Why should Titan's ocean be organic rich?

What thermodynamic modeling of the dewatering of undifferentiated versus differentiated moons can tell us

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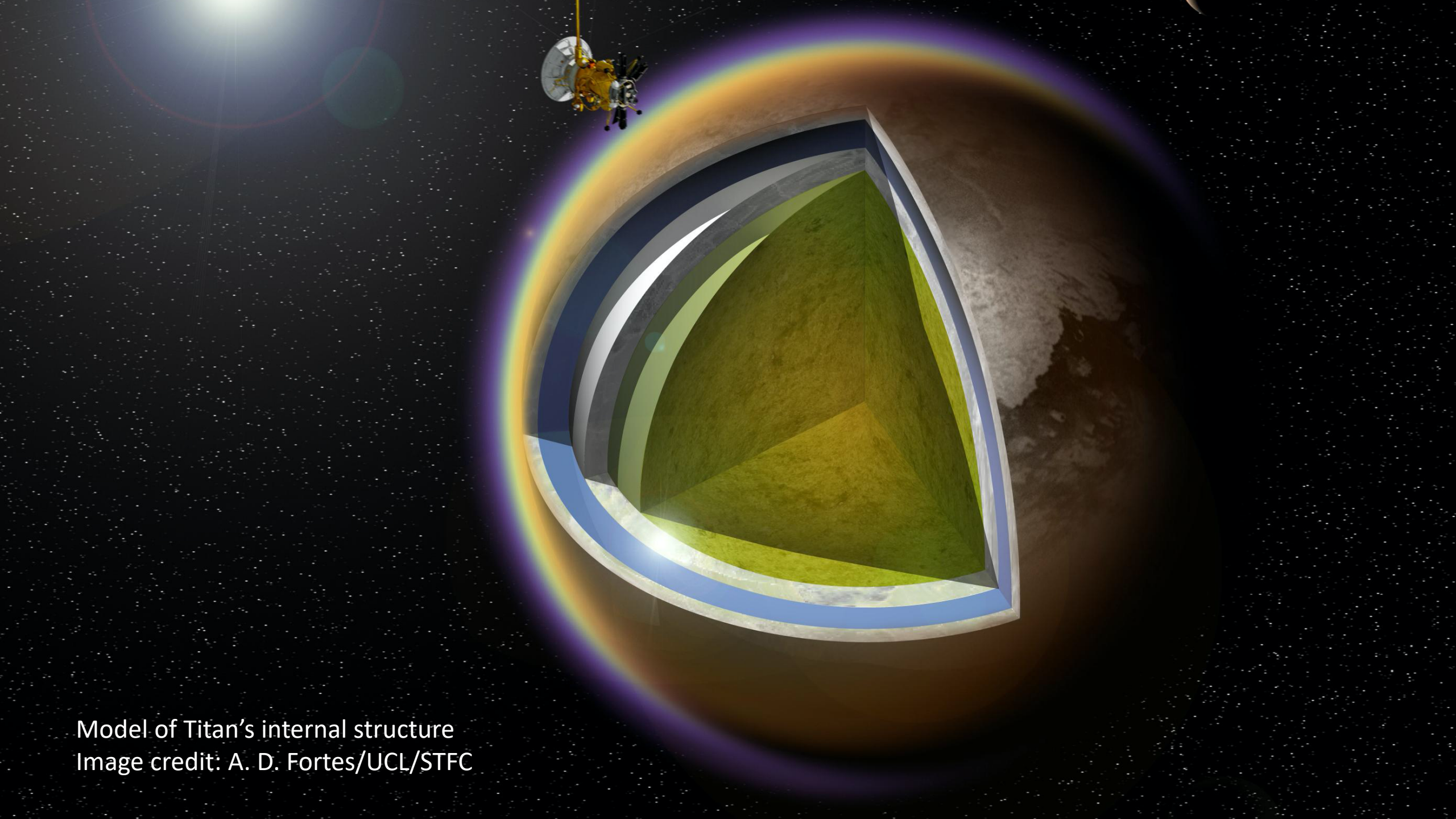


Model of Titan's internal structure
Image credit: A. D. Fortes/UCL/STFC

Background

- Titan's ocean chemistry is inferred from the composition of the surface and atmosphere.
- Tidal Love number, obliquity and gravity field measurements only inform about the ocean's extent and density (e.g., Baland et al., 2018).
- High-pressure ice may limit present-day water-rock reaction at Titan's seafloor that would permit delivery of organics and redox sensitive species to the ocean (but see also: Kalousova and Sotin, 2018).
- However, early high heat flow and tidal dissipation within Titan's rocky interior probably allowed interactions between the ocean and rock (Tobie et al. 2006).
- Are the organics and ammonia at Titan's surface a result of this earlier water-rock interaction, or are they a result of later delivery?
- And why should Callisto, Ganymede or Europa's ocean compositions be any different?

Overarching questions

- What influence does the interior structure of Titan have over the composition of its ocean?
  - Vary interior structure models and bulk compositions
  - Constrain the reactions and fluid compositions resulting from interior heating
  - How does the ocean composition change with depth?

In parallel, we are generating a suite of ocean compositions for our interior structure models (*PlanetProfile*, Vance et al., 2018, JGR Planets), that will further refine our understanding of the interior structure

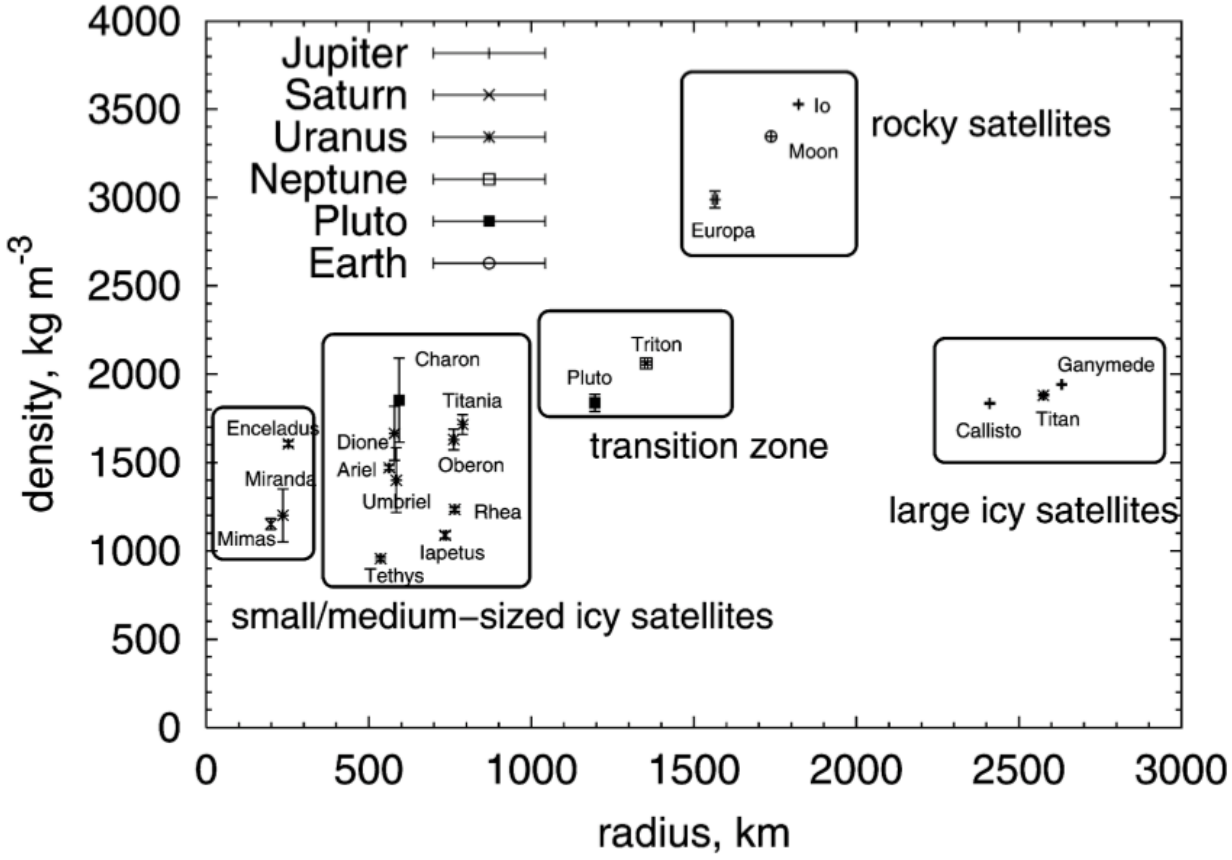
What was Titan's initial bulk composition?

- Different meteoritic building blocks contain different masses of water:

CI (~11 wt. %) > CM (~10 wt. %) > Europa > L (~1 wt. %) > H (~0.3 wt. %) > CV (~0.2 wt. %)

(Meteorite water contents from Lodders and Fegley, 1998.)

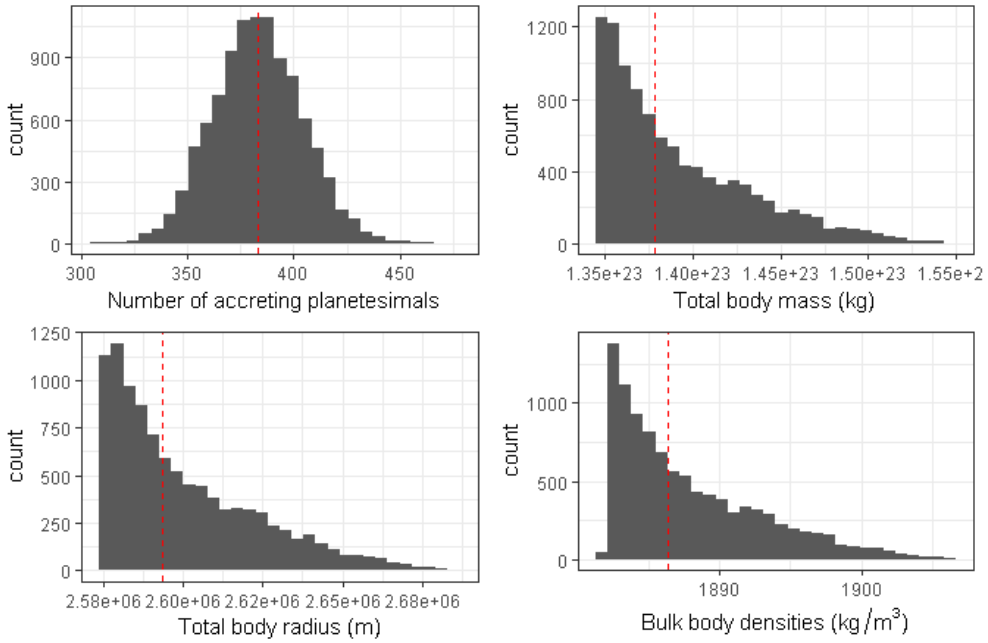
- Cometary material could form a significant fraction of the initial bulk composition.
- What is the bulk concentration of carbon?

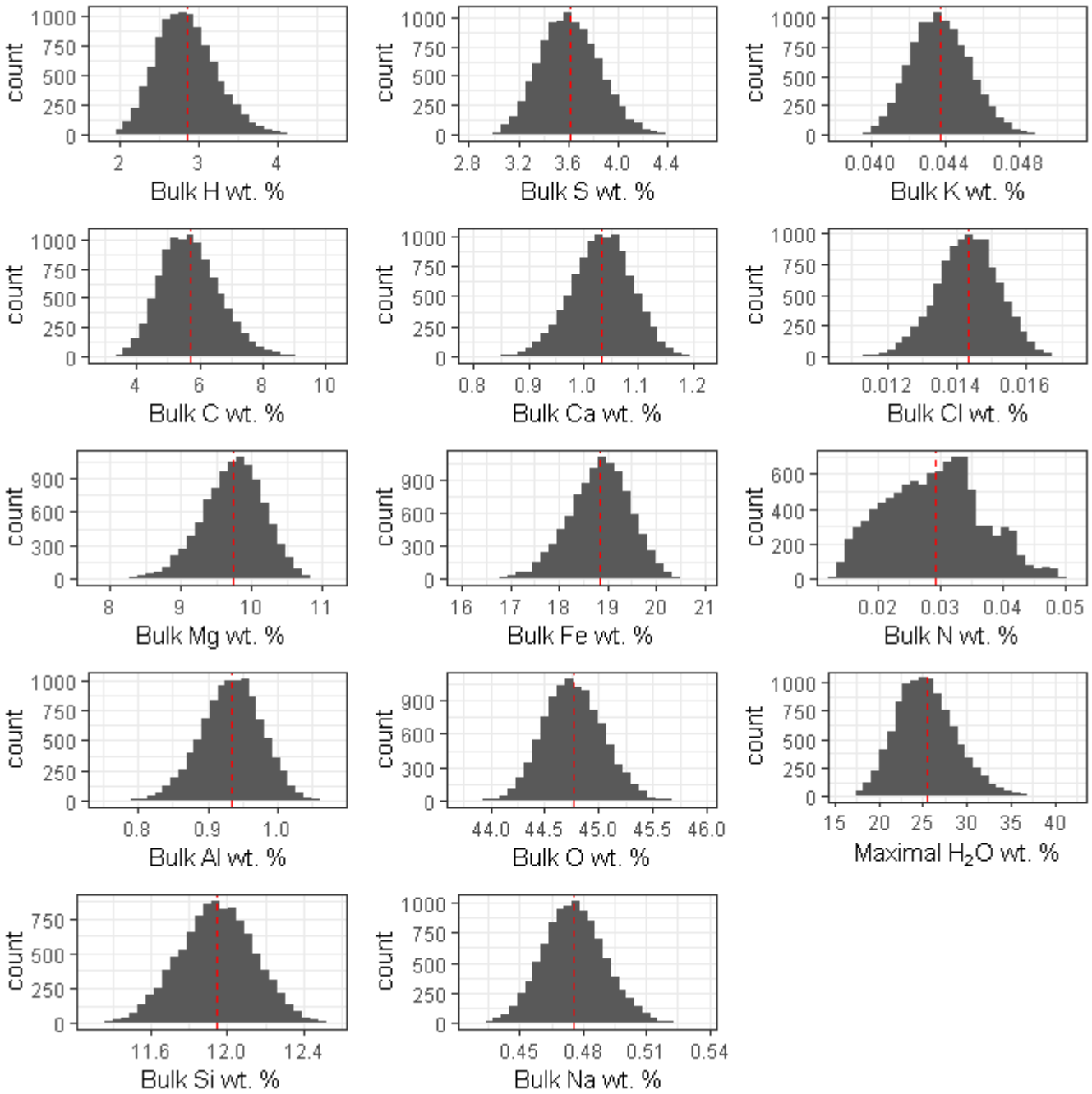


Summarized results of the accretion model for 10,000 accreted Titans

Hard constraints and assumptions:

- Titan's bulk mass and radius have not changed since accretion (i.e. current values)
- Uniform probability of CI, CM and cometary planetesimal building blocks
  (~ In line with Desch et al. 2018, ApJ.)
- Runaway, non-ablative growth

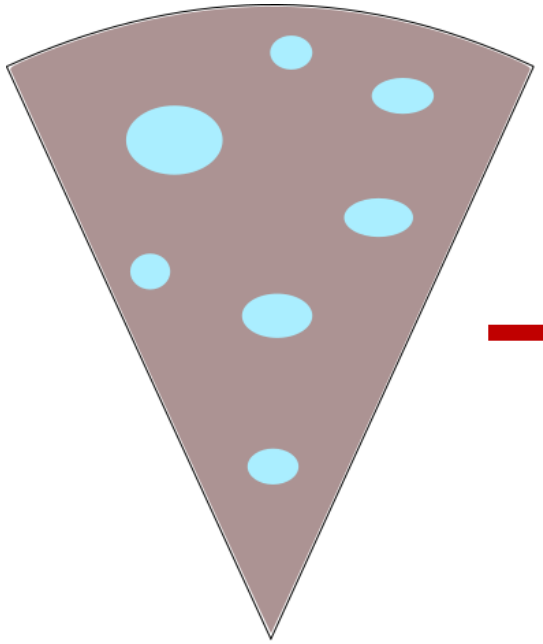




Scenarios modeled

Accreted Titan

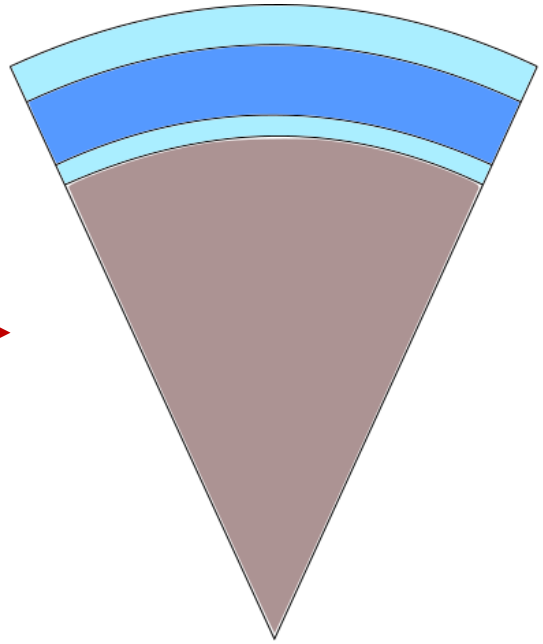
(homogeneous composition)



1

Core-less Titan

(current Titan?)

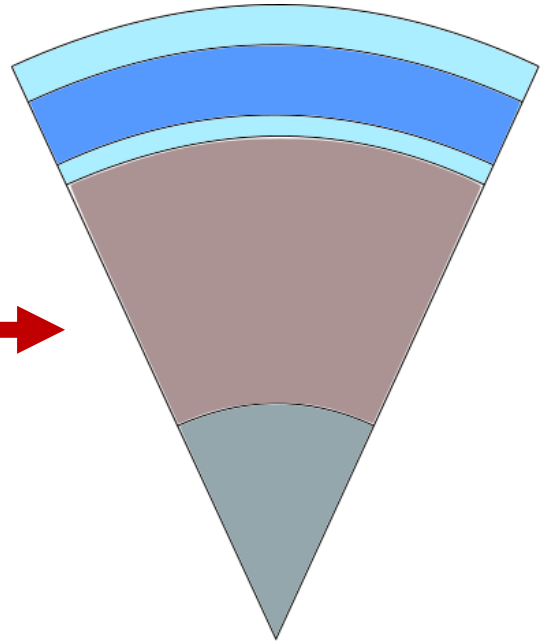


Differentiation trend

2

"Europan Titan"

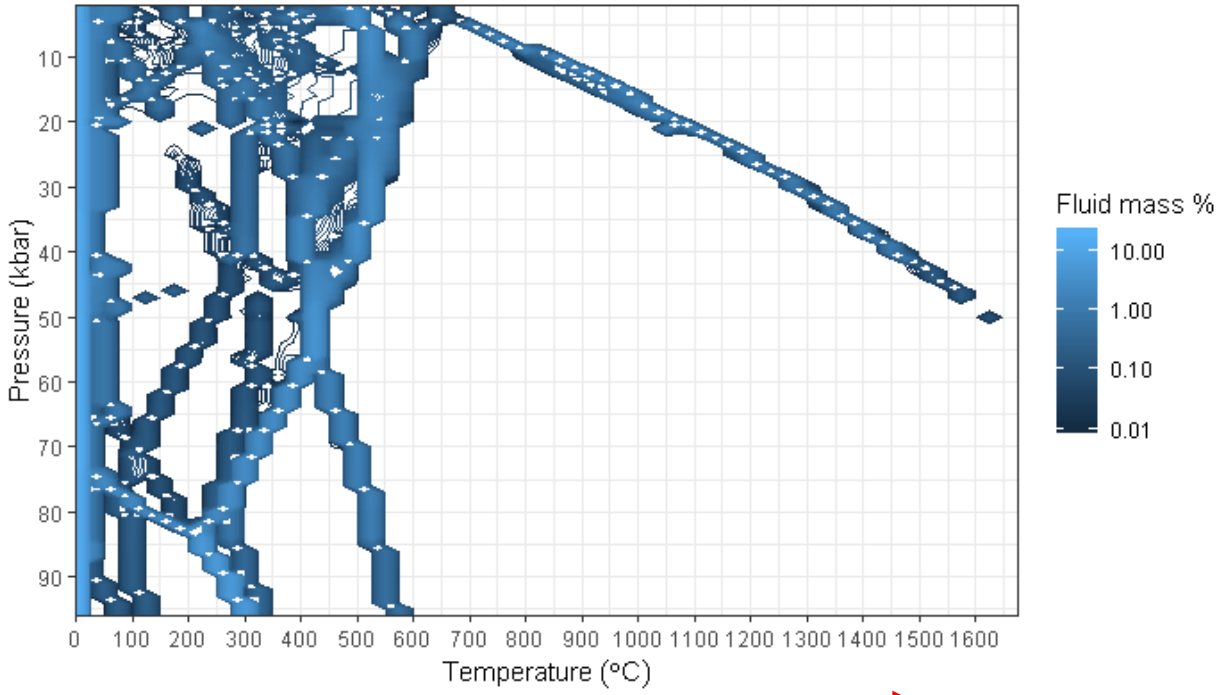
(Titan with an iron core)



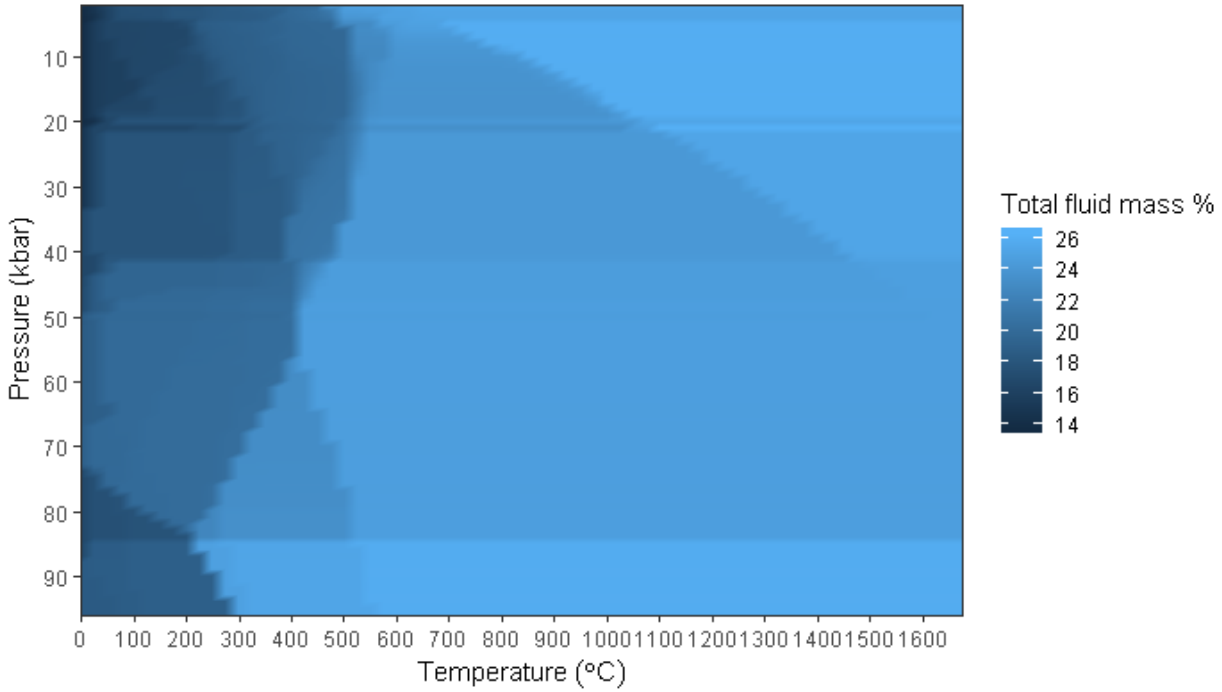
For now, let's ignore that it would have a very different bulk density and moment of inertia, and let's focus only on composition

Interior heating models: Constraining the amount of fluid produced inside Titan

Fluid mass produced in the interior at different pressures /depths and temperatures



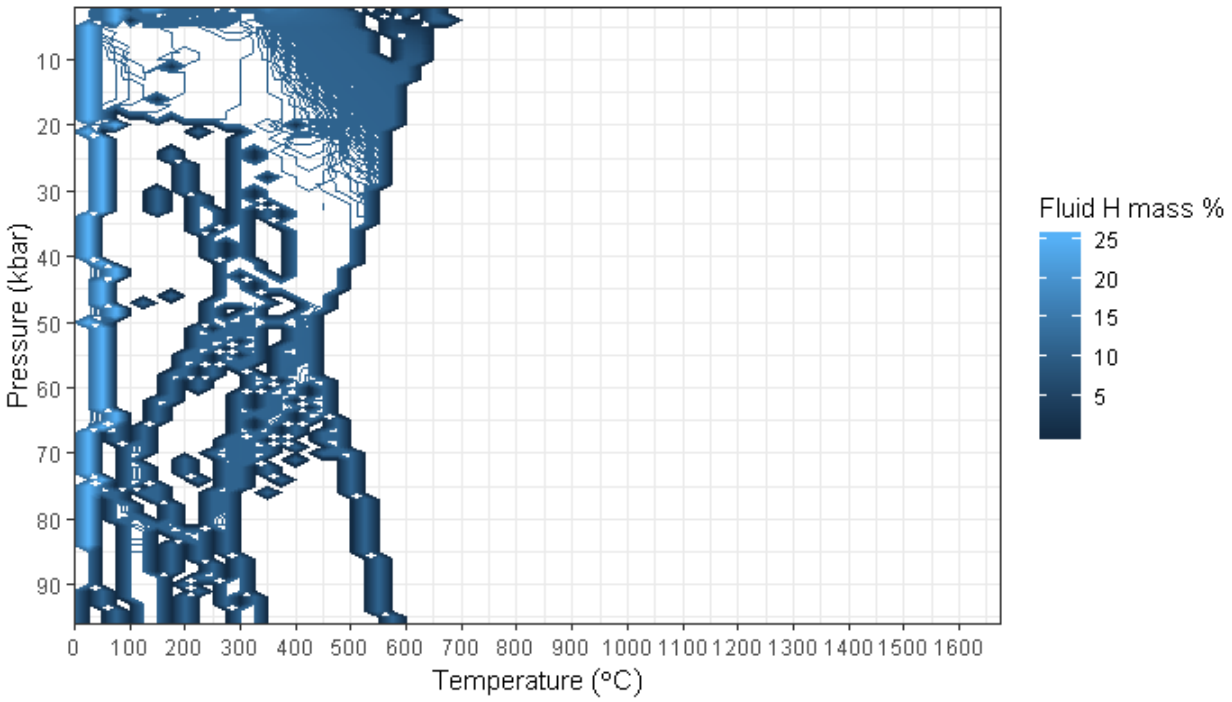
Integrated fluid mass produced in the interior at different pressures and temperatures



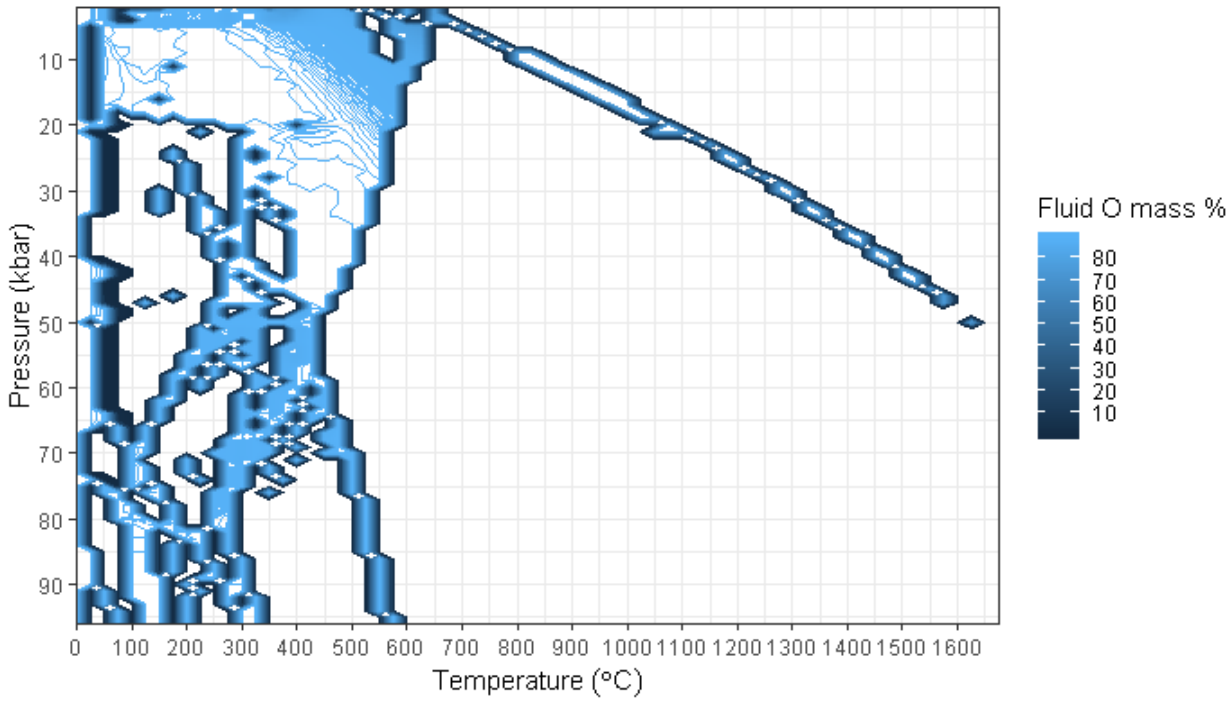
Heating homogeneously (left to right on graph). Fluids are removed from the system as they are produced. Calculated using free energy minimization with Perple_X (Connolly 2005; 2009).

Composition of the fluid (I)

Hydrogen mass % in the fluid



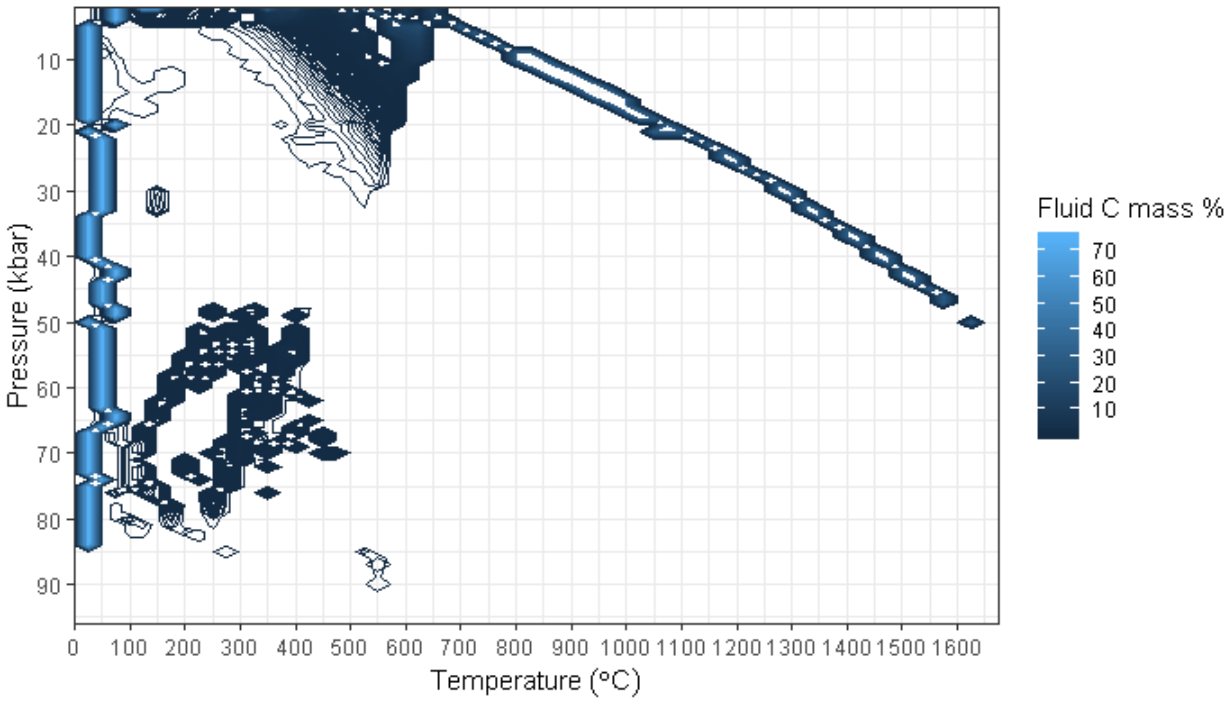
Oxygen mass % in the fluid



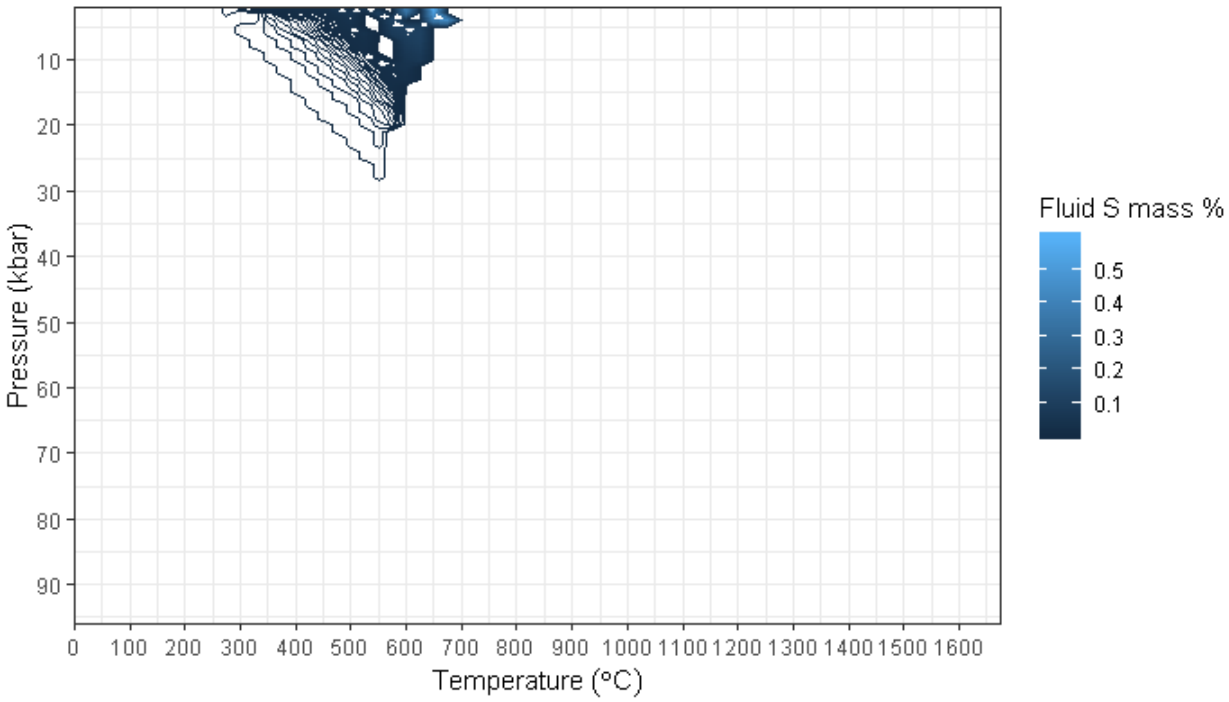
Heating homogeneously (left to right on graph). Fluids are removed from the system as they are produced. Calculated using free energy minimization with Perple_X (Connolly 2005; 2009).

Composition of the fluid (II)

Carbon mass % in the fluid



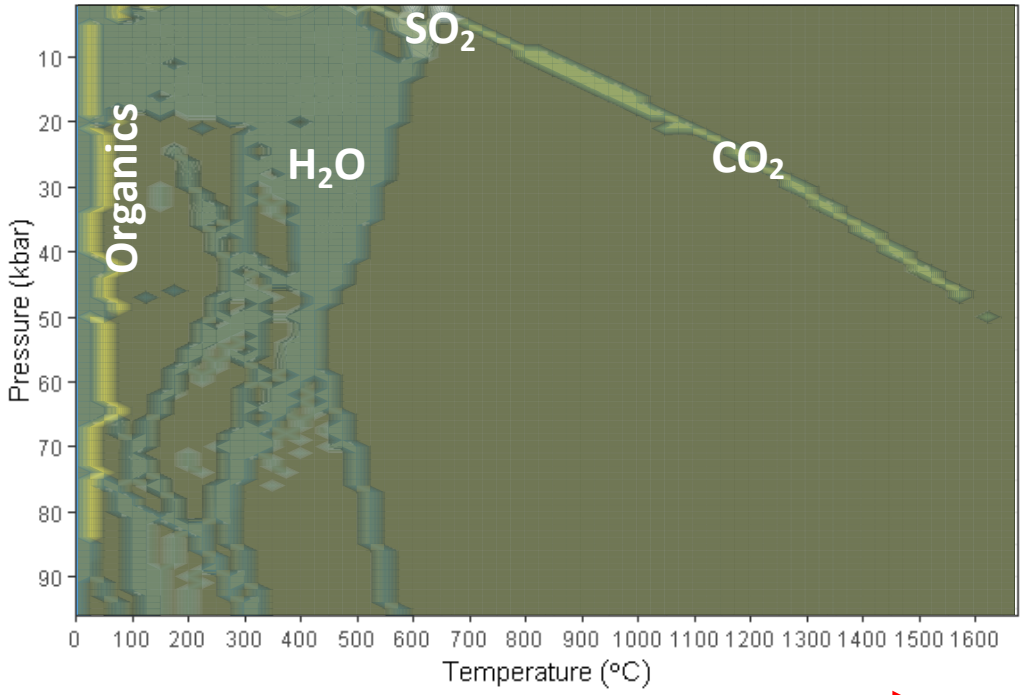
Sulfur mass % in the fluid



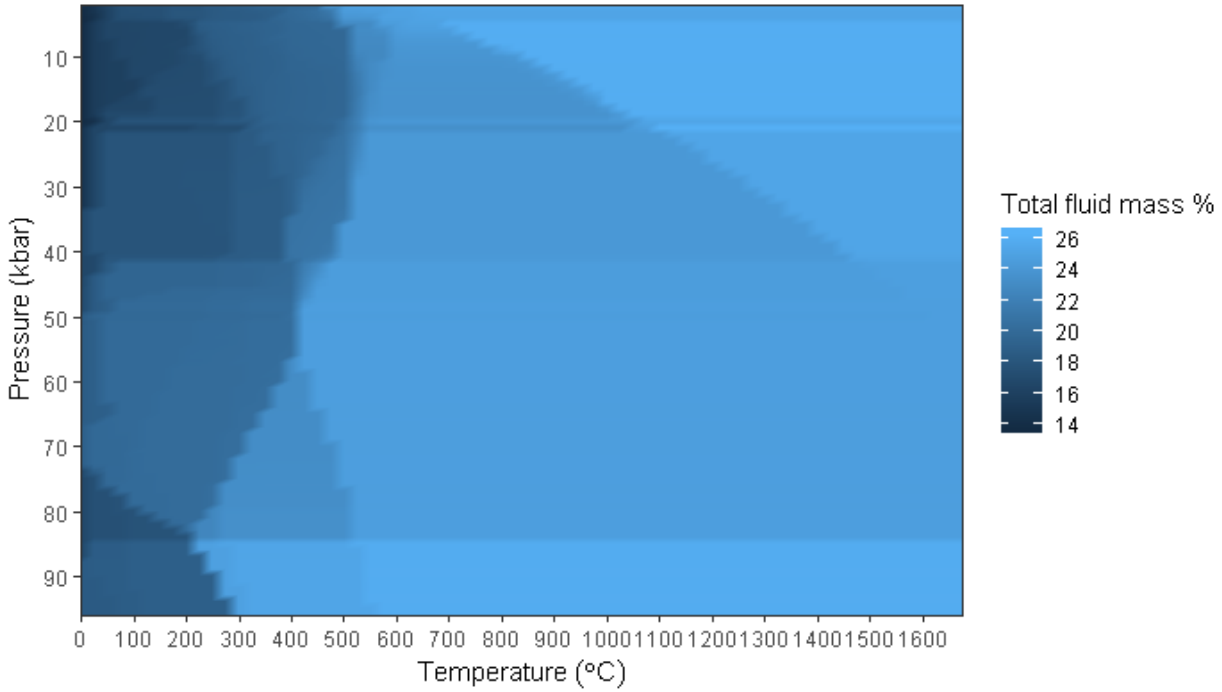
Heating homogeneously (left to right on graph). Fluids are removed from the system as they are produced. Calculated using free energy minimization with Perple_X (Connolly 2005; 2009).

Composition of the fluid (III)

Fluid composition



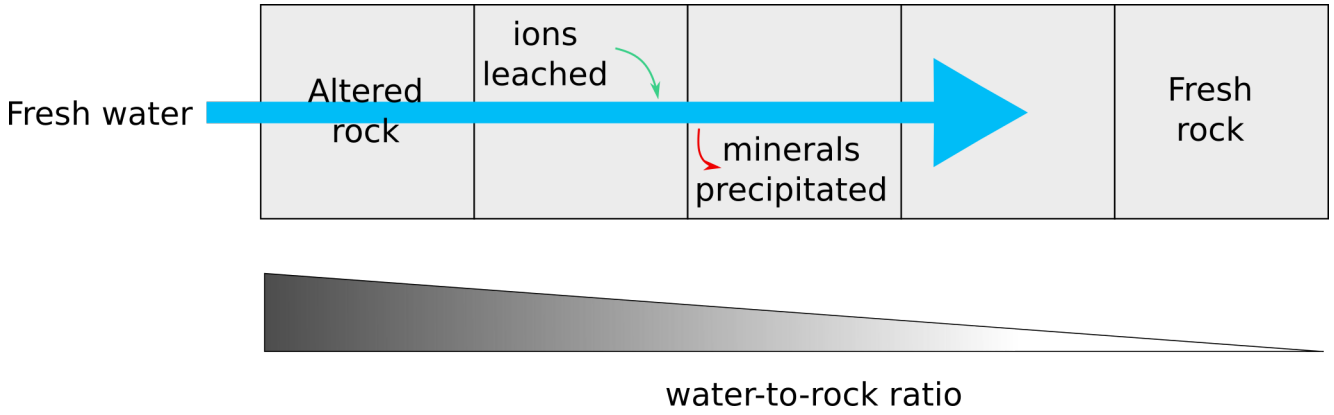
Integrated fluid mass produced in the interior at different pressures and temperatures



Heating homogeneously (left to right on graph). Fluids are removed from the system as they are produced. Calculated using free energy minimization with Perple_X (Connolly 2005; 2009).

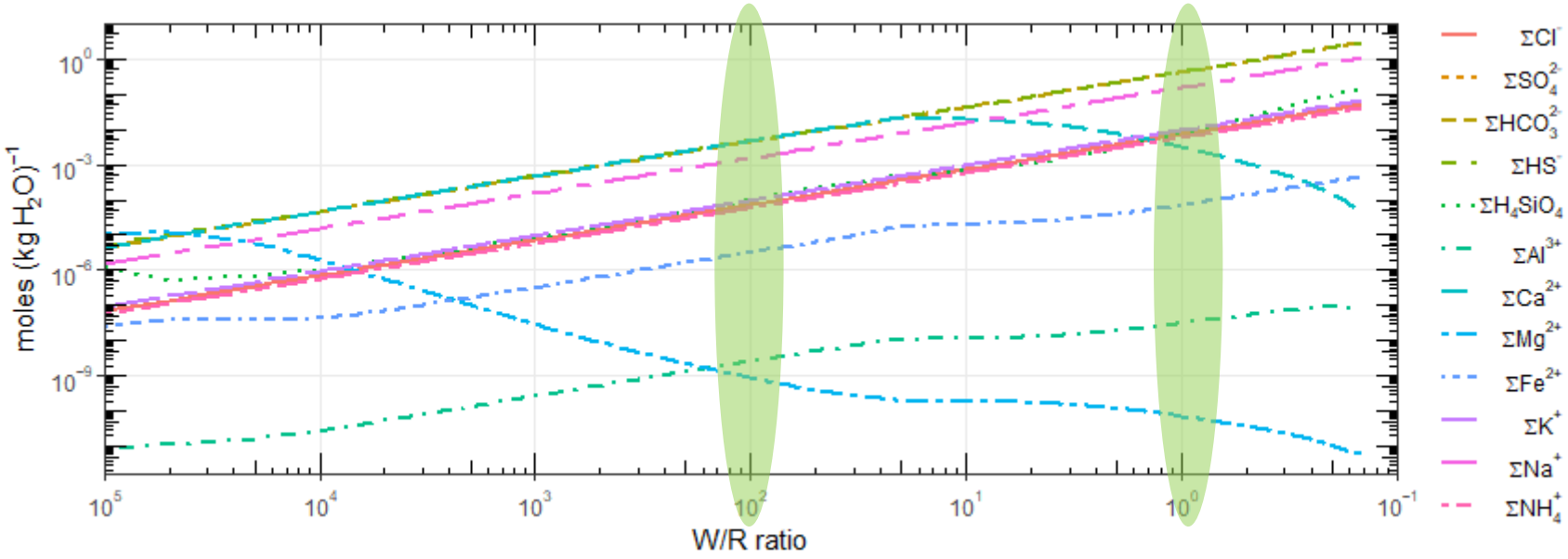
Water-rock reaction at the seafloor

- *PlanetProfile* informs about realistic geophysical conditions.
- *CHIM-XPT* (Reed, 1998)
  - Debye-Hückel fluid-rock-gas equilibria model, in “batch” reaction mode.
  - No kinetic considerations, other than disallowing minerals. (Probably reasonable for water-rock interaction on Gyr timescales.)
- Pressure at seafloor = 0.8 GPa
- Assumed average temperature of the ocean = 0.01 °C
- Water-CH_4 equilibrium permitted here: We assume any methane, ethane, etc. formed by water-rock reaction early in Titan’s history (as seen in previous slides)

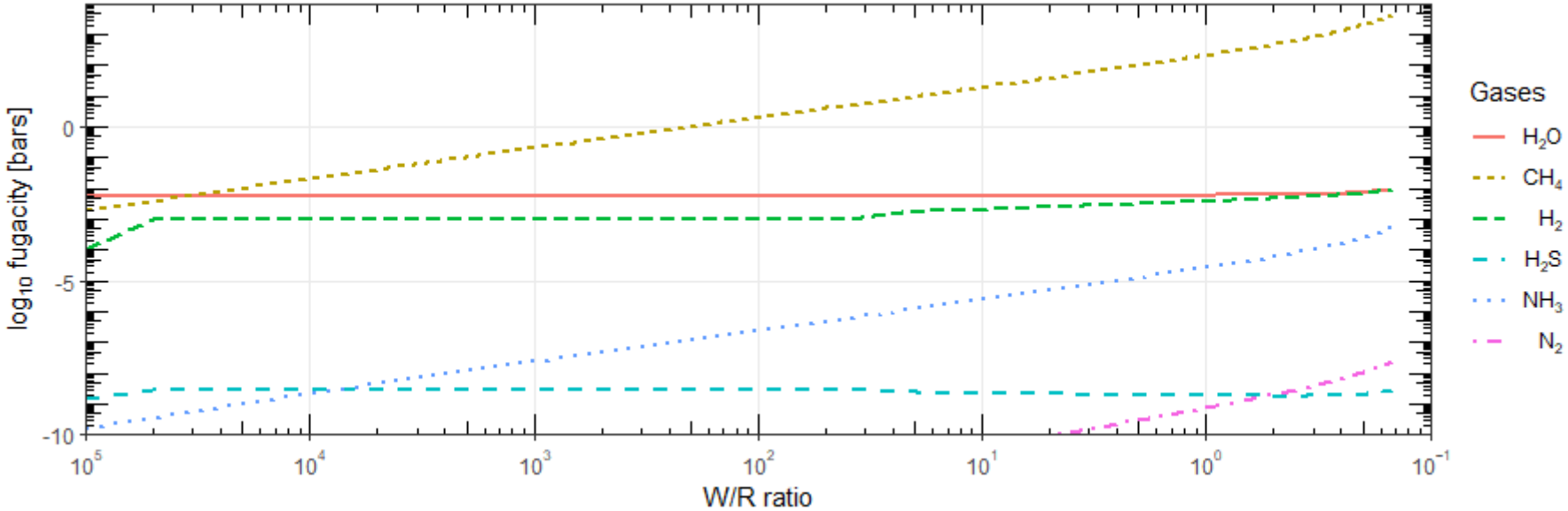


Titan today: water-rock equilibrium at 800 MPa, ~0 °C
(methane-water equilibrium allowed in this scenario because we assume methane was produced early)
Silicate composition = CV chondrite undifferentiated body

Fluid composition

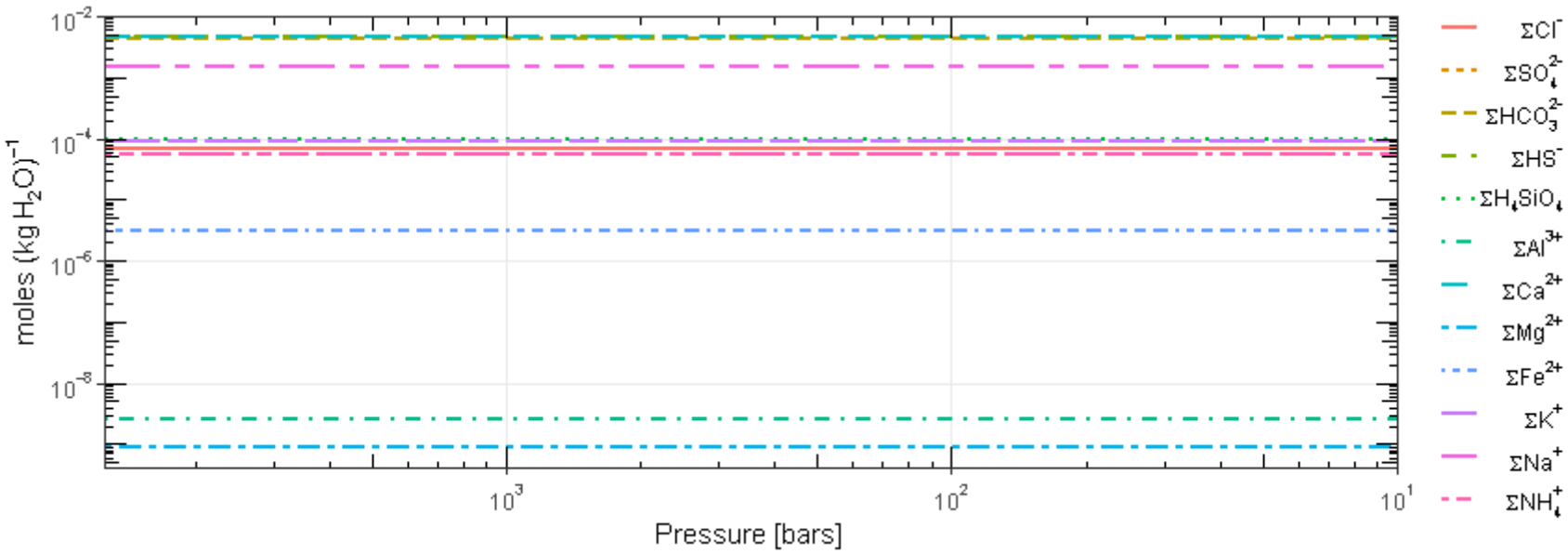


Gas fugacity



Isothermal decompression of the fluid, from 800 MPa to 0.1 MPa
Fluid derived from water-rock reaction at water/rock ratio = 100
Solids and gases fractionated, i.e. this is the fluid composition only

Fluid composition



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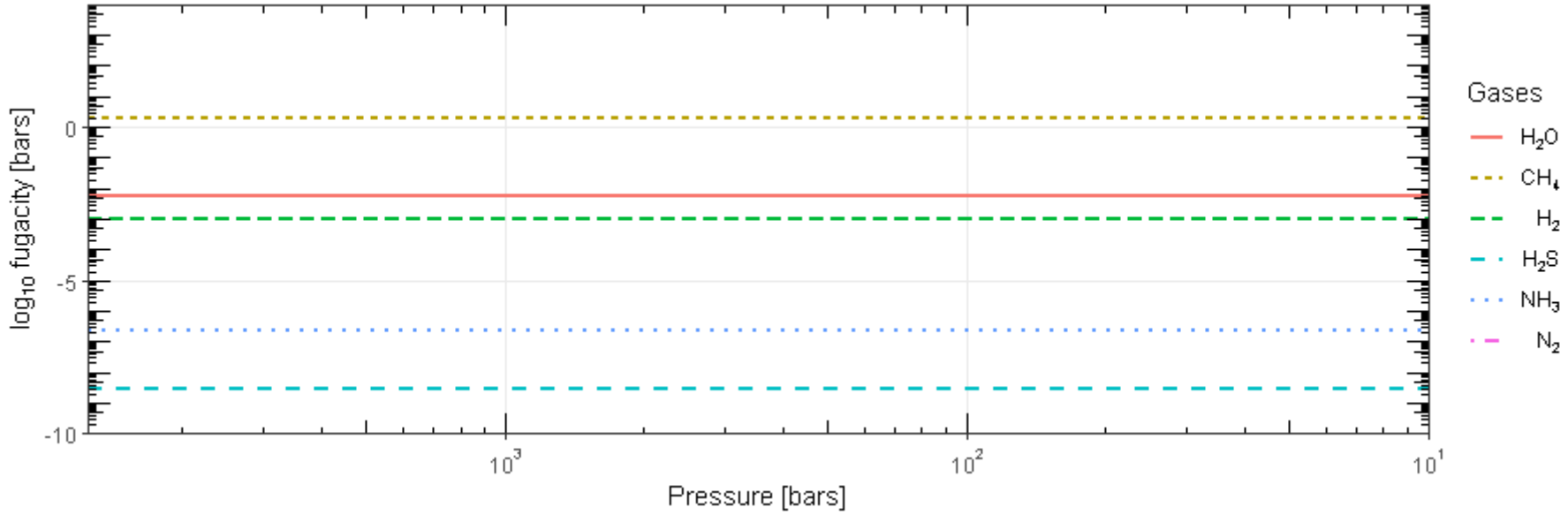
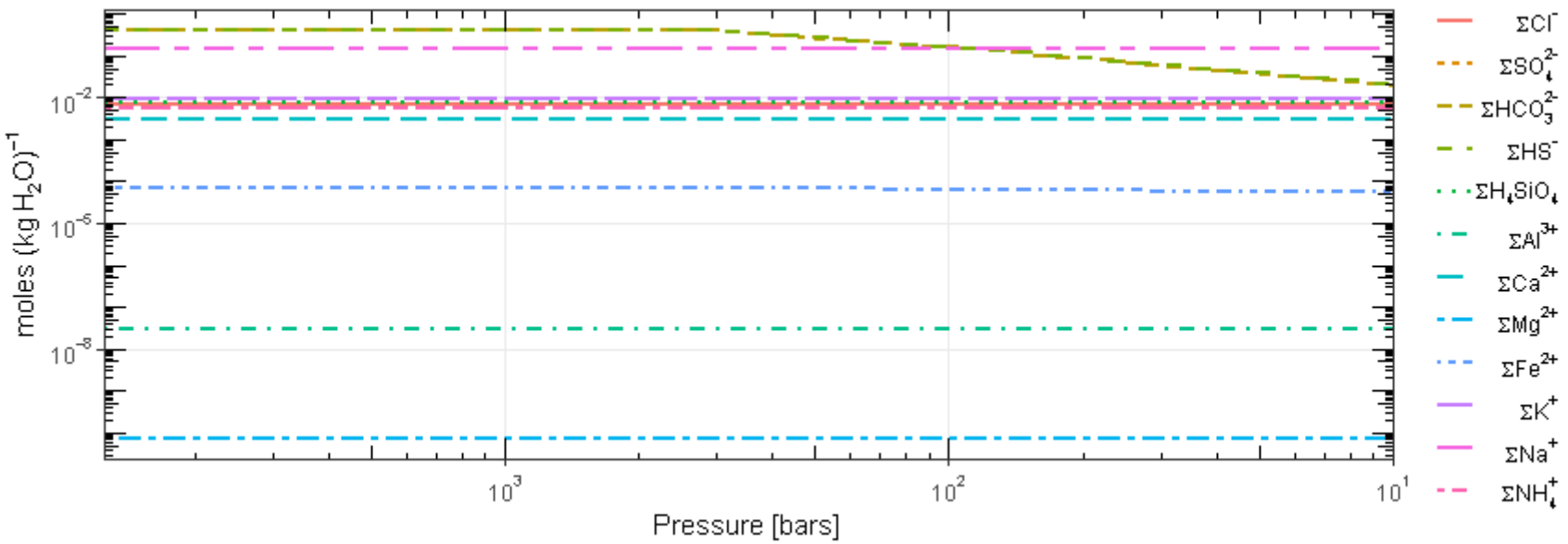


Isothermal decompression of the fluid, from 800 MPa to 0.1 MPa
Fluid derived from water-rock reaction at water/rock ratio = 1
Solids and gases fractionated, i.e. this is the fluid composition only

Fluid composition



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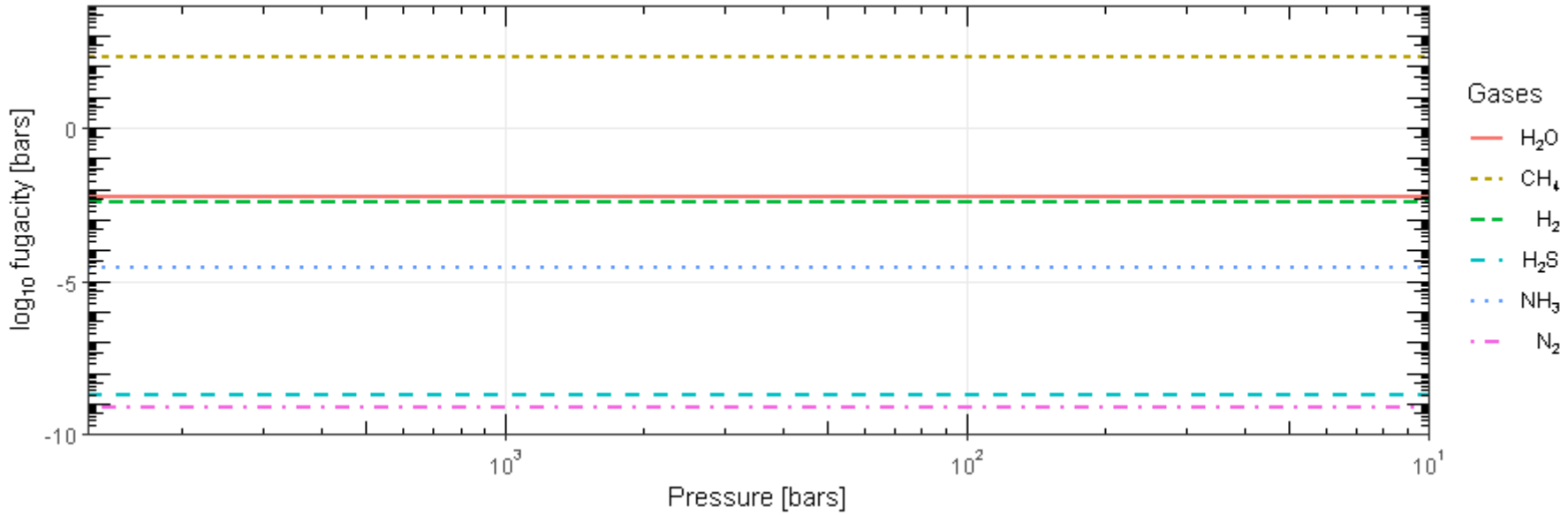
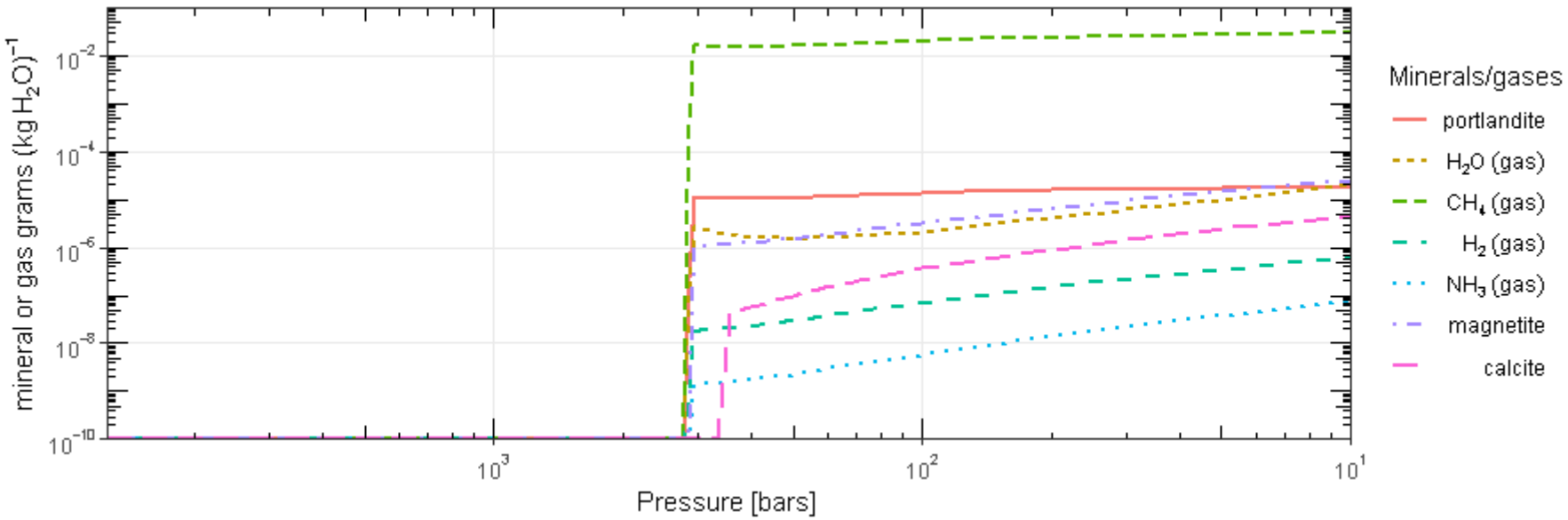


Isothermal decompression of the fluid, from 800 MPa to 0.1 MPa
Fluid derived from water-rock reaction at water/rock ratio = 1
Solids and gases fractionated, i.e. this is the fluid composition only

Minerals and gases formed in the water column
(and removed from equilibrium assemblage at each decompression step)



Calcite lysocline for this particular ocean composition is at ~75 Mpa

Next steps

- Follow realistic pressure-temperature ocean profiles
- Go from pressure -> depth
- Account for solubility of atmospheric species and crust at surface -> fluid-fluid mixing
- Mass balance in time: could the atmospheric species and “crust” compositions have been produced from water-rock interaction early, before the formation of a HP ice layer?

Backup slides

More details about the accretion model (*AccretR*)

- Assumes Titan follows a power law growth track:
  $(\text{Radius}/\text{Radius}_{\text{Earth}}) = 1.2705 \times (\text{Mass}/\text{Mass}_{\text{Earth}})^{0.302}$
  Modified from Sotin et al. (2007) *Icarus*
- Initial embryo radius = 10 m
- Energy of accretion = $\int_{10}^{2574730} \frac{GM}{R} dR$
- Temperature difference between embryo's surface and space $= \frac{GM}{RC_p}$
- CV and CM chondrite compositions from Lodders and Fegley (1998). CI composition from Lodders (2010). Chlorine from Clay et al. (2017) for all chondrites. Bulk densities from Flynn et al. (2018). Heat capacities from Ostrowski and Bryson (2019). Comet 67P/Churyumov-Gerasimenko is a synthesis of Pätzold et al. (2016), Dhooghe et al. (2017), Le Roy et al. (2015) and Bardyn et al. (2017). Heat capacity of 67P/C-G adopted from Hu et al. (2017), and density and dust-to-ice ratio of 4 from Pätzold et al. (2017).
- Runaway growth prescribed as planetesimal size distribution = [0.1*embryo, 0.5*embryo]
- Written in *R* language, can run in "embarrassingly parallel" mode. Works also for Europa and Enceladus. Code and documentation available at: https://github.com/mmelwani/AccretR