

„Extinct radionuclides“ – timing and reconstruction of Early Earth's evolution

Jörg Pfänder  
TU Freiberg, Germany

What are „extinct radionuclides“?

„Extinct radionuclides“ are short living isotopes that were produced during nucleosynthesis by e, s, r, and p-processes in stars and supernovas (star explosions).

Supernovas distribute them into the space, where they are incorporated into newly forming solar systems (and thus into newly forming planets!).

As they have short half-lives, they become extinct early after solar system and planet formation. But ...

What are „extinct radionuclides“?

.... some of them have half-lives that make them suitable tracers to reconstruct the early history of the solar system. Some examples:

- |   |                    |
|---|--------------------|
| $^{53}\text{Mn} \rightarrow ^{53}\text{Cr}$   | Half-life = 3.7 Ma |
| $^{107}\text{Pd} \rightarrow ^{107}\text{Ag}$ | Half-life = 6.5 Ma |
| $^{182}\text{Hf} \rightarrow ^{182}\text{W}$  | Half-life = 9.0 Ma |
| $^{129}\text{I} \rightarrow ^{129}\text{Xe}$  | Half-life = 16 Ma  |
| $^{92}\text{Nb} \rightarrow ^{92}\text{Zr}$   | Half-life = 36 Ma  |
| $^{146}\text{Sm} \rightarrow ^{142}\text{Nd}$ | Half-life = 103 Ma |

What are „extinct radionuclides“?

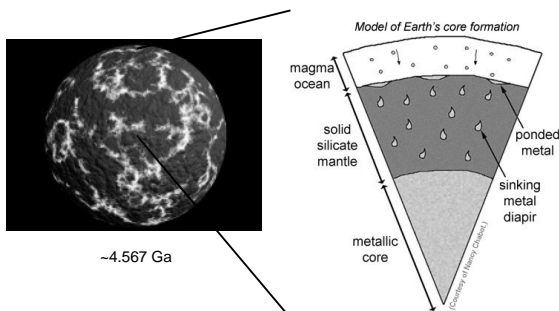
From these, the following are of particular interest for the early planetary evolution:

- |   |                    |
|---|--------------------|
| $^{182}\text{Hf} \rightarrow ^{182}\text{W}$  | Half-life = 9.0 Ma |
| $^{92}\text{Nb} \rightarrow ^{92}\text{Zr}$   | Half-life = 36 Ma  |
| $^{146}\text{Sm} \rightarrow ^{142}\text{Nd}$ | Half-life = 103 Ma |

the latter not to confuse with the long-lived

- |   |                    |
|---|--------------------|
| $^{147}\text{Sm} \rightarrow ^{143}\text{Nd}$ | Half-life = 106 Ga |
|---|--------------------|

Example: Core formation on Earth



When did the Earth's core form, and how long does this process last?

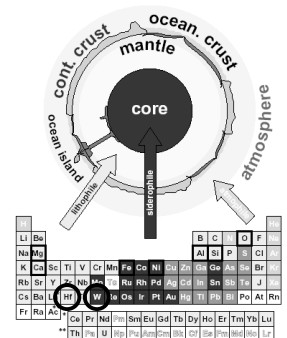
The  $^{182}\text{Hf} - ^{182}\text{W}$  decay system: Timing of core formation on Earth

Key:

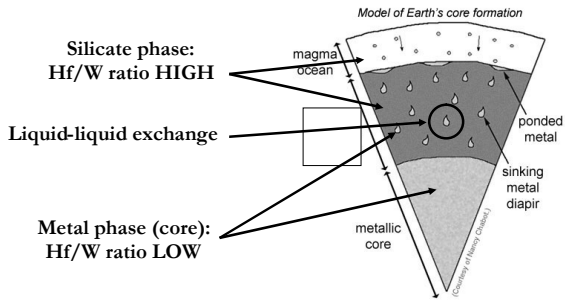
$D_{\text{SM}} = D$  between silicate melt and liquid metal phase

Hf = lithophile,  $D_{\text{SM}} > 1$

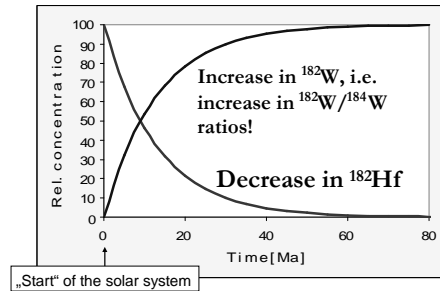
W = siderophile,  $D_{\text{SM}} < 1$



### Example: Core formation on Earth



### Evolution of $^{182}\text{Hf}$ and $^{182}\text{W}$ over time



This means: After ~60 Ma, all of the  $^{182}\text{Hf}$  is gone, and no increase in  $^{182}\text{W}$  (expressed as  $^{182}\text{W}/^{184}\text{W}$  ratio) does occur any more!

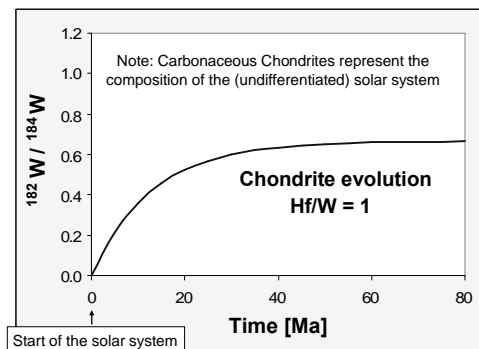
### Example: Core formation on Earth

Therefore:

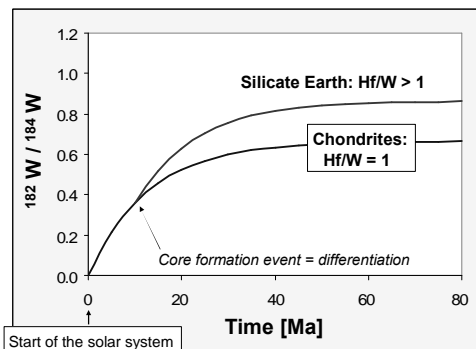
If core formation on Earth was within ~60 Ma after the „Start“ of the solar system ( $t = 0$ ), then the fractionation of the Hf/W ratio must have produced a positive  $^{182}\text{W}/^{184}\text{W}$  anomaly in the silicate portion of the Earth with respect to chondrites (due to enrichment of Hf over W in the silicate Earth).

If core formation was after ~60 Ma, no anomaly with respect to chondrites is expected.

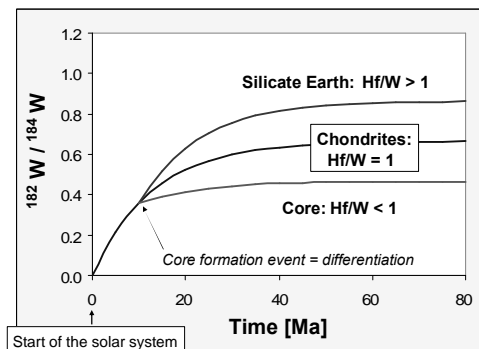
### $^{182}\text{W}/^{184}\text{W}$ evolution



### $^{182}\text{W}/^{184}\text{W}$ evolution



### $^{182}\text{W}/^{184}\text{W}$ evolution



**Example: Core formation on Earth**

To summarize:

Only if core formation (i.e. fractionation of Hf/W ratios) on Earth was within ~60 Ma after the start of the solar system, an excess in  $^{182}\text{W}$  is expected in terrestrial samples relative to chondrites.

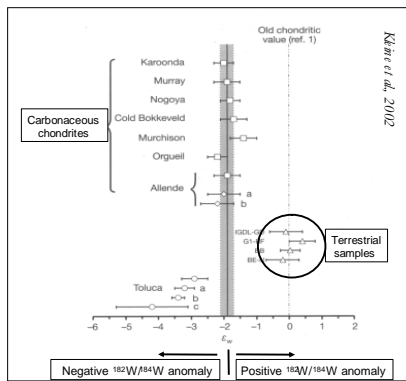
If core formation occurred after ~60 Ma, no  $^{182}\text{W}$  excess can have developed as the Hf contains no  $^{182}\text{Hf}$  any more (as it is extinct after 60 Ma!).

**Example: Core formation on Earth**

In other words:

If core formation occurred after ~60 Ma, Hf/W will also fractionate between the silicate portion of the Earth and the liquid metal phase, but the Hf-enriched silicate portion will not develop an  $^{182}\text{W}$  anomaly, as there is simply no  $^{182}\text{Hf}$  left anymore!

$^{182}\text{W}/^{184}\text{W}$  in chondrites & terrestrial samples



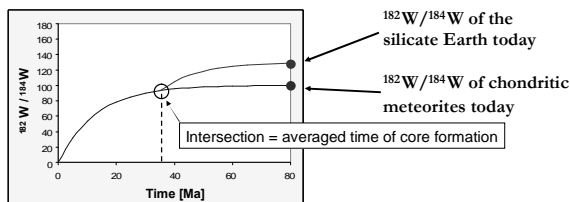
**Example: Core formation on Earth**

This indicates:

Core formation on Earth was early after the start of the solar system, i.e. simultaneously or short after the accretion of the Earth!

Okay, early – but when?

**Example: Core formation on Earth**



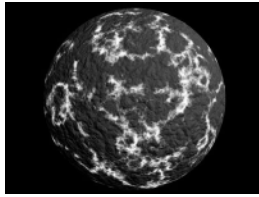
Core formation on Earth was at about 35 Ma after the start of the solar system, i.e. after the start of Earth accretion

**Example: Core formation on Earth**

Note, that this is a model age and not an exact date of a single event, as:

„Even if >50% of the mass of the core formed yesterday, it would not change the W-isotopic composition of the silicate Earth!“ (Halliday, 2003)

### Example II: Early crust formation



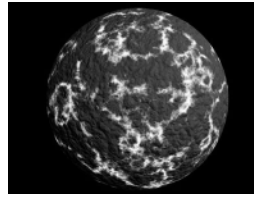
Earth ~4.567 Ga ago ??

What does the Planet Earth look like after accretion?  
Was it molten? Partly solid?

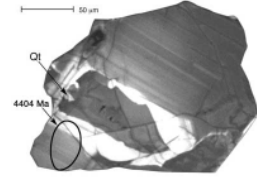
And, when did the first crustal rocks form, i.e. when did the „first tectonic processes occur on Earth“?

These questions can be addressed by using Geochronology in combination with short and long living isotope systematics!

### Example II: Early crust formation



Earth ~4.567 Ga ago ??



Zircon from Jack Hills, Australia

Zircons from Jack Hills, Western Australia, are as old as 4.40 Ga and thus indicate early cooling and differentiation of the Earth

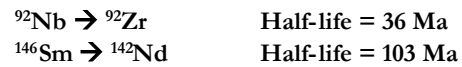
### Example II: Early crust formation

Is there any other evidence for early crust formation?

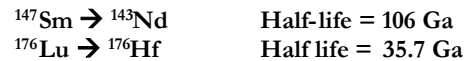
Or, more generally, is there any evidence for early differentiation of the silicate portion of the Earth?

### Example II: Early crust formation

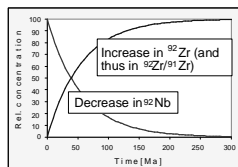
This can be evaluated in particular by using the two lithophile element short-lived isotopic systems:



but also by using the long-lived systems:



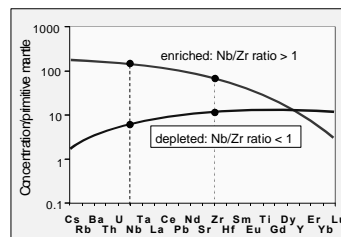
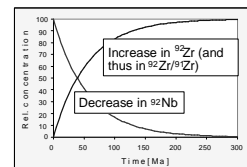
### Evidence from $^{92}\text{Nb} \rightarrow ^{92}\text{Zr}$ ?



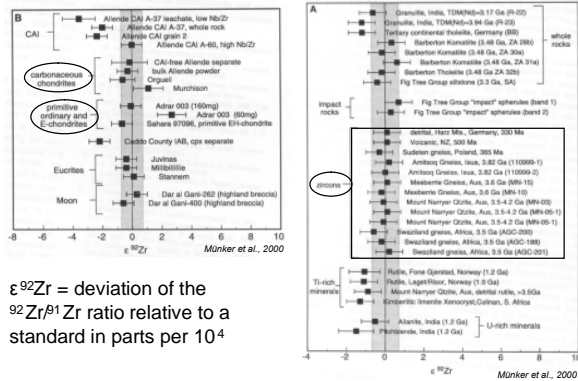
#### Basics:

Fractionation between Nb and Zr by partial melting or crystallisation processes within the first ~100 Ma after the start of the solar system is expected to produce anomalies in  $^{92}\text{Zr}/^{91}\text{Zr}$  ratios (an excess in Nb-enriched samples, and a deficit in Nb-depleted samples, e.g. in early zircons with extremely low Nb/Zr).

### Evidence from $^{92}\text{Nb} \rightarrow ^{92}\text{Zr}$ ?



Evidence from  $^{92}\text{Nb} \rightarrow ^{92}\text{Zr}$  ?



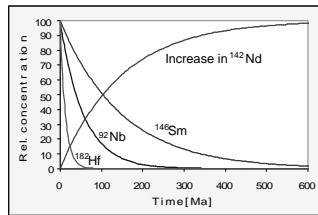
$\epsilon^{92}\text{Zr}$  = deviation of the  $^{92}\text{Zr}/^{91}\text{Zr}$  ratio relative to a standard in parts per 10<sup>4</sup>

Evidence from  $^{92}\text{Nb} \rightarrow ^{92}\text{Zr}$  ?

**NO !!!**

Either there was no extensive early differentiation of the silicate Earth, or this did not affect the  $^{92}\text{Zr}/^{91}\text{Zr}$  ratios, e.g. if the initial  $^{92}\text{Nb}$  abundance at the beginning of the solar system was too low to produce a resolvable  $^{92}\text{Zr}/^{91}\text{Zr}$  anomaly in terrestrial and lunar rocks.

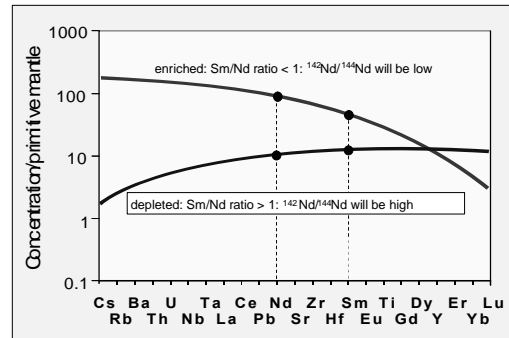
Evidence from  $^{146}\text{Sm} \rightarrow ^{142}\text{Nd}$  ?



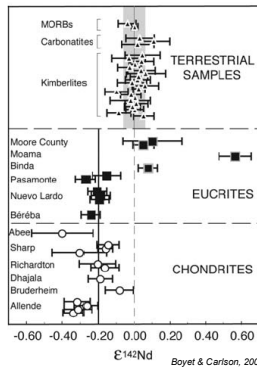
Basics:

As for Nb-Zr, fractionation between Sm and Nd by partial melting or crystallisation processes within the first ~300 Ma after the start of the solar system will produce variations in Sm/Nd ratios and thus in  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios in terrestrial samples.

Evidence from  $^{146}\text{Sm} \rightarrow ^{142}\text{Nd}$  ?



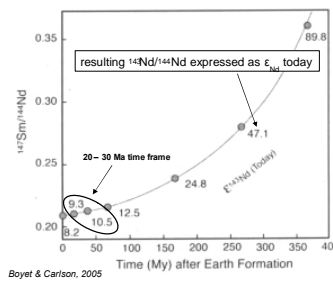
Evidence from  $^{146}\text{Sm} \rightarrow ^{142}\text{Nd}$  !



Although small (only about 20 ppm), the deviation in  $^{142}\text{Nd}/^{144}\text{Nd}$  between terrestrial samples and chondrites indicates early differentiation of the silicate Earth (must have happened during the lifetime of  $^{146}\text{Sm}$ !).

Evidence from  $^{146}\text{Sm} \rightarrow ^{142}\text{Nd}$  !

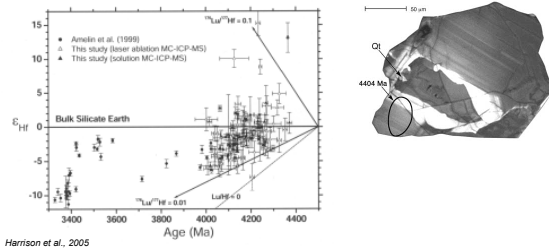
The combined decay of  $^{147}\text{Sm} \rightarrow ^{143}\text{Nd}$  and  $^{146}\text{Sm} \rightarrow ^{142}\text{Nd}$  constrains the time-frame of this event:



Only if the fractionation event occurred about 30 – 40 Ma after the start of the solar system, the Sm/Nd is within the range to produce an excess of ~20 ppm in  $^{142}\text{Nd}/^{144}\text{Nd}$  and simultaneously the  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios as observed in today's mantle derived rocks.

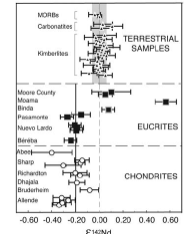
### Evidence also from $^{176}\text{Lu} \rightarrow ^{176}\text{Hf}$ !

This time frame is consistent with recently published  $^{176}\text{Hf}/^{177}\text{Hf}$  data of the zircons from Jack Hills:



### Where is the enriched reservoir?

However, all terrestrial samples measured so far have an excess in  $^{142}\text{Nd}$  (due to an elevated Sm/Nd ratio) – and thus must come from a (slightly) depleted reservoir.

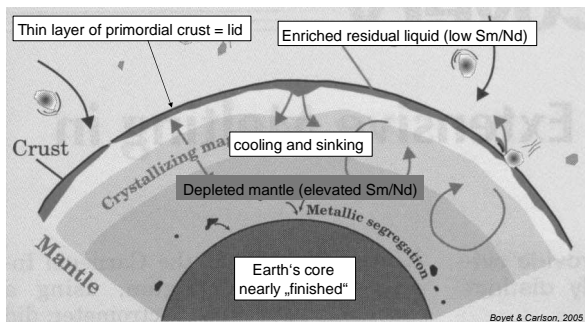


(alternatively, we may assume that the BSE was not chondritic with respect to Sm/Nd, ...)

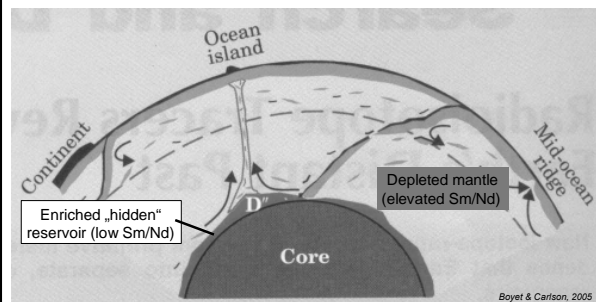
This requires, that a (complementary) reservoir with a lower Sm/Nd ratio must exist somewhere in the Earth, possibly in the deep mantle?

### Evolution of the Early Earth

A possible model of the Earth at ~4.53 Ga



### Earth today



### Conclusions I

The combination of short- and long-lived decay systems, such as  $^{182}\text{Hf} \rightarrow ^{182}\text{W}$ ,  $^{146}\text{Sm} \rightarrow ^{142}\text{Nd}$ ,  $^{147}\text{Sm} \rightarrow ^{143}\text{Nd}$  and  $^{176}\text{Lu} \rightarrow ^{176}\text{Hf}$  place important constraints on the evolutionary history of the Earth short after its formation.

Applications indicate, that ....

### Conclusions II

... the Earth's core was generated within the first 30 Ma after the start of our solar system, likely simultaneously to Earth accretion.

Within the same period of time, the silicate portion of the Earth differentiated to form the first enriched and depleted reservoirs and likely to generate the first fragments of „continental crust“, from which remnants are preserved until today within single zircon grains.