Early Solar System chronology

present by Bill McDonough

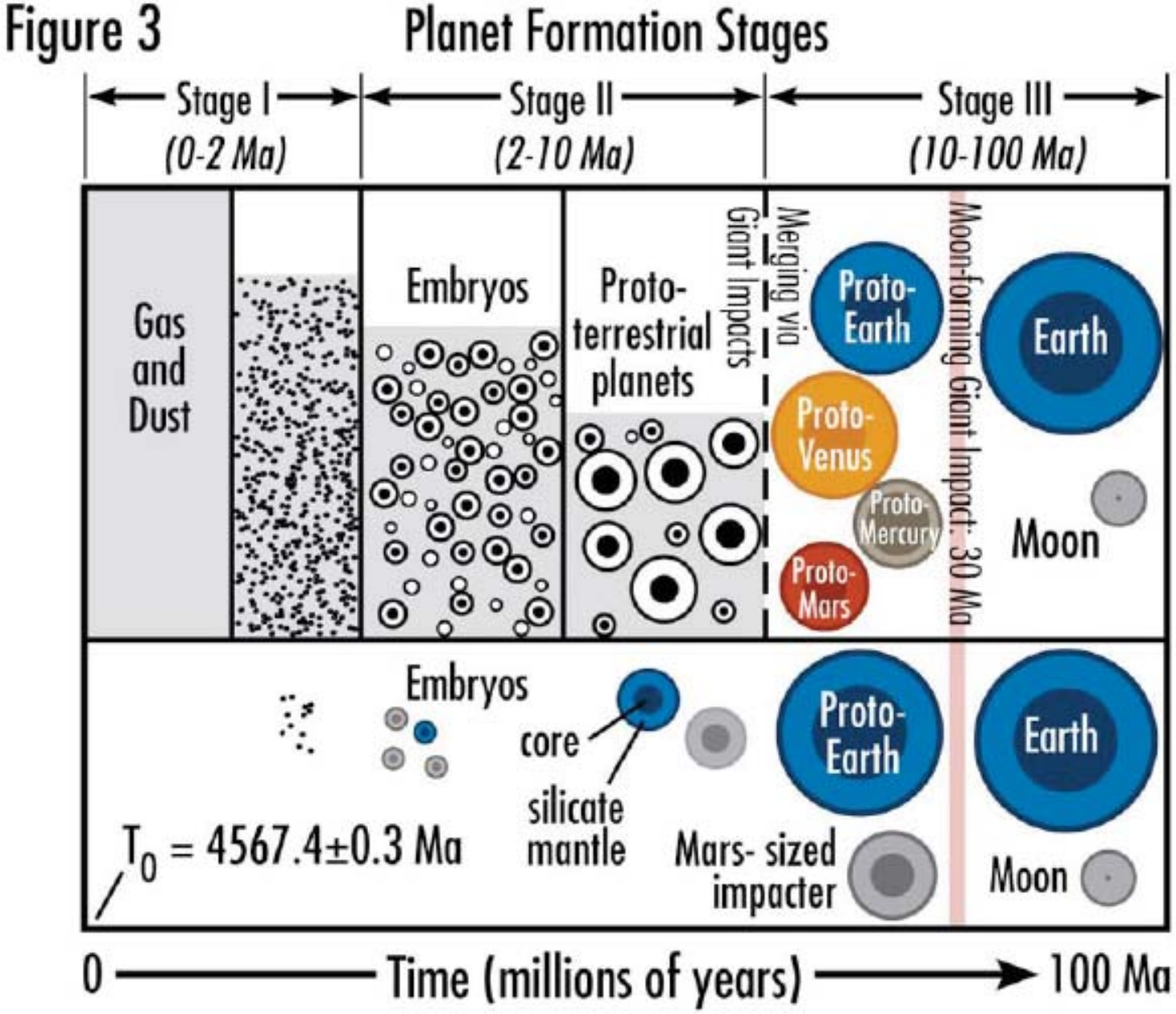
All slides are from

- Rich Walker, Thorsten Kleine, Herbert Palme, Lars Borg, Rick Carlson, Qing-Zhu Yin --- *thank you to these generous scientists!*

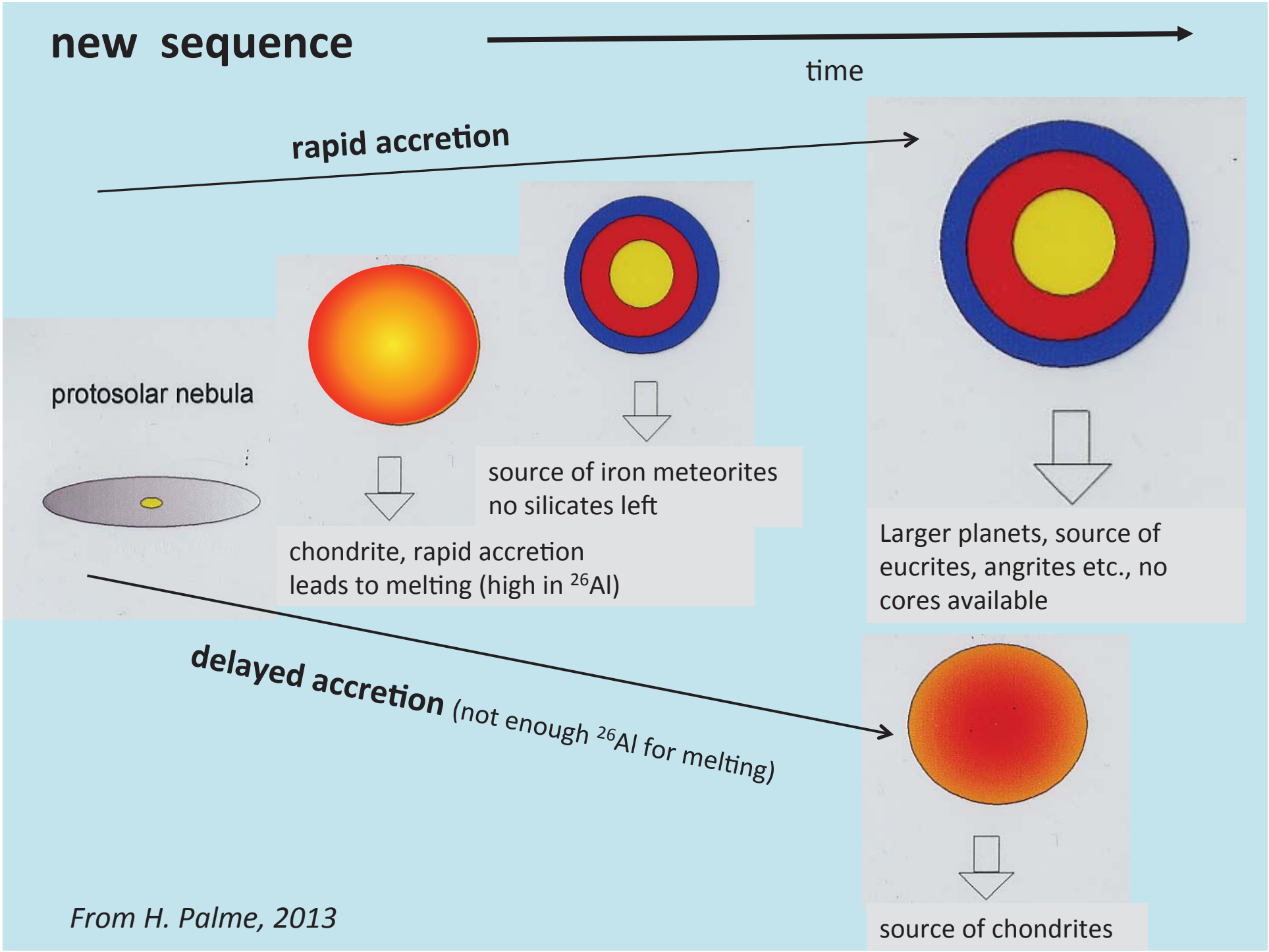
Take away message:

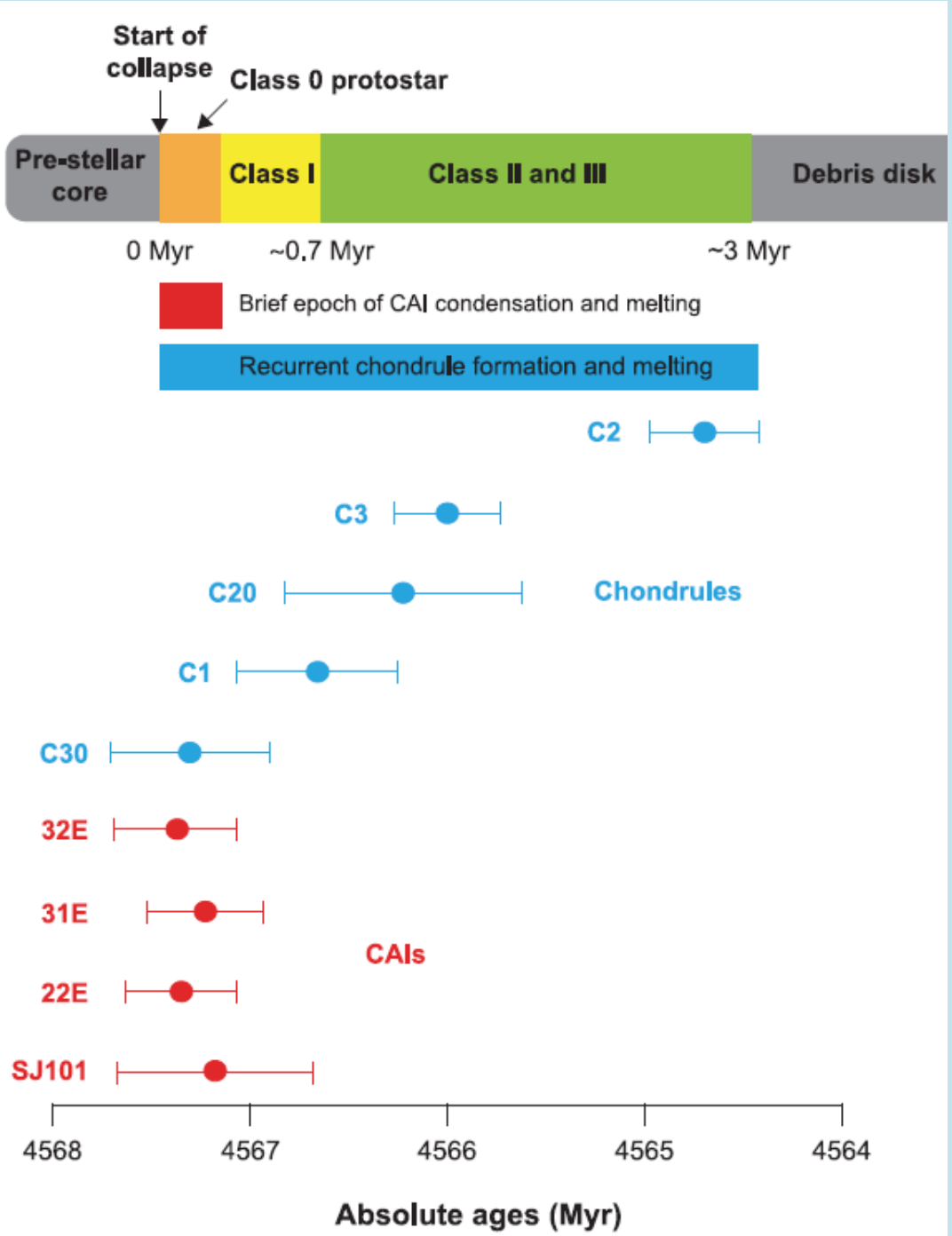
- CAI formed at 4568 Ma (i.e., t_{zero})
- Chondrules formed from 0.5 to ~5 Ma after t_{zero}
- Cores and Mantles of small planets (10 to 1000 km) formed between t_{zero} + 0.5 Ma to t_{zero} + ~5 Ma
- Earth & Moon fm between t_{zero}+~30 and t_{zero}+~150 Ma
- Accretion models, consider rapid planetary growth

Constraints on 2nd & 3rd stages



Q.-Z. Yin (2010)


new sequence
time
rapid accretion
protosolar nebula
source of iron meteorites
no silicates left
chondrite, rapid accretion
leads to melting (high in ^{26}Al)
Larger planets, source of
eucrites, angrites etc., no
cores available
delayed accretion (not enough ^{26}Al for melting)
source of chondrites
From H. Palme, 2013



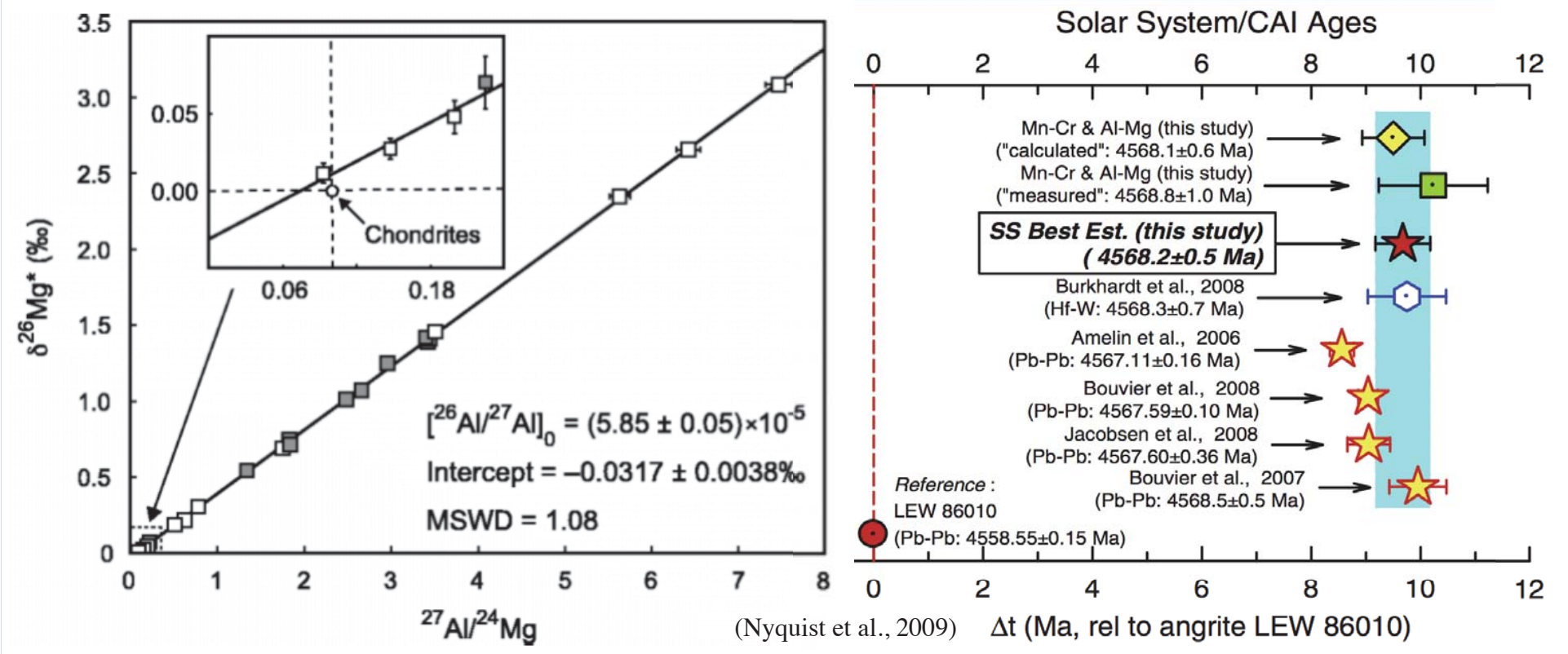
Oldest chondrules are as old as CAI.
Chondrules from a single meteorite seem to have formed over more than a million years.

Some chondrules formed after iron meteorites.

C3O and C20 Allende
C1, C2, C3 NWA 5697, OC

Conelly et al. 2012

High Chronological Resolution

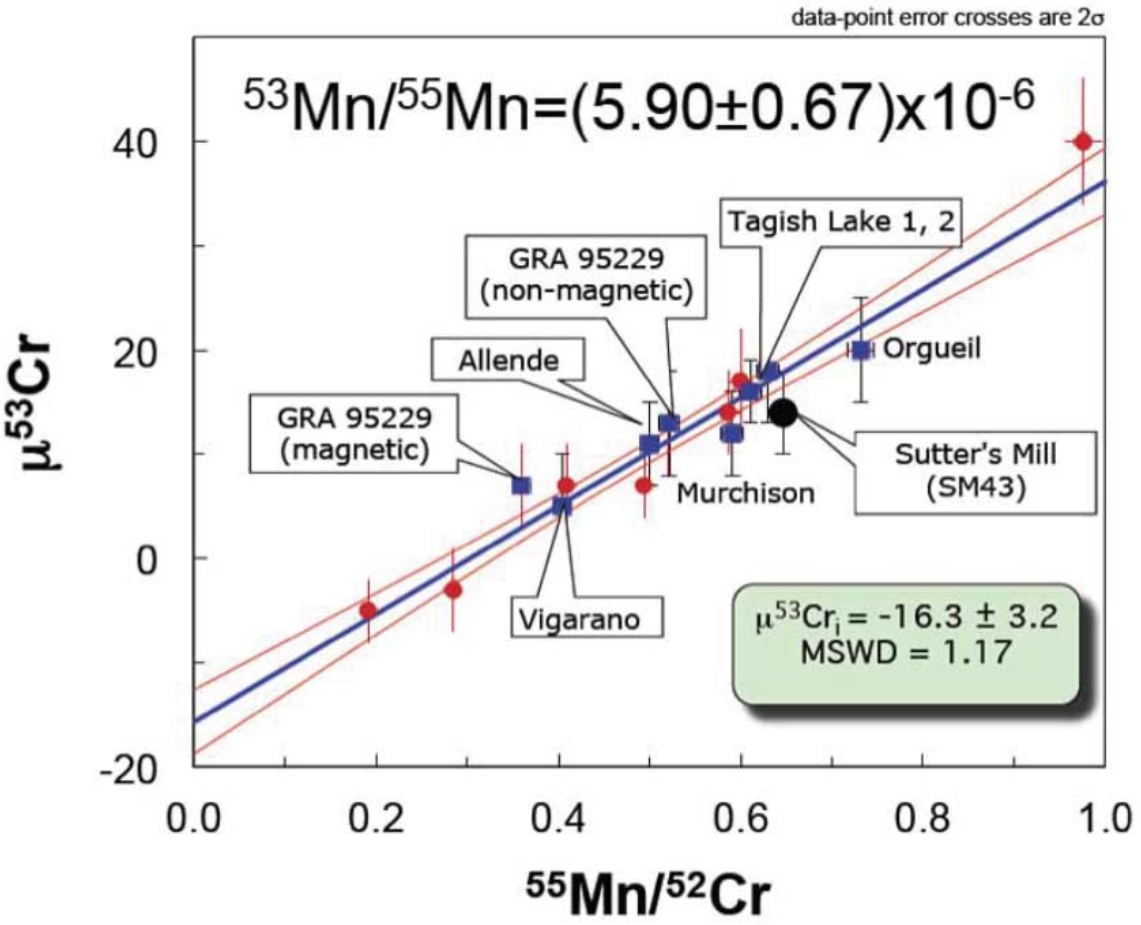


(Nyquist et al., 2009)

Al-Mg systematics for calcium-aluminum-rich inclusions from various carbonaceous chondrites (Thrane et al., Astrophys. J., 2006) provide a potential age precision of ± 9000 years. Accuracy, however, is of the order 1 Ma due to remaining questions of extinct nuclide calibrations.

From R. Carlson, 2015

Volatile Depletion occurred early in Solar System



^{53}Mn-^{53}Cr age = 4566.57±0.66 Ma

The first stage (Stage-1) of planet formation from dust to planetesimals

(complete within ~1.3 Ma)

Yin et al (2009); Jenniskens, Fries, Yin et al (2012 Science)

from Q. Z. Yin, 2015

Step 4: Planetesimals get Big Enough to Retain Enough Heat to Melt – Separate Cores and Form Crusts

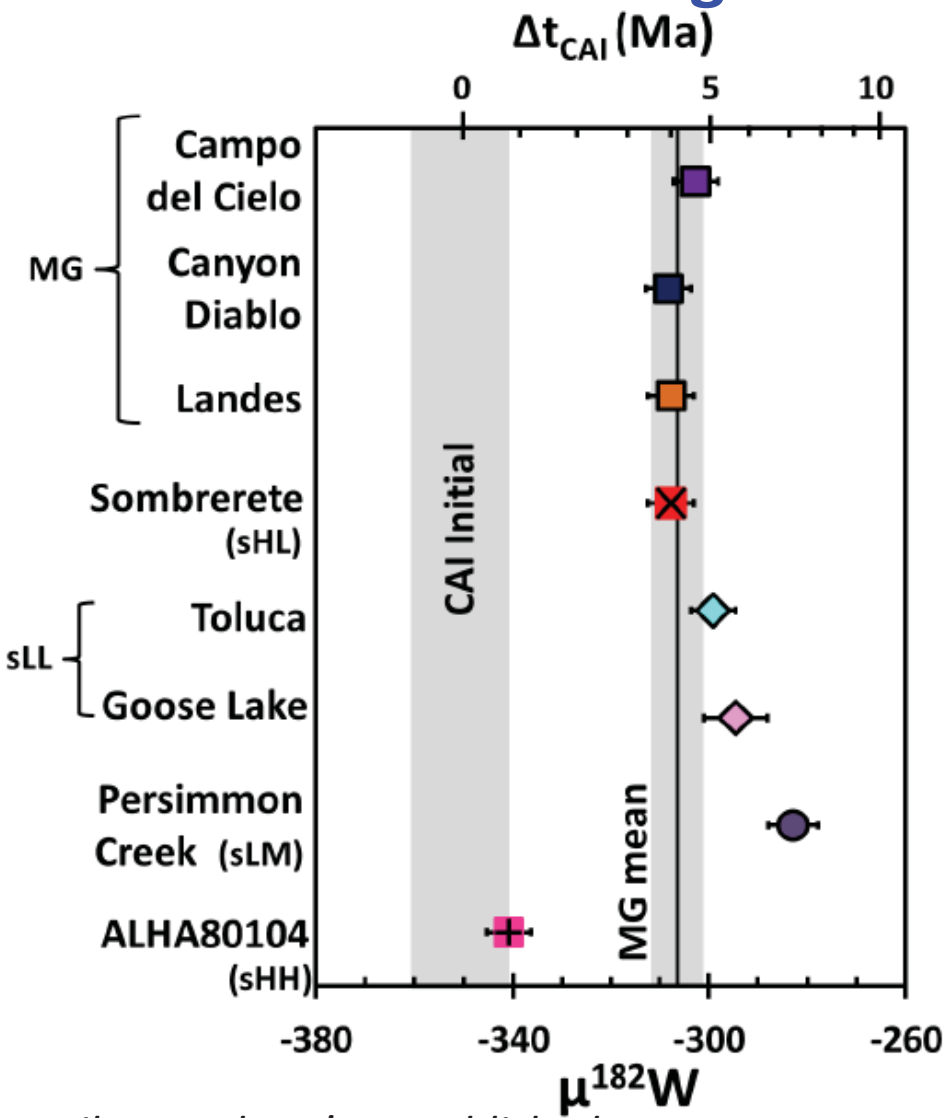
From R. Carlson, 2015

The D'Orbigny Angrite

Age:
U-Pb = 4563.4 ± 0.4 Ma
(Brenneka&Wadhwa, 2012)
Mn-Cr = 4562.9 ± 0.6 Ma (Glavin et al., 2004)
Hf-W = 4562.4 ± 1.5 Ma (Markowski+, 2007)
Al-Mg = 4562.8 ± 0.5 Ma
(Spivack-Birndorf et al., 2005)

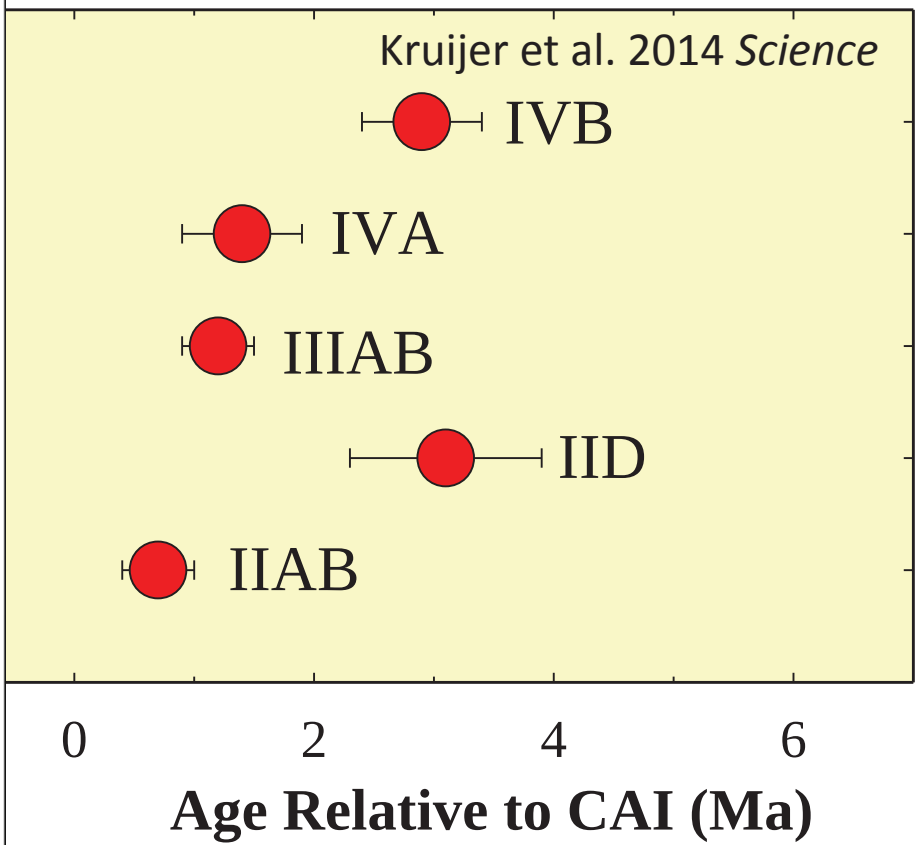
Small planet growth in just a few Myr)

IAB irons : non-magmatic



Emily Worsham's unpublished data (UMd Ph.D. student)

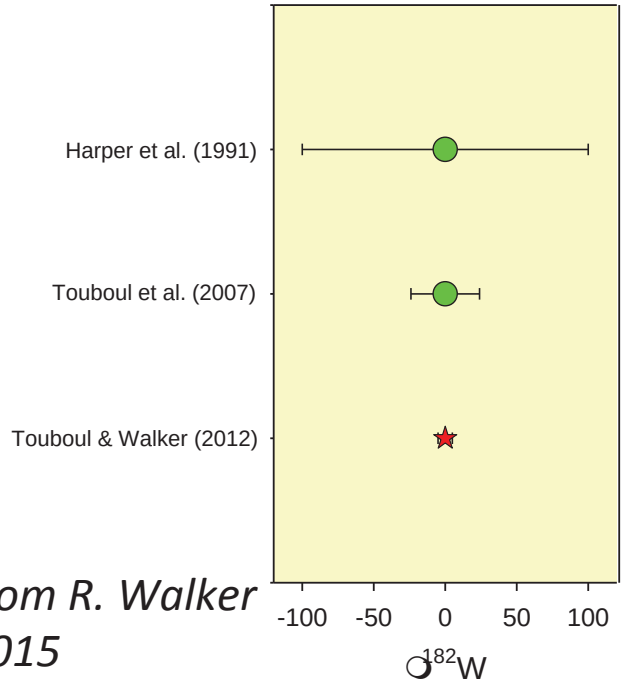
Magmatic irons



W isotope constrain these ages

from R. Walker 2015

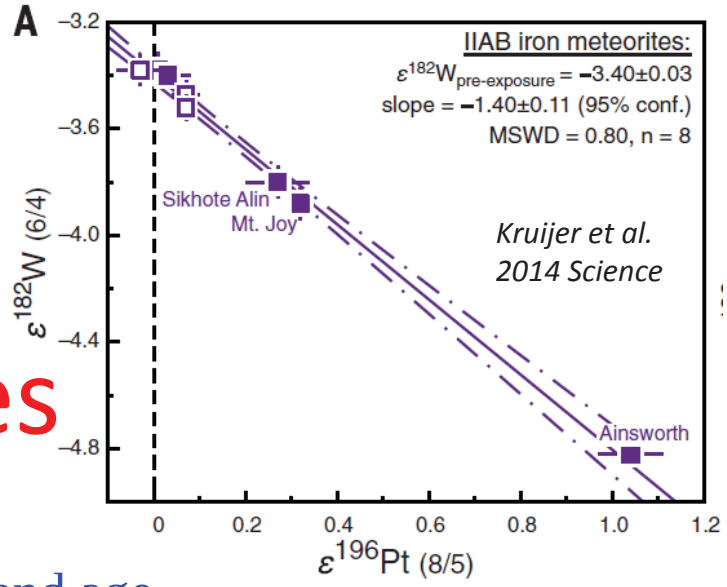
Advances in Measurement Techniques



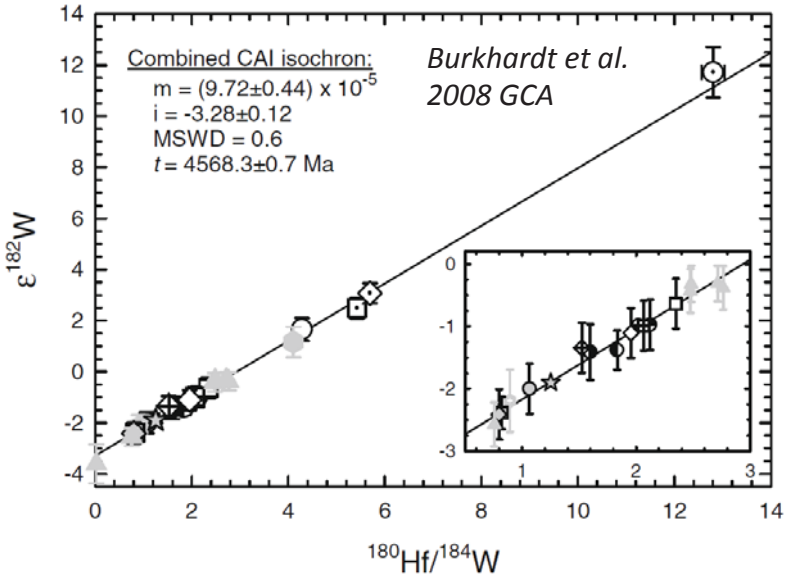
from R. Walker 2015

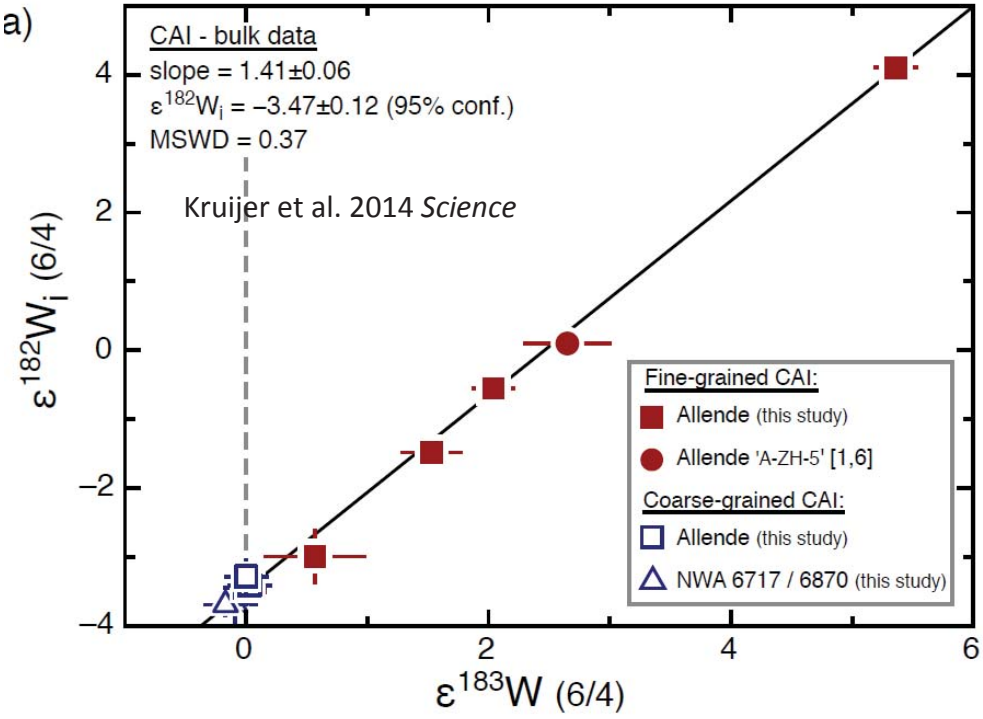
Advances

Pt & Os dosimeters of neutron fluence



CAI initial value and age





Lithophile (Hf) –Siderophile (W) System

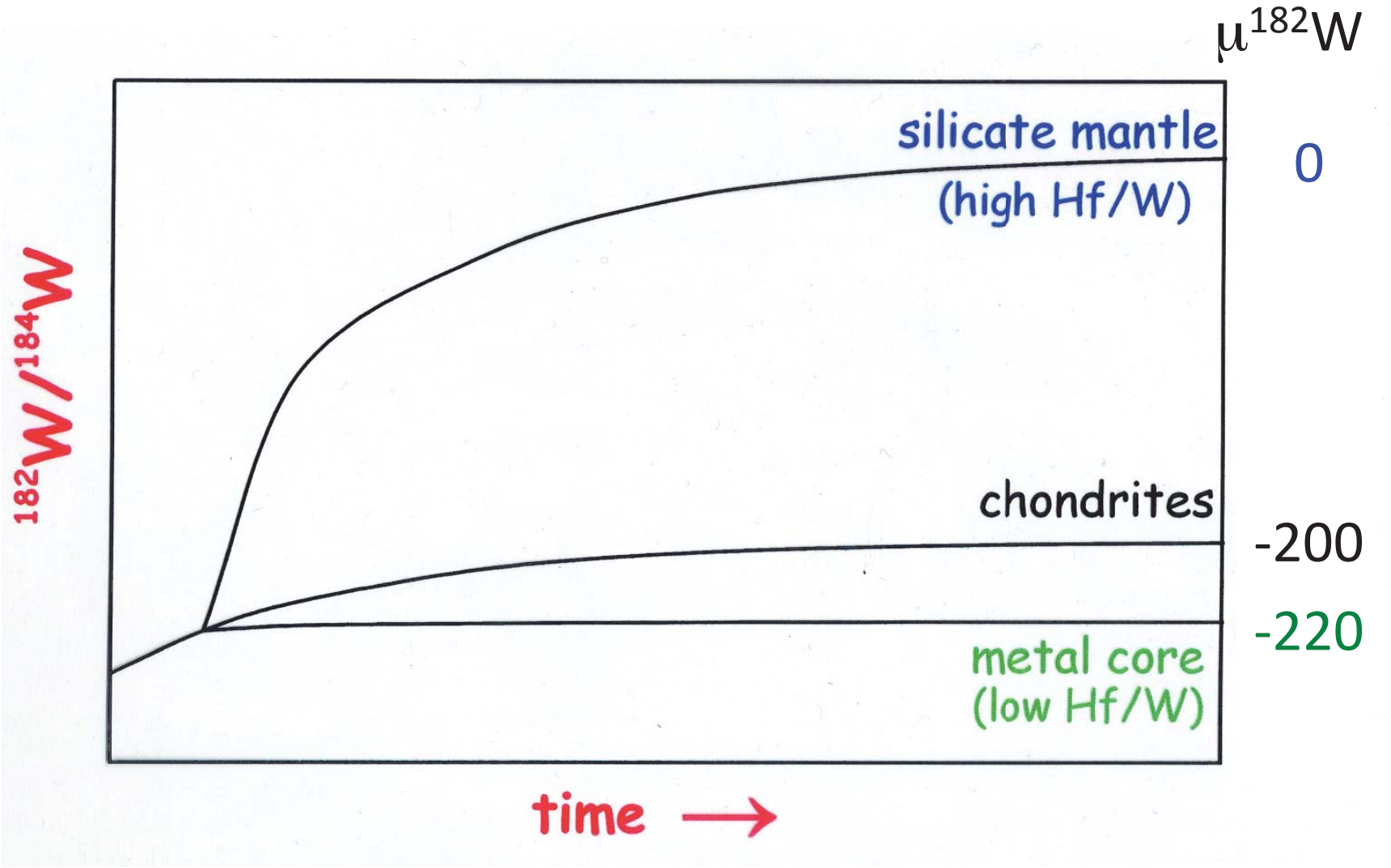
$$^{182}Hf \rightarrow {}^{182}W + \beta^-$$

$$t_{1/2} = 8.9 \times 10^6 \text{ yr}$$

	Hf (ppb)	W (ppb)	Hf/W	$\mu^{182}W$
Chondrites	200	180	1.2	-200
Mantle	280	15	19	0
Core	0	470	0	-220

$\mu^{182}W$ is the deviation in parts per million of $^{182}W/^{184}W$ ratio from standards.

from R. Walker 2015

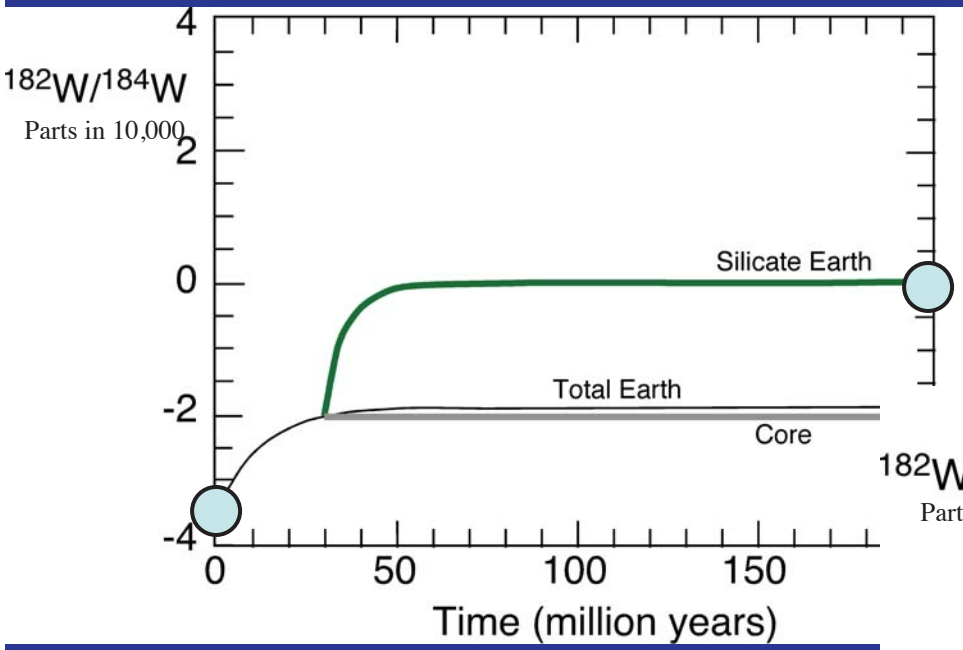


from H. Palme 2015

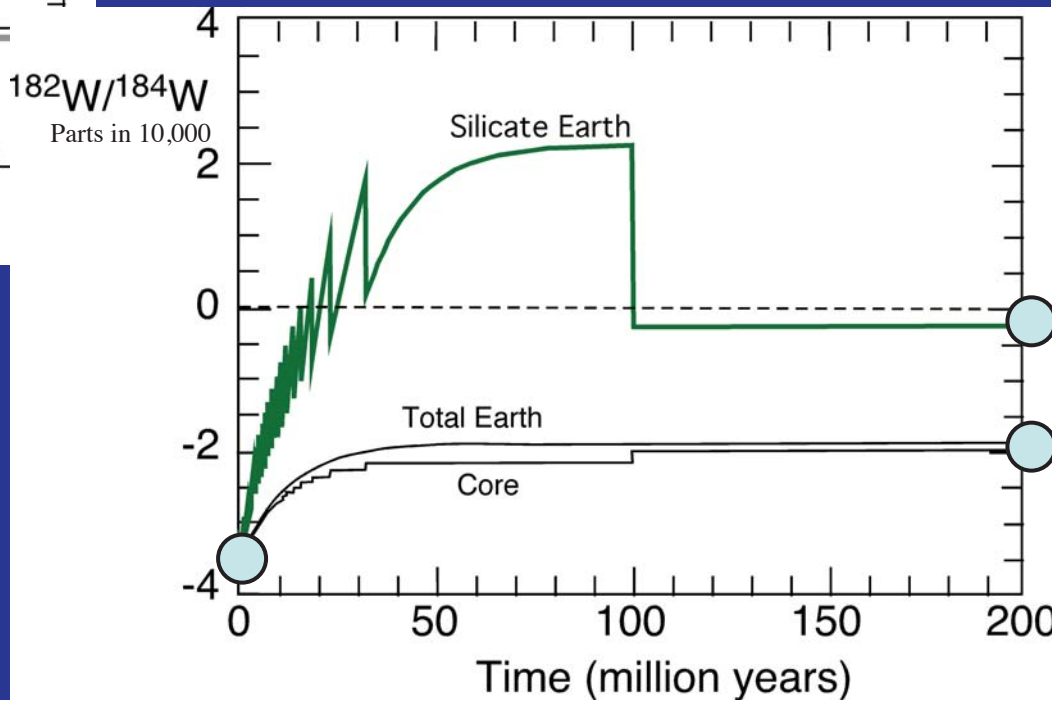
When Did Earth's Core Form?

If core formation were simple 33 ± 2 Ma after Solar System formation or 4.534 Ga

from R. Carlson 2015



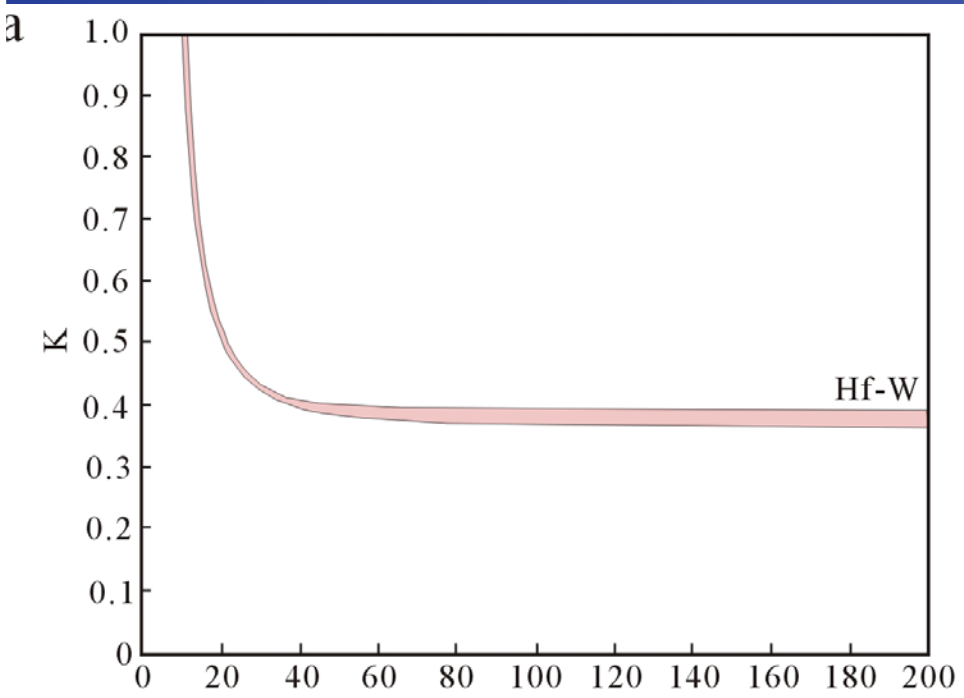
If Earth grew slowly and involved many "accumulation events", then the answer depends on the details of Earth accumulation

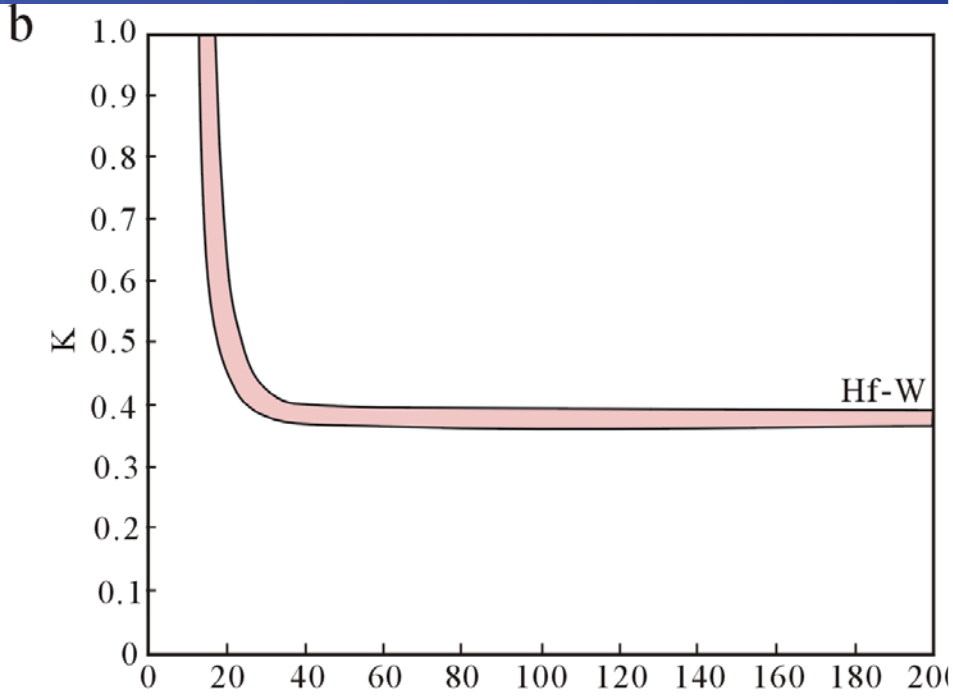


^{182}Hf -> ^{182}W ($t_{1/2}$ = 9 Ma)
Chondrite Hf/W = 1
Metal Hf/W = 0
Mantle Hf/W = 10

Hf-W chronology determines core-mantle differentiation time or equilibration degree?

Debated ever since Yin et al (2002) & Kleine et al (2002)



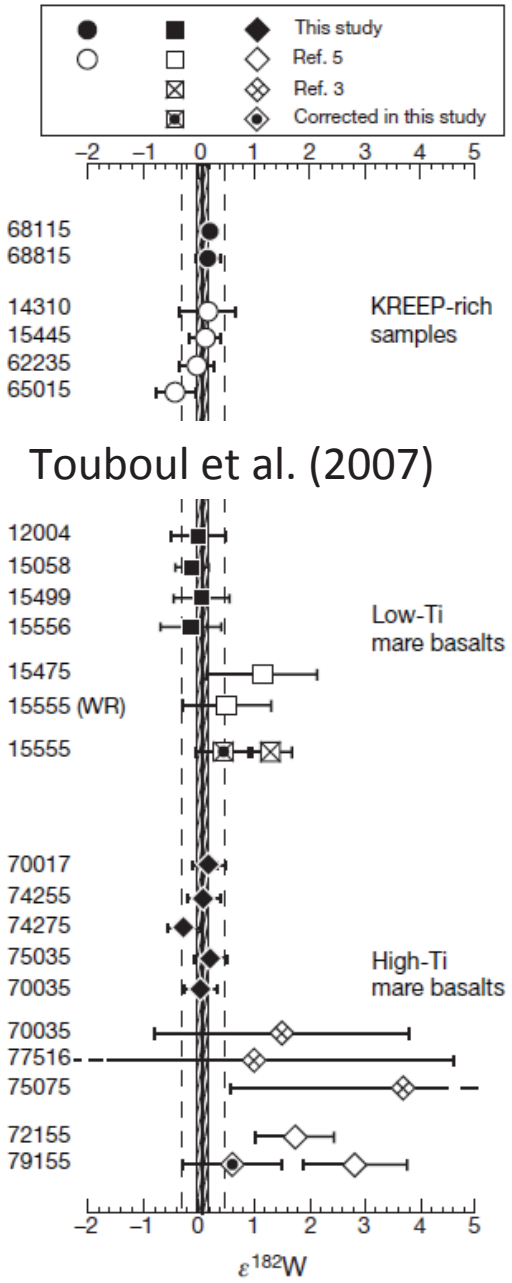


Exponential accretion model

Two stage model

Rudge et al (2010)

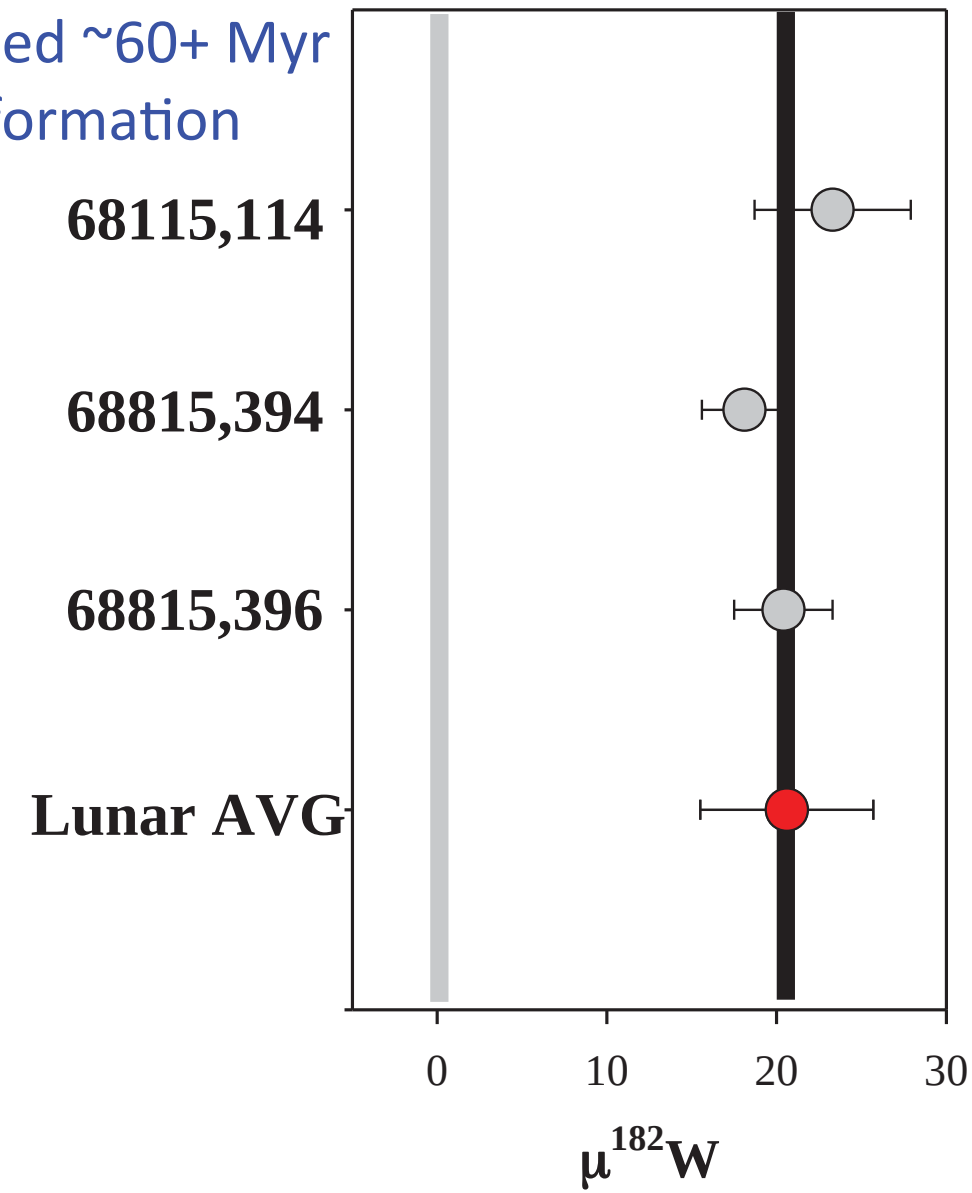
from Q-Z. Yin 2015



Touboul et al. (2007)

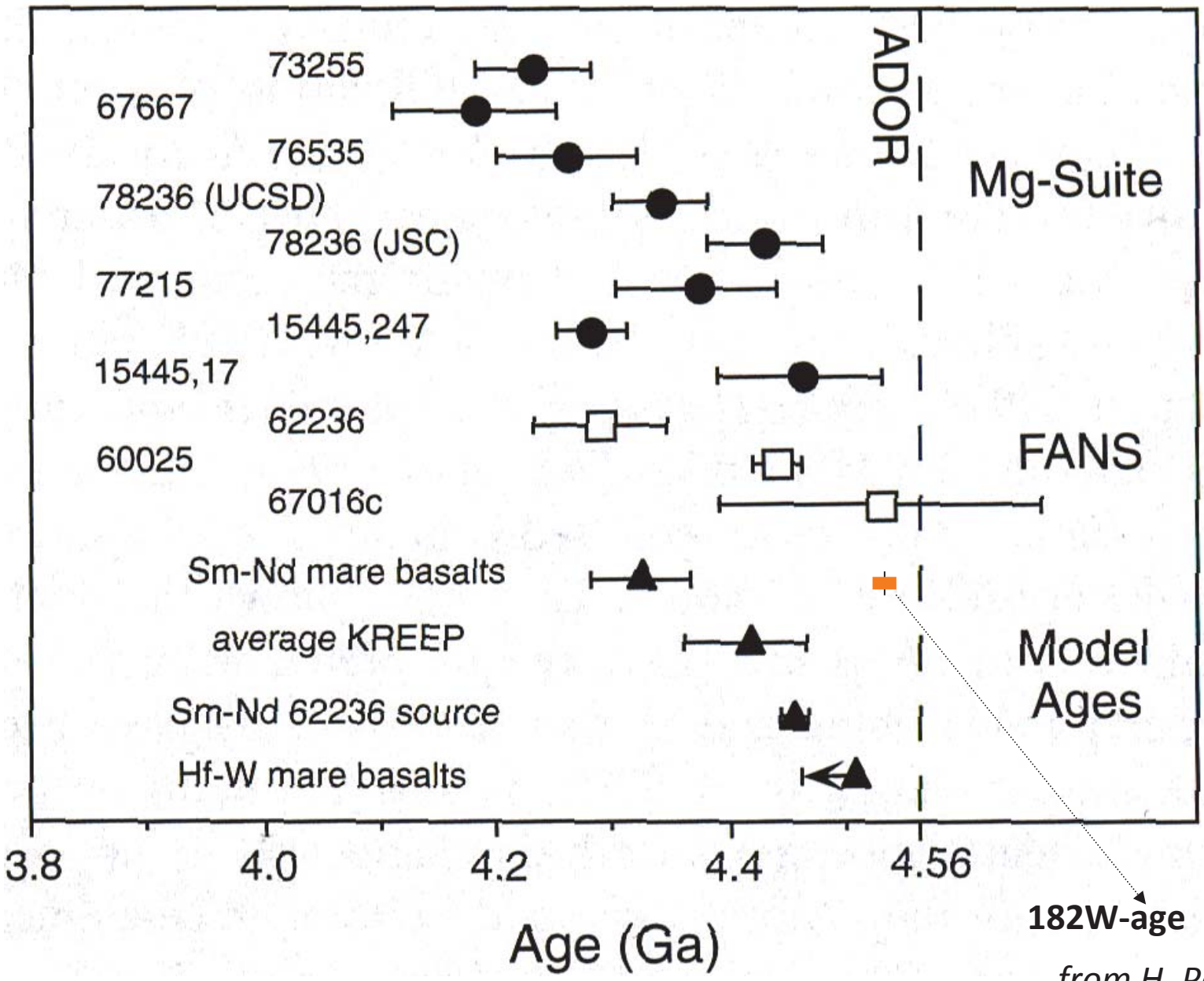
Moon W homogeneous at ~ ±30 ppm

Lunar Magma Ocean Crystallized ~60+ Myr after SS formation



from R. Walker 2015

$\mu^{182}W$ for 68115 & 68815 $+20.6 \pm 5.1$ (2σ SD)



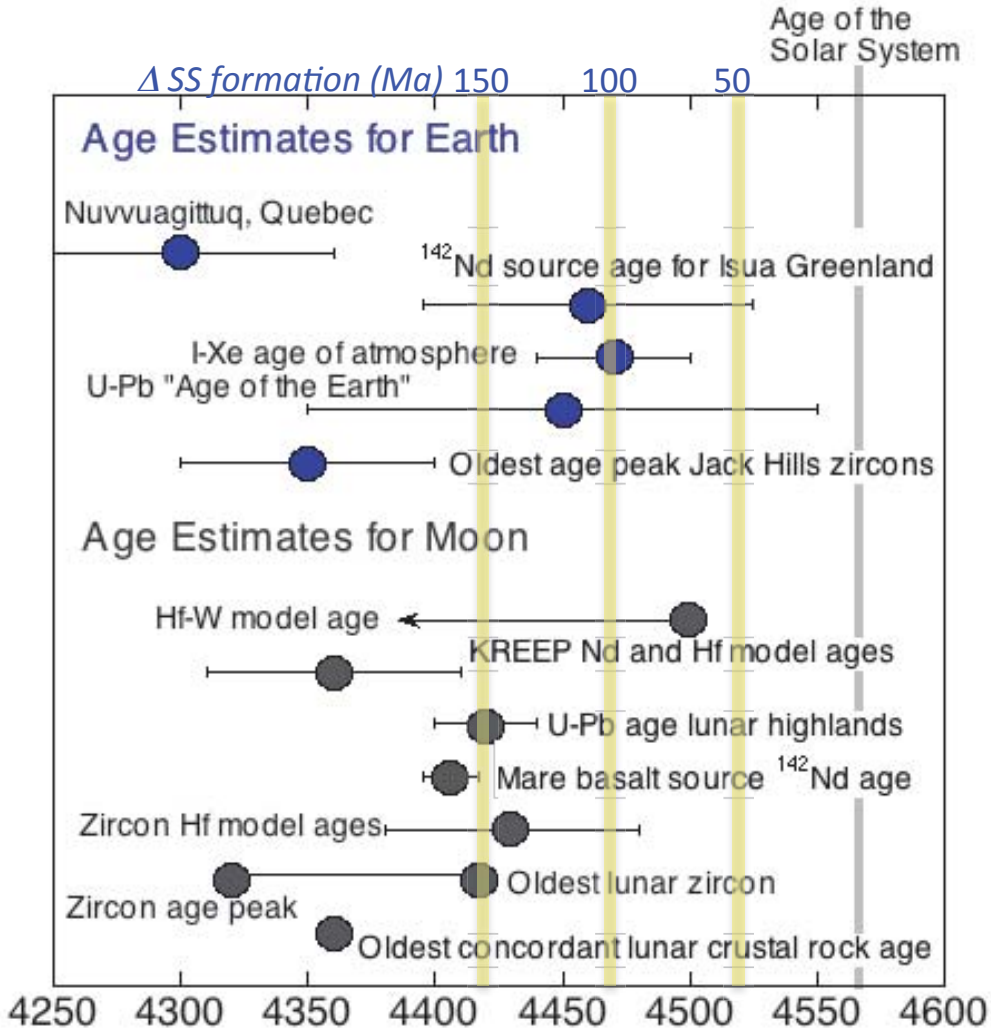
from H. Palme 2015

When Did the Giant Impact Occur?

Because the chronological resolution is now much higher than the duration of Earth formation, there is no easy answer to the "Age of the Earth".

These data suggest a major step in Earth growth, and Moon formation, as late as ~4.4 billion years ago

From R. Carlson, 2015



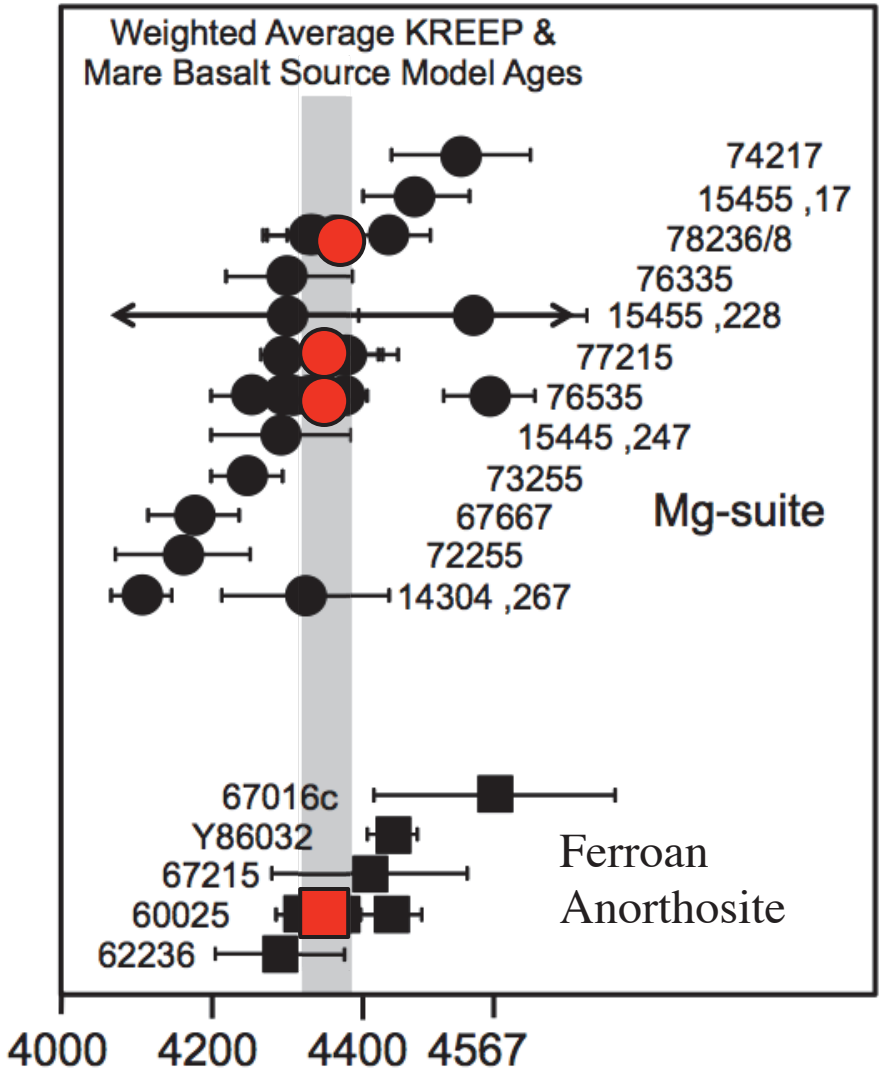
When/How Did the Lunar Crust Form?

CARNEGIE INSTITUTION FOR SCIENCE | DTM

Harrison Schmidt at the Station 7 Boulder, Apollo 17

Black points are literature data measured over the last 35 years. Red points from recent DTM studies of lunar highlands rocks. Grey band is the KREEP and mare basalt source model ages from Boyet and Carlson (2007).

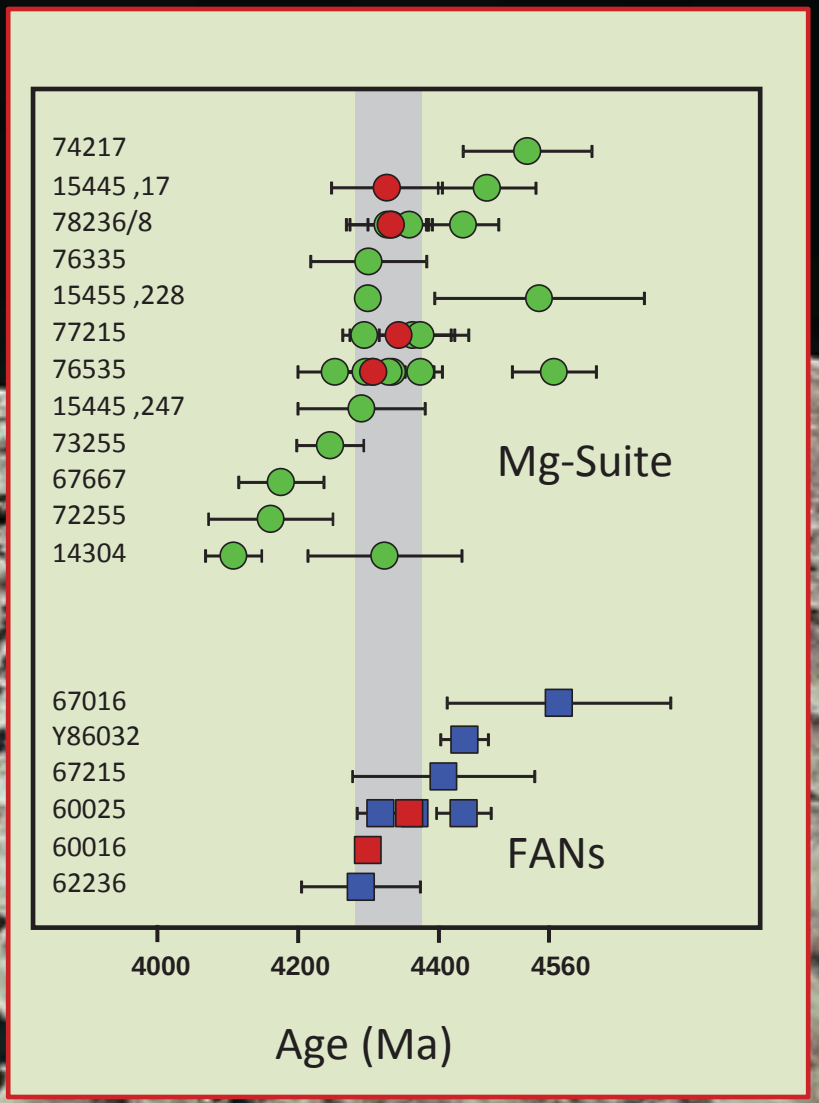
From R. Carlson, 2015

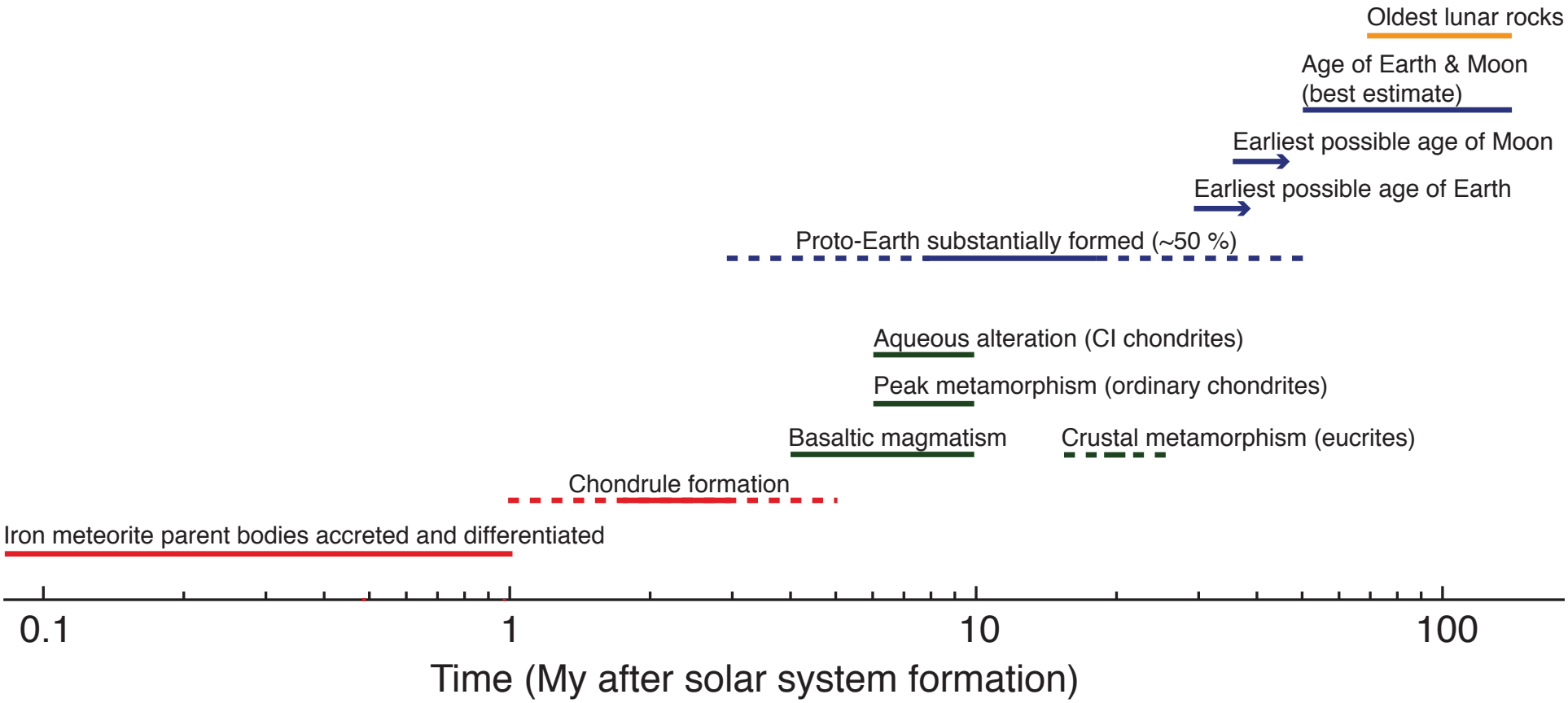


from L. Borg, 2015

Rb-Sr, Sm-Nd, & U-Pb Highland Rock Ages

- Red circles are average of $^{146}Sm \rightarrow ^{142}Nd$ ages and $^{147}Sm \rightarrow ^{143}Nd$ ages determined on same samples
- $^{146}Sm \rightarrow ^{142}Nd$ $t_{1/2}$ = 103 Ma is ideal to identify samples older than 4.45 Ga
- Only recently applied to lunar chronology due to technical challenges
- Ages imply anorthosite and Mg-suite magma contemporaneous over limited time span of 4310 to 4360 Ma





from T. Kleine, 2015