Linking the Core heat content to Earth's accretion history

Renaud Deguen & Vincent Clési

ISTerre, Université Grenoble Alpes
LGL-TPE, Université Claude Bernard Lyon 1, ENS de Lyon

EGU 2020

European Research Council
Established by the European Commission

ISTerre
Institut des Sciences de la Terre

UGA
Université Grenoble Alpes

Laboratoire de Géologie de Lyon
Terre Planètes Environnement

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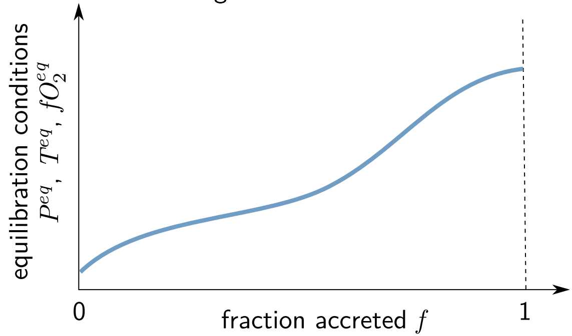
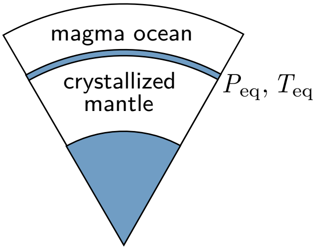
Introduction

Constraints on core formation from estimated core/mantle chemical partitioning

$$\underbrace{\text{Estimated core/mantle partitioning } D_{\mathrm{core/mantle}} \quad + \quad \text{partitioning behaviour } D(P, T, fO_2)}_{P_{\mathrm{eq}},\, T_{\mathrm{eq}},\, fO_{2\,\mathrm{eq}} \text{ during Earth's formation}}$$





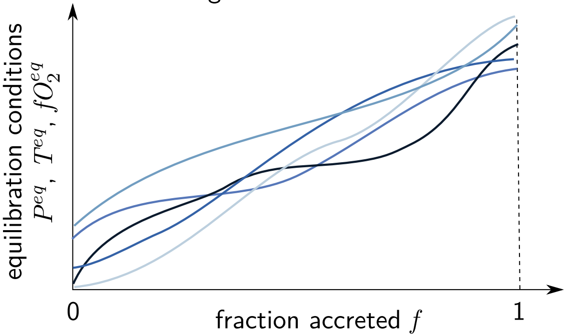
e.g.
Siebert *et al.* (2012)
Rubie *et al.* (2015)
Badro *et al.* (2015)
Fischer *et al.* (2015)

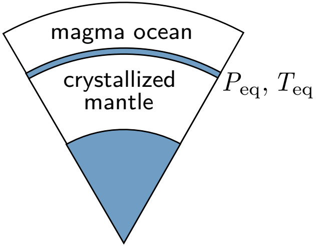
Introduction

Constraints on core formation from estimated core/mantle chemical partitioning

Estimated core/mantle partitioning $D_{\text{core/mantle}}$ + partitioning behaviour $D(P, T, fO_2)$

$P_{\text{eq}}, T_{\text{eq}}, fO_{2\text{eq}}$
during Earth's formation





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Introduction

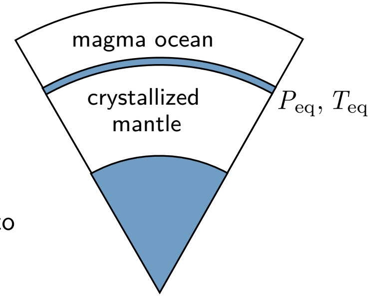
- Can we tell something about the temperature of the Core at the end of accretion from the constraints on P_{eq}, T_{eq} ?

- Or, alternatively, can we use the Core heat content as an additional constraint on the P, T conditions during core formation?

Method

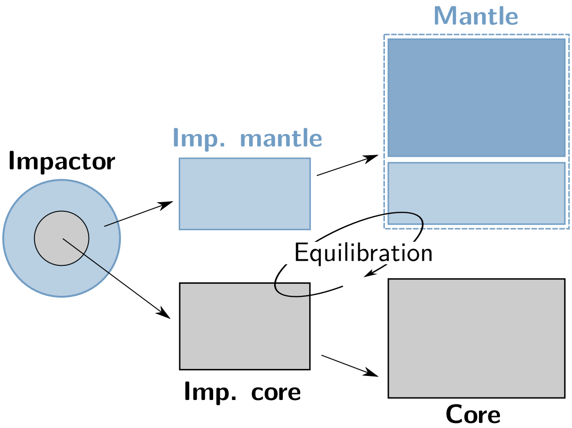
1. Geochemical modelling
   Generate a set of geochemically consistent accretion histories $P_{\mathrm{eq}}(f)$, $T_{\mathrm{eq}}(f)$ (Monte-Carlo inversion)

2. Thermal modelling
   For each P_{eq}, T_{eq} accretion trajectories,
   - Estimate, for each metal mass addition, the evolution of its temperature as it travels toward the core.
   - Add the temperature increase due to compression associated to the subsequent growth of the Earth.
   - Either
     - keep the metal where it has been added
     - assume the core has been well-mixed by impacts



1. Geochemical modelling

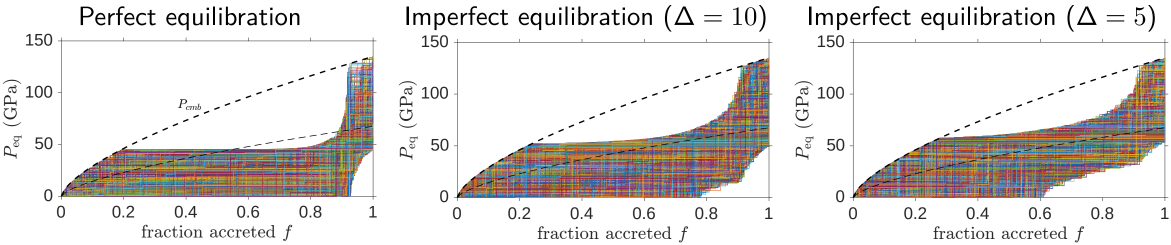
Core formation box model



"Dilution" of the metal phase $\Delta = \frac{\text{mass of equilibrated silicates}}{\text{mass of equilibrated metal}}$

1. Geochemical modelling

Geochemically consistent (Ni & Co) accretion histories

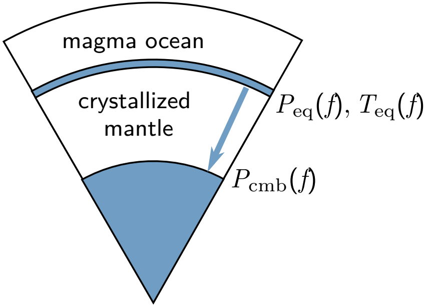


Imperfect equilibration $\Rightarrow$ higher $P_{\mathrm{eq}}, T_{\mathrm{eq}}$

2. Thermal modelling

Thermal evolution of the metal phase

1. Start with initial conditions $P_{\mathrm{eq}}(f)$, $T_{\mathrm{eq}}(f)$, assumed to be the conditions at the base of the magma ocean.



2. Thermal modelling

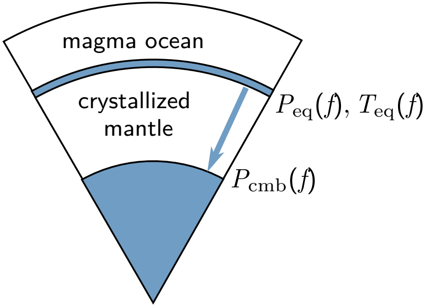
Thermal evolution of the metal phase

2. The descent to the Core through the Mantle (as a metal diapir): $P_{eq}(f) \rightarrow P_{\mathrm{cmb}}(f)$

$$M_d c_p \frac{d\bar{T}}{dt} = \text{Compression Heating} + \text{Heat exchange with silicates} + \text{Dissipative heating}$$

Only a fraction ϵ of the total dissipation happens in the metal phase:

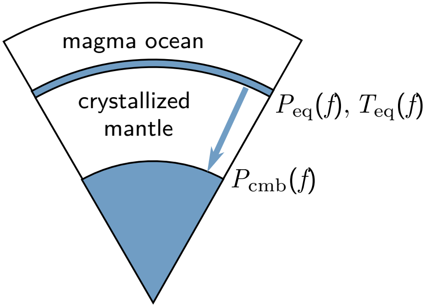
$$\Phi = -\epsilon \frac{dE_p}{dt}$$



2. Thermal modelling

Thermal evolution of the metal phase

3. Compression heating due to subsequent growth of the Earth: $P_{\mathrm{cmb}}(f) \rightarrow P_{\mathrm{final}}$

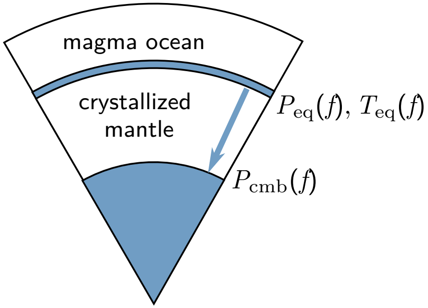


2. Thermal modelling

Thermal evolution of the metal phase

4. Assume the core to be mixed (impacts...), additional dissipation.

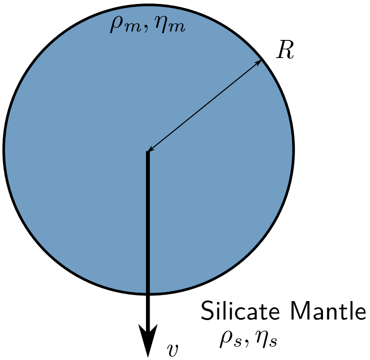
$\Rightarrow T_{\mathrm{cmb}}$



2. Thermal modelling

Diapir model

- Stokes velocity
- Heat flux from diapir to mantle : $Nu \sim Pe^{1/2}$
- Dissipation $\Phi = \eta_m \left(\boldsymbol{\nabla v} + \boldsymbol{\nabla v}^T \right) : \boldsymbol{\nabla v}$



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- Stokes velocity
- Heat flux from diapir to mantle : $Nu \sim Pe^{1/2}$
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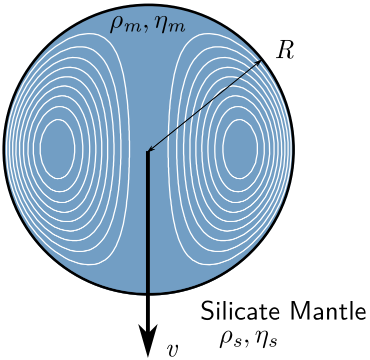
1. If the flow within the diapir is laminar:

$$\epsilon = \frac{\Phi}{\frac{dE_p}{dt}} \sim \frac{\eta_m}{\eta_s} \lesssim 10^{-18}$$



2. Thermal modelling

Diapir model

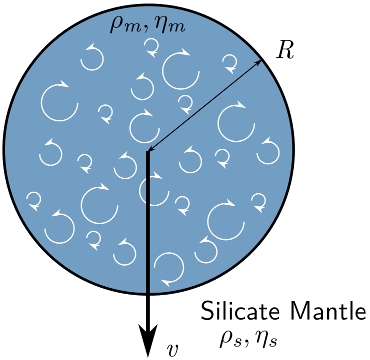
- Stokes velocity
- Heat flux from diapir to mantle : $Nu \sim Pe^{1/2}$
- Dissipation $\Phi = \eta_m \left(\boldsymbol{\nabla v} + \boldsymbol{\nabla v}^T\right) : \boldsymbol{\nabla v}$

2. If the flow within the diapir is turbulent:

$$\Phi \sim \text{rate of energy input} \sim \frac{M_{\text{diapir}}\, v^2}{R/v}$$

which predicts

$$\epsilon = \frac{\Phi}{\frac{dE_p}{dt}} \sim \frac{\rho_m}{\rho_s} Re_{\text{sil}} \lesssim 10^{-6}$$



2. Thermal modelling

Diapir model

- Stokes velocity
- Heat flux from diapir to mantle : $Nu \sim Pe^{1/2}$
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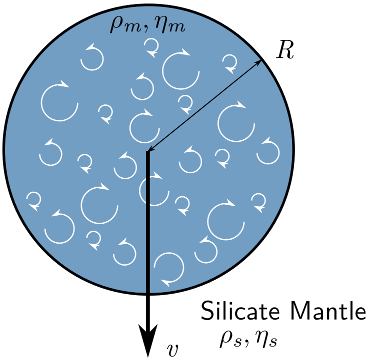
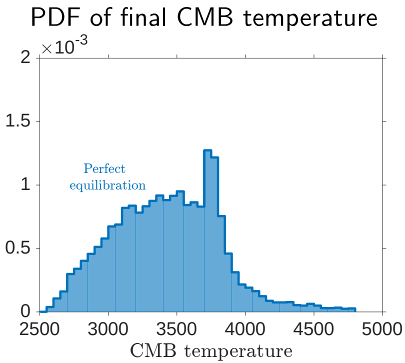


Negligible dissipative heating in the diapir

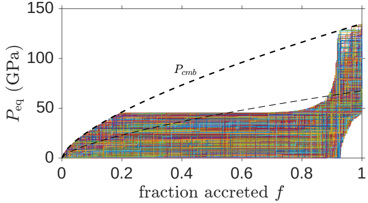
Results

Perfect equilibration

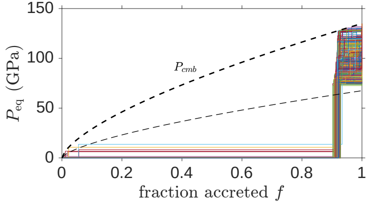


Many geochemically consistent accretion histories yield a low core temperature...

- full set of P_{eq} trajectories

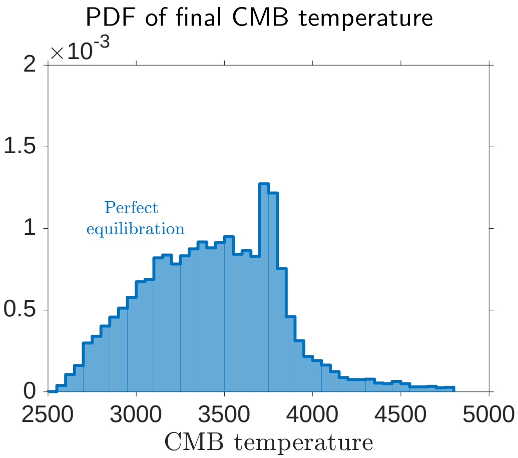


- subset with $T_{cmb} > 4200$ K



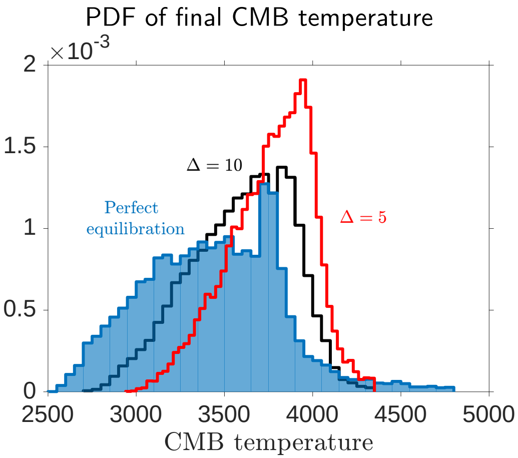
Results

Effect of imperfect equilibration



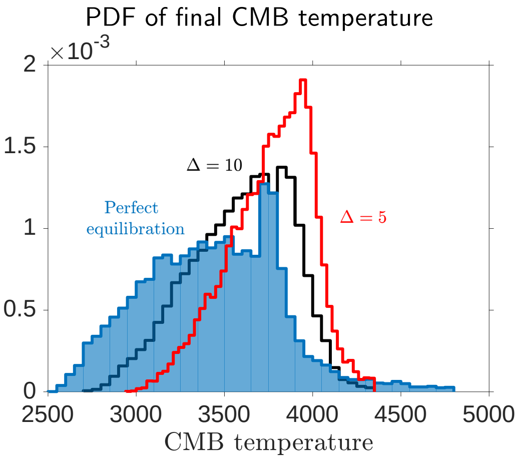
Results

Effect of imperfect equilibration



Results

Effect of imperfect equilibration



Imperfect equilibration $\Rightarrow$ slightly higher T

Conclusion

1. **Results:**
   - We can find geochemically consistent $P_{\mathrm{eq}}, T_{\mathrm{eq}}$ trajectories which are consistent with estimates of the current core temperature...
     ... but many give a core temperature which is much too low.

     $\Rightarrow$ the core heat content can be used as a constraint on Earth's accretion conditions
     Favours accretion histories with low equilibration pressure in the first $\sim 80-90\%$ of accretion, and high equilibration pressure in the last $10-20\%$, which are consistent with the Moon-forming giant impact scenario.

2. **Issues/difficulties**
   Requires a number of assumptions:
   - on the mechanisms of metal/silicates separation
   - on the interpretation of the $P_{\mathrm{eq}}, T_{\mathrm{eq}}$ conditions
   - the results are somewhat sensitive to the assumed physical properties of iron
   - ...