Early Mantle Dynamics seen by the Isotope Signature of Archean Samples

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OUTLINE OF THE TALK

1. Introduction
2. Chemical tools
3. $^{146}\text{Sm} - ^{142}\text{Nd}$ 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

- Structure and Dynamics of the Deep mantle -

Maud Boyet – November 14th 2012

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
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 fractionated during silicate processes.

Geochemical tools

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 $\rightarrow ^{182}$W $\quad T = 9$ Ma
$^{146}$Sm $\rightarrow ^{142}$Nd $\quad T = 68$ Ma

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

$^{147}$Sm $\rightarrow ^{143}$Nd $\quad T = 106$ Ga, $\lambda = 6.54 \times 10^{-12}$ a$^{-1}$
$^{176}$Lu $\rightarrow ^{177}$Hf $\quad T = 35.9$ Ga, $\lambda = 1.867 \times 10^{-11}$ a$^{-1}$

Systems robust against alteration and metamorphism
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
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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
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

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

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

Touboul et al., 2012
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

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 $[\text{Nd}]_{\text{core}} < 2$ 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 – Collisonal 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.
An early silicate differentiation seen in terrestrial samples

**Nuvvuagittuq Greenstone Belt**
North Quebec, Canada

**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

O’Neil et al., 2012
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 crystallization 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; Carlson et al., 1988; Nyquist et al., 2006; 2010.*

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

The Moon formed late in the solar system history: $\Delta T \sim 150$ Ma

Touboul et al., 2007
Is it contemporaneous to the Moon formation?

The Earth-Moon relationship:

146Sm-142Nd data for lunar crustal rocks, mare basalts, and the Isua rocks with positive 142Nd 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

142Nd excesses measured in different localities:
- SW Greenland
- SW Australia
A global scale differentiation event

More information are obtained by coupling different isotope systematics

\[
\begin{align*}
\text{Sm} & \rightarrow \text{Nd} \\
\text{Lu} & \rightarrow \text{Hf}
\end{align*}
\]

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

Rizo et al., 2011
A global scale differentiation event

Upper mantle minerals
\[ D_{\text{Nd, Hf}} < D_{\text{Sm, Lu}} \]

High pressure minerals
\[ D_{\text{Nd}} < D_{\text{Sm}} \]
But \[ D_{\text{Lu}} < D_{\text{Hf}} \] 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
142Nd signature through time

Initial 142Nd signature in terrestrial samples

- Nuvvuagittuq
  - 4.3 - 4.4 Ga
- Acasta Gneiss
  - 4.0 Ga
- Greenland Eoarchean Amphibolites and tonalites
  - 3.85 Ga
- Greenland Ferrodiorites
  - 3.8 Ga
- Greenland Orthogneisses
  - 3.8 Ga
- Baberton komatites
  - 3.7 Ga
- Yilgarn Craton
  - 3.7 Ga
- Greenland Ferrodiorites
  - 3.6 Ga
- Greenland Orthogneisses
  - 3.6 Ga
- Baberton komatites
  - 3.5 Ga
- Greenland Ameralik dykes
  - 3.4 Ga
- Greenland Ameralik dykes
  - 3.3 Ga
- Greenland Carbonatites
  - 3.0 Ga
- Kostomuksha and Belingwe komatites
  - 2.8 Ga
- Khariar alkaline rocks
  - 2.7 Ga
- Kimberlites
  - 1.5 Ga
- Kimberlites
  - 0.8 - 0.2 Ga
- MORB
- OIB
- Abyssal Peridotites
- Pyroxenite

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

Flanika Rino, Maud Boyet, Janne Bliebert, Tott, Jonathan O’Neil, Minuk T. Rosang & Jean-Louis Pasquet
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)

Andrews et al., 2008; Bennett et al., 2007; Boyet et al., 2006; Caro et al., 2006; Cipriani et al., 2011; Murphy et al., 2011; O’Neil et al., 2012, Rizo et al., 2011; Rizo et al., 2012; Upadhyay et al., 2009 + unpublished data
142Nd signature of lunar samples and martian meteorites

**MARS**
- Large $^{142}$Nd anomalies = very early Sm/Nd fractionation
  $\Delta T = 40 \pm 20$ Ma
- Anomalies preserved through time

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

**MOON**
- Small $^{142}$Nd anomalies = the differentiation occurred late
  $\Delta T = 100 - 170$ Ma
- Anomalies preserved through time

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

4568 Ma
Beginning of accretion
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?

*Modified from Carlson and Boyet 2008*
Conclusion

If the Earth has been formed by the accretion of chondrites, two major silicate differenciation events occurred 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)

- EARTH
  - Isua (Greenland)
  - Amitsoq (Greenland)
  - Labrador (Canada)

- MOON
  - Zircons (SW Australia)
  - 60025
  - Zircon
  - Nuvvuagittuq (Canada)

Giant Impact

Magma ocean crystallization