From the early solar system to Earth's interior: new clues from new isotope tools

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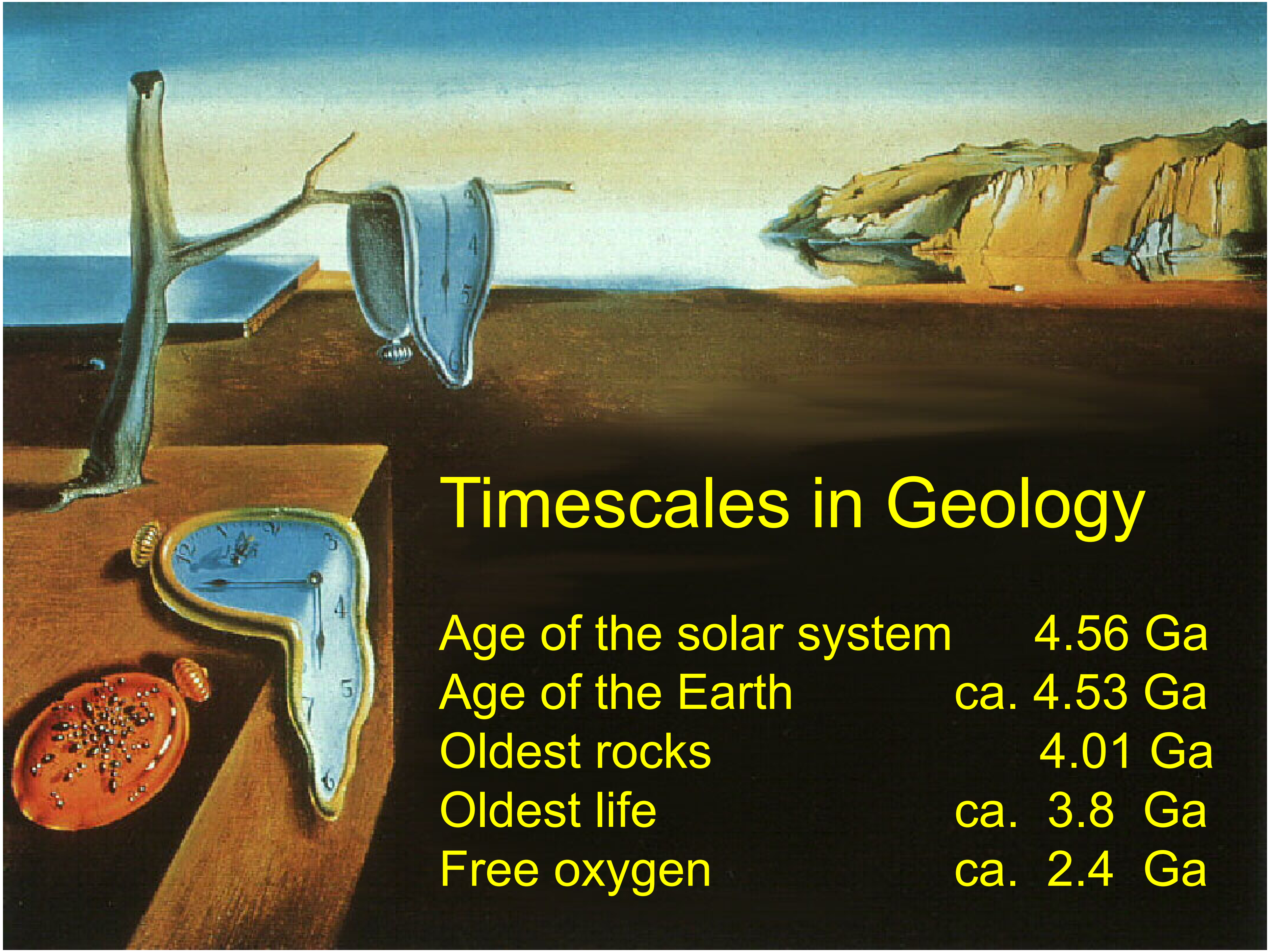
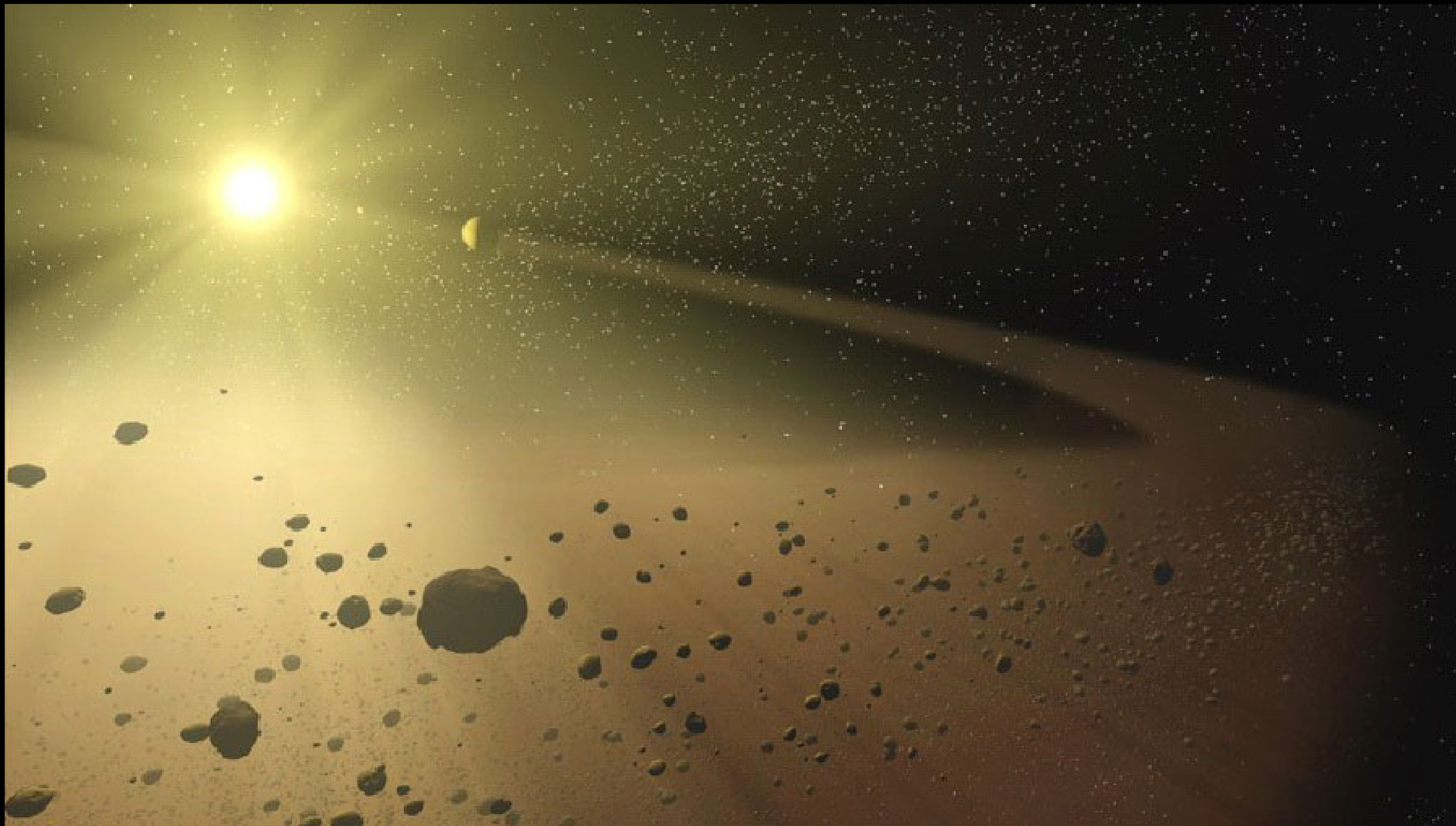
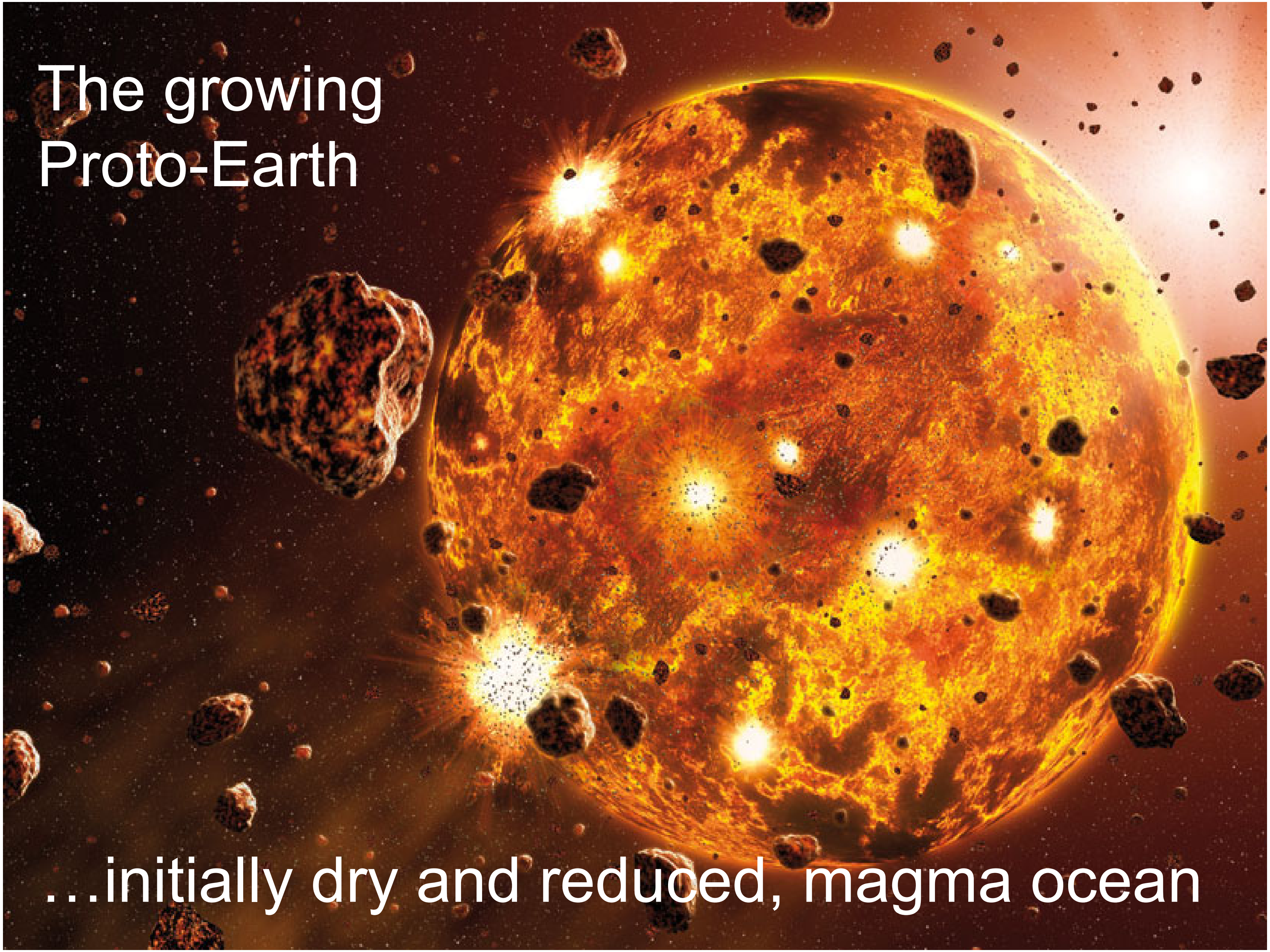
SPP1833
Building a Habitable Earth

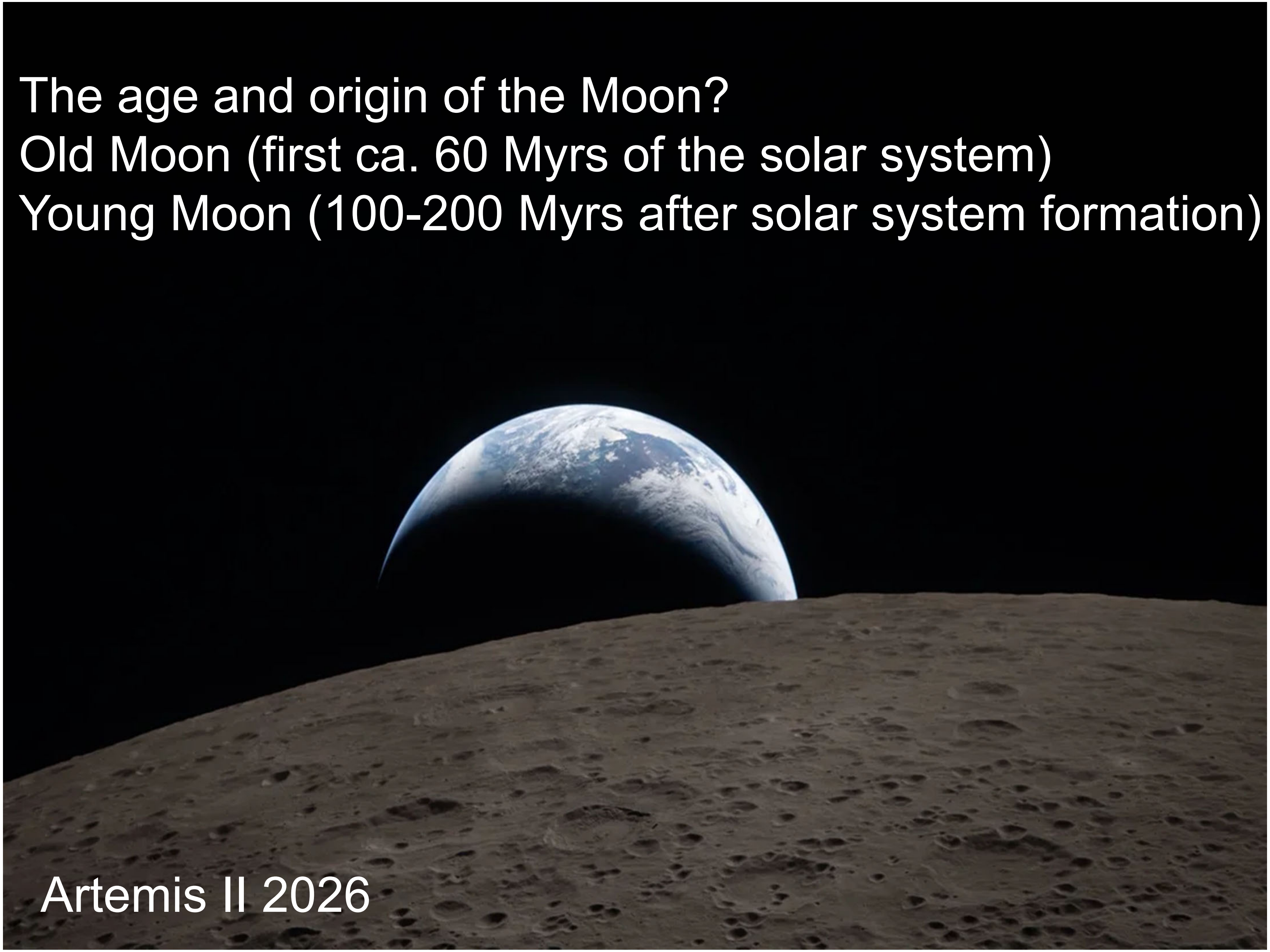

Timescales in Geology
Age of the solar system 4.56 Ga
Age of the Earth ca. 4.53 Ga
Oldest rocks 4.01 Ga
Oldest life ca. 3.8 Ga
Free oxygen ca. 2.4 Ga

Larger planets formed via collisions of different asteroid types

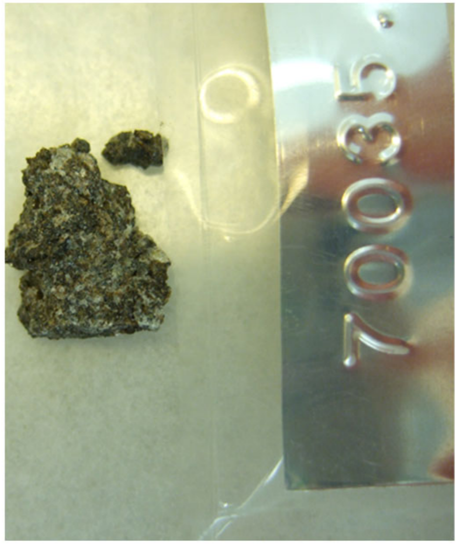



The growing
Proto-Earth
…initially dry and reduced, magma ocean

The most important collisional event:
Formation of the Moon – Magma Ocean – Core Formation


The age and origin of the Moon?
Old Moon (first ca. 60 Myrs of the solar system)
Young Moon (100-200 Myrs after solar system formation)
Artemis II 2026

Ongoing research: lunar samples

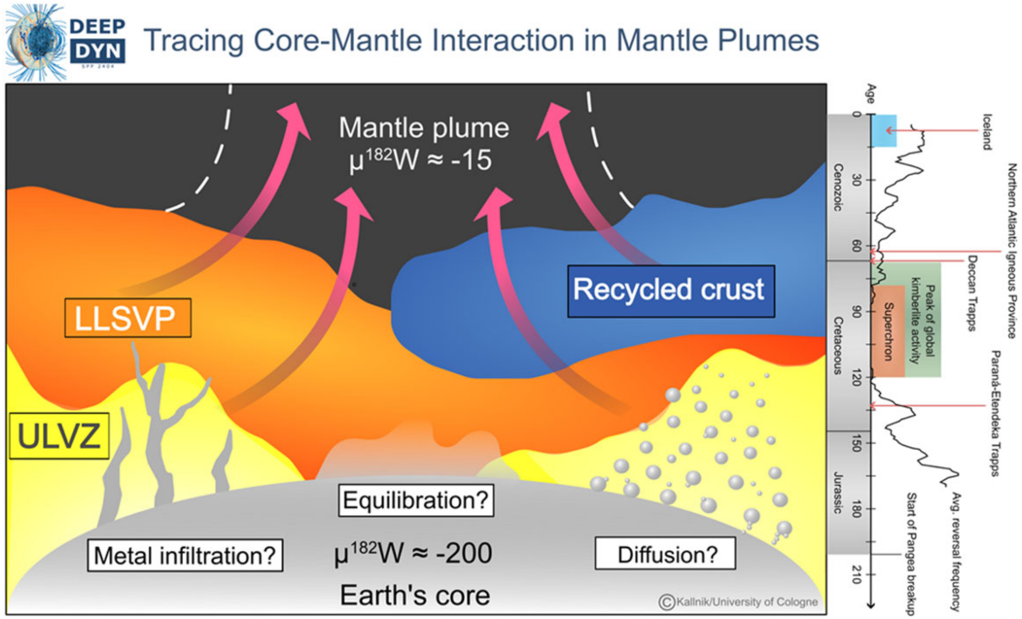


Apollo(NASA)

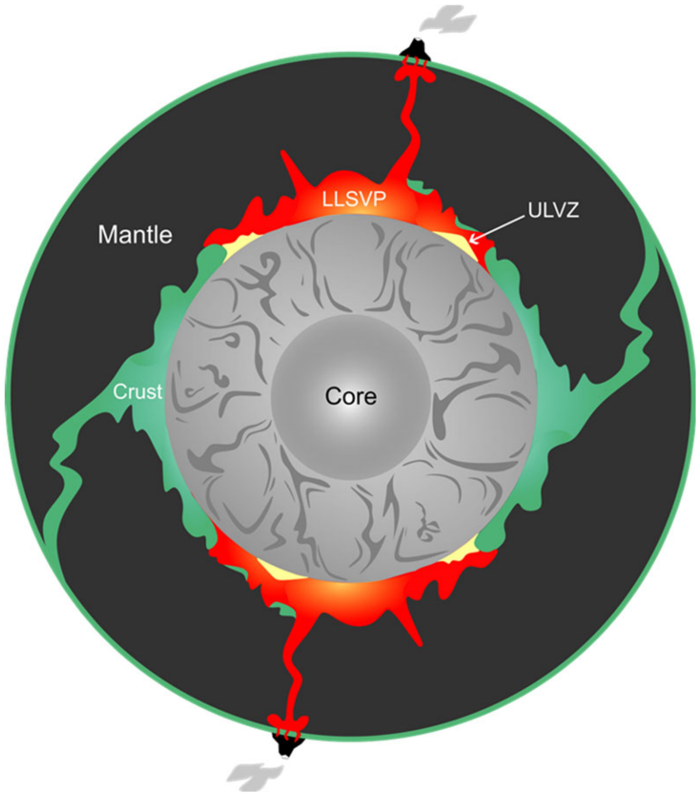
Chang'e 5 (CNSA)

- 2 g lunar soil
- 1/3 groups in Europe
- 1/7 groups outside China

Ongoing research: geodynamics

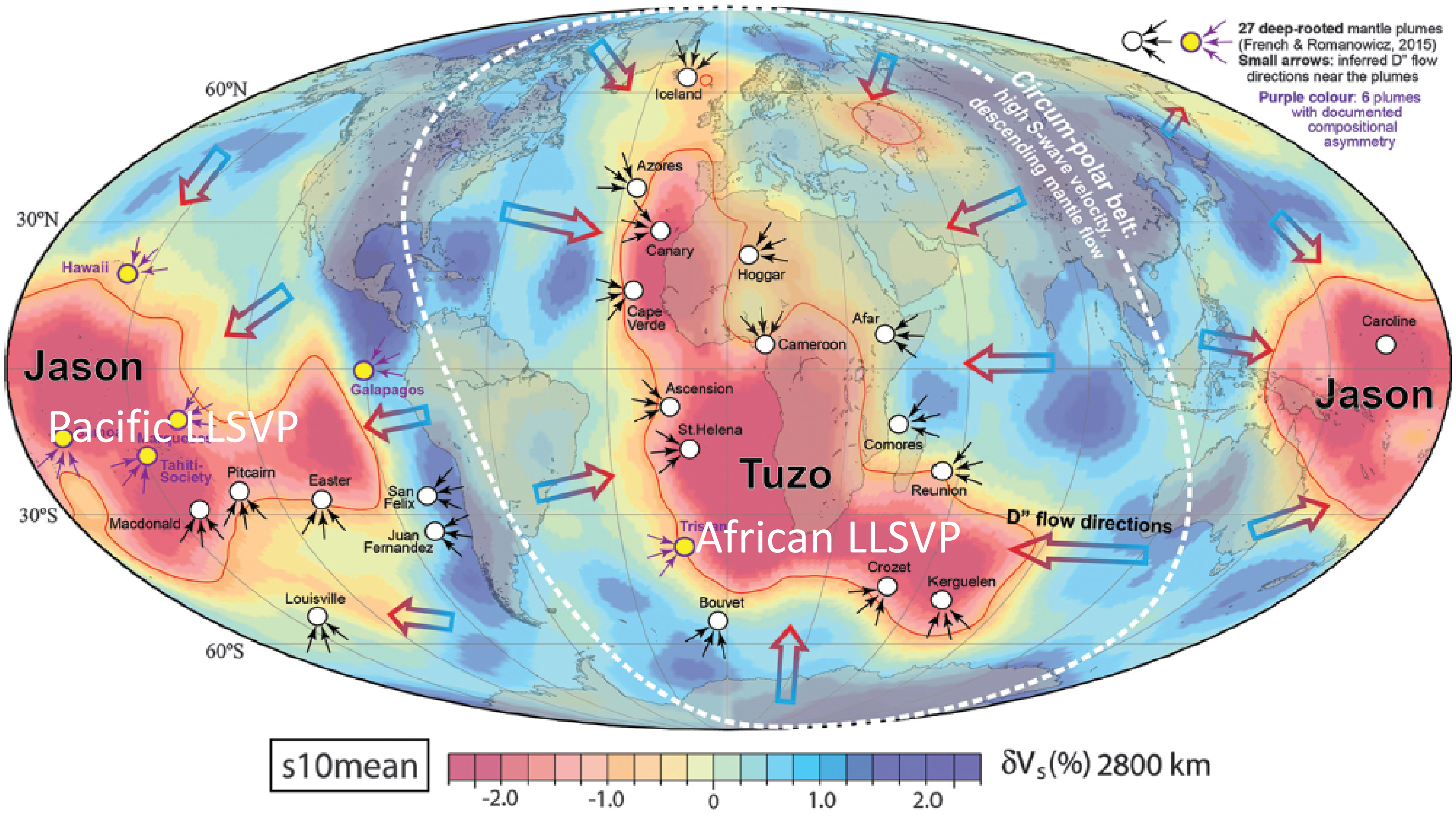


Credit: N. Kallnik



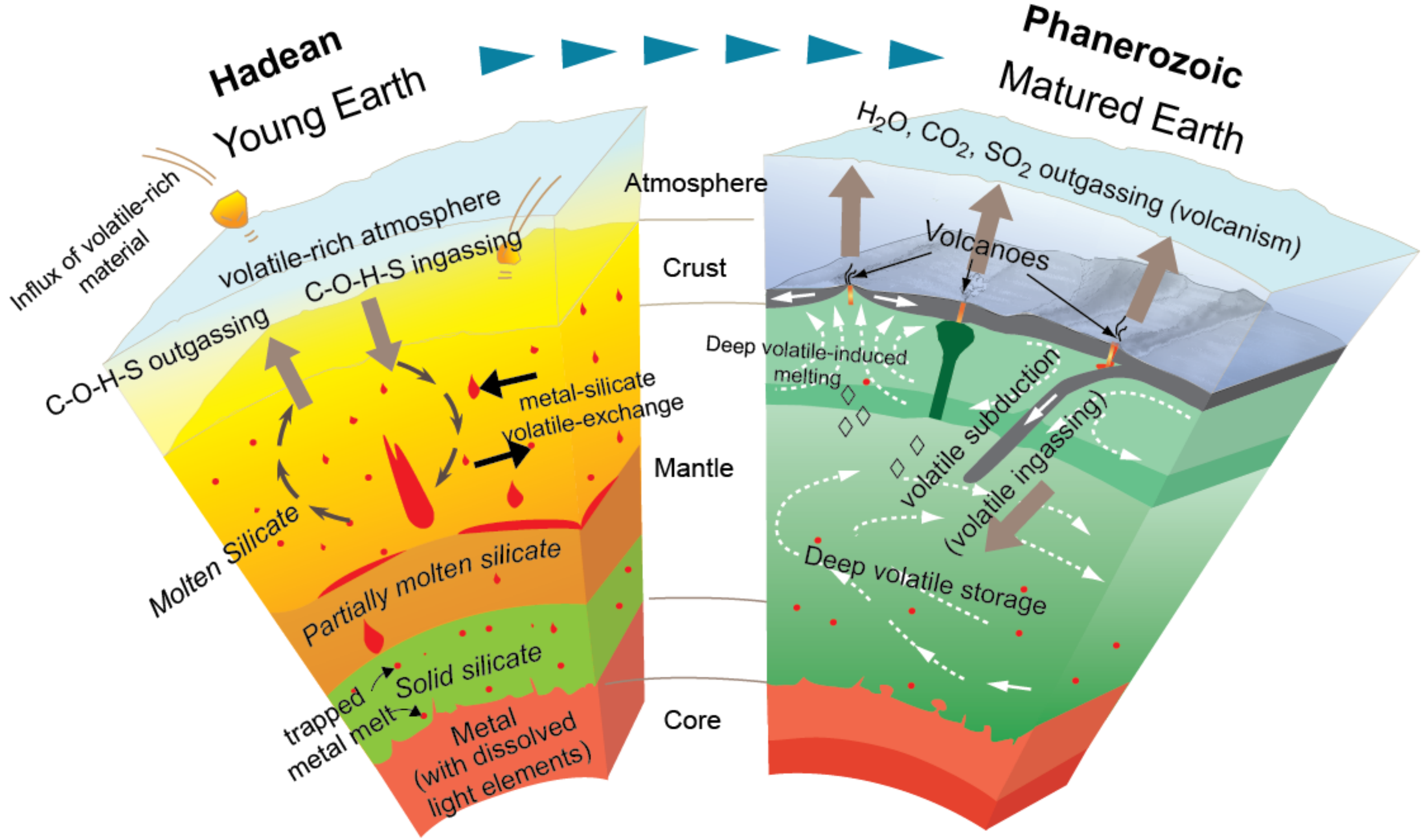
How well is the mantle mixed ?

LLSVPs in the deep mantle vestiges of Archean silicate reservoirs?



Torsvik et al. 2016 after French & Romanowicz 2015

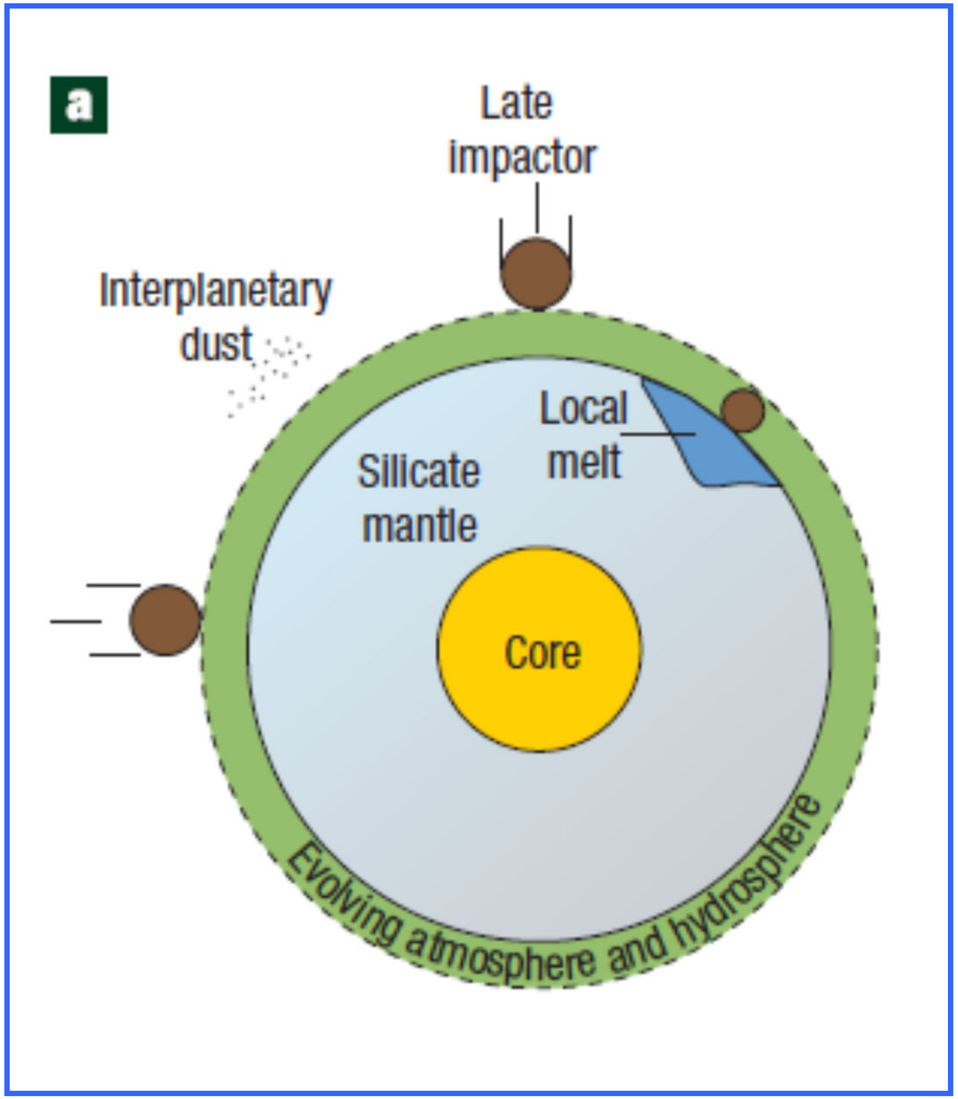
Non-uniformitarian evolution of Earth‘s mantle



From magma ocean to stagnant lid regime to plate tectonics

Meteorite bombardment strongly affected Earth‘s early surface and composition…

The „Late Veneer“
ca. 1-3 % of Earth‘s mass were added later



from Marty, 2008

The Hadean Eon (4.56 – 4.0 Ga)
Changing views of Earth's first 500 myrs

1952

2006

Looking back: the isotope toolbox ….

Cologne isotope facility (est. 2017)

Stable vs. long lived radiogenic isotopes

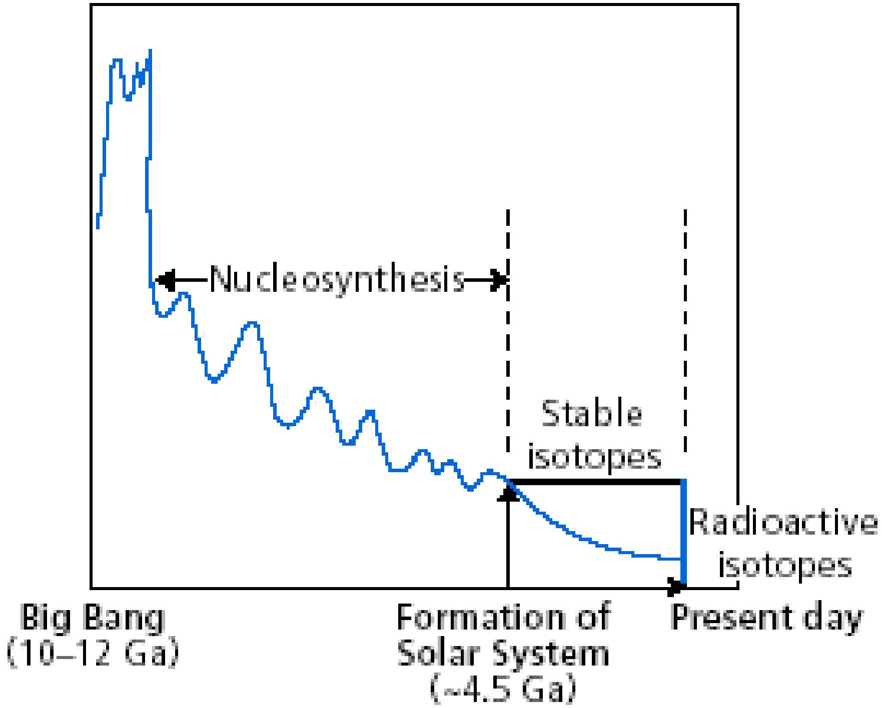
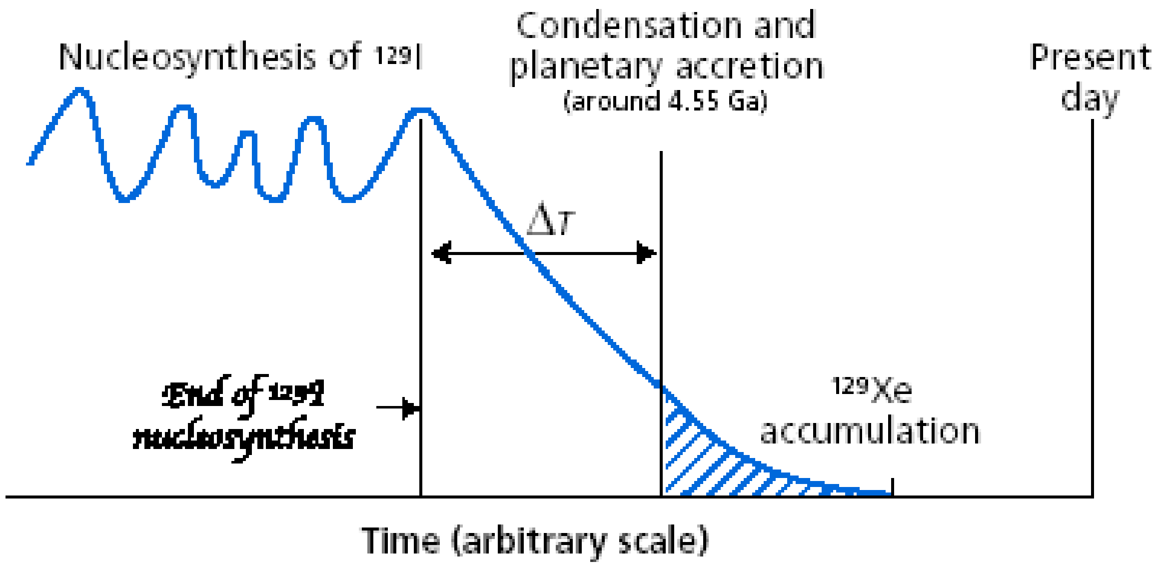


Figure 5.33 Nucleosynthesis of elements forming the Solar System before 4.5 Ga. Isotopes are synthesized (and destroyed) in stars. From 4.5 Ga, stable isotopes maintain the same abundance ratios and radioactive isotopes decay.

Extinct (short lived radiogenic isotopes)
Example: $^{129}I - ^{129}Xe$



Popular long-lived decay systems in geology

^{147}Sm-^{143}Nd (106 Ga)

^{176}Lu-^{176}Hf (37.2 Ga)

^{87}Rb-^{87}Sr (48.8 Ga)

^{238}U-^{206}Pb (4.47 Ga)

^{235}U-^{207}Pb (0.7 Ga)

Short-lived decay systems in geology and their use

lithophile - siderophile

^{182}Hf-^{182}W (9 Ma)

^{107}Pd-^{107}Ag (6.5 Ma)

- Core formation
- In-mixing of late veneer

lithophile - lithophile

^{26}Al - ^{26}Mg (0.7 Ma)

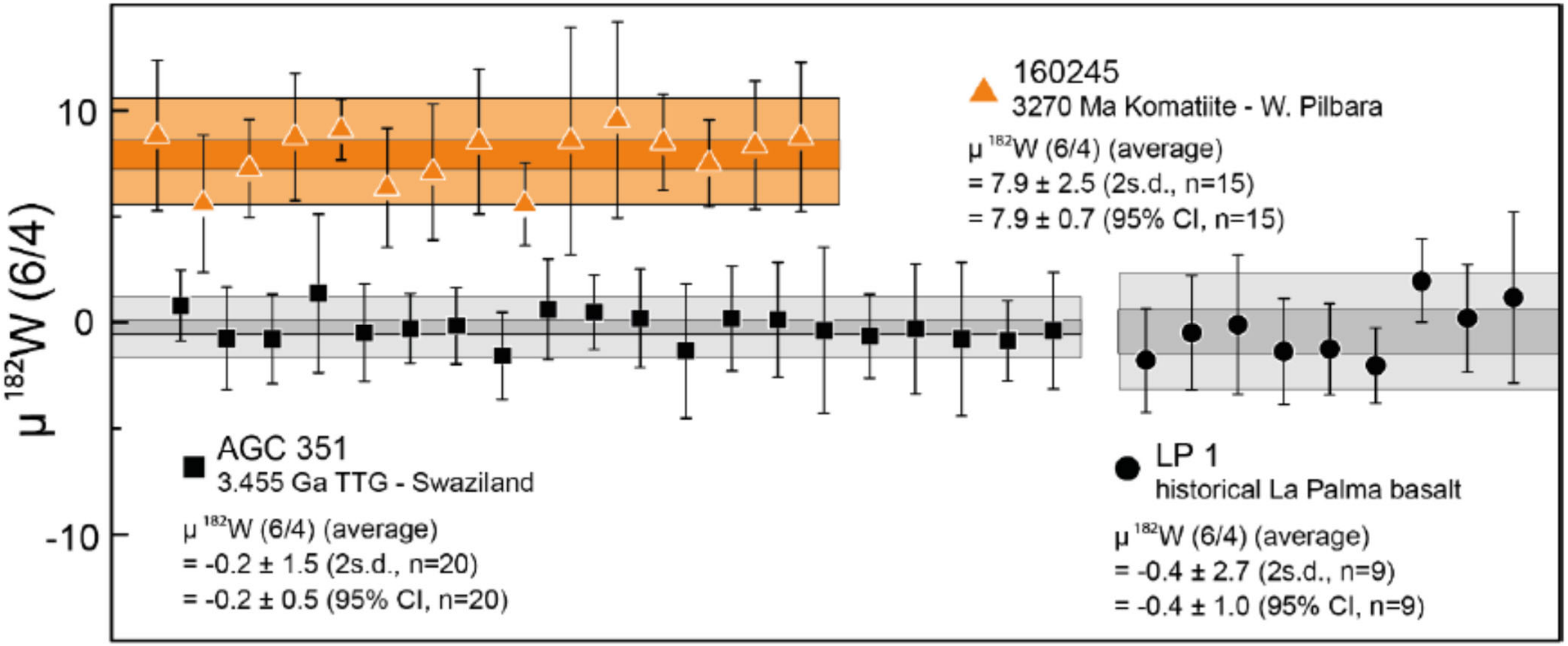
^{53}Mn - ^{53}Cr (3.7 Ma)

^{146}Sm-^{142}Nd (103 Ma)

^{92}Nb – ^{92}Zr (36 Ma)

- Early silicate differentiation

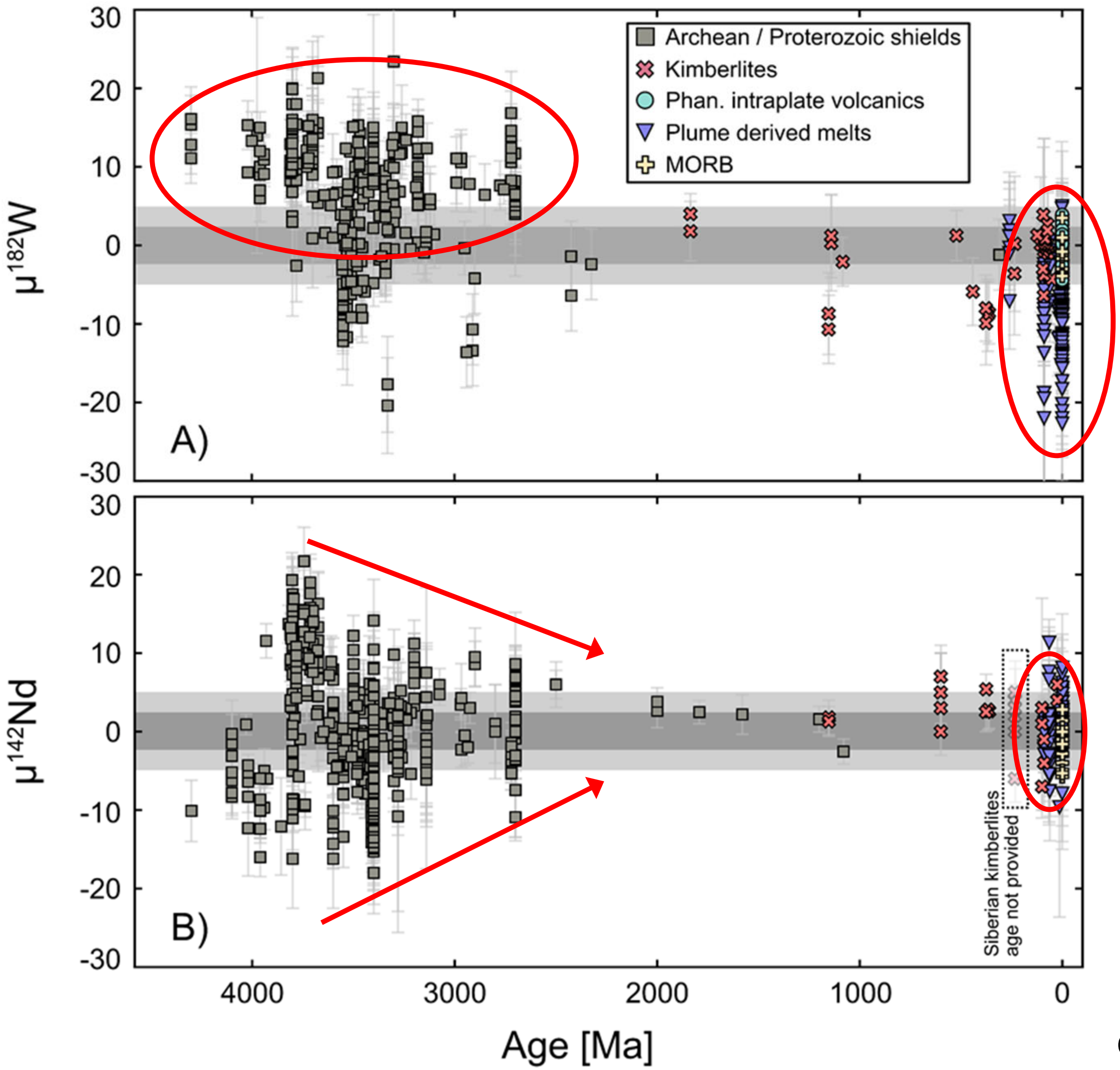
Precision & accuracy matter (!!): ^{182}W isotope measurements by MC-ICPMS at Cologne



$100\mu = 1\varepsilon$

- More than ten-fold improvement in precision (±0.02 ε units c.i.)!

^{182}W and ^{142}Nd through geologic time

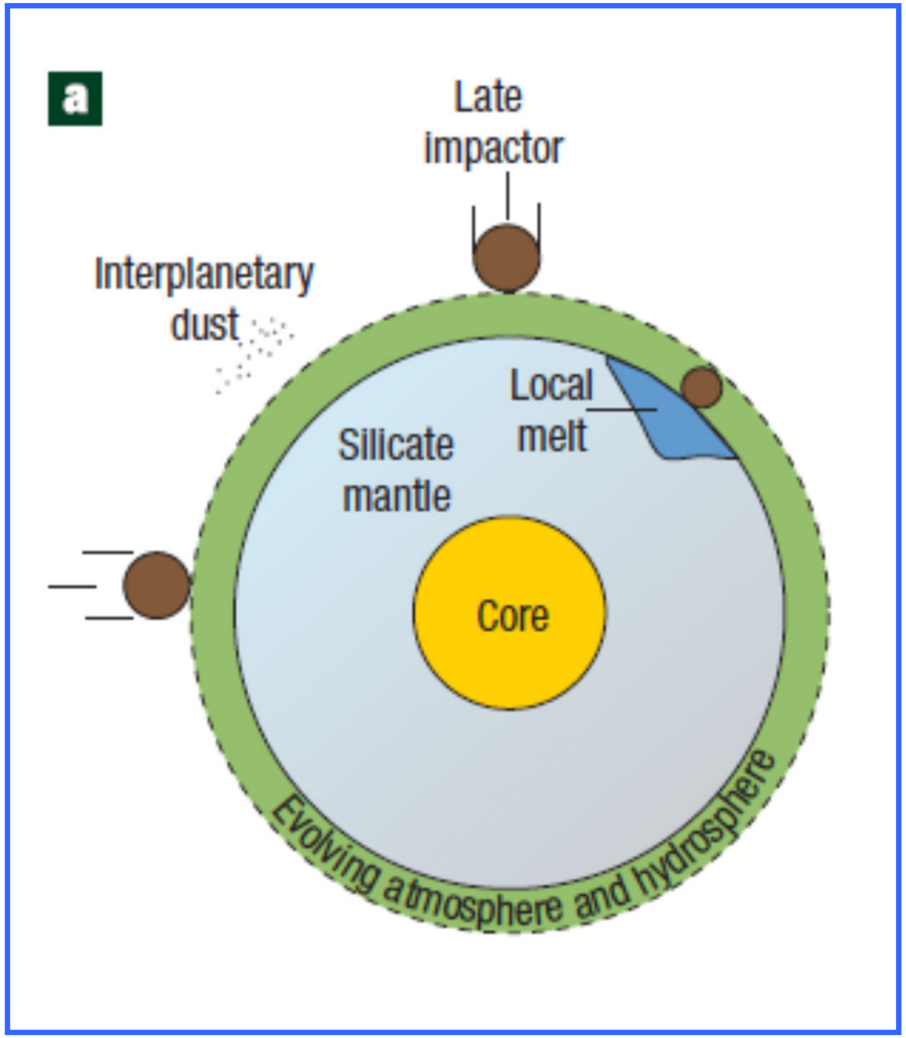


- positive ^{182}W in Archean rocks (mostly)
- negative ^{182}W in young OIBS

- positive ^{142}Nd in Archean rocks
- negative ^{142}Nd in Archean rocks
- only small ^{142}Nd variations in young OIBS

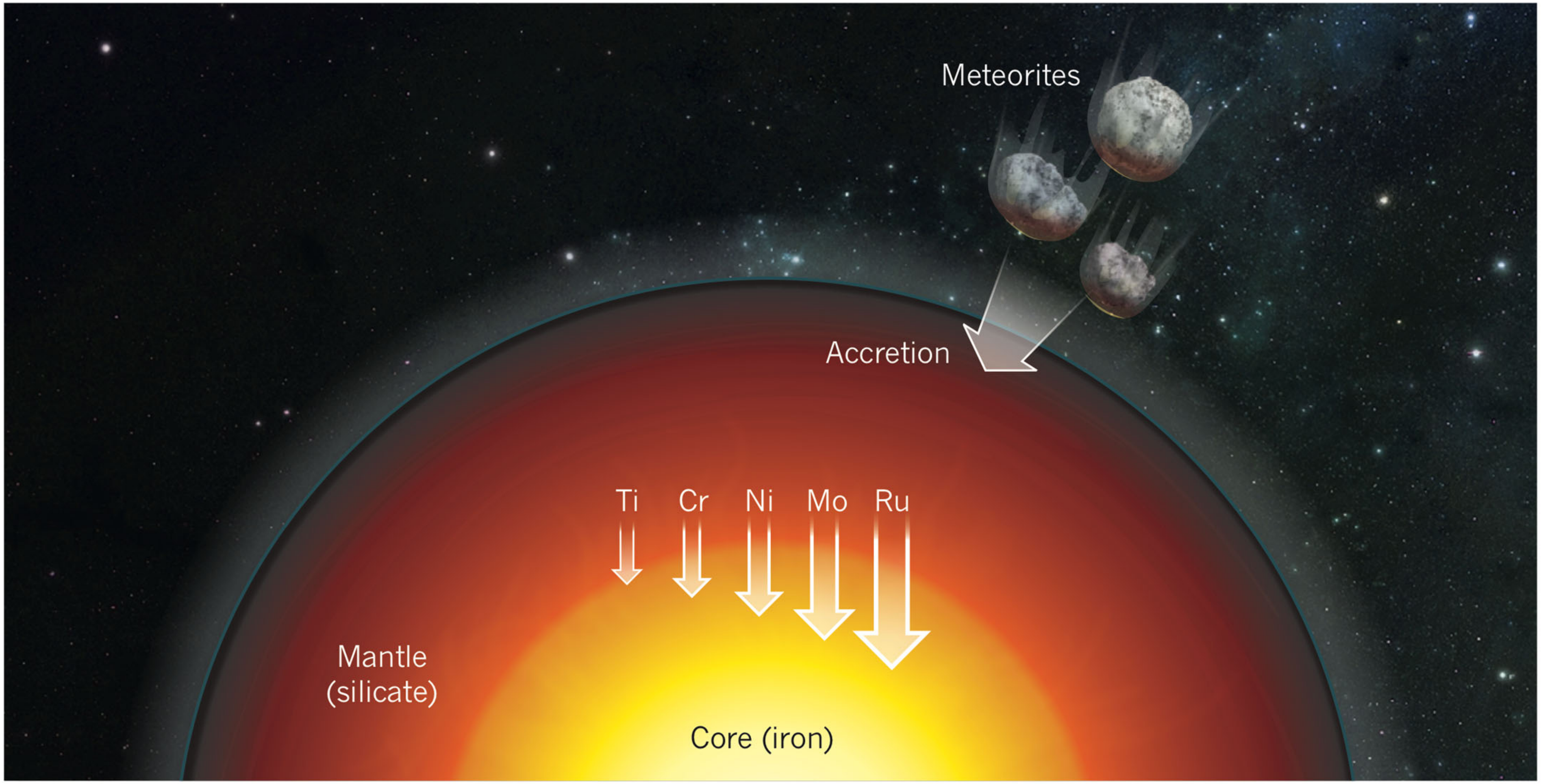
compilation Pakulla, 2026

Back to the „Late Veneer“
Ca. 1-3 % of Earth‘s mass added after core formation



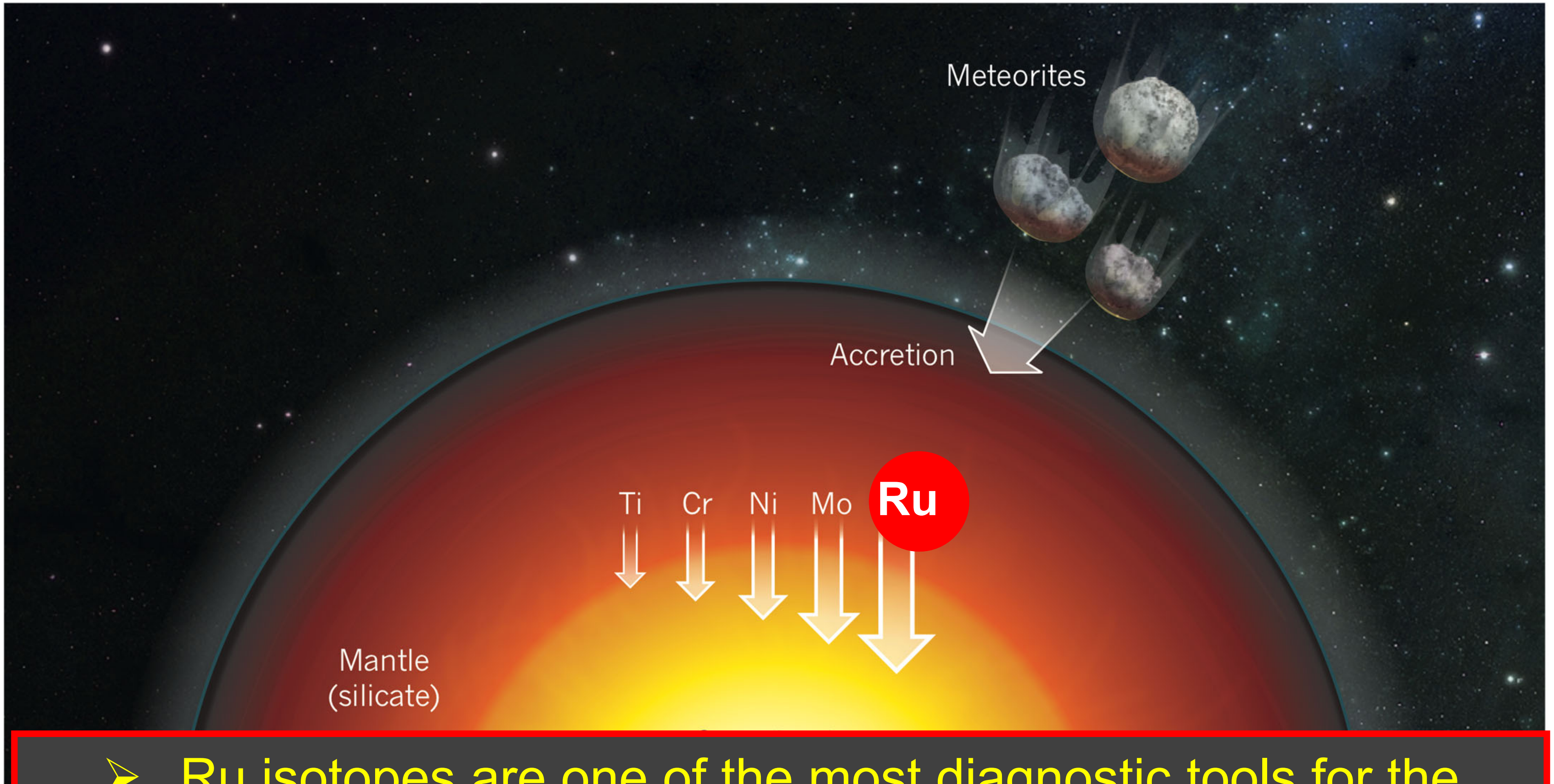
From Marty, 2008

Isotope Tool: Highly siderophile elements



Carlson (2017)

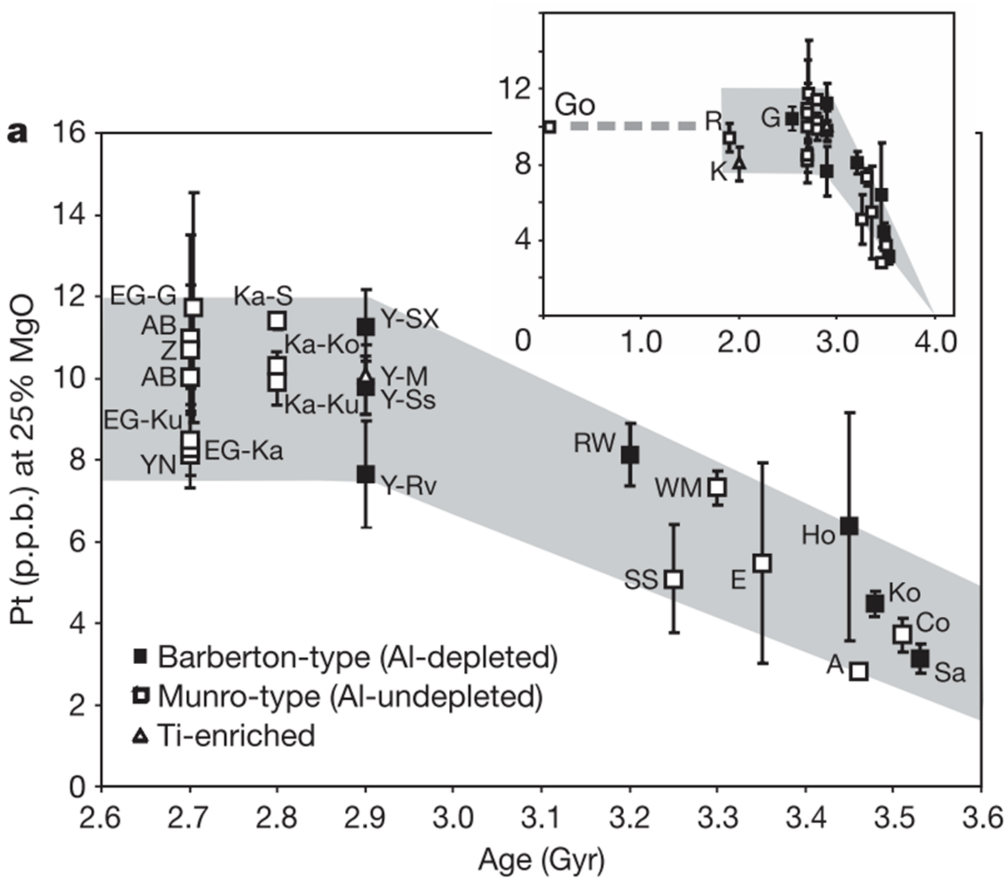
Isotope Tool: Highly siderophile elements



- Ru isotopes are one of the most diagnostic tools for the composition and mixing timescales of the late veneer

Late veneer origin of highly siderophile elements (HSE)

Decreasing PGE depletions suggest progressive in-mixing of late veneer

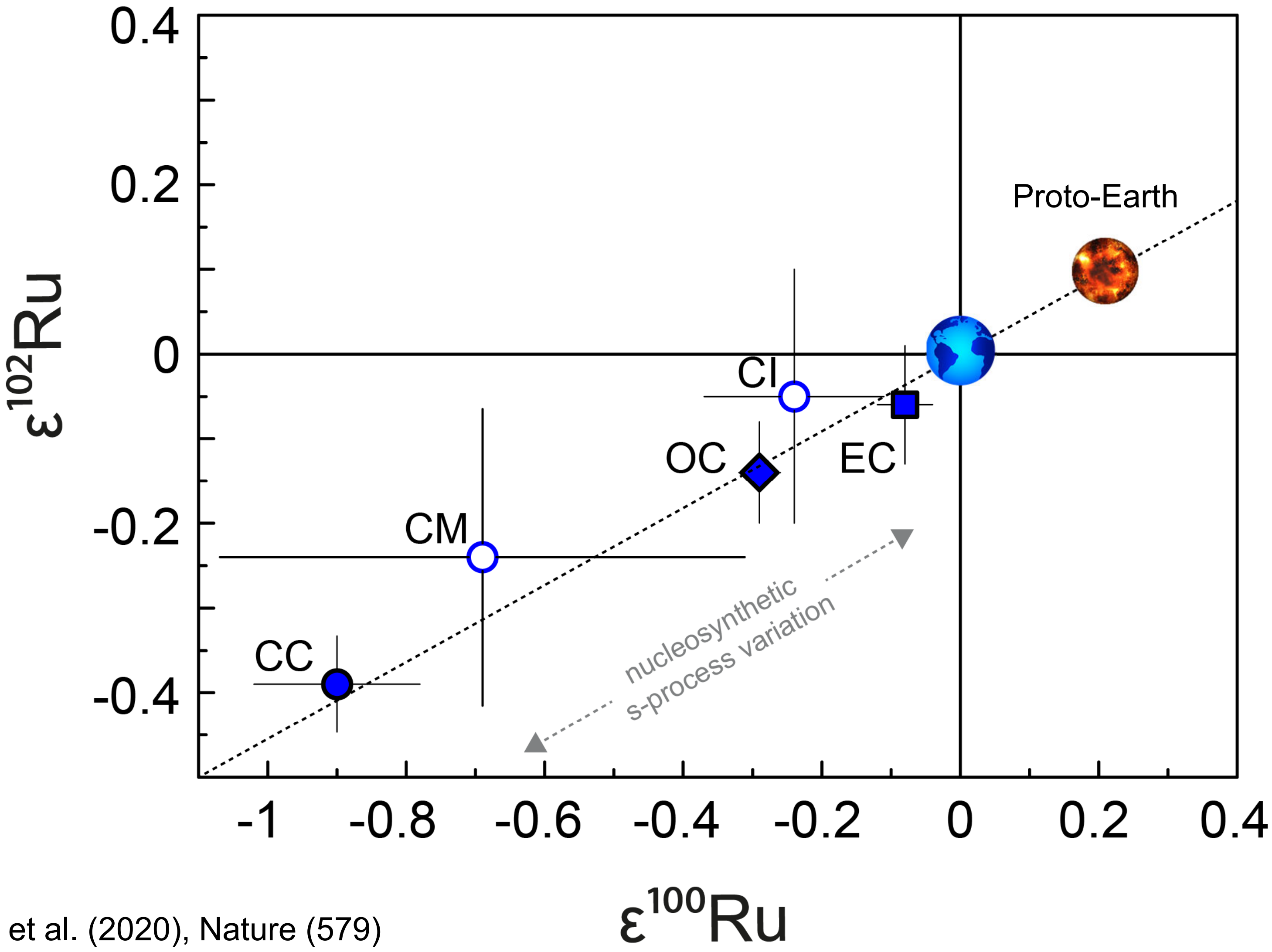


Maier et al. (2009) Nature (460)

Ru isotopes – a much more sensitive tool

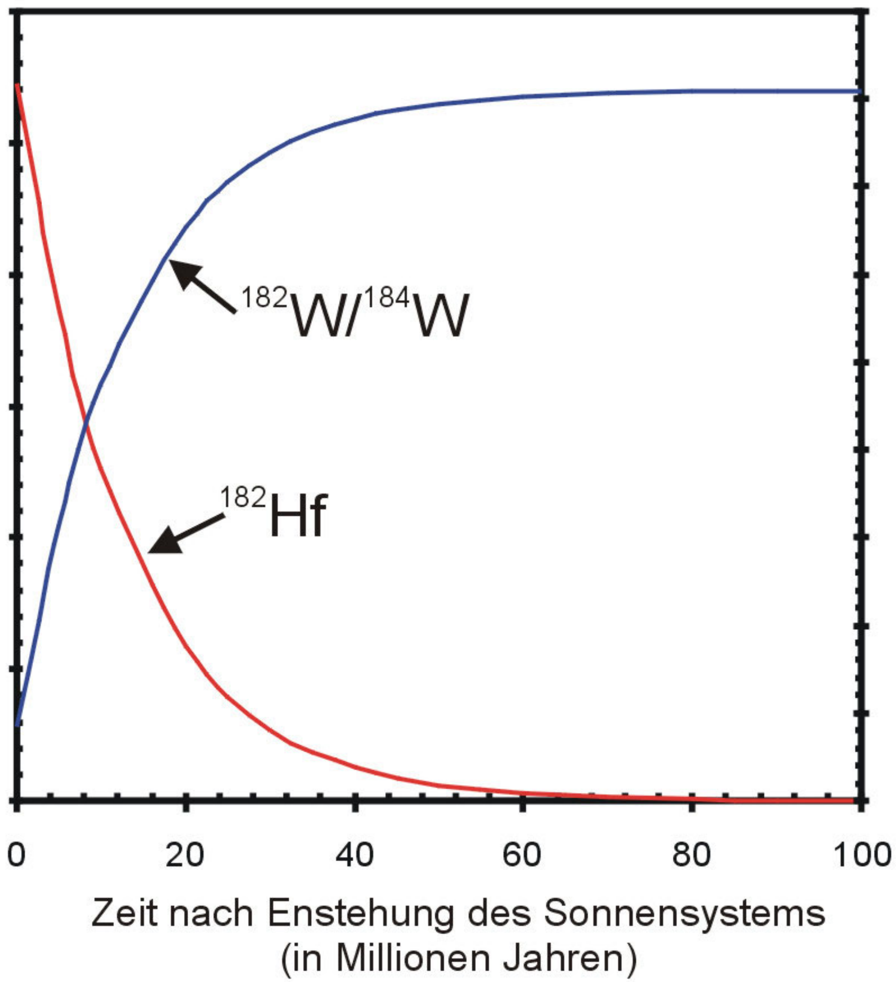
Fischer-Gödde et al. (2020), Nature (579)

Chondrites all have a nucleosynthetic deficit in s-process Ru relative to Earth

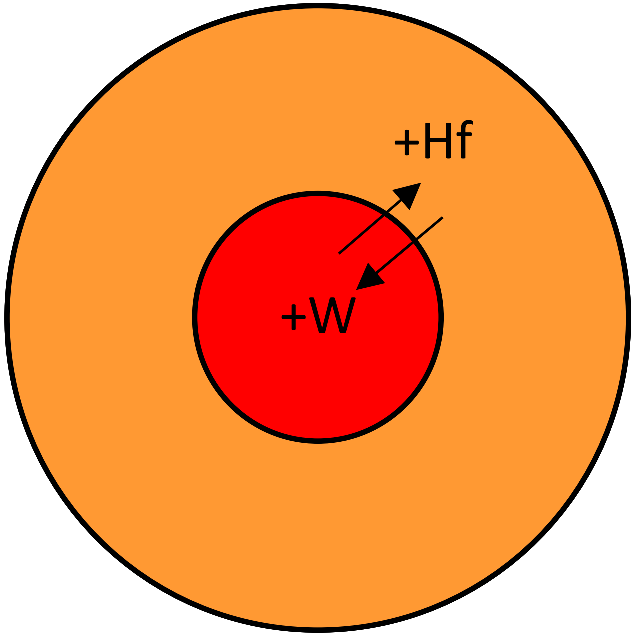


After Fischer-Gödde et al. (2020), Nature (579)

Isotope tool: The extinct ^{182}Hf-^{182}W-system

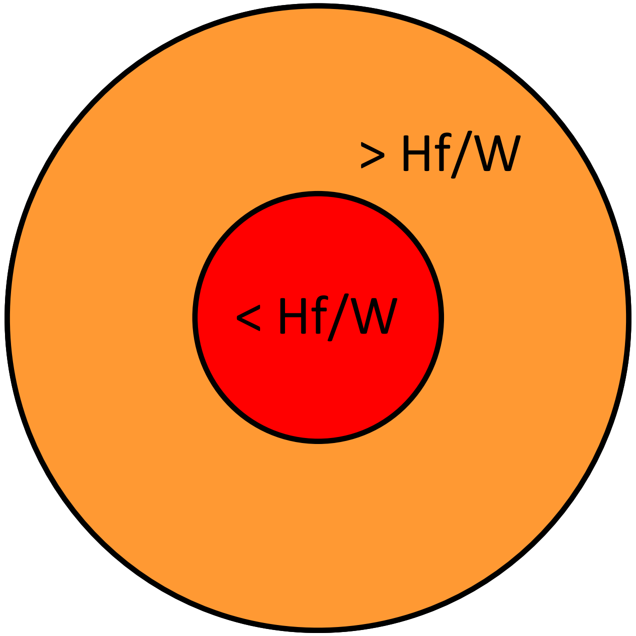


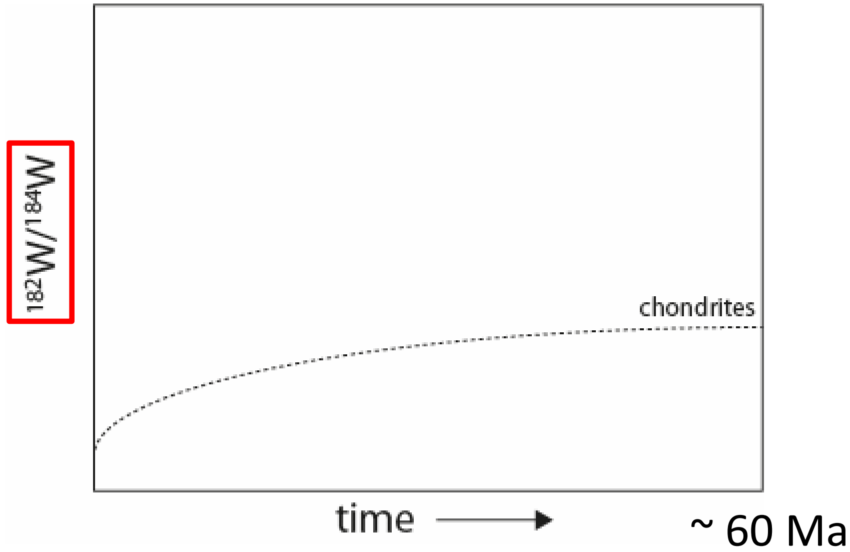
- The ^{182}Hf - ^{182}W system only records geological events < 60 Myrs !



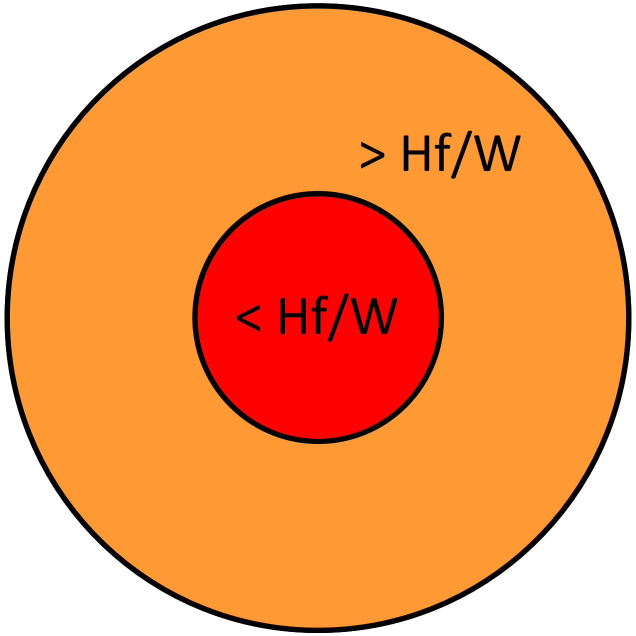
+Hf
+W

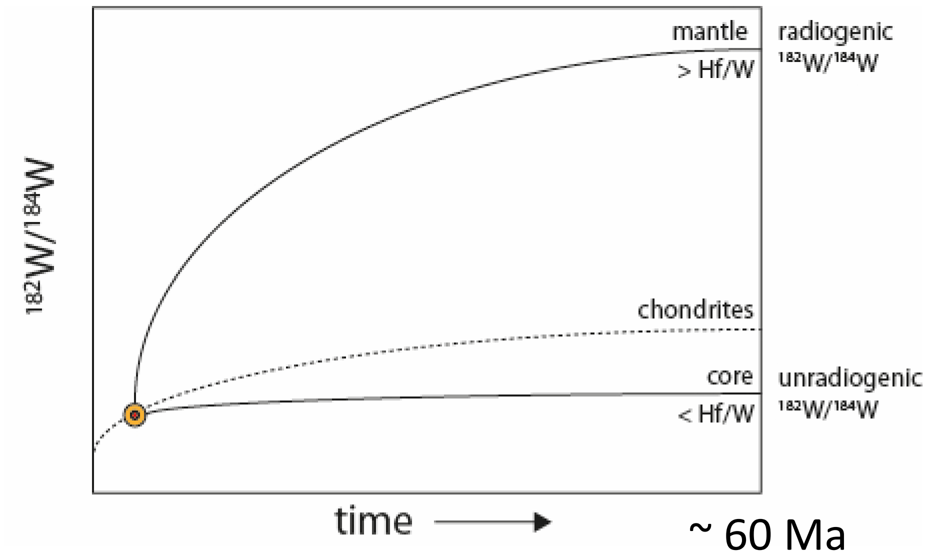
$^{182}Hf \rightarrow {}^{182}W + \beta^-$ $t_{1/2} = 8.9$ Ma



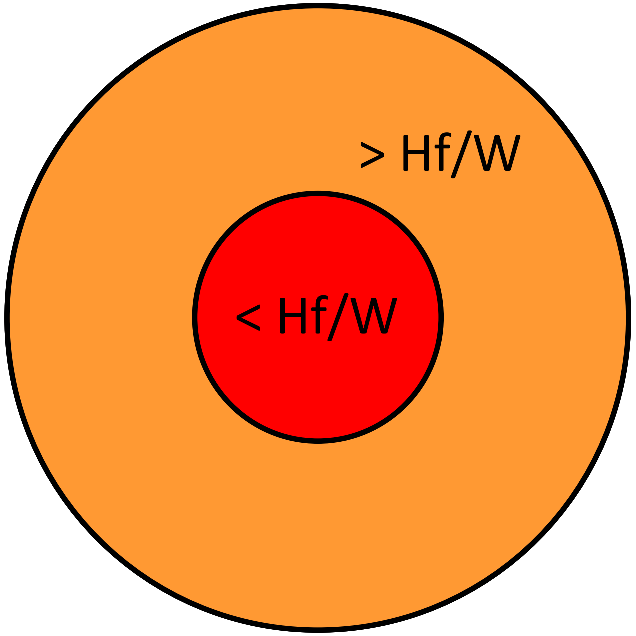


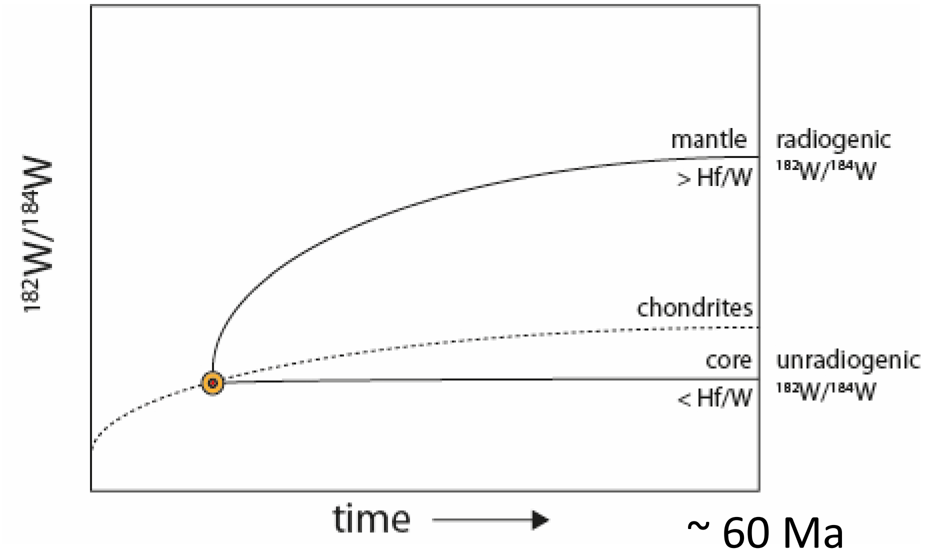
$^{182}Hf \rightarrow {}^{182}W + \beta^{-}$ $\quad t_{1/2} = 8.9$ Ma



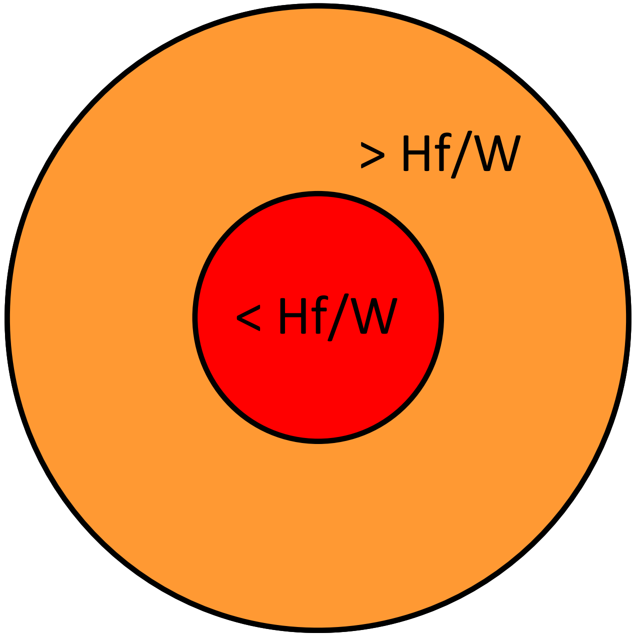


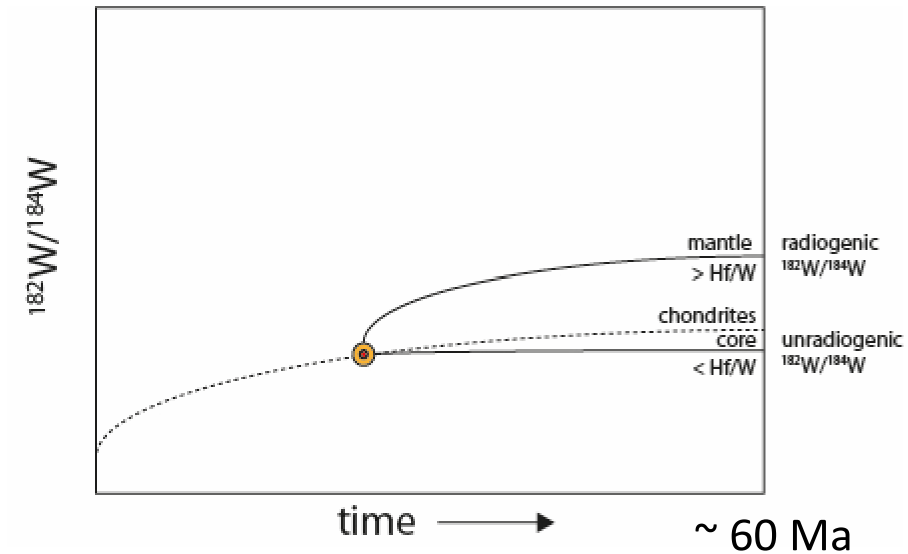
$^{182}Hf \rightarrow {}^{182}W + \beta^-$ $t_{1/2} = 8.9$ Ma



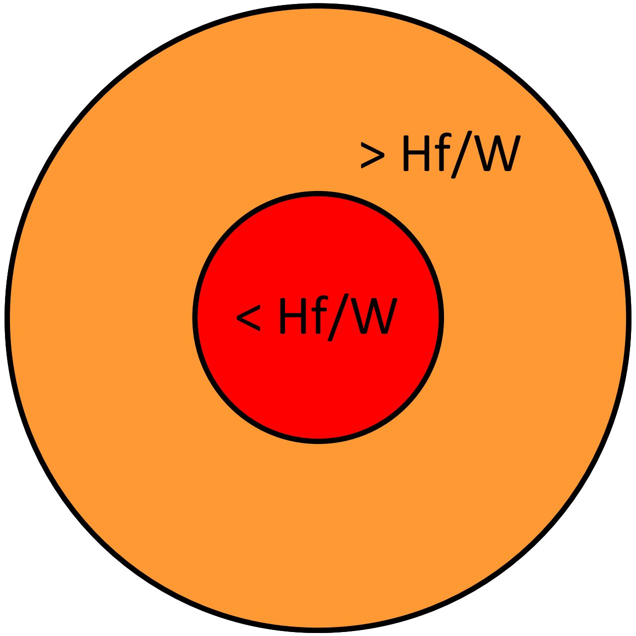


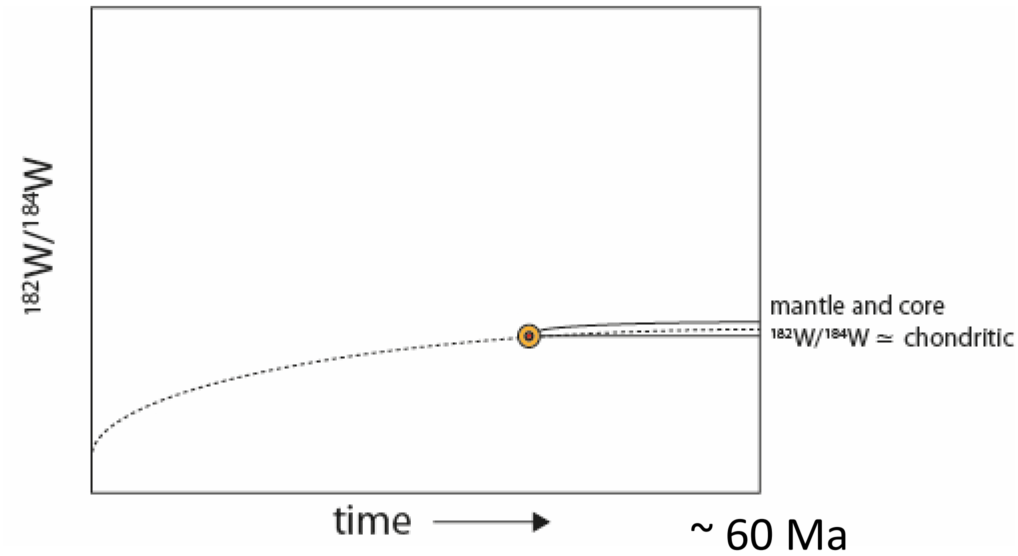
$^{182}Hf \rightarrow {}^{182}W + \beta^-$ $\quad t_{1/2} = 8.9$ Ma



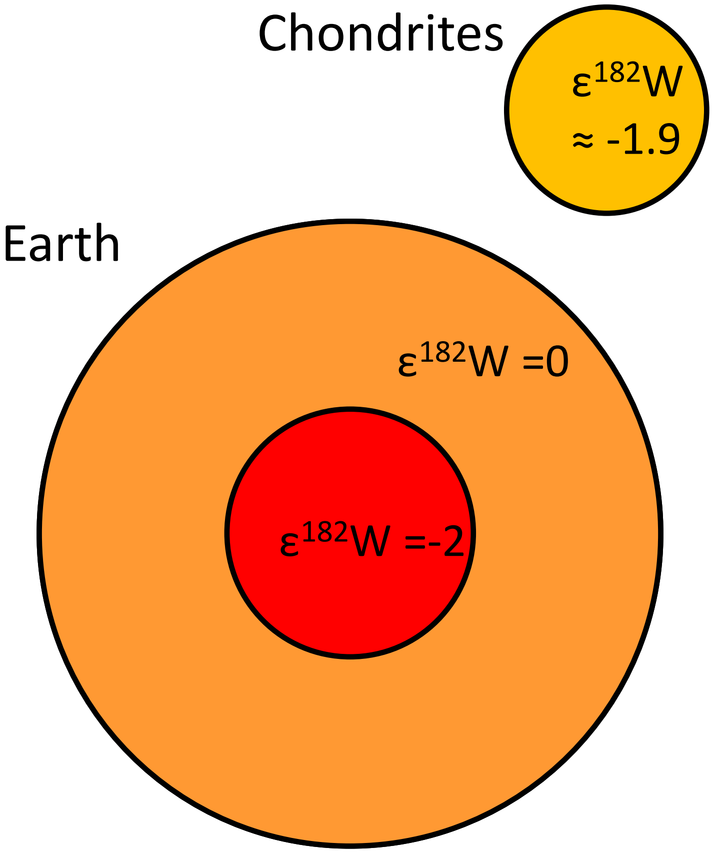


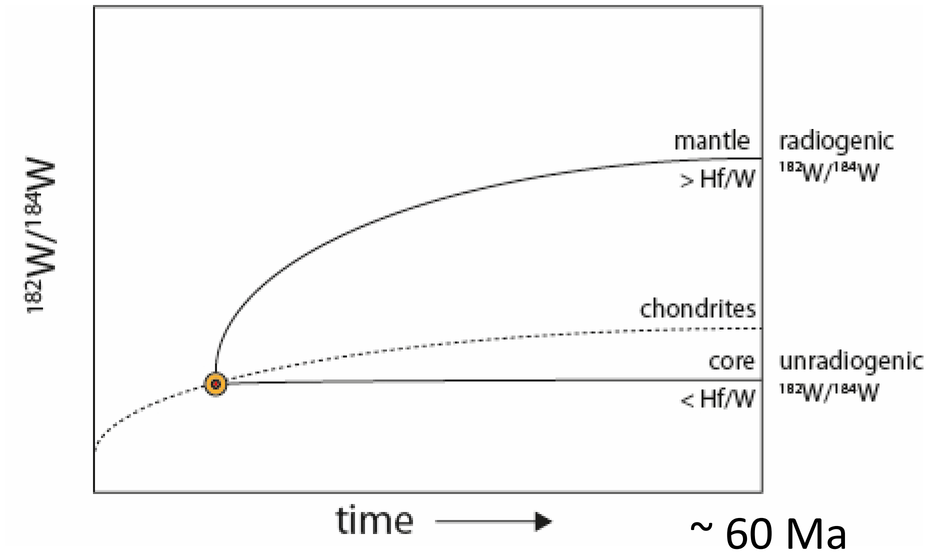
$^{182}Hf \rightarrow {}^{182}W + \beta^-$ $t_{1/2} = 8.9$ Ma





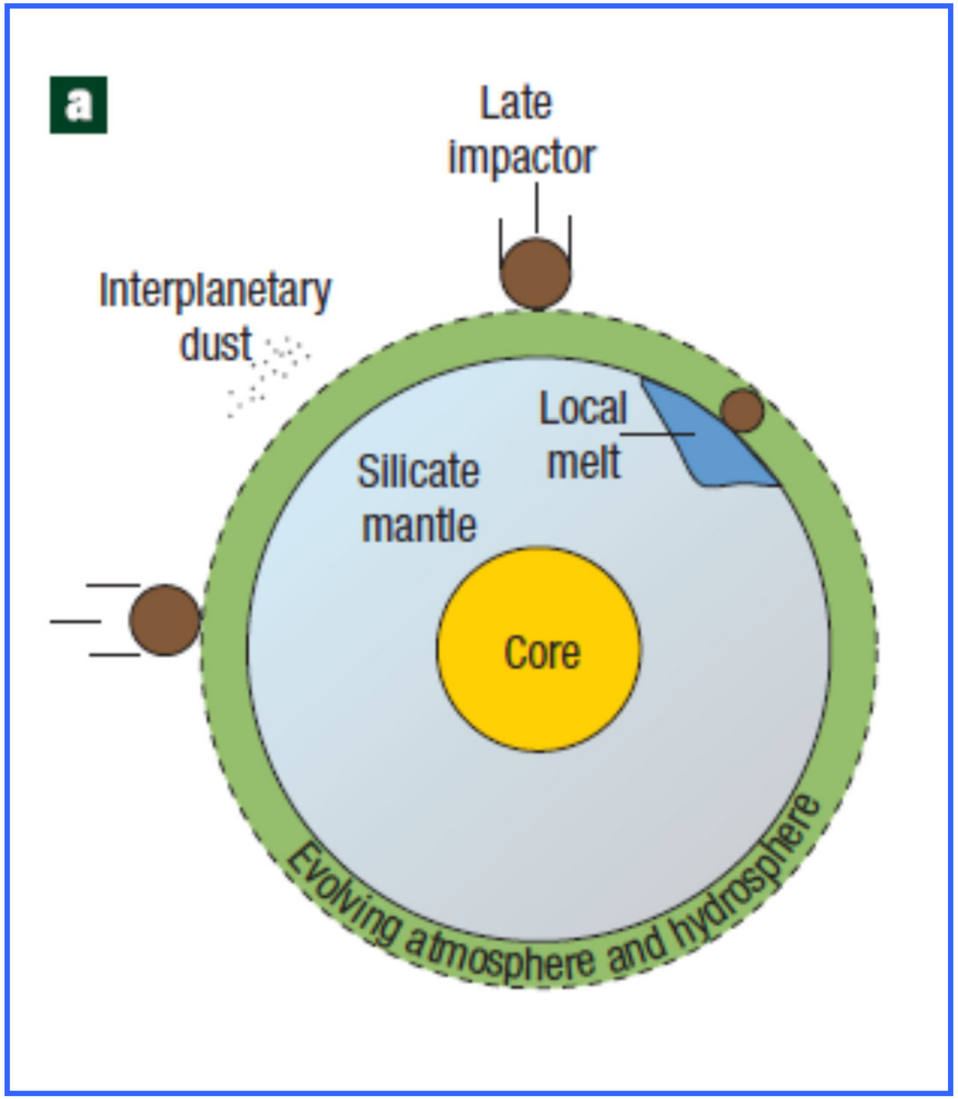
$$\varepsilon^{182}W = \left[\left(\frac{^{182}W}{^{184}W} \right)_{res} \div \left(\frac{^{182}W}{^{184}W} \right)_{terr} - 1 \right] \times 10000$$





- Earth‘s mantle has high $\varepsilon^{182}W$ due to its high Hf/W ratio !!
- Early depleted reservoirs have ^{182}W excess, enriched reservoirs deficit

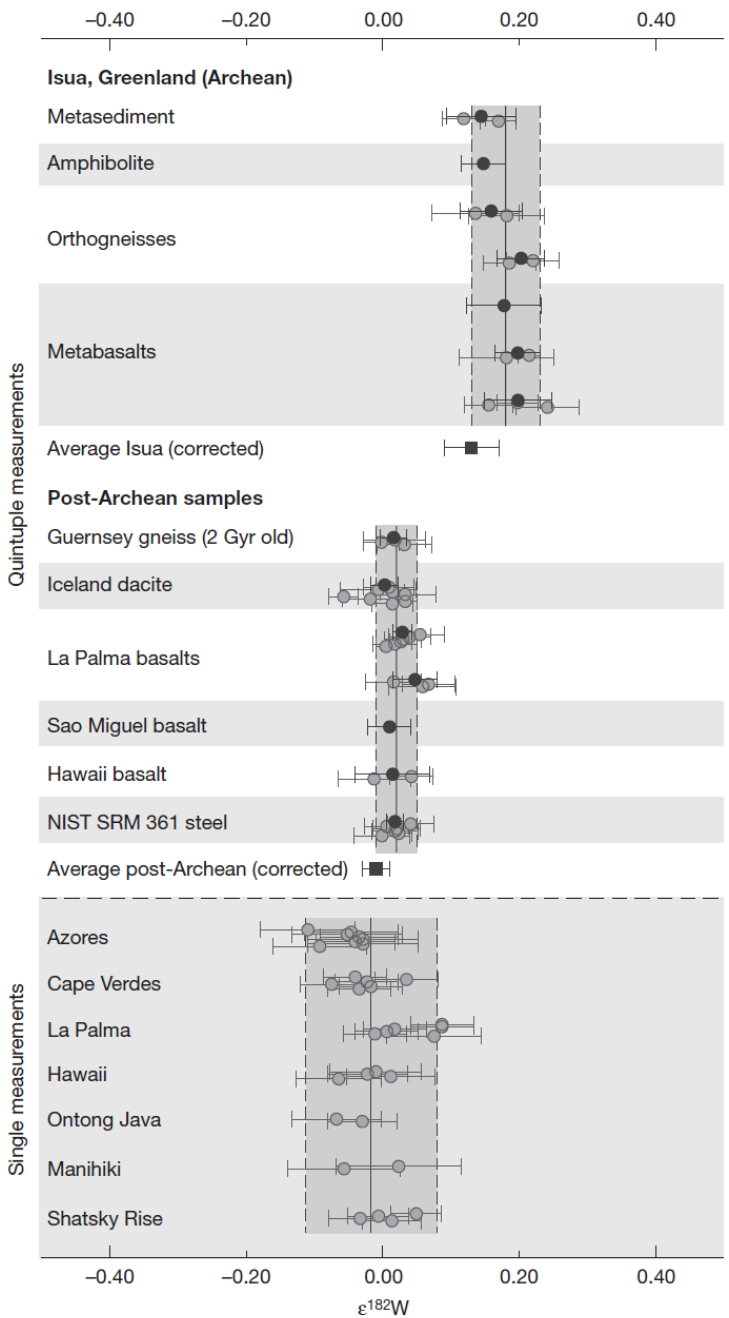
The „Late Veneer“ - ca. 1-3 % of Earth‘s mass were added after core formation



Chondrites have $\varepsilon^{182}W$ of ca. -2!
Proto-Earth + Chondrite = $\varepsilon^{182}W$ of 0

Proto-Earth had a ε182W of +0.2!

from Marty, 2008



Historical: First reported ^{182}W anomalies in Archean rocks from Isua

(Willbold et al. 2011, Nature)

Lunar ^{182}W: less late veneer or old Moon ??

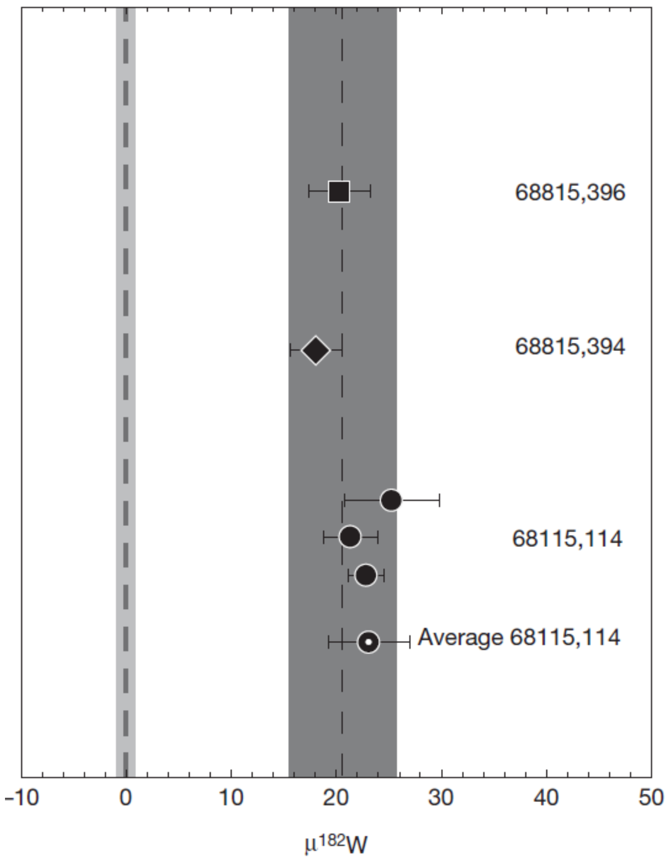


Figure 1 | Values of μ^{182}W of lunar metals separated from KREEP-rich impact melts analysed by negative thermal ionization mass spectrometry in this study. The data for 68115,114, 68815,394, and 68815,396 are shown as

Touboul et al. 2015 Nature

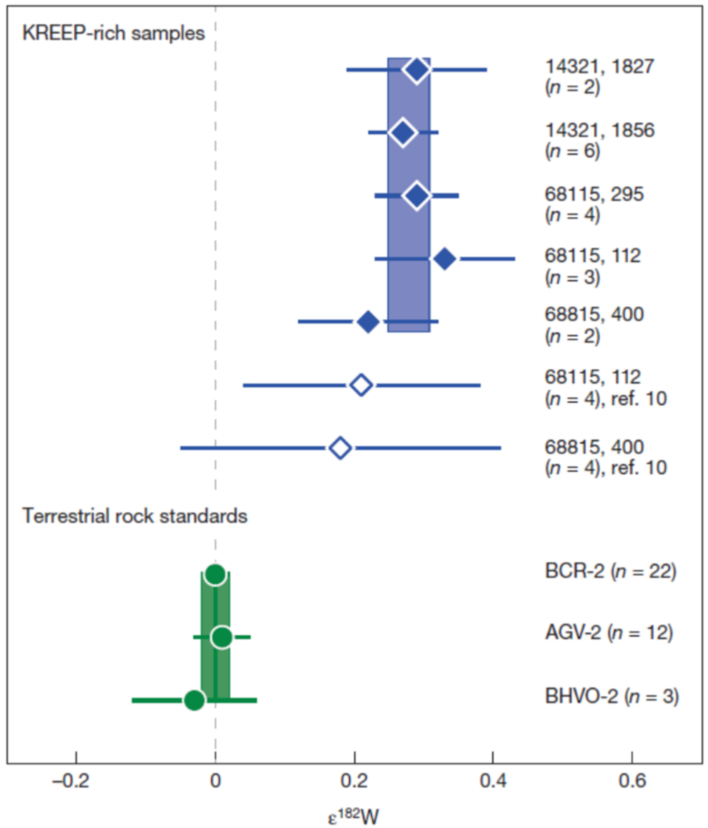


Figure 2 | ε^{182}W data of KREEP-rich samples and terrestrial rock standards. Top panel, data from this study (filled symbols) and for metal samples from ref.

Kruijer et al. 2015 Nature

$100\mu = 1\varepsilon$

- Small ^{182}W excesses in lunar rocks (KREEP) !!

Two competing models to explain Archean (and lunar) ^{182}W anomalies

- The small ^{182}W excesses mirror a missing late veneer (e.g., Willbold et al. 2011, Kruijer et al. 2017).

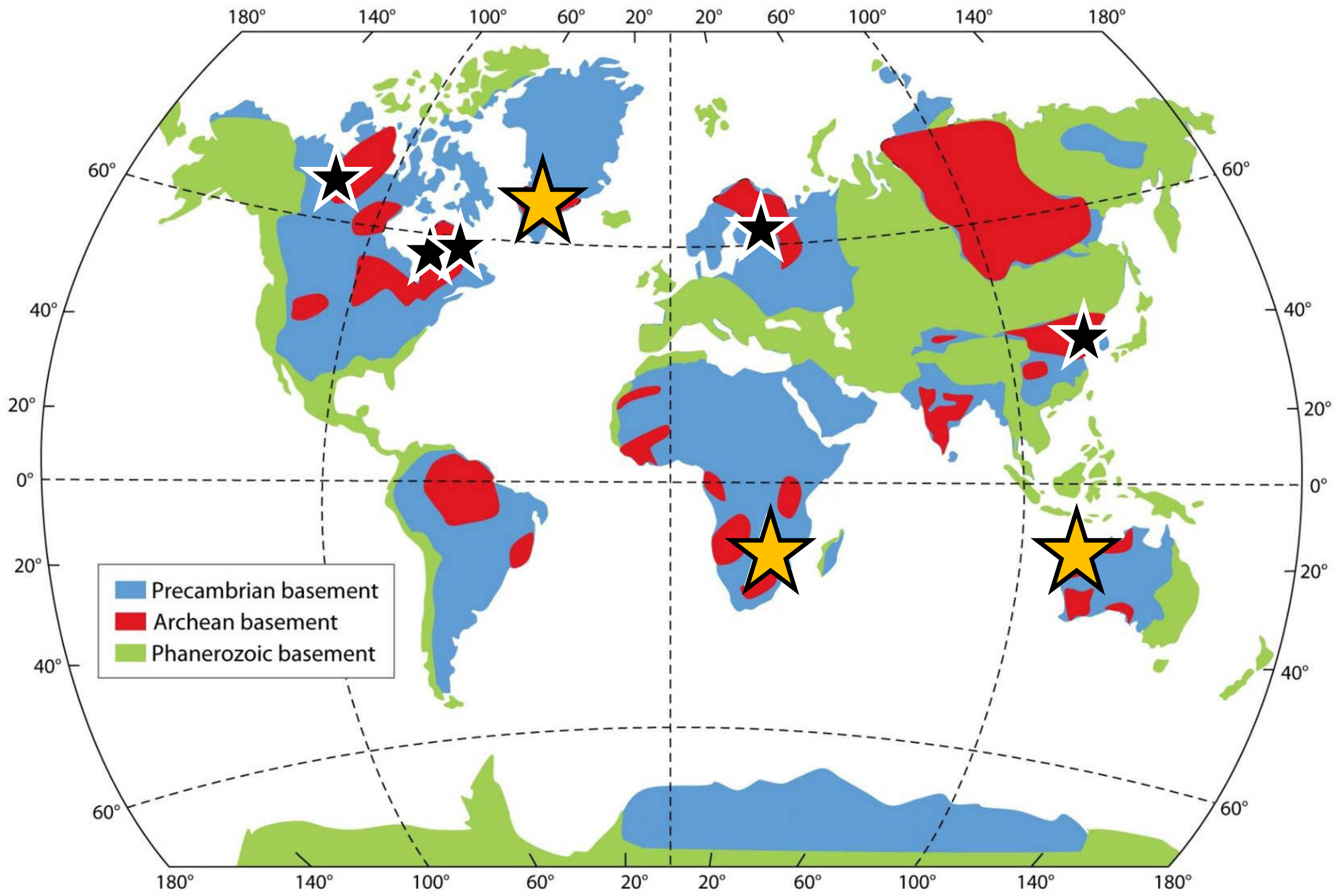
- The ^{182}W excesses reflect radiogenic ingrowth due to early silicate differentiation with different Hf/W (< 60 Myrs after solar system formation) (e.g., Touboul et al. 2012, Rizo et al. 2016).

- In case II, the Earth Moon System must have formed earlier than 60Myrs after solar system formation !


Hot debate 1:
Was there a late veneer, and when and how efficient was it added to Earth‘s mantle?


Hot debate 2:
The age and origin of the Moon?
Artemis II 2026

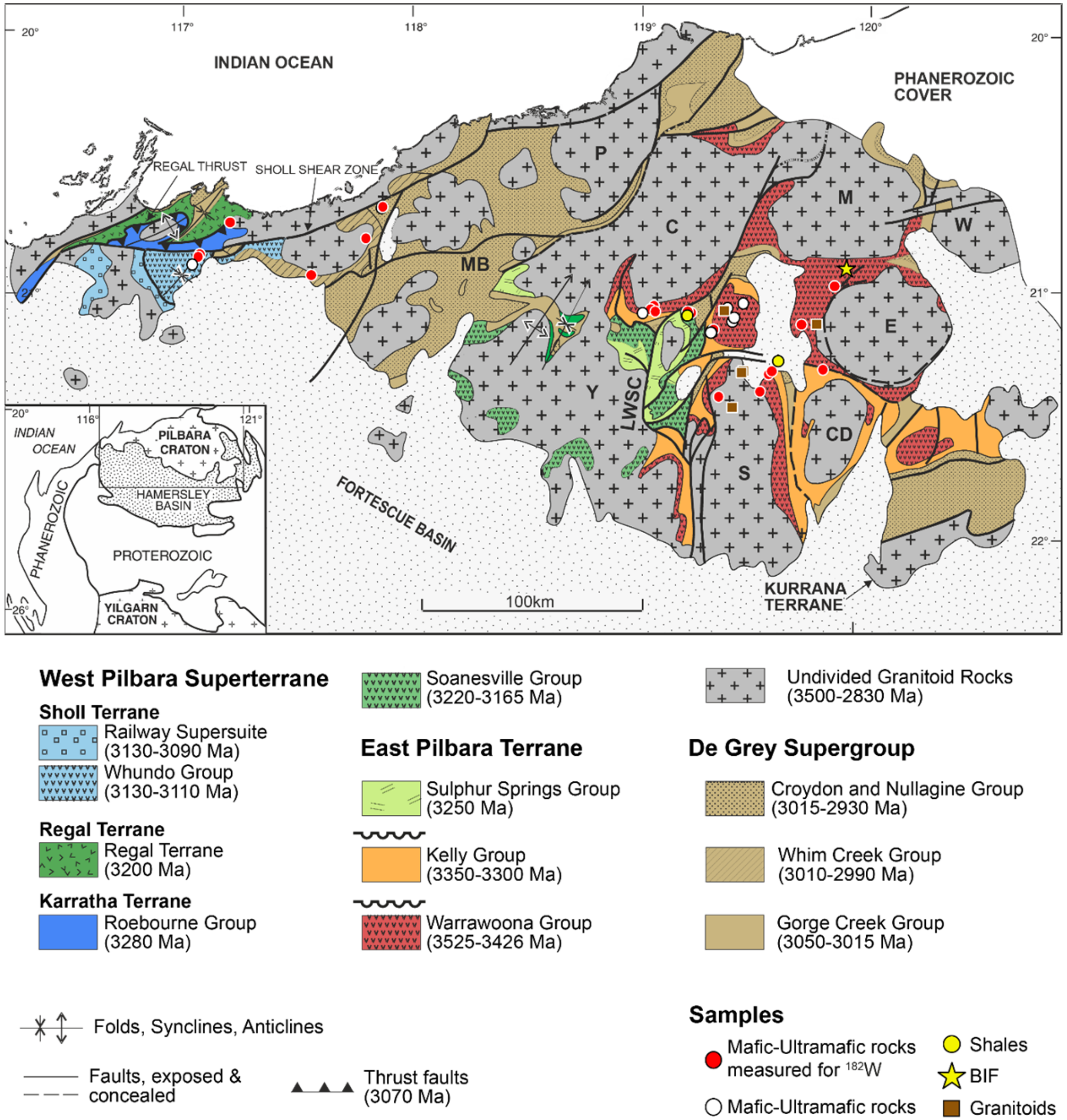
Three terrestrial case studies



Lee et al., 2011, Annual Review of Earth and Planetary Sciences

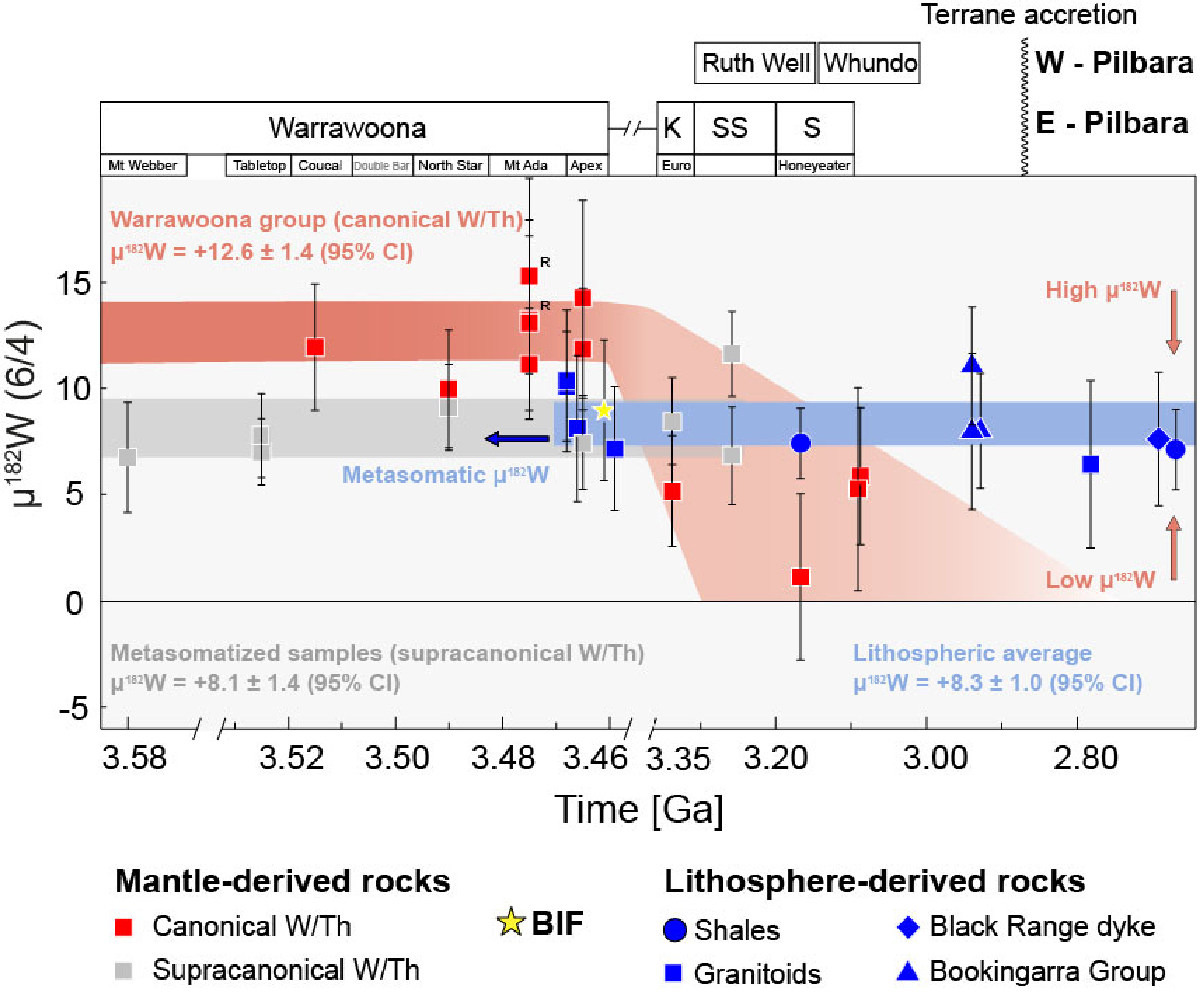
- This talk: Isua, Kaapvaal and Pilbara Cratons

Pilbara Craton, Australia - geology



- 3.6 to 2.7 Ga geological evolution.
- Older mafic greenstone belts.
- Younger TTGs and granites.
- Dome and keel structures

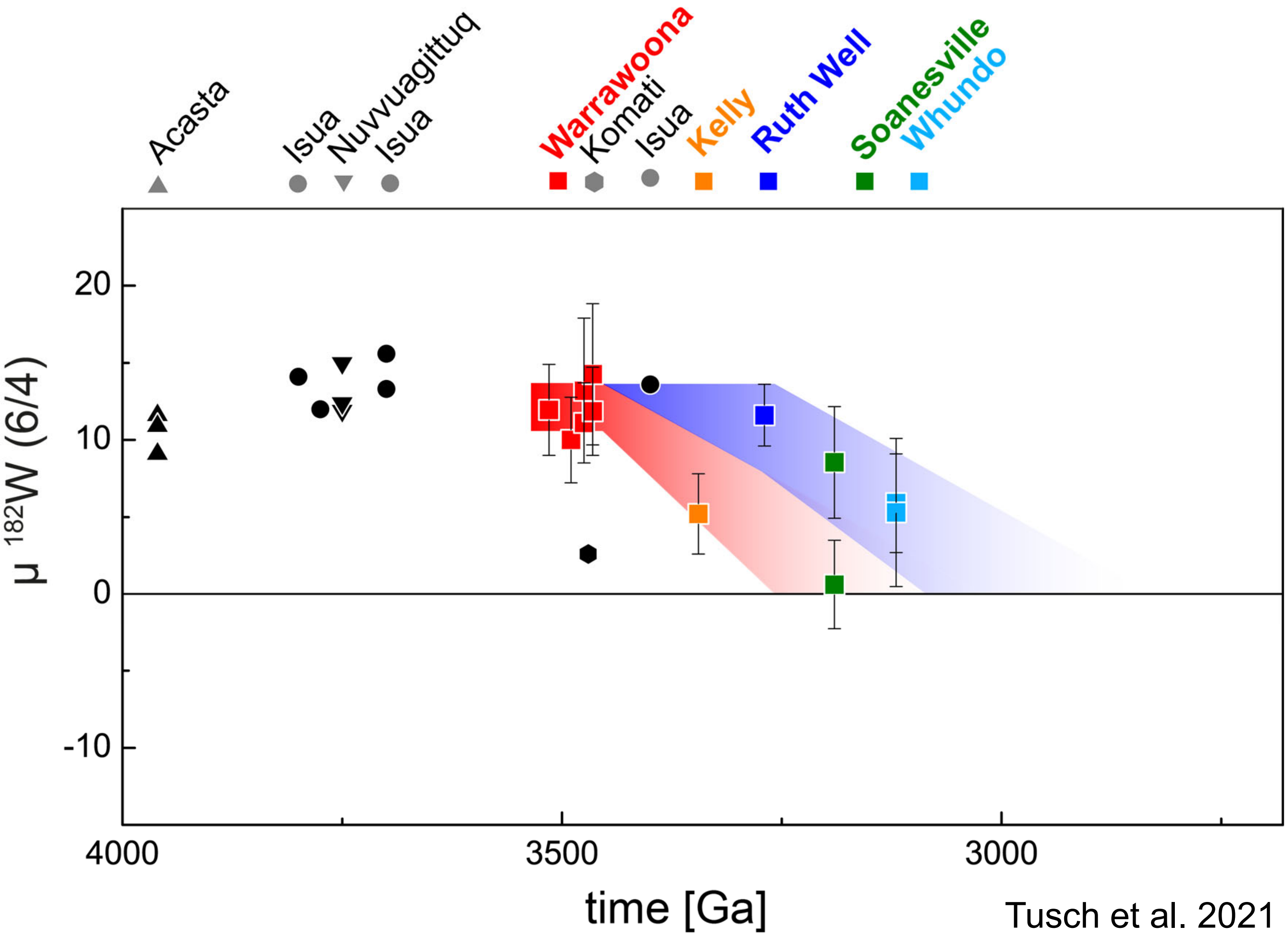
W isotopes as geodynamic tracer - Pilbara



Tusch et al. 2021 PNAS 117

- ^{182}W excesses vanish by ca. 3.3 Ga – onset of plate tectonis?

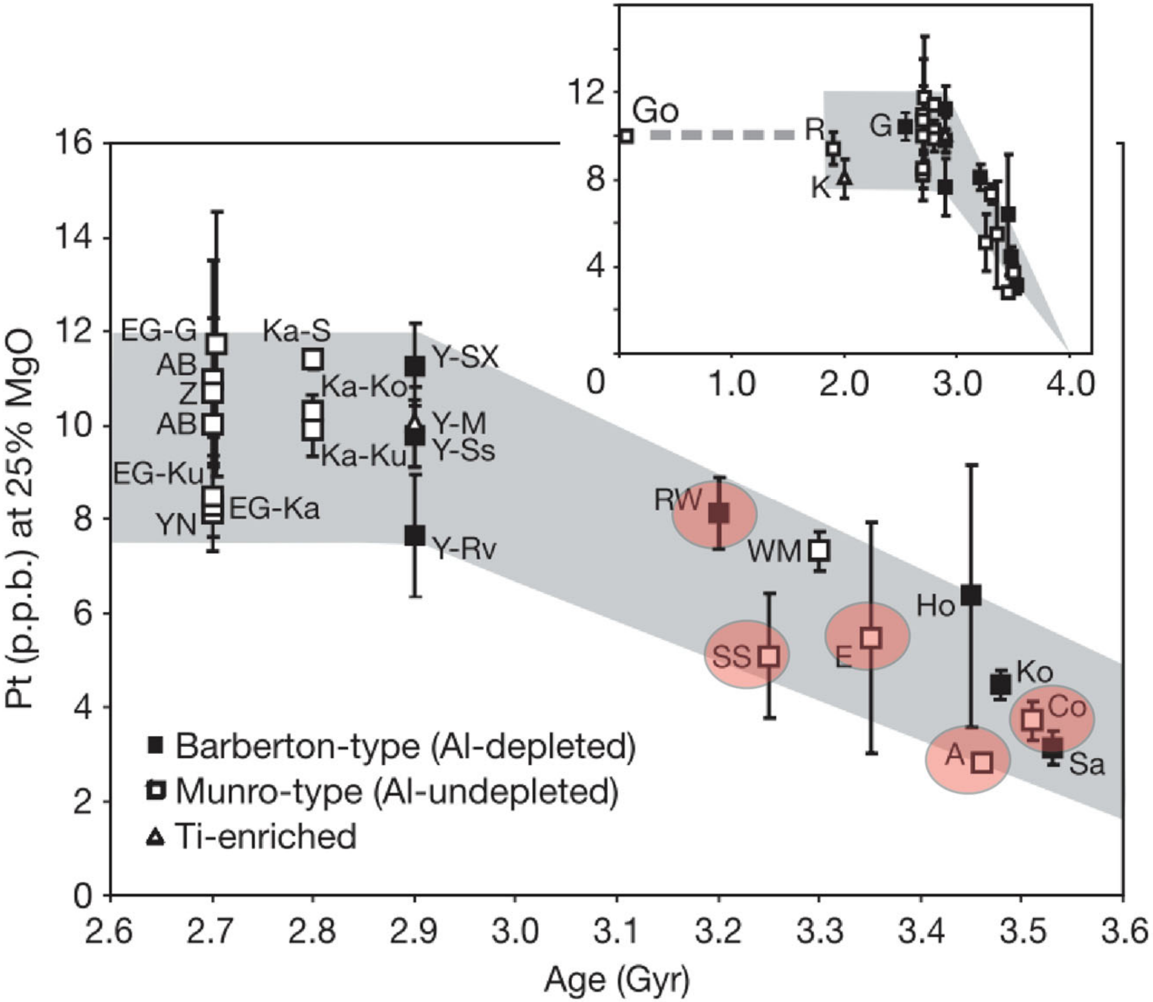
^{182}W isotope studies – bigger picture



Tusch et al. 2021 PNAS 118

- Only samples with pristine W inventory (canonical W/Th)!

Origin of ^{182}W excesses in the Pilbara

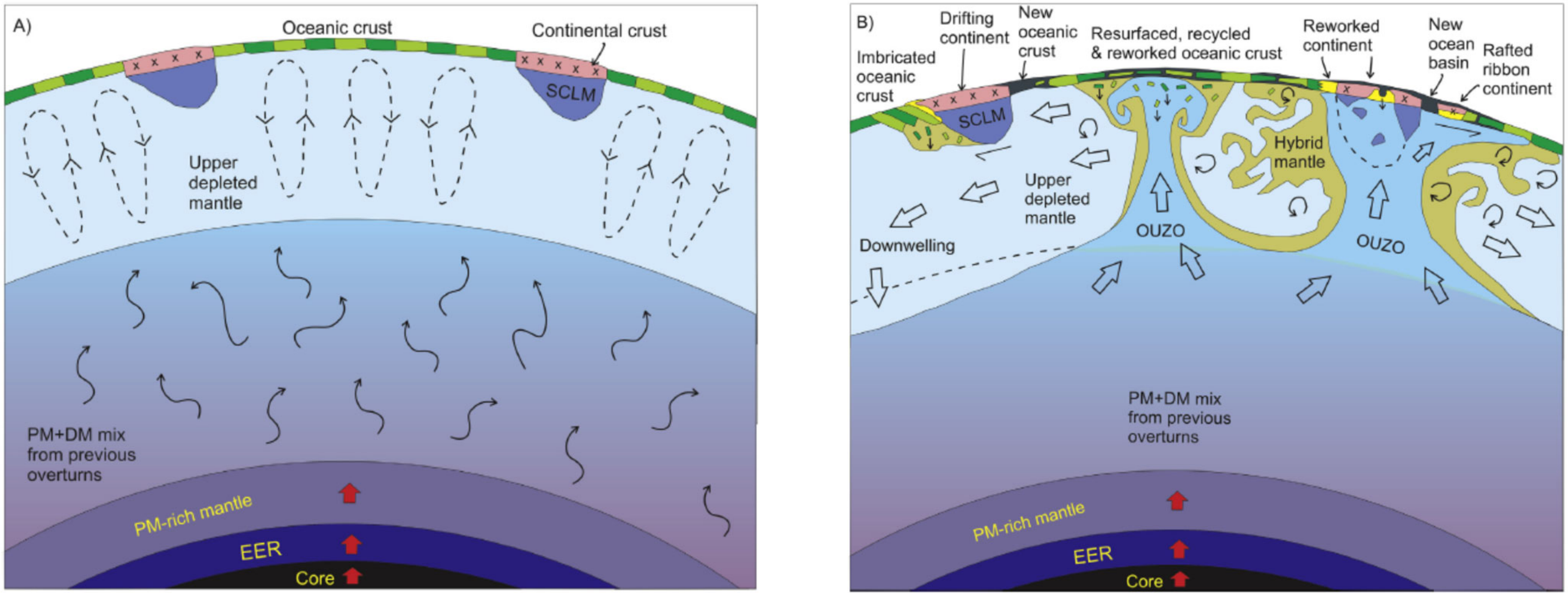


Maier et al., 2009, Nature 460, 620-623

- Measured samples labelled in red
- Decreasing PGE depletion with age

→ progressive in-mixing of late veneer?

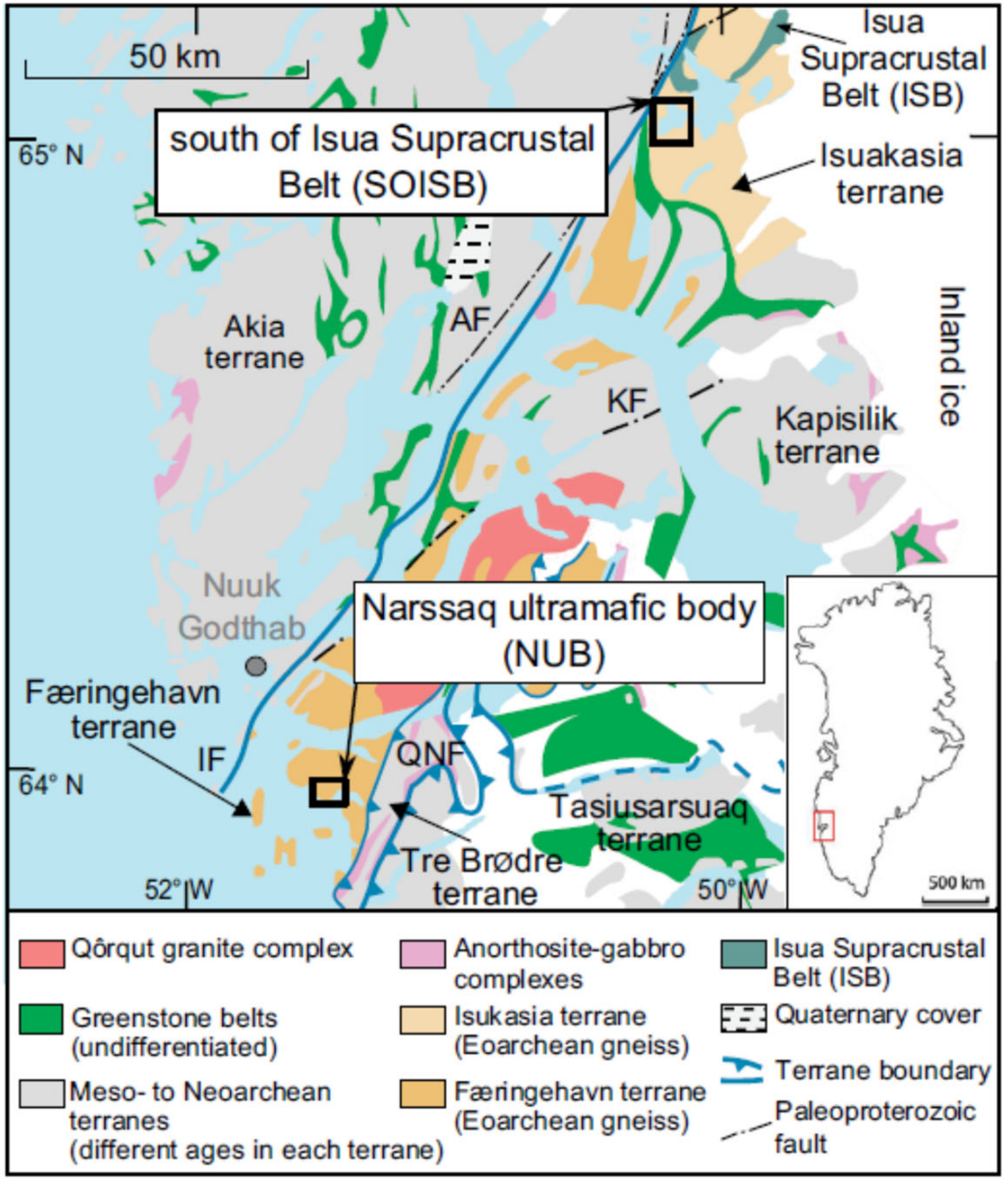
Stagnant lid tectonics in the Archean with small convection cells ?



from Bédard 2018

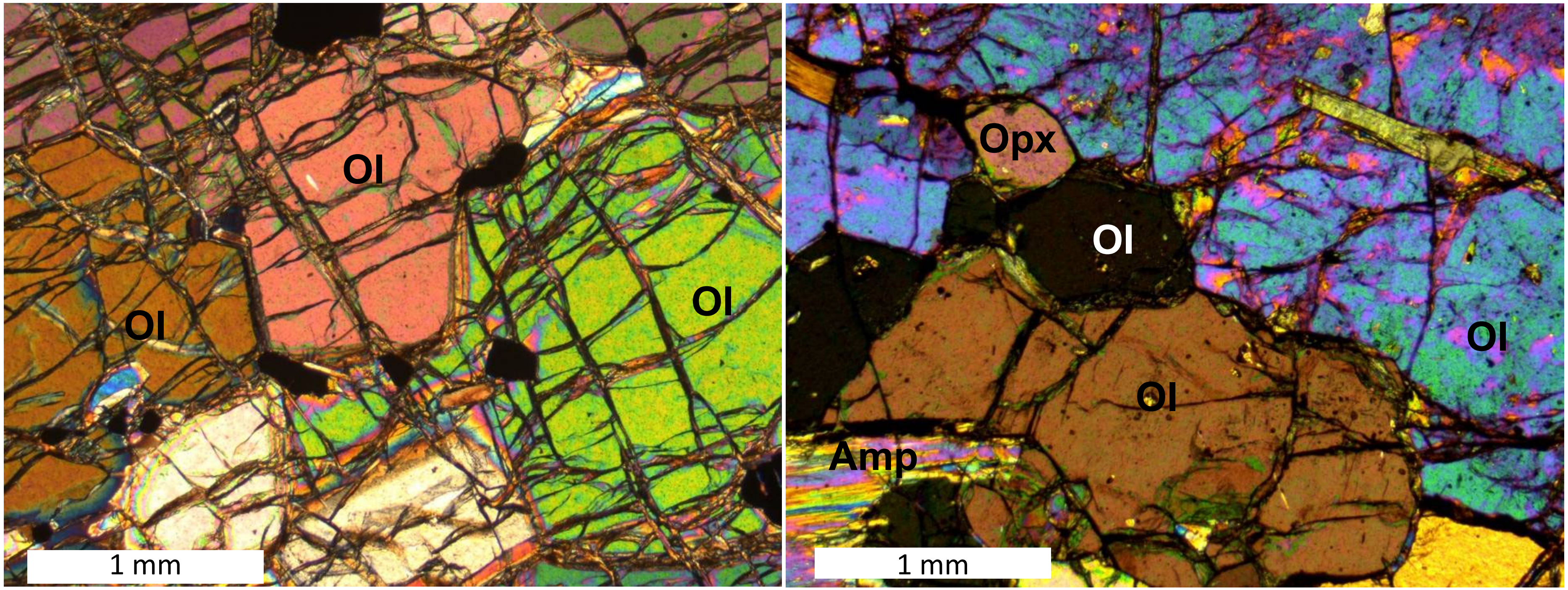
- Onset of plate tectonics by ca. 3.2 Ga may have caused efficient mantle convection – preservation of old reservoirs!

Occurrence of well preserved mafic crust/mantle fragments in SW Greenland



Map after
Escher and Pulvertaft (1994)
in Van Kranendonk et al. (2007)

Well preserved 3.8 Ga peridotites of mantle origin from SW Greenland (S'Isua)

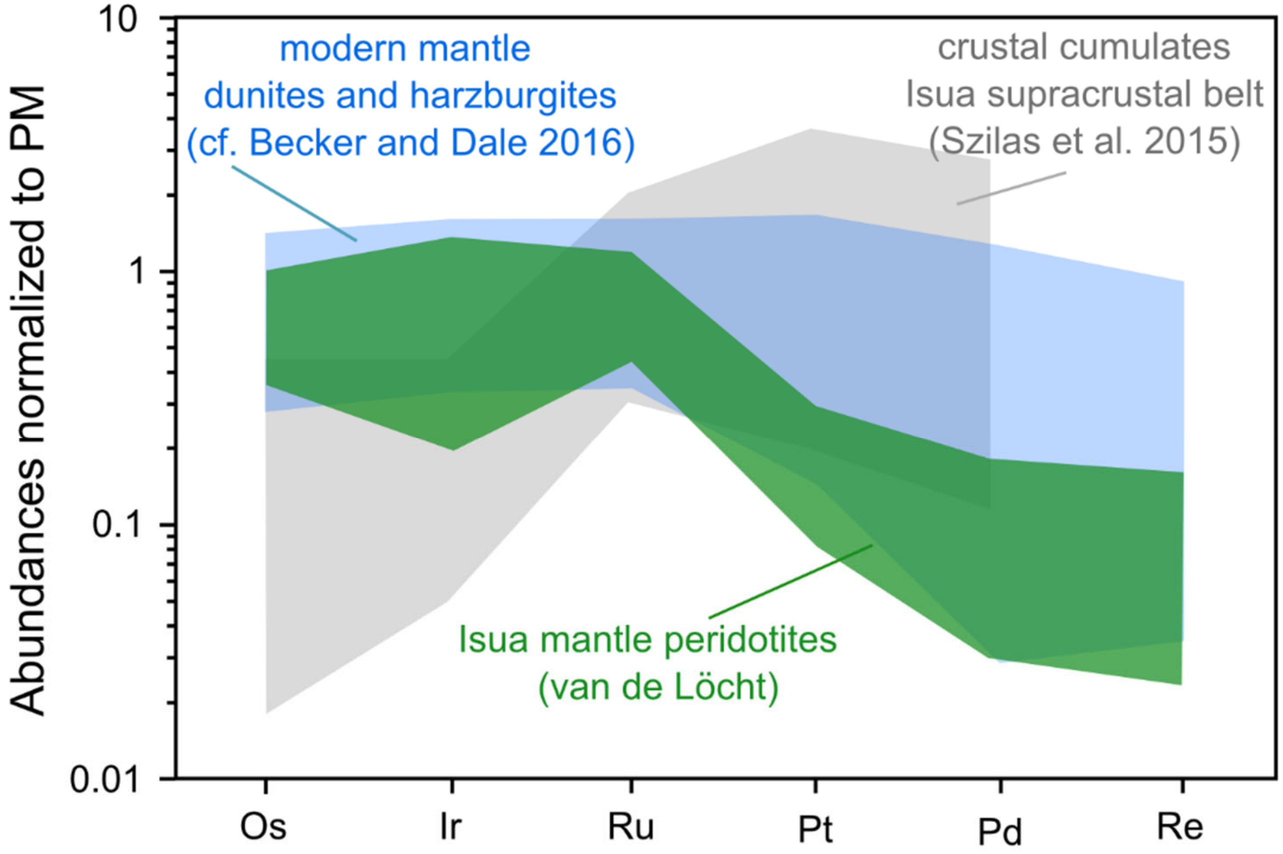


Meta-dunites
(olivine +orthopyroxene +amphibole +spinel)

Meta-harzburgites
(olivine +orthopyroxene +amphibole +spinel)

van de Löcht et al. (2018) Geology 46(3)
van de Löcht et al. (2020) GCA 280

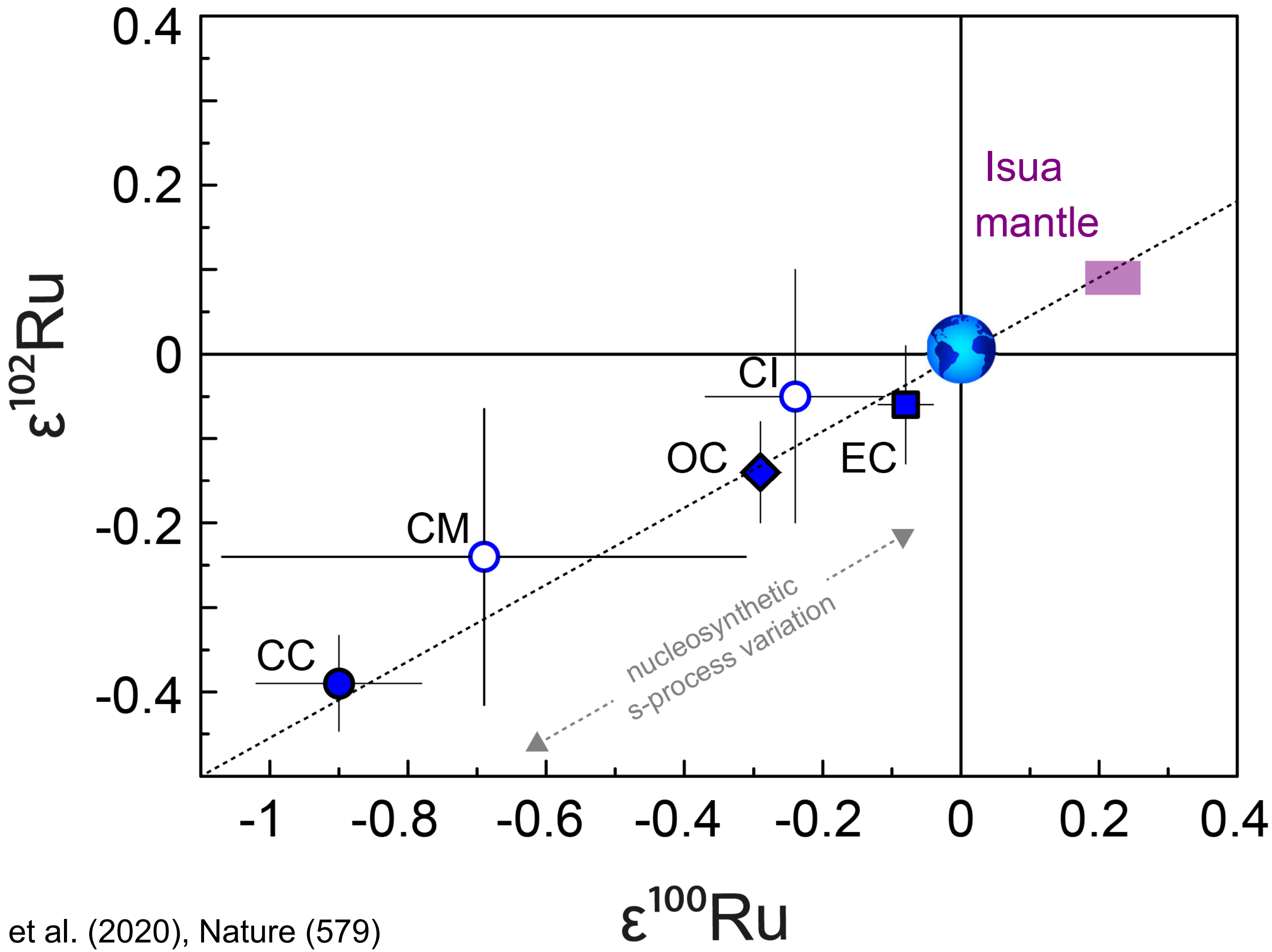
HSE patterns in 3.85 Ga mantle peridotites



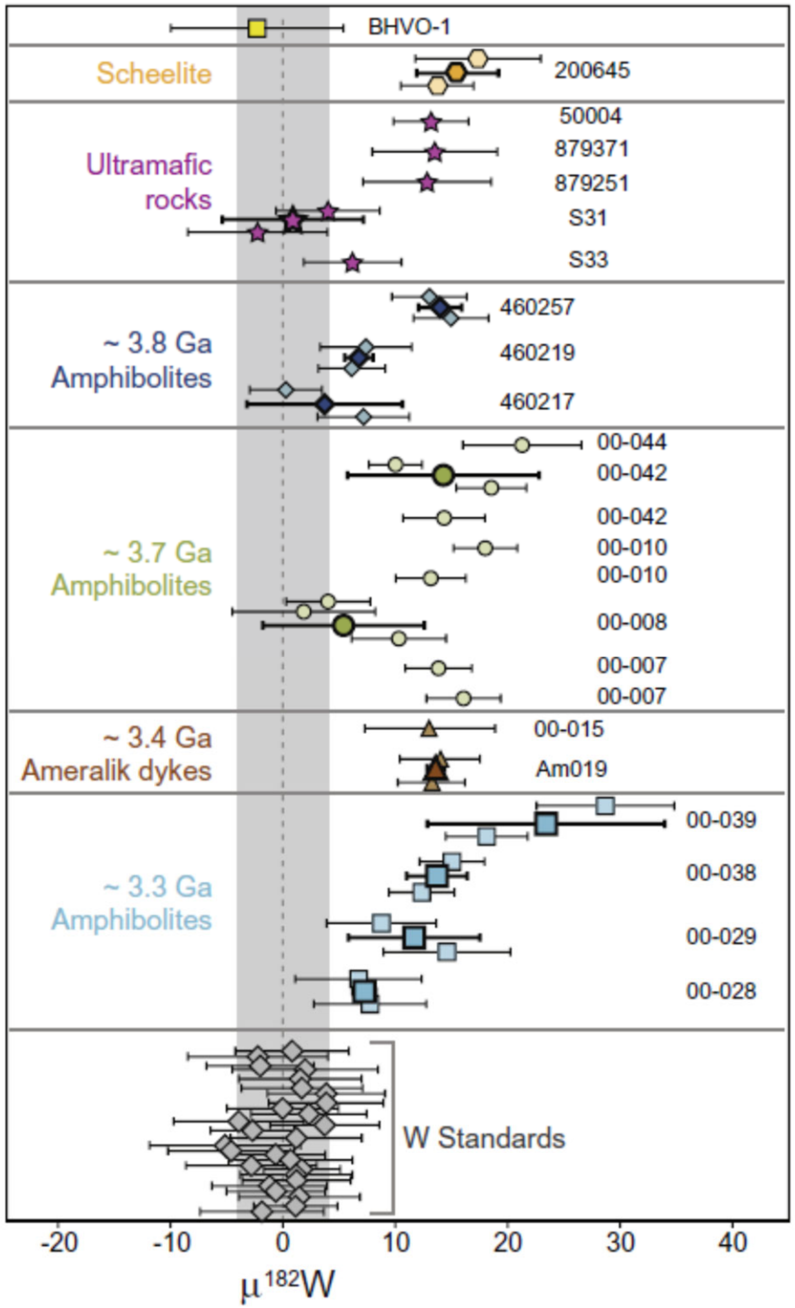
van de Löcht et al. (2018) Geology 46 (3)

- Patterns are indistinguishable from Earth‘s modern mantle
- A minimum of >60% of late veneer must already have been delivered !!

However, Isua rocks have an excess in s-process Ru relative to modern Earth‘s mantle



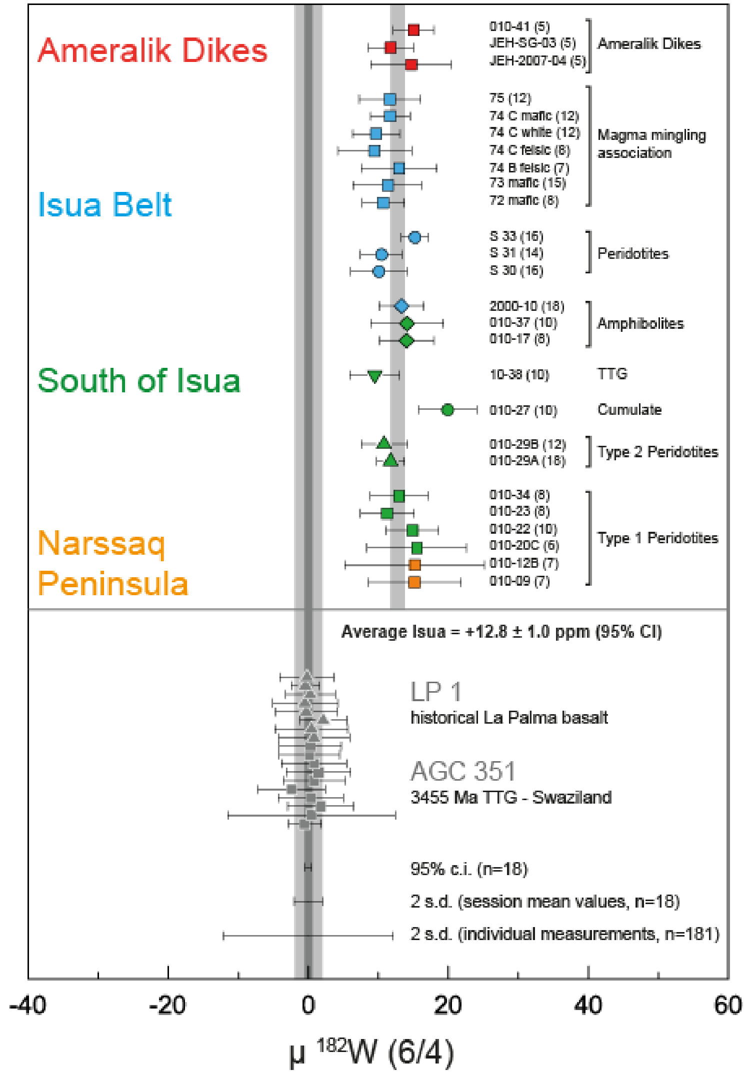
After Fischer-Gödde et al. (2020), Nature (579)



Variable ^{182}W – anomalies reported in rocks from SW-Greenland = Variable Late Veneer ??

$100\mu = 1\varepsilon$ From Rizo et al, 2016

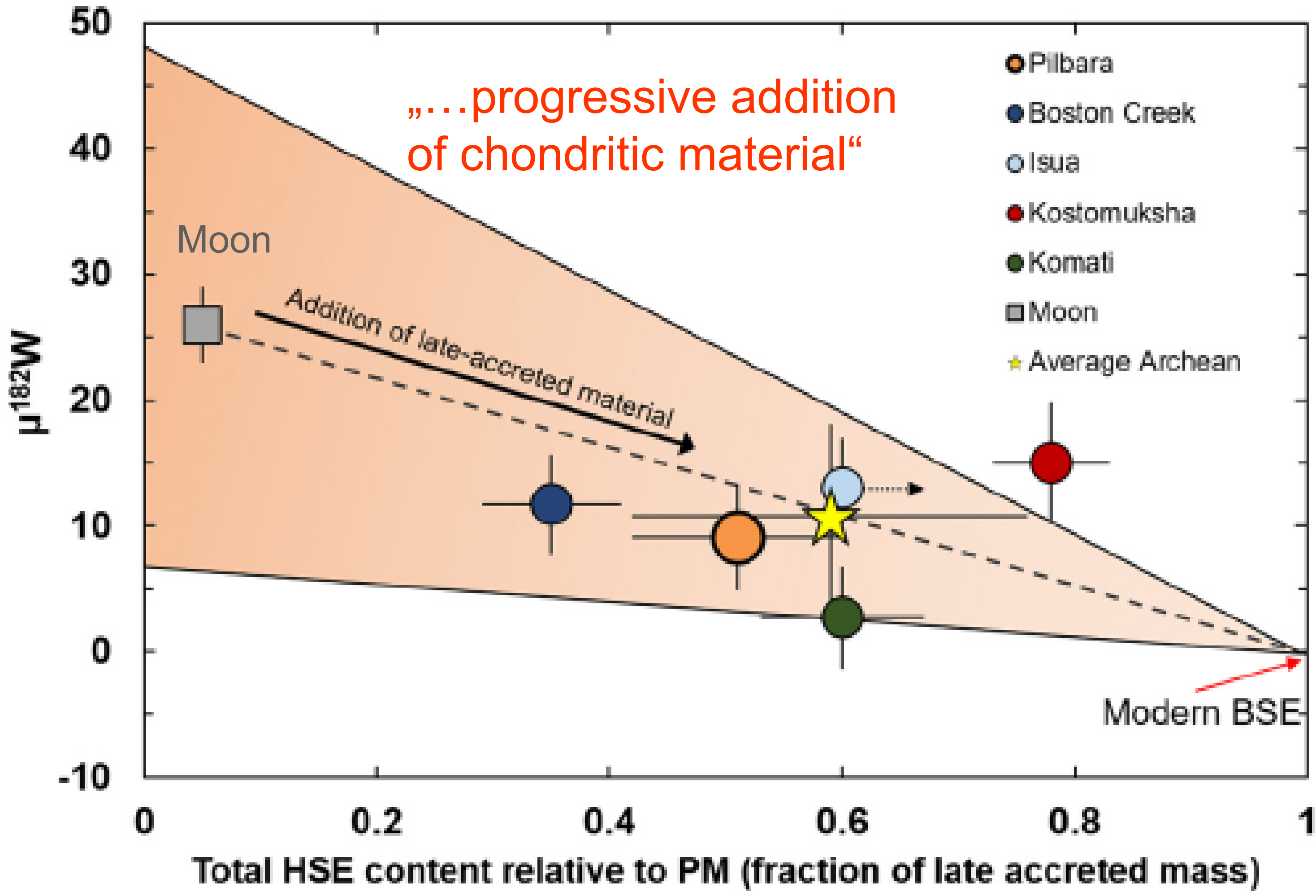
High precision ^{182}W data from Cologne



Tusch et al., 2019 GCA

- Uniform ^{182}W excesses in SW Greenland rocks (ca.+12 ppm) !

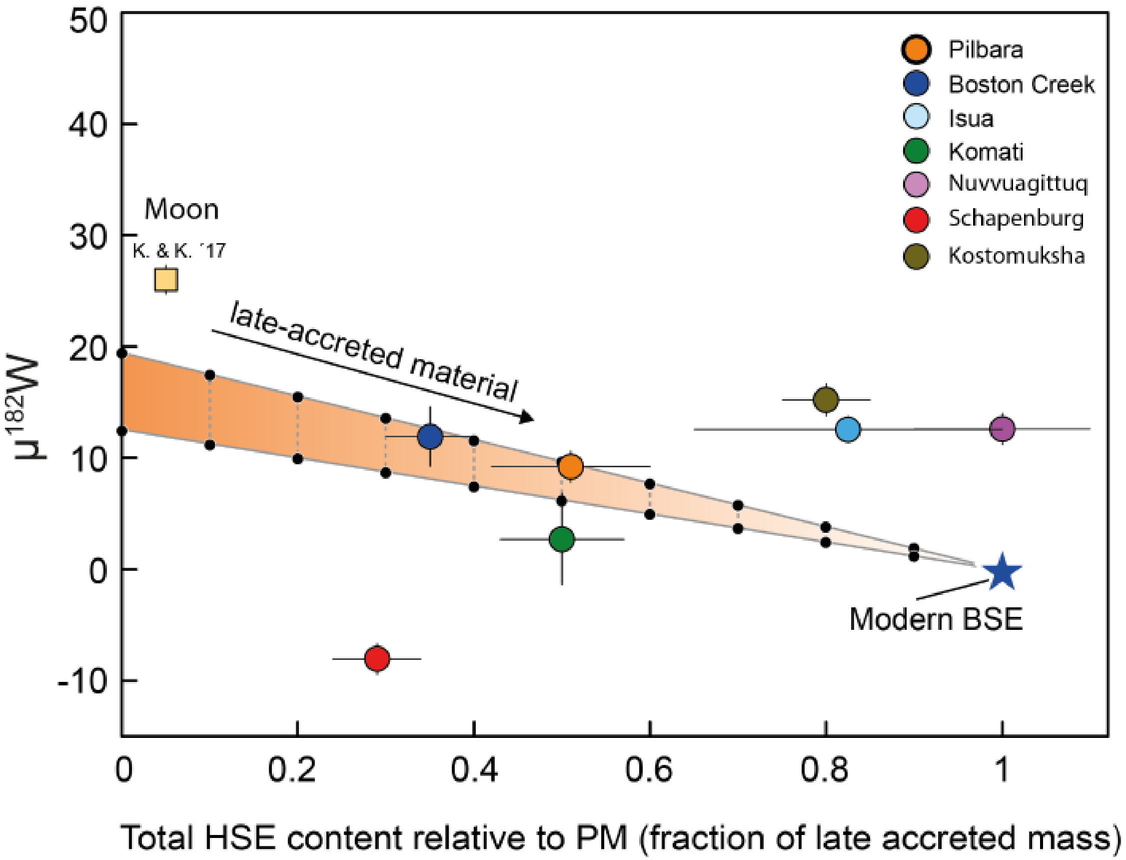
Can the ^{182}W excesses in early Earth rocks and the Moon be explained by missing late veneer?



Archer et al., 2019

HSE= Highly Siderophile Elements; $100\mu = 1\varepsilon$

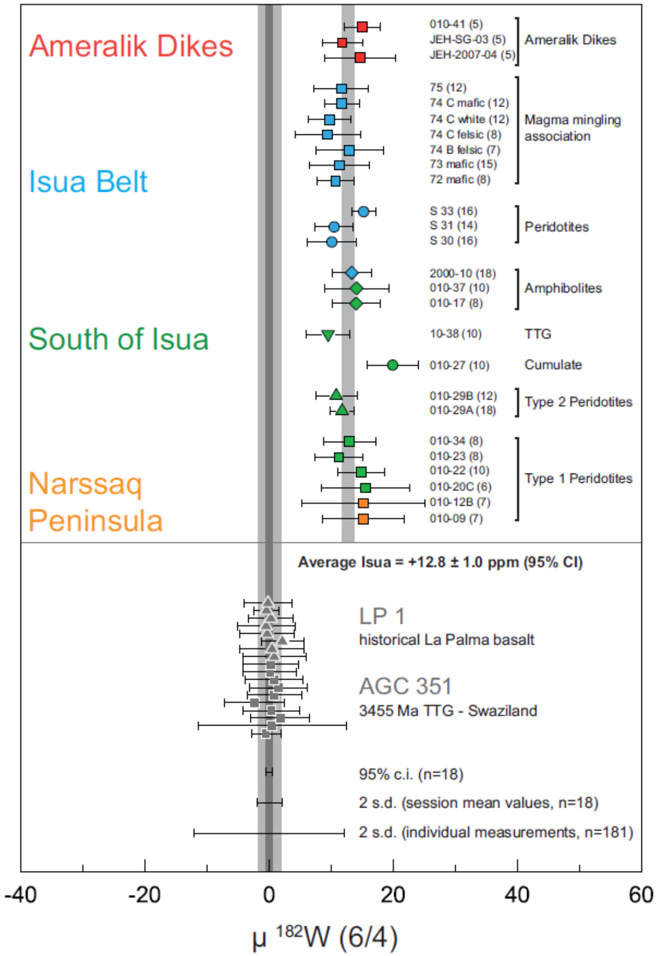
Subtraction of CI/CM-like late veneer (most realistic model)

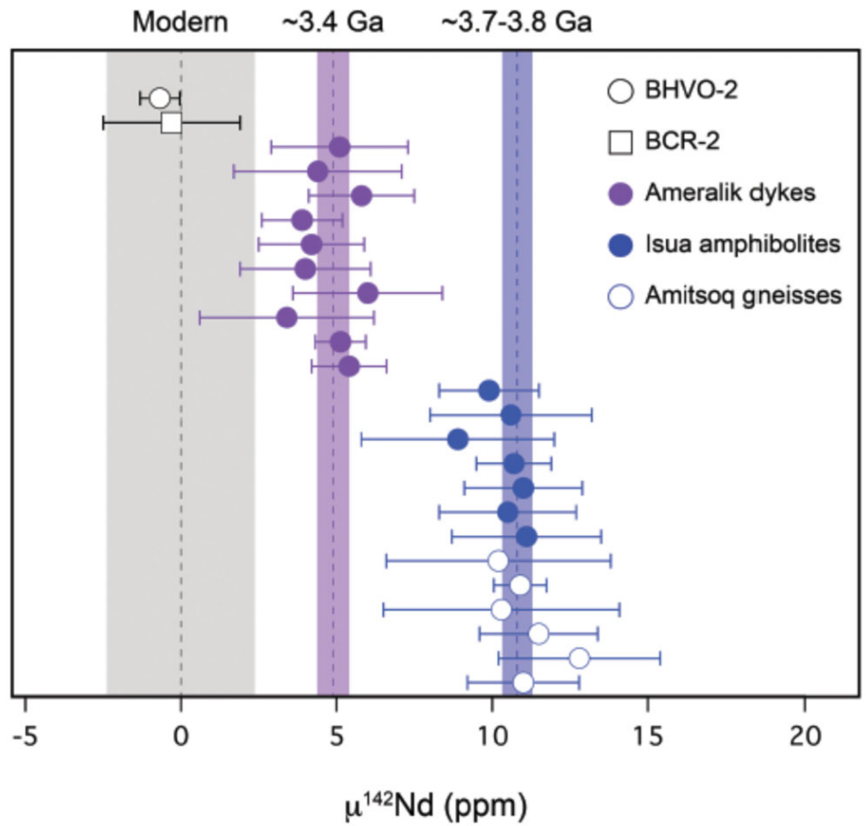


Thiemens et al. 2021
Nature Geosc. Reply

- Missing late veneer model fails to explain compositions of many Archean cratons (e.g., Isua or Kaapvaal) and the Moon !

Newer ^{142}Nd-^{182}W data for Isua

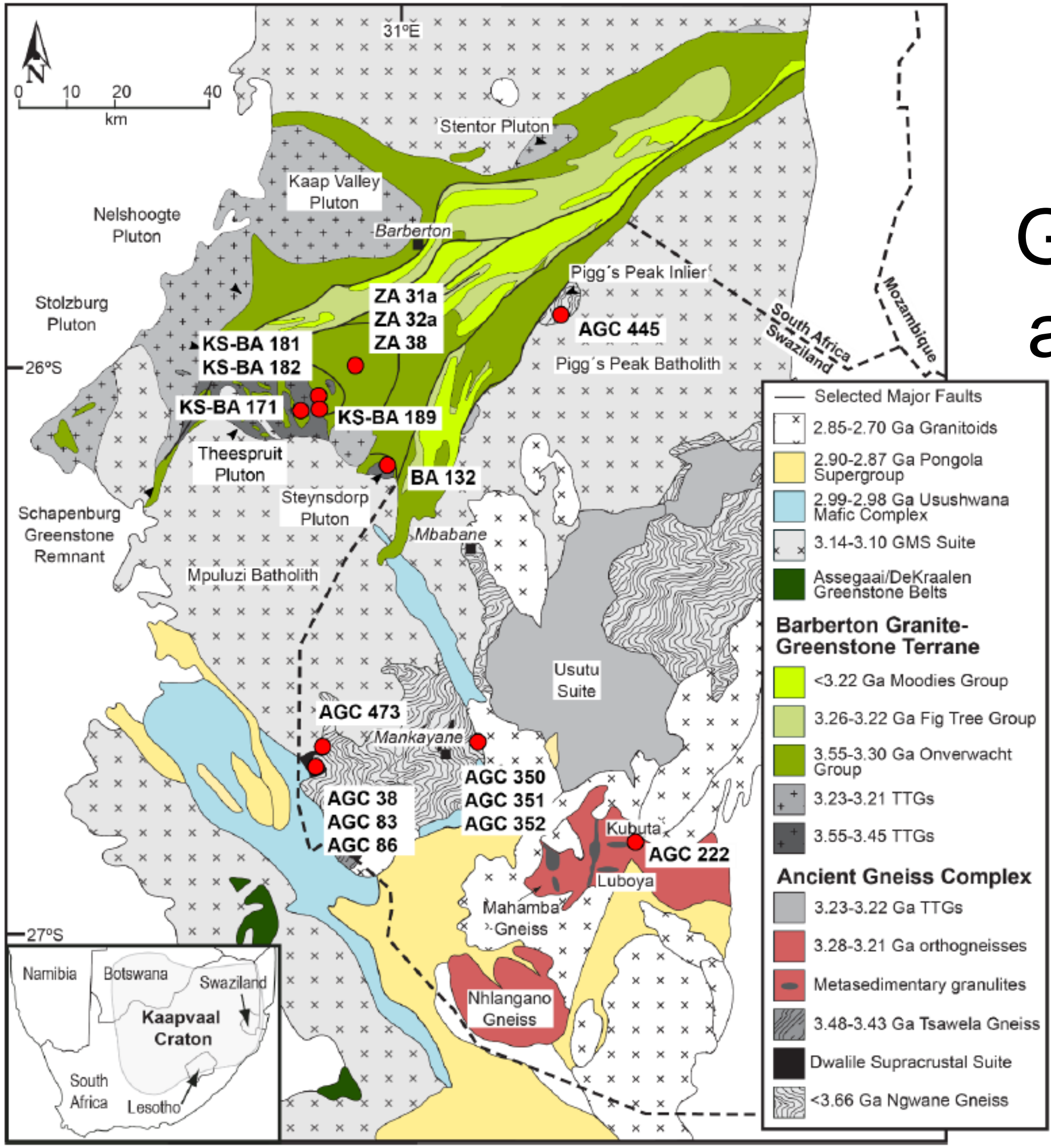




From Tusch et al. 2019 and Saji et al.2018

- Coupled ^{182}W - ^{142}Nd excesses indicate early differentiated silicate reservoirs, as ^{142}Nd is NOT affected by late veneer.

Nearly 2/3 of the ^{182}W excess in rocks from Isua must originate from early silicate differentiation!



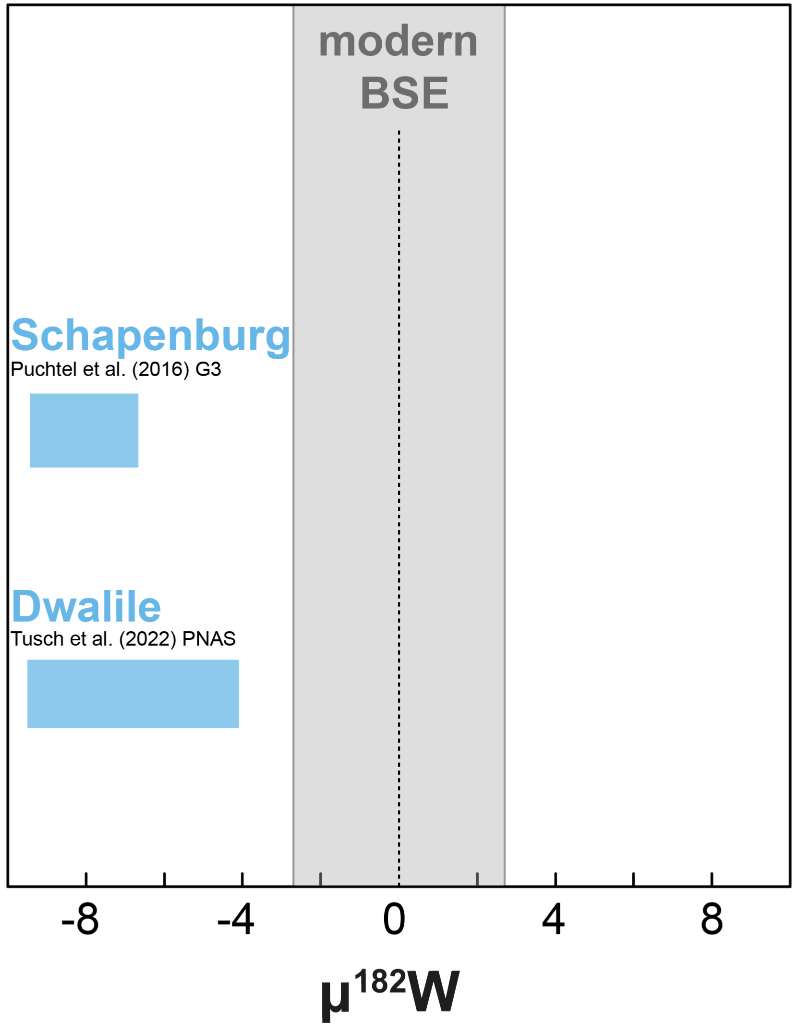
Early Archean (>3.2 Ga) komatiites, basalts and gneisses from the Kaapvaal Craton, southern Africa!

New ^{182}W data fro rocks from the Kaapvaal Craton – first ^{182}W deficits in old rocks

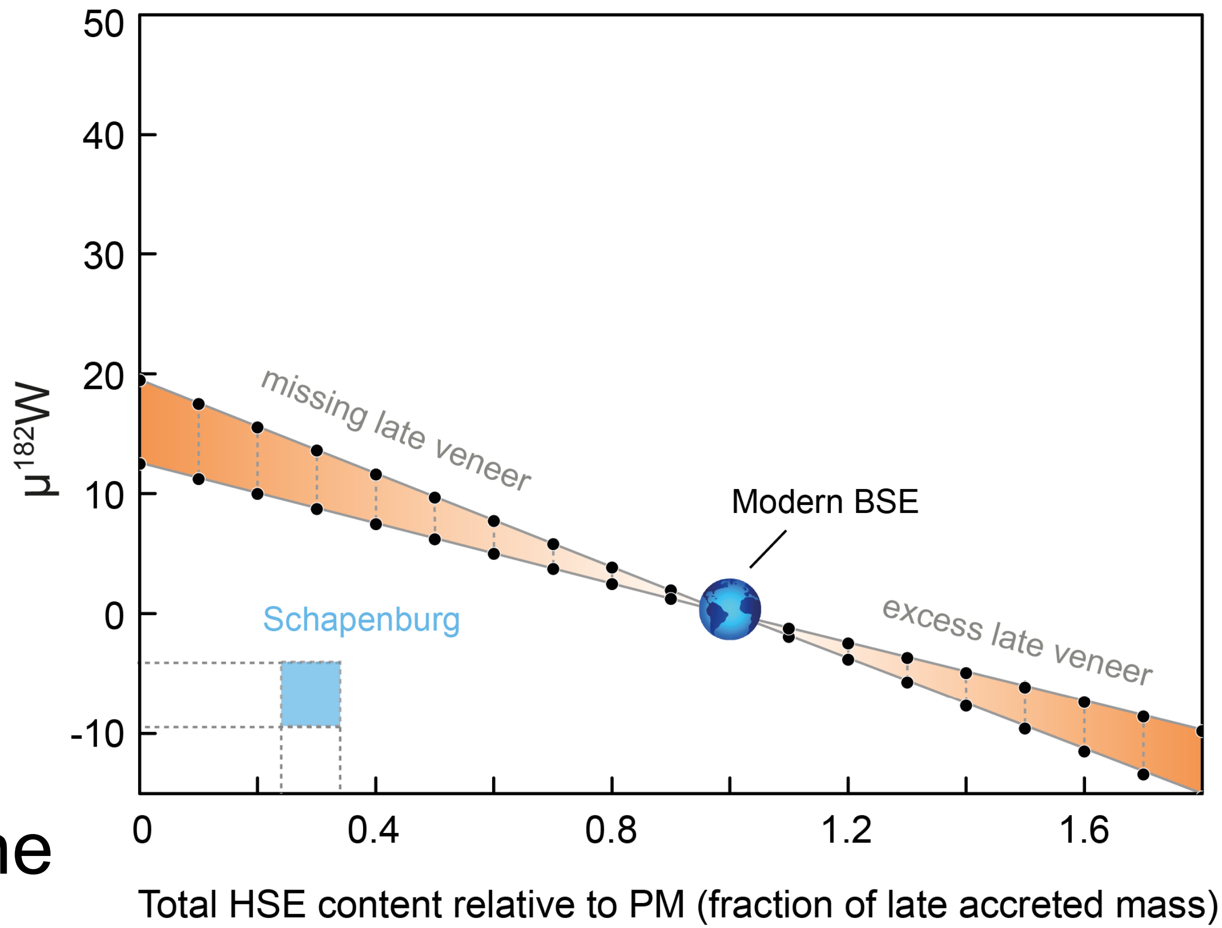
Negative ^{182}W anomalies found in Kaapvaal greenstone remnant komatiites

- Schapenburg
- Dwalile

Tusch et al. (2022) PNAS



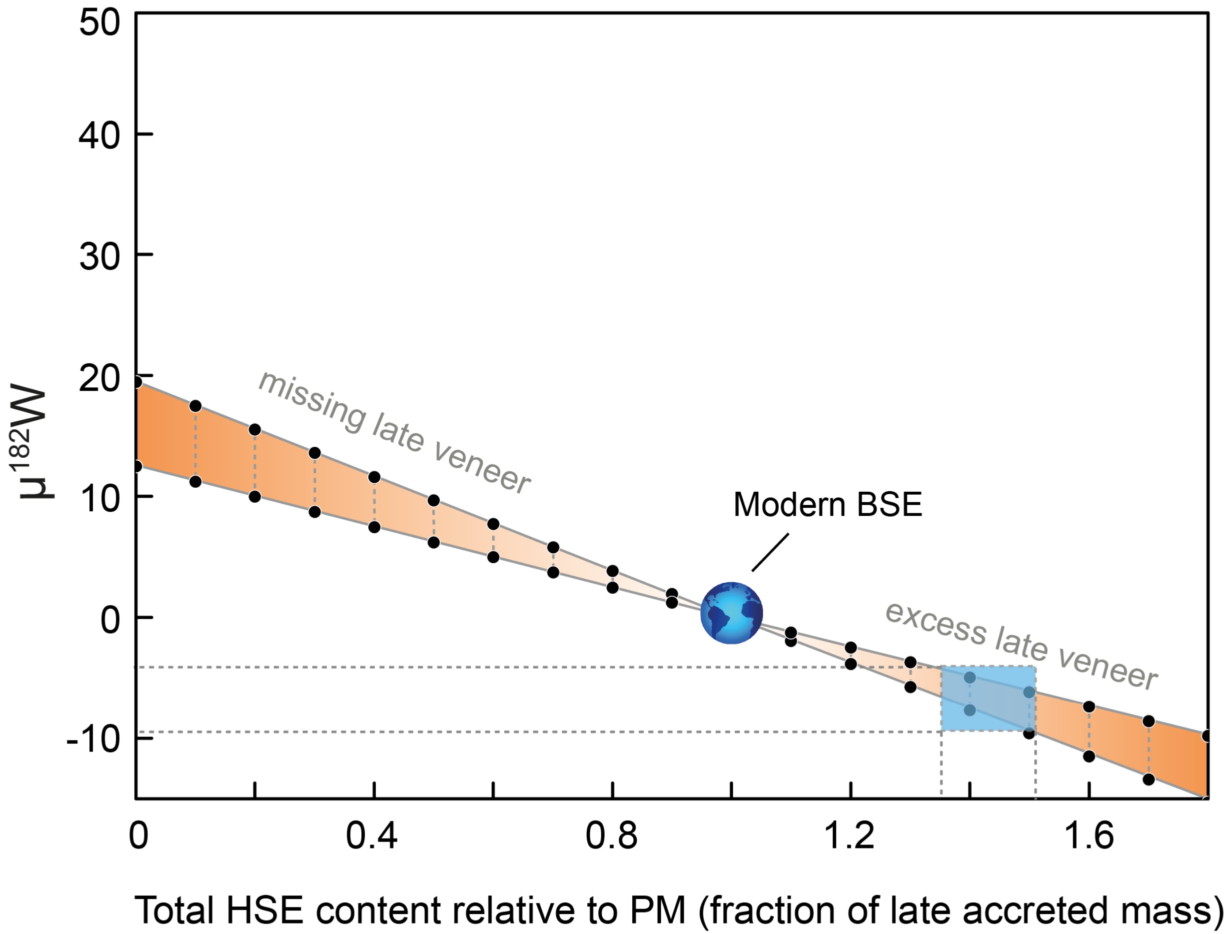
No match with late veneer trend



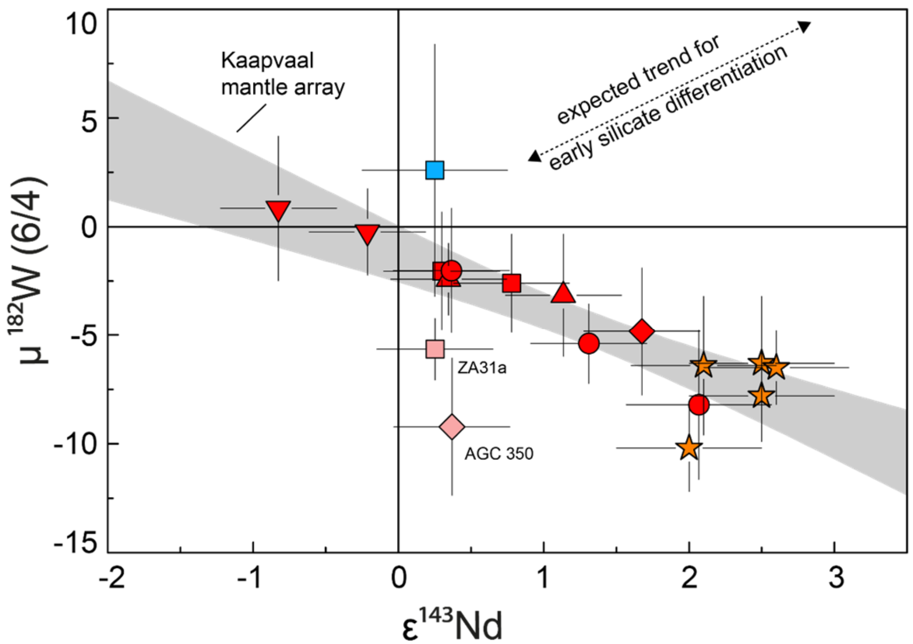
Negative ^{182}W anomalies found in Kaapvaal greenstone remnant komatiites

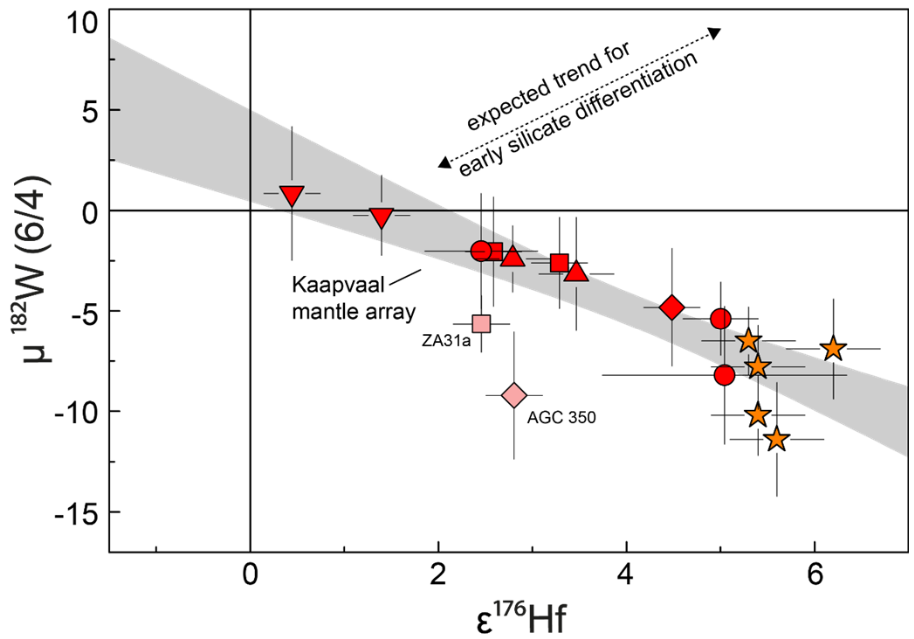
No match with late veneer trend

Higher HSE contents would be required!



Kaapvaal: Combined ^{182}W-^{143}Nd-^{176}Hf data



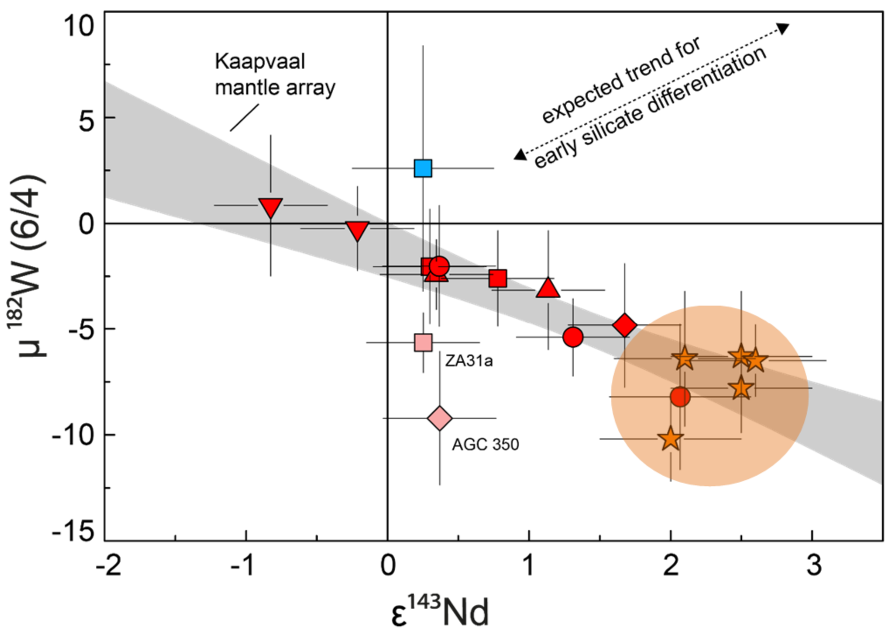


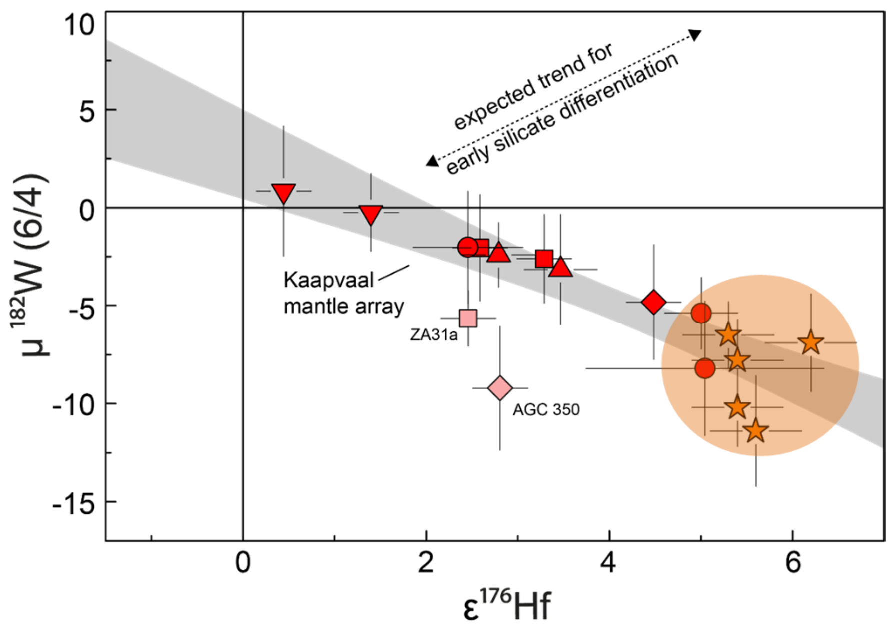
Tusch et al. 2022 PNAS

- Correlated arrays confirm early silicate differentiation!

Literature data: Puchtel et al. (2016), G3, Touboul et al. (2012), Science, Puchtel et al. (2013), GCA

Kaapvaal: Combined ^{182}W-^{143}Nd-^{176}Hf data





Tusch et al. 2022 PNAS

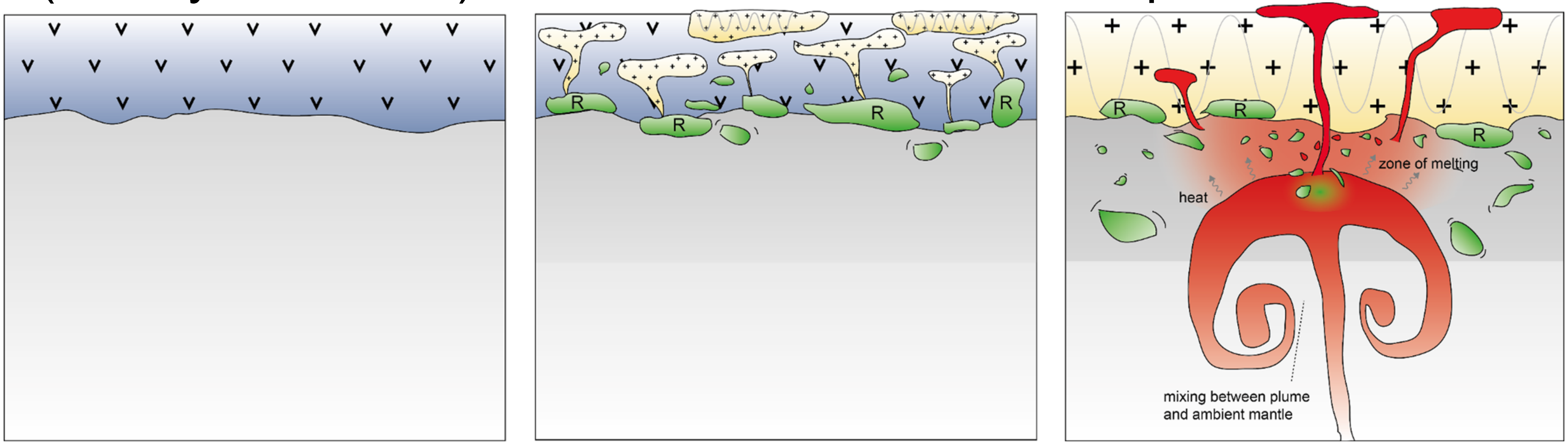
- Mixing between two endmembers, present day-like mantle and „Schapenburg/Dwalile source“!

Geodynamic model for Schapenburg/Dwalile source

(1) Protocrust formation (<60Myrs after ssf)

(2) Intracrustal fractionation TTGs & Restites

(3) Melting of hybrid sources during plume arrival

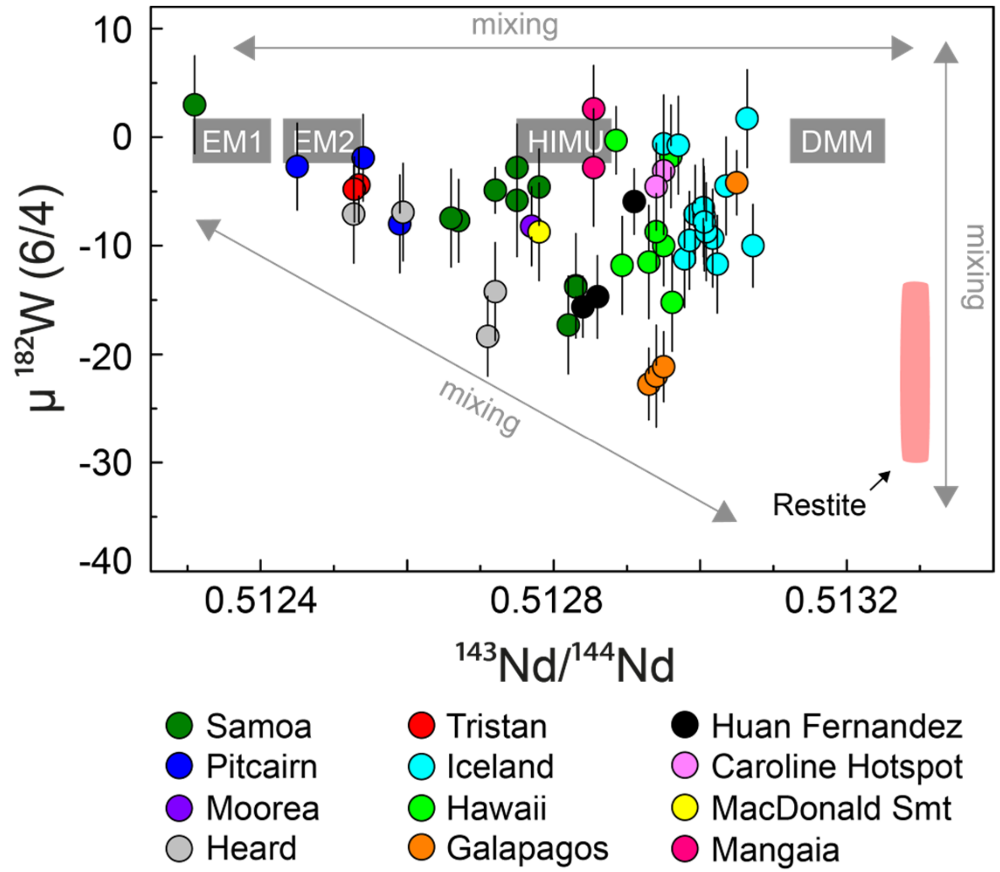


Tusch et al. 2022 PNAS

Hadean crustal restites in the sources of modern OIBs??

Delaminated Hadean restites constitute a viable endmember in the global OIB array (…and possibly be stored in LLSVPs)

→ Alternative explanation for the origin of negative ^{182}W anomalies in modern OIBs!



Restite recalculated to present day
Tusch et al. 2022 PNAS

Geodynamics from ^{182}W, ^{100}Ru & HSE

- ^{182}W excesses mirror the pre-late veneer signatures of the Earth‘s mantle! - Pilbara
- ^{182}W deficits caused by *in situ* radiogenic ingrowth during Earth‘ s first 60 Myrs! – Kaapvaal
- ^{182}W excesses are a combined feature – Isua
- Rather isolated mantle convection cells until ca. 3.2 Ga – Pilbara
- ^{182}W deficits in modern OIBS – recycled protocrust?
- Silicate differentiation during lifetime of ^{182}Hf-^{182}W - Earth-Moon system and first terestrial protocrust formed during the first 60Myrs of the solar system !!

Lunar rocks and (hence) the lunar mantle have higher Hf/W than Earth‘s mantle

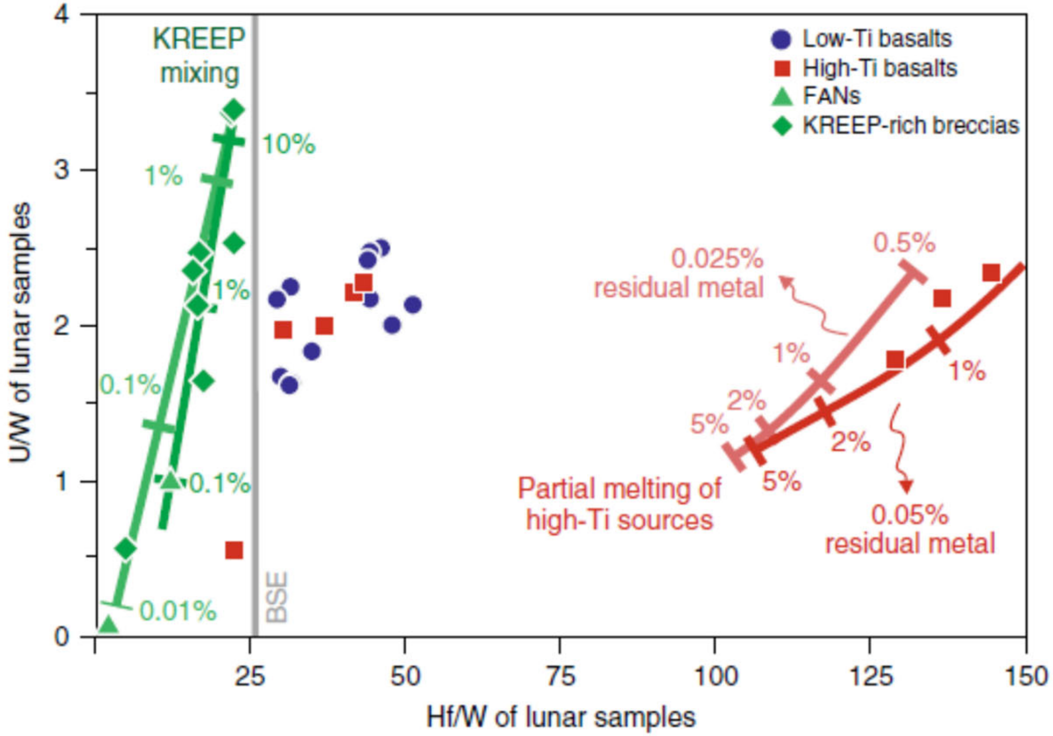
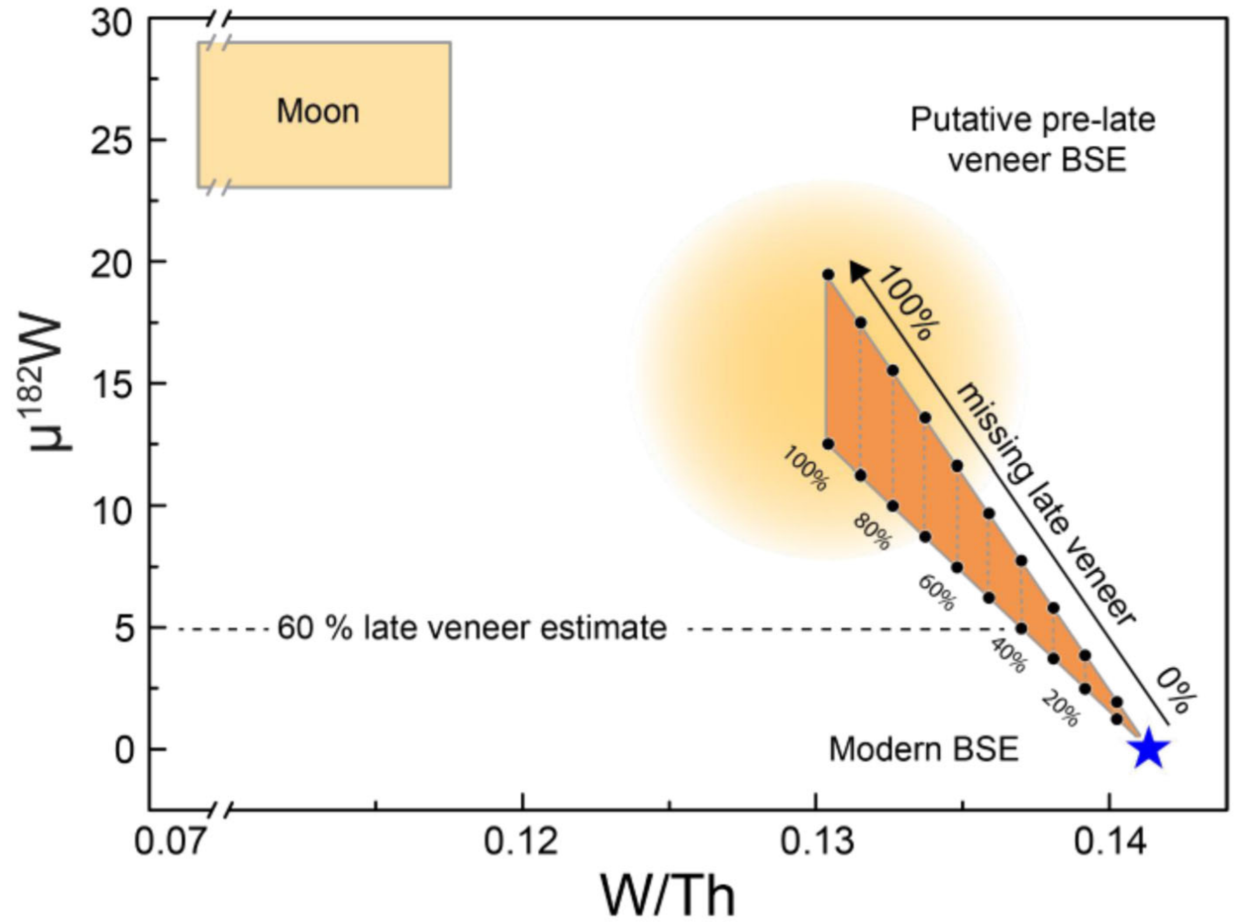


Fig. 1 | New U/W versus Hf/W data measured in lunar samples compared to crystallization and melting models for the LMO[35]. Errors are less than the symbol sizes. Measured lunar highland breccia compositions straddle the mixing lines between a KREEP-enriched end member[32] and FAN compositions as determined in this study. Contamination with W-rich meteoritic components produces virtually identical trajectories and raises the absolute W content. The high-Ti mare basalt source mineral assemblage is defined by a mixture of LMO cumulates that match Apollo 17 mare basalt Hf and Nd isotope systematics[12,27,32-35]. Note the overall excess of Hf/W in lunar basalts compared to recent BSE estimates[23].

Thiemens at al. 2019 Nature Geoscience

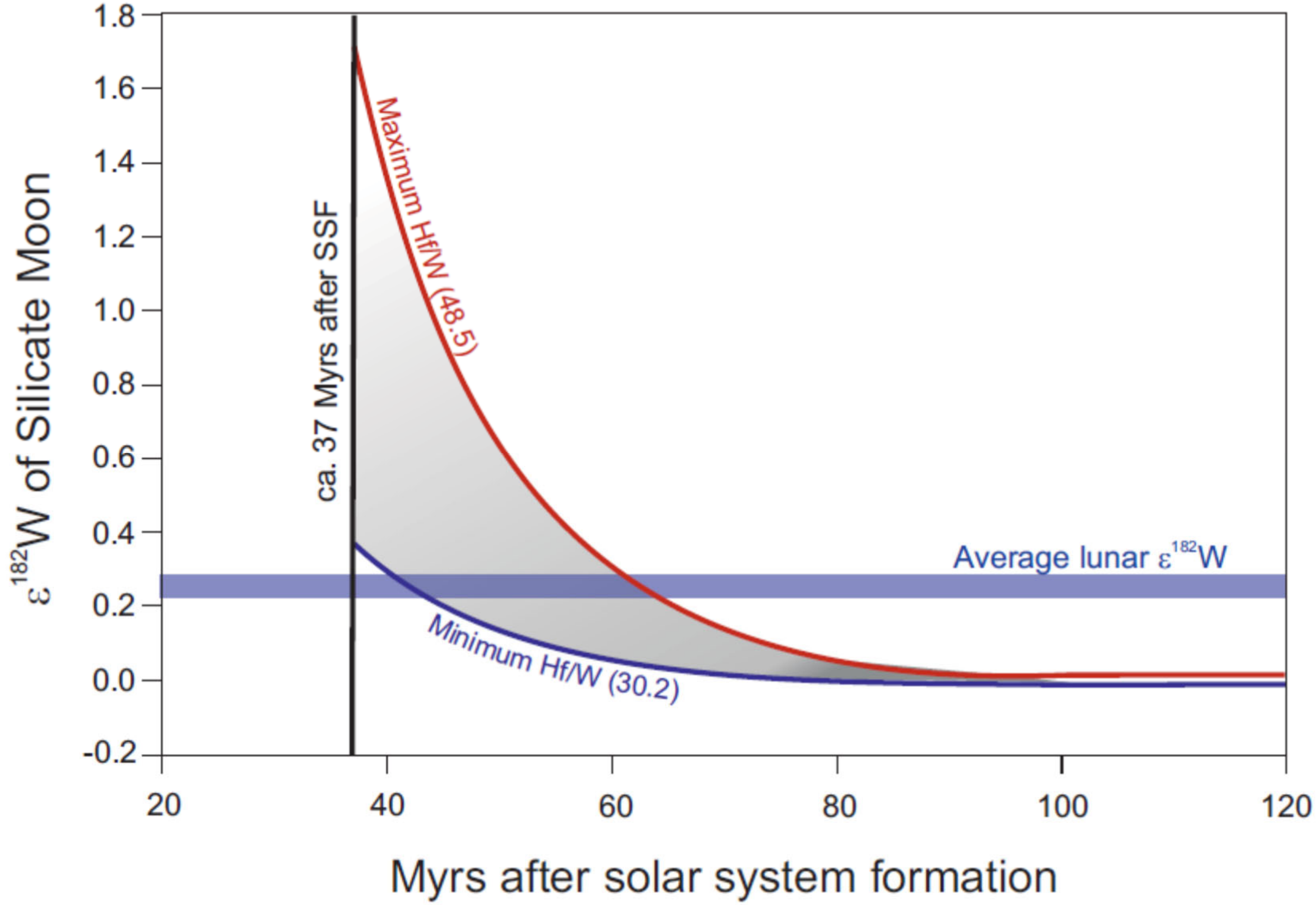
^{182}W and W/Th on the early Earth (and the Moon)



Thiemens et al. 2021

- Missing late veneer model can explain ca. 5 ppm ^{182}W excess!
- The Moon is not a pre-late veneer analogue for W!

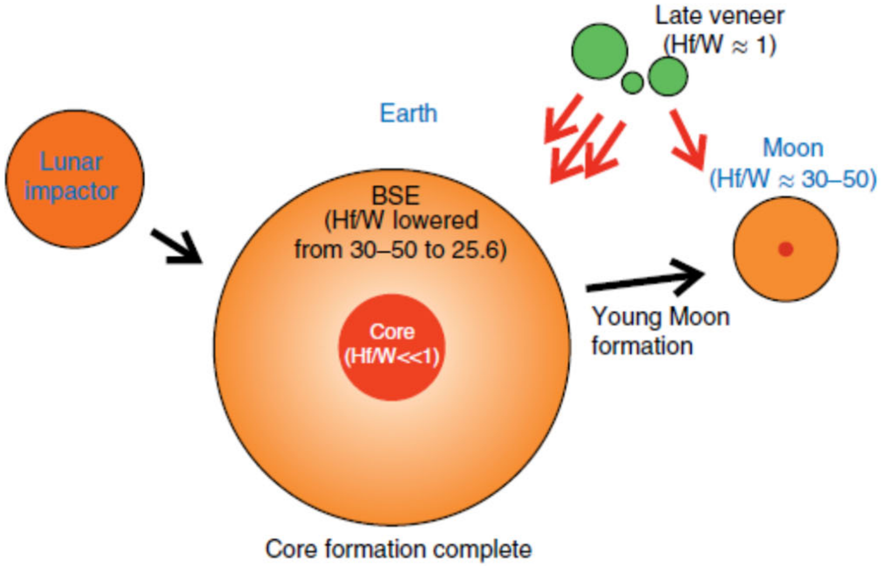
The high ^{182}W and Hf/W in the lunar mantle have an age significance



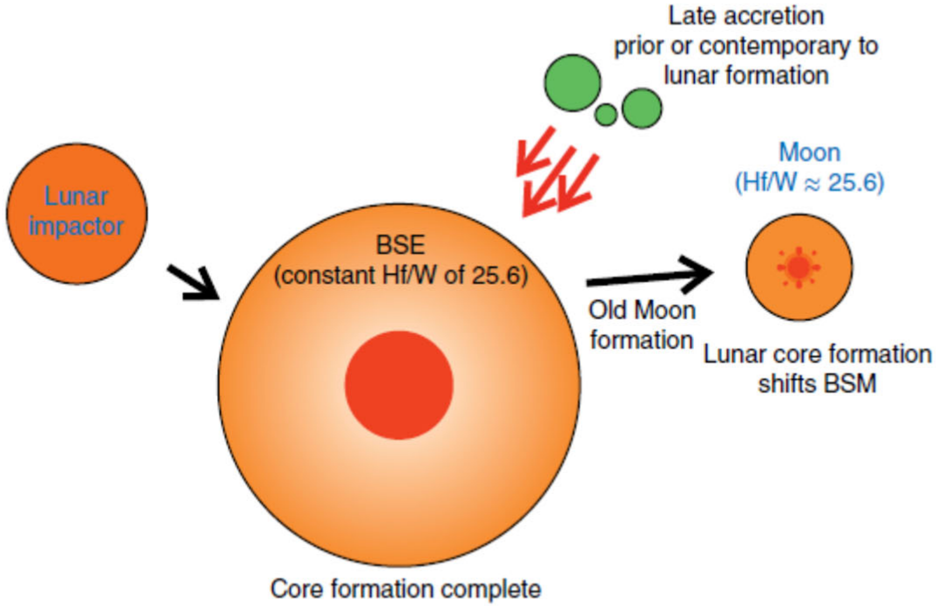
From Thiemens et al. 2019

Mean lunar $\varepsilon^{182}W$ from Kruijer et al. 2017

Lunar Models



Late Veneer Model



Core formation model

From Thiemens et al. 2019

- Only the core formation model (during lifetime of ^{182}Hf) can explain lunar W/Th versus ^{182}W systematics.

Implications for lunar chronology

- Earth-Moon system and first terrestrial protocrust formed during the first 60Myrs of the solar system during lifetime of ^{182}Hf (Thiemens et al. 2019)!!
- Younger ^{146}Sm-^{142}Nd age likely dates younger differentiation event in the lunar mantle, e.g., LMO cumulate overturn.
- Consistent with U-Pb and Lu-Hf constraints from zircons (e.g., Barboni et al. 2017; Greer et al. 2023)
- Also consistent with up to date Pb isotope evolution models (e.g., Ballhaus et al. 2013; Maltese & Mezger 2020)


Thank you!
(field impression SW Greenland)