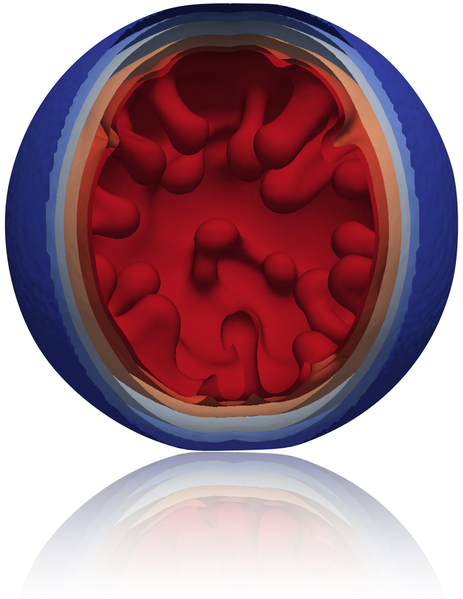
Volatile partitioning and mantle stratification during late-stage magma ocean solidification

Tim Lichtenberg

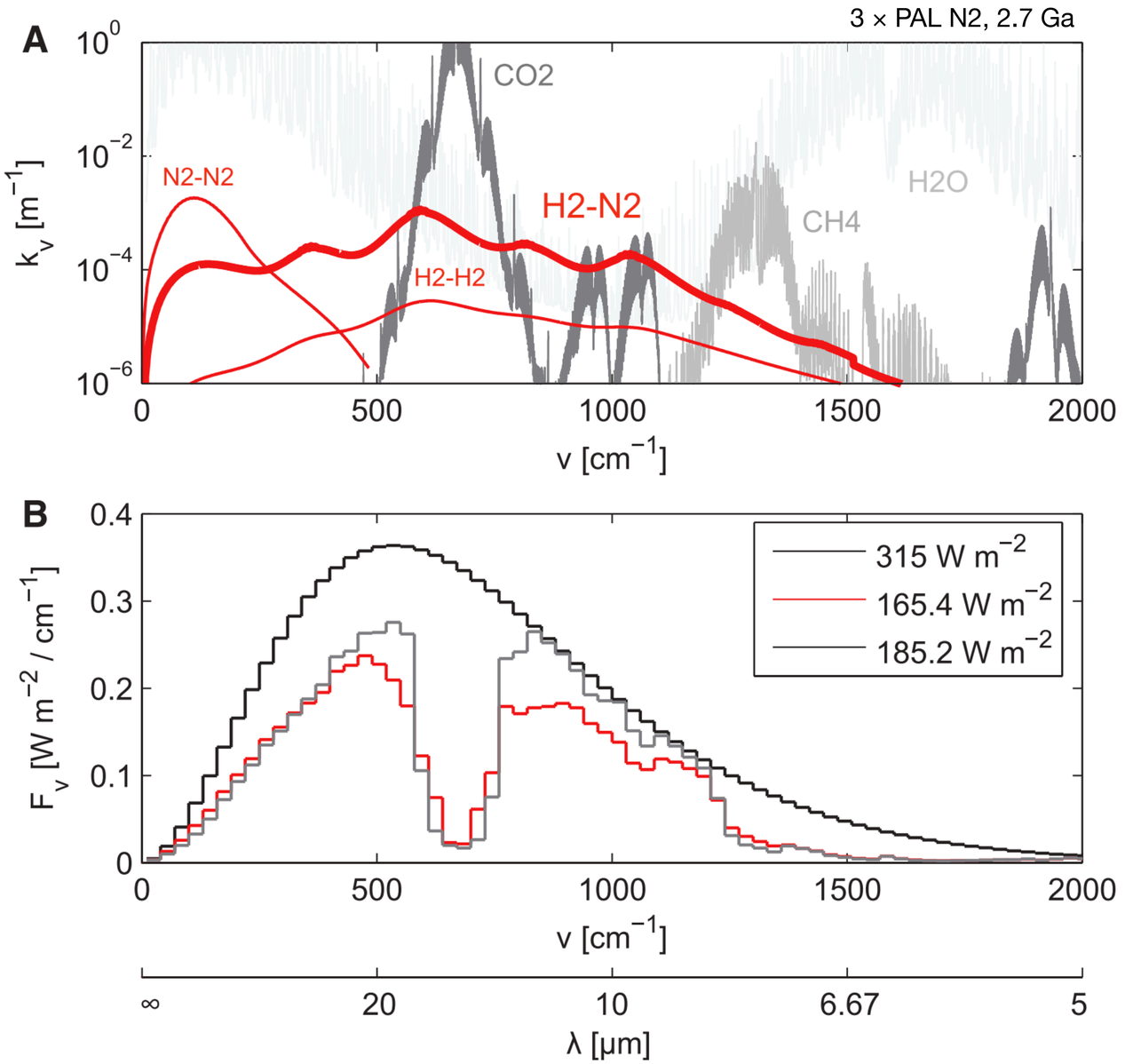


UNIVERSITY OF OXFORD
SIMONS FOUNDATION
FNSNF Swiss National Science Foundation

FOALAB, 7 Feb 2019

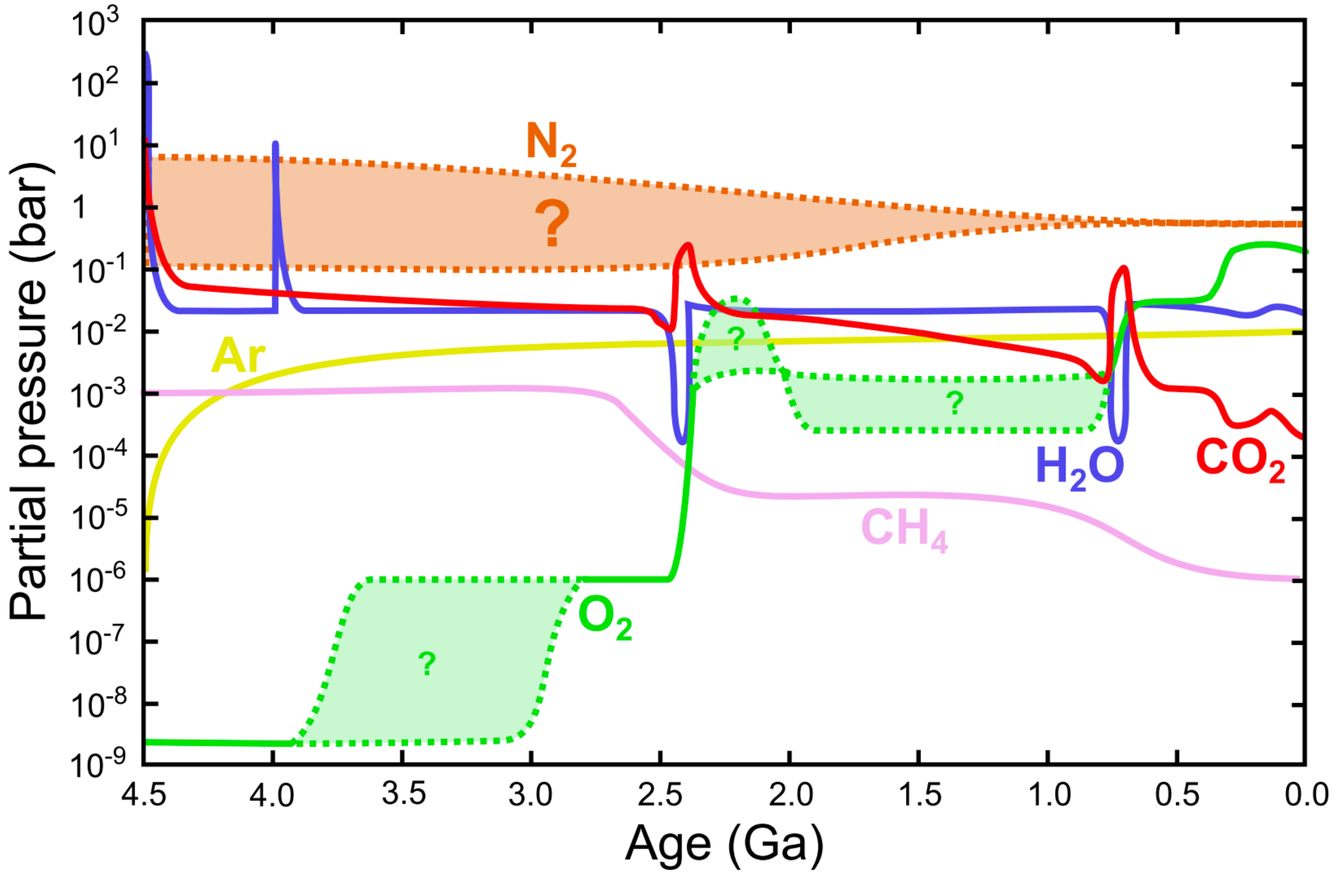
Relevance

- Atmospheric composition
- Faint Young Sun paradox
- Mantle redox state
- Cessation of core formation
- Tectonic regime of early Earth
- Extrapolation to exoplanets
- Mars-Earth divergence
- Subaerial prebiotic chemistry



Relevance

- Atmospheric composition
- Faint Young Sun paradox
- Mantle redox state
- Cessation of core formation
- Tectonic regime of early Earth
- Extrapolation to exoplanets
- Mars-Earth divergence
- Subaerial prebiotic chemistry

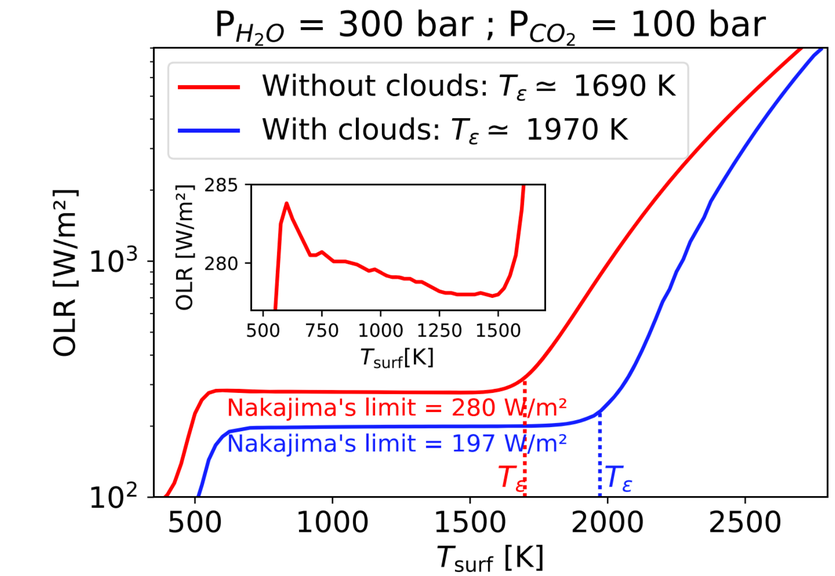


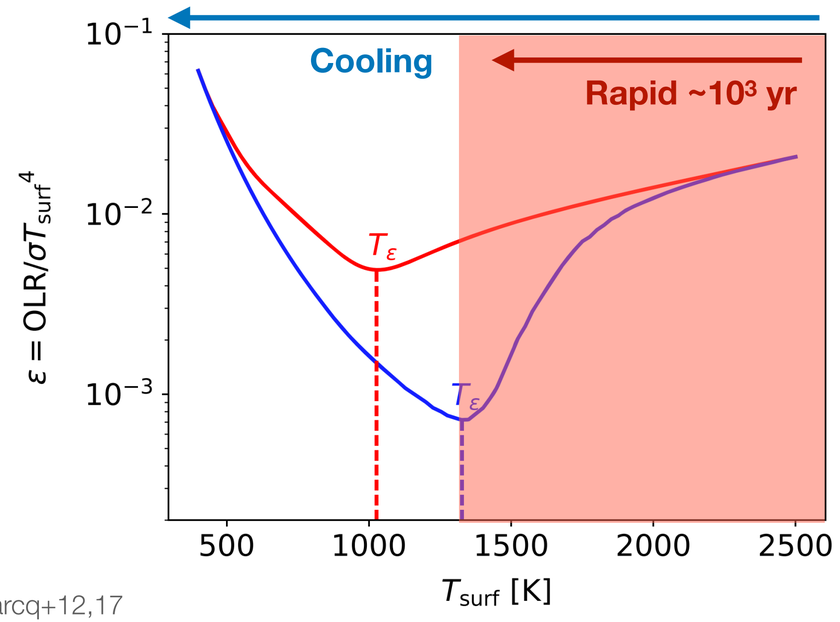
Major challenges & opportunities

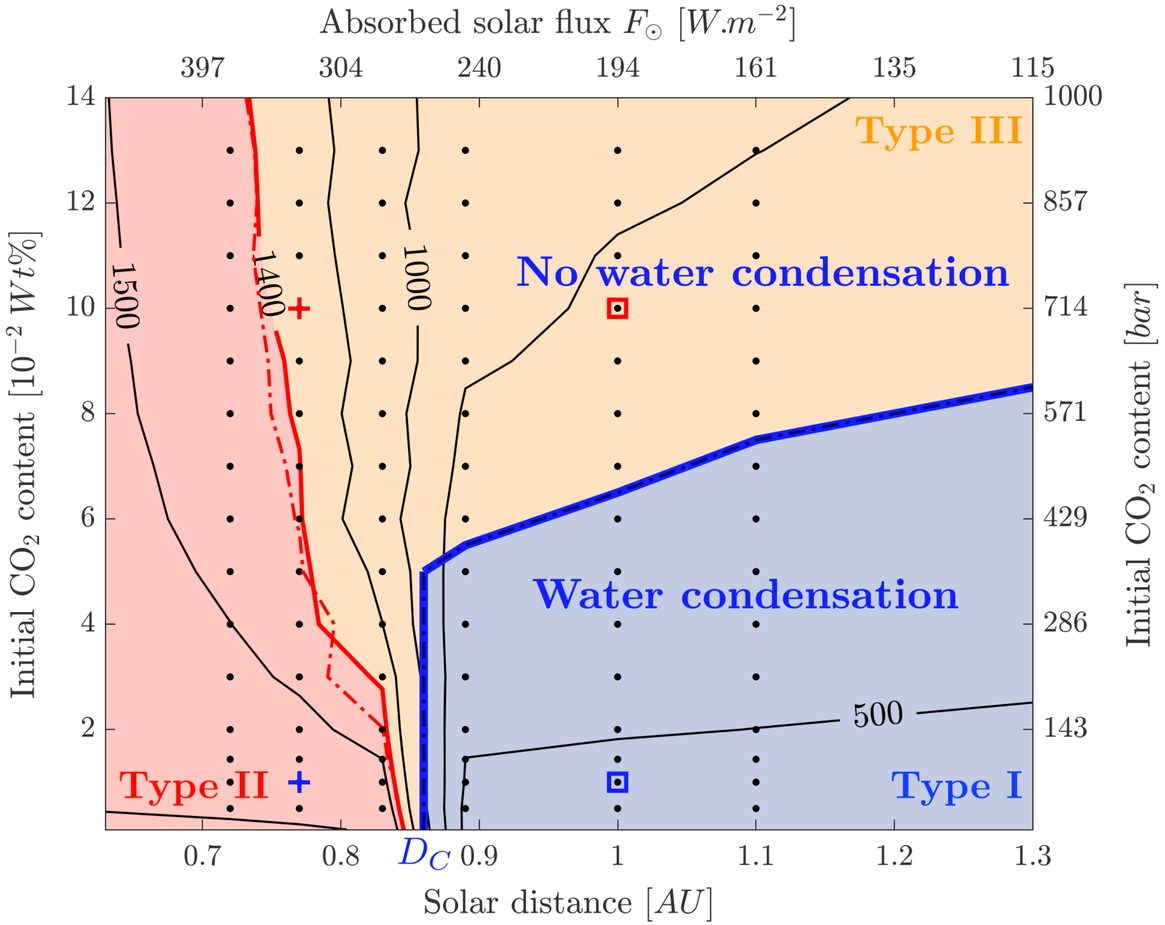
- Provide a bridge from planet formation to long-term planet evolution
- Constraints on early Earth geochemistry poor
- Magma ocean (MO) evolution complex: interplay between siderophile + atmophile partitioning, atmospheric chemistry/radiation, fluid dynamics
- Suspension flow regime (so far) inaccessible/too expensive for computational geodynamics

- Timing of volatile addition better constrained
- Majority of former results based on 0D to 1D approximations
- Former models neglect mantle fluid dynamics
- Only very few studies w/ two-phase flow approach
- Synergies of expertise in Katz + Pierrehumbert groups

Early Earth's surface environment



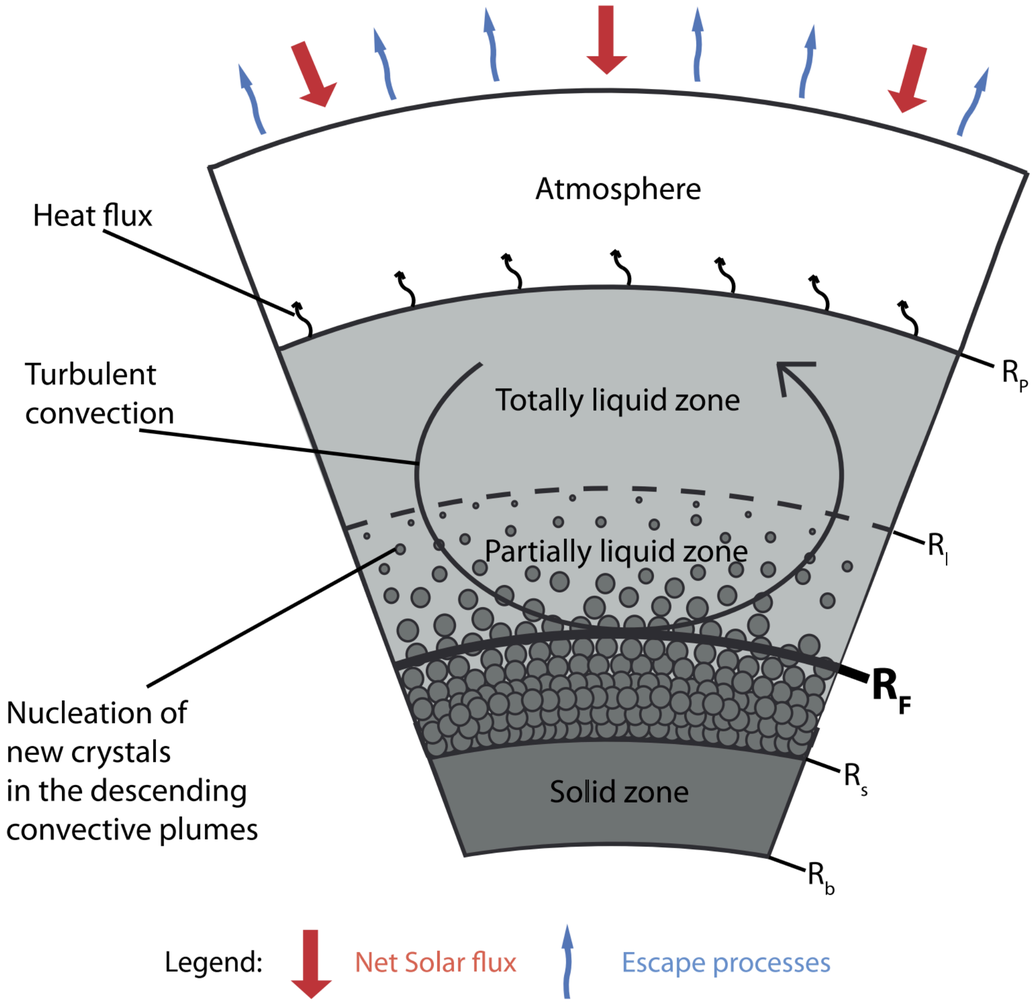


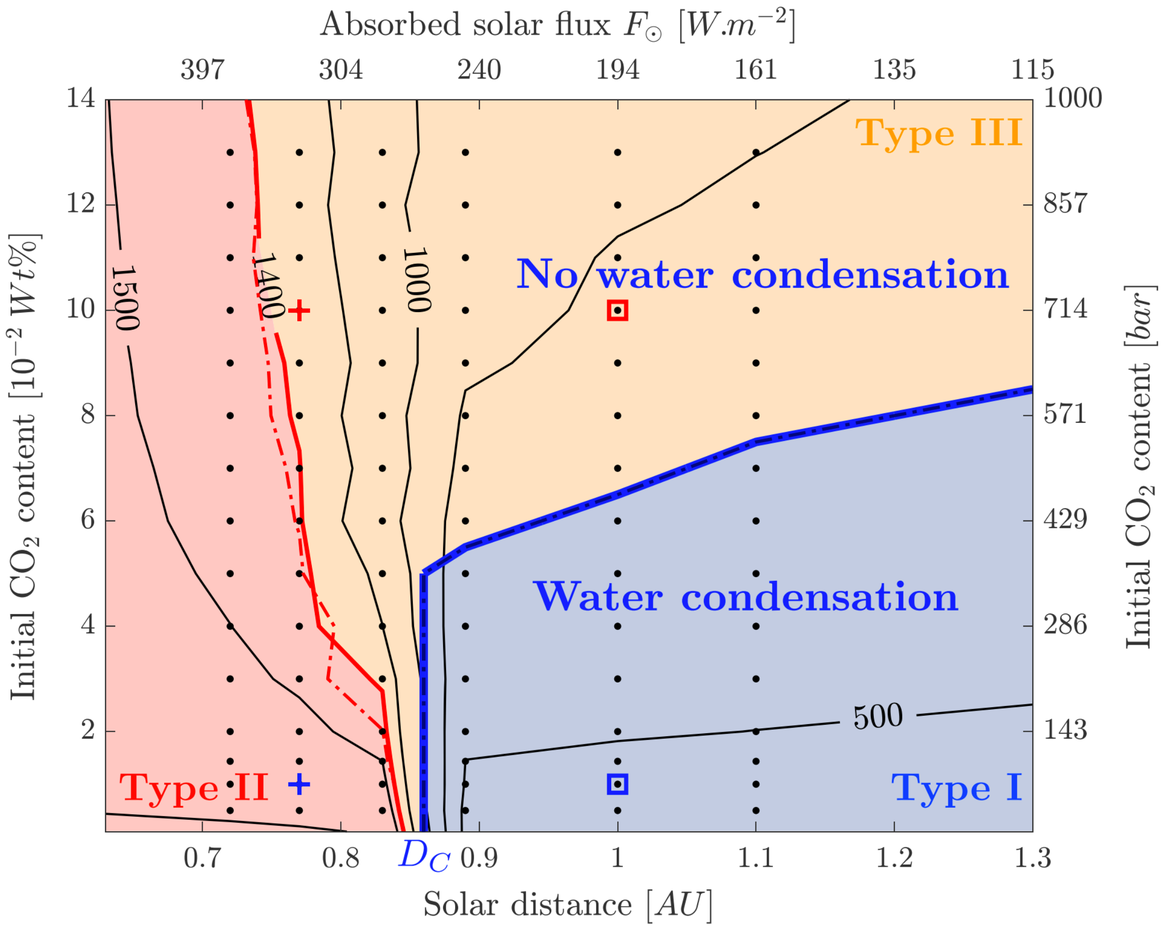


Lebrun+13; Marcq+12,17

Salvador+17

Atmosphere – MO connection

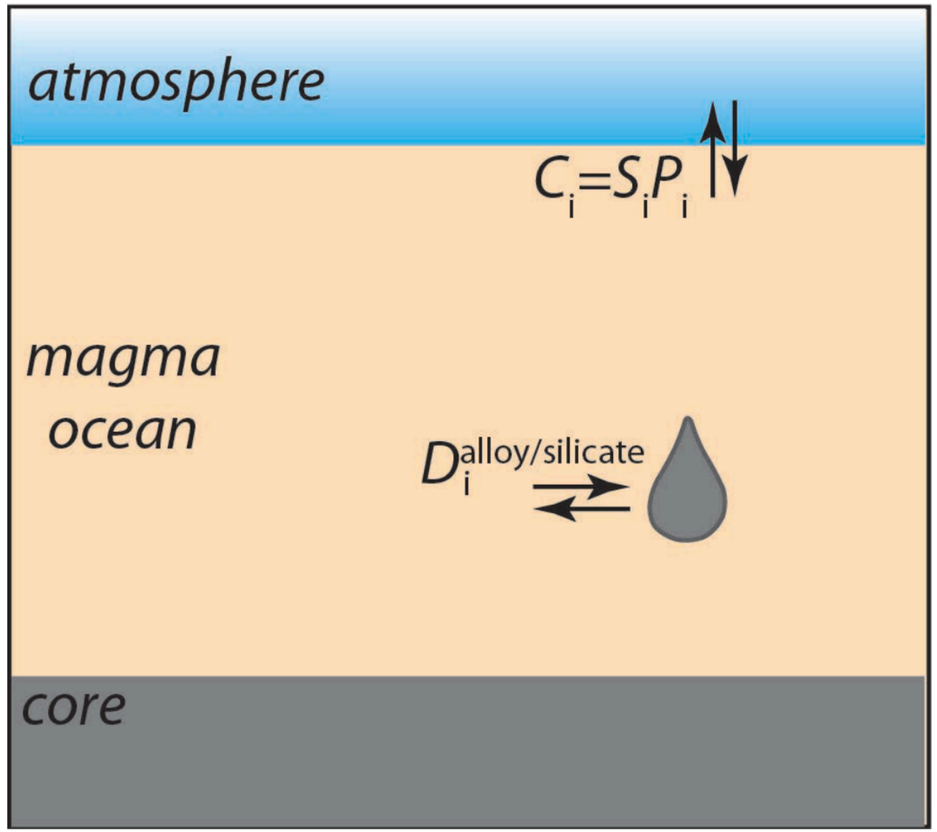


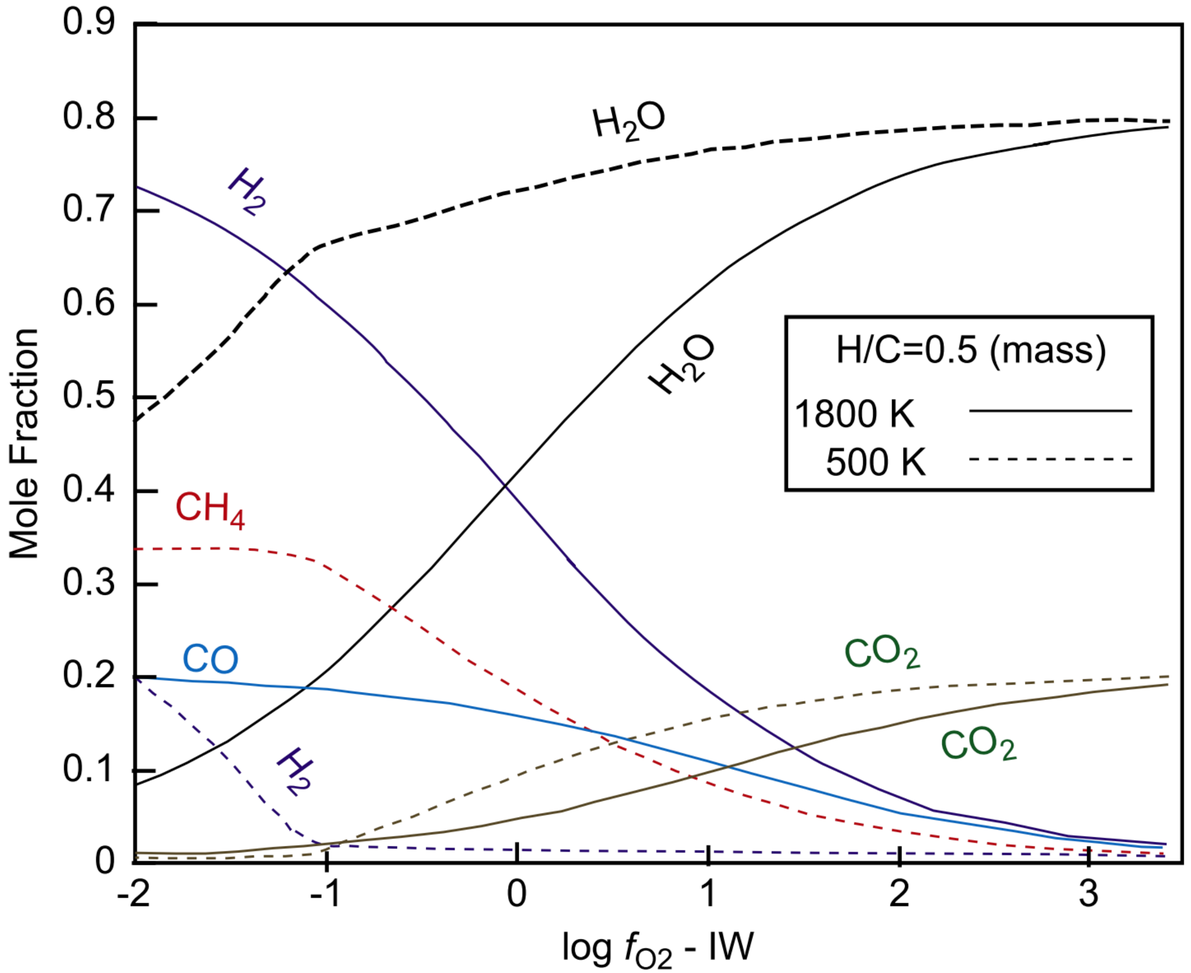


Solomatov 15; Massol+16

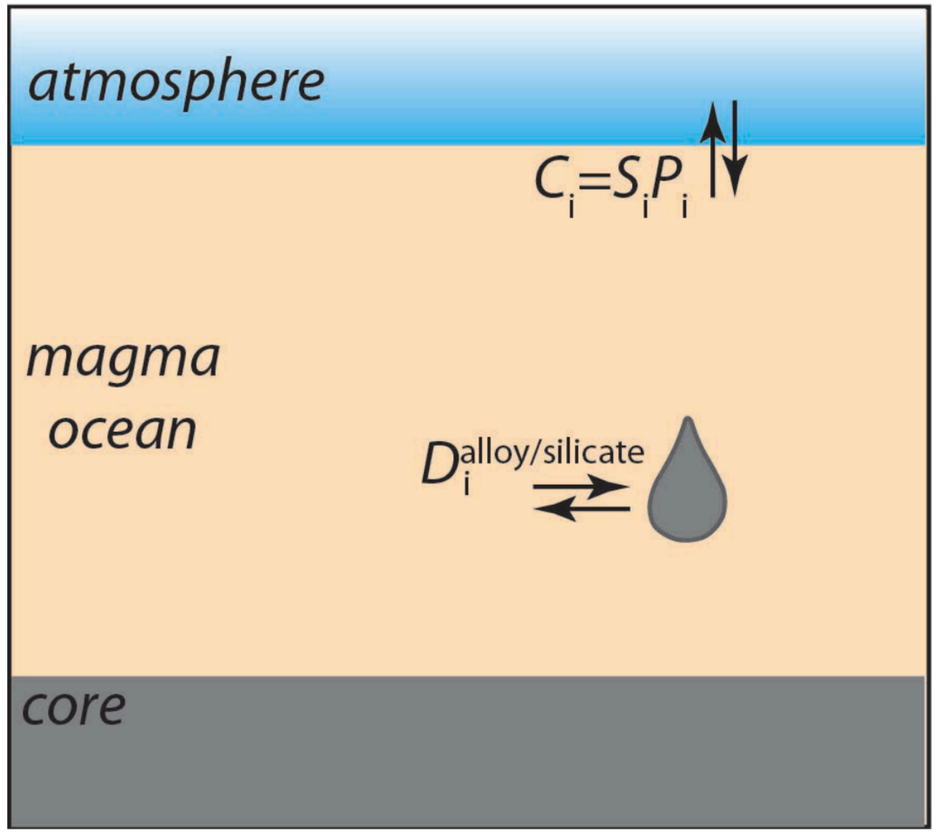
Salvador+17

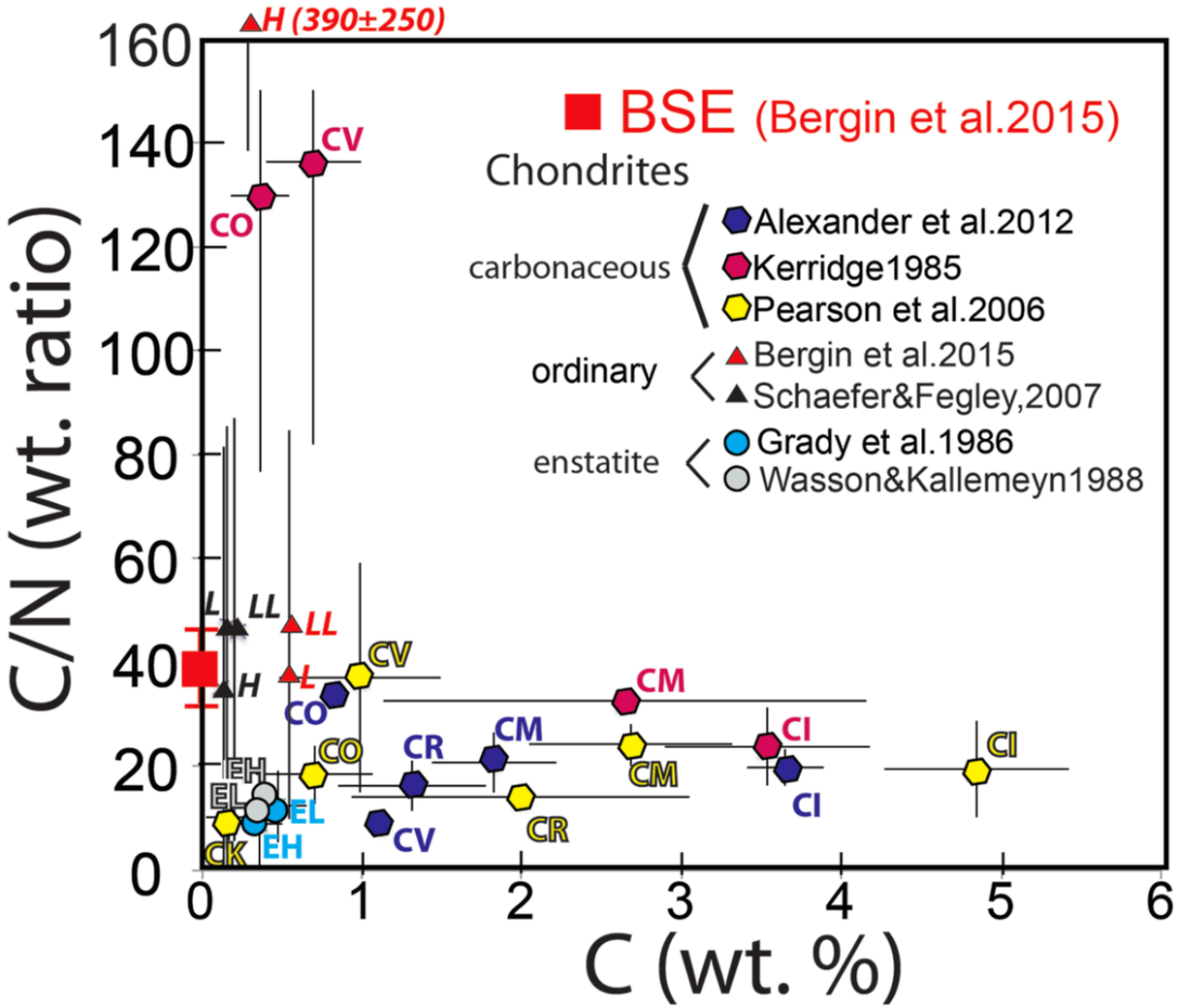
Simplistic equilibrium partitioning models



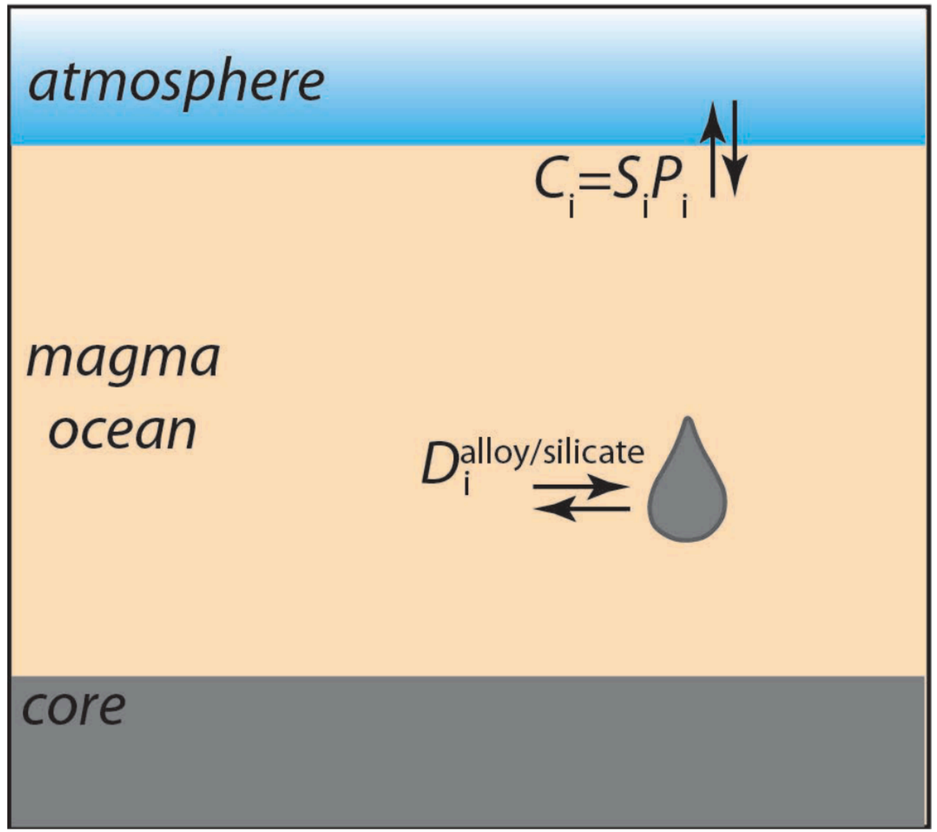


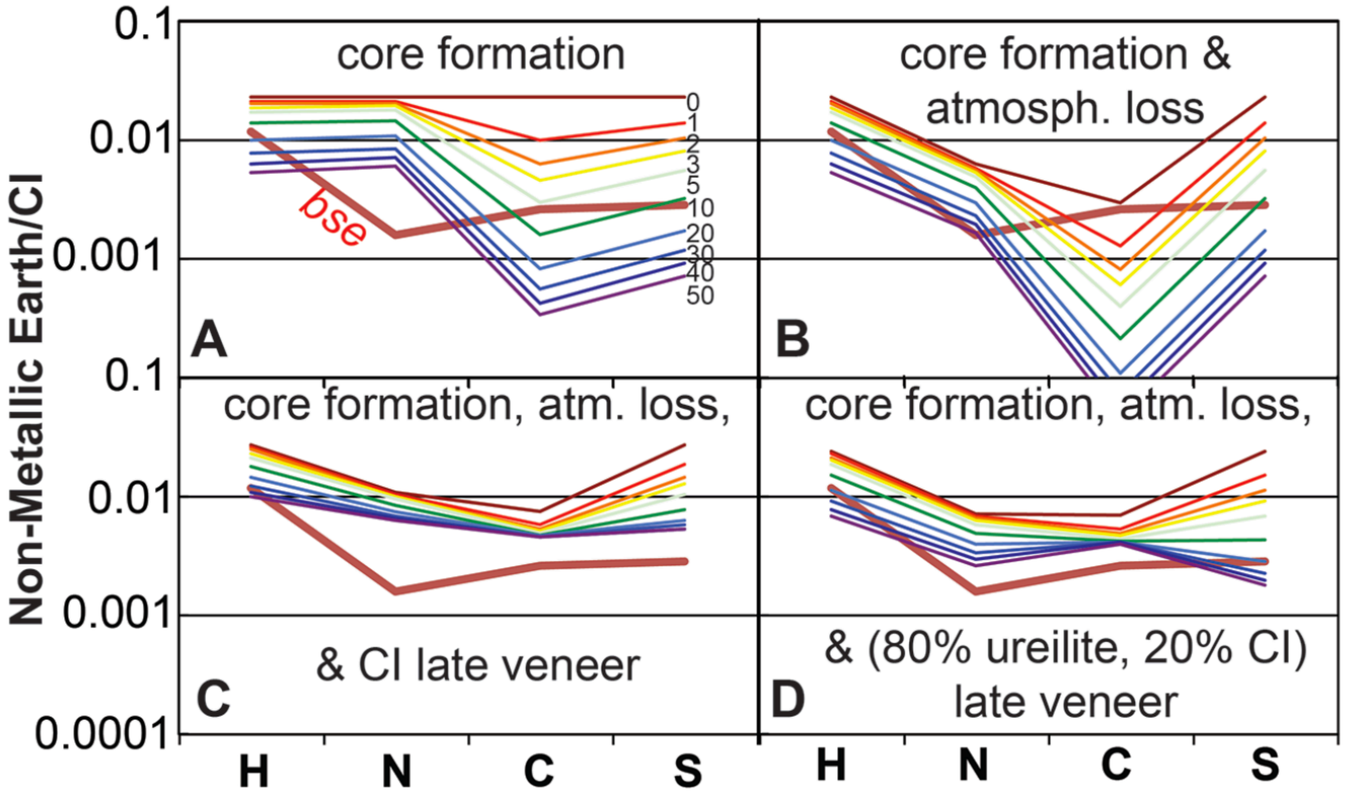
Simplistic equilibrium partitioning models



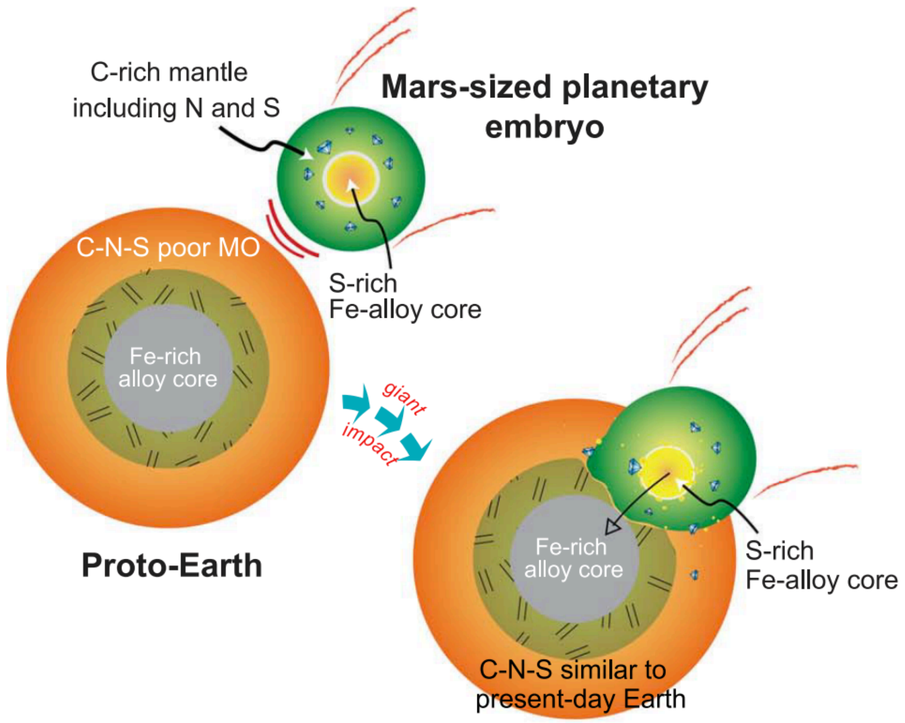


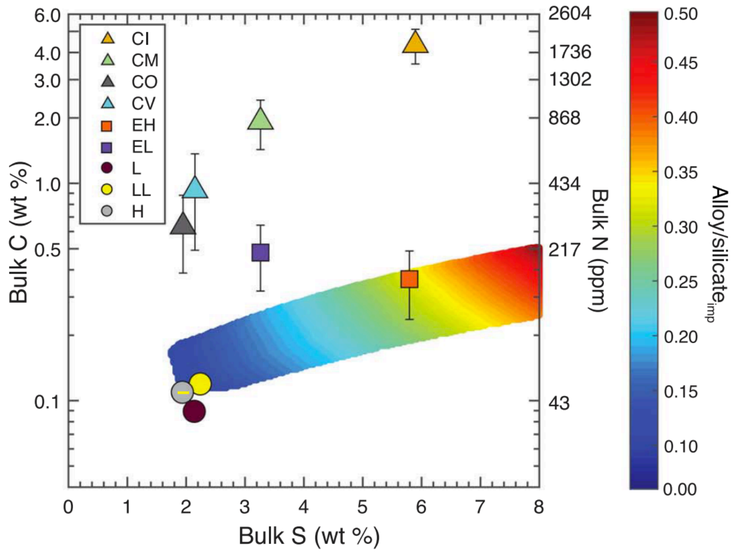
Equilibrium partitioning + *some* evolution

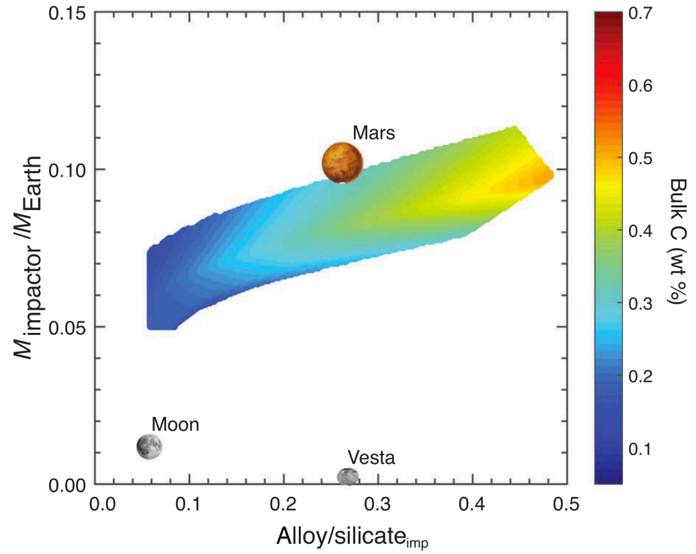


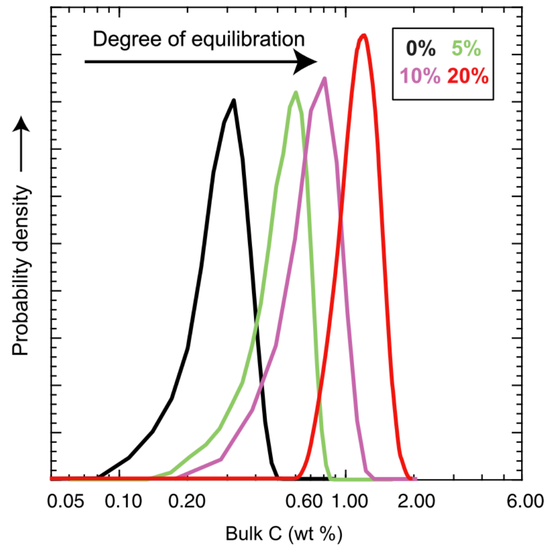


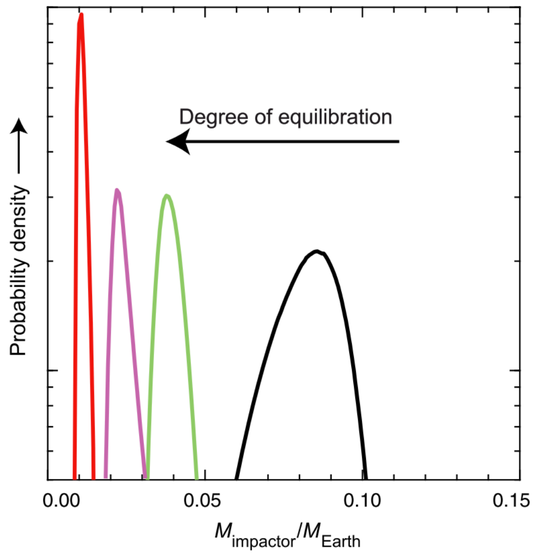
The Moon-forming impact to the rescue





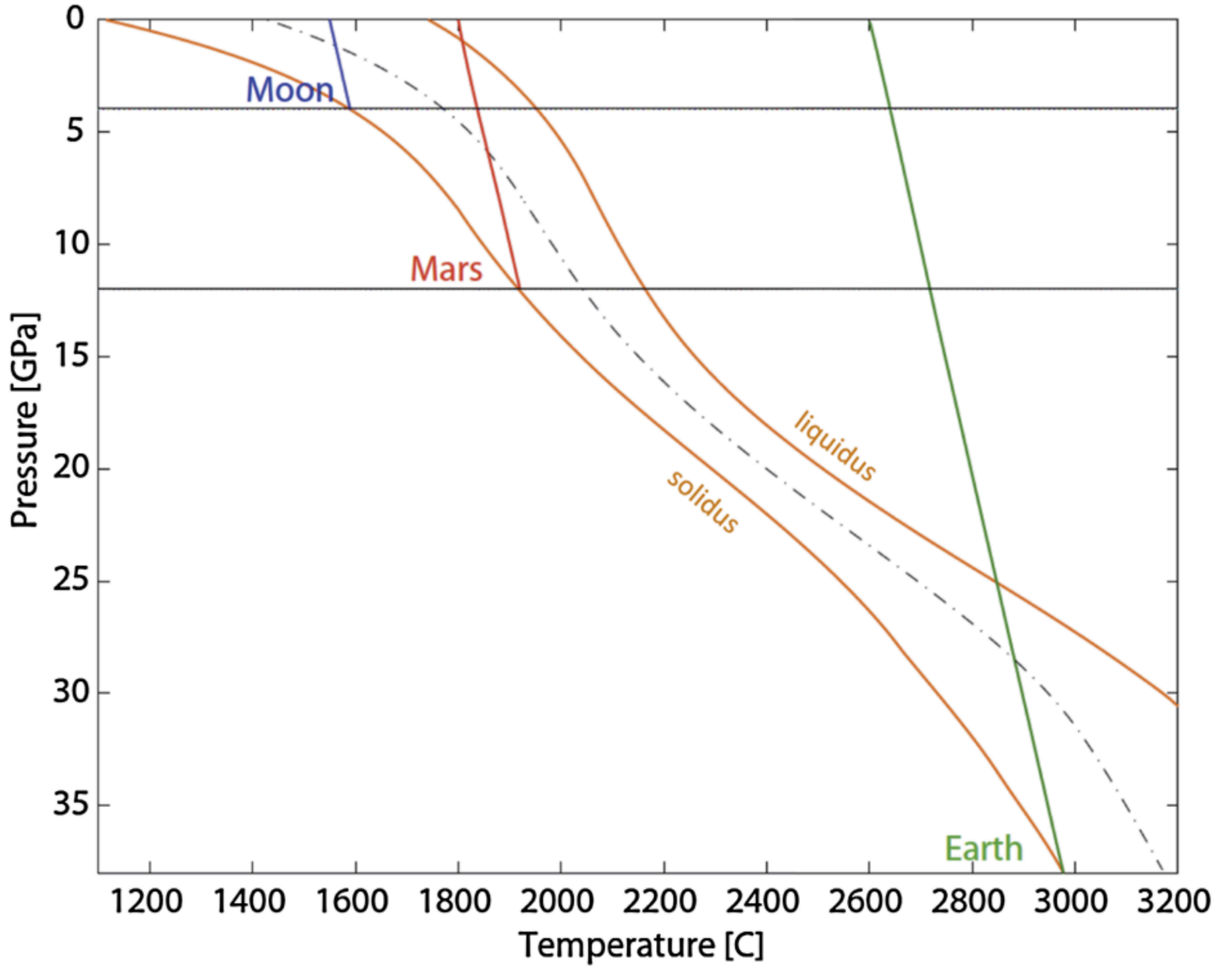


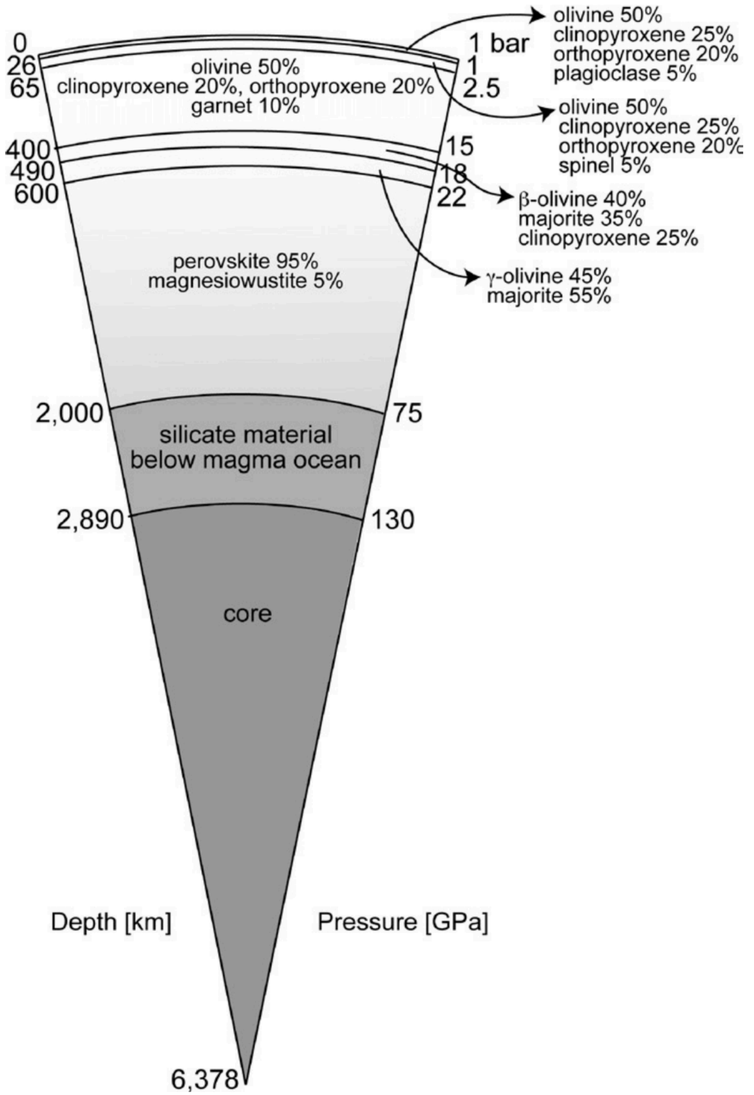




Grewal+19

Fractional crystallisation during freezing

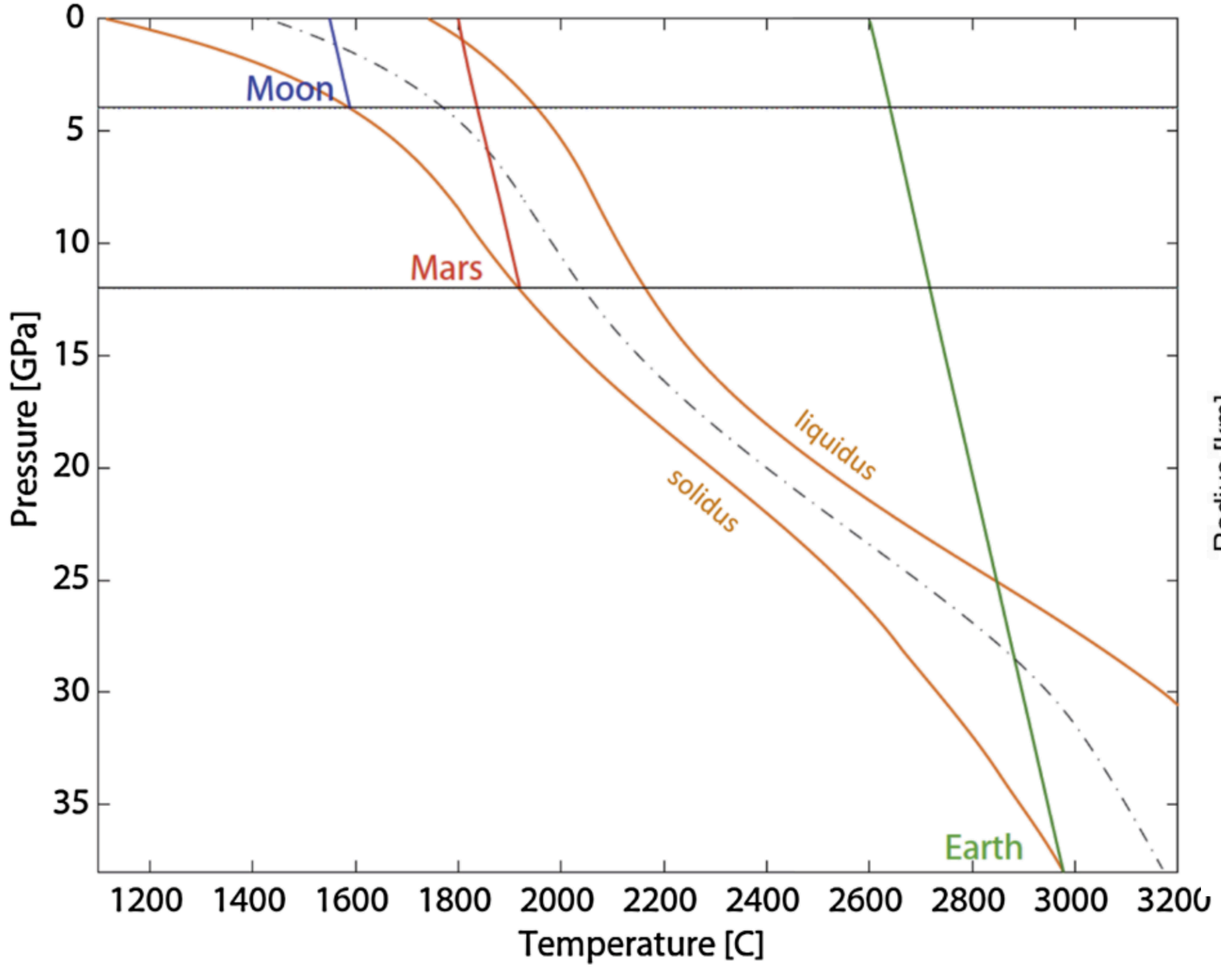


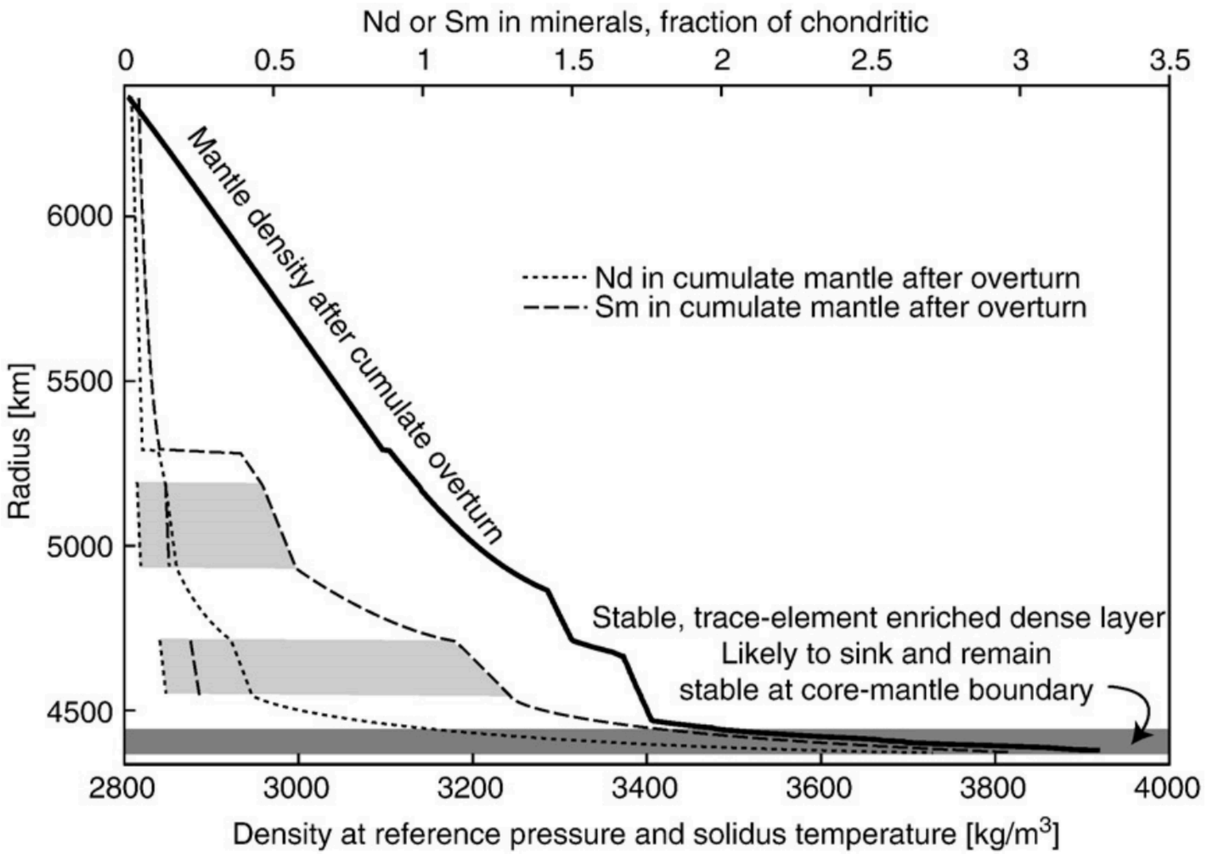


Elkins-Tanton 12; Ikoma+18

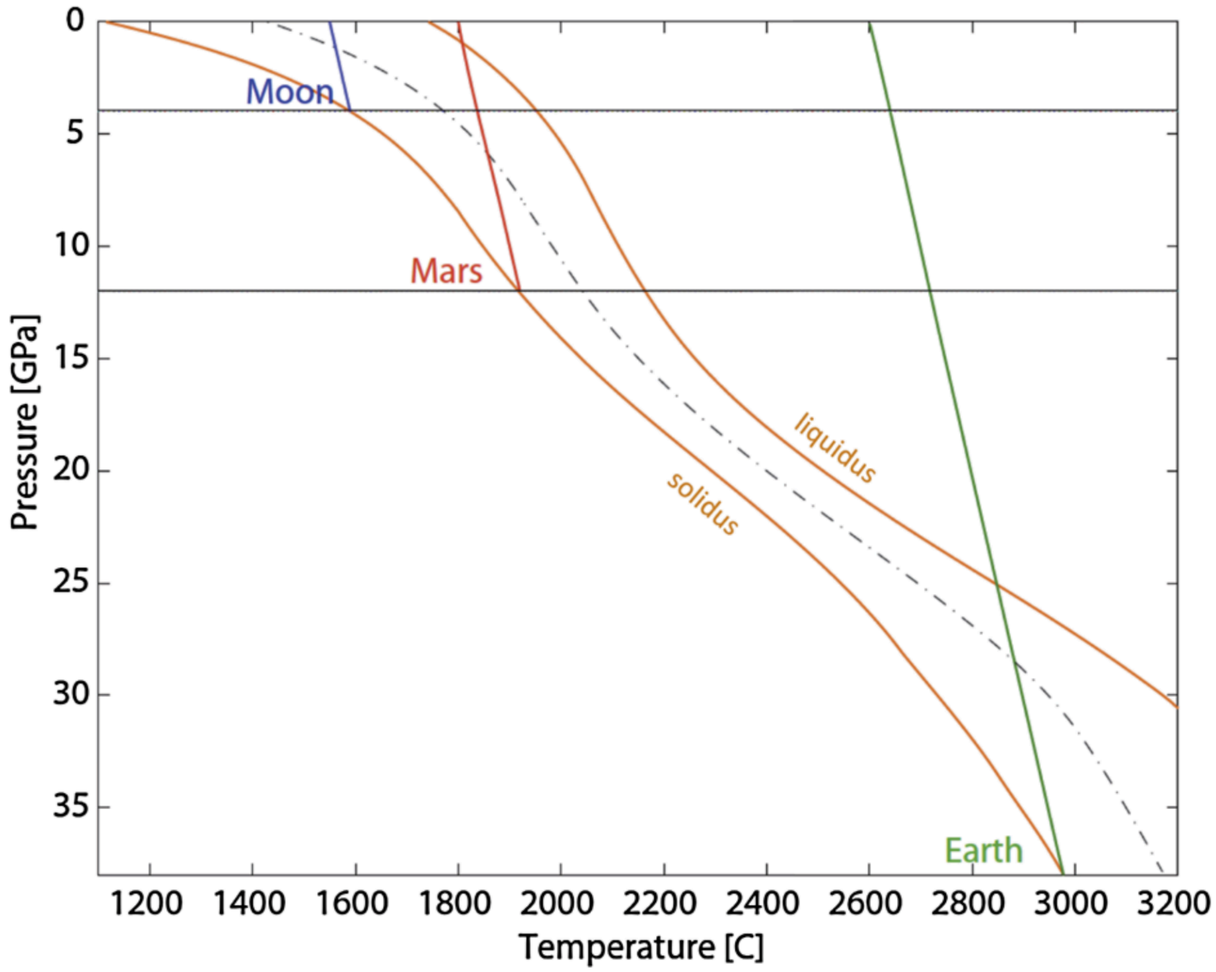
Elkins-Tanton+08

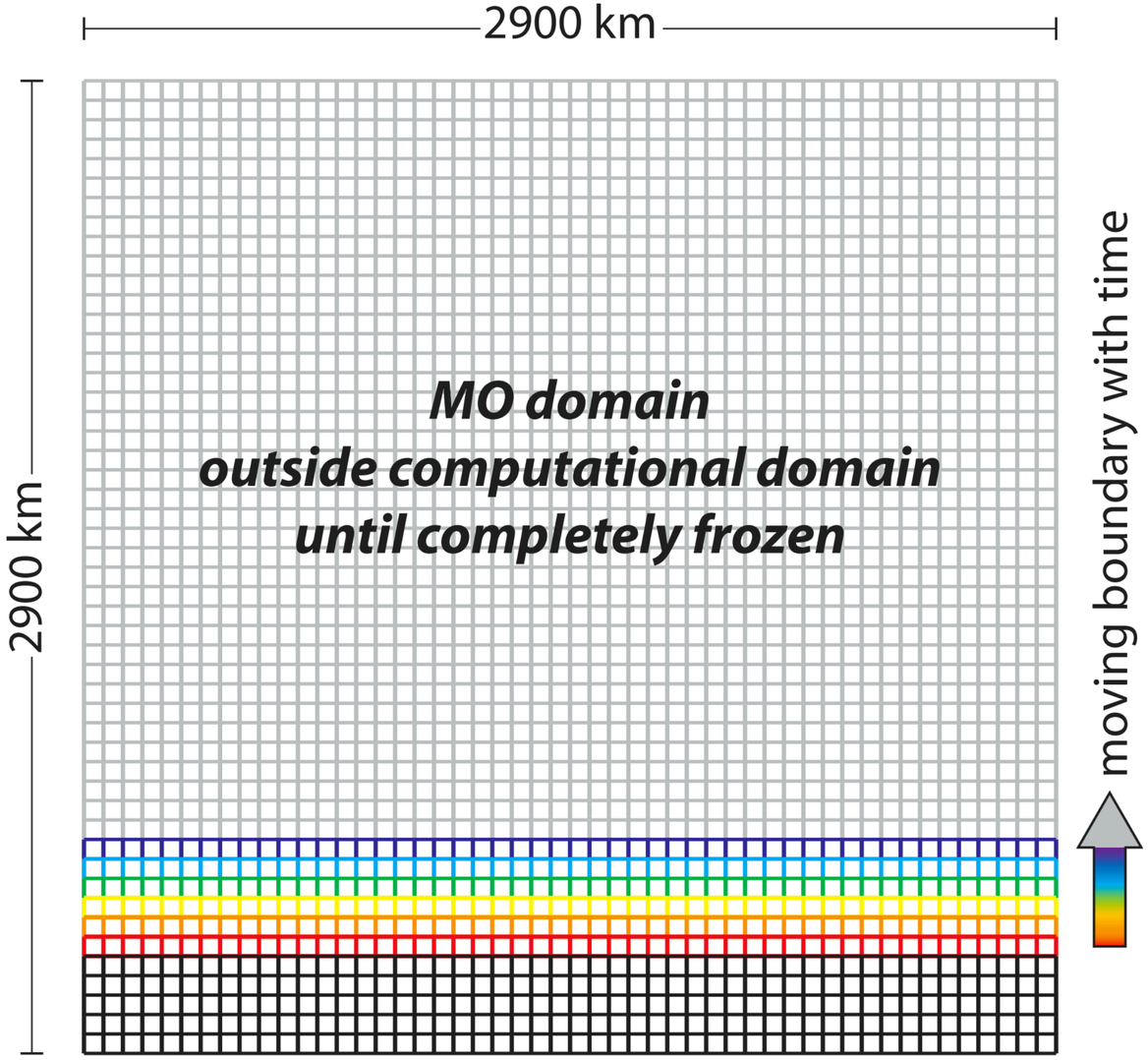
Fractional crystallisation during freezing





Fractional crystallisation during freezing

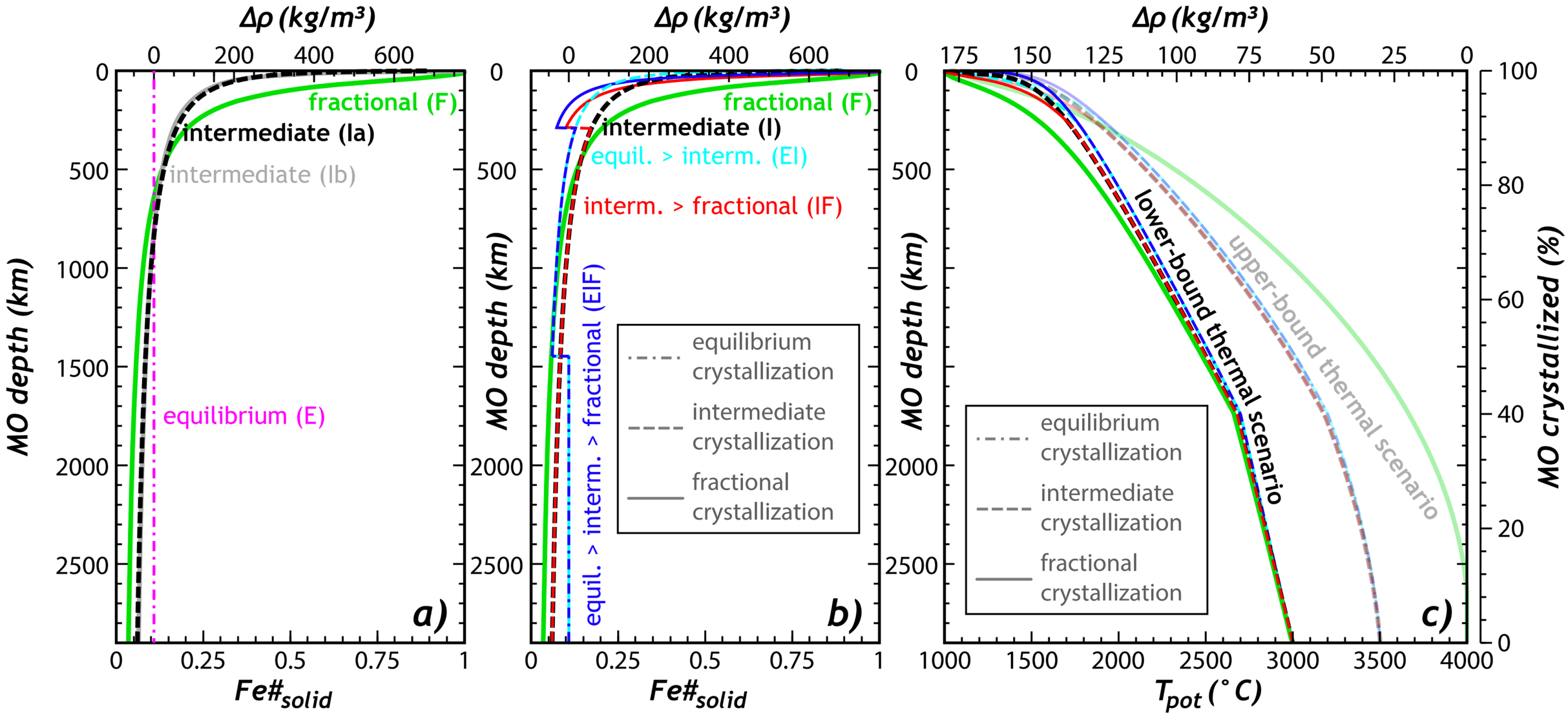




Elkins-Tanton 12; Ikoma+18

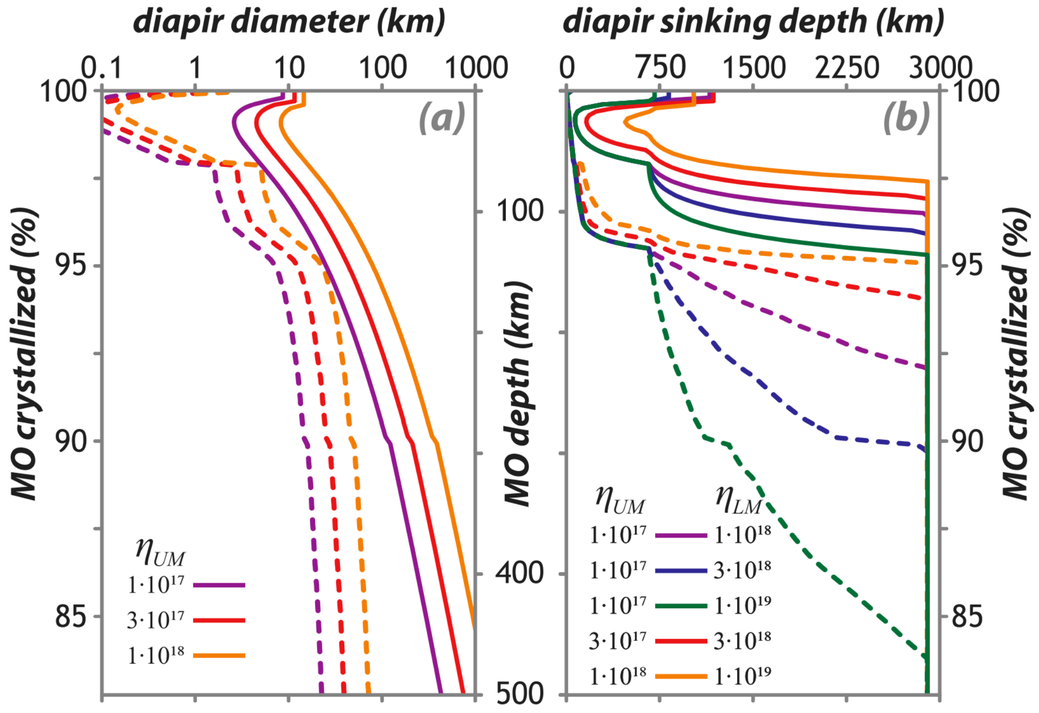
Ballmer+17, Maurice+17

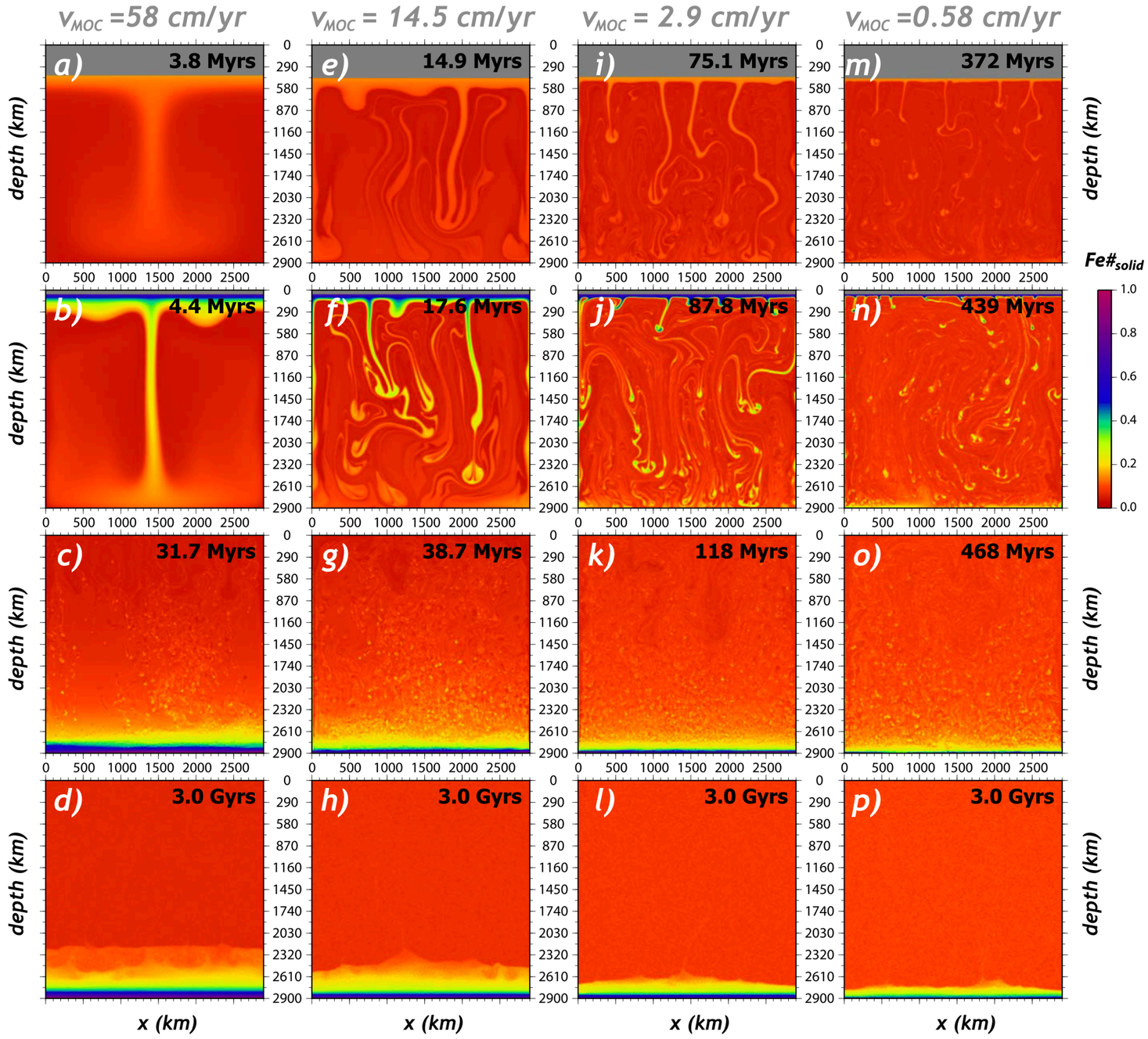
MO thermal structure bracketed



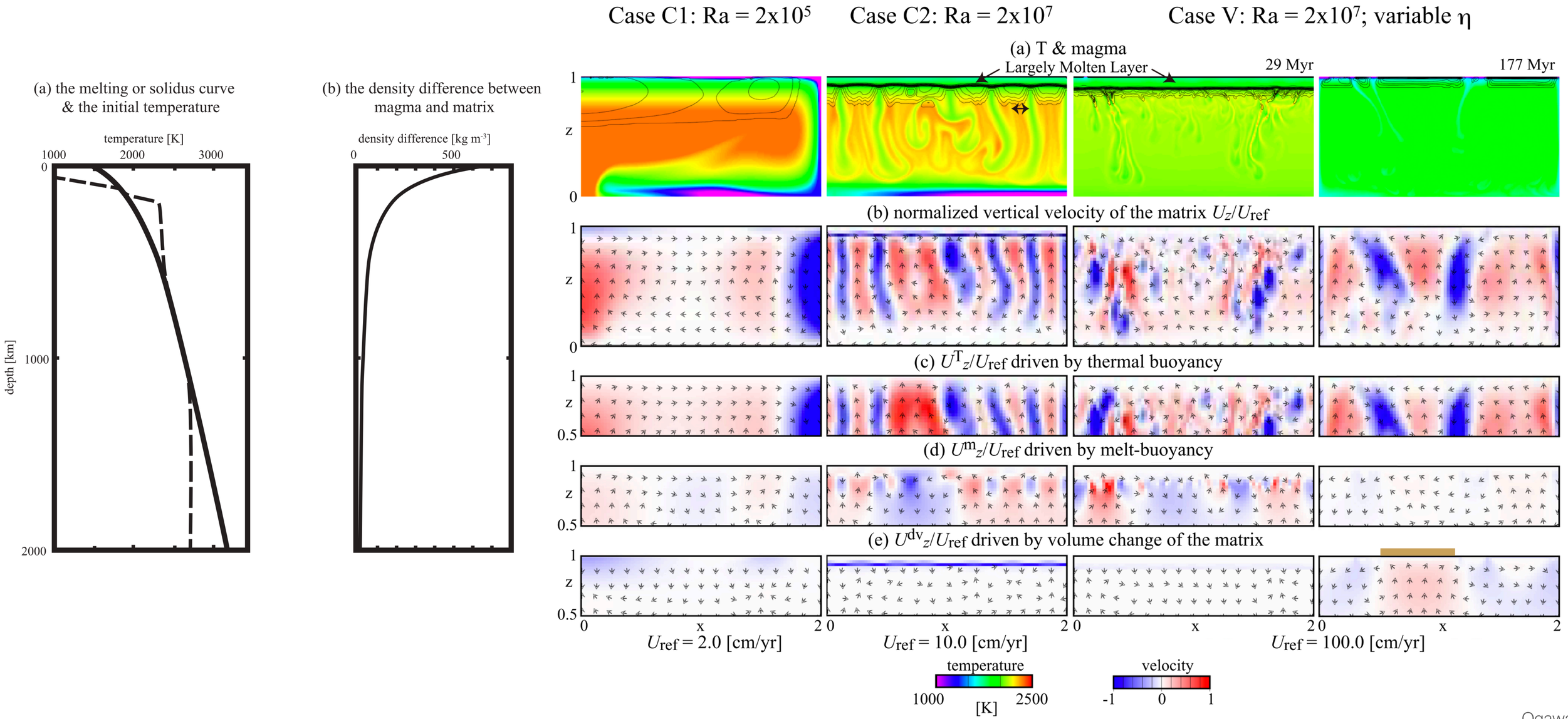
Ballmer+17

Incremental overturns?

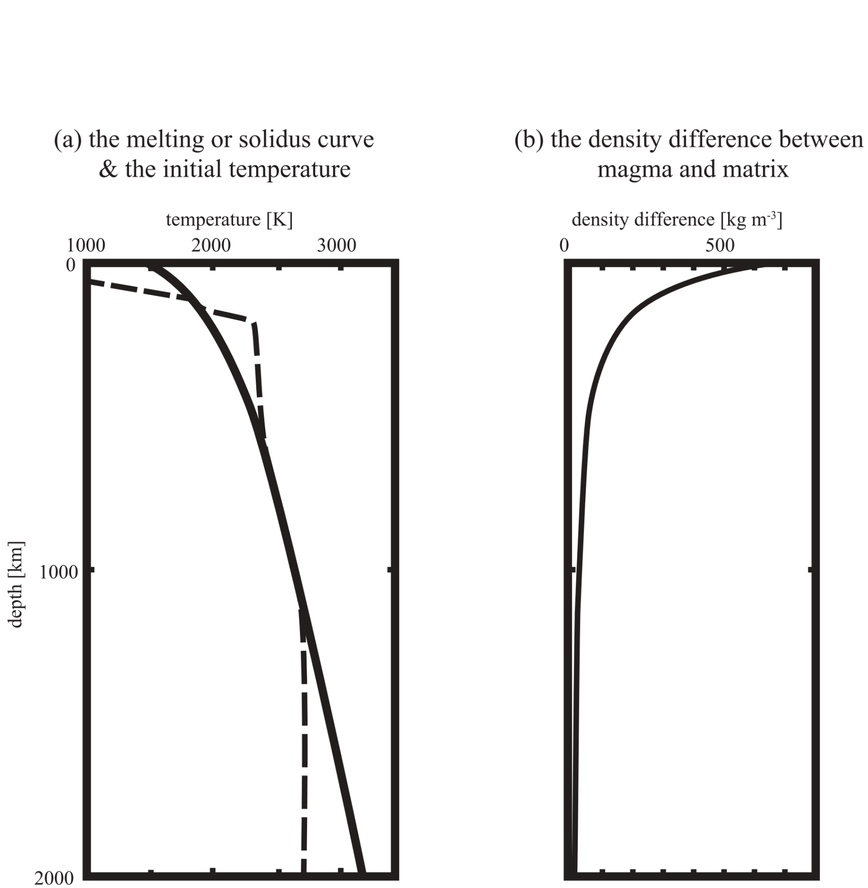


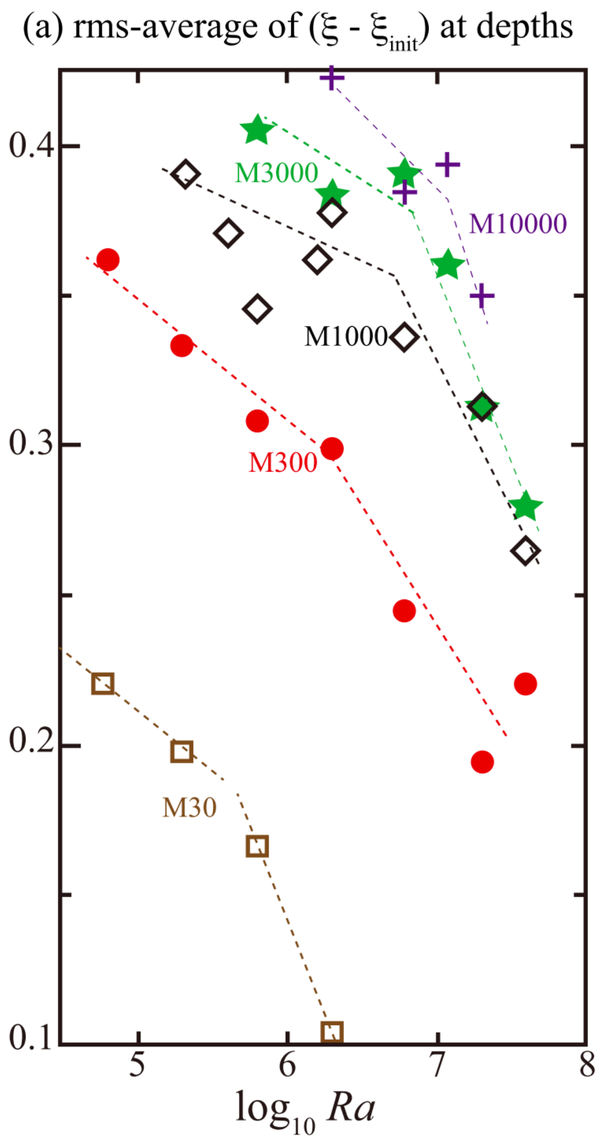


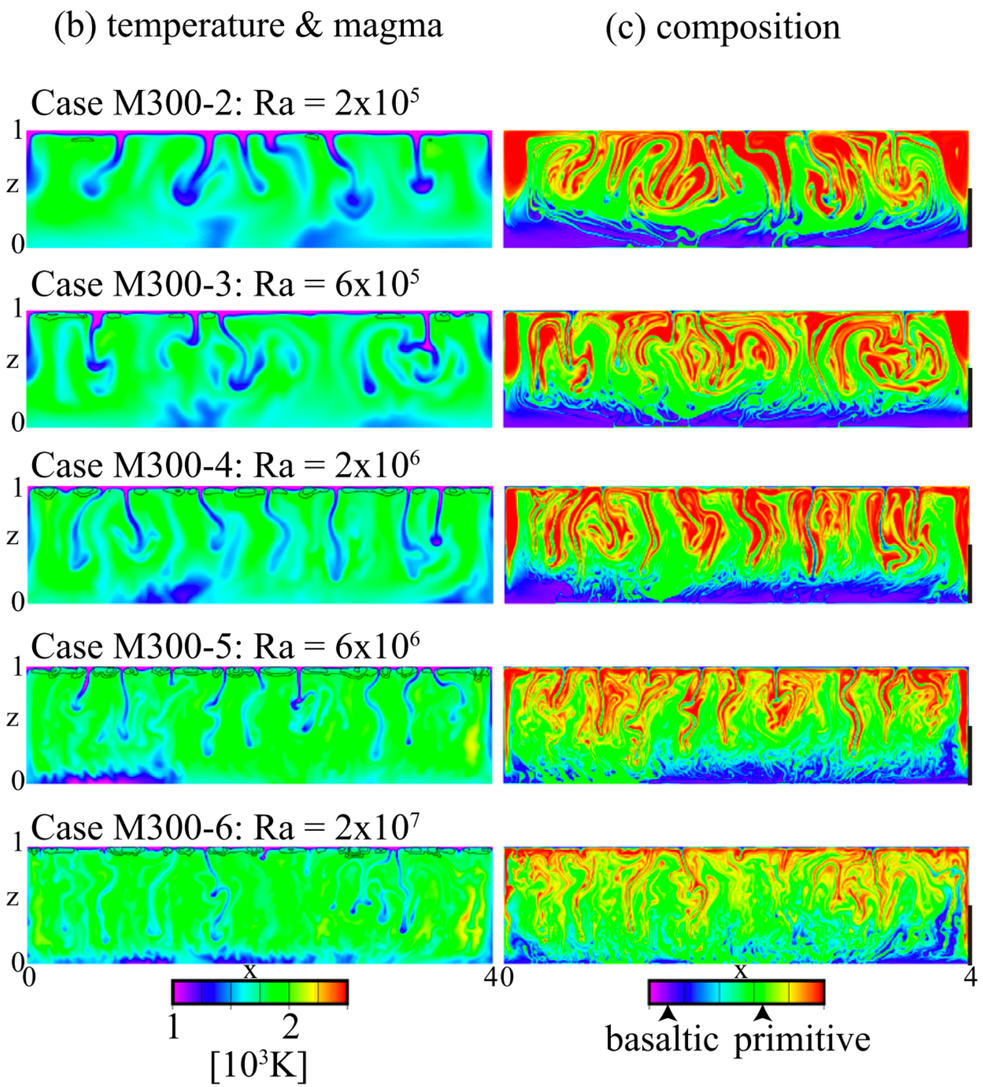
Two-phase flow to remix stratified mantle?



Two-phase flow to remix stratified mantle?







What to do / project goals

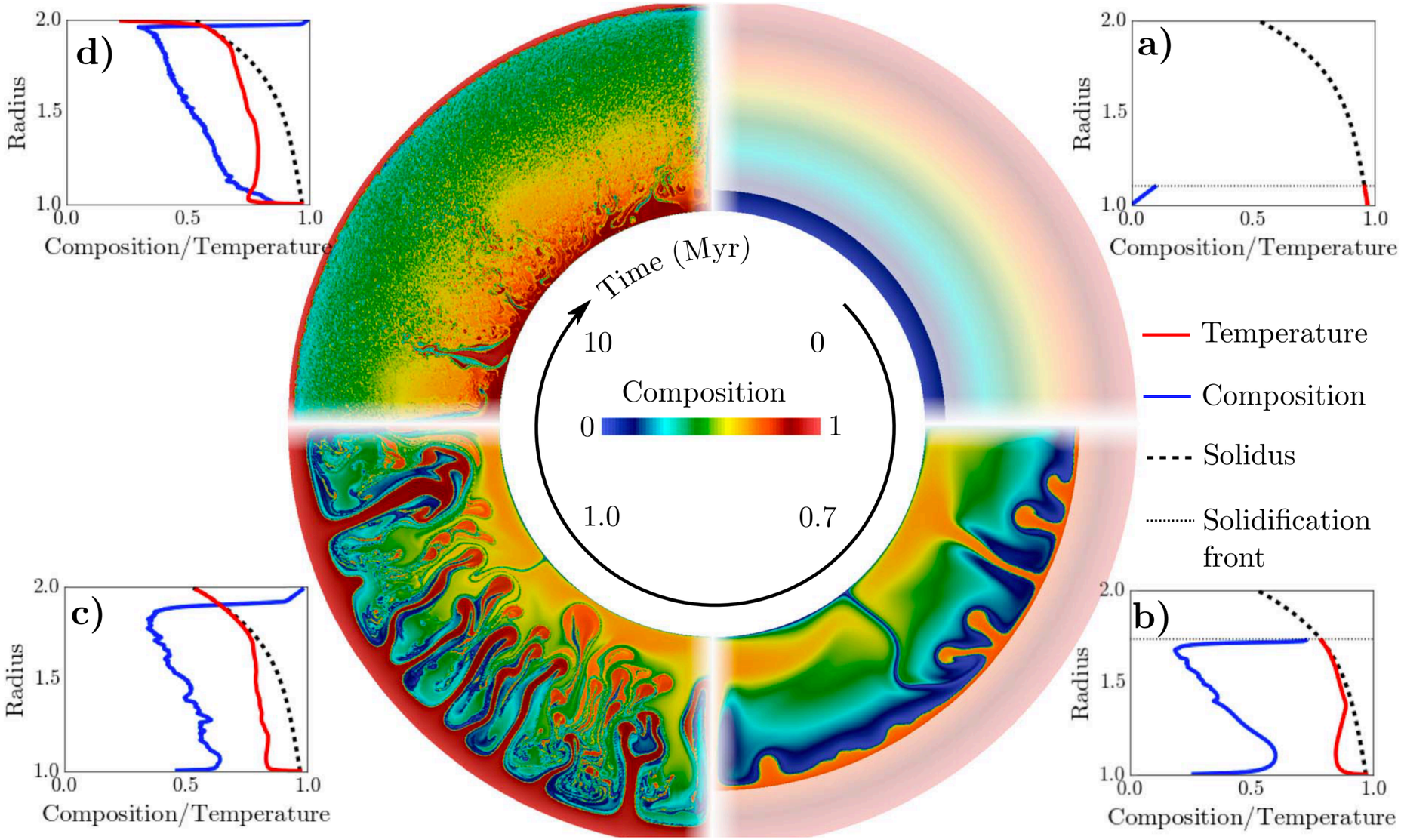
- Quantify impact of incremental overturns
  - Mantle compositional stratification
    - ➡ Mantle redox gradient
    - ➡ Layering stability
  - BSE C-H-N-S ratio/total budget
  - Uppermost mantle/plume chemistry?
- Earliest atmospheric composition
- Avoid bracketing of thermal evolution(?)
- Self-consistent atmospheric treatment
  - Pre-computed flux for various atmospheric compositions (+ solar insolation) as boundary condition
- Melt-solid compositional distribution
  - Composition tracking
- Computational feasibility
- Starting conditions

What to do / project goals

- Quantify impact of incremental overturns
  - Mantle compositional stratification
    - ➡ Mantle redox gradient
    - ➡ Layering stability
  - BSE C-H-N-S ratio/total budget
  - Uppermost mantle/plume chemistry?
- Earliest atmospheric composition
- Avoid bracketing of thermal evolution(?)

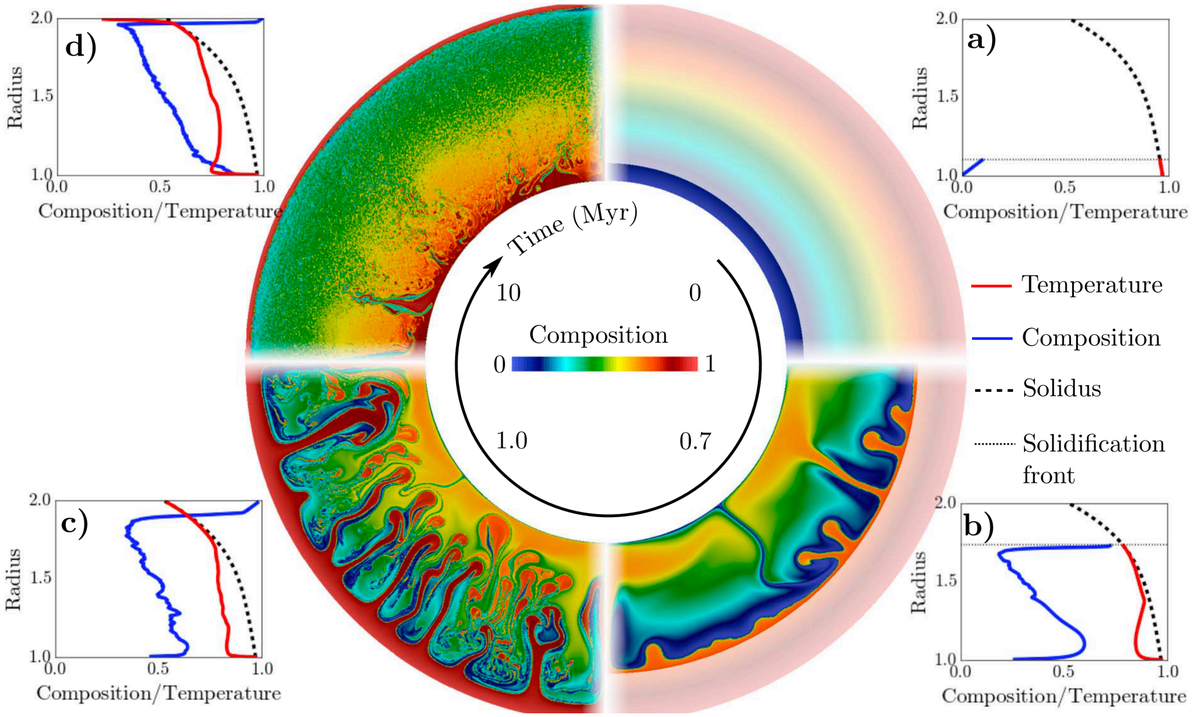
1. **Whole-mantle MO**
   - Density-inverted incremental overturns
2. **After overturn**
   - Bracket overturn stratification
   - Compute remixing of stratification + volatile partitioning
3. **Intermediate (late-stage) MO**
   - Bracket early thermal evolution, assume end-member late-stage thermal-compositional profile

1. Whole-mantle MO —> global volatile budget



1. Whole-mantle MO —> global volatile budget

- Whole mantle completely molten
- Initial temperature profile following adiabat when bottom intersects with liquids
- Employ partition coefficients for alloy/O + CHNS ratios
  - Track composition/mixing + density inversion
  - Oversaturated volatiles released to atmosphere
- MO heat flux through eddy diffusivity



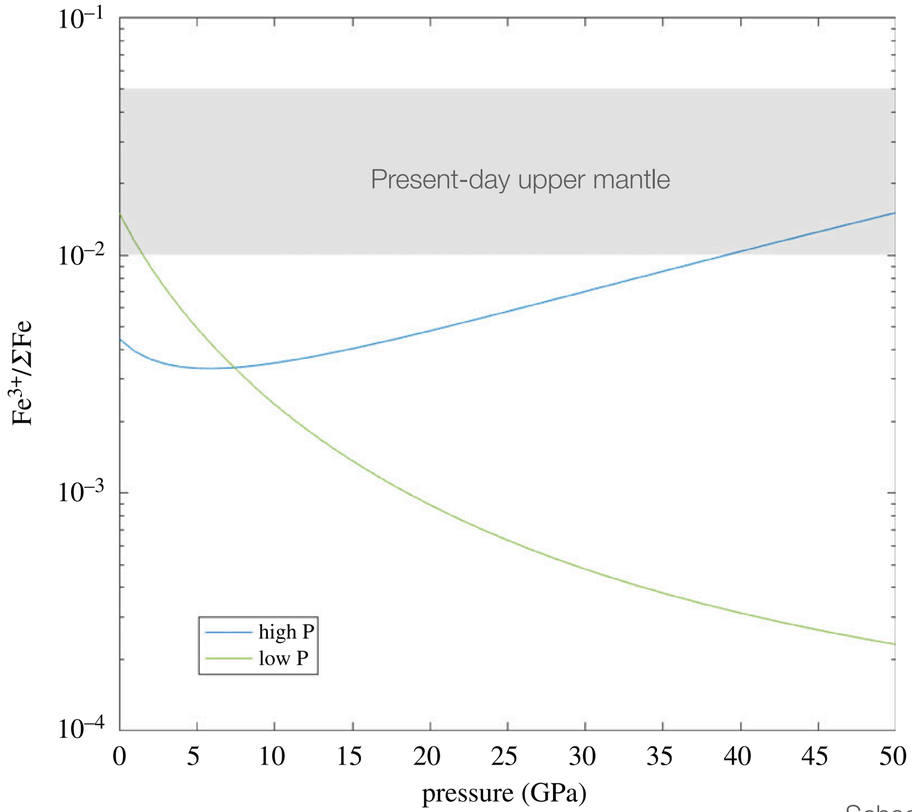
1. Whole-mantle MO

- Whole mantle completely molten
- Initial temperature profile following mantle liquidus
- **Employ partition coefficients for alloy/O + CHNS ratios**
  - Track composition/mixing + density inversion
  - Oversaturated volatiles released to atmosphere
- MO heat flux through eddy diffusivity

TABLE 2. Volatile solubilities and partition coefficients used for model calculations

		Solubility constants S_i (Eq. 6) (ppm/MPa)	Partition coefficients $D_i^{alloy/silicate}$
C	oxidized	1.6	500
	reduced	0.55	1000
	very reduced	0.22	3000
H	oxidized	[a]	6.5
	reduced	[a]	6.5
	very reduced	5	6.5
N	oxidized	1	20
	reduced	5	20
	very reduced	50	20
S	oxidized	5000	60
	reduced	5000	60
	very reduced	5000	60

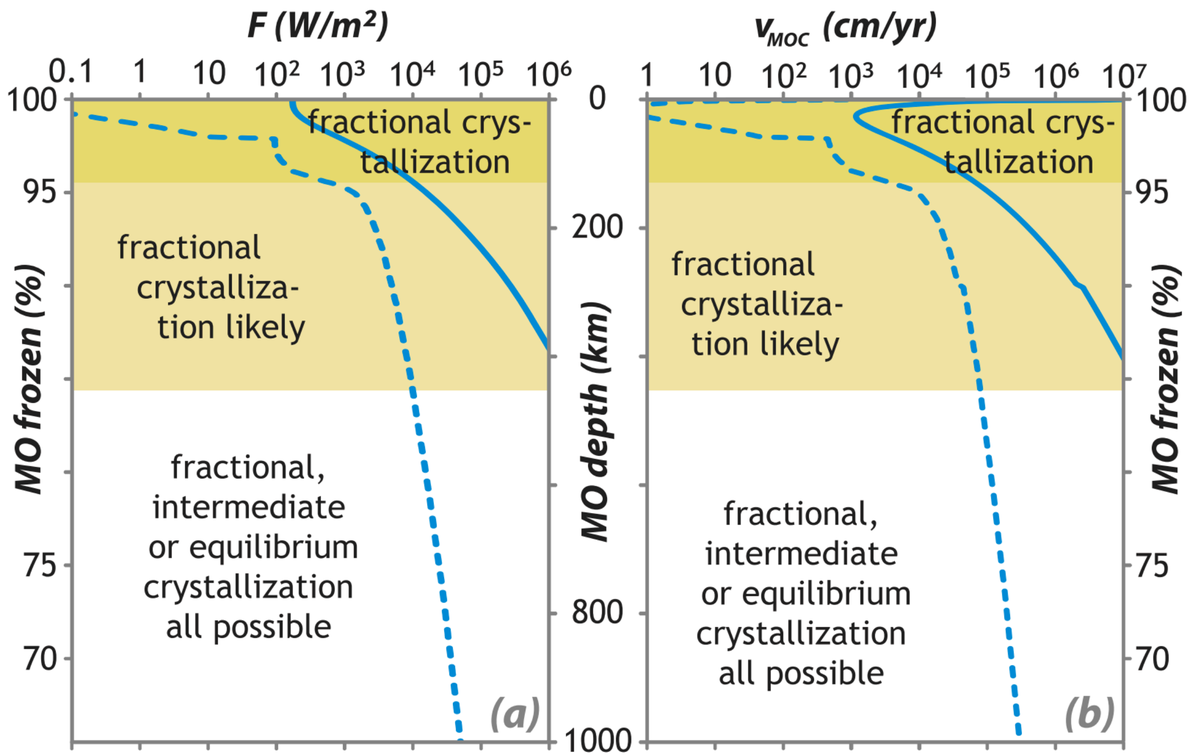
Hirschmann 16



Schaefer & Elkins-Tanton 18

1. Whole-mantle MO —> global volatile budget

- Whole mantle completely molten
- Initial temperature profile following mantle liquidus
- Employ partition coefficients for alloy/O + CHNS ratios
  - Track composition/mixing + density inversion
  - Oversaturated volatiles released to atmosphere
- **MO heat flux through eddy diffusivity**

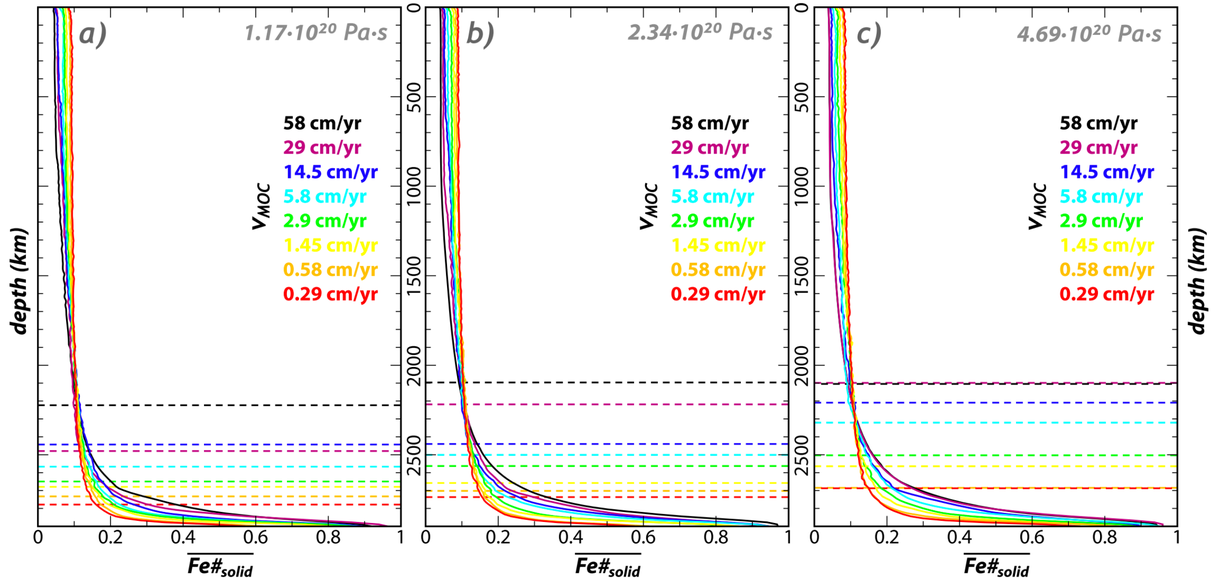


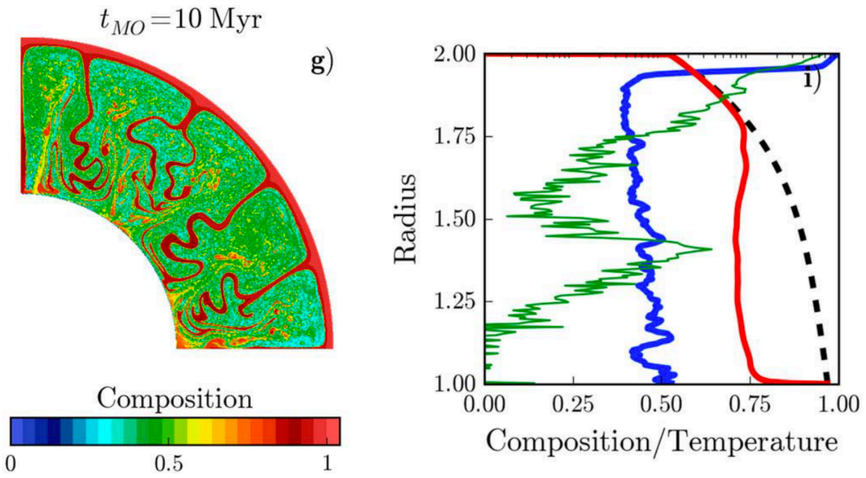
Ballmer+17

2. After overturn: remixing of stratified mantle

- Overturn is bracketed, primary late-stage result of overturn must be assumed
  - Mixing scenarios predicted differ
  - Some constraints can be taken from average mantle convection time + LLSVP compositions
- Density inversions are reduced to variations due to mantle composition
- Remixing from MMU feedback + enhanced plutonism?
  - Radiogenic heat-source partitioning

Ballmer+17

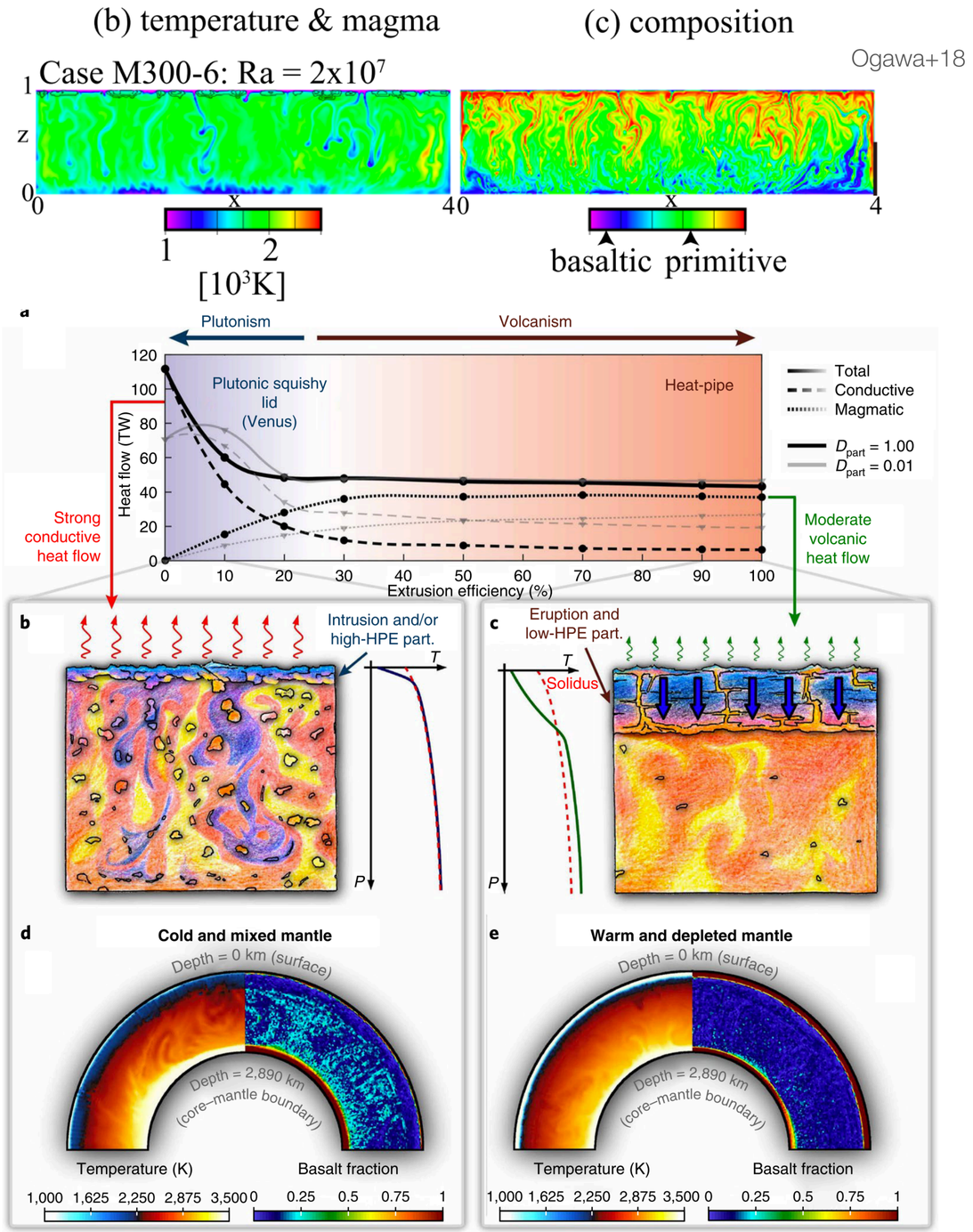




Maurice+17

2. After overturn

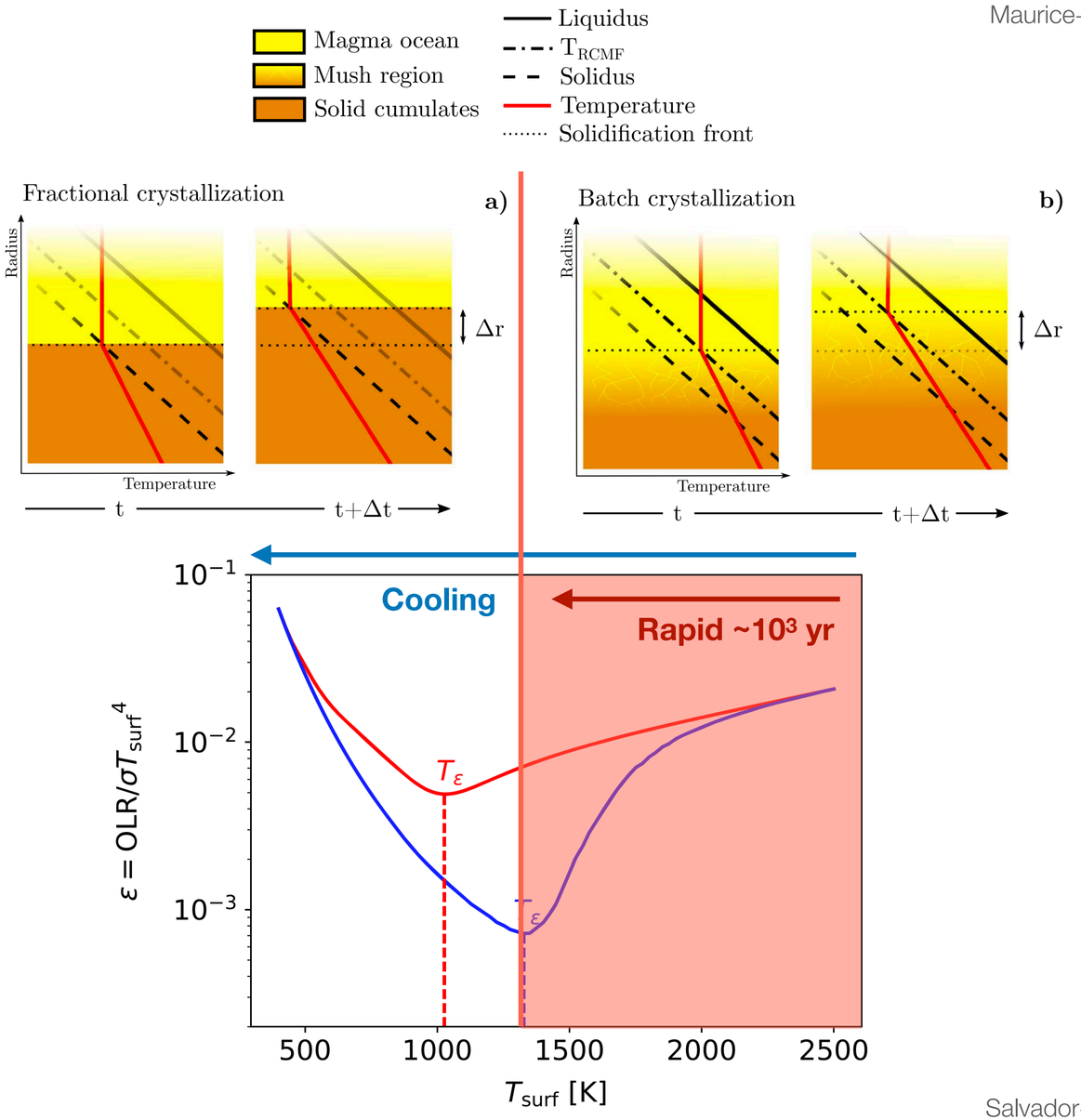
- Overturn is bracketed, primary late-stage result of overturn must be assumed
  - Mixing scenarios predicted differ
  - Some constraints can be taken from average mantle convection time + LLSVP compositions
- Density inversions are reduced to variations due to mantle composition
- **Remixing from MMU feedback + enhanced plutonism?**
  - **Radiogenic heat-source partitioning**



3. Intermediate (late-stage) MO

- Bracketing rapid early MO evolution
  - Initial atmospheres dominated by either H_2O/CO_2 (oxidised) or H2/CO (reduced)
  - Initial rapid cooling phase dominated by batch crystallisation
- Cannot avoid largely molten regions, but reduces uncertainties related to Fe partitioning
  - Fe-related density inversions
  - + MMU feedback (Ogawa+18)
  - + Intrusion feedback (Lourenco+18)
- Computationally a compromise

Maurice+17



Salvador+17

Summary & open questions

- 2D global or quarter-shell model
- Two-phase separation between melt and solid
- *Chemical partitioning of iron phases (or mantle chemical evolution) between silicate melt and rock?*
  - *Feedback between density inversions, MMU effect + plutonism?*
- *Volatiles continually released + fed to uppermost mantle vs. parameterised using Salvador+17 scaling relations?*
  - *Atmospheric phase space?*
- *Partitioning/chemical evolution?*
  - *Constants derived from geochemical experiments?*
  - *Parameterisation à la Rees Jones+?*
  - *Mixture of both w/ regards to Fe vs. H_2O/CO_2/volatiles and high/low melt regions?*
- *Eddy diffusivity?*
- *Numerical feasibility?*