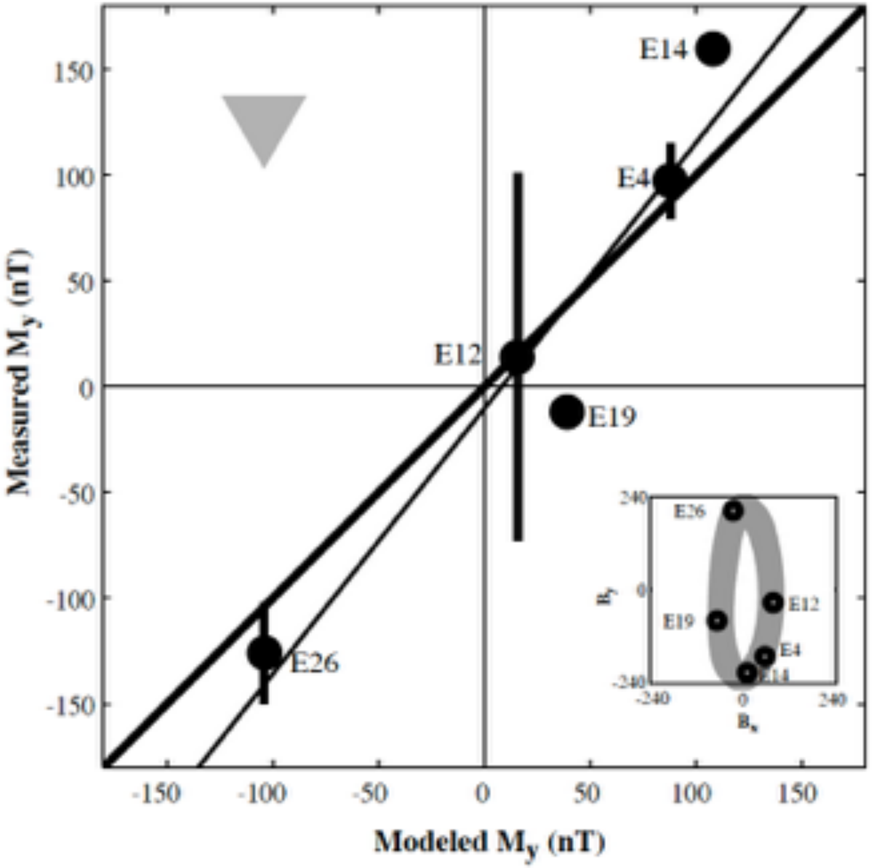

CO_2
H_2O
Distance from Sun
(temperature)

Oceanic plumes may not always reach the surface



Vance and Brown 2005, Vance and Goodman 2009

Evidence for present-day oceans in Europa, Ganymede, Callisto



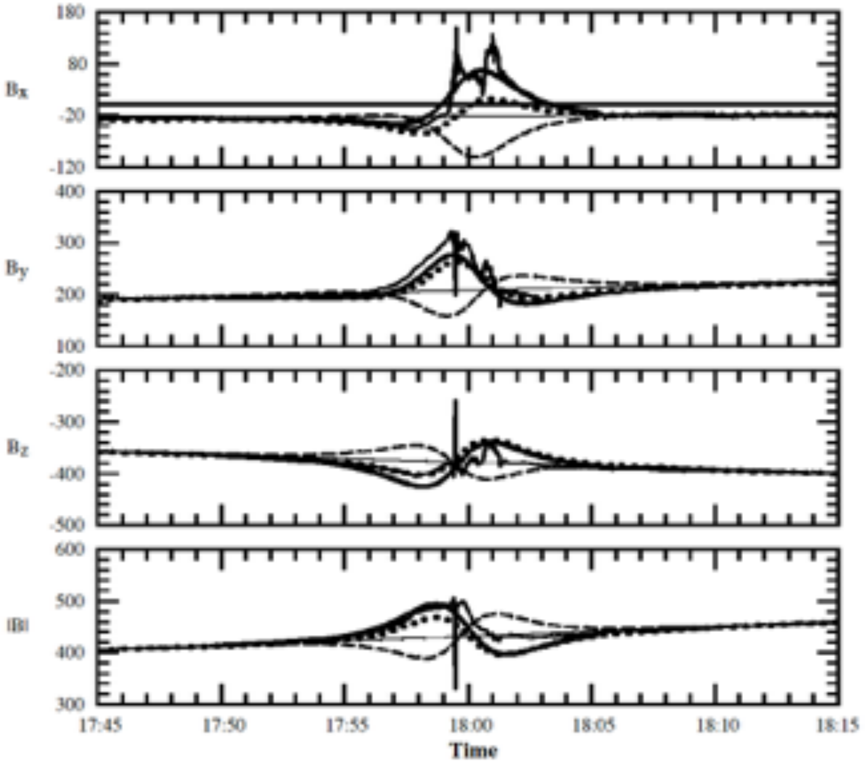


Fig. 4. The E26 pass on 3 January 2000: data within 5 R_E from Europa's center. Curves are as in Fig. 2. The dashed curves computed from the dipole moment fit to the E4 pass are in antiphase to both the dipole fitted to the E26 data (heavy solid curves) and to the inductive response model (dotted curves).

Kivelson et al. 2000

Porosity and Permeability

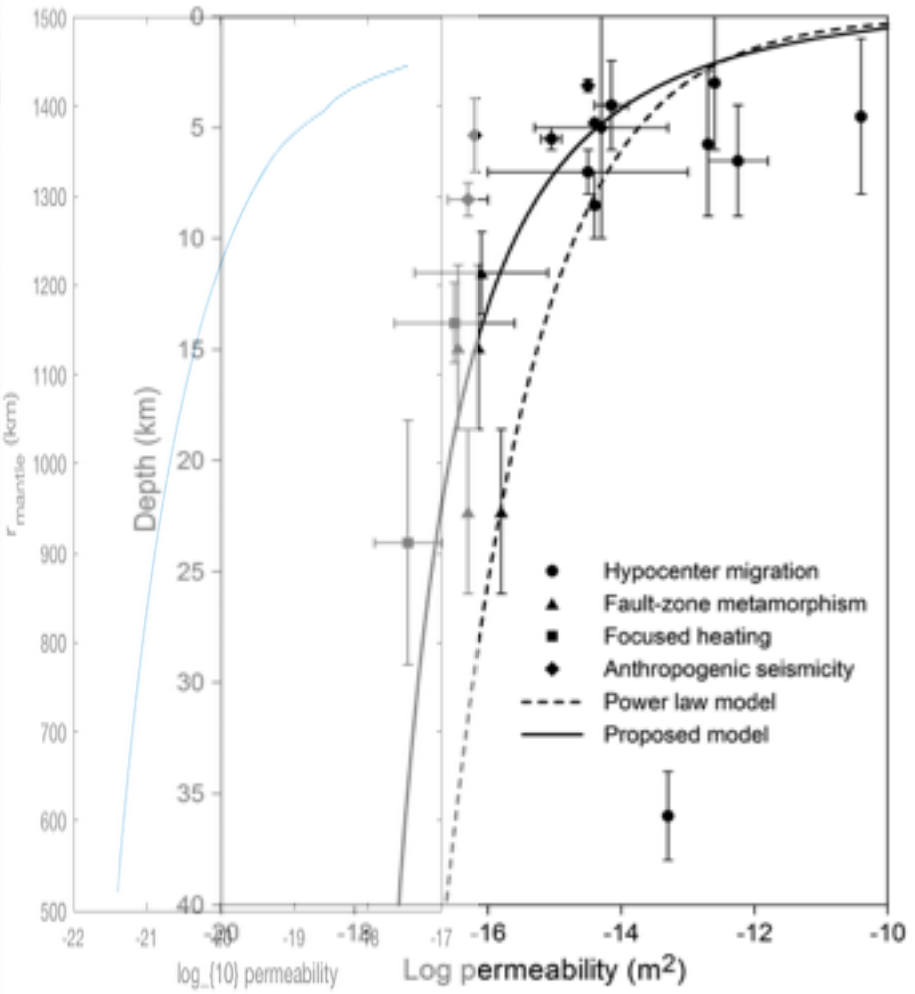
$$log(\phi) = -0.65 - 0.1d + 0.0019d^2$$

$$\rho = \phi\rho_f + (1 - \phi)\rho_g$$

Vitovtova et al. 2014

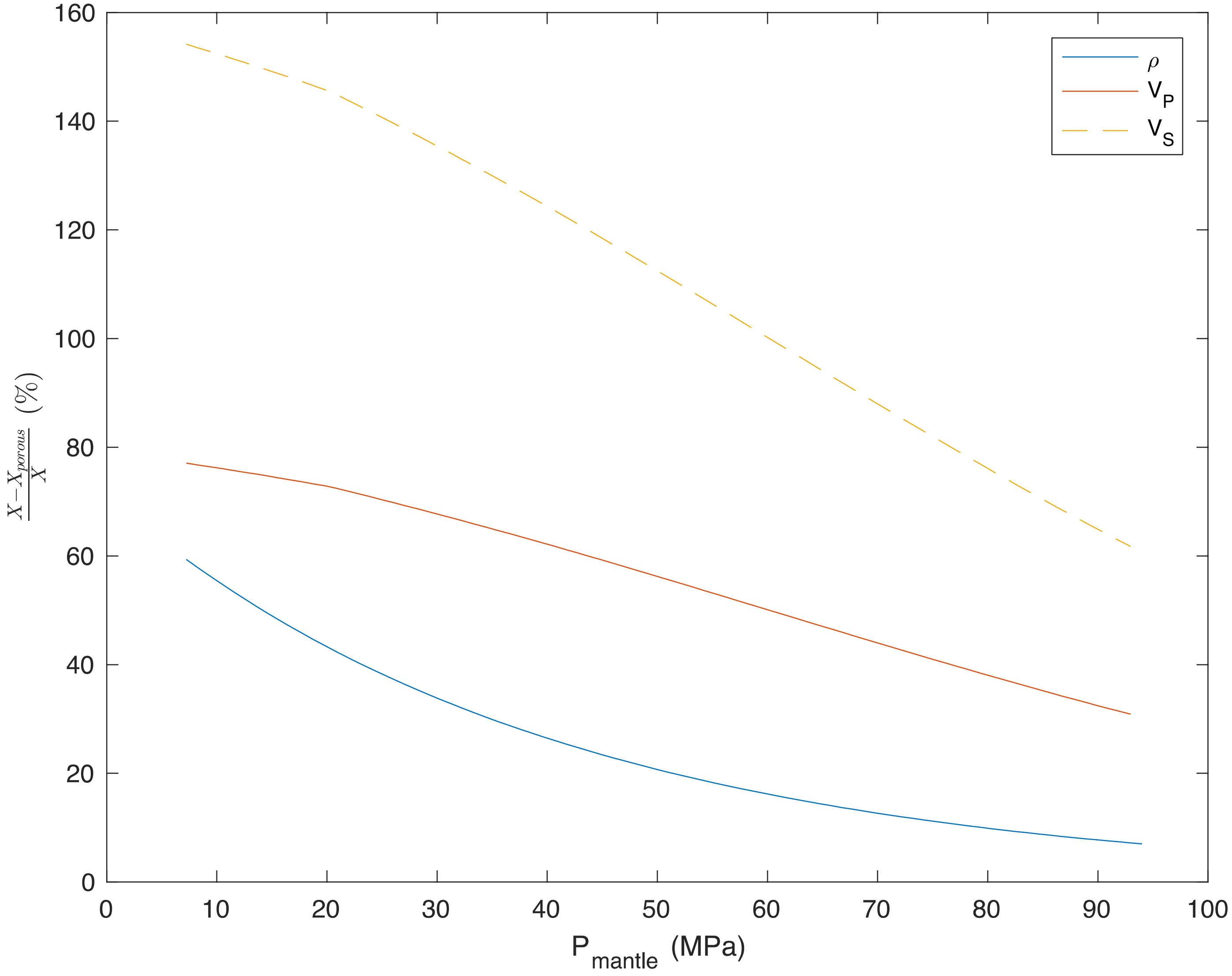
$$\log k = \log k_r + (\log k_s - \log k_r)\ (1 + z)^{-\alpha}$$

Kuang and Jiao 2014



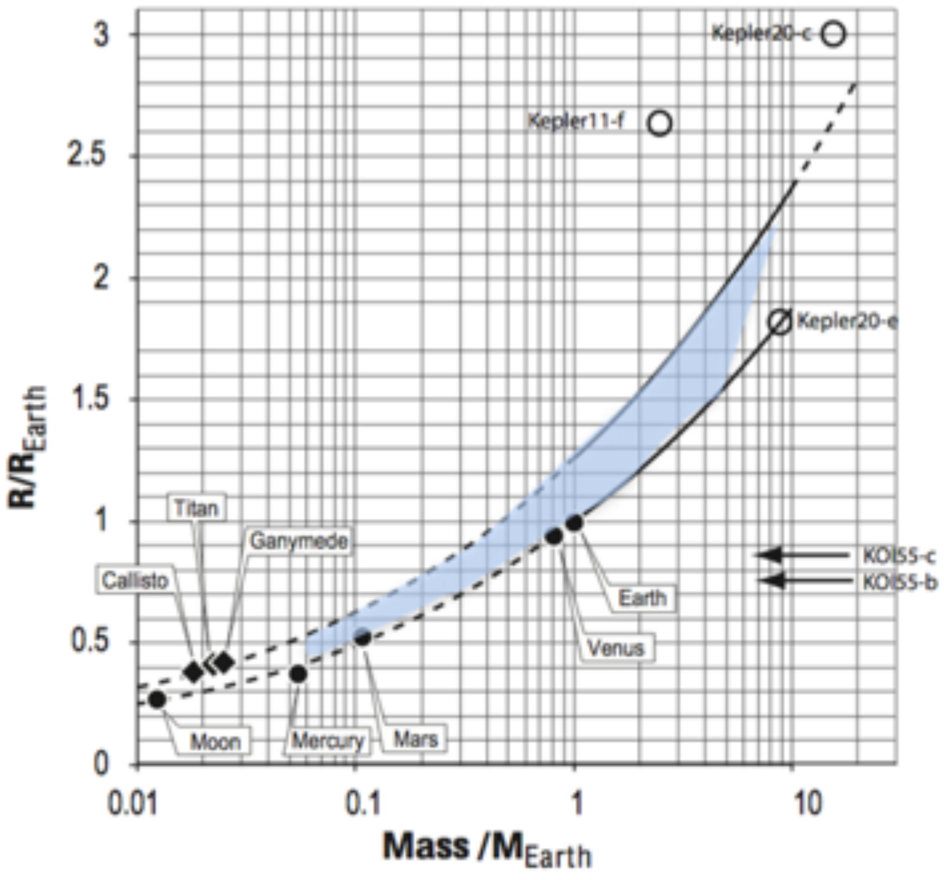
Vance et al., *in submitted*.

Enceladus

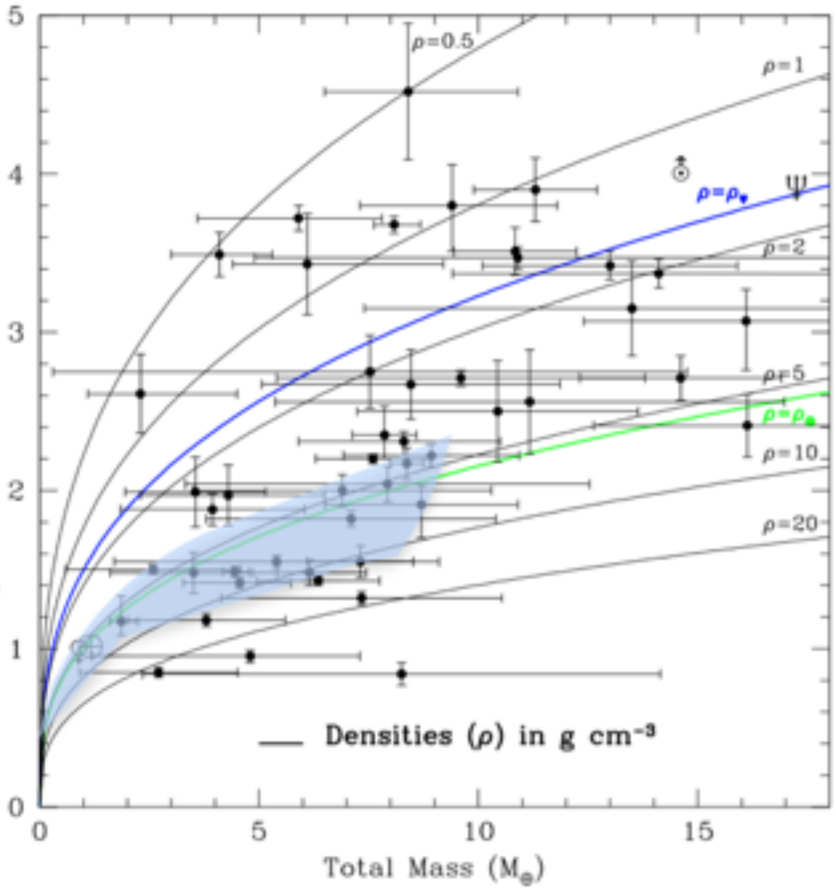


Vance et al., *in submitted*.

Oceanic exoplanets should define a portion of the M-R curve
Additional axes are needed for stellar type, orbit distance…



modified from Baraffe+ 2014



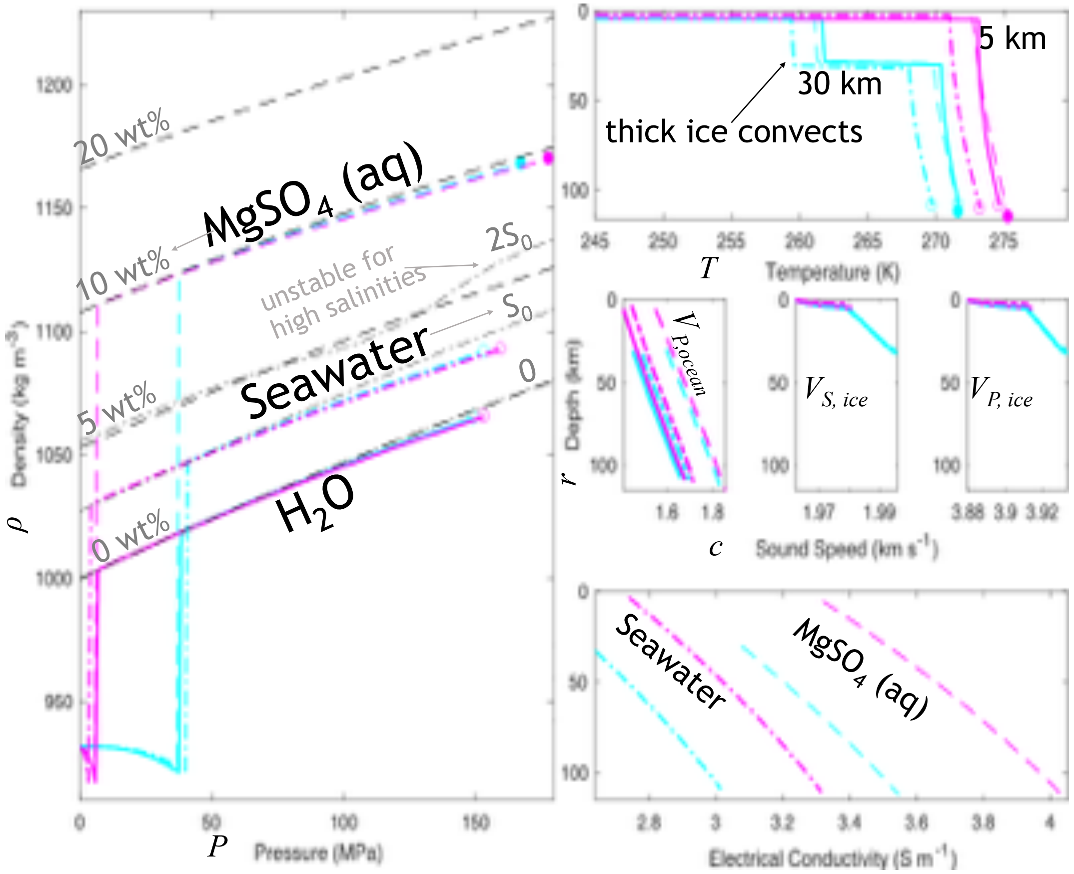
modified from Howe+ 2014

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	m	G_x
Thermal Expansivity	a	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 accurately determined from sound speeds vs P, T, and X



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unstable for
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S0
5 wt%
Seawater
0
0 wt%
H2O
ρ
Density (kg m-3)
P
Pressure (MPa)
5 km
30 km
thick ice convects
T
Temperature (K)
VP,ocean
VS, ice
VP, ice
r
Depth (km)
c
Sound Speed (km s-1)
Seawater
MgSO4 (aq)
Electrical Conductivity (S m-1)