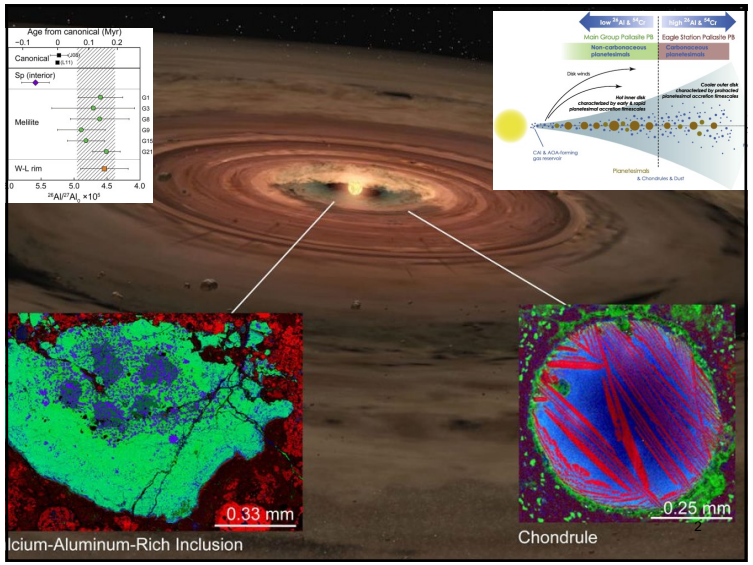
Early Solar System chronology

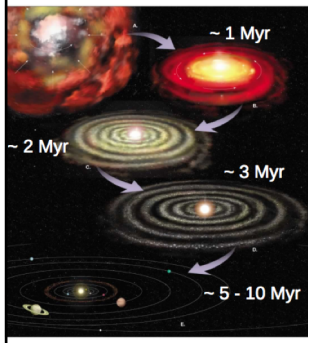
Take away message:

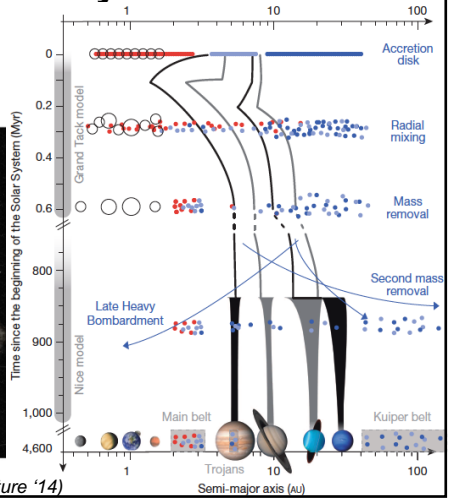
- CAI formed at 4568 Ma (i.e., t_{zero})
- Chondrules formed from 0.5 to ~5 Ma after t_{zero}
- Cores and Mantles of small planets (10 to 1000 km) formed between t_{zero} + 0.5 Ma to t_{zero} + ~5 Ma
- Earth & Moon fm between t_{zero}+~30 to +~60 Ma
- Accretion models: rapid planetary growth



Early planetary evolution

Planet building
- starts fast (<1 Ma)
- radial mixing





DeMeo & Carry, (Nature '14)

First ~3 Ma of Solar System history

time

rapid accretion

protosolar nebula

chondrite, rapid accretion leads to melting (^{26}Al rich)

source of iron meteorites no silicates left

Larger planets, source of eucrites, angrites etc., no cores available

delayed accretion (not enough ^{26}Al for melting)

source of chondrites

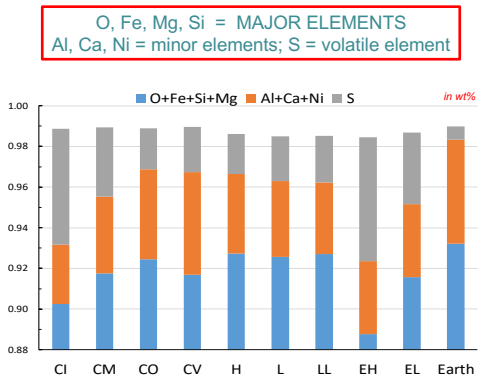
From H. Palme, 2013

Two-fold classification of elements

Refractory	>1400 K
"Si, Mg, Fe, Ni…	1350 to 1250 K
Moderately volatile	1250 to 650 K
Volatile	<650 K

classified	affinity	where
Siderophile	iron	core
Lithophile	oxide	mantle
Chalcophile	sulfur	mostly core

Redox conditions in the Solar System…..

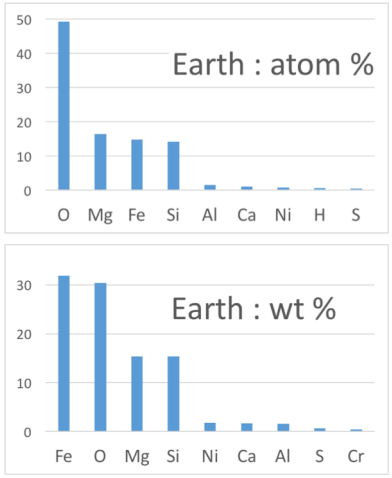


6

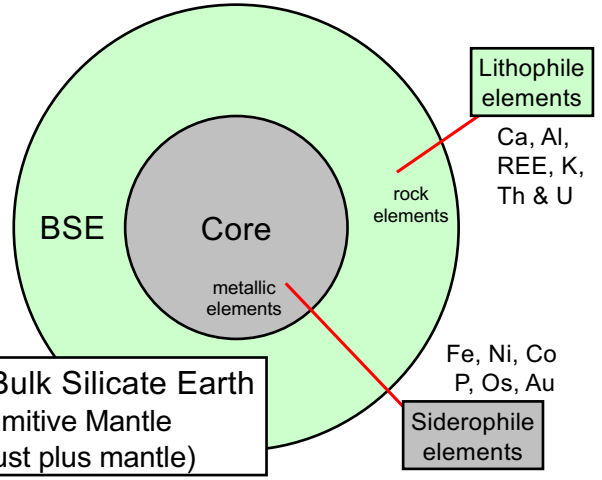
Most abundant 9 elements in the Earth

O & Fe
Mg & Si
Ni, Ca, & Al
S, & Cr or H…

93%
98%
99%



Element Distribution in the Earth



BSE: Bulk Silicate Earth
aka, Primitive Mantle
(i.e., crust plus mantle)

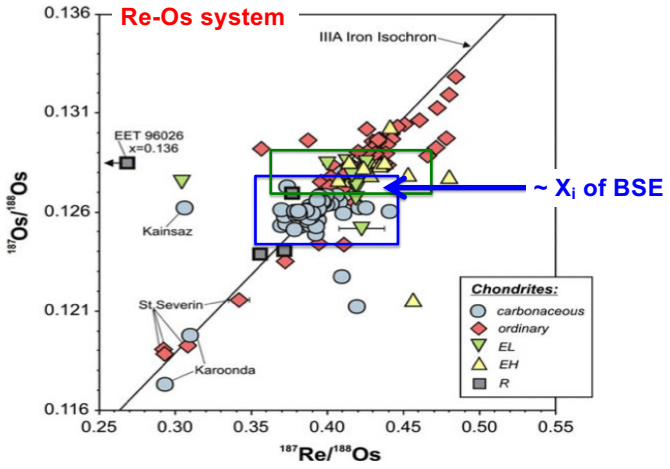
Useful long-lived Isotope Systems

Parent nuclide	Daughter nuclide	Half-life	Tracer ratio (daughter/stable)
^{40}K	^{40}Ar	1.26 Ga	$^{40}Ar/^{36}Ar$
^{87}Rb	^{87}Sr	49.6 Ga	$^{87}Sr/^{86}Sr$
^{147}Sm	^{143}Nd	106 Ga	$^{143}Nd/^{144}Nd$
^{176}Lu	^{176}Hf	37.1 Ga	$^{176}Hf/^{177}Hf$
^{187}Re	^{187}Os	41.6 Ga	$^{187}Os/^{188}Os$
^{232}Th	^{208}Pb	14.1 Ga	$^{208}Pb/^{204}Pb$
^{235}U	^{207}Pb	0.7035 Ga	$^{207}Pb/^{204}Pb$
^{238}U	^{206}Pb	4.468 Ga	$^{206}Pb/^{204}Pb$

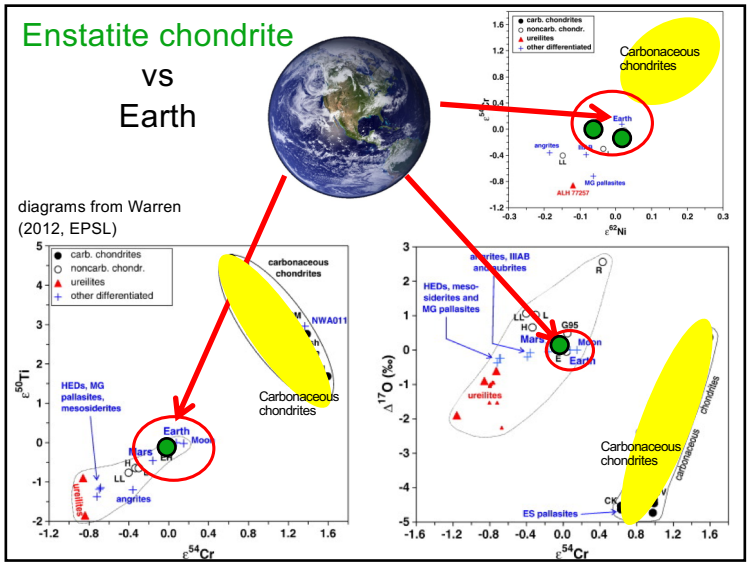
Useful short-lived Isotope Systems

Parent nuclide	Daughter nuclide	Half-life	Tracer ratio (daughter/stable)
^{26}Al	^{26}Mg	0.717 Ma	$^{26}Mg/^{24}Mg$
^{60}Fe	^{60}Ni	2.62 Ma	$^{60}Ni/^{61}Ni$
^{182}Hf	^{182}W	8.9 Ma	$^{182}W/^{184}W$
^{129}I	^{129}Xe	15.7 Ma	$^{129}Xe/^{130}Xe$
^{244}Pu	^{232}Th ($^{131-136}Xe$)	81.1 Ma	$^{131-136}Xe$(fission)
^{146}Sm	^{142}Nd	103 Ma	$^{142}Nd/^{144}Nd$

Isotopic differences between chondrites: refractory elements

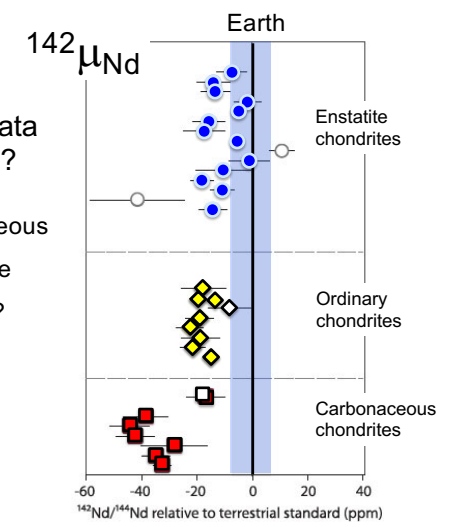


Fischer-Godde et al (2011)



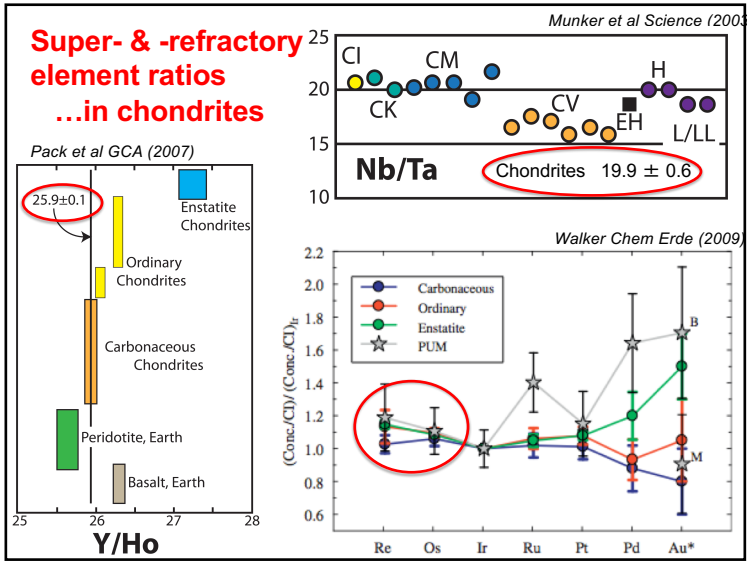
What does this Nd data mean for the Earth?

- Solar syst. heterogeneous
- Chondrites are a guide
- Planets ≠ chondrites ?



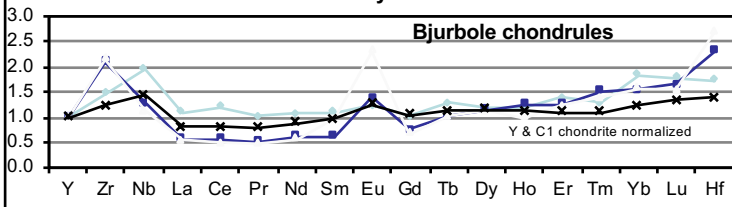
Data from:
Gannoun et al (2011, PNAS)
Carlson et al (Science, 2007)
Andreasen & Sharma (Science, 2006)
Boyet and Carlson (2005, Science)
Jacobsen & Wasserburg (EPSL, 1984)

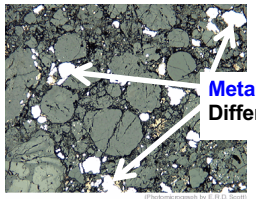
Super- & -refractory element ratios …in chondrites



Causes of chemical variations in chondrules

Common in chondrules: Volatility controlled REE fractionation

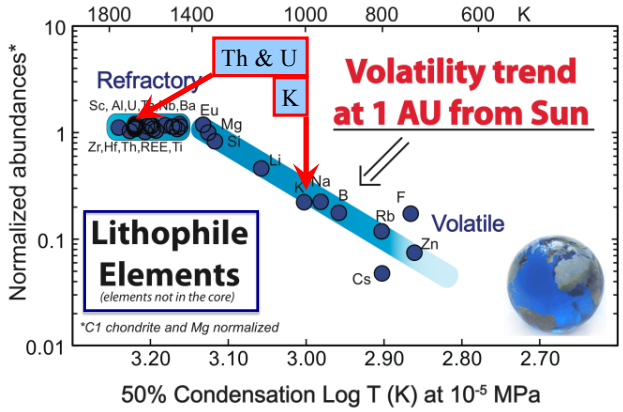




Ed Scott - http://www.psrd.hawaii.edu/Dec01/Oisotopes.html

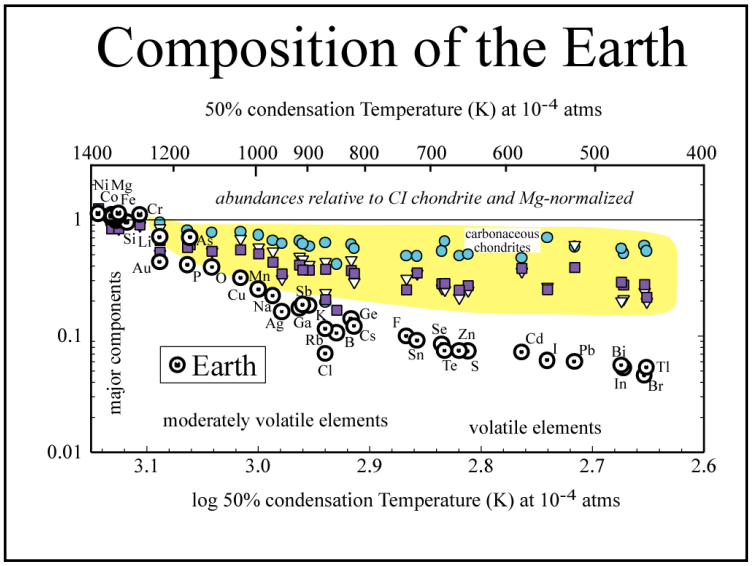
Differences in starting materials

Bulk Silicate Earth

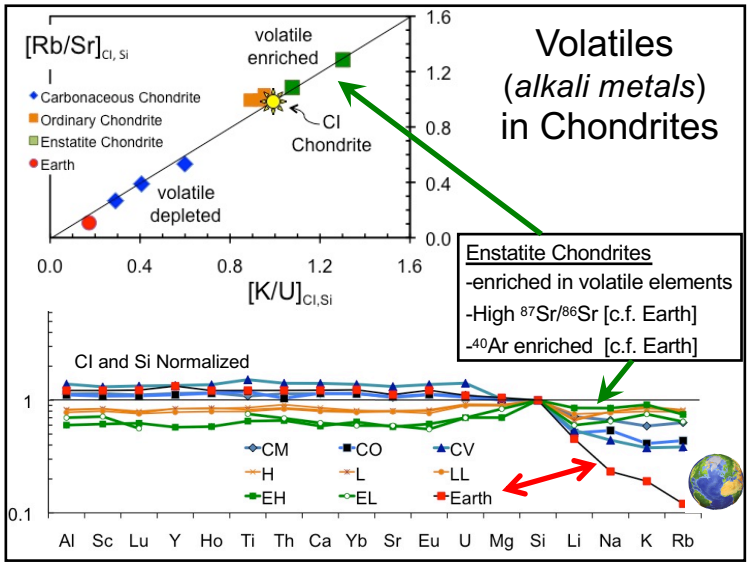


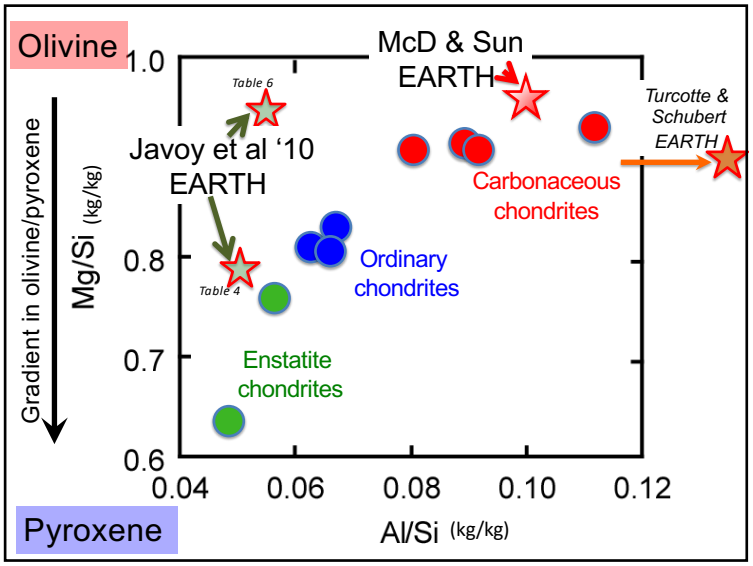
McDonough and Sun '95

Composition of the Earth

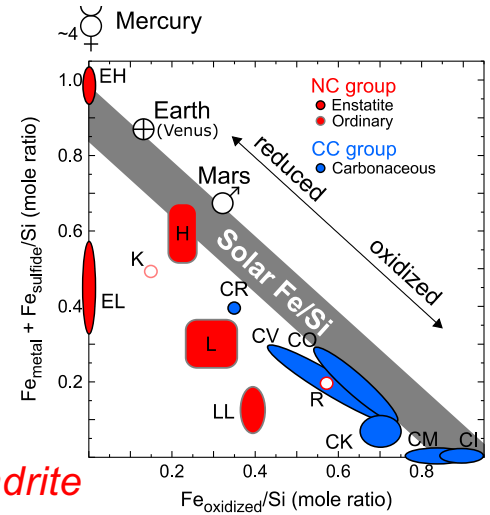


Volatiles (*alkali metals*) in Chondrites

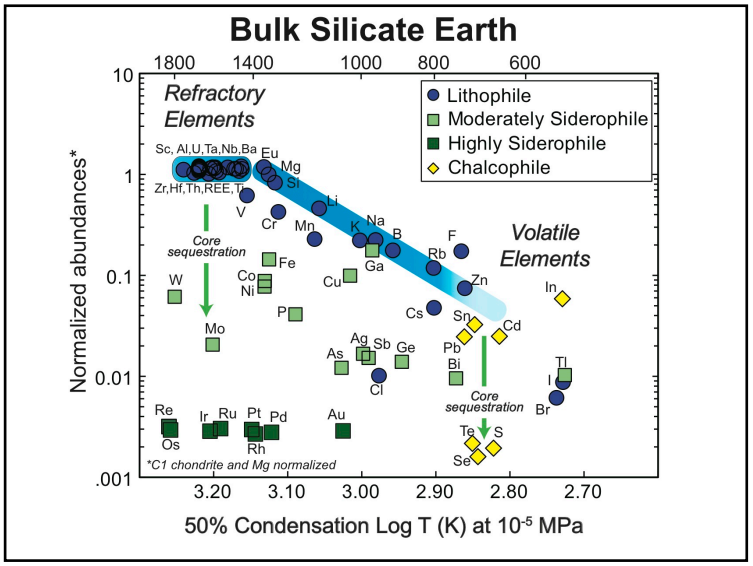




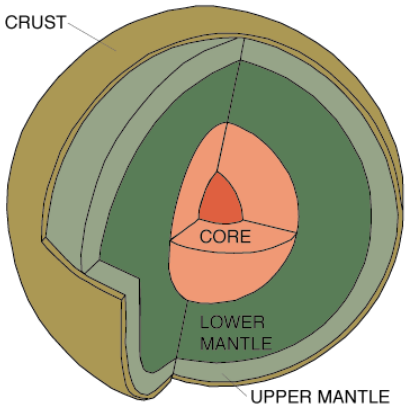
Redox state of the Earth



Which *chondrite* is the Earth?



The Earth is differentiated

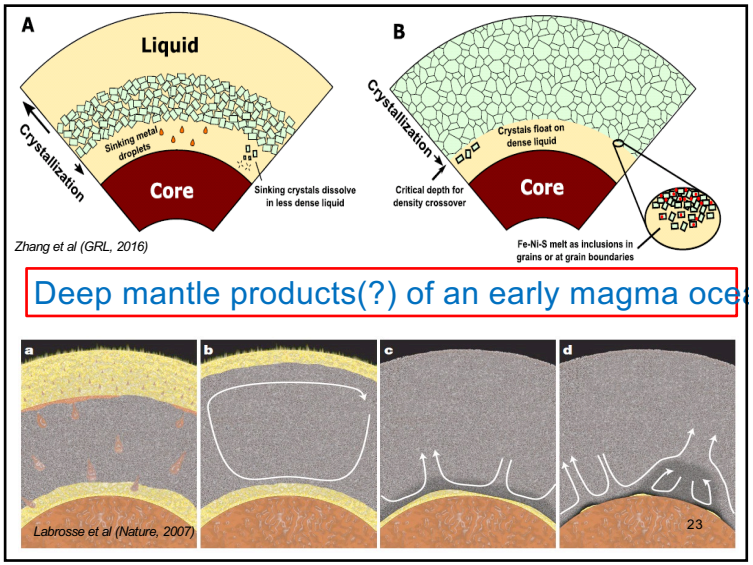


How and When did this occur?

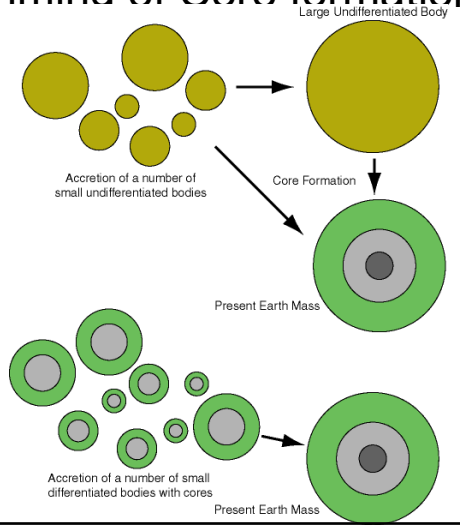
Two Sets of Constraints:

Physical Mechanisms and
Chemical Signatures

Slide 22



Timing of Core formation



Slide 24

Lithophile (Hf) –Siderophile (W) System

$$^{182}Hf \rightarrow {}^{182}W + \beta^-$$
$$t_{½} = 8.9 \times 10^6 \text{ yr}$$

	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

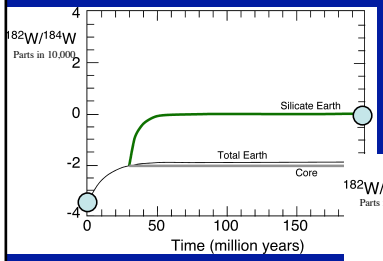
$\mu^{182}W$ is the deviation in parts per million of $^{182}W/^{184}W$ ratio from standards.

from R. Walker 201

When Did Earth's Core Form?

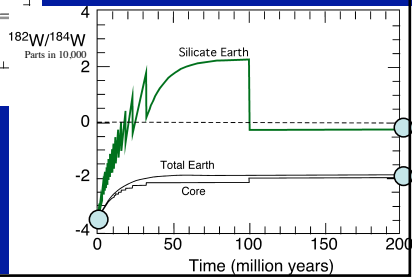
If core formation were simple 33 ± 2 Ma after Solar System formation or 4.534 Ga

from R. Carlson 2015



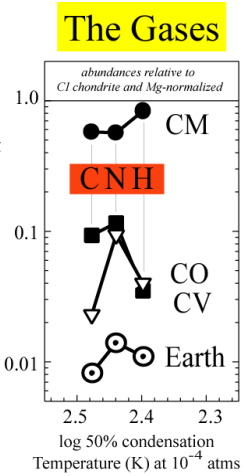
If Earth grew slowly and involved many "accumulation events", then the answer depends on the details of Earth accumulation

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



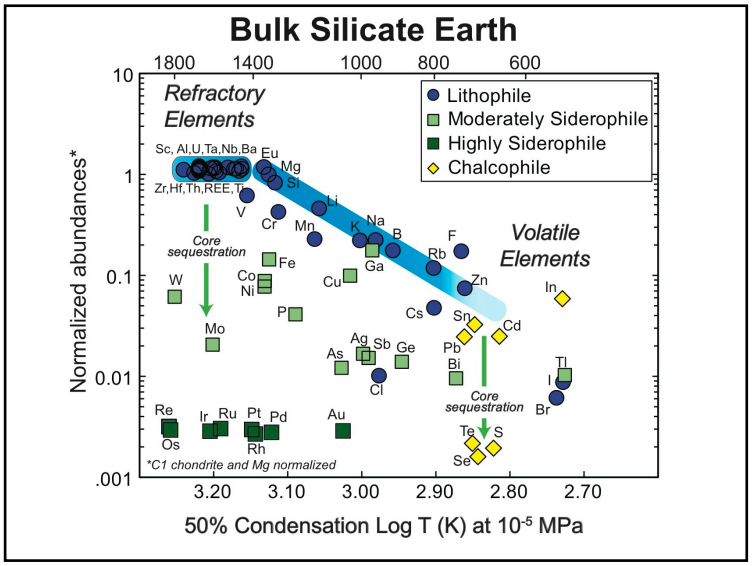
The Gases

Abundances of element Gases in the Primitive Mantle



Volatile questions

- What are the volatile elements?
- What are their abundances in the Earth?
- When did we inherit them?
- How did we inherited?
- Is there a secular variation in the volatile elements abundances of the Earth?

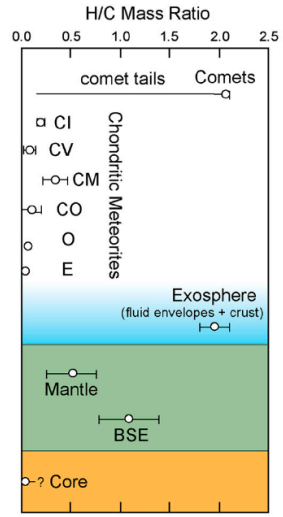


Volatiles: defined

- H_2O, CO_2, N_2, CH_4, (i.e., H, C, N, O)
- Noble gases (group 18 elements)
- elements with half-mass condensation T <1250 K
- elements readily degassed (e.g., Re, Cd, Pb…)
- chalcogens (group 16: i.e., O, S, Se and Te)
- halides (group 17: i.e., F, Cl, Br, I)?
- alkali metals (group 1: Cs, Rb, K…)?

Volatiles: distribution

- **Atmosphere** (N_2 78%, O_2 21%, Ar 1%, other)
- **Mantle volatiles**: H_2O, C(C, CO_2, CO, CH_4), sulfides, etc
- **Core volatiles**: FeC, FeN, FeO, FeS, FeH



Volatile Budget!

H/C ratio of the bulk silicate Earth is superchondritic, owing chiefly to the high H/C ratio of the exosphere.

H/C ratio of the mantle is lower than that of the exosphere, requiring significant H/C fractionation during ingassing or outgassing at some point in Earth history.

Hirschmann and Dasgupta (2009)