Geochemical constraints on the core formation and composition

Bernard Bourdon
ENS Lyon

with:
Mathieu Touboul, Caroline Fitoussi,
John Rudge and Thorsten Kleine

Collège de France November 25th

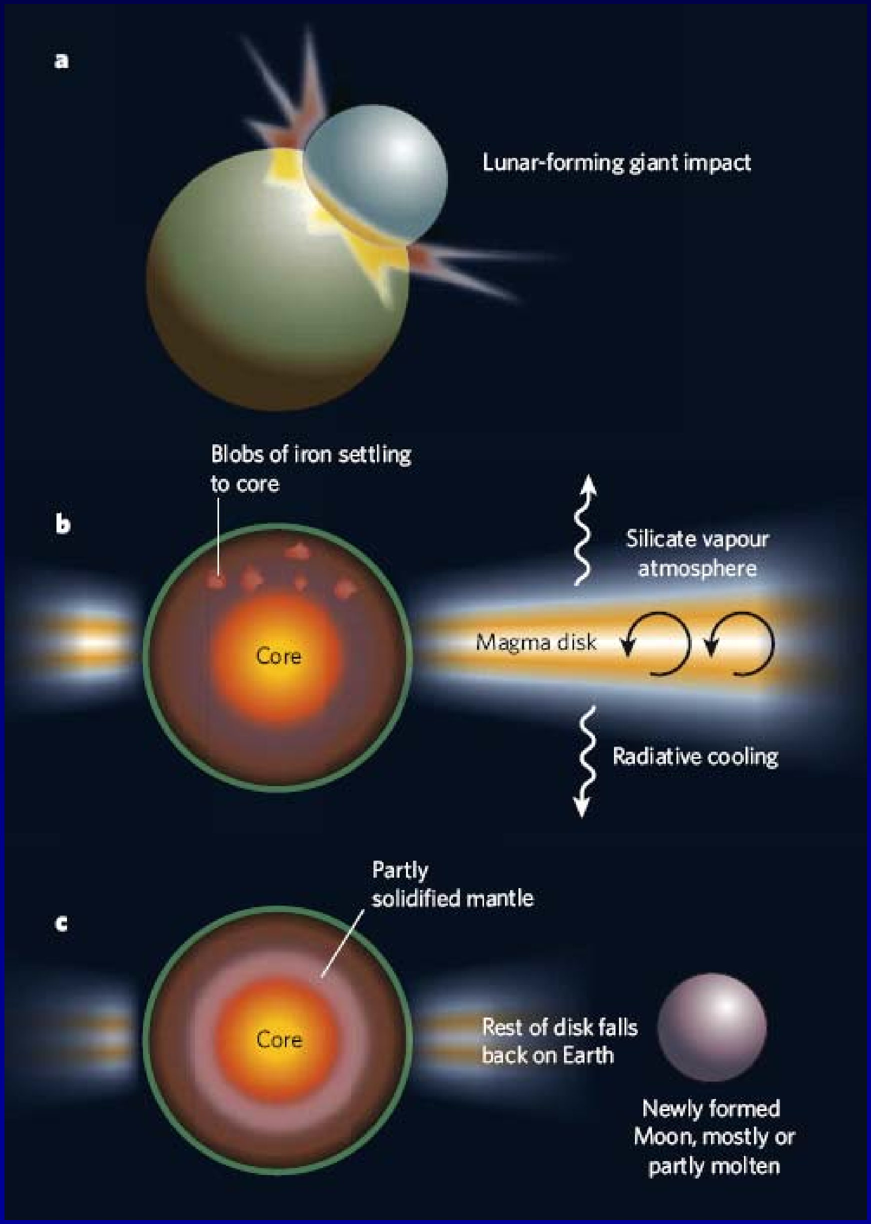
- Core formation models inform us about the composition of the core.
- Isotope constraints on the timescale and the conditions of Earth core formation.

Outline of talk

- Timescale of core formation
- Geochemical models of core formation
- Si in the core: evidence from Si isotopes

Earth formed by giant impacts

- Terrestrial accretion proceeds by giant impact when its mass exceeds 20% of the current mass.
- The Moon-forming giant impact is probably the last of a series of impact events.



Coupling of accretion and core formation

The sinking velocity of liquid metal or metal diapirs is short relative to accretion timescales of the Earth (50-100 Ma).

↓

Core formation proceeds at the rate of accretion.

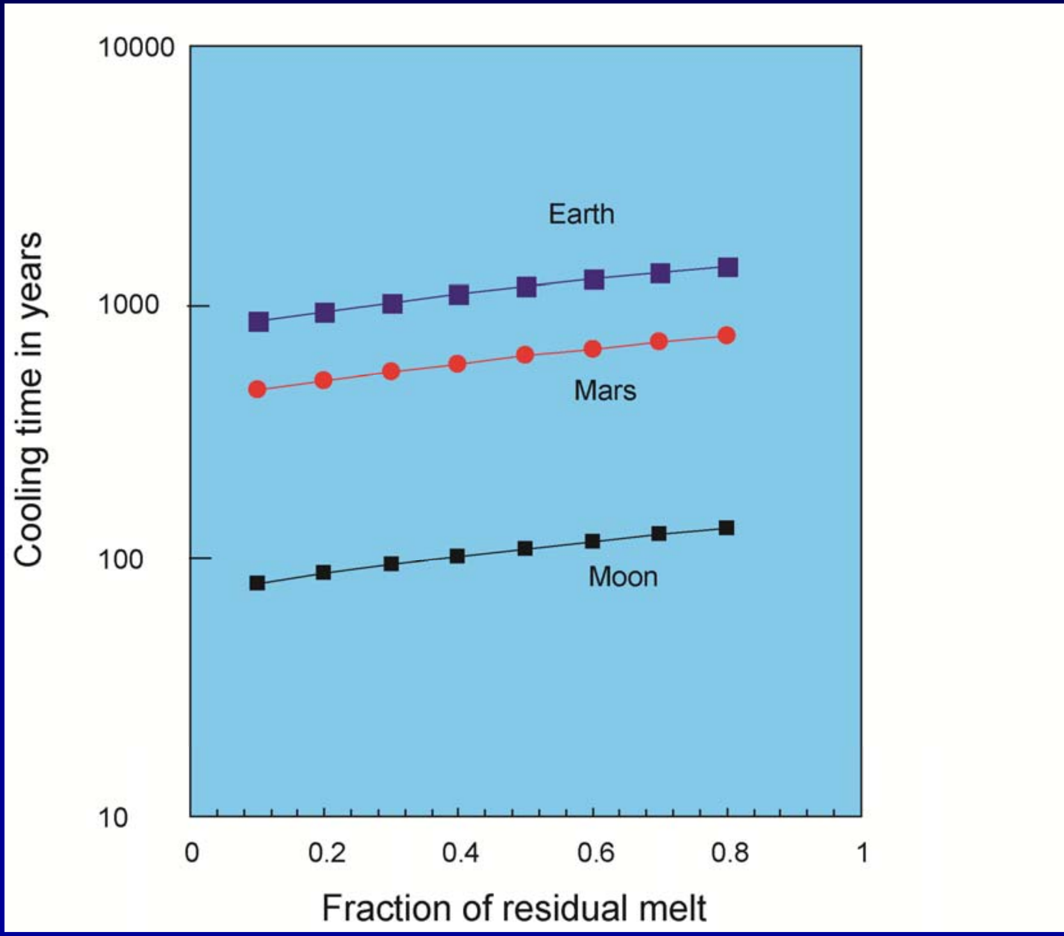
Importance of rate of accretion

- The physical state of the mantle (molten or solid) during core accretion will depend on the frequency of impacts (accretion rate).

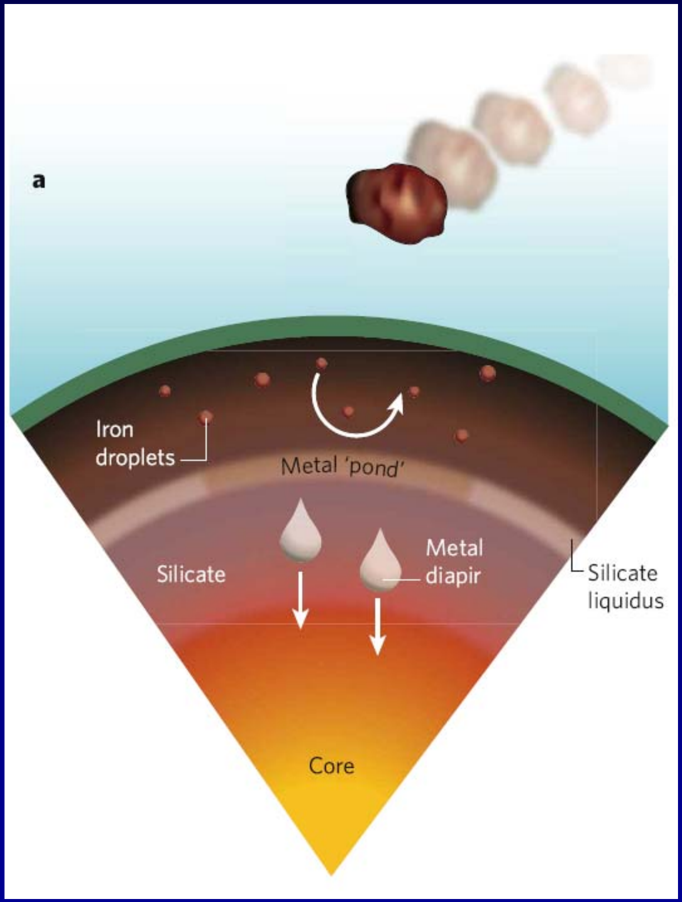
- Fast accretion means less time for cooling and crystallization between impacts.

Timescale of magma ocean crystallization

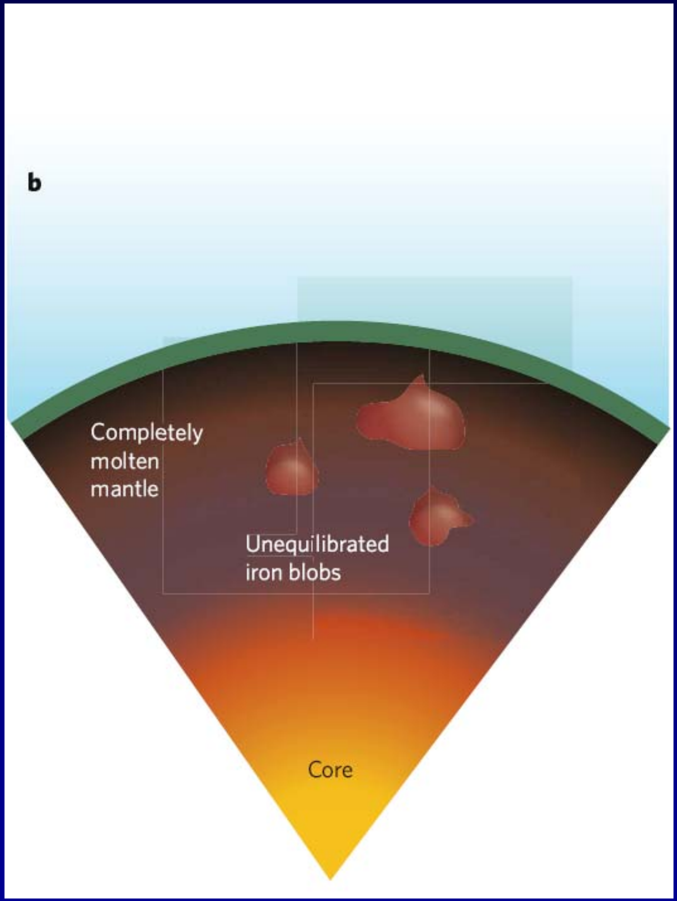
- For the Earth, the crystallization of a magma ocean up to 60% crystals is fast and further cooling is still fast (~ 10 Myr).



How should we model core formation?



- The mantle is partially molten, there is metal silicate equilibration until the base of the magma ocean.



- The mantle is totally molten, and the liquid metal migrates as a whole to the proto-core. No chemical equilibration.

Timescale of core formation

^{182}Hf-^{182}W

- ^{182}Hf decays to ^{182}W (half life 8.9 Ma).

- U-Pb: ^{238}U decays to ^{206}Pb (half life 4.4 Ga)
- ^{235}U decays to ^{207}Pb (half life 700 Ma)

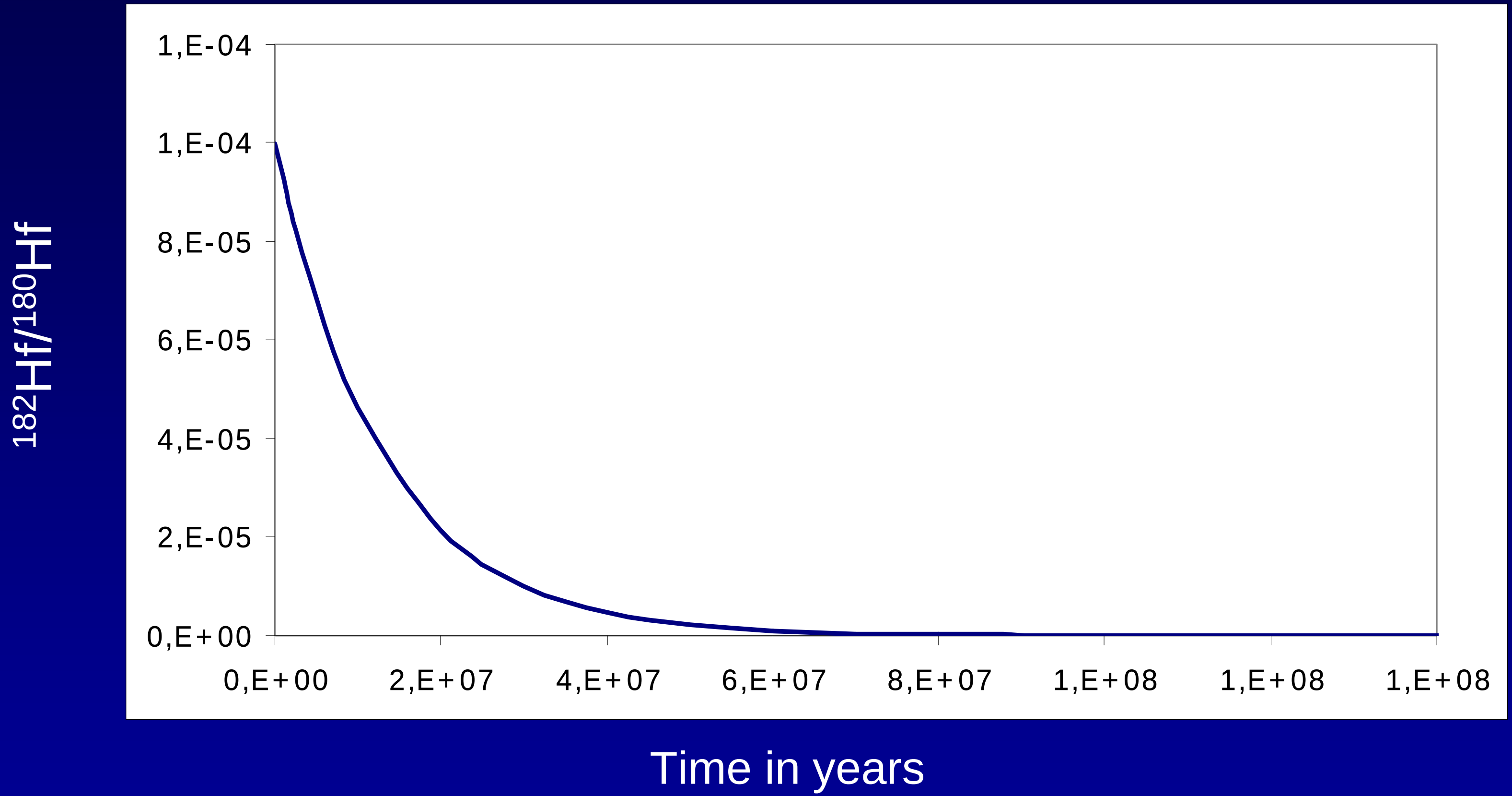
$$\varepsilon^{182}W = \left(\frac{R_{sample}}{R_{s\tan dard}} - 1 \right) \times 10^4$$

The Hf-W method

- Hf and W are both refractory elements.
- Hf is lithophile
- W is siderophile

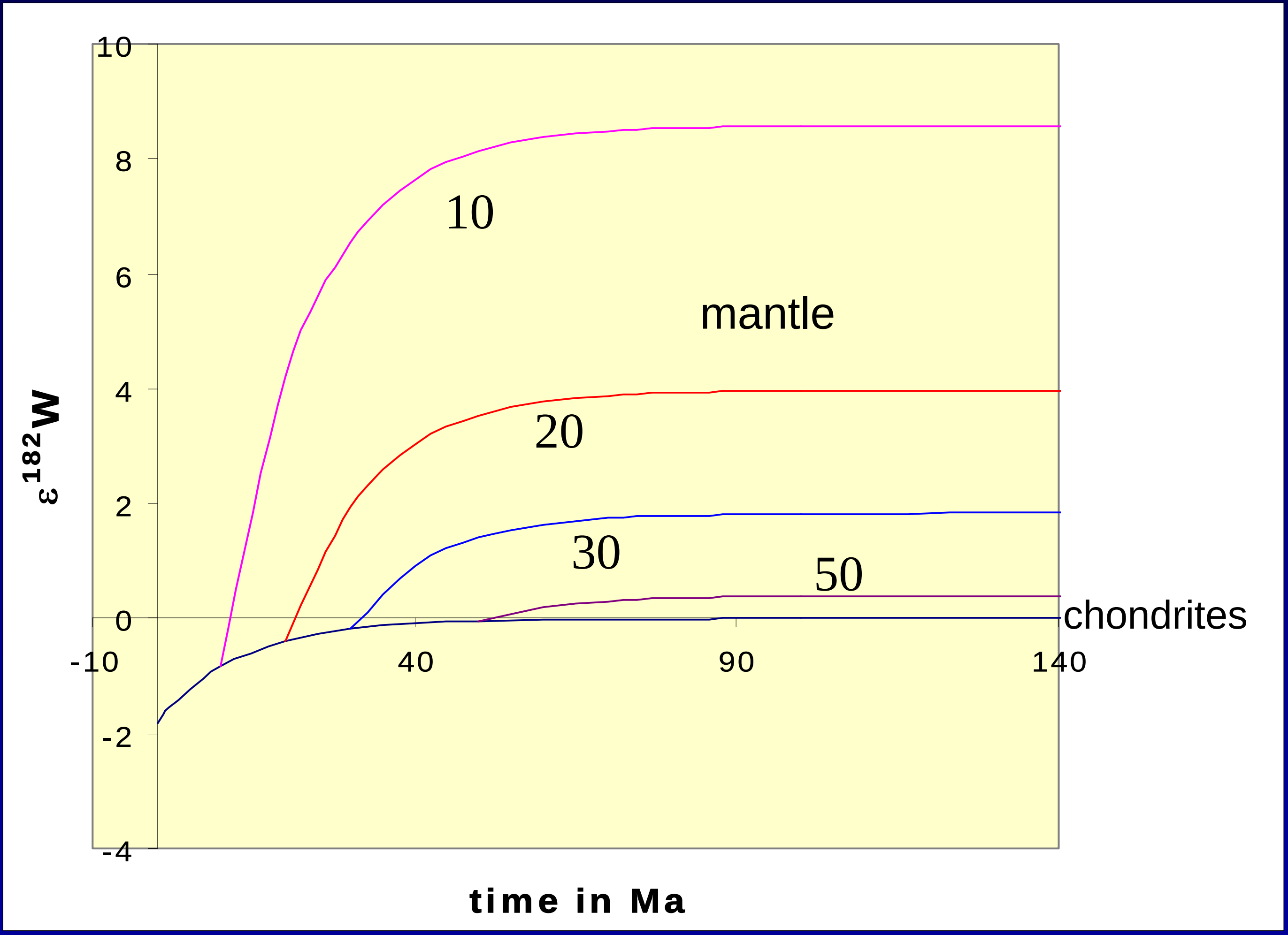
- The Hf/W ratio is fractionated by metal-silicate separation.

Decay of ^{182}Hf

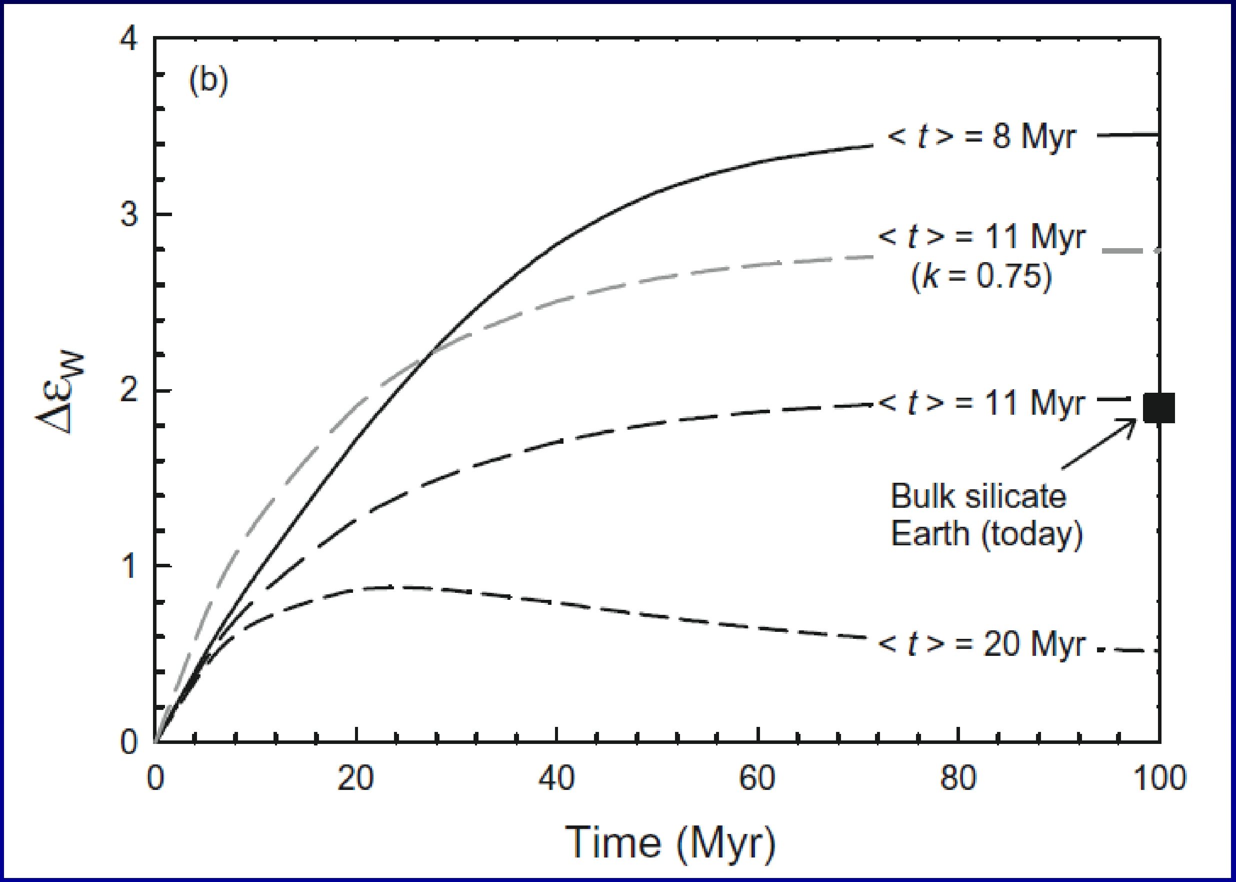


After 60 Ma, there is no ^{182}Hf left.The relative abundance of ^{182}W is no longer modified, we can only date an event younger than 60 Ma after the beginning of the solar system

Timing of core formation with Hf-W



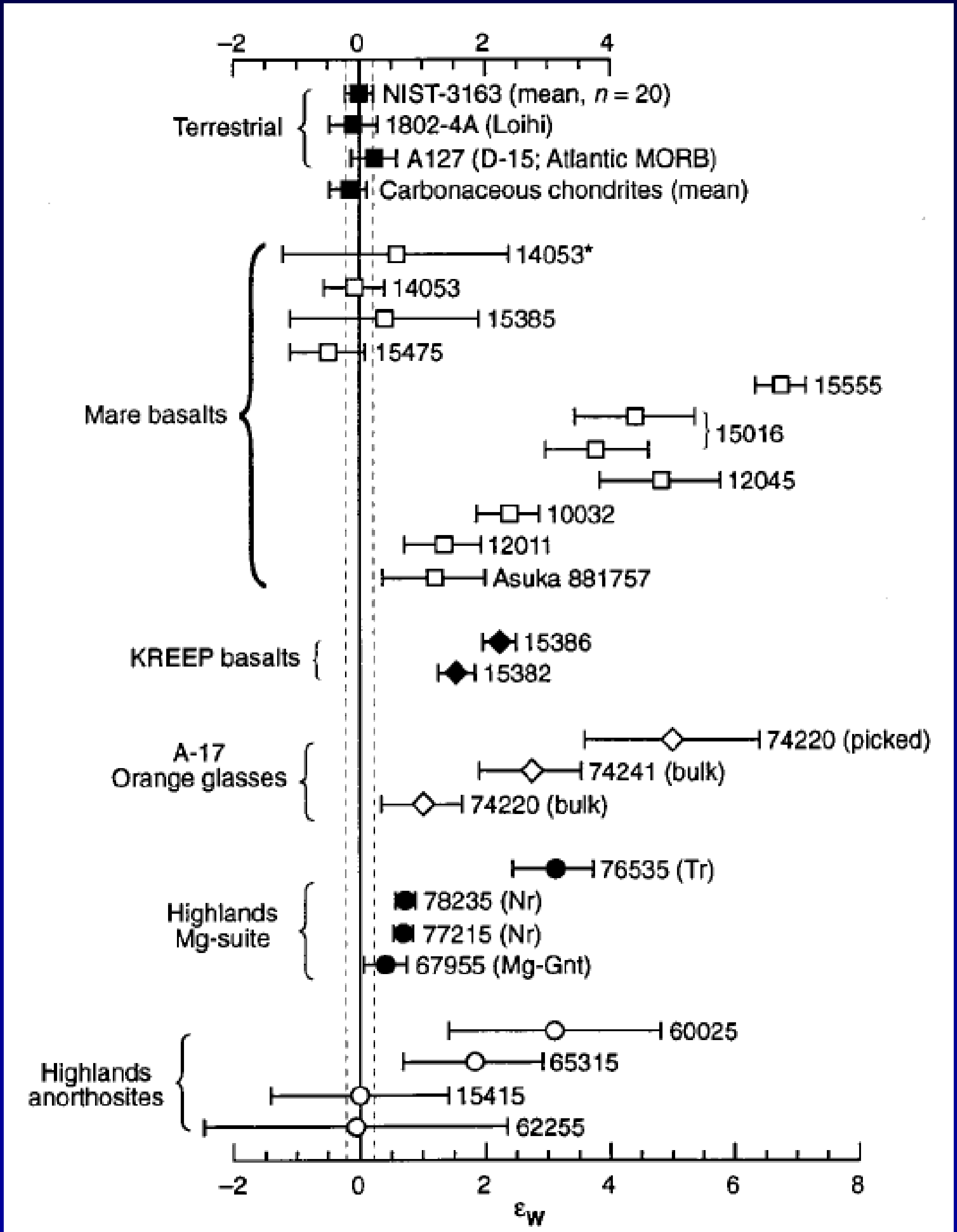
Timing of core formation



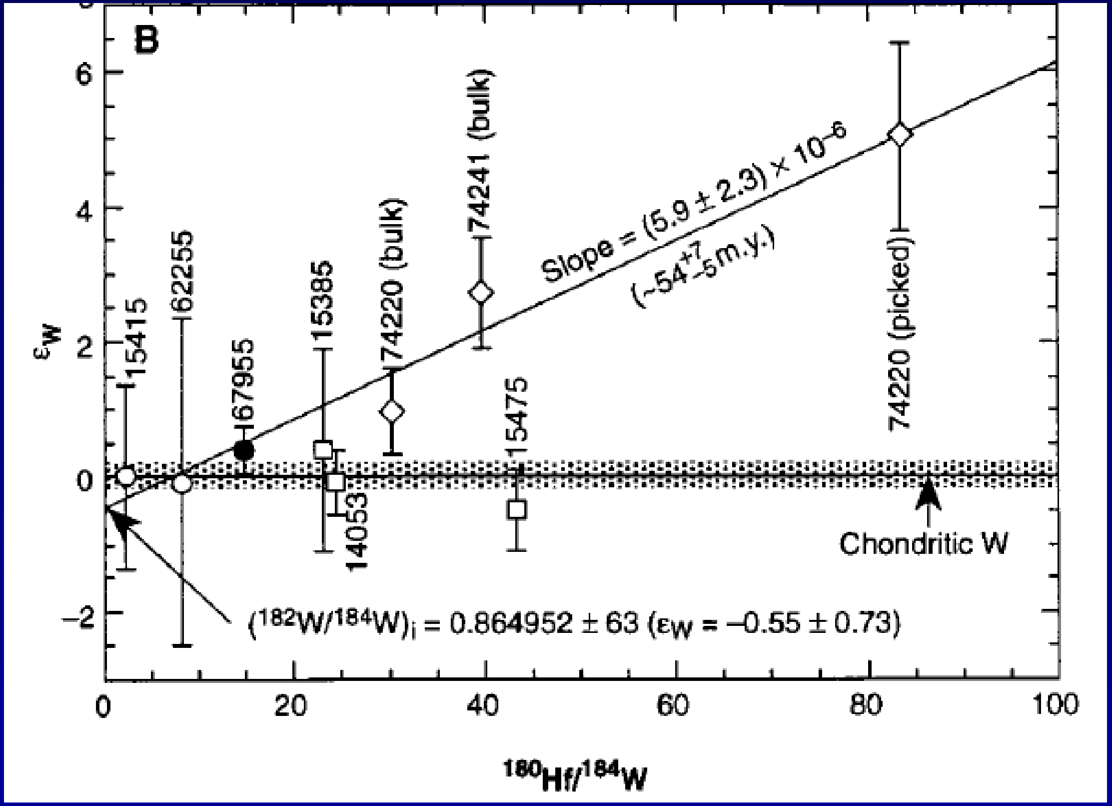
Kleine et al. 2009

Early attempts to constraint the age of the Moon= termination of core formation.

- Lee et al. (1997) showed a large range in W isotopes in lunar samples.



Early W data indicated an age for the Moon of 54 Ma

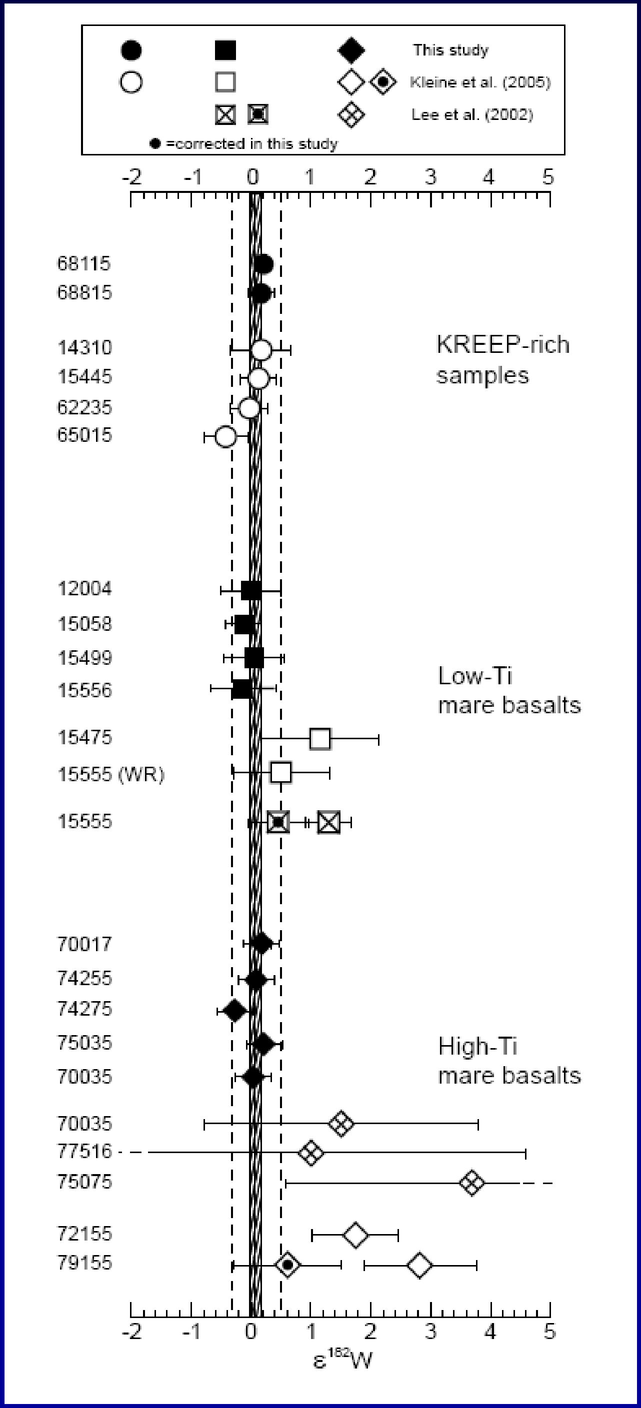


Lee et al. 1997

New ^{182}W data for Moon

- Large sample size allows large pure Fe-metal fraction to be collected.

- Metal does not contain Ta and the following reaction $^{181}Ta(n, \gamma)$ does not take place (no cosmogenic production of ^{182}W).



Touboul et al, Nature 2007

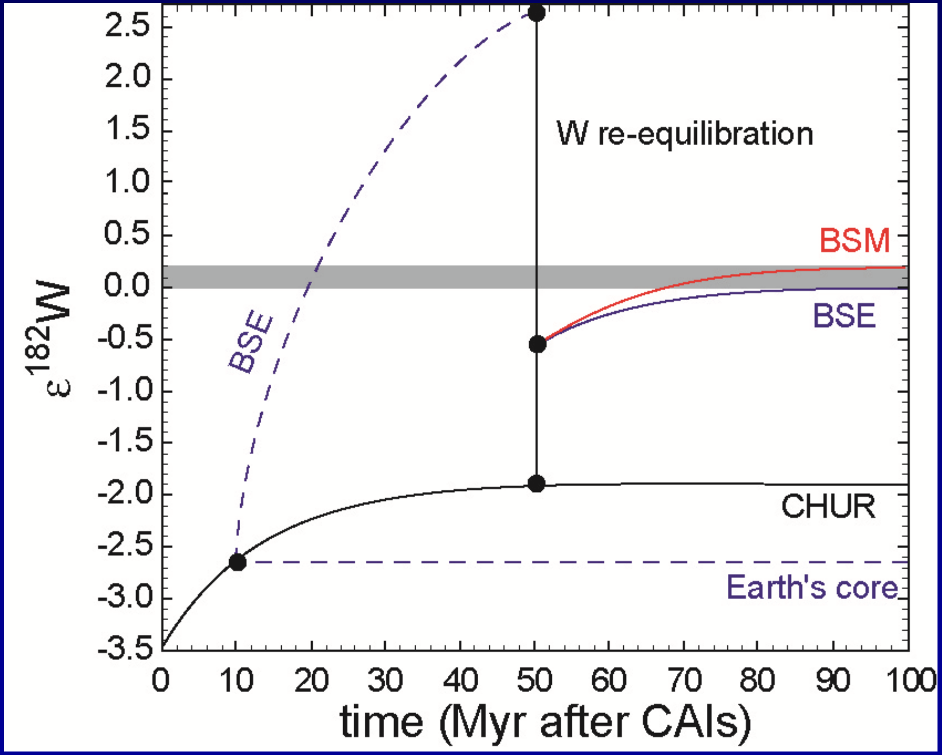
Deriving time constraints from a flat isochron!

- The ^{182}W isotope in Moon and Earth are identical but their Hf/W ratios are not strictly identical :
- $Hf/W_{moon}=26.4\pm1.5$
- $Hf/W_{earth}=19.7\pm1.6$

By comparing the bulk ^{182}W of Moon and Earth, we can derive time constraints on the Giant impact.

A model with Impactor-Earth mantle equilibration

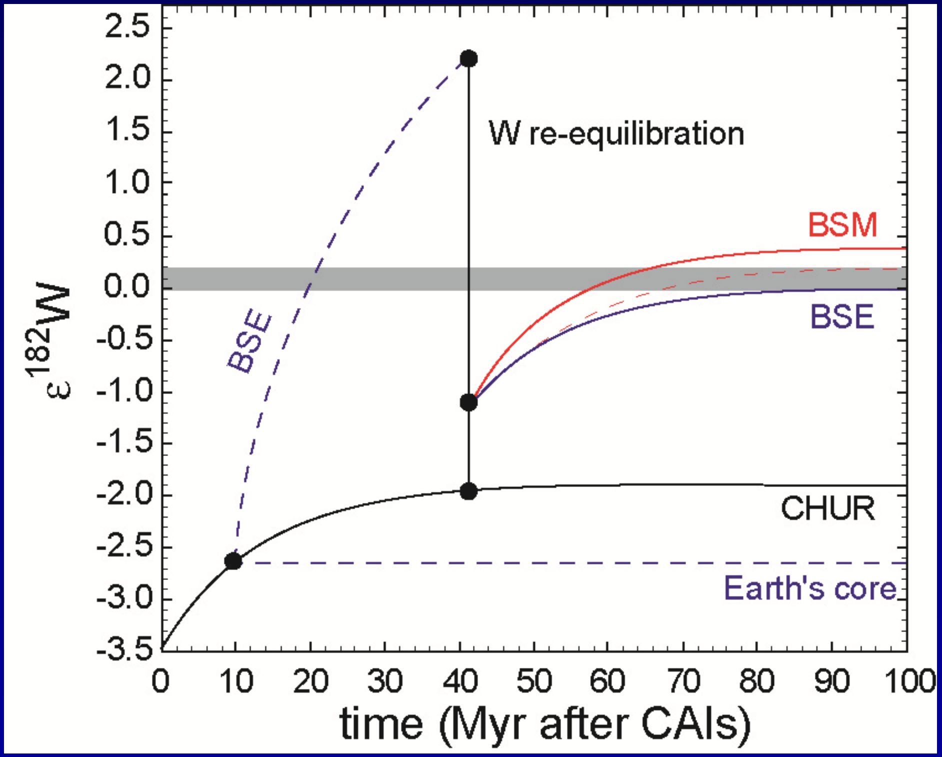
- In this model including equilibration, it is possible to match the observations with a Giant impact later than 50 Ma and partial reequilibration of the impactor core.



Bourdon et al. 2008

A model with Impactor-Earth mantle equilibration

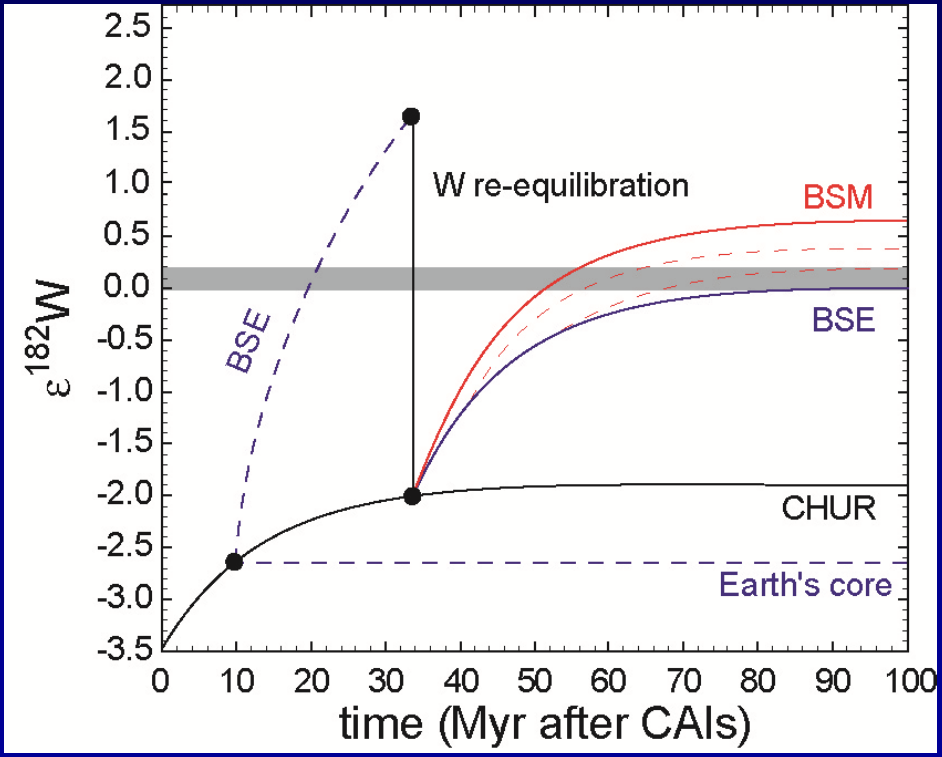
- If age of Giant impact is too early, it is difficult to match the ^{182}W composition of the Moon.



Bourdon et al. 2008

A model with Impactor-Earth mantle equilibration

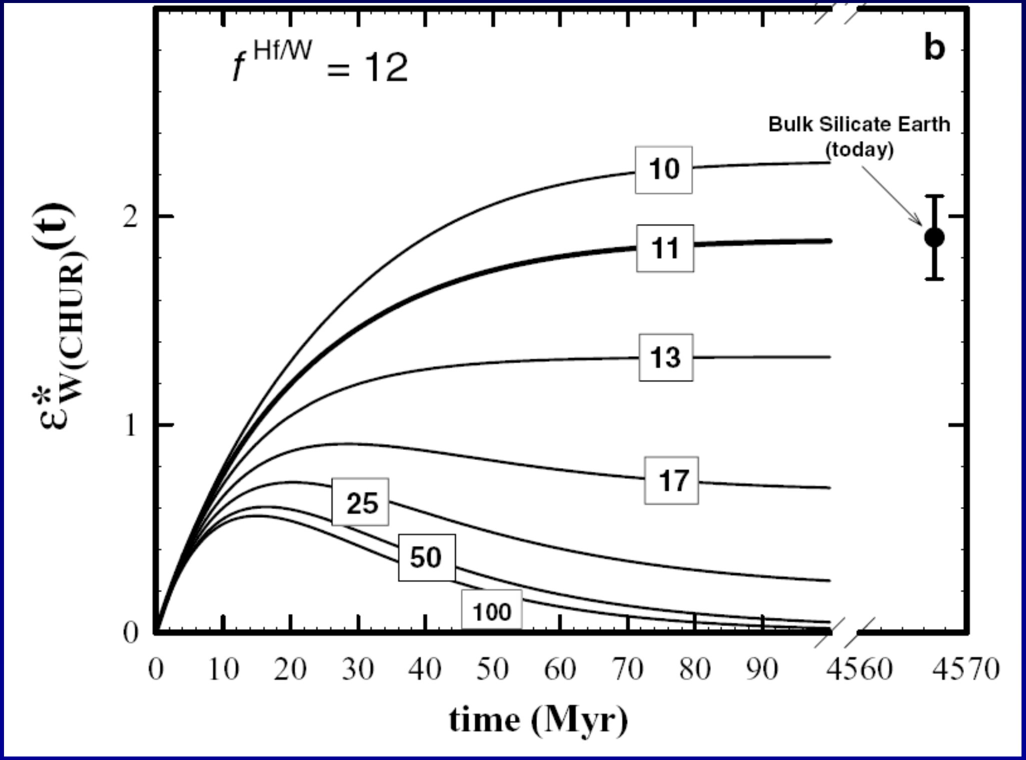
- If age of Giant impact is too early, it is difficult to match the ^{182}W composition of the Moon.



Bourdon et al. 2008

What about the age of the Earth and core formation?

- With the Hf/W measured in the Earth's mantle, the timescale for accretion is 11 Ma (69% accreted) or 30 Ma with a 2 stage model.
- This model assumes that there is full equilibration between metal and silicate during accretion and exponential growth.



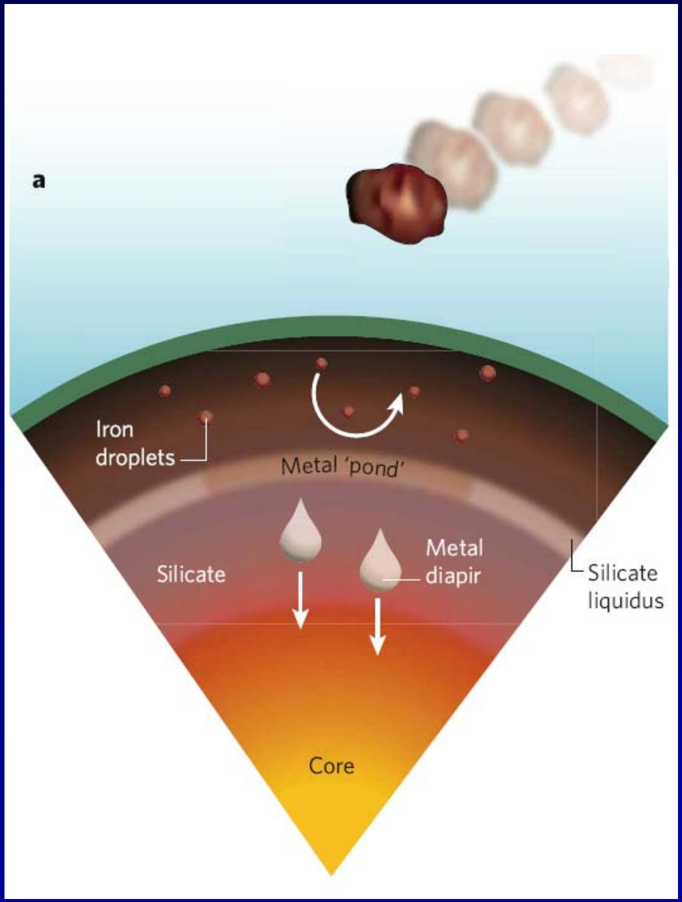
Jacobsen 2005

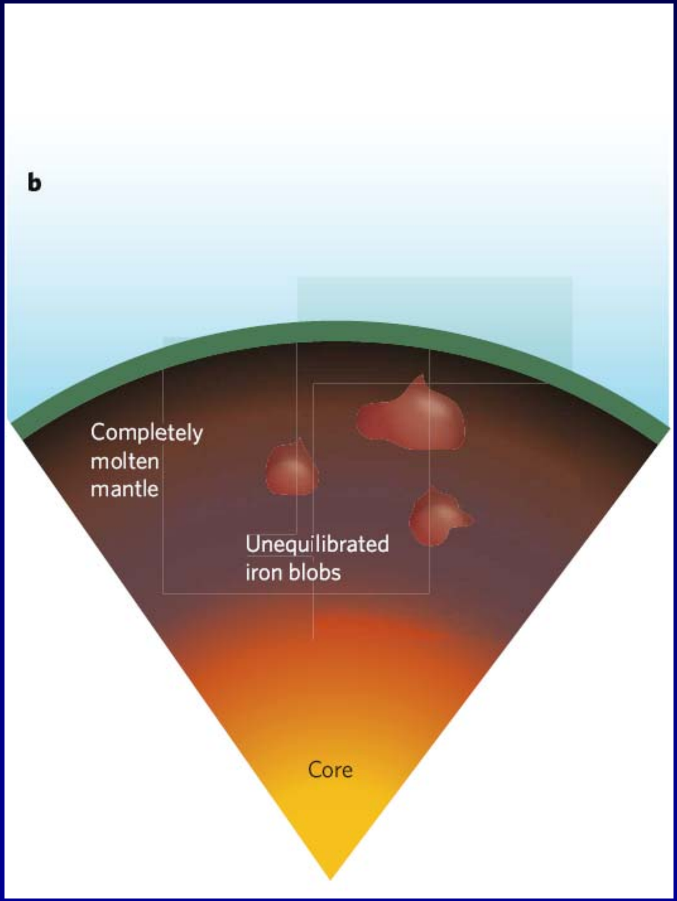
A refined model for core formation and Earth accretion

- We relax the imposed constraints of full metal-silicate equilibration and exponential growth

- We include the constraints given by siderophile elements and let the oxygen fugacity evolve freely.

How should we model core formation?

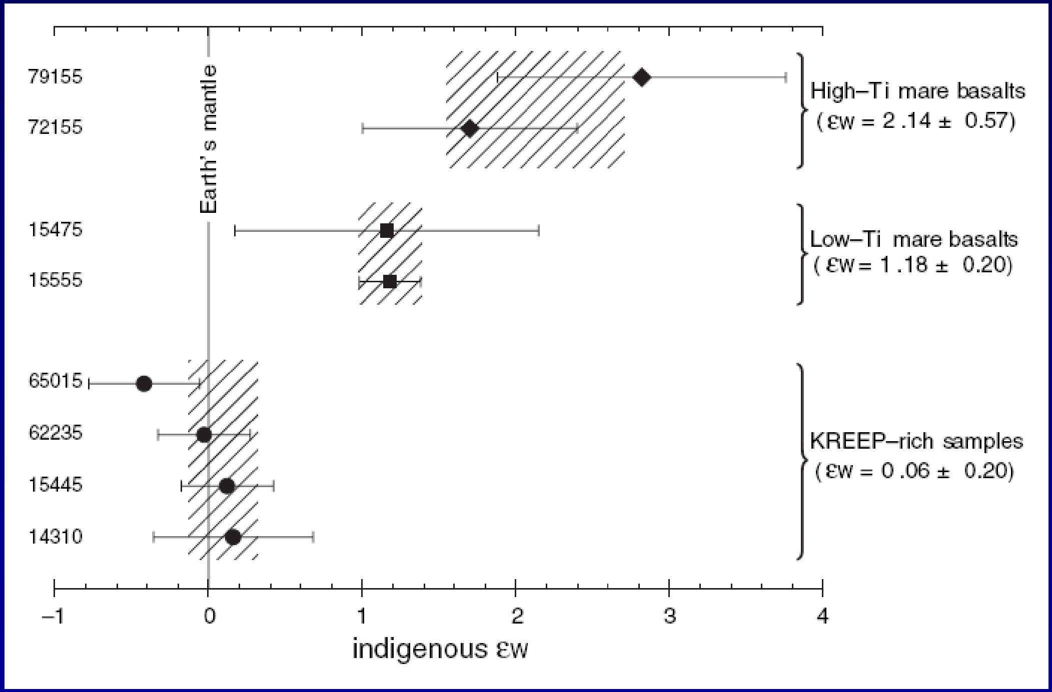




- The mantle is partially molten, there is metal silicate equilibration until the base of the magma ocean.
- The mantle is totally molten, and the liquid metal migrates as a whole to the proto-core. No chemical equilibration.

Age of the Moon based on W isotopes

- A more recent attempt to date the Moon with Hf-W revealed differences between lunar rock types.



Analysis of metal-rich fractions in lunar rocks

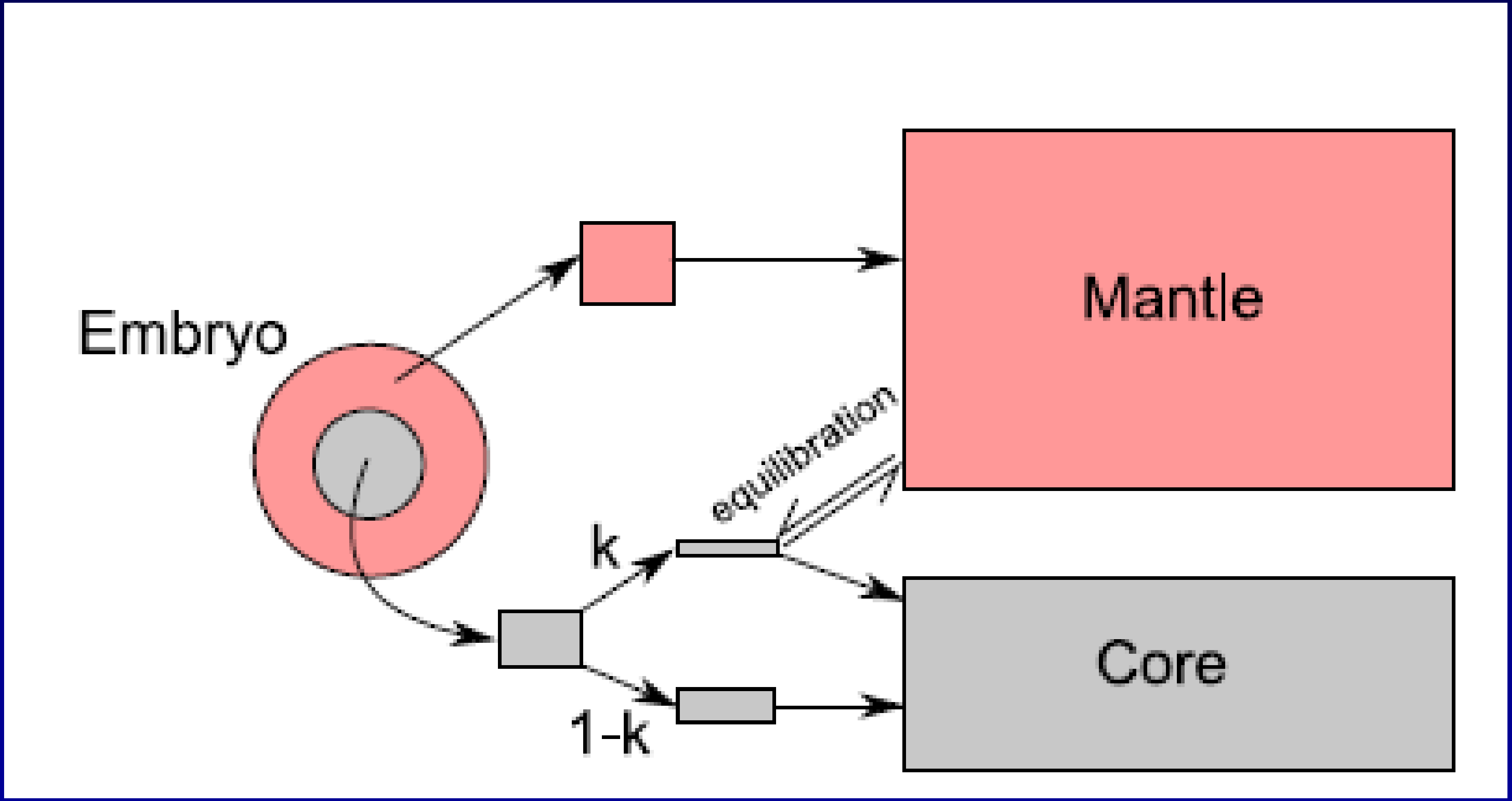
Kleine et al. 2005

A refined model for Earth's accretion and core formation

- All the models based on siderophile elements consider that metal and silicate equilibrate at the base of a magma ocean.

- Models based on Hf-W or U-Pb chronology consider the possibility of core merging during giant impacts.

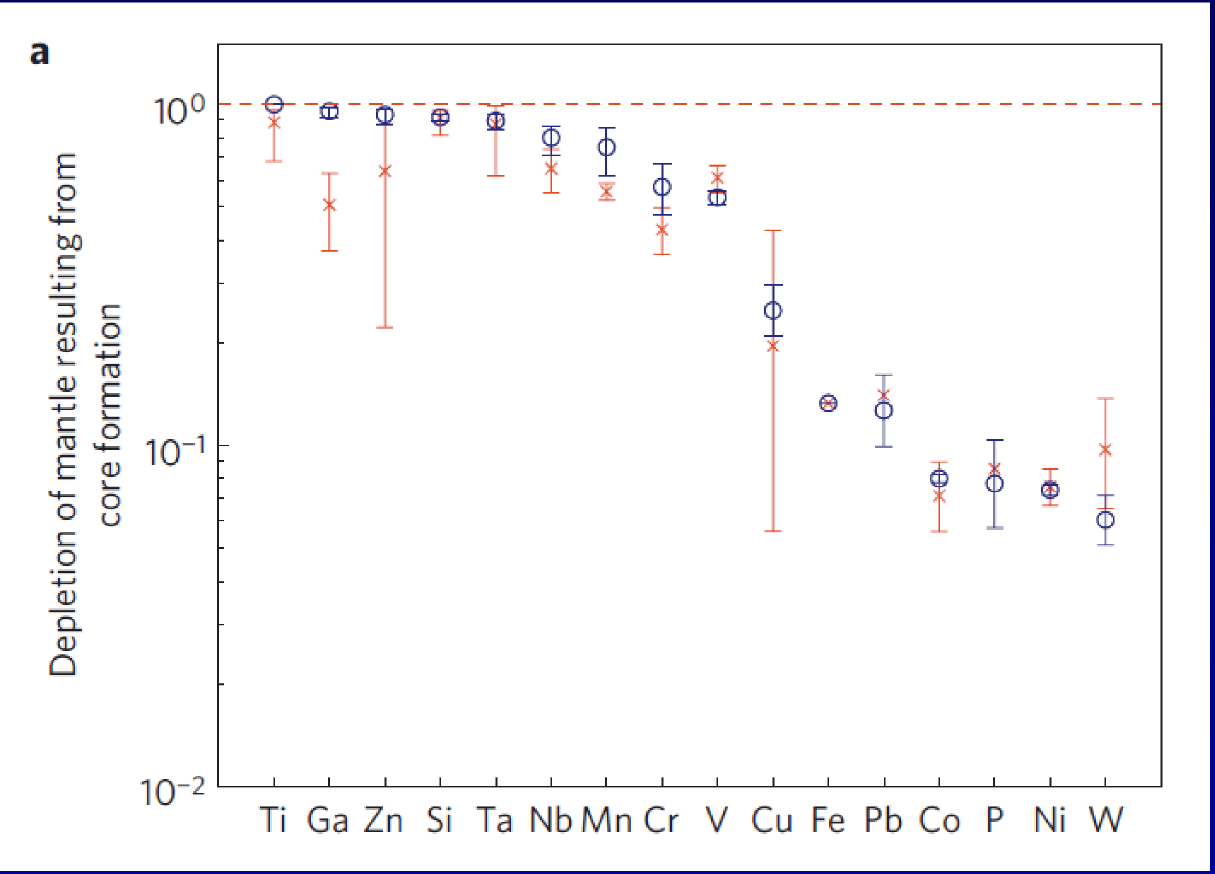
A refined model for Earth's accretion and core formation



Rudge et al. Nature Geosci. 2010

Core formation model with metal silicate equilibration

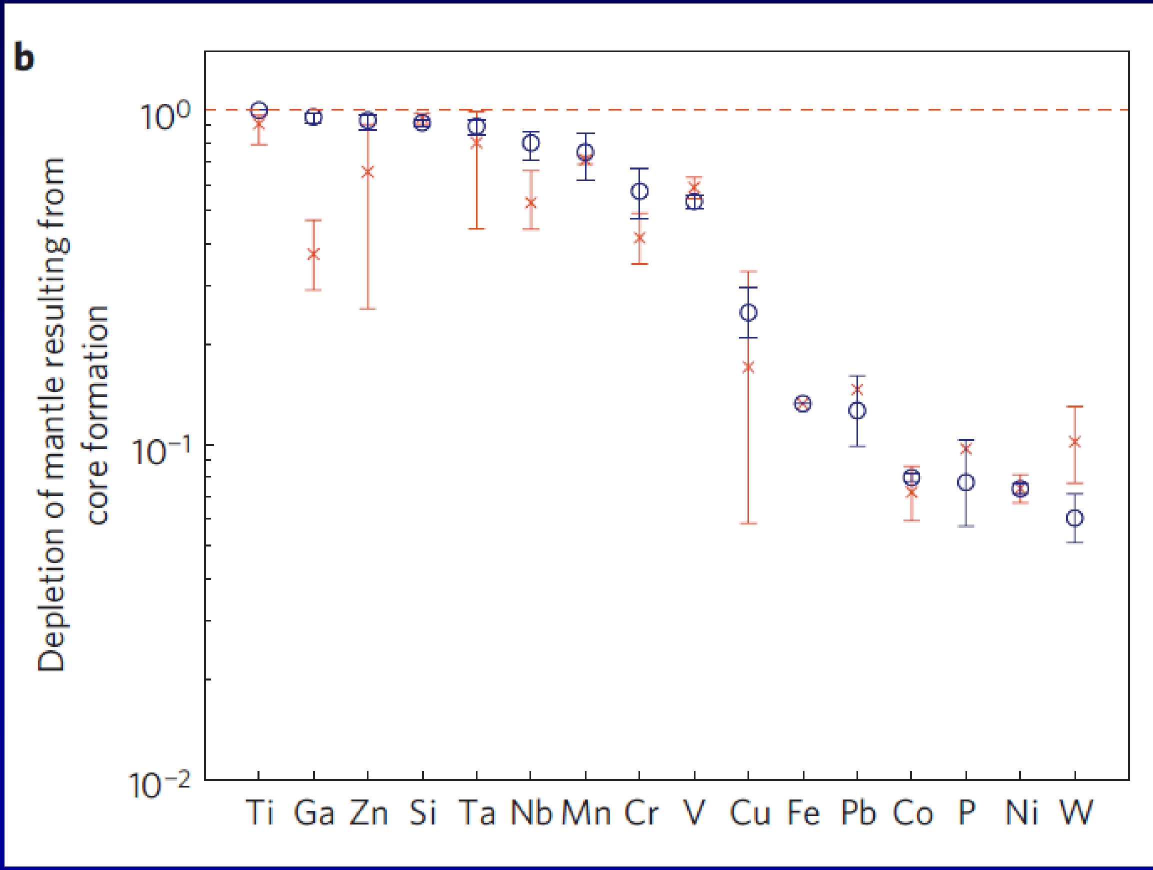
The siderophile element constraints can be matched.



Rudge et al. 2010

Core formation model with *partial* metal silicate equilibration

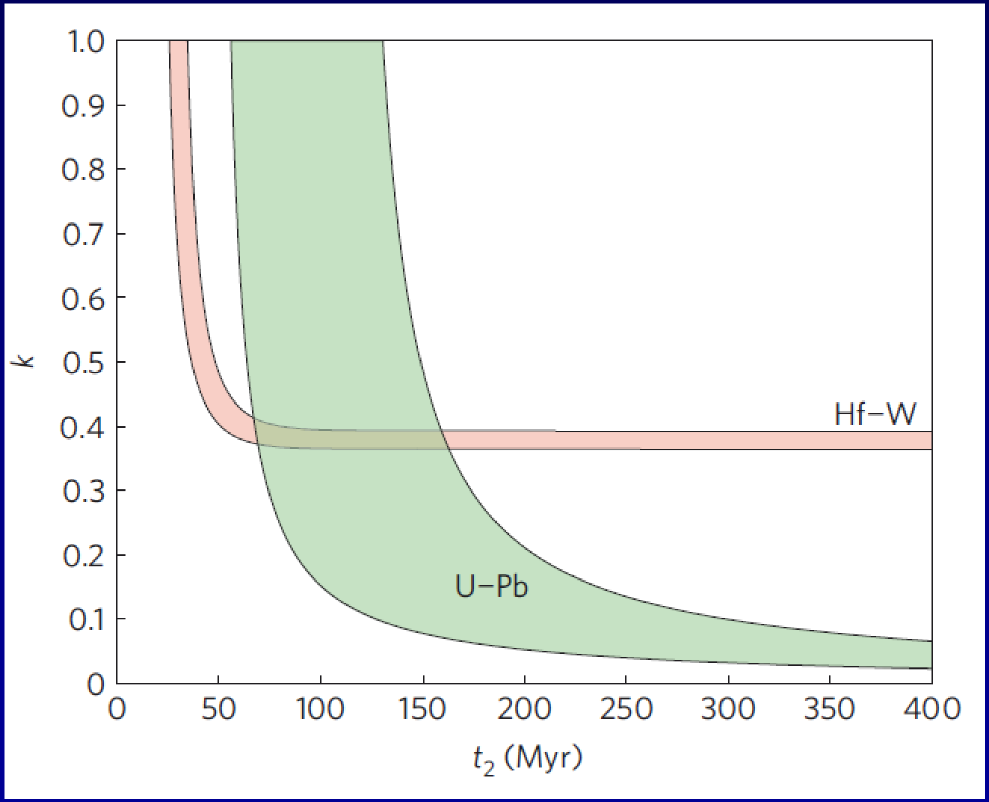
- With only 40% equilibration it is still possible to match the observations.



Rudge et al. 2010

Two-stage core formation models

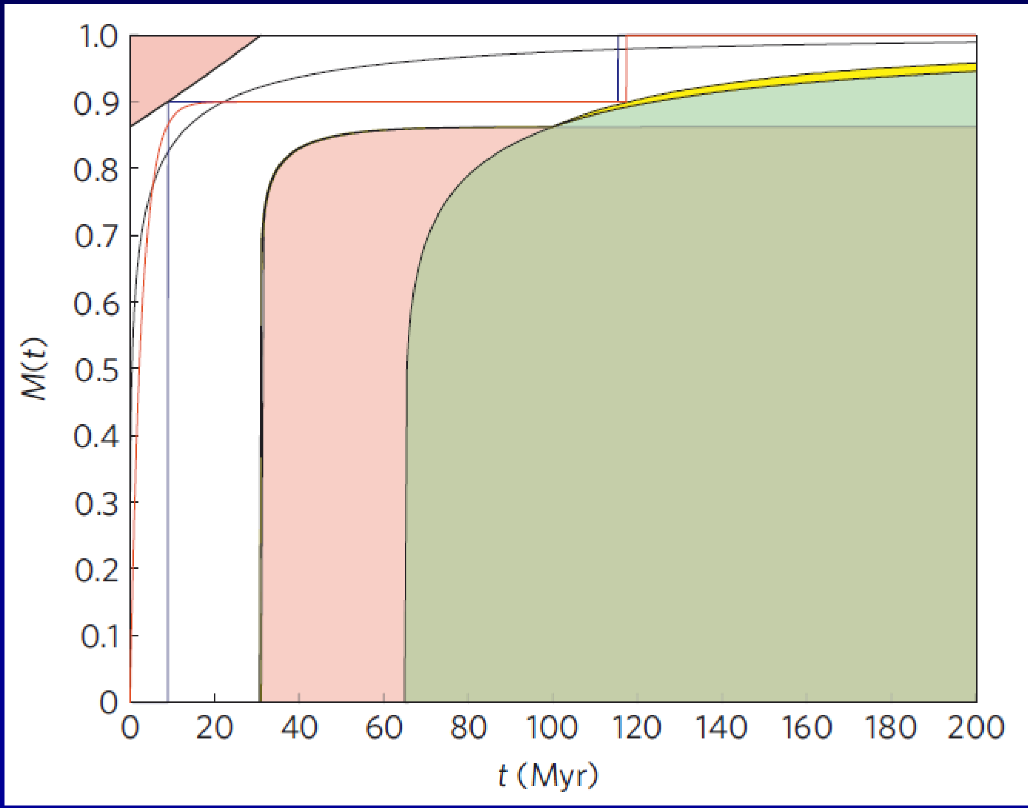
If one combines only the constraints from Hf-W and U-Pb, one can get constraints on the degree of equilibration (k) and the age of core formation t_2.



Rudge et al. 2010

Constraints on the duration of core formation (I)

- If one assumes that the metal equilibrates with the silicate, then accretion and core formation is fast at the beginning and slows down subsequently.

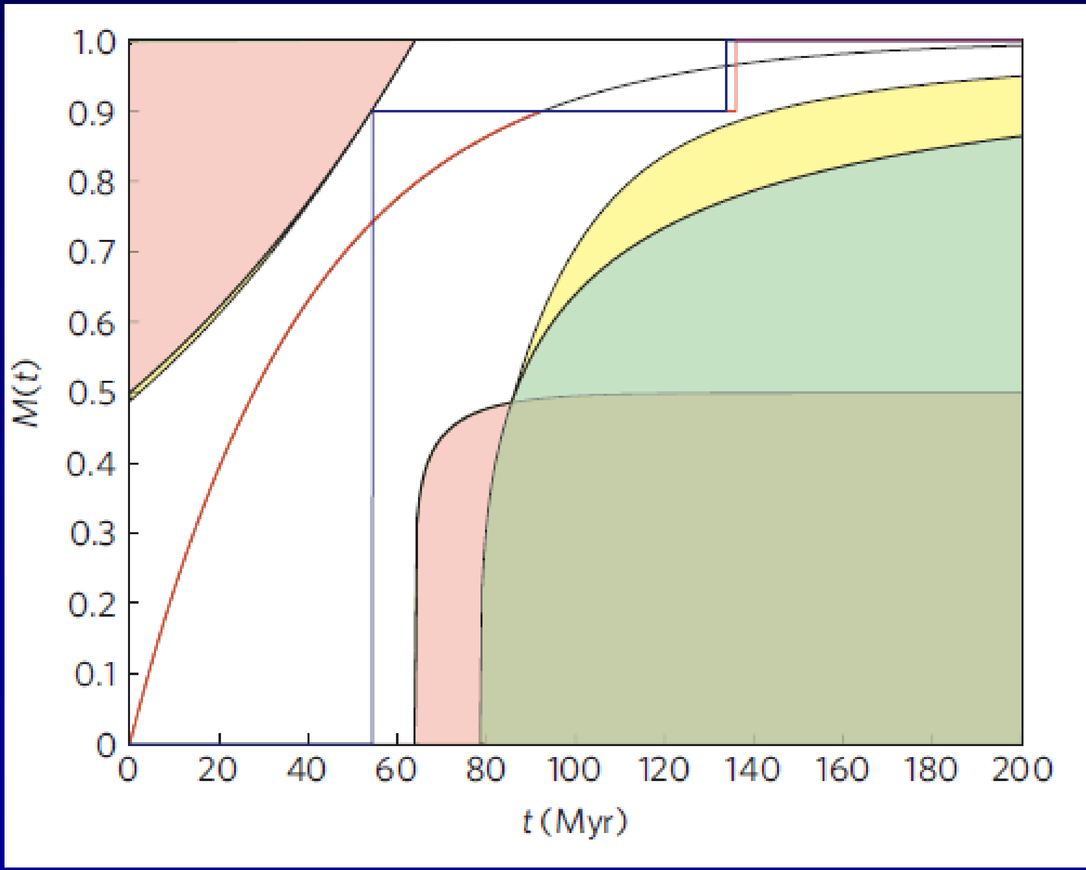


White: allowed solutions
Hf–W (pink), U–Pb (green) and combined (yellow)

Rudge et al. 2010

Constraints on the duration of core formation (II)

- If one assumes partial metal-silicate equilibration (40%), then accretion and core formation can be protacted and end at 100 Ma, while accounting for the siderophile element constraints.



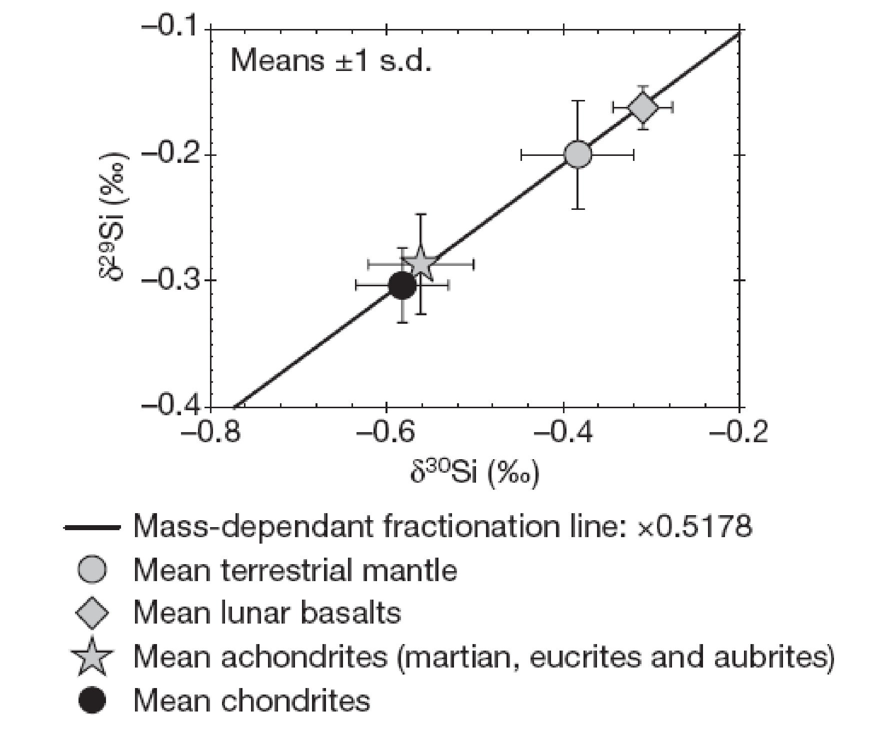
White: allowed solutions
Hf–W (pink), U–Pb (green) and combined (yellow)

Rudge et al. 2010

Conditions of core formation: what do we learn from Si isotope?

- Georg et al. (2007) observed a difference of 0.2‰ between the bulk silicate Earth and chondrites.

- Si in the core?
- Conditions of core formation?



Georg et al. 2007

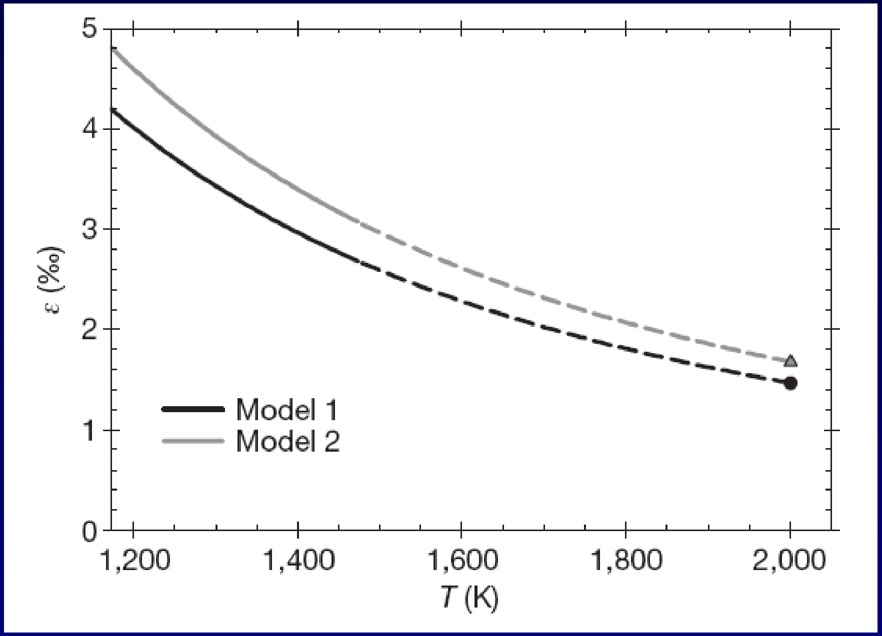
Si isotope constraints

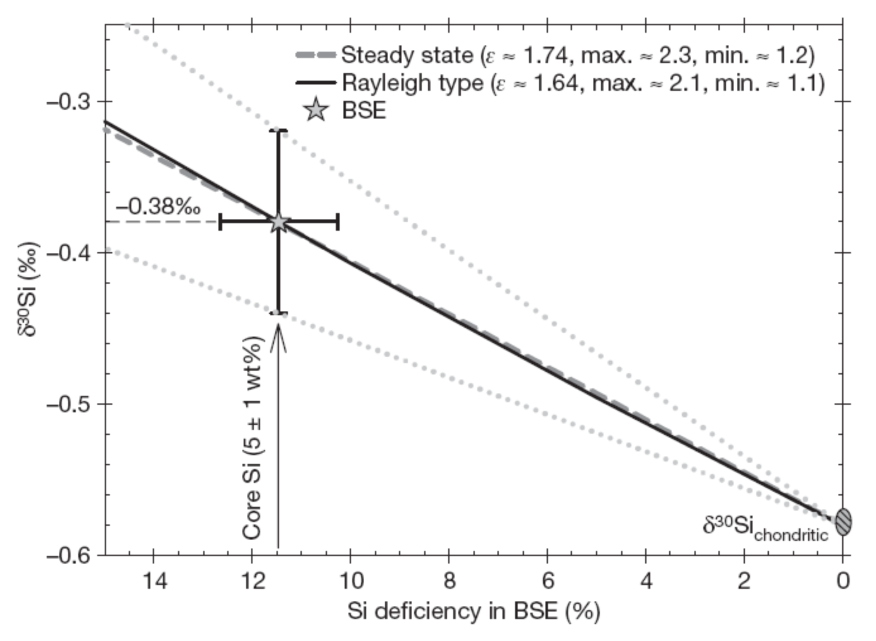
- Si has three isotopes: ^{28}Si, ^{29}Si and ^{30}Si.

- During metal silicate separation, Si can be incorporated in the metal in reduced form (Si^0). This induces an isotope fractionation relative to the silicate as the strength of Si-O is different from Si-Fe.
- The fractionation depends on temperature.

A cold magma ocean?

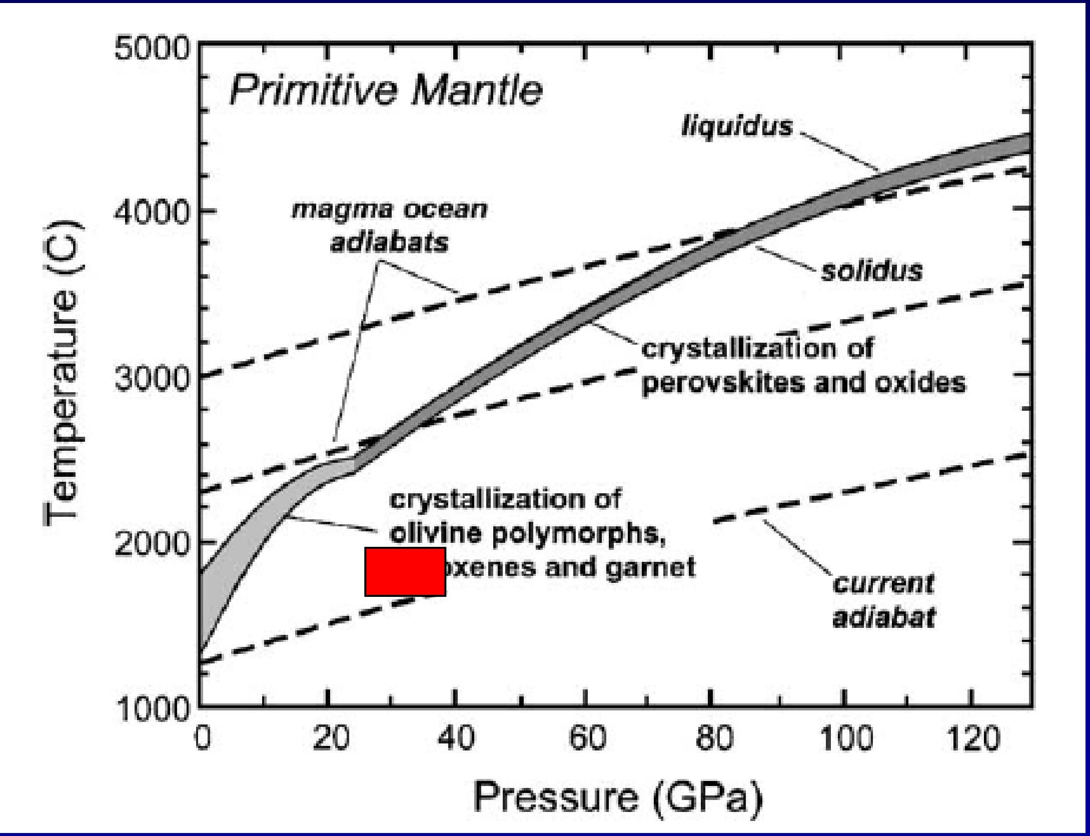
- The temperature of metal-silicate equilibration calculated by Georg et al. (2007) ranges from 1580 to 1730 °C.



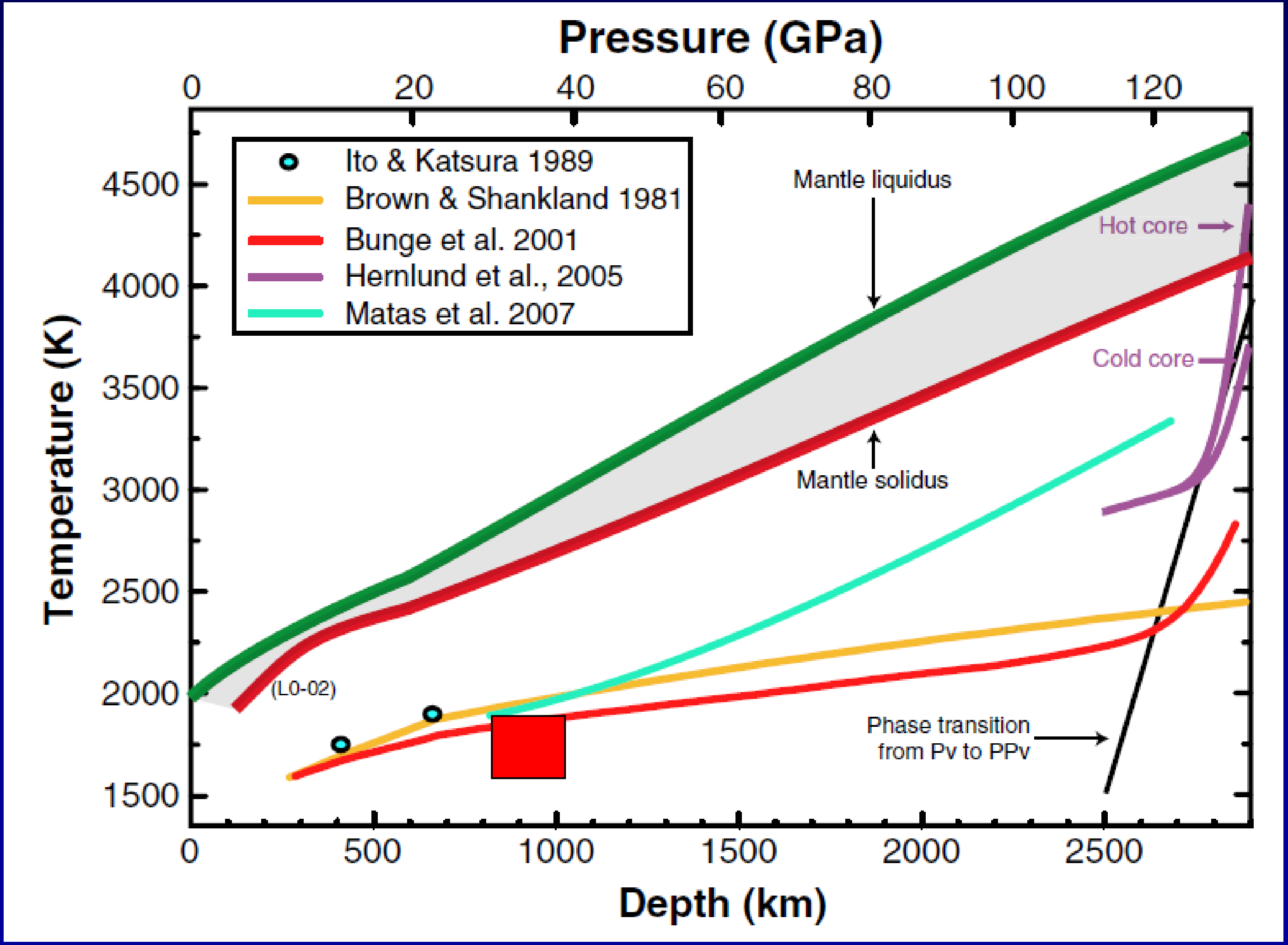


Solidus and liquidus of the terrestrial mantle

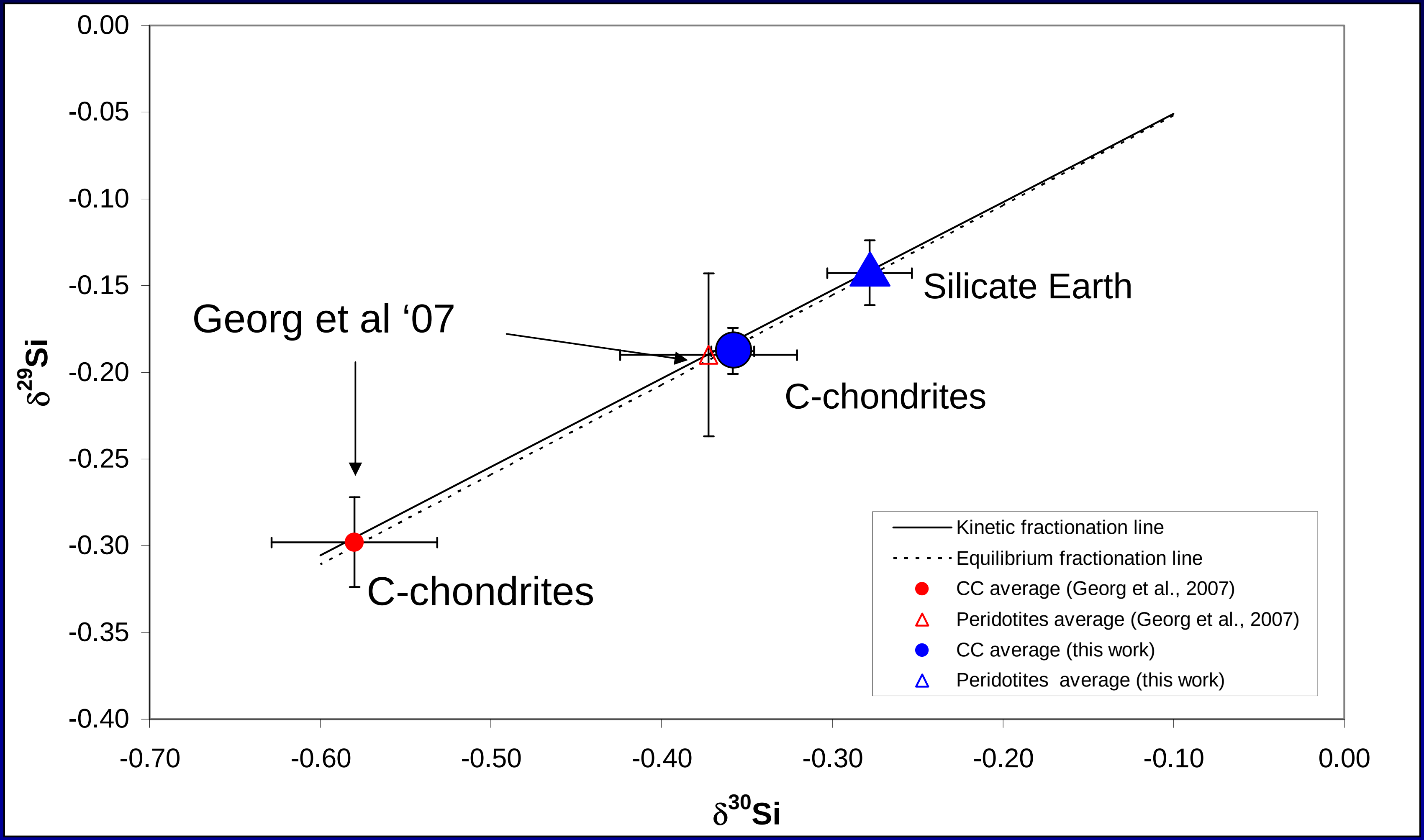
- A cold magma ocean!



Solidus and liquidus of the terrestrial mantle (Andrault et al. 2011)

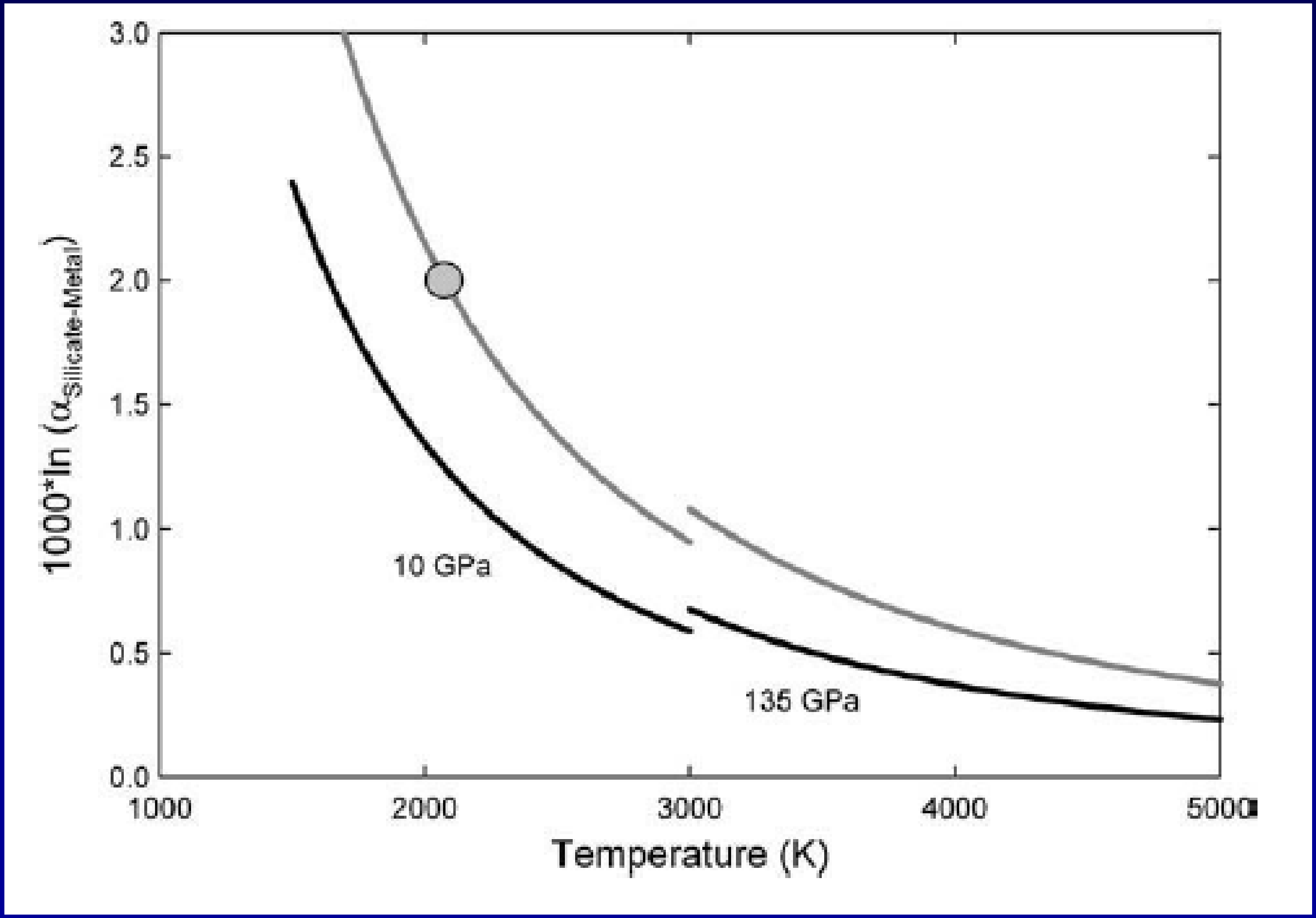


The difference in $\delta^{30}Si$ between Earth and chondrites is smaller

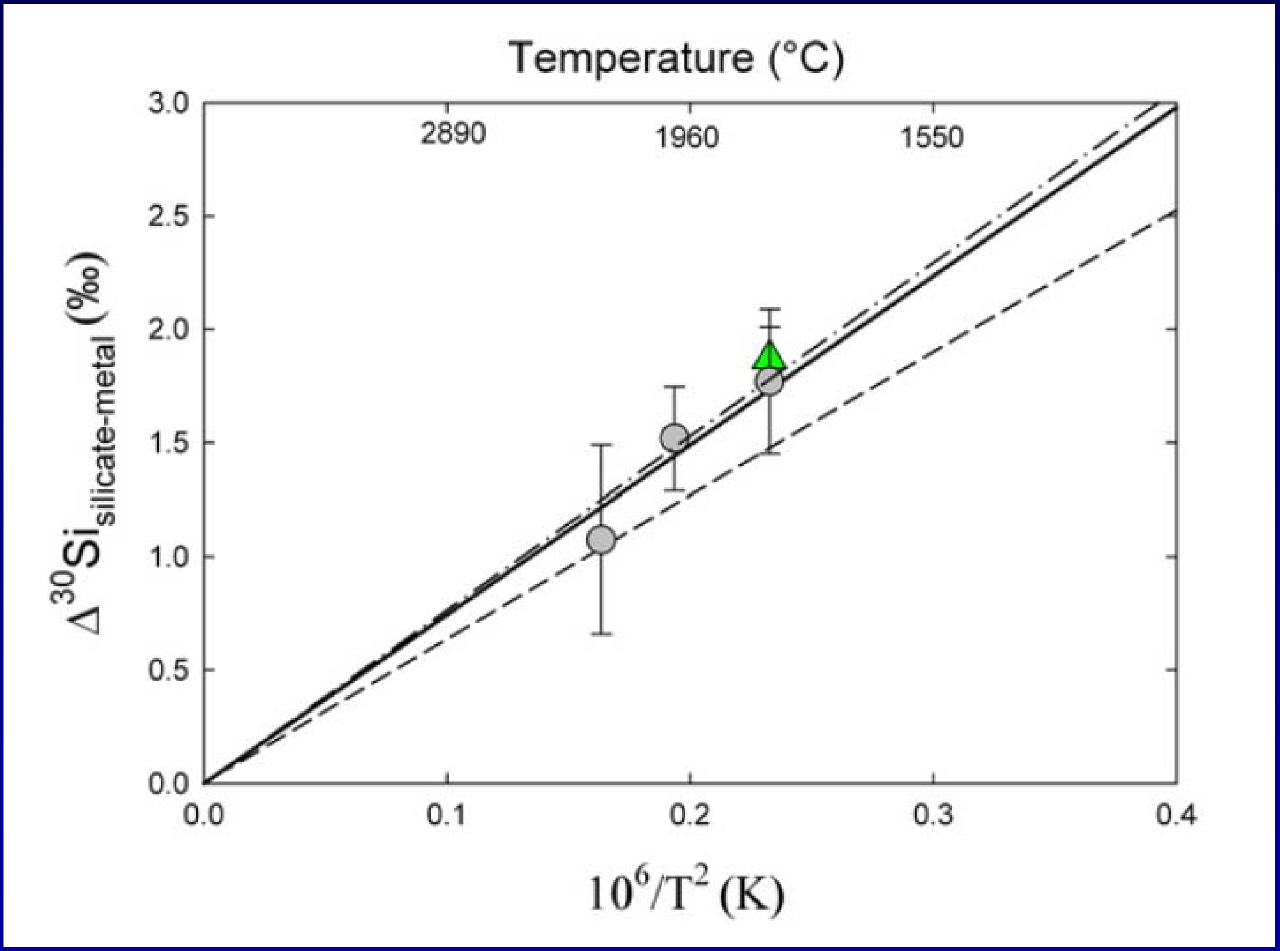


Fitoussi et al. 2009

Si isotope fractionation as a function of T and P

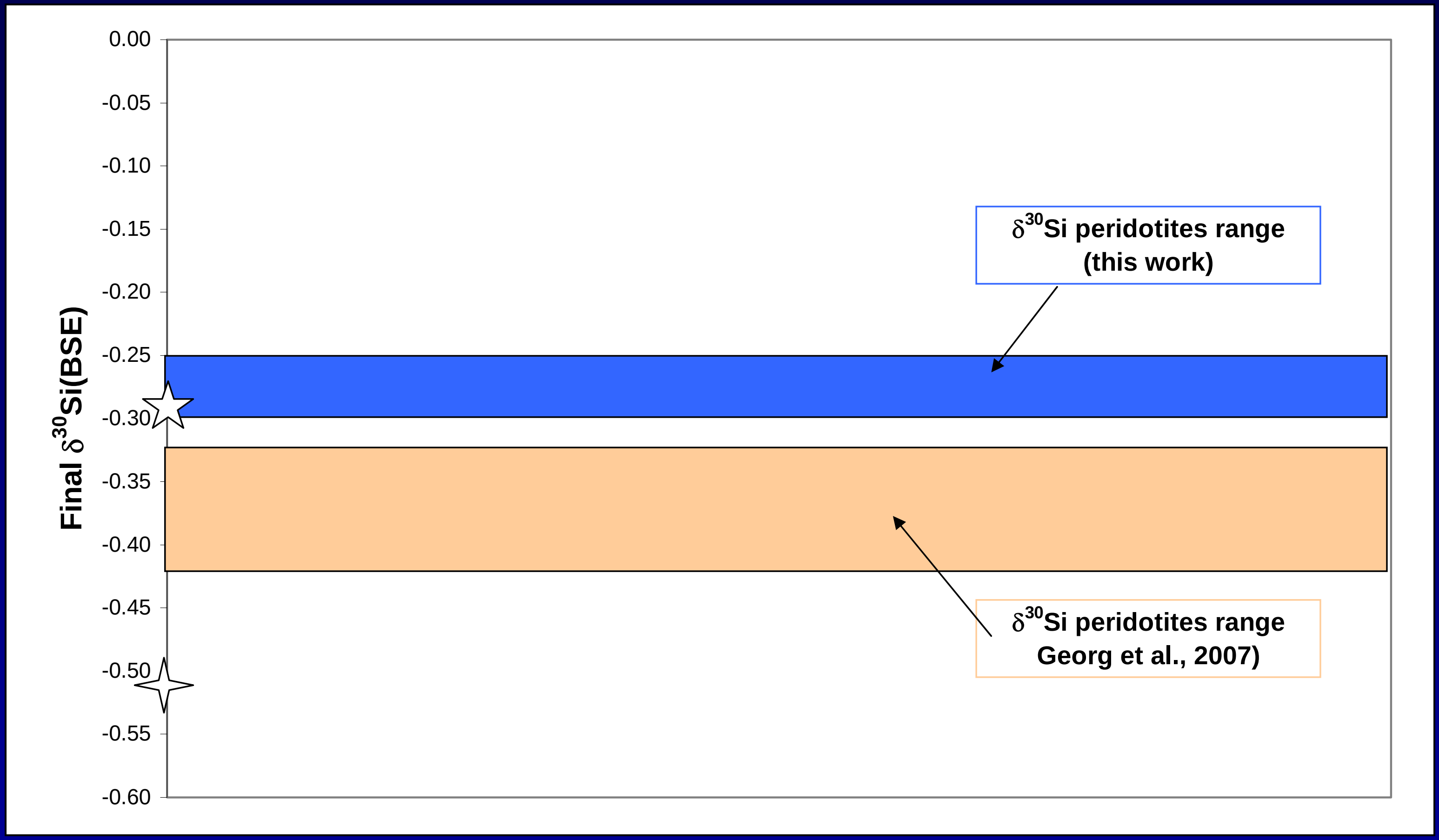


Shahar et al. 2009



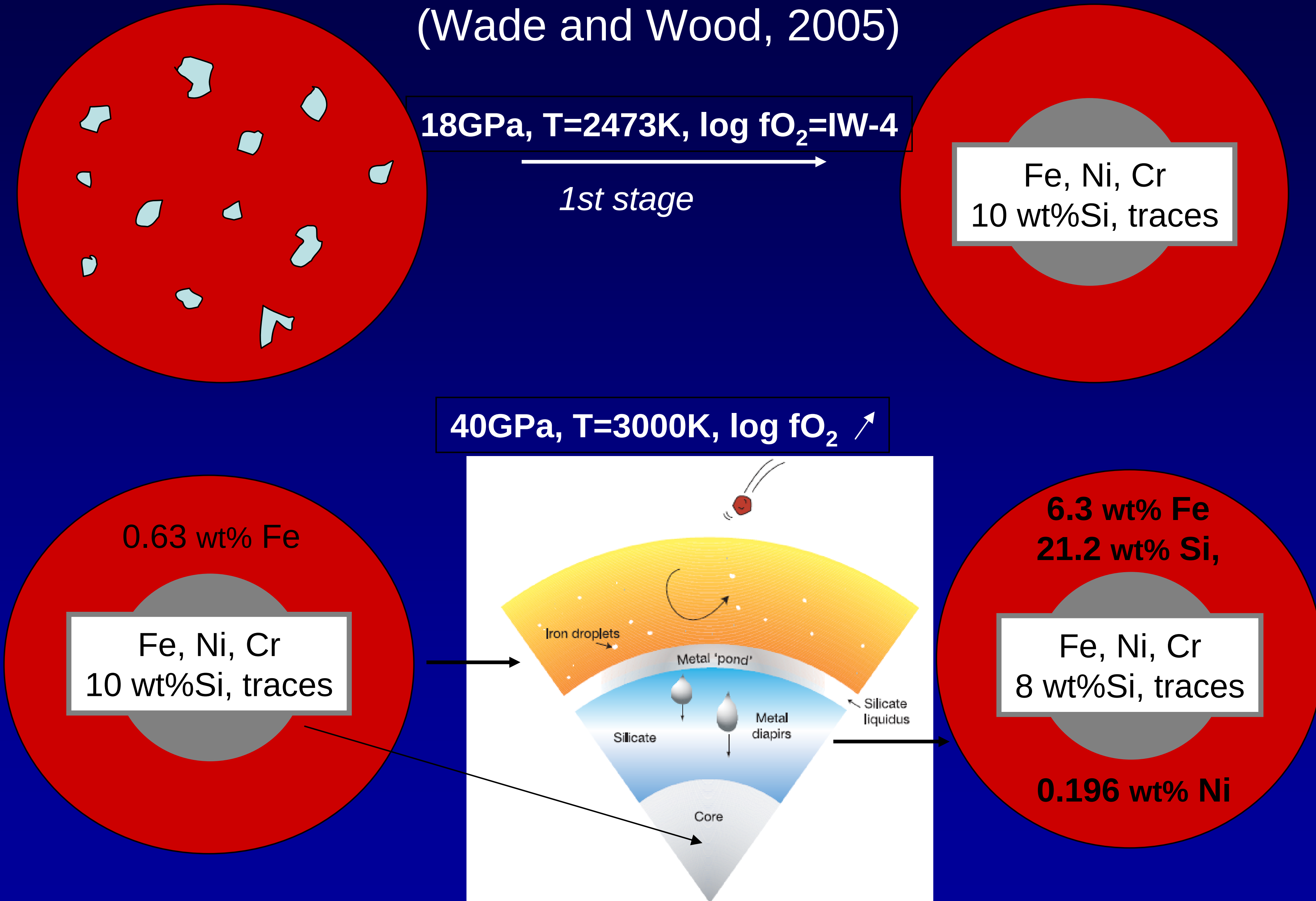
Shahar et al. 2011

Single stage core formation model

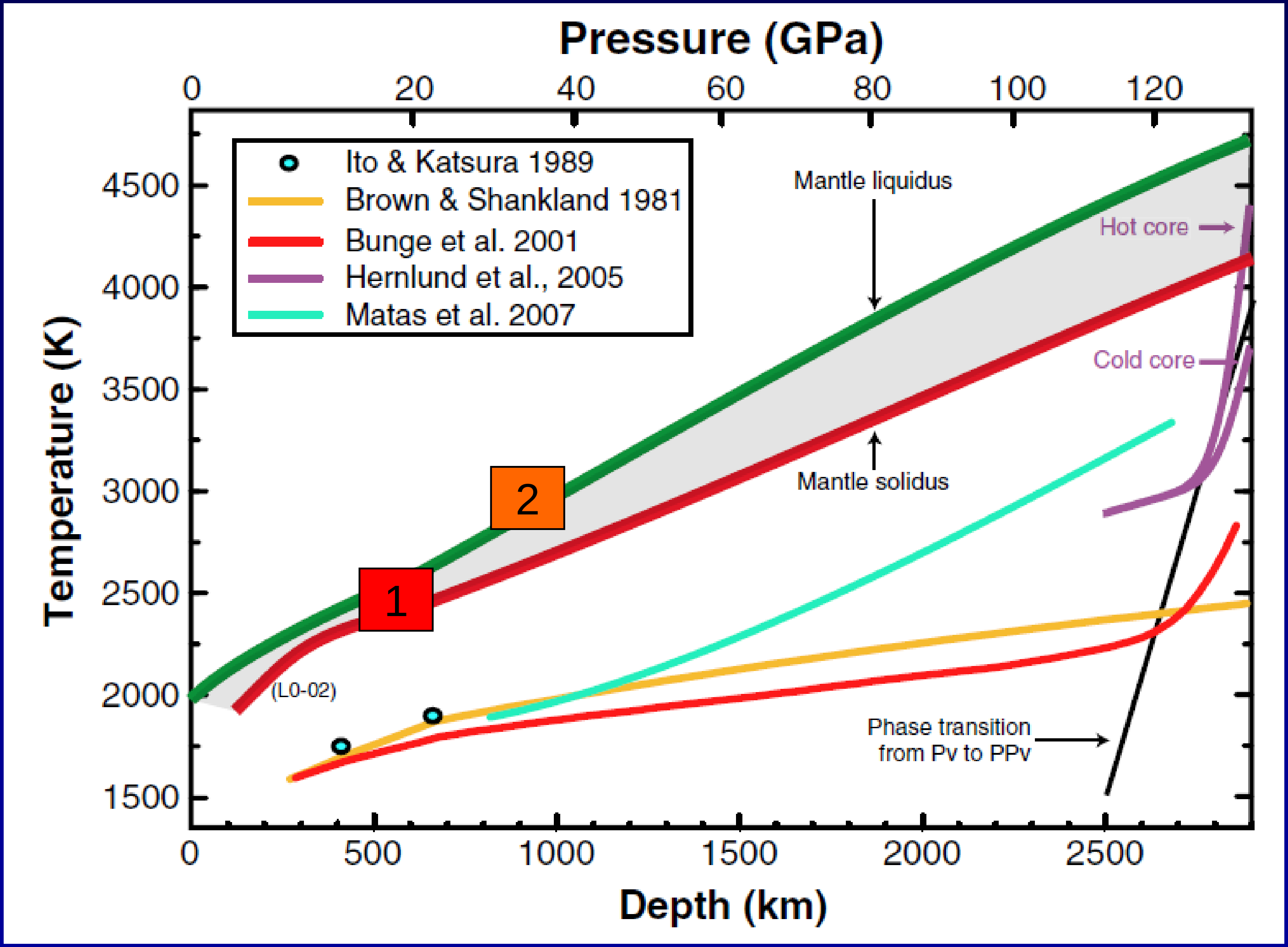


- 1 stage model P=30 GPa, T=3000K, log(fO2)=IW-2, $\delta^{30}Si_{CC}$=-0.36 ‰ (Fitoussi et al. 2009)
- 1-stage model P=30 GPa, T=3000K, log(fO2)=IW-2, $\delta^{30}Si_{CC}$=-0.58 ‰ (Georg et al., 2007)

Two-stage core formation model (Wade and Wood, 2005)

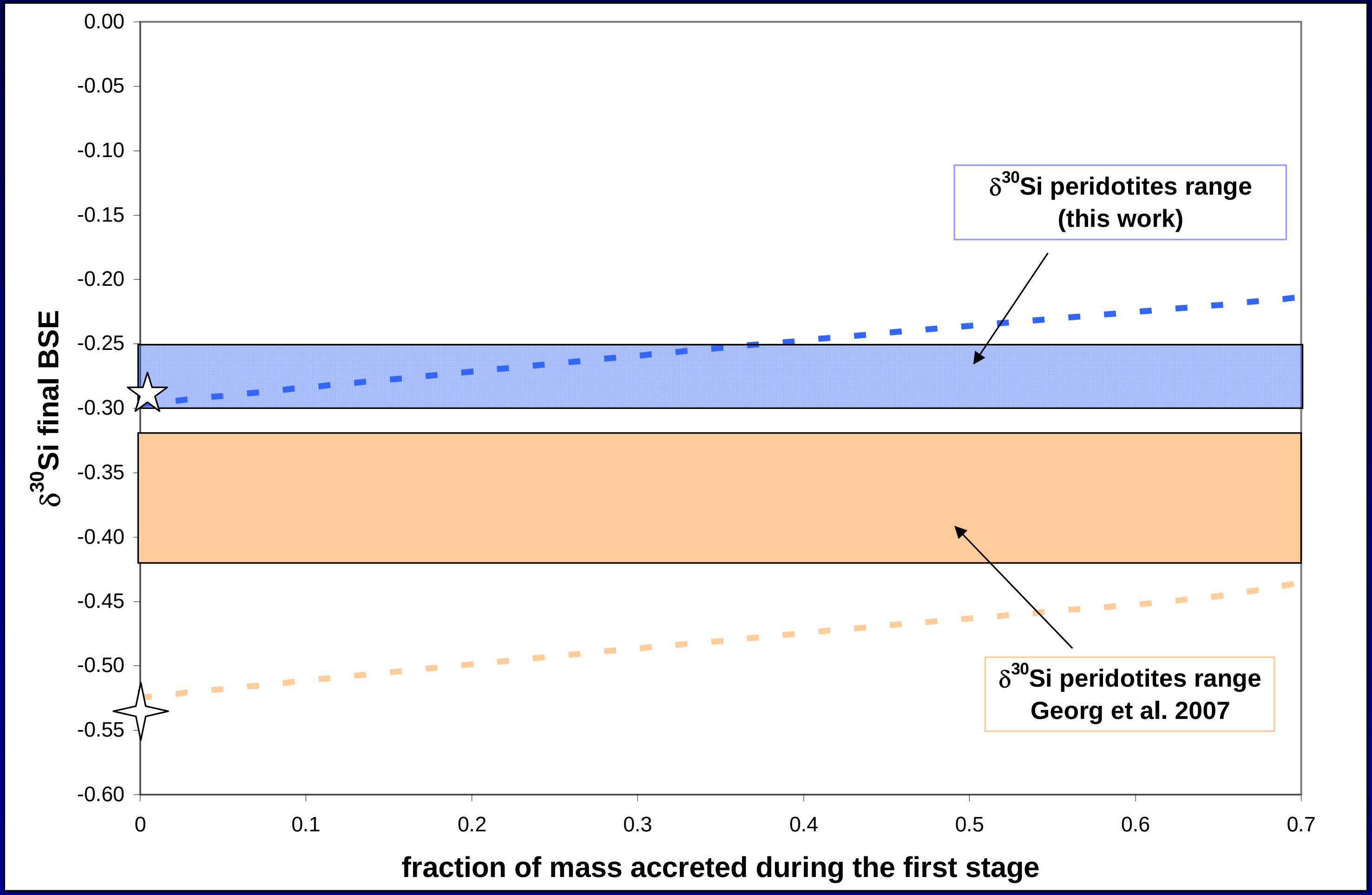


Solidus and liquidus of the terrestrial mantle



Andrault et al. 2011

Two-stage core formation model
(Wade and Wood, 2005)

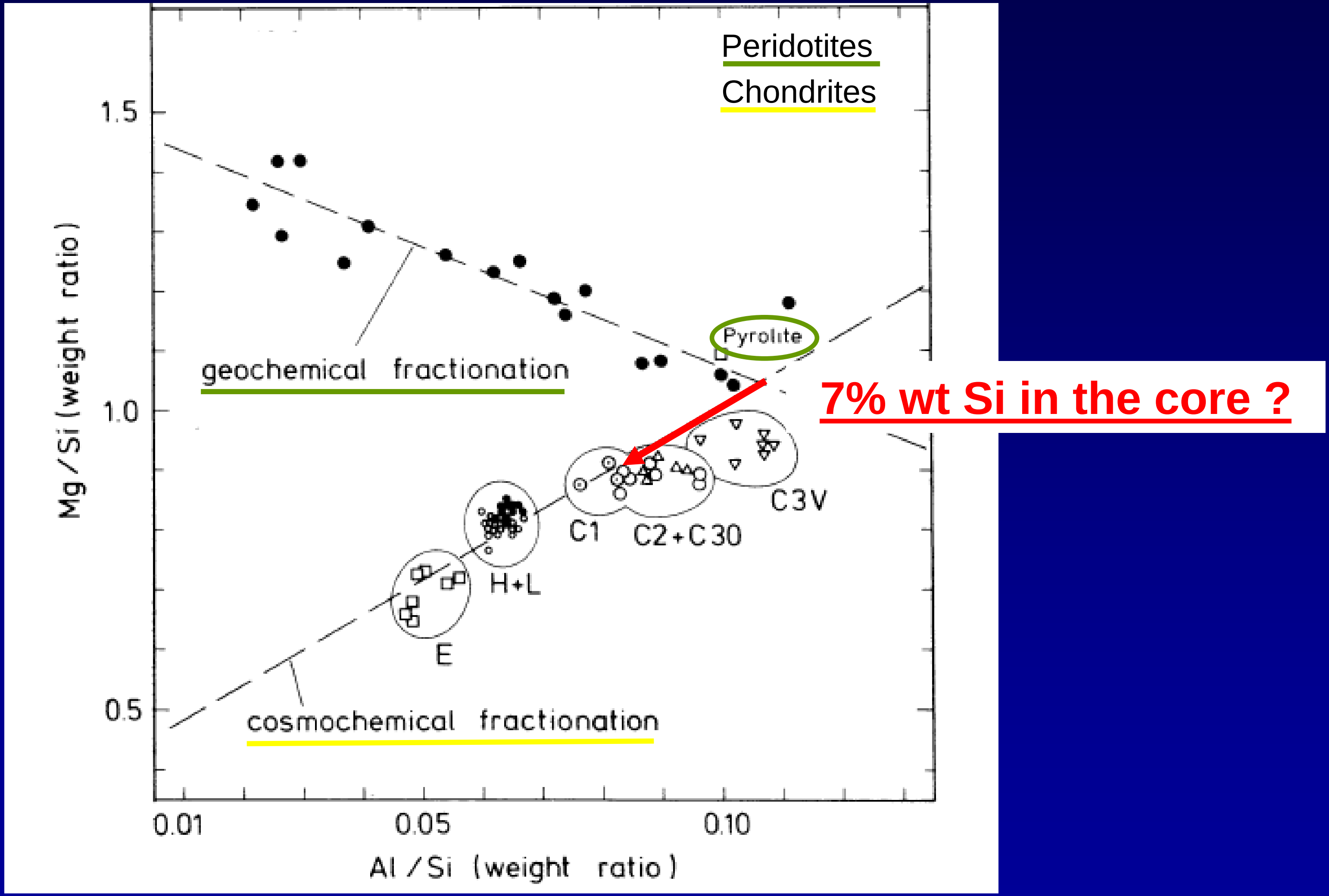


One stage model P=30 GPa, T=3000K, $\log(fO_2)$=IW-2, $\delta^{30}Si_{CC}$=-0.36 ‰ (Fitoussi et al. 2009)

One stage model P=30 GPa, T=3000K, $\log(fO_2)$=IW-2, $\delta^{30}Si_{CC}$=-0.58 ‰ (Georg et al., 2007)

Two stage model: Stage 1 P=18 GPa, T=2473K, $\log(fO_2)$=IW-4, Stage 2 P=40 GPa, T=3000K, $\log(fO_2)$ ↗

Mg/Si in chondrites and terrestrial rocks



Jagoutz et al., 1979

Implications of core formation models

- The Earth's core formed in less than 140 Ma with a large part of the accretion in less than 50 Ma.

- Si isotopes show that Si is a light element in the core.

- Our model combining W and Pb isotopes with siderophile elements shows that the core could have formed under disequilibrium conditions, implying that the composition of the Earth's core is partly controlled by the core composition of embryos.

- Inverse models show that the conditions of core formation must have been reducing at the early stage of accretion.

Summary

- Core formation could have been a disequilibrium process (core merging).
- In this case, it would have lasted up to 140 Ma (lower limit 50 Ma).
- Models for core formation imply reduced conditions.
- Si isotopes provide evidence for Si in the Earth‘s core (7 wt%).