

organic-rich atmosphere
and surface

de-coupled outer shell
(water-ice / clathrate)

global subsurface ocean

high-pressure ice VI shell

hydrous silicate core
~2000 km radius

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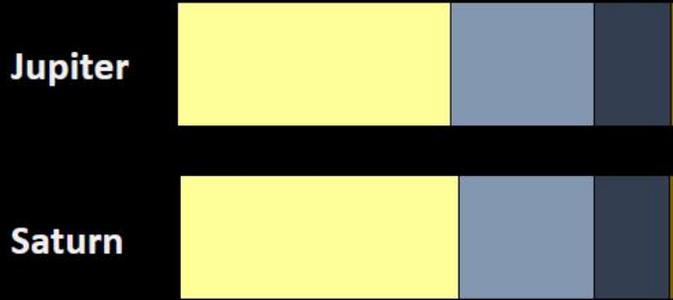
NAI Titan team

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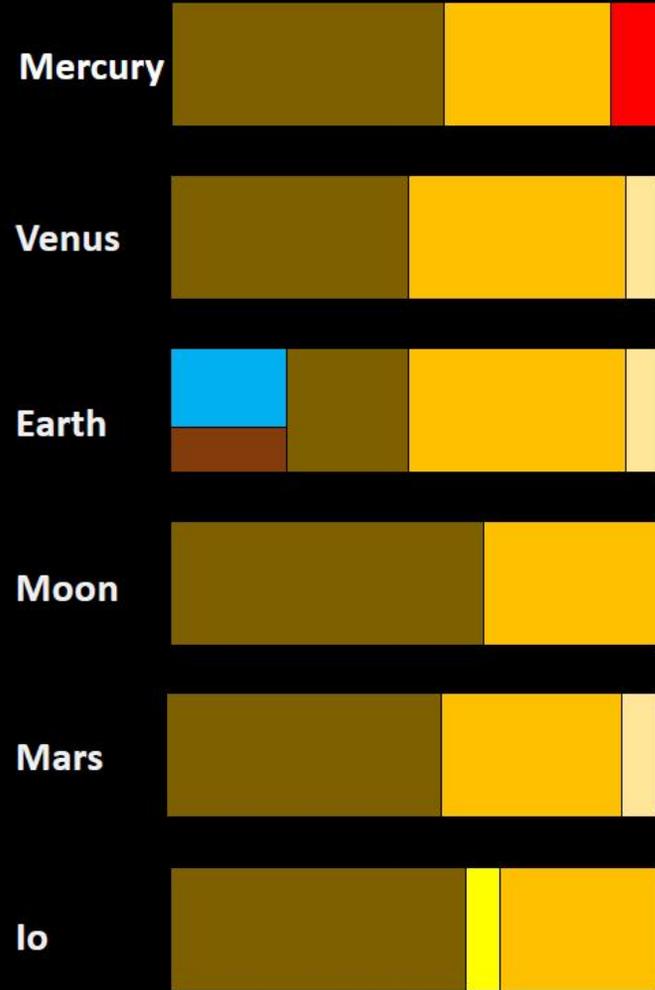
A Depth Transect of Potential Titan Environments

Log-scale normalized interior models of different worlds

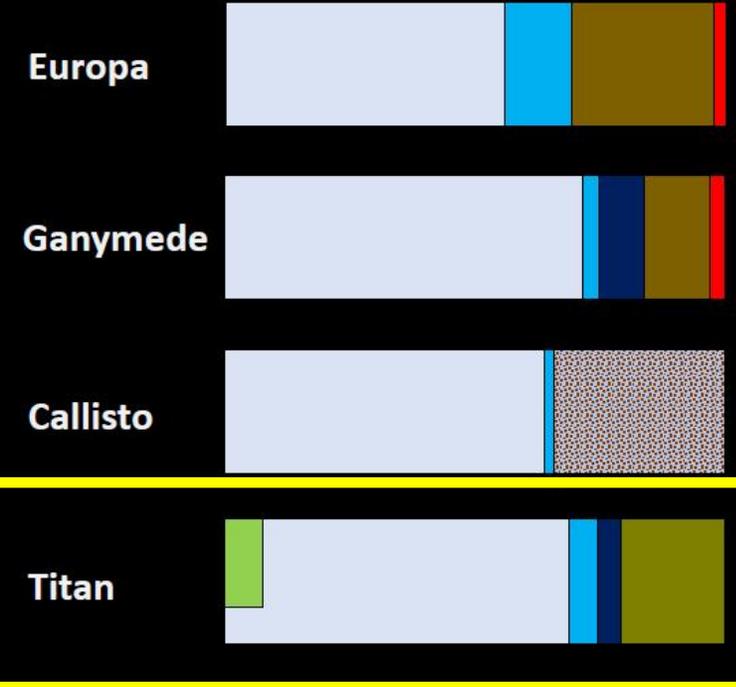
Gas giants



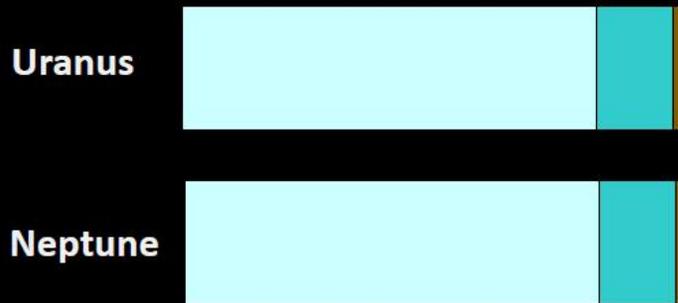
Rocky worlds



Ocean worlds



Ice giants



Color key

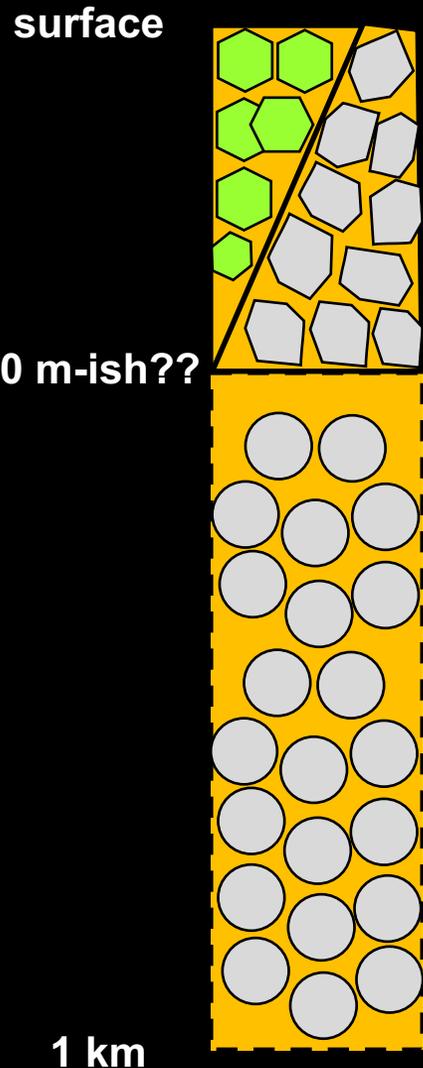
H ₂ gas		organic solids		H ₂ O (Ih) solid		SiO ₂ silicic		SiO ₂ hydrous	
H ₂ / He gas		H ₂ O / NH ₃ mix		H ₂ O liquid		SiO ₂ ductile		Fe (Ni) liquid	
H ₂ supercritical				H ₂ O (IV) solid		SiO ₂ liquid		Fe (Ni) solid	
H ₂ metallic				H ₂ O / SiO ₂ mix		SiO ₂ solid			

Based on available data in Wikipedia 2017 and other sources.

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Titan subsurface: The first 1 km

Speculative structure – need better estimates and constraints

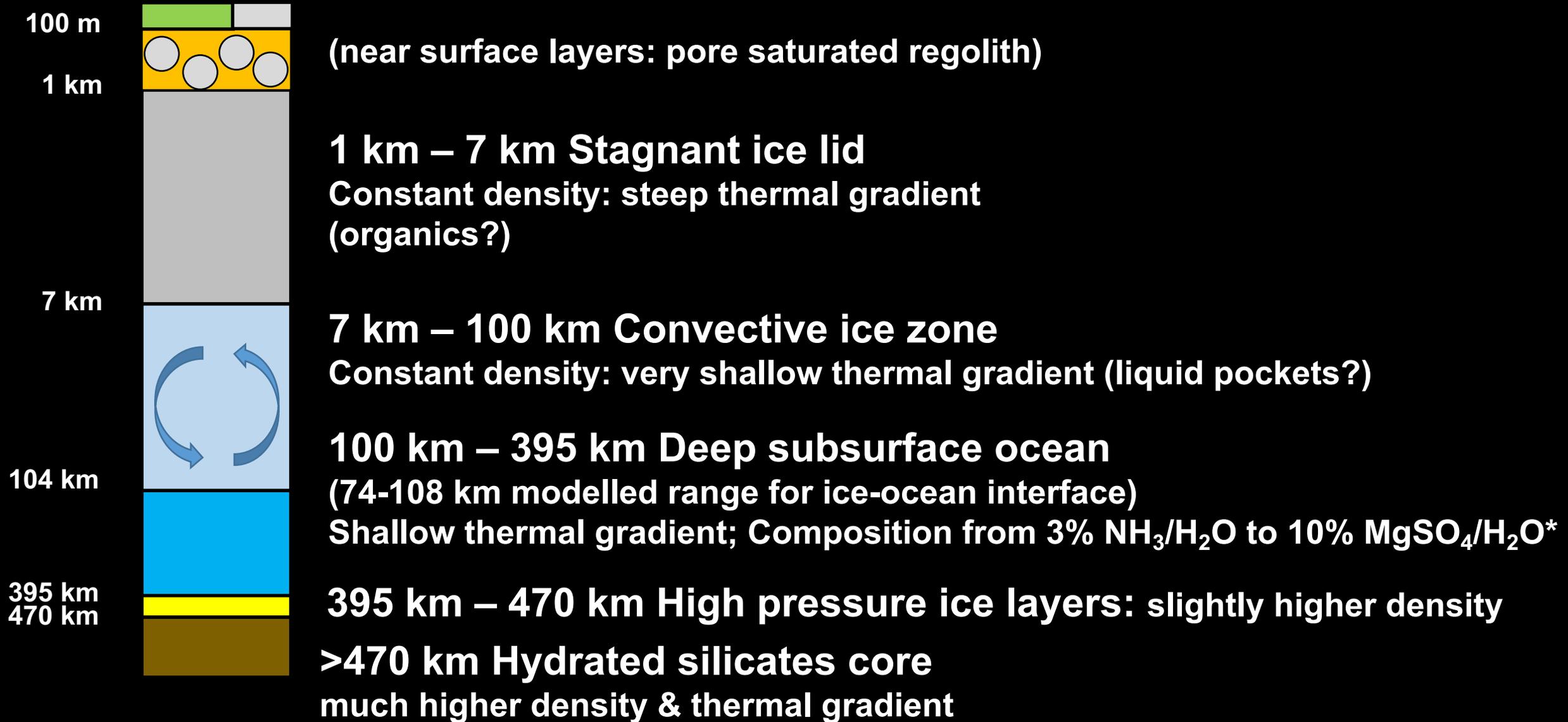


surface– 100 m: organic deposit depth – spatially variable depths
Possibly liquid hydrocarbon saturated

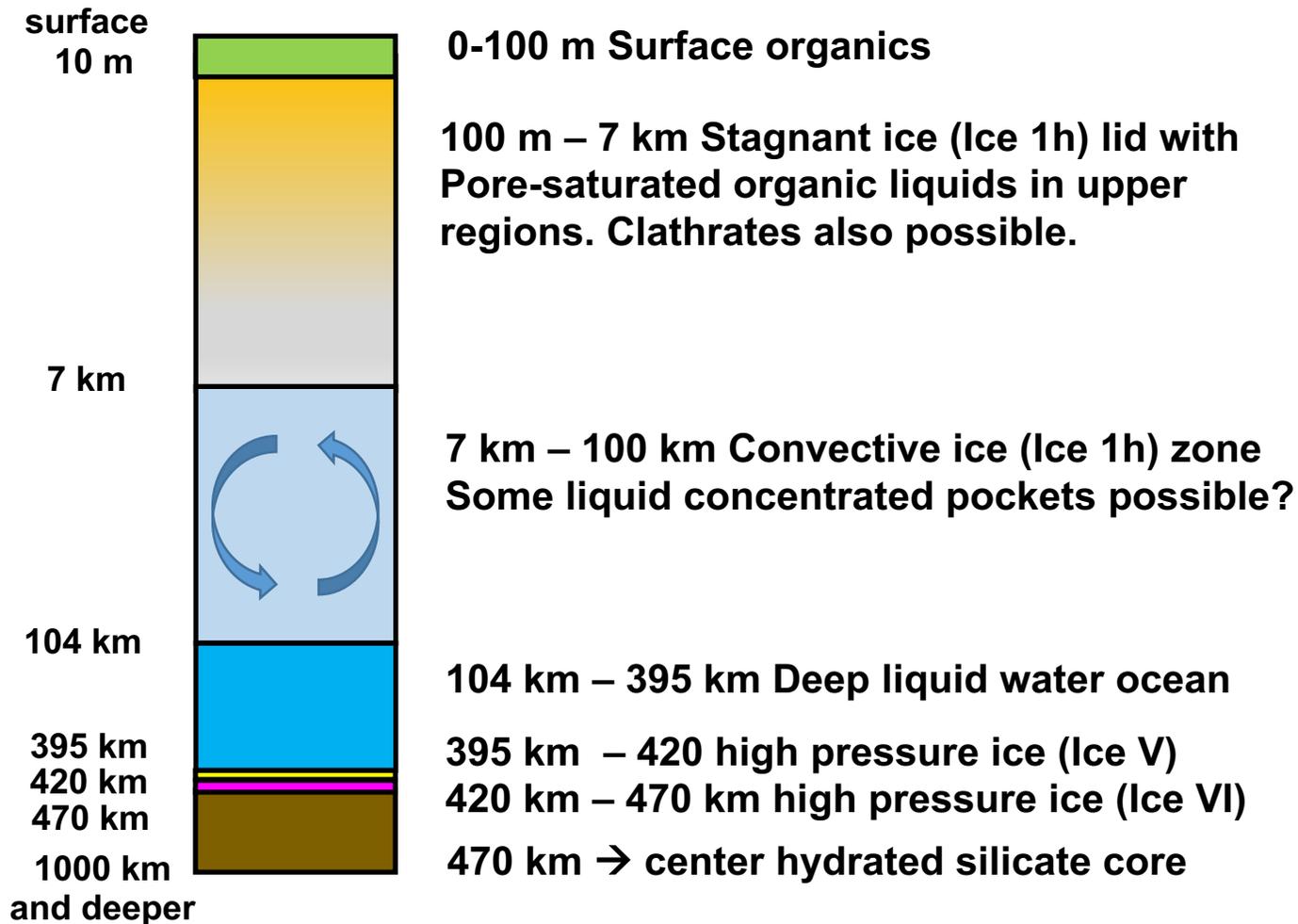
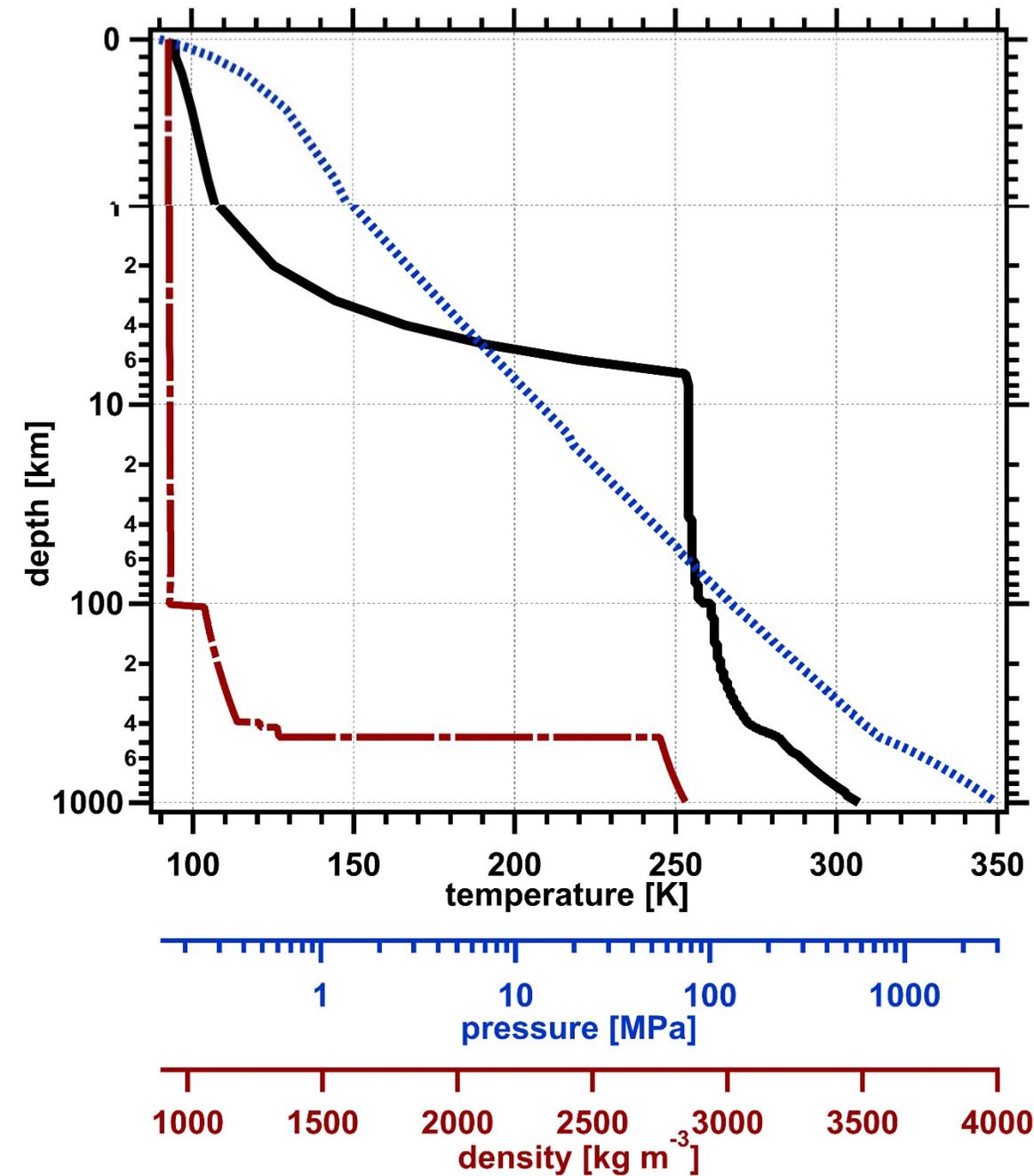
100 m – 1 km: Hydrocarbon (ethane?)-saturated regolith
From 10 m ethane accommodated in 5% void areas in regolith →200 m-ish.
How deep do organics penetrate from surface?
Fluids with dissolved material?
Clastic materials?

>1 km: Mostly H₂O / clathrate?

Titan deep subsurface: 1 km – 1000 km



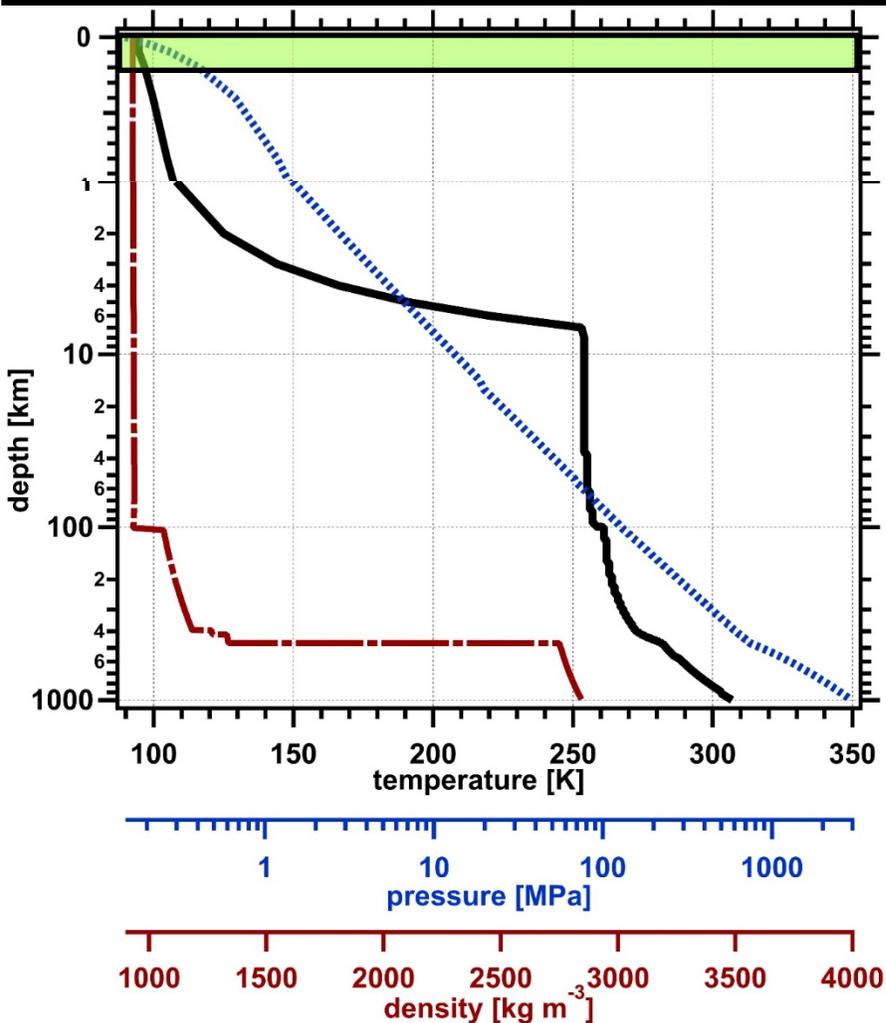
*Based on Cassini gravitational data and modelling in Vance et al., 2018



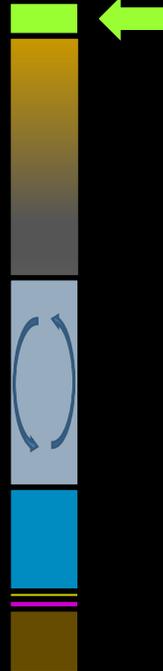
Titan modeled T, P , and density

Note scale change in y-axis. 0-1 km has a linear scale
>1 km depth is a log scale.

Surface – 100 m Surface organics layer



Note scale change in y-axis. 0-1 km has a linear scale
>1 km depth is a log scale.



Organic airfall deposit

Processed geology: eolian, erosion, dissolution
Likely methane saturated: wet dry cycles

$T = 90 - 95 \text{ K}$

$P = 0.15 \text{ MPa}$

Density: organic, so 0.9 g/cm^3

Kinetically inhibited reactions - sloooooooooow
Physical (geology) movements \gg biology
("Hey, I was gonna eat that!")

Cryogenic methane is a poor solvent

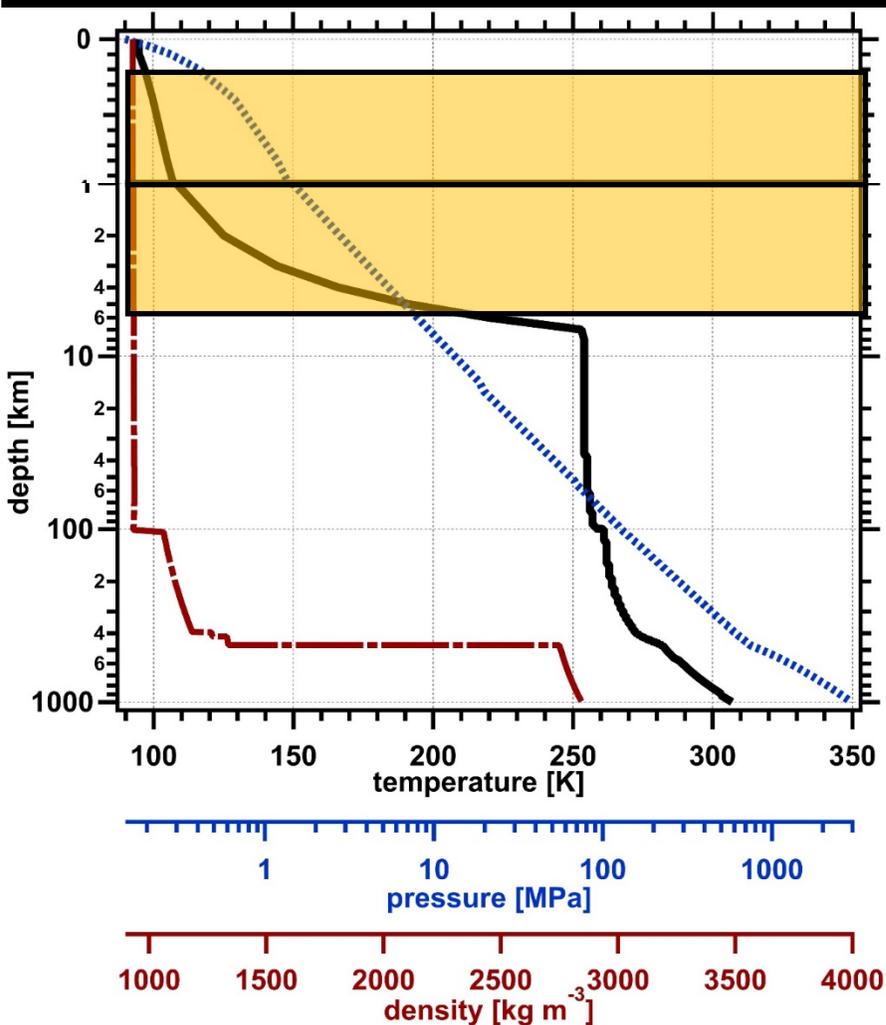
Building bigger molecules makes them insoluble!

(Life would require weak-transient, not covalent bonds)

Key questions:

What are typical dominant organics at surface?

100 m – 7 km Stagnant ice lid



Note scale change in y-axis. 0-1 km has a linear scale
>1 km depth is a log scale.

Hydrocarbon saturated ice (Ice 1h) zone

Porous (ice 1h) regolith? Possible clathrate ice.
Some organic penetration from tectonics, hydrocarbon fluid circulation

T = 95 K – 253 K steep thermal gradient

P = 0.15 MPa – 10 MPa

Density: 0.93 g/cm³

Warmer, better hydrocarbon solvents? ethane, propane

Some organics transported by fluid flow?

Cryovolcanic emplacements on ascent?

Crater impact mixing / injection

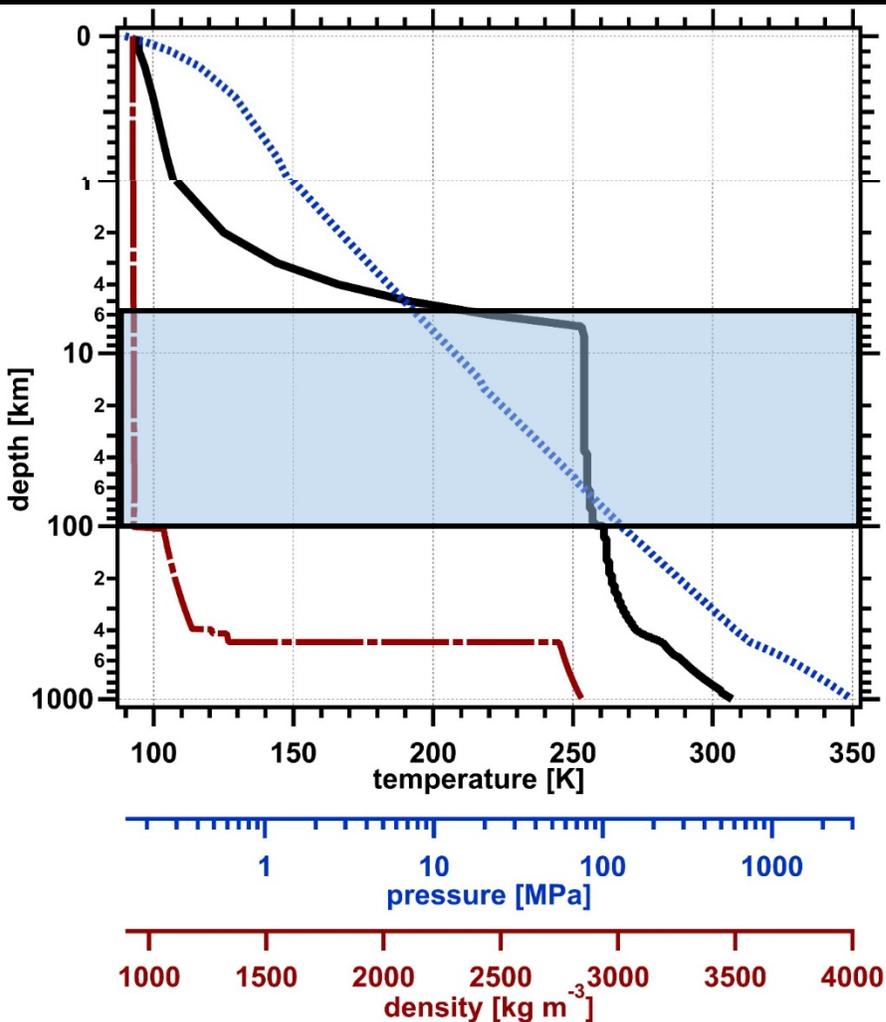
Key questions:

How deep do hydrocarbon liquids go?

How deep are organics (dissolved?) transported?

What are downward transport mechanisms/fluxes

7 km – 104 km Convective ice zone



Note scale change in y-axis. 0-1 km has a linear scale
>1 km depth is a log scale.

Convecting warm ice zone “conveyer belt”

T = 253 K – 261 K shallow thermal gradient
P = 10 MPa – 130 MPa
Density: 0.93 g/cm³

Organics descending!
Jacked liquid salt water solutions from upwelling!
Mixing of solid water/organics/liquids! Wheee!
Steep thermal gradient at ice-ocean interface

Key questions:

What are freezing points of relevant salt solutions at pressure?

What is limit for ascending liquid water solution?

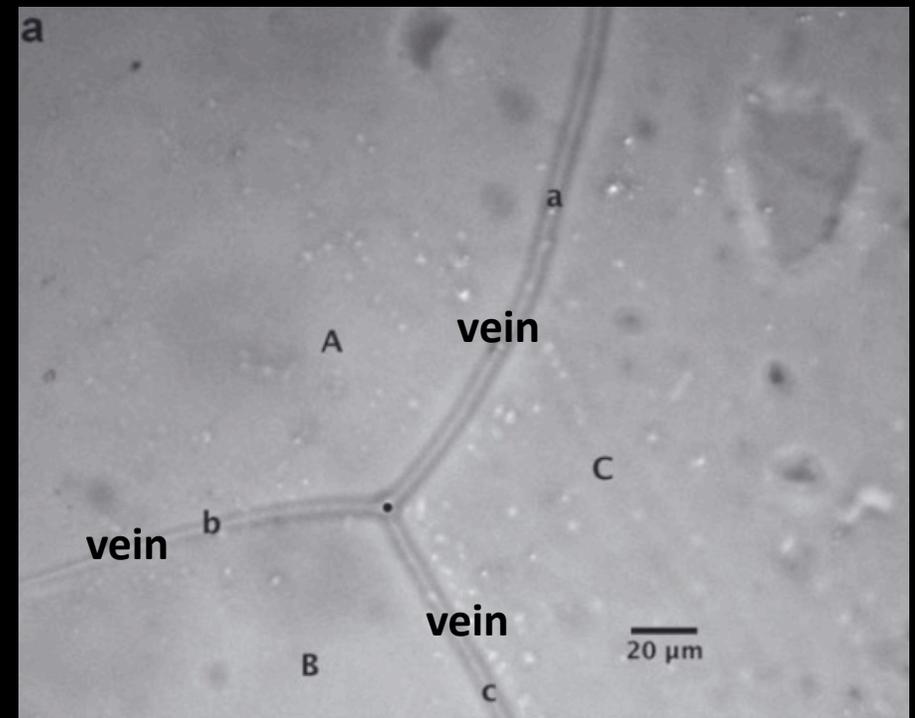
What terrestrial life could exist in these conditions?

Chemical concentration

As ice grains freeze out chemical concentrate

Data from GISP 2 ice core at 146 m depth

<u>ion</u>	<u>bulk</u>	<u>vein</u>	<u>Conc factor</u>
Sulfate	0.26 μM	101 mM	200,000
Nitrate	0.89 μM	53.6 mM	400,000



GISP 2 ice core 146 m depth image
Vein structures shown

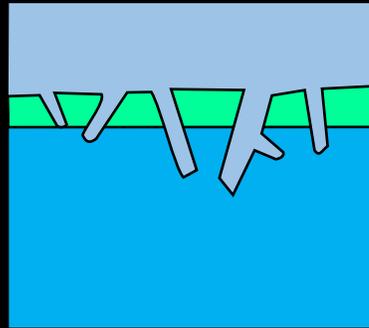
Huge increase in local ion concentrations in ice veins
Potential chemical microenvironments
10 – 100 μL volume per L of bulk ice volume (1 ppm)

Titan ice-ocean interface:

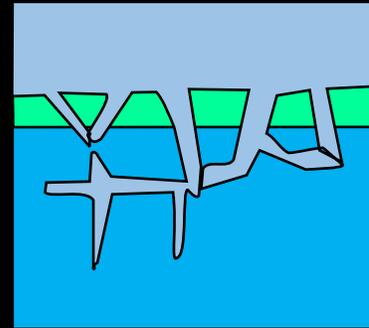
Convecting ice interface could make diverse isolated chemical environments



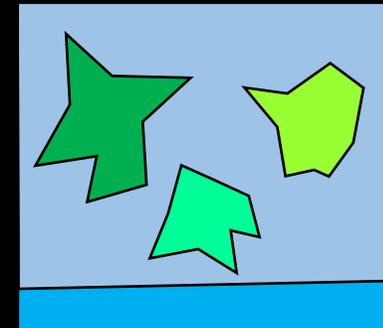
1) Ice-ocean interface



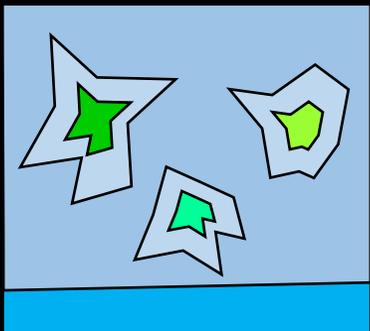
2) Freezing front advances



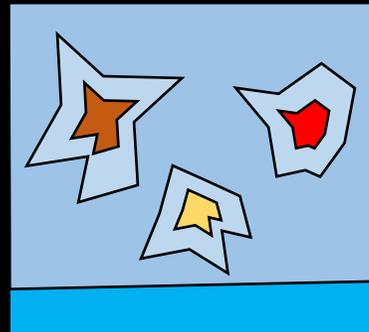
3) Ice crystals trap near surface materials



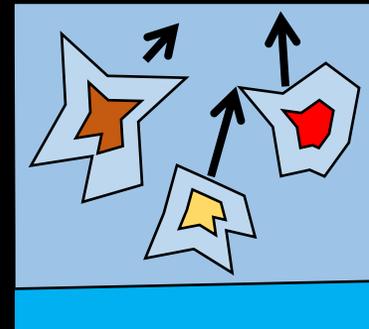
4) Material entombed in growing ice structure



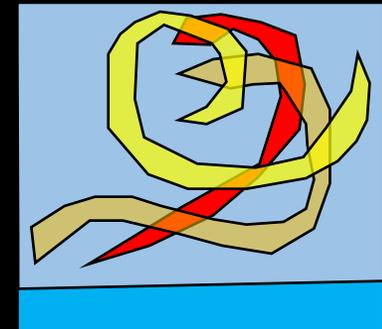
5) Water freezes out;
jacks concentration



6) Chemistry happens?

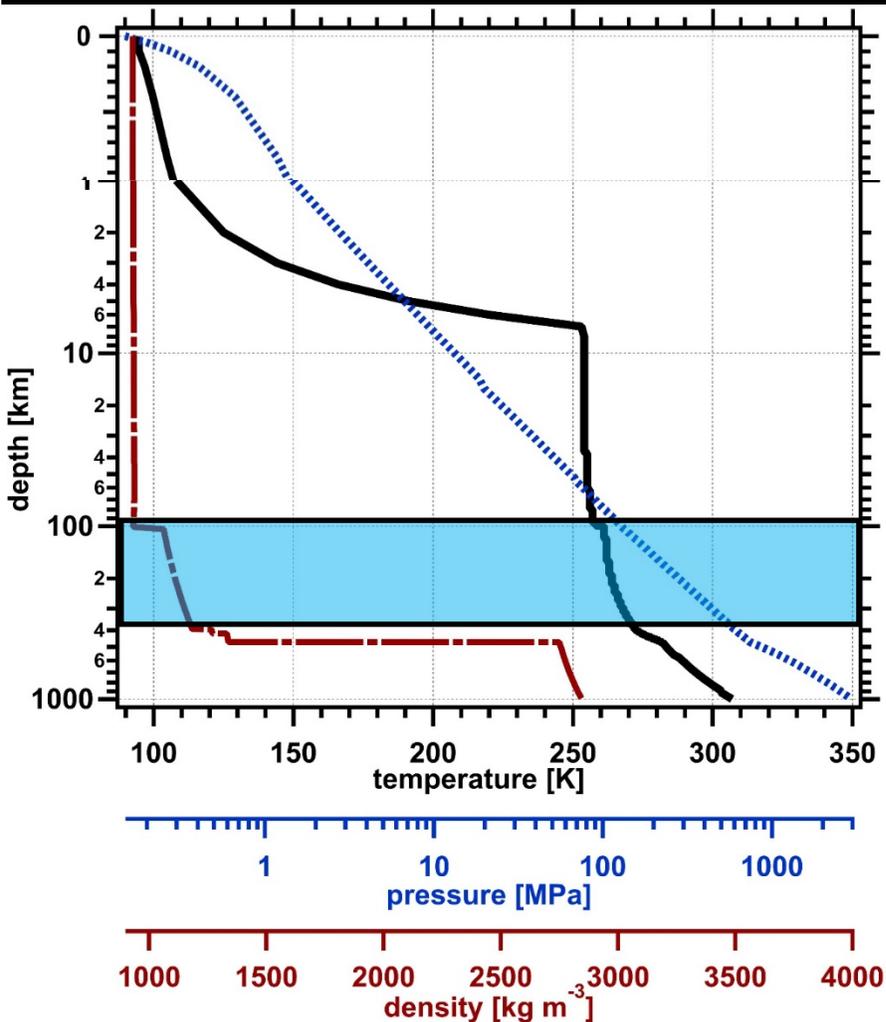


7) Convective transport



8) Wonderful mixing
during convection

100 km – 395 km Deep subsurface Ocean



Note scale change in y-axis. 0-1 km has a linear scale
>1 km depth is a log scale.

Water ocean

Composition 0-3% NH₃/H₂O – 0-10% MgSO₄/H₂O

Exact depth to Ocean 74-108 km from Cassini-Huygens

T = 261 K – 272 K shallow thermal gradient

P = 133 MPa – 600 MPa

Density: 1.1 g/cm³ – 1.2 g/cm³

Water ocean!

Reducing conditions

Interfaces of ice layers (and core?)

Potential for salts extracted from core mixing

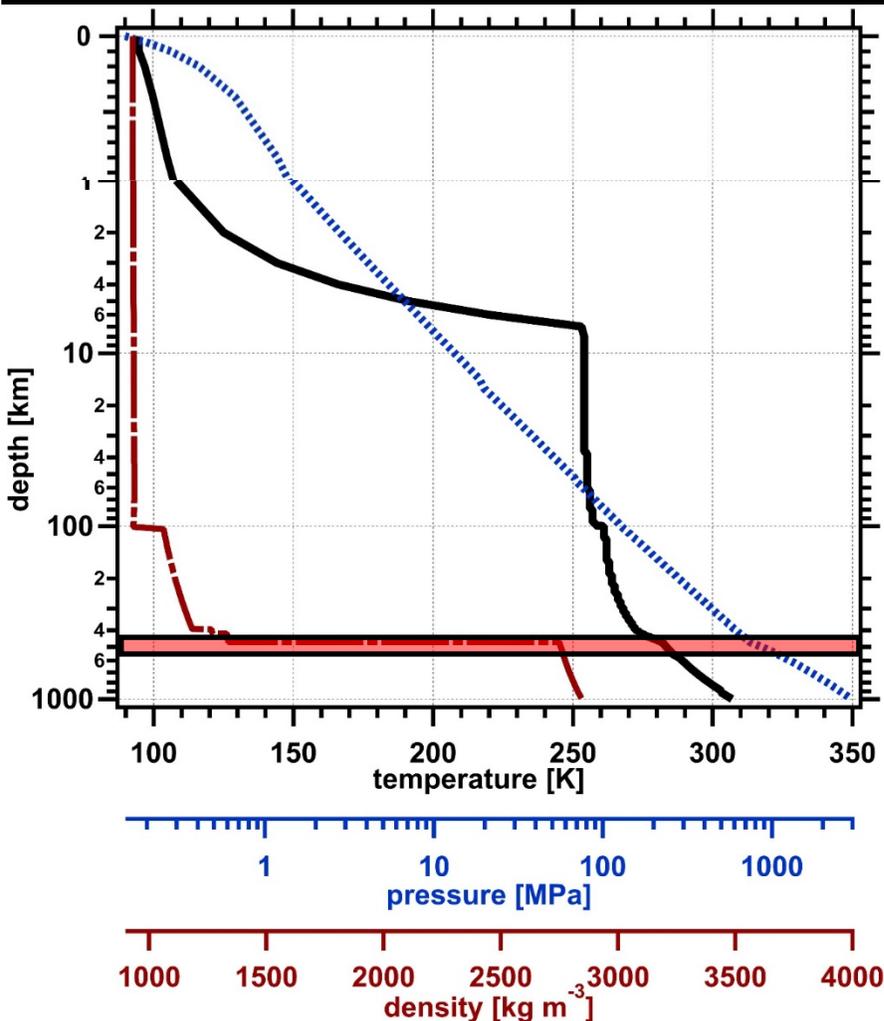
Repository for transported organics

Key questions:

Exactly how deep to ocean?

What are likely chemical compositions?

395 km – 470 km High Pressure Ice Layers



Note scale change in y-axis. 0-1 km has a linear scale
>1 km depth is a log scale.

HP ices (ice V and Ice VI)

May not completely seal off core from Ocean
(Limited exchange)
Layer thickness, presence of ice V layer parameter dependant.

T = 272 K – 282 K shallow thermal gradient
P = 600 MPa – 750 MPa
Density: 1.3 g/cm³

Freezing conditions (squeezing ocean from both sides)
may allow similar jacking of trapped chemicals

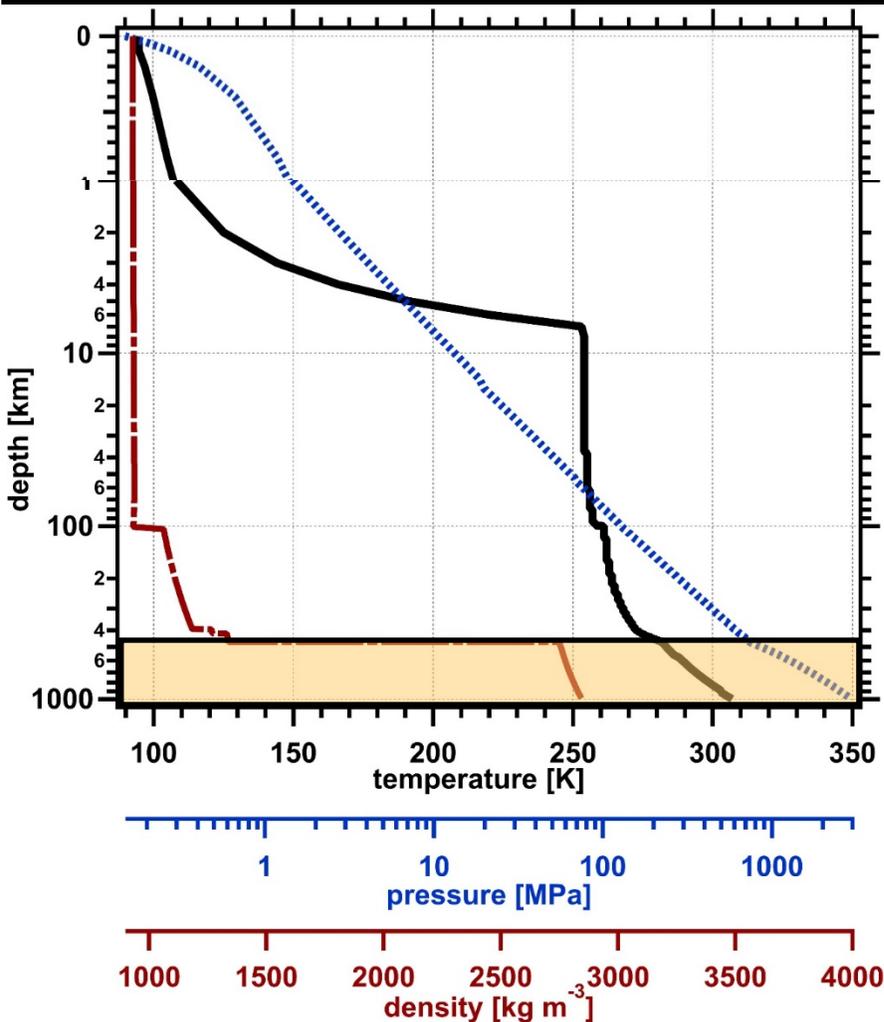
Key questions:

Exactly how deep to ocean?

What are likely chemical compositions?

470 km – center Hydrated silica core

Hydrated silicates



Note scale change in y-axis. 0-1 km has a linear scale
>1 km depth is a log scale.

T = 282 K – 340 K (500 K?) shallow thermal gradient
P = 750 MPa – 9.9 GPa (Earth life limit is 2.1 GPa)
Density: 2.7 – 3.2 g/cm³

Possible inhomogenities could create diverse microenvironments in core and contact with HP ice

Primarily inorganic environment

Source of CH₄, NH₃, and organics! (Miller et al., 2019)

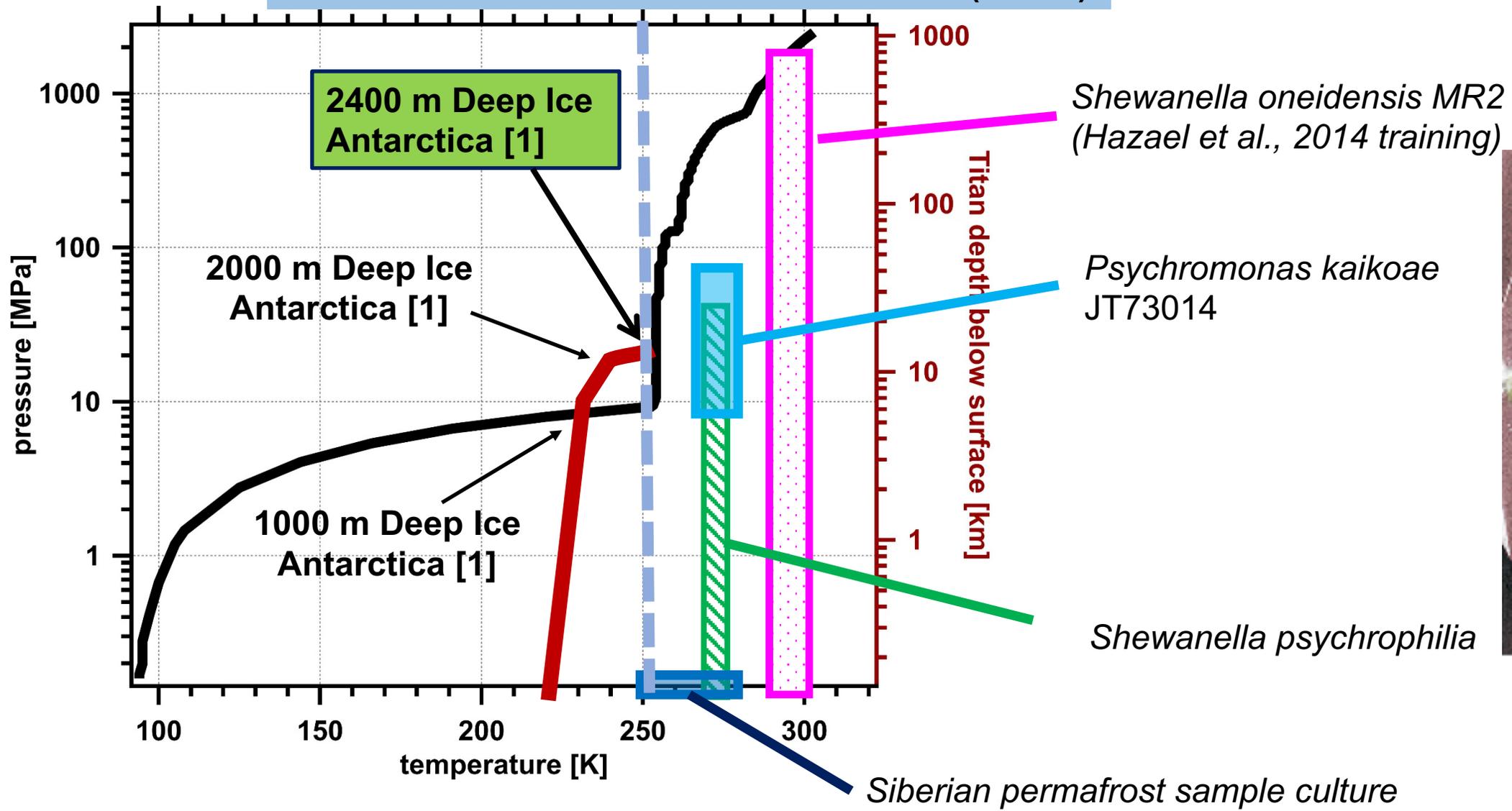
In theory, life could exist to 2000 km depth at Titan pressure, temperature conditions.

Key questions:

How much exchange with Ocean now? In past?
Pore spaces/fracture/fluid convection?
What are high pressure limits for terrestrial life?

Titan P,T plot overlaps with terrestrial Deep Ice habitats!

Putative limit for active metabolism 253 K (-20 °C)

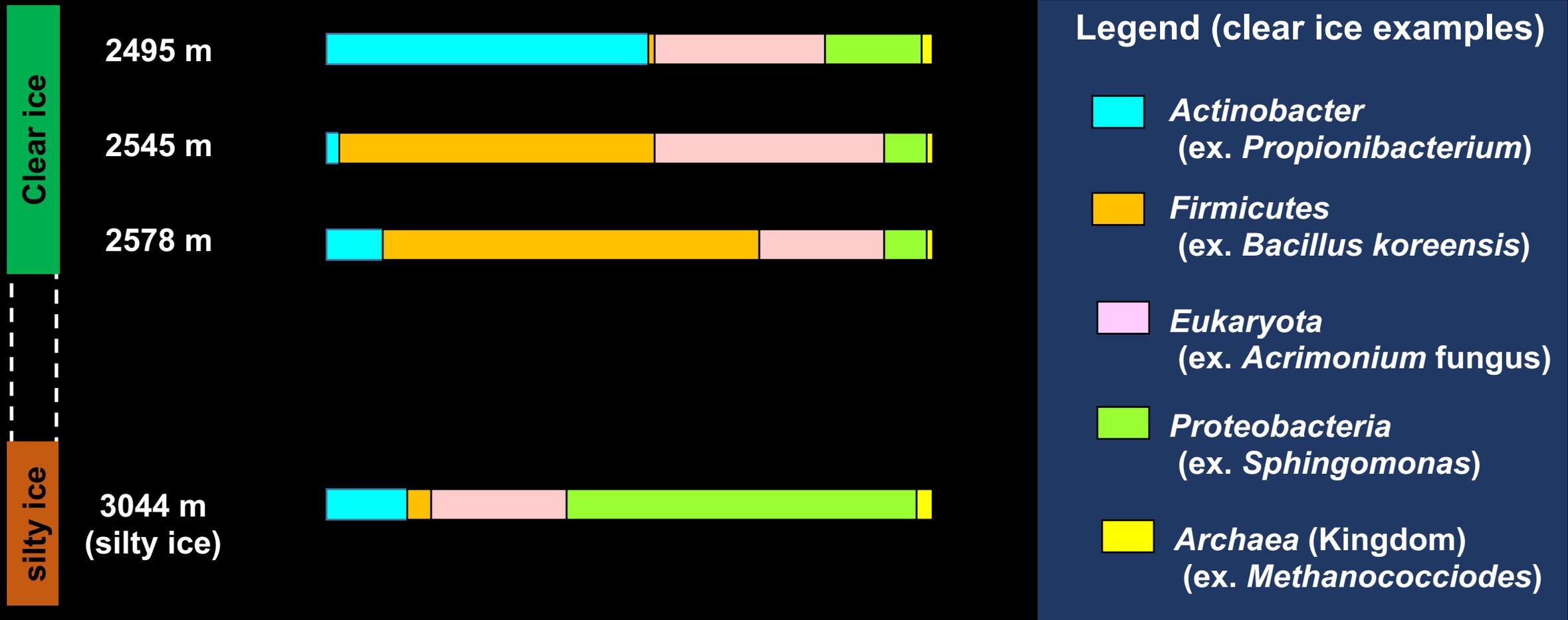


[1] Data from AMANDA boreholes, see Price et al., PNAS 99 (2002), 7844-7847.

Microbial diversity in terrestrial Deep Ice

Data from GISP2 core melt and culture experiments

Corresponding *P.T* conditions of 11 km deep in Titan's subsurface



Titan's Layers: Conclusions, Implications, and Questions

Multiple layers of Titan; Multiple opportunities to mix organics / water

How deep do organics go down from surface?

Or come up from interior?

Some Titan conditions similar to conditions in Antarctic/Greenland Deep Ice environments

Convective ice layer (7 km - 100 km) and crustal ice ocean interface (100 km) might be most favorable for life to exist, and even originate on Titan.

Large areas of habitable *T* and *P* (and some liquid H₂O) could exist on Titan

Need a combo psychrophile-piezophile

What are the cold-pressure combination limits of adapted terrestrial life

What are further constraints on physical/chemical environment?

What are transport mechanisms/fluxes?