Early Mantle Dynamics seen by the Isotope Signature of Archean Samples

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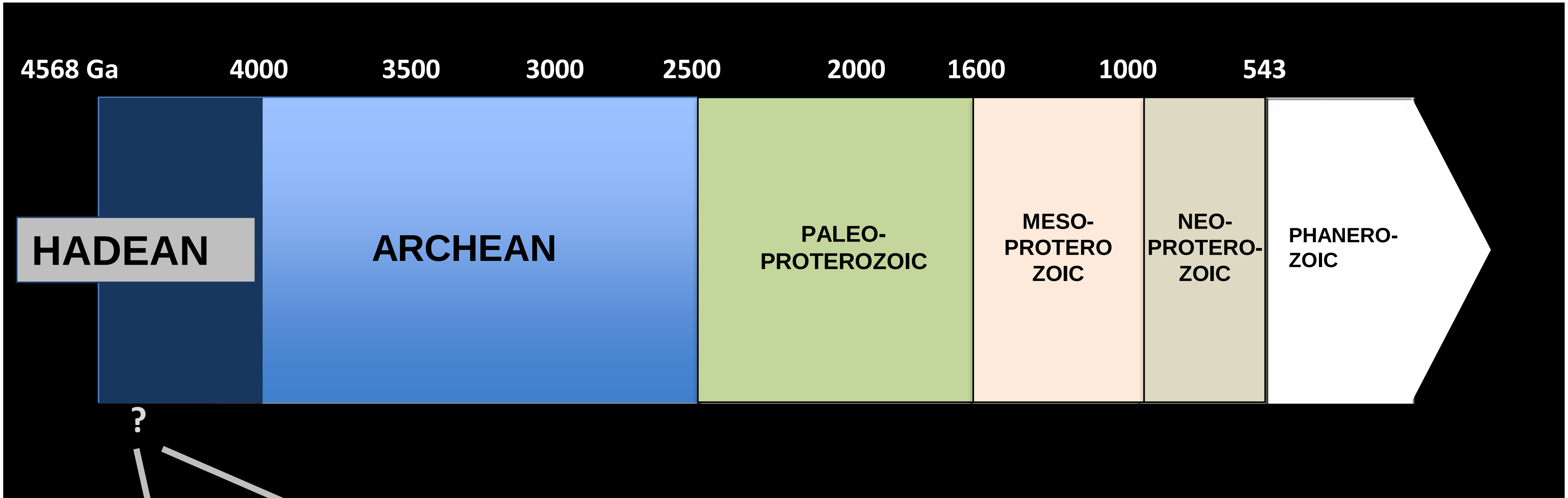
In collaboration with Rick Carlson, Mary Horan, Lars Borg, James Connelly, Hanika Rizo, Janne Blichert-Toft, Jonathan O'Neil, Jean-Louis Paquette, Ali Bouhifd, Mouhcine Gannoun, Francis Albarède, Minik Rosing

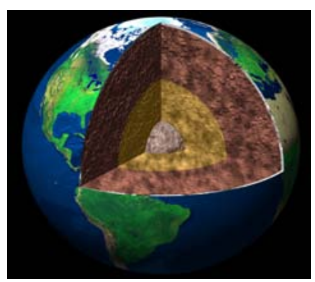
OUTLINE OF THE TALK

1. Introduction
2. Chemical tools
3. ^{146}Sm-^{142}Nd systematics : terrestrial samples *vs*. Chondrites
    - Different explanations
    - Major implication
4. An early silicate differentiation seen in terrestrial samples
    - Is it a global scale event?
    - Age?
    - Earth-Moon relationship
5. Early mantle dynamics
6. Conclusion

The importance of early events

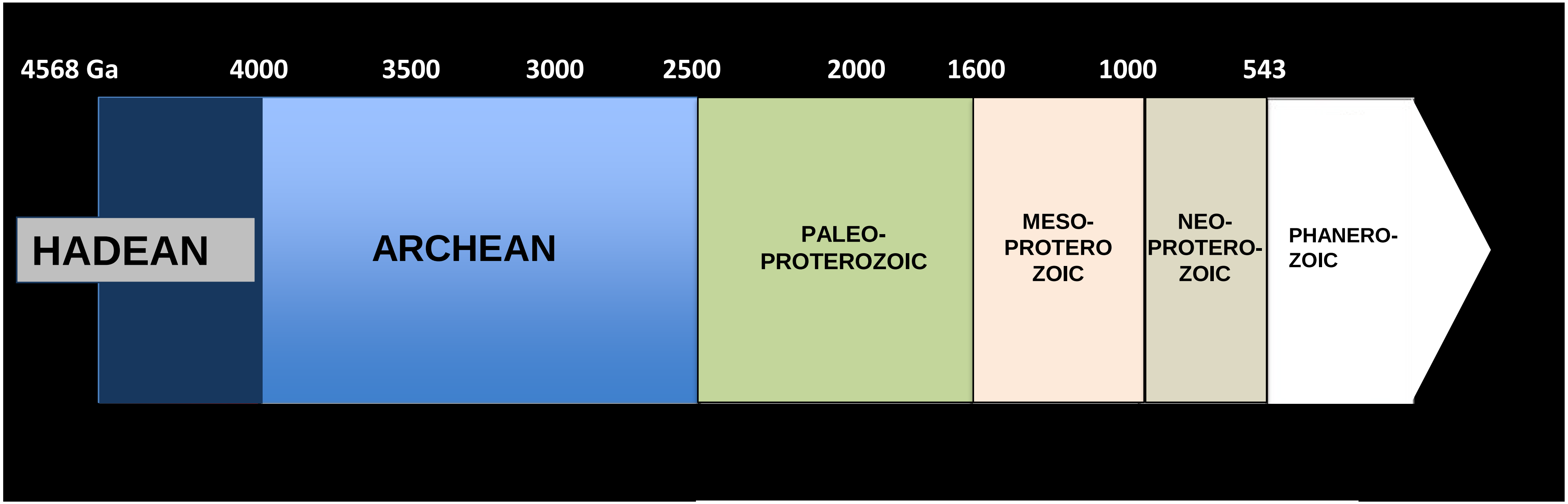


Origin of the Moon in a giant impact

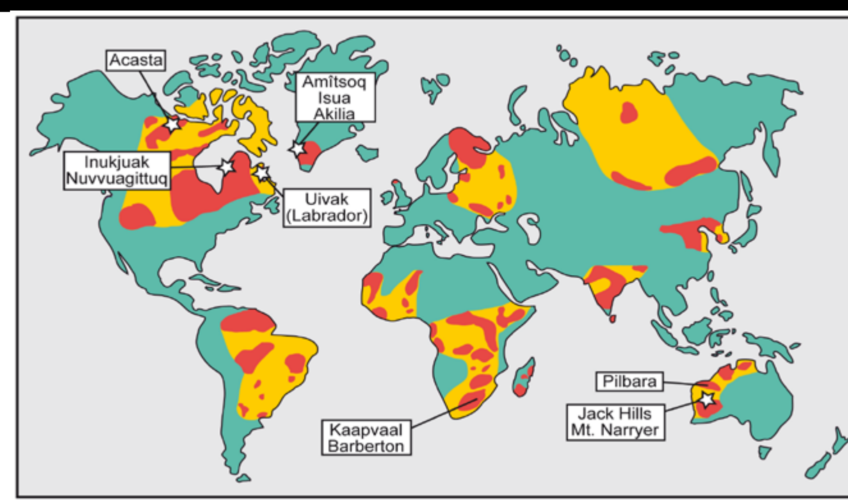


Global differentiation of the Earth

Ages of the oldest geological records

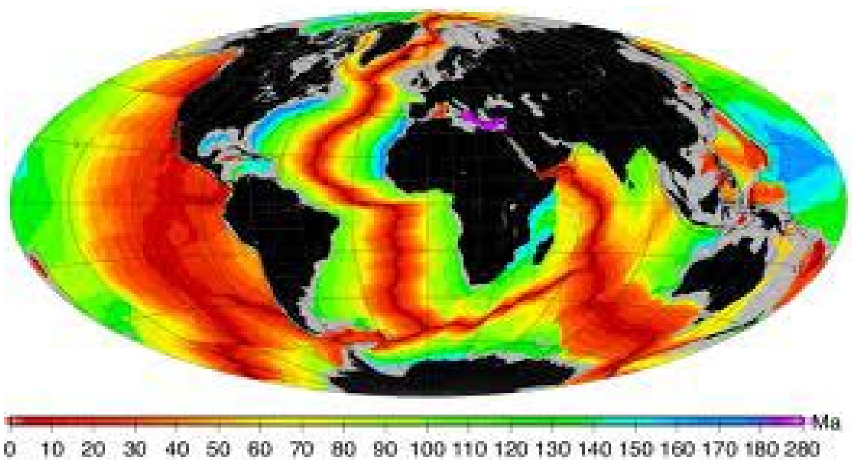


4.4 Ga: Jack Hills, Nuvvuagittuq
4.0 Ga: Acasta
3.8 Ga: Isua



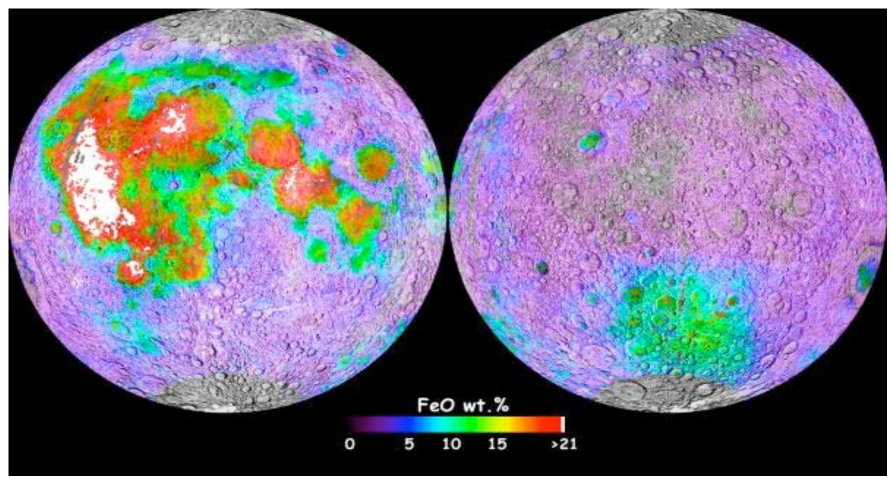
Martin et al., 2006

Ages of the oldest geological records



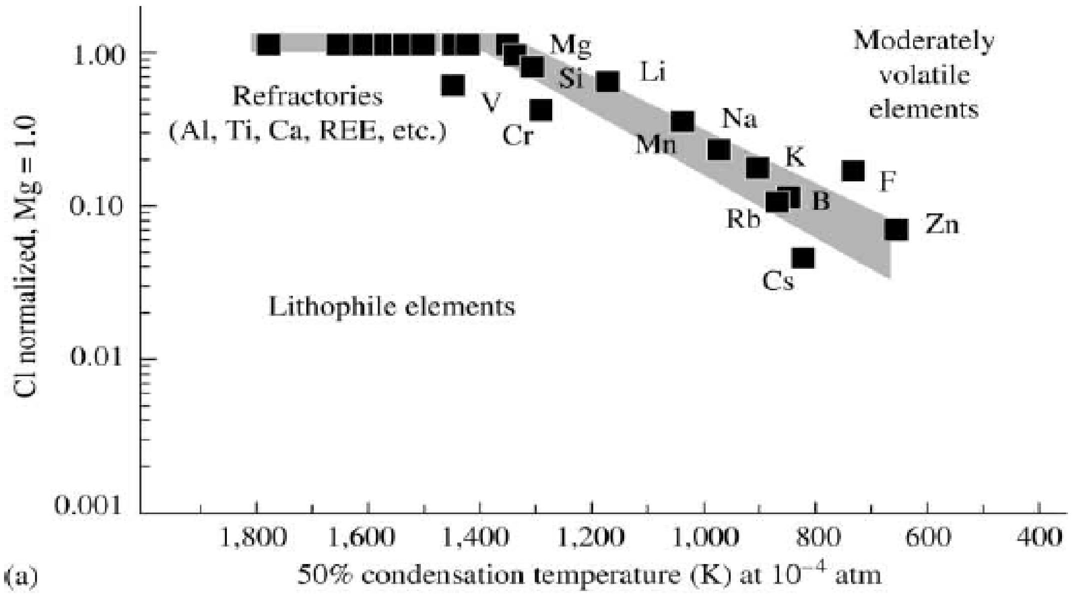
The terrestrial rocks are young :
80% of ages < 200 Ma

Comparison to the Moon:
95% of ages > 3 Ga
80% of ages > 4 Ga



http://meteorites.wustl.edu/lunar/moon_meteorites.htm

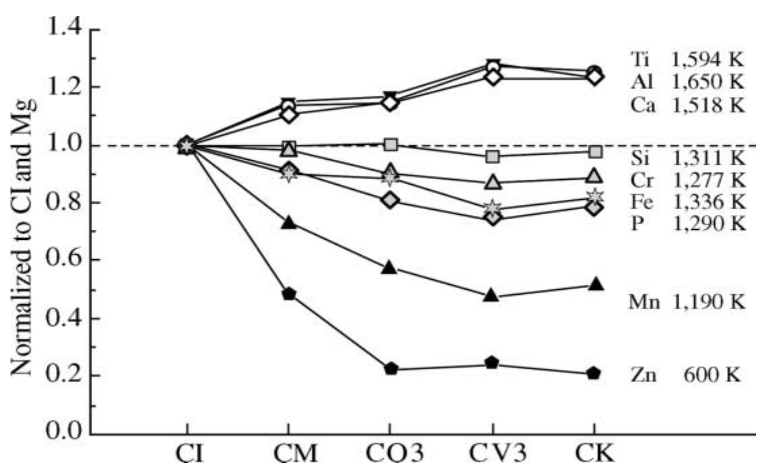
Geochemical tools



The refractory lithophile elements (RLEs) are present in the same ratio relative to each other and to the solar composition

No fractionation during :
- solar system condensation
- core formation

RLEs are not fractionated in chondrites:



RLEs are fractionationed during silicate processes

Palme and Jones 2003

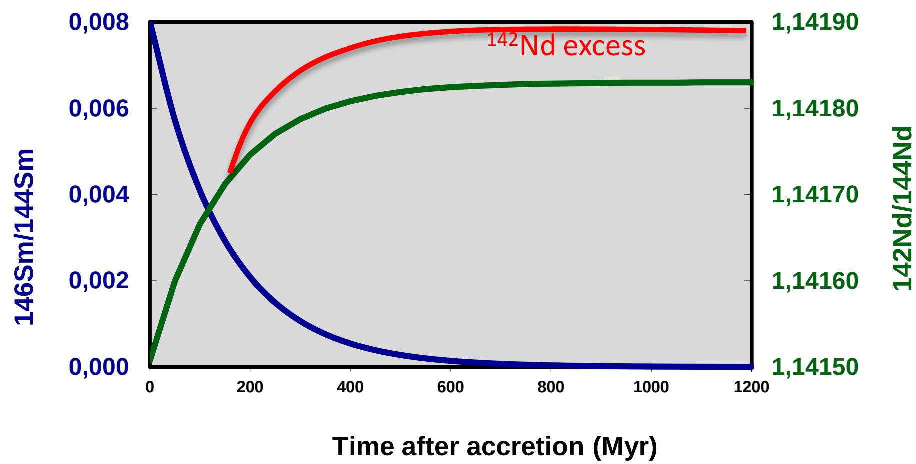
Geochemical tools

Extinct radioactivities (short-lived chronometers)

$10^6 < T_{1/2} < 10^8$: sufficiently long-lived to survive interval between end of nucleosynthesis and planetary accretion and sufficiently short-lived to be extinct during the Hadean.

$^{182}Hf \longrightarrow {}^{182}W$ T = 9 Ma

$^{146}Sm \longrightarrow {}^{142}Nd$ T = 68 Ma



Long-lived chronometers

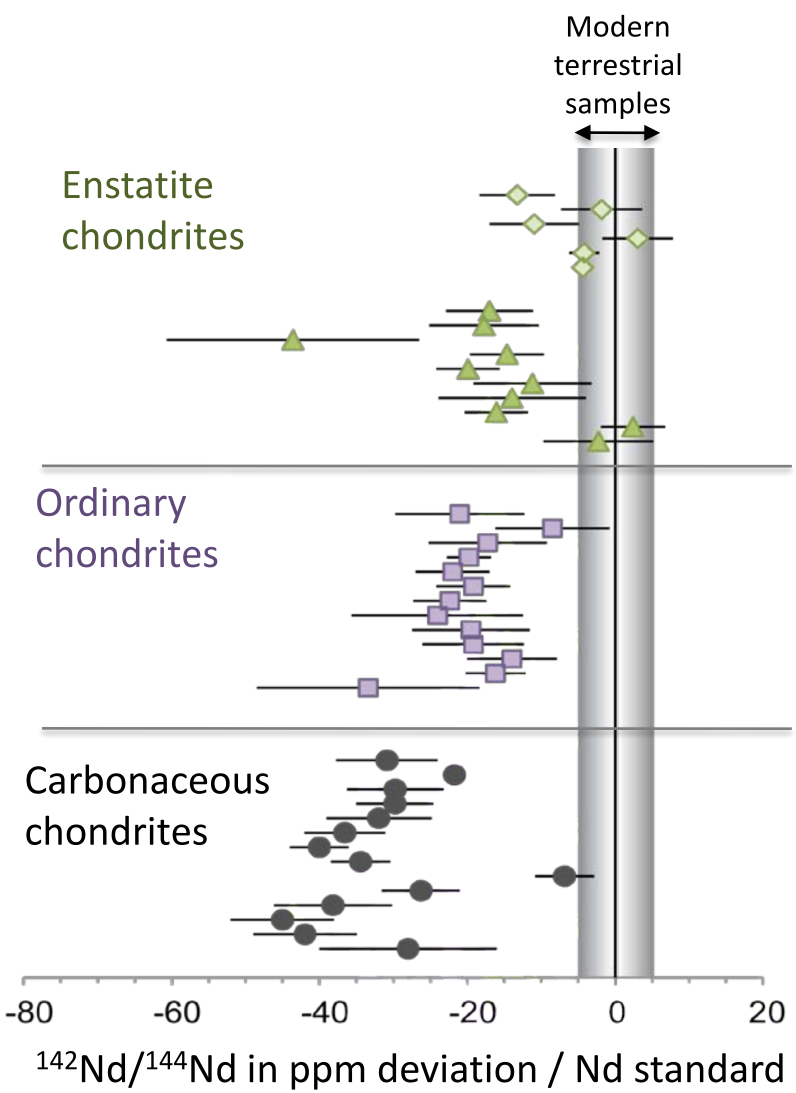
$T_{1/2} > 10^8$: parent isotope still alive today.

$^{147}Sm \longrightarrow {}^{143}Nd$ T = 106 Ga, λ= 6.54 x 10^{-12} a^{-1}

$^{176}Lu \longrightarrow {}^{177}Hf$ T = 35.9 Ga, λ= 1.867 x 10^{-11} a^{-1}

Systems robust against alteration and metamorphism

^{142}Nd in chondrites vs. terrestrial signature

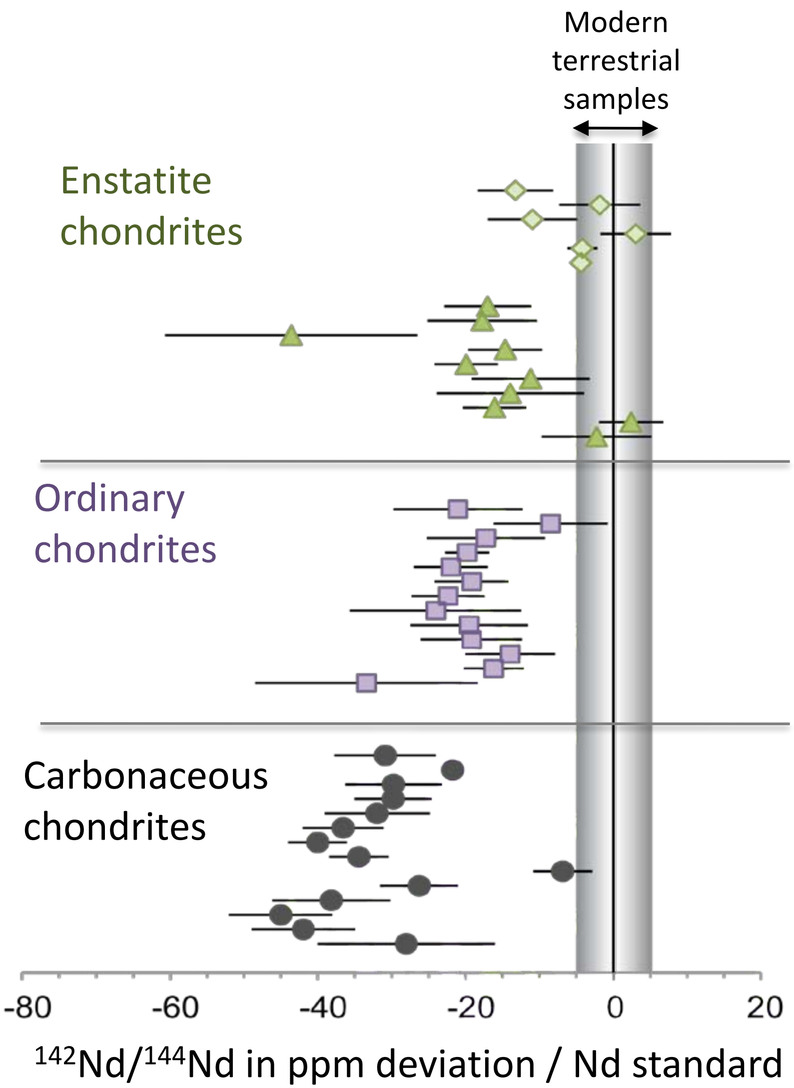


High precision measurements show that modern terrestrial samples have ~20 ppm excess in ^{142}Nd relative to chondrites

1. The Bulk Silicate Earth (BSE) has a Sm/Nd ratio higher than chondrites
2. All samples derived from a depleted mantle reservoir (high Sm/Nd ratio) formed very early
3. The difference reflects isotopic heterogeneity in the solar nebula

Refs: Boyet and Carlson 2005; Andreasen and Sharma, 2006; Carson et al., 2007 ; Gannoun et al., 2011

^{142}Nd in chondrites vs. terrestrial signature



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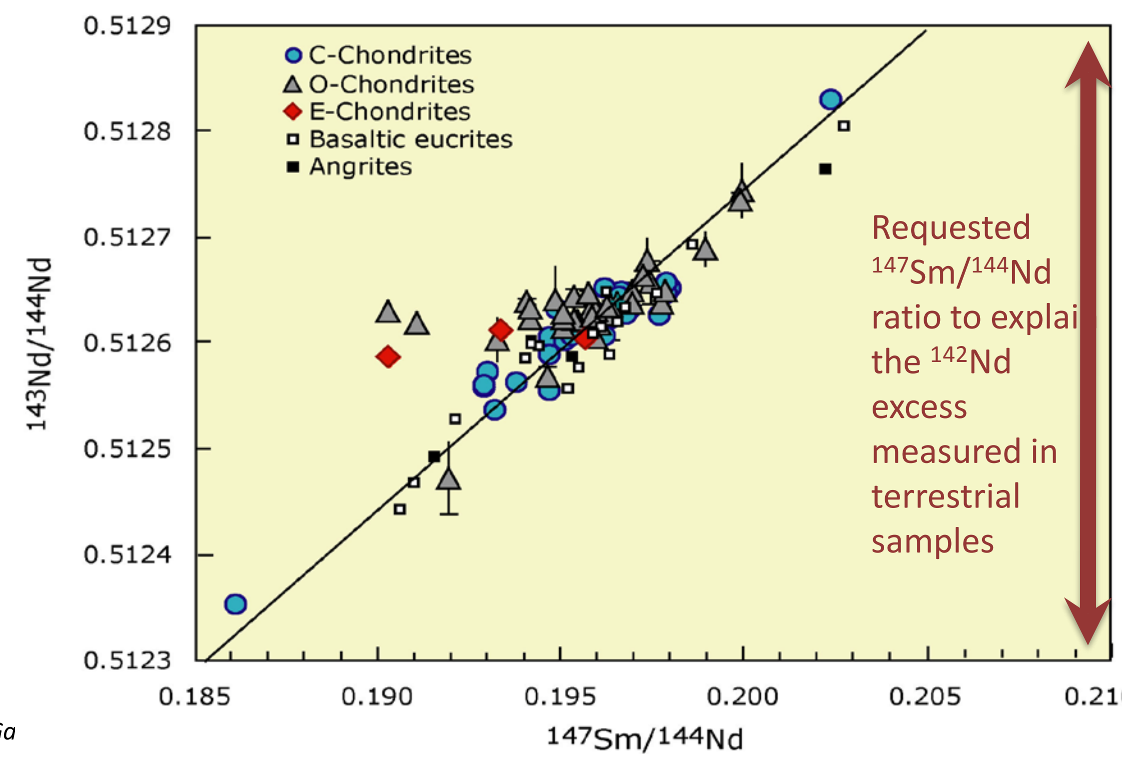

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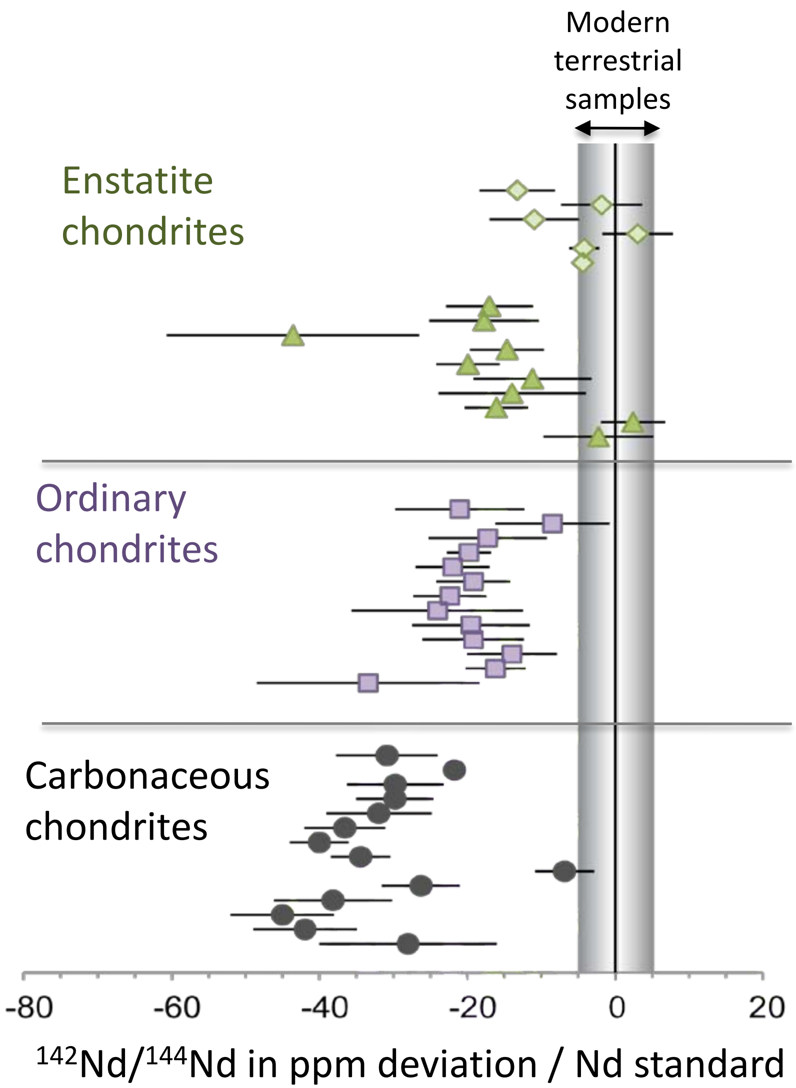
^{142}Nd in chondrites vs. terrestrial signature



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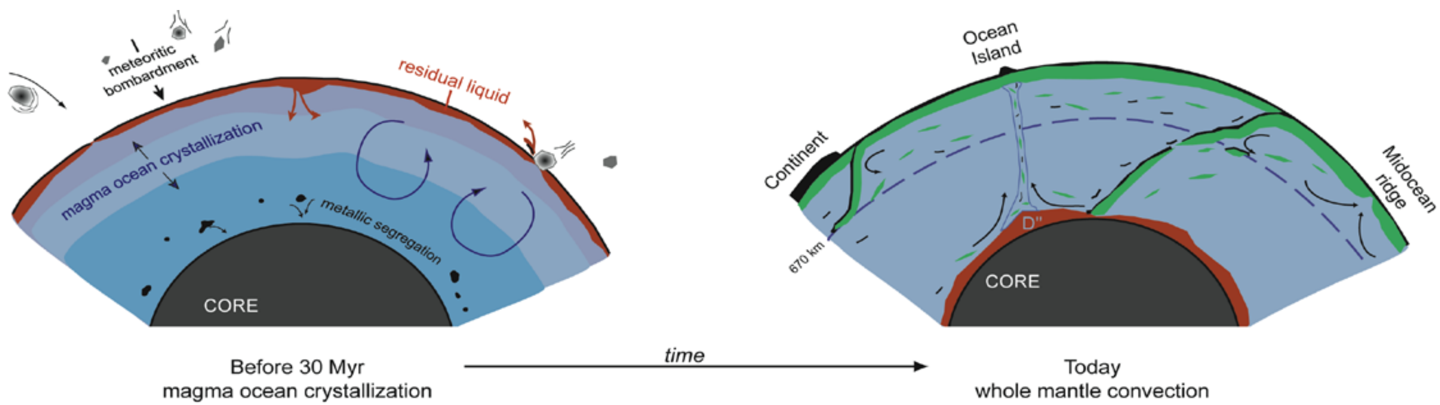
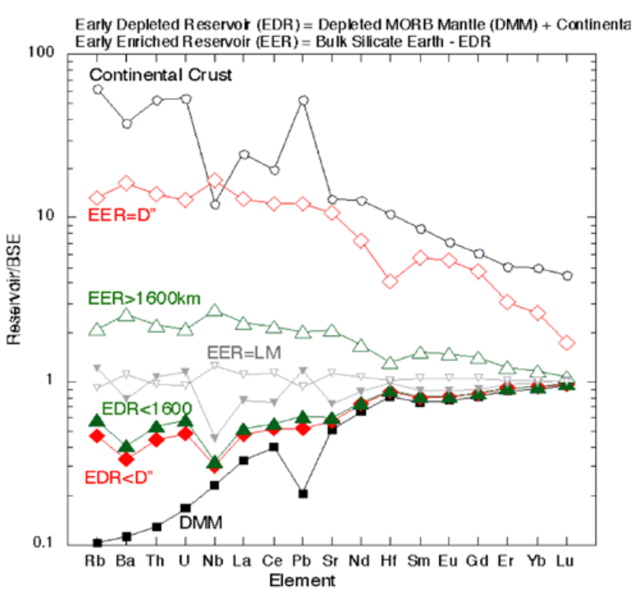
Does the ^{142}Nd signature of terrestrial samples reflect an early differentiation event?

1. Early crust subducted in the deep mantle

Chase and Patchett, 1988; Boyet and Carlson 2005; Tolstikhin and Hofmann , 2005





The hidden early enriched reservoir (EER) contains more than 40% of the Earth's K, U and Th.

A mantle reservoir unsampled and preserved from mantle convection since its formation.

Boyet and Carlson 2005

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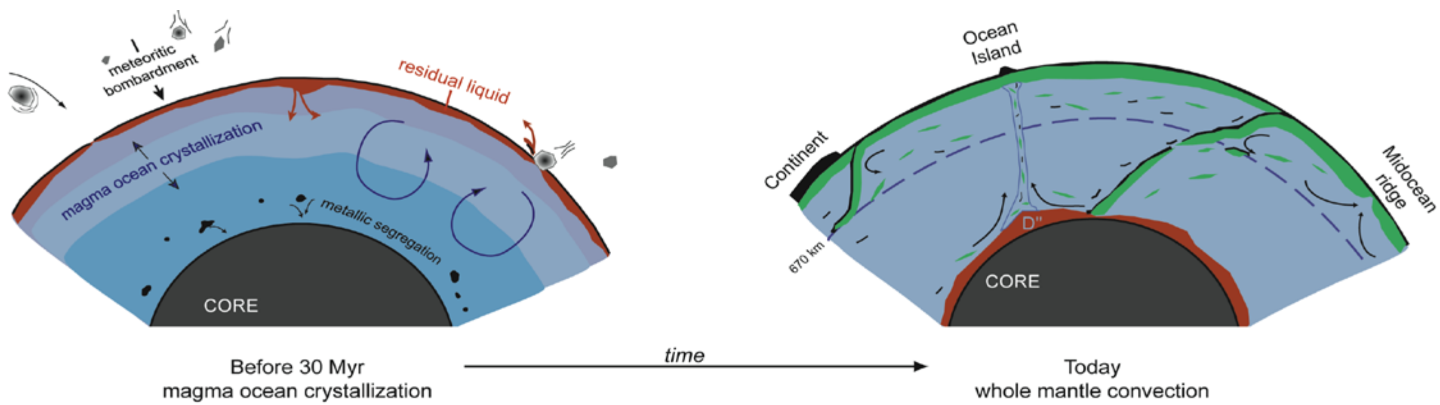
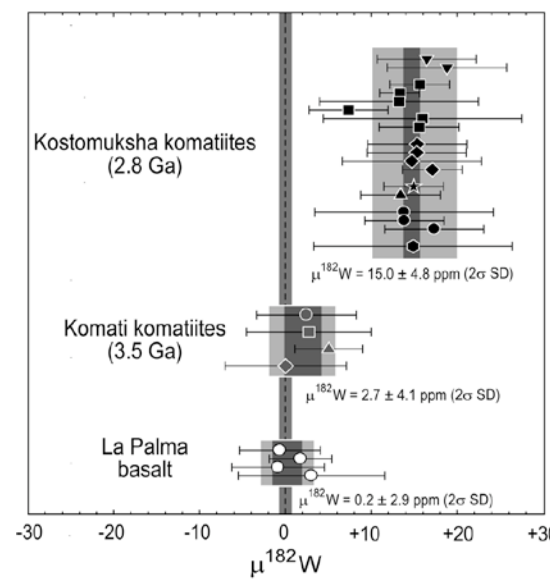


• A chemical differentiation produced before the Moon formation.
• The collision (giant impact) would have not melted and homogeneized the Earth's mantle.

^{182}W anomalies measured in archean samples
^{182}Hf → ^{182}W ($T_{1/2}$ = 9 Ma)
Hf/W fractionation produced before 40 Ma

Touboul et al., 2012



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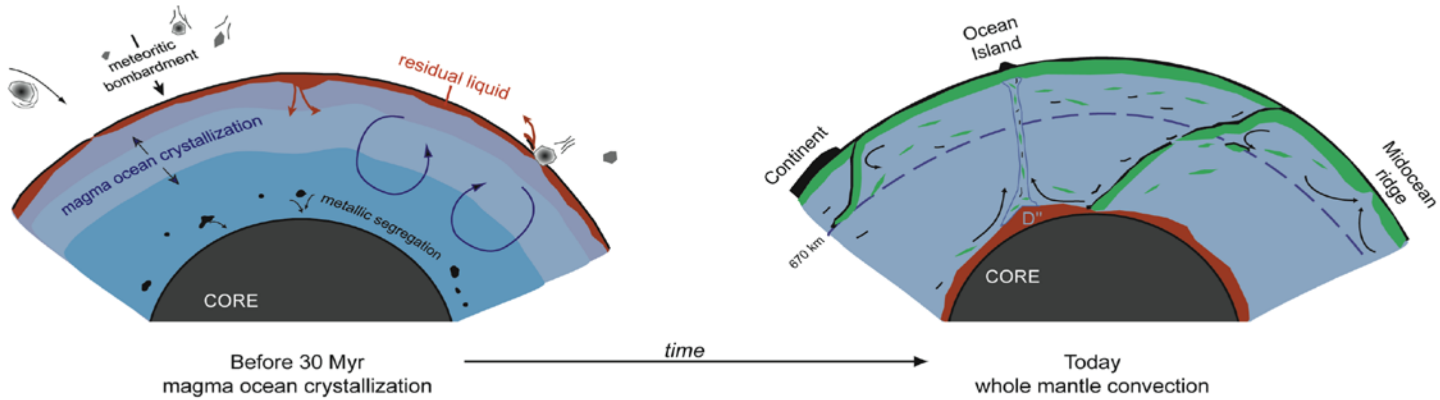
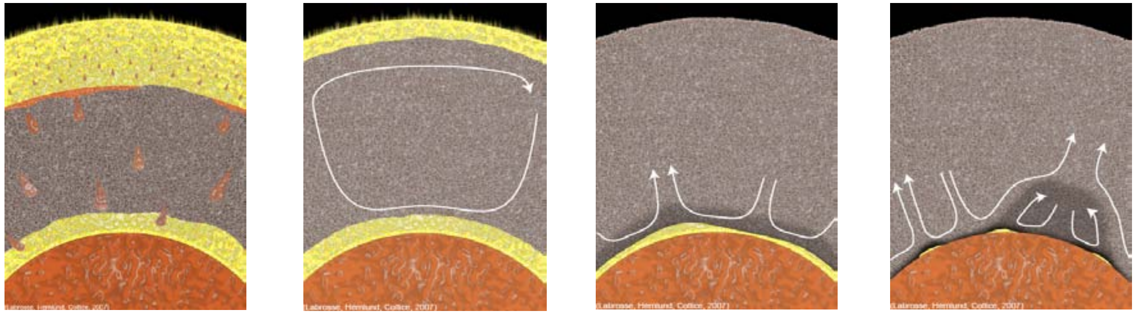


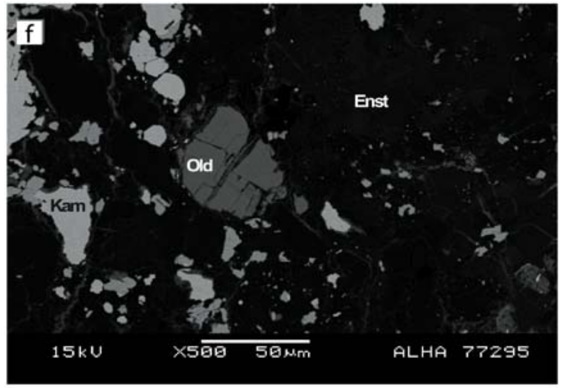
2. A basal magma ocean *(Labrosse et al., 2007)*

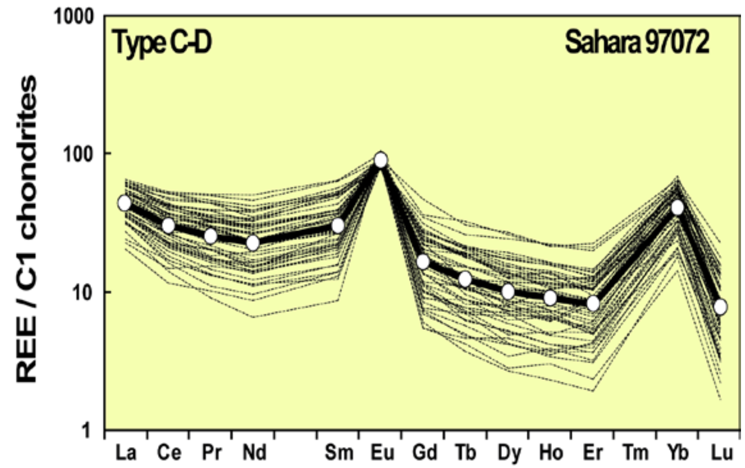


Does the ^{142}Nd signature of terrestrial samples reflect an early differentiation event?

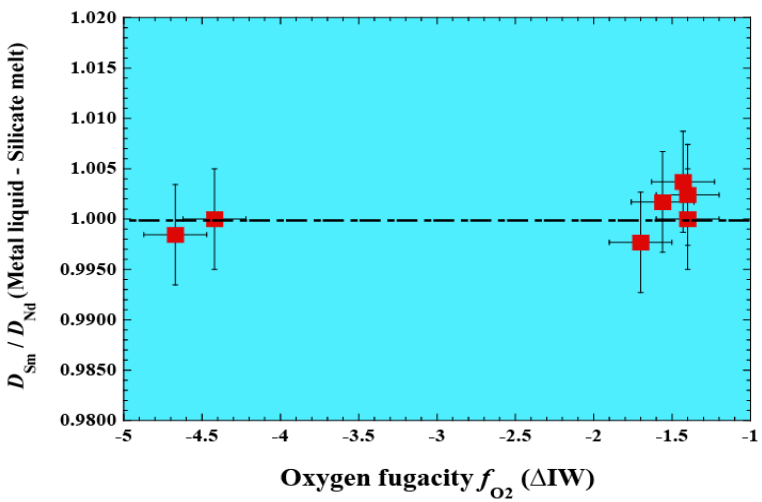
3. REE partitioning in the core *(Andreasen et al., 2007)*

No REE identified in Iron meteorites





In enstatite chondrites 50% of the REEs are concentrated in CaS *(Gannoun et al., 2007)*



Results from experiments:

Sm and Nd are not fractionated by metal-silicate segregation

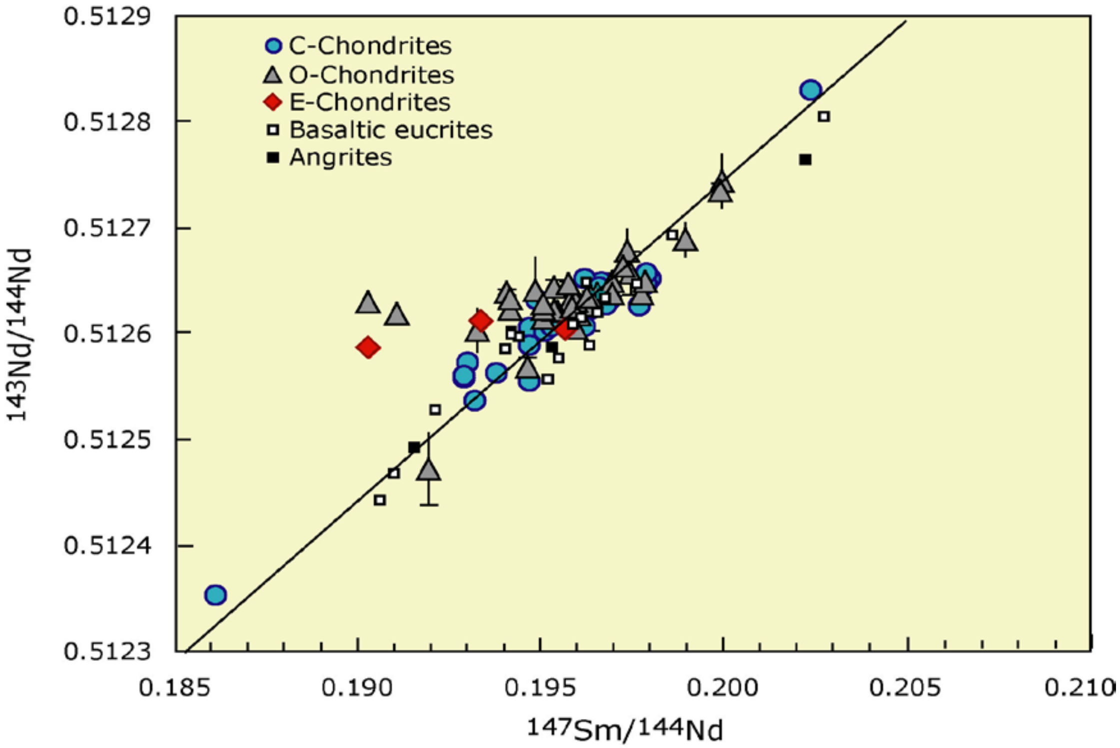
$[Nd]_{core}$ < 2 ppb

Bouhifd et al., in prep

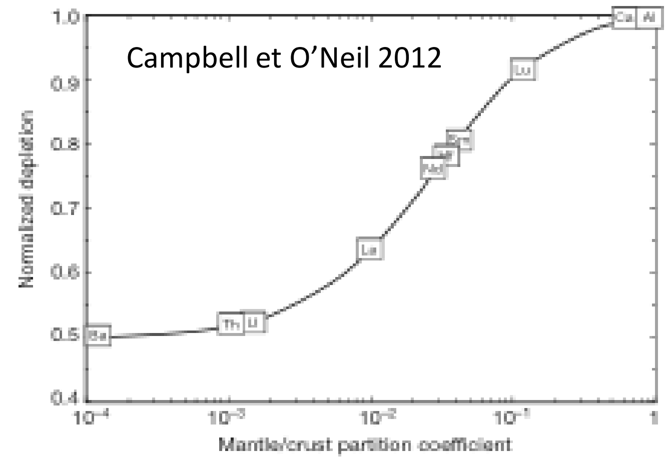
Does the ^{142}Nd signature of terrestrial samples reflect an early differentiation event?

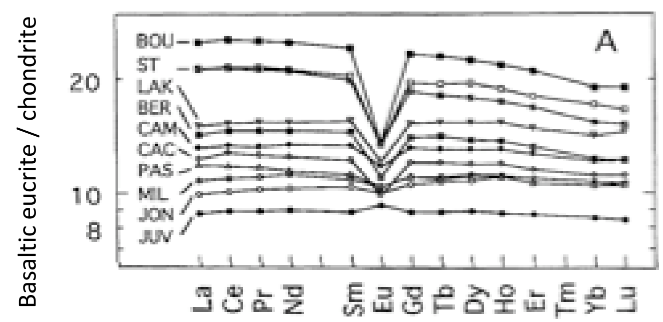
4. The loss of the early crust – Collisional erosion model

Agnor and Asphaug 2004; O'Neil and Palme 2008; Campbell and O'Neil 2012; Caro et al., 2008; Bourdon and Caro 2010.



Jacobsen and Wasserburg, 1980, 1984 ; Prinzhofer et al., 1992 ; Blichert-Toft et al., 2002 ; Patchett et al., 2004; Boyet and Carlson 2005; Carlson et al., 2007.





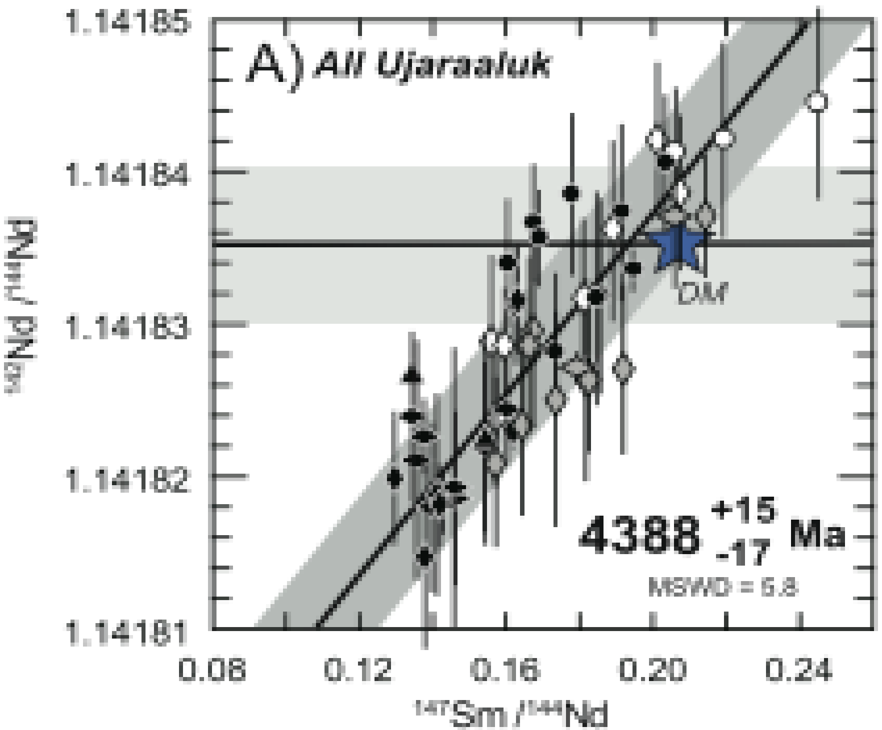
Barrat et al., 2000

An early silicate differentiation seen in terrestrial samples

1

Nuvvuagittuq Greenstone Belt

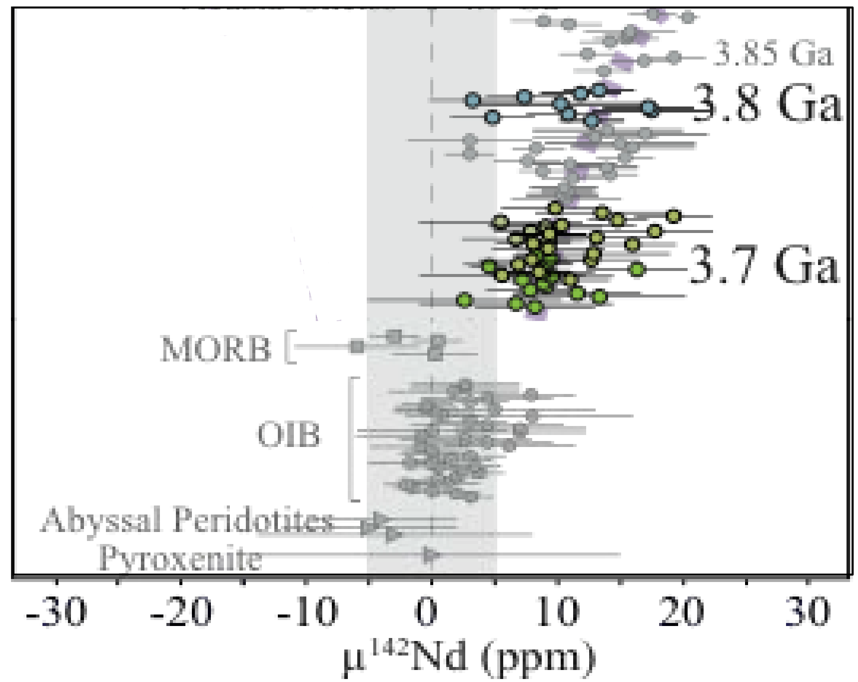
North Quebec, Canada



O'Neil et al., 2012

2

SW Greenland

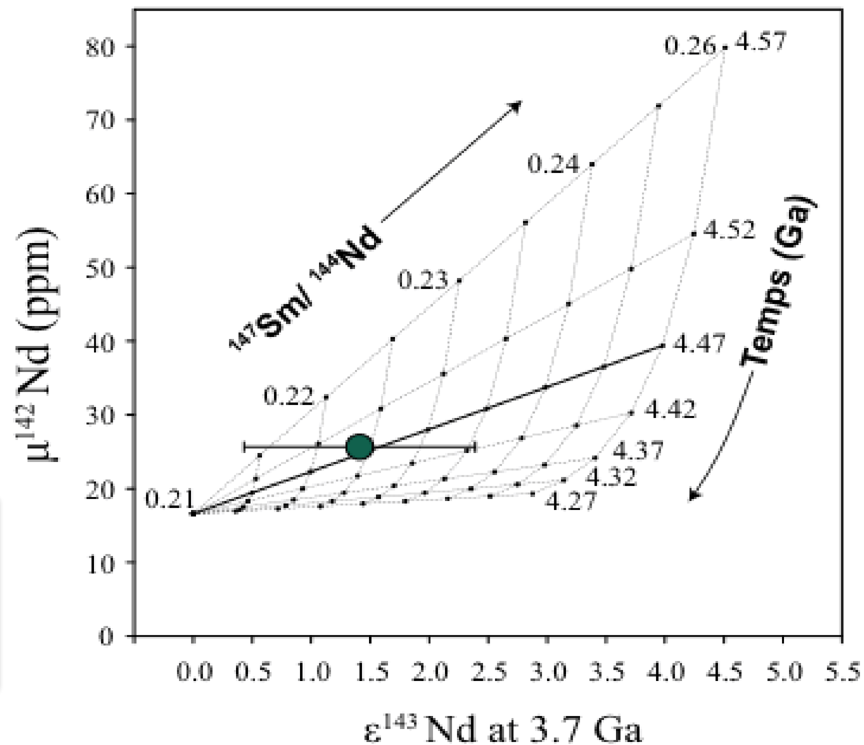


Data : Bennett et al., 2007; Boyet et al., 2006; Caro et al., 2003; Rizo et al., 2011; Andreasen et al., 2008; Murphy et al., 2010; Cipriani et al., 2011; + unpublished data

Age of the differentiation event

Age calculated from Sm-Nd data on Isua samples:
Before 4.42 Ga, during the first 150 Ma of the solar system history

Rizo et al., 2011

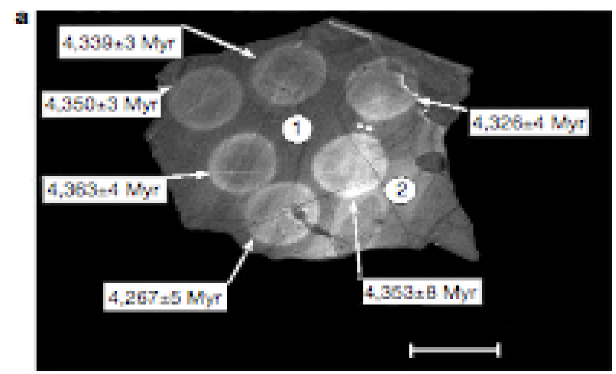


Chemical fractionation associated to the cristallization of the magma ocean

An age recorded in a few localities:

- Age of the oldest Jack Hills zircon: 4404 ± 8 Ma

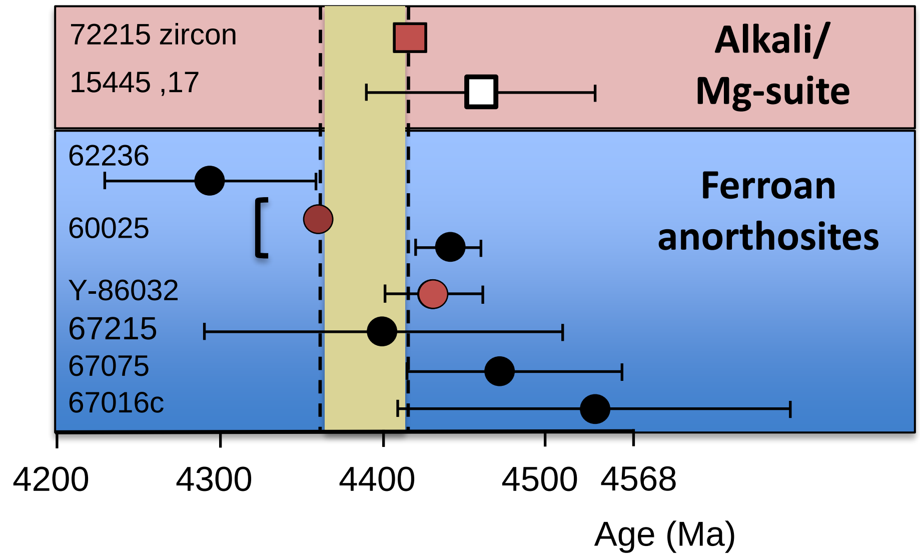
Wilde et al., 2001



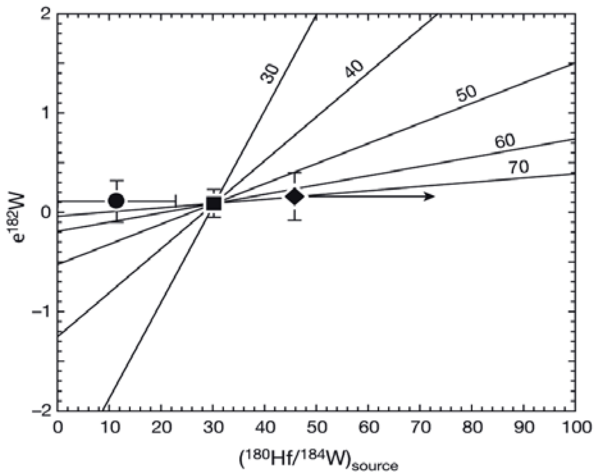
Age of the differentiation event

Absolute ages obtained on lunar samples from the crust :

Figure modified from Borg et al., 2011
Data: Alibert et al., 1994; Borg et al., 1999; 2011; Calrson et al., 1988; Nyquist et al., 2006; 2010.



Results in agreement with data obtained on extinct radioactivities.
Ex. ^{182}Hf-^{182}W

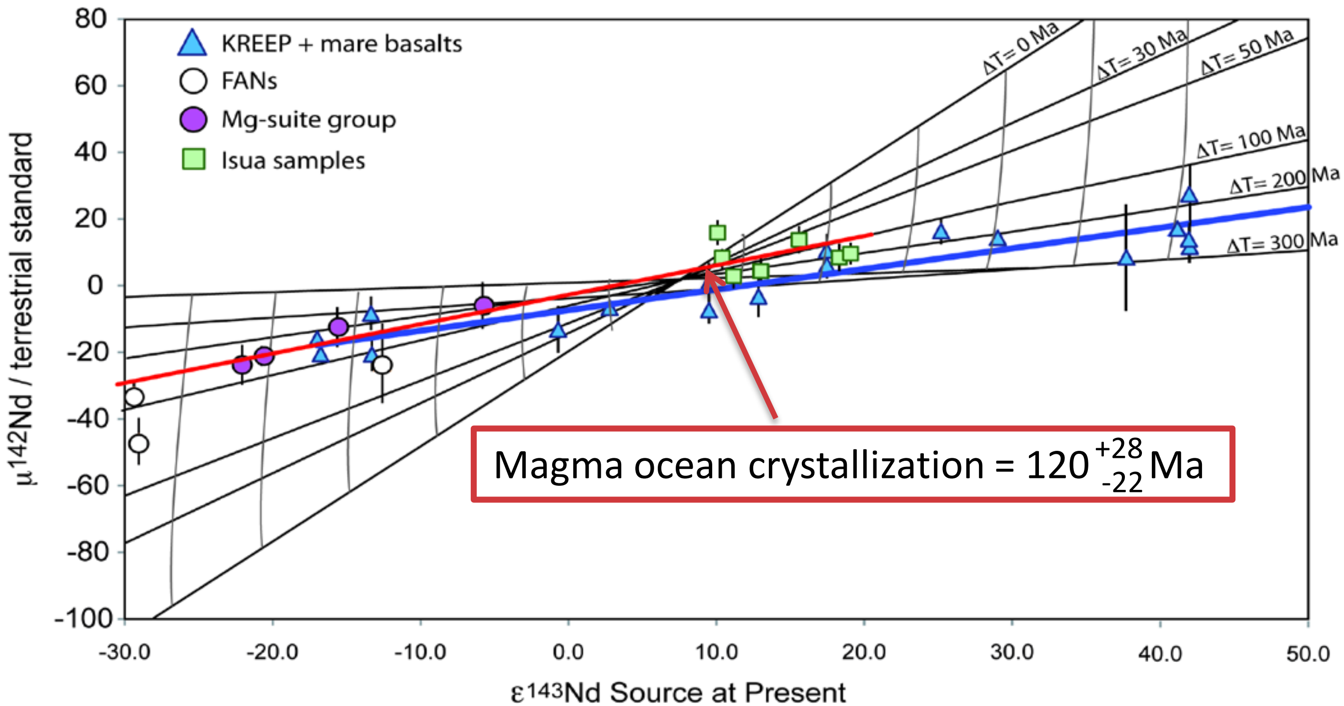


Touboul et al., 2007

The Moon formed late in the solar system history : ΔT ~ 150 Ma

Is it contemporaneous to the Moon formation?

The Earth-Moon relationship :

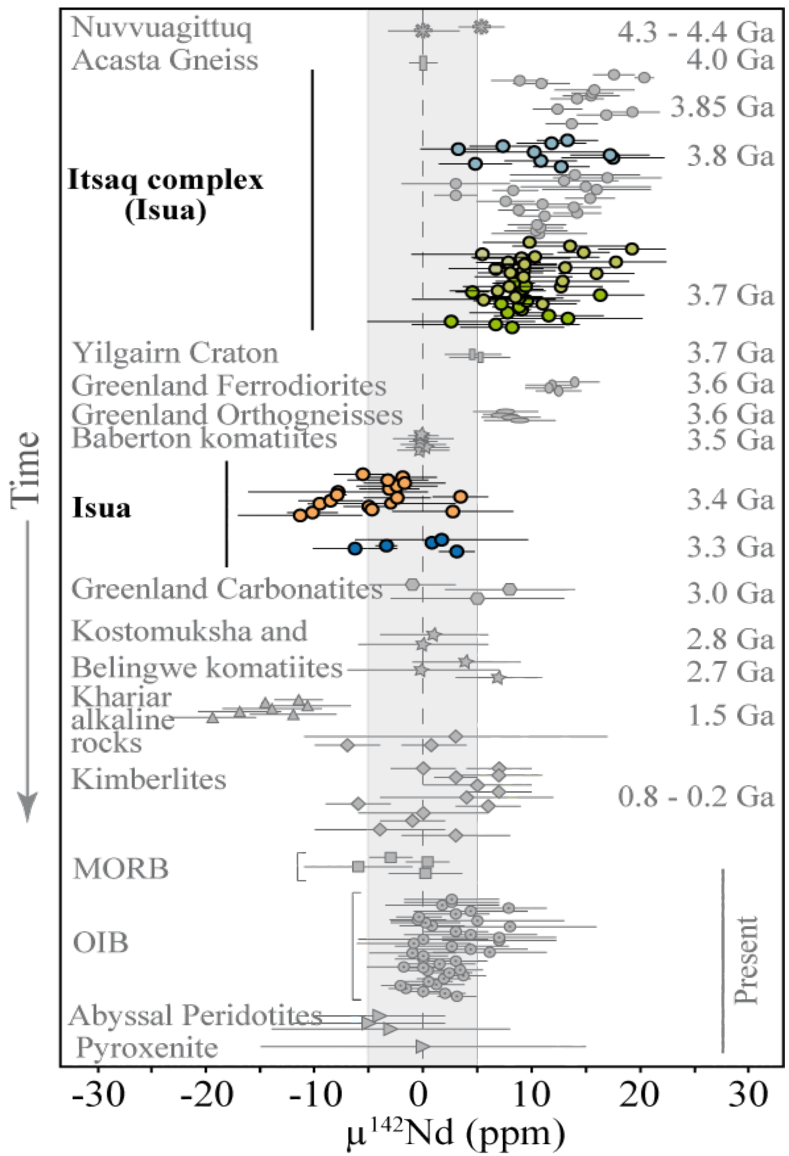


Data from Rizo et al., 2011; Brandon et al., 2009; Boyet et al., 2007+ unpublished data

^{146}Sm-^{142}Nd data for lunar crustal rocks, mare basalts, and the Isua rocks with positive ^{142}Nd anomalies suggest a global differentiation age in the circa 4.45 Ga range. Is this the time of the giant impact and Moon formation?

A global scale differentiation event

Initial ^{142}Nd signature in terrestrial samples

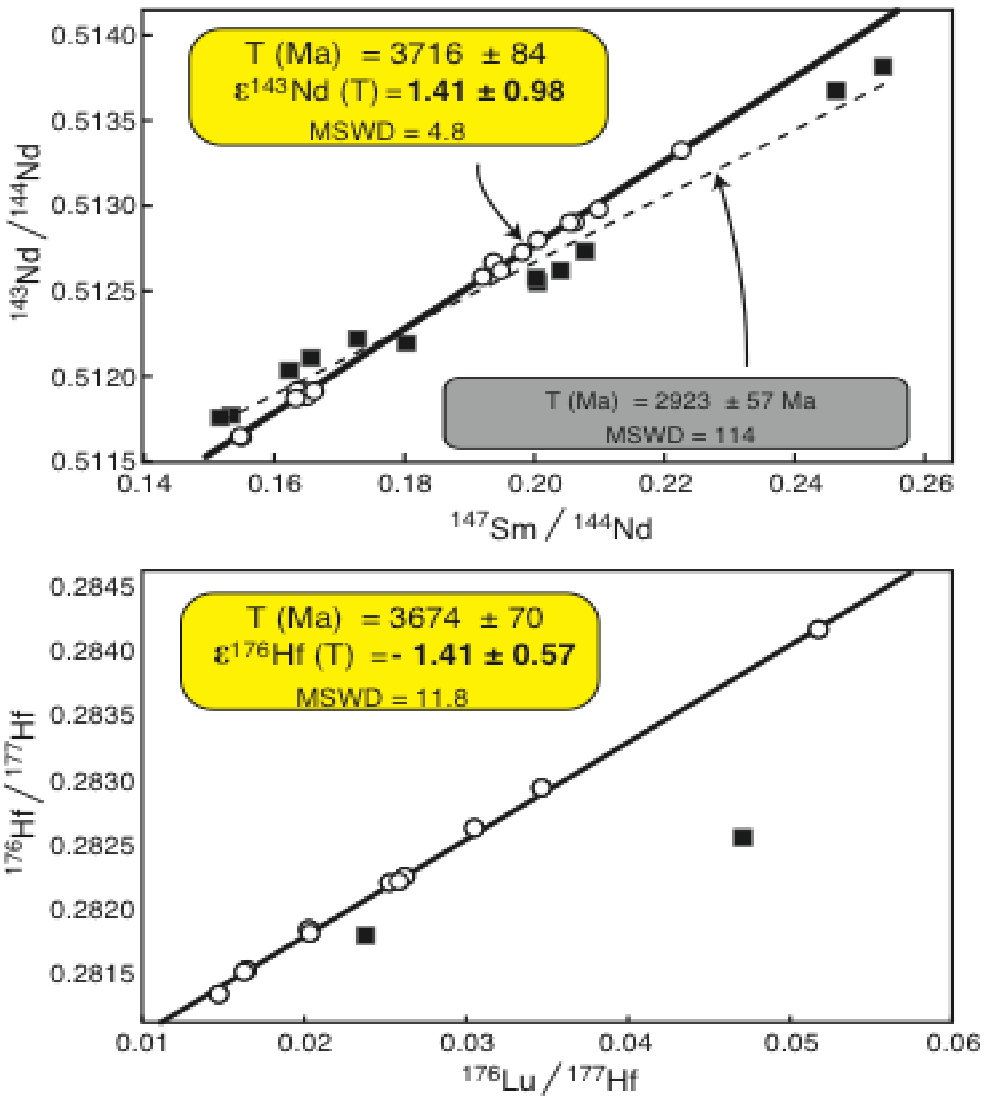


^{142}Nd excesses measured in different localities :

- SW Greenland
- SW Australia

Figure from Rizo 2012

A global scale differentiation event

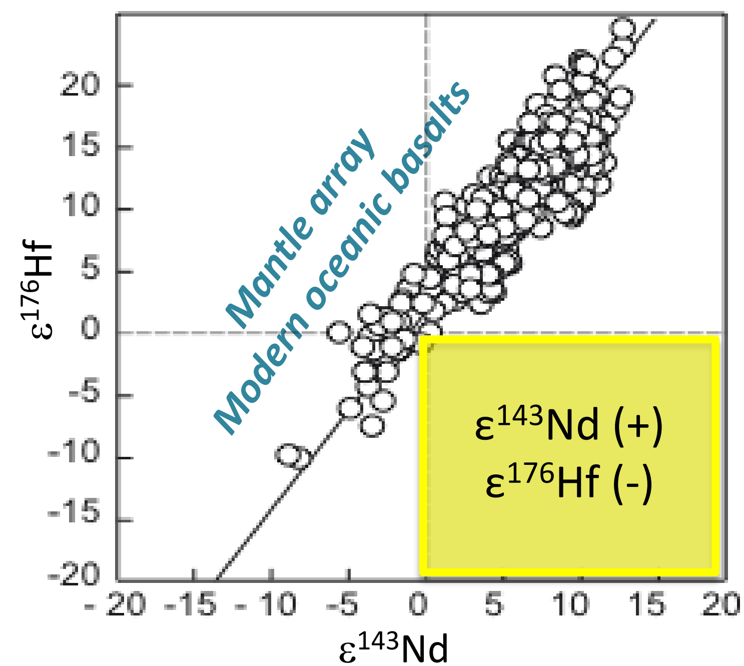


Rizo et al., 2011

More information are obtained by coupling different isotope systematics

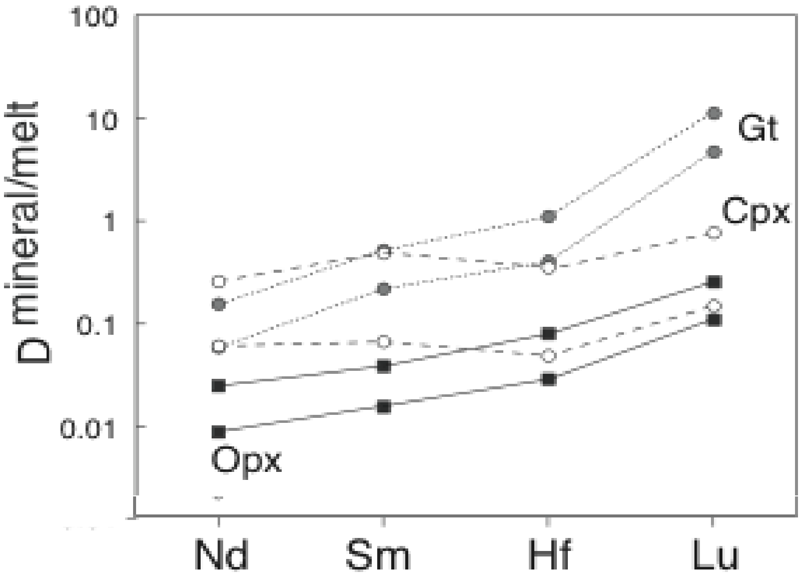
Sm → Nd

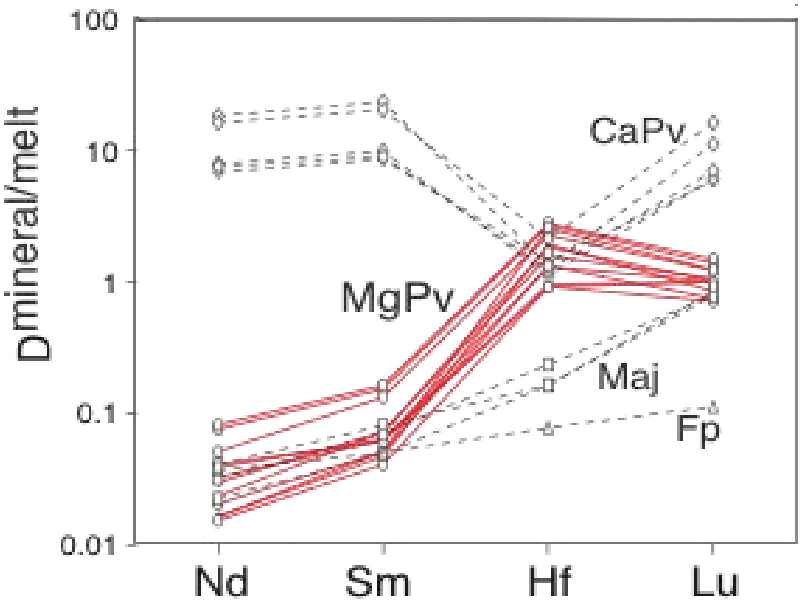
Lu → Hf



Decoupled Sm/Nd and Lu/Hf in the source of Isua basalts

A global scale differentiation event





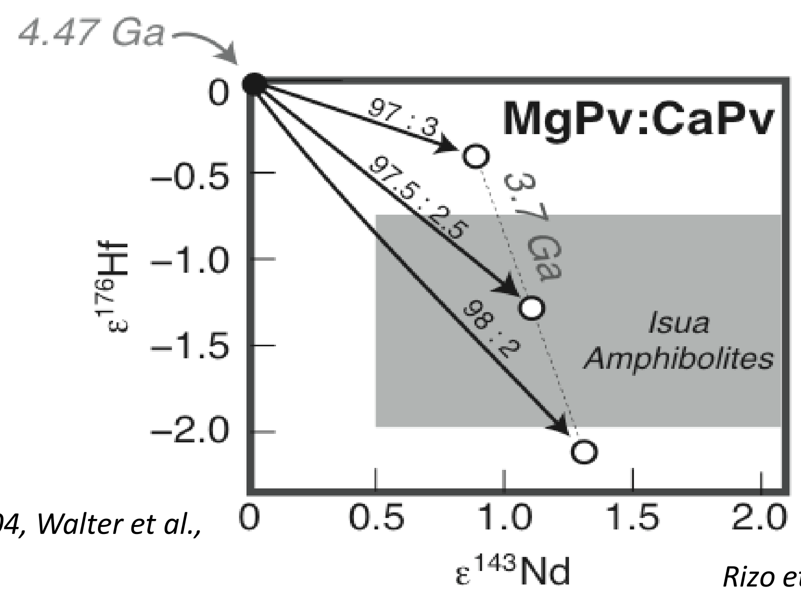
Upper mantle minerals

$D_{Nd,Hf} < D_{Sm,Lu}$

High pressure minerals

$D_{Nd} < D_{Sm}$

But $D_{Lu} < D_{Hf}$ for MgPv

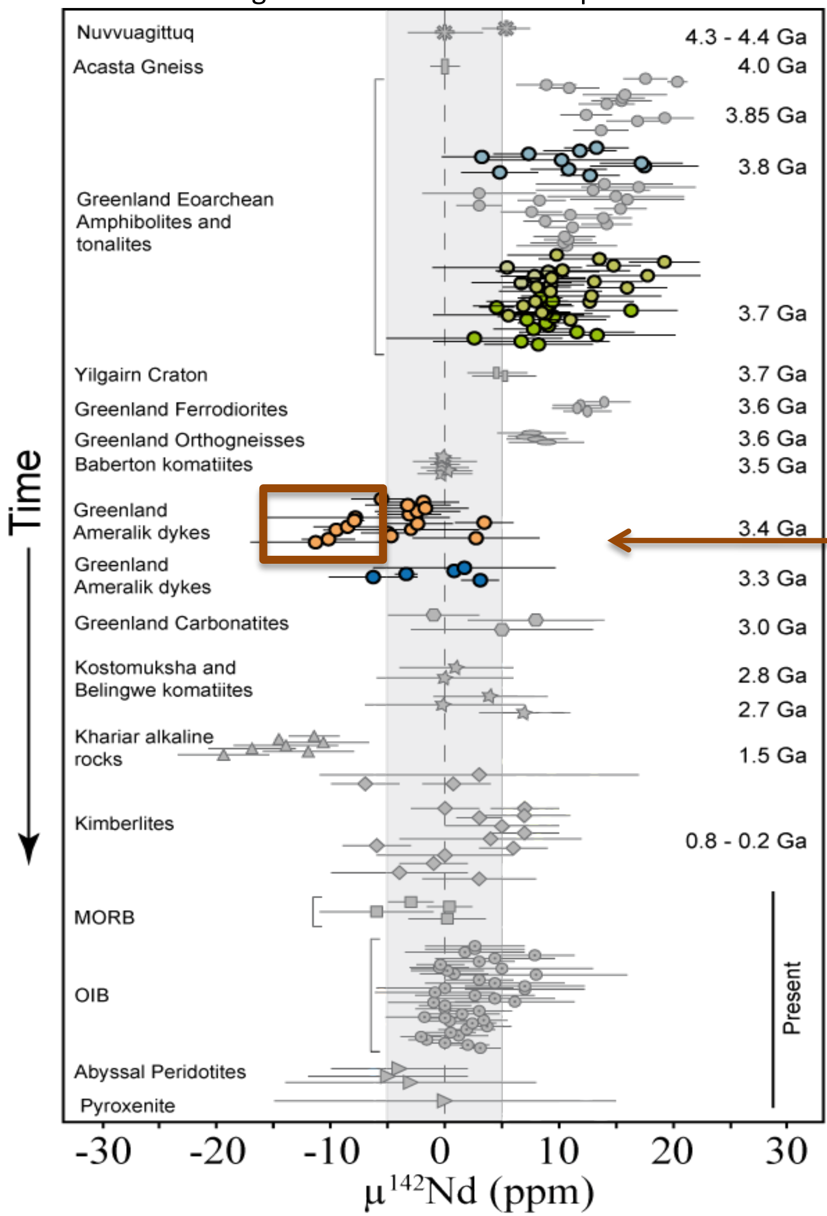


Partition coefficient values from : Corgne and Wood, 2002 ; Corgne et al., 2004, Walter et al., 2004, Corgne et al., 2005, Liebske et al., 2005 ; Salters and Longhi, 2009

Rizo et al., 2011

^{142}Nd signature through time

Initial ^{142}Nd signature in terrestrial samples

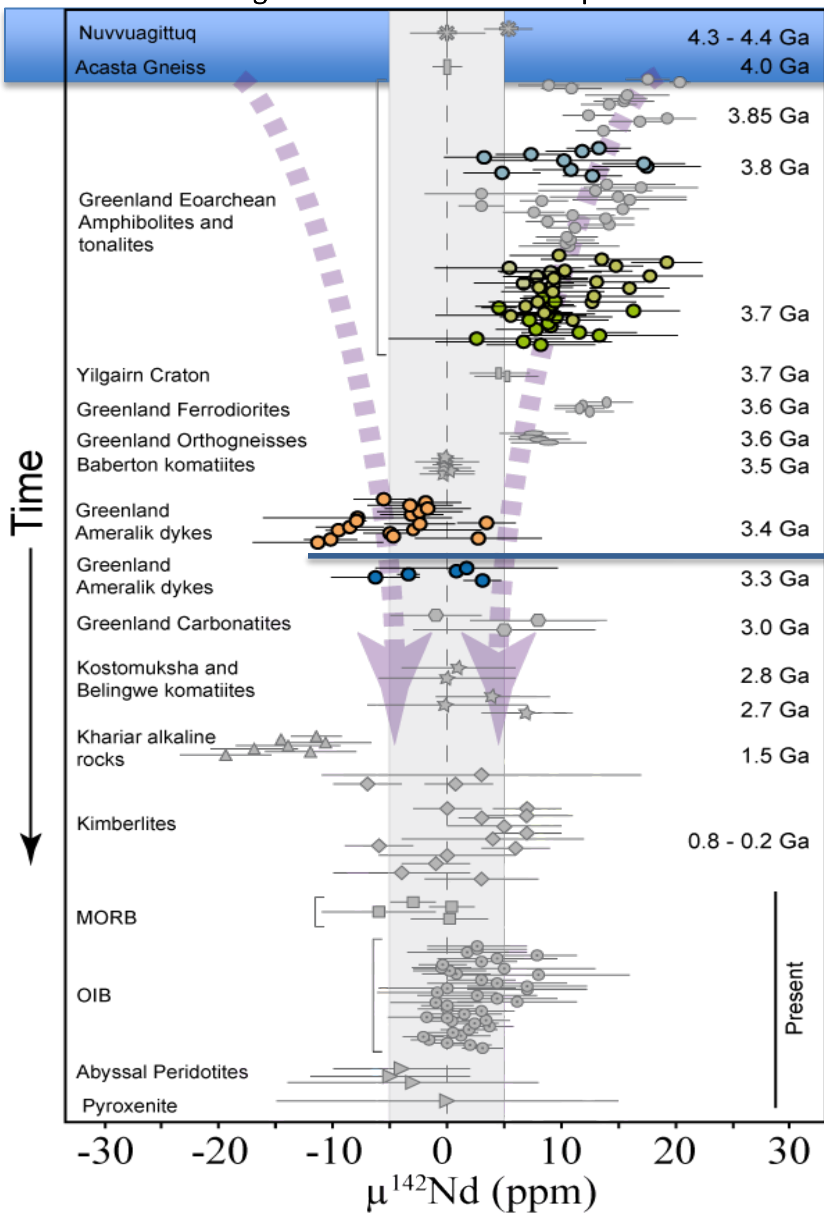


The elusive Hadean enriched reservoir revealed by ^{142}Nd deficits in Isua Archaean rocks

Hanika Rizo[1], Maud Boyet[1], Janne Blichert-Toft[2], Jonathan O'Neil[1], Minik T. Rosing[3] & Jean-Louis Paquette[1]

^{142}Nd signature through time

Initial ^{142}Nd signature in terrestrial samples



Mantle dynamic in the Hadean?

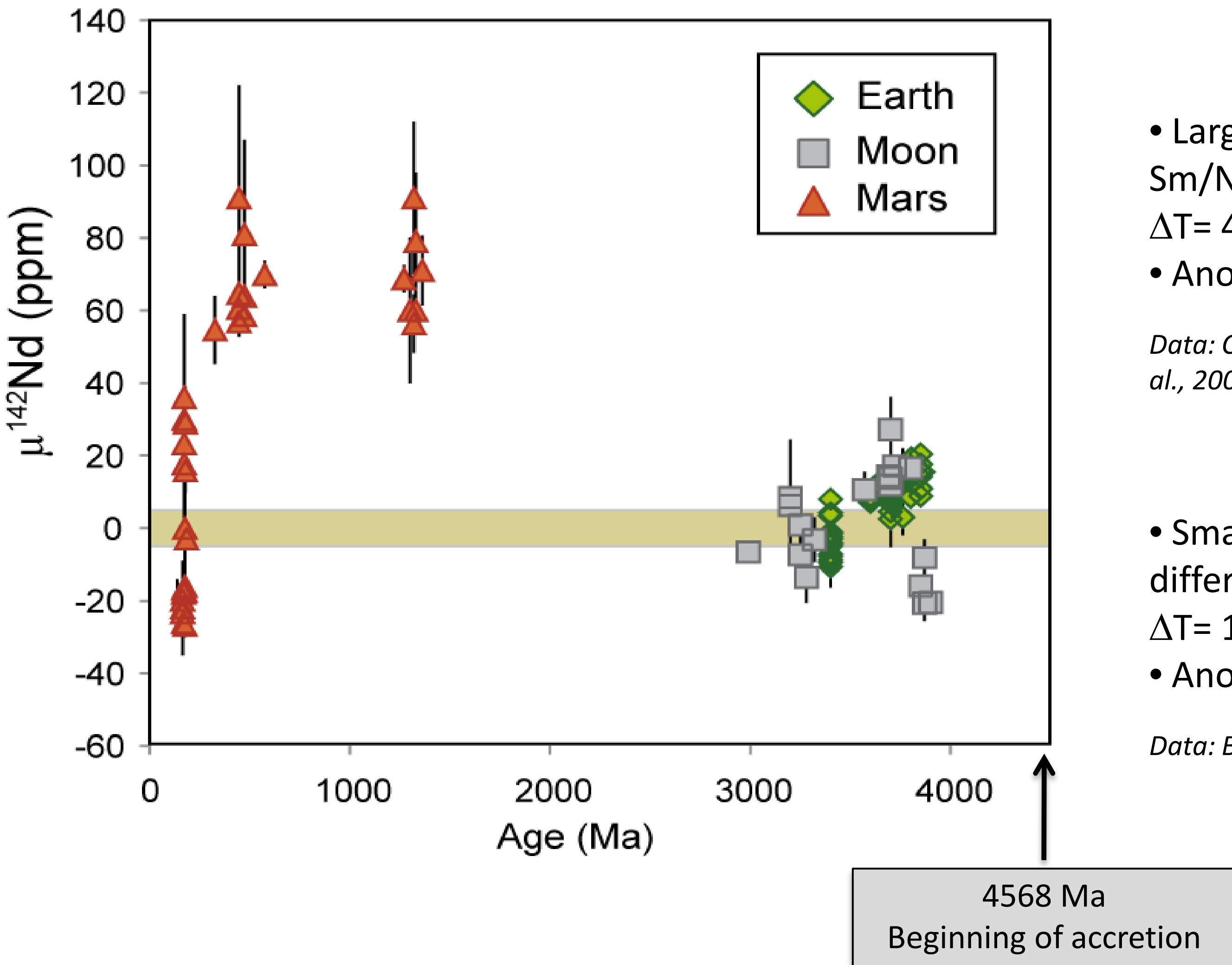
Early chemical heterogeneities preserved until 3.4 Ga:
Complementary depleted and enriched reservoirs have been identified

Efficient Mixing:
no more ^{142}Nd anomalies are detected

Data on Khariar alkaline rocks (Upadhyay et al., 2009) have not been reproduced (Roth et al., 2012)

Andreasen et al., 2008; Bennett et al., 2007; Boyet et al., 2006; Caro et al., 2006; Cipriani et al., 2011; Murphy et al., 201; O'Neil et al., 2012, Rizo et al., 2011; Rizo et al., 2012; Upadhyay et al., 2009 + unpublihed data

^{142}Nd signature of lunar samples and martian meteorites



MARS

- Large ^{142}Nd anomalies = very early Sm/Nd fractionation
  ΔT= 40 ± 20 Ma
- Anomalies preserved trought time

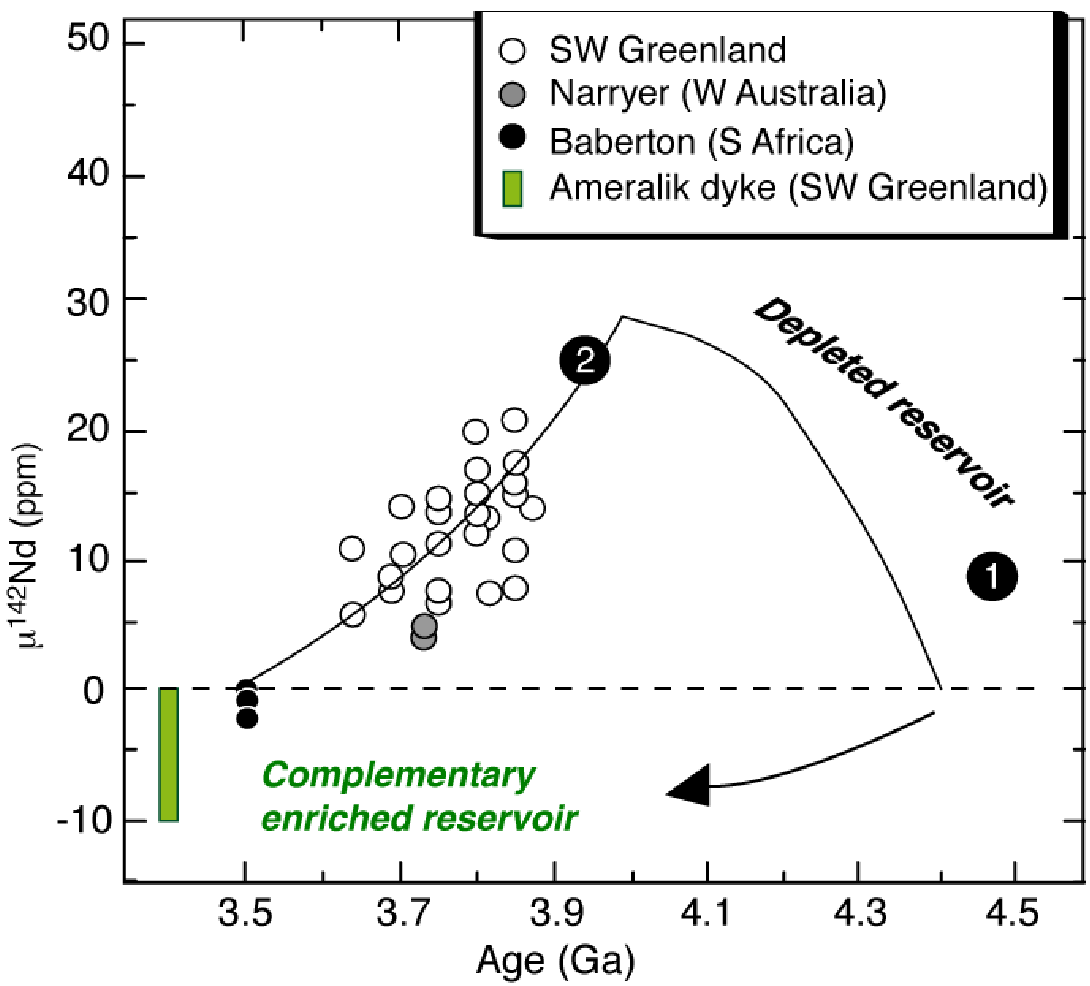
Data: Caro et al., 2006; Debaille et al., 2007; Foley et al., 2005

MOON

- Small ^{142}Nd anomalies = the differenciation occured late
  ΔT= 100 -170 Ma
- Anomalies preserved trought time

Data: Boyet at al., 2007; Brandon et al., 2009

^{142}Nd signature through time



Modified from Carlson and Boyet 2008

The mantle source of 3.8-3.7 Ga samples (SW Greenland) has not been mixed until ~4.0 Ga

How to explain this feature whereas the hadean mantle must be hotter and the convection more vigorous?

Conclusion

If the Earth has been formed by the accretion of chondrites, two major silicate differenciation events occured during the first 150 Ma of the solar system history:

1. < 30 Ma
   Differentiation preserved on the solar system history

2. ~150 Ma
   magma ocean crystallization associated to the Moon formation. Chemical heterogeneities preserved in the mantle during 1 Ga (^{142}Nd) - 2 Ga (^{182}W)