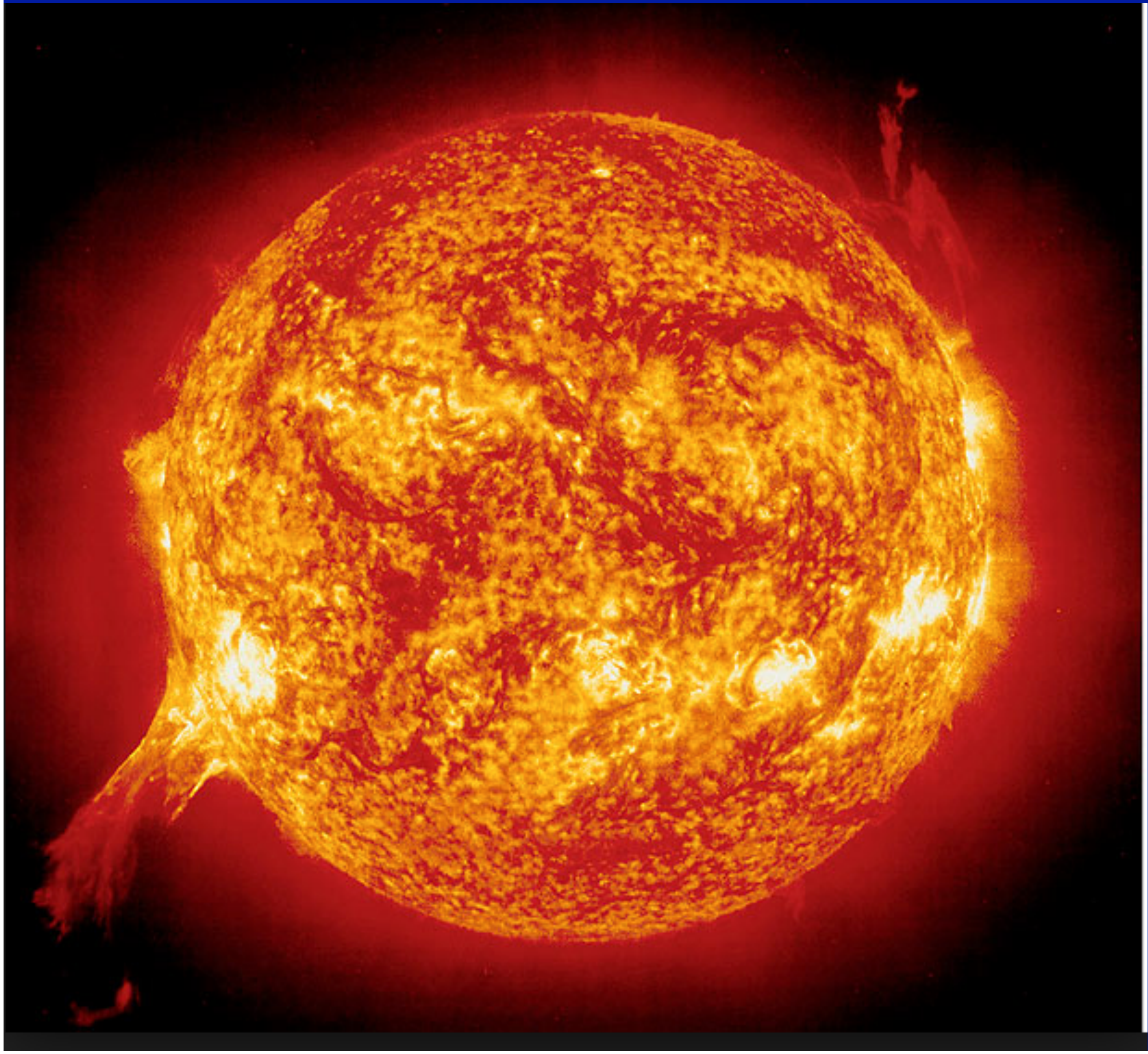
Cosmic Building Blocks: From What is Earth Made?



The Sun constitutes 99.87% of the mass of the Solar system.

Earth is big and important, so its composition should be similar to that of the average Solar system, e.g., Sun

Richard Carlson
Carnegie Inst. Science
CIDER Geoneutrinos 2014

A Solar Compositional Analog in the Laboratory

Orgueil, CI Carbonaceous Chondrite

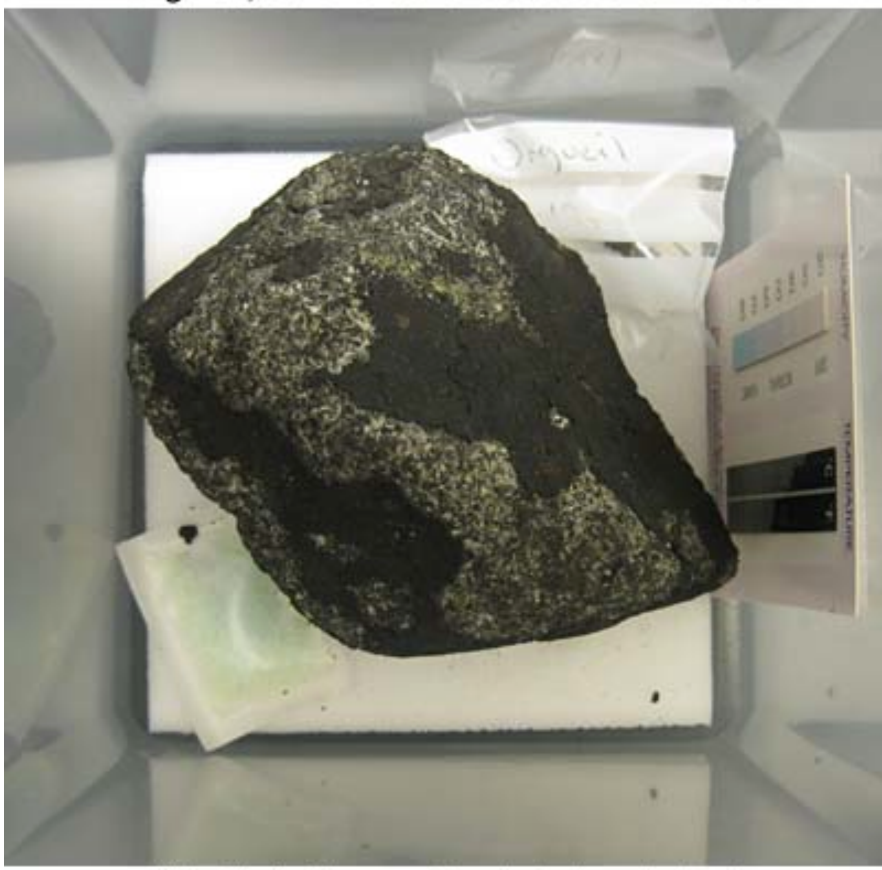
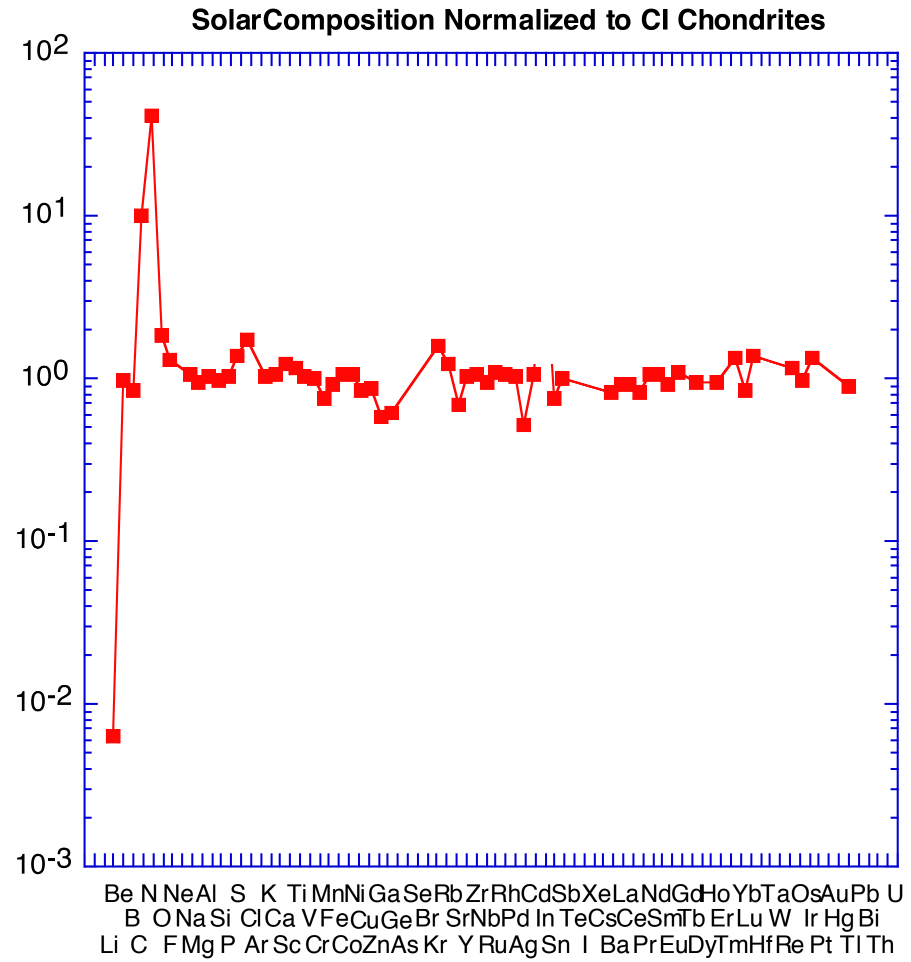
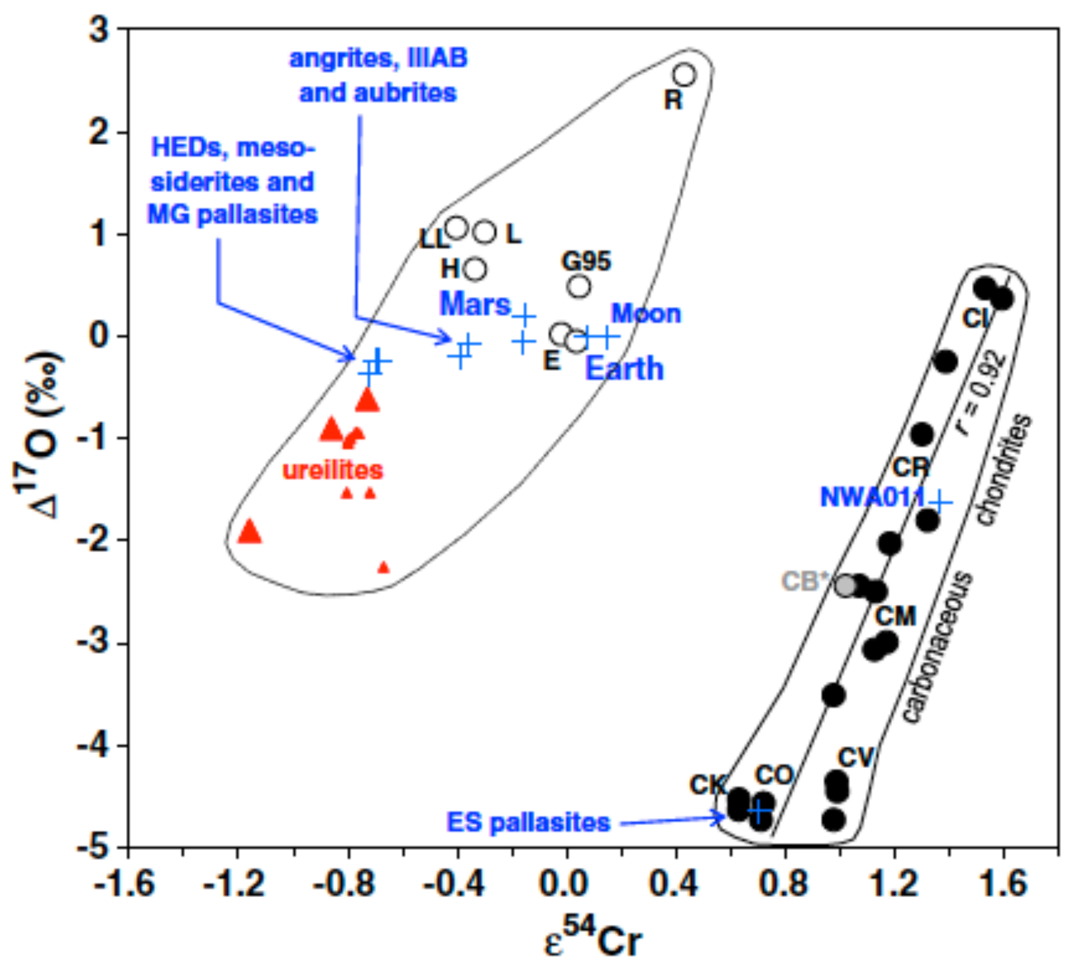
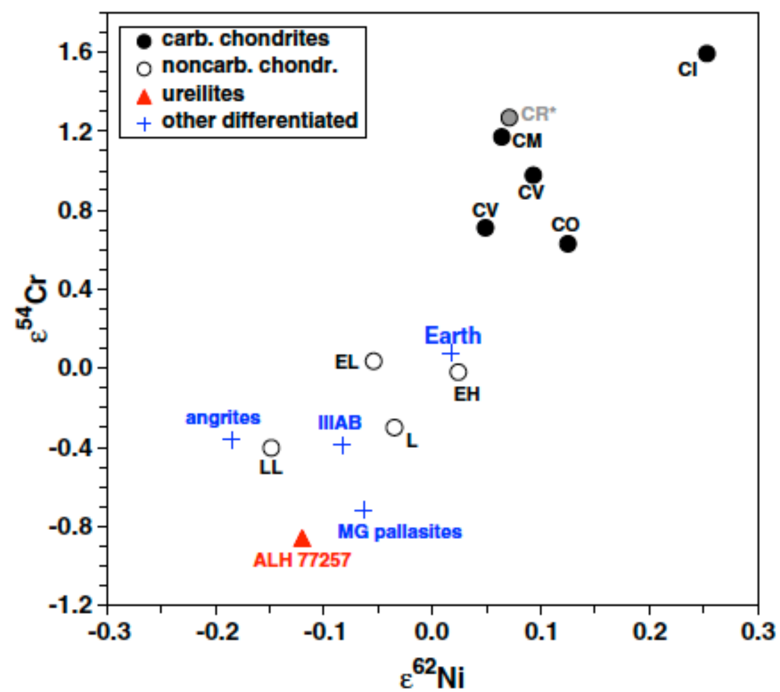


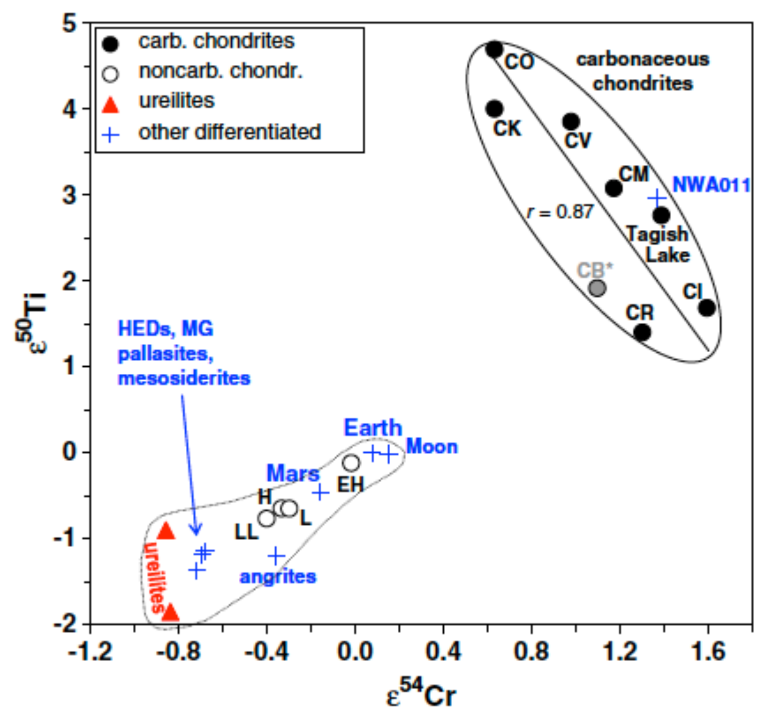
Photo by L. Martel, www.psrd.hawaii.edu with permission of Natural History Museum, London.



Elements in Order of Atomic Mass







Isotopic studies are revealing an ever increasing number of elements where Earth is isotopically distinct from most meteorites, particularly C-chondrites

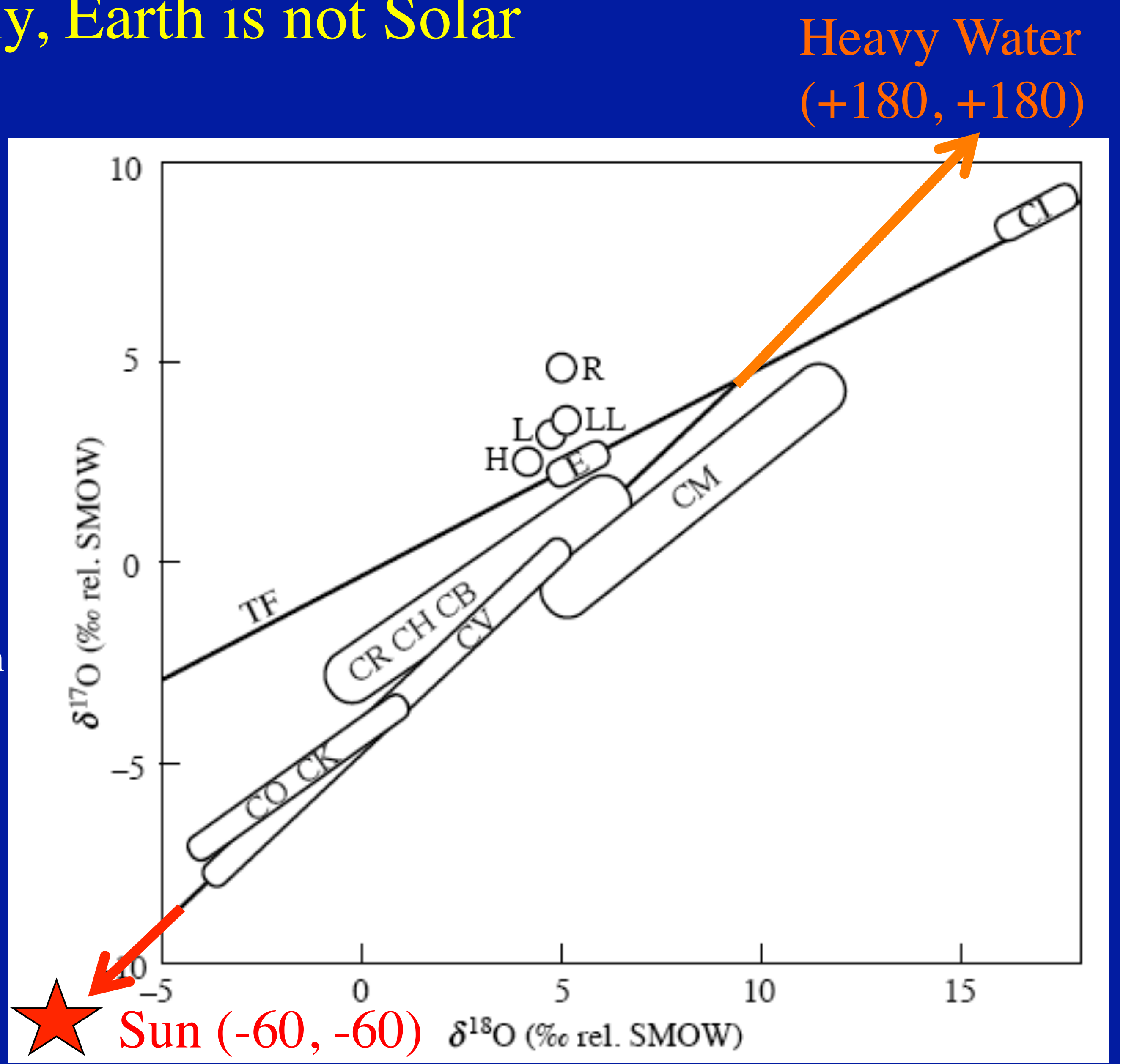
ε = parts in 10,000 difference between sample and terrestrial standard

Figures from Warren (EPSL, 2011)

Isotopically, Earth is not Solar

Only E and CI chondrites lie on the same oxygen mass fractionation line as does Earth

(Figure from Clayton, TOG, 2004, with the addition of Solar oxygen from McKeegan et al., Science 2011)



δ = difference in $^{x}O/^{16}O$ between sample and terrestrial standard in per mil

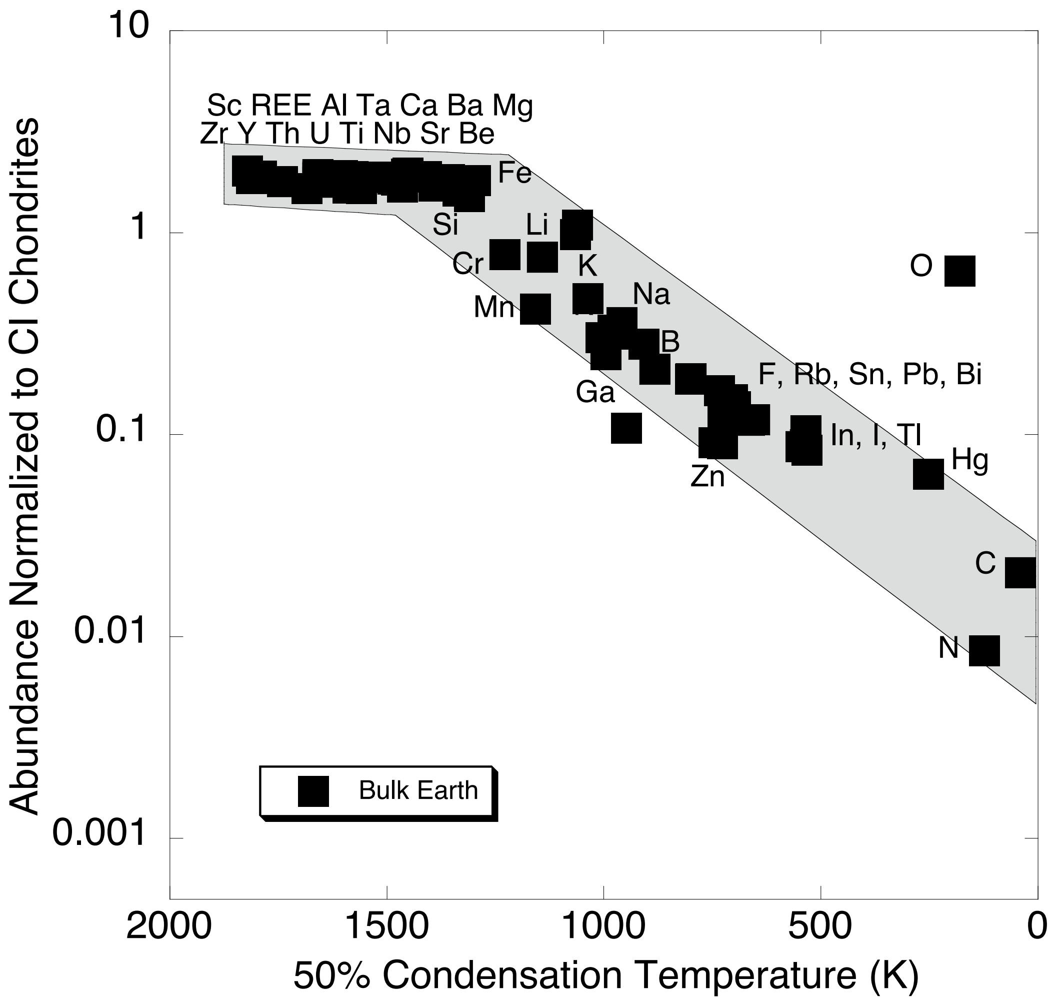
If the Bulk-Earth is E-Chondrite then the Lower Mantle ≠ Upper Mantle

Estimates of Bulk Silicate Earth (BSE) Composition

	C-Chondrite /Earth BSE[1]	E-Chondrite[2]	Upper Mantle[2]	E-Chondrite Lower Mantle[2]
SiO_2	45.0	49.8	45.8	51.8
MgO	37.8	36.5	39.0	35.3
FeO	8.04	8.84	7.94	9.28
Al_2O_3	4.43	2.42	3.59	1.85
K µg/g	240	120	180	90
Th ng/g	80	44	67	33
U ng/g	20	12	18	9

1- (McDonough & Sun, Chem. Geol. 1995), 2- (Javoy et al., EPSL 2010a)

Earth does not have Solar Abundances of Volatile Elements, not even Moderately Volatile Elements



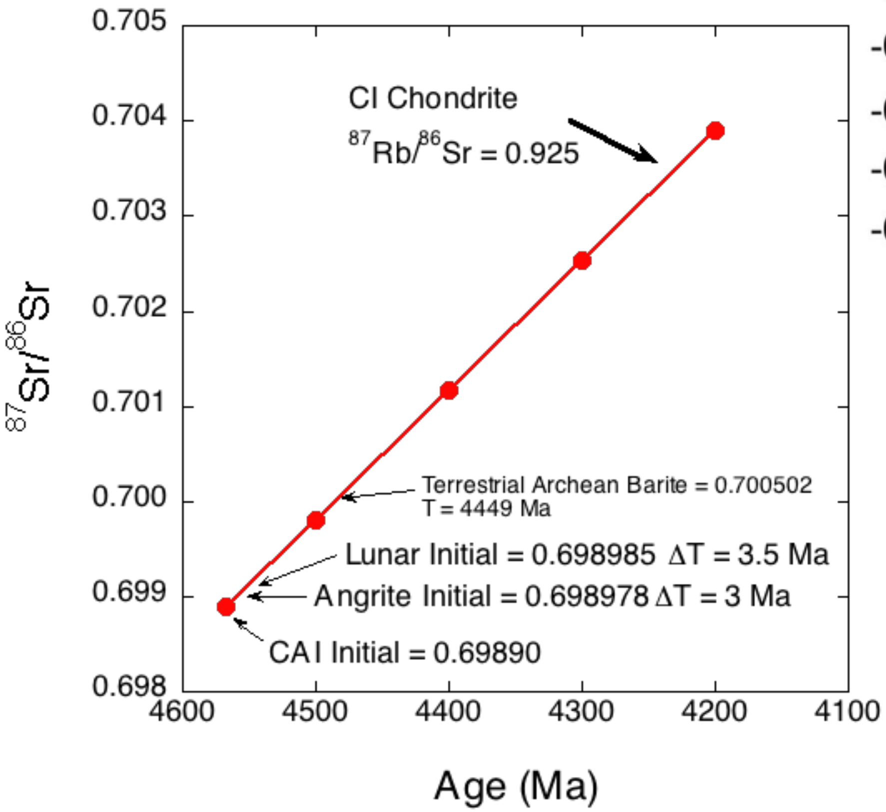
Estimates of bulk-Earth abundances from Palme and O'Neil (TOG, 2003)

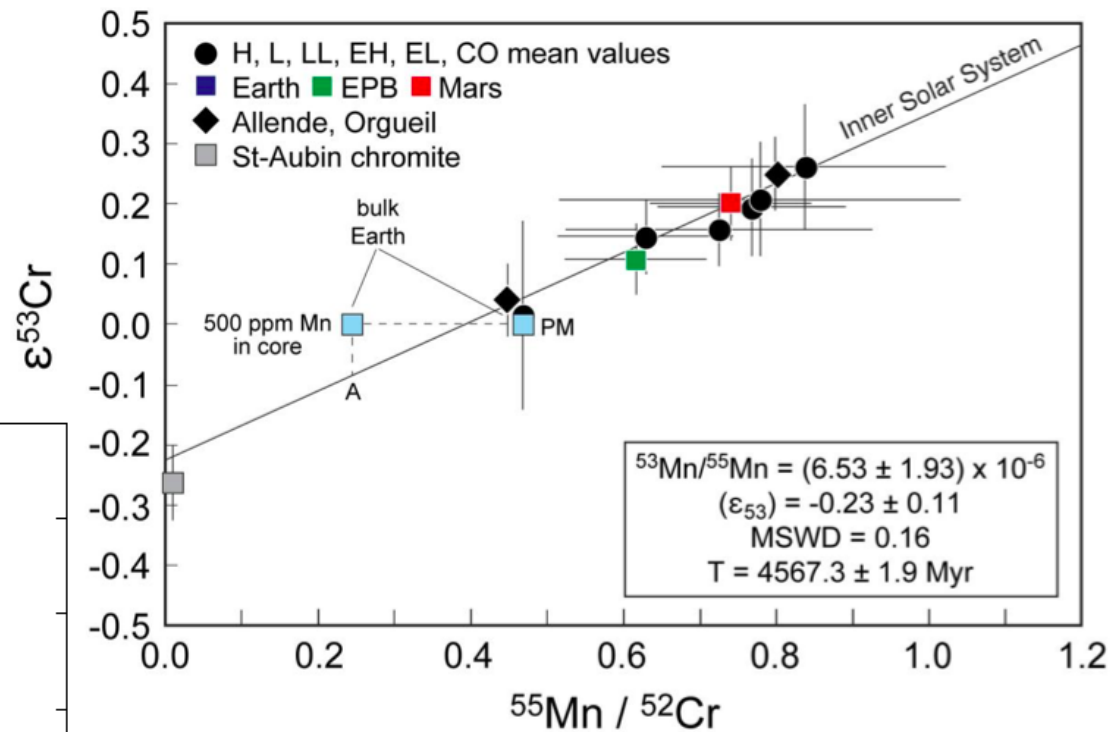
Condensation temperatures from Lodders Ap.J. (2003)

Dating Planetary Volatile Depletion

$^{87}Rb \rightarrow {}^{87}Sr$ $t_{1/2} = 49$ Ga $^{53}Mn \rightarrow {}^{53}Cr$ $t_{1/2} = 3.7$ Ma

Rb-Sr: Need to know the Rb/Sr ratio of the portion of the nebula from which Earth formed, and the initial $^{87}Sr/^{86}Sr$ of Earth/ Moon

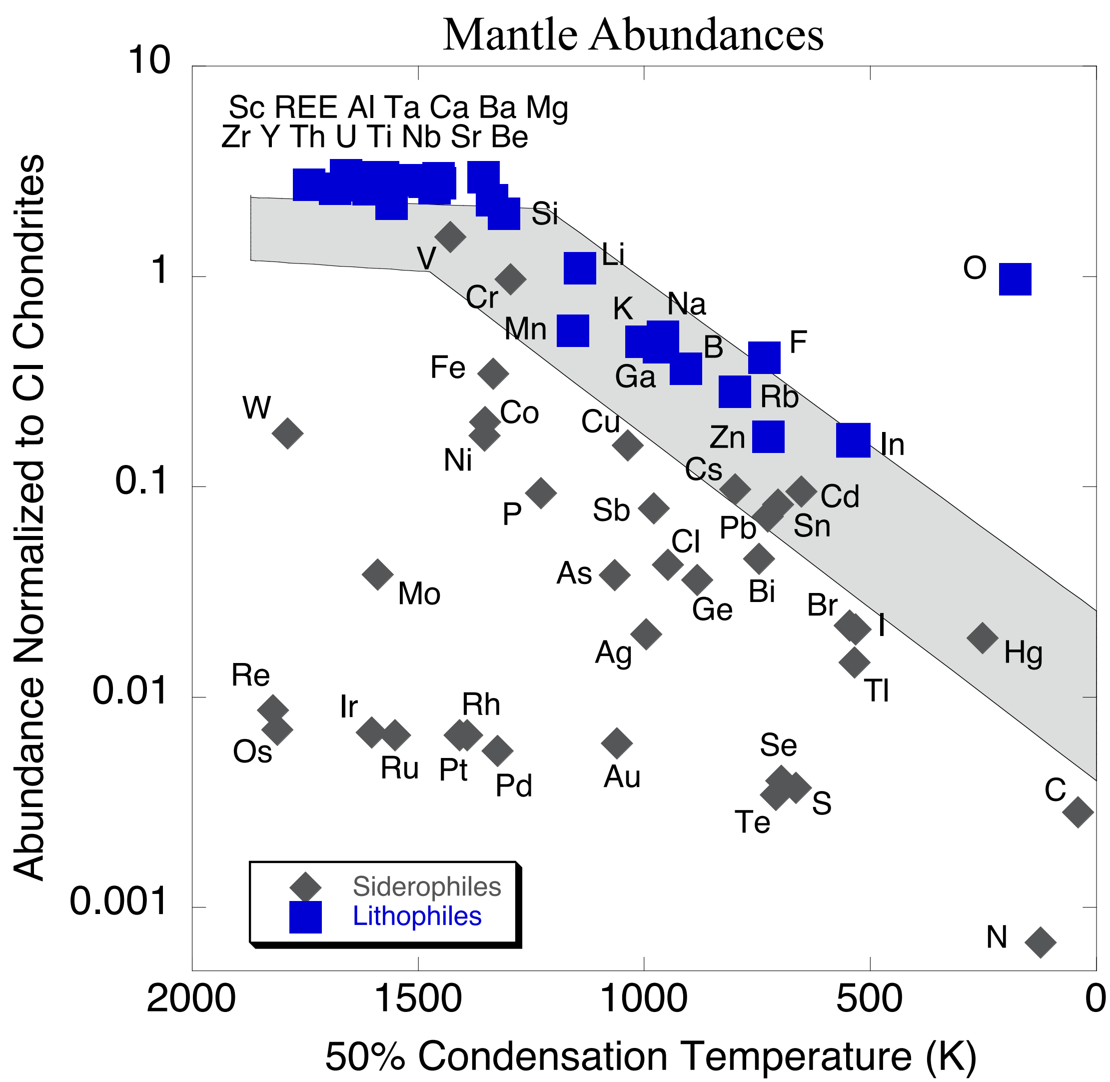




^{53}Mn: Main uncertainty is when, and the degree to which, mantle Mn/Cr was changed by core formation

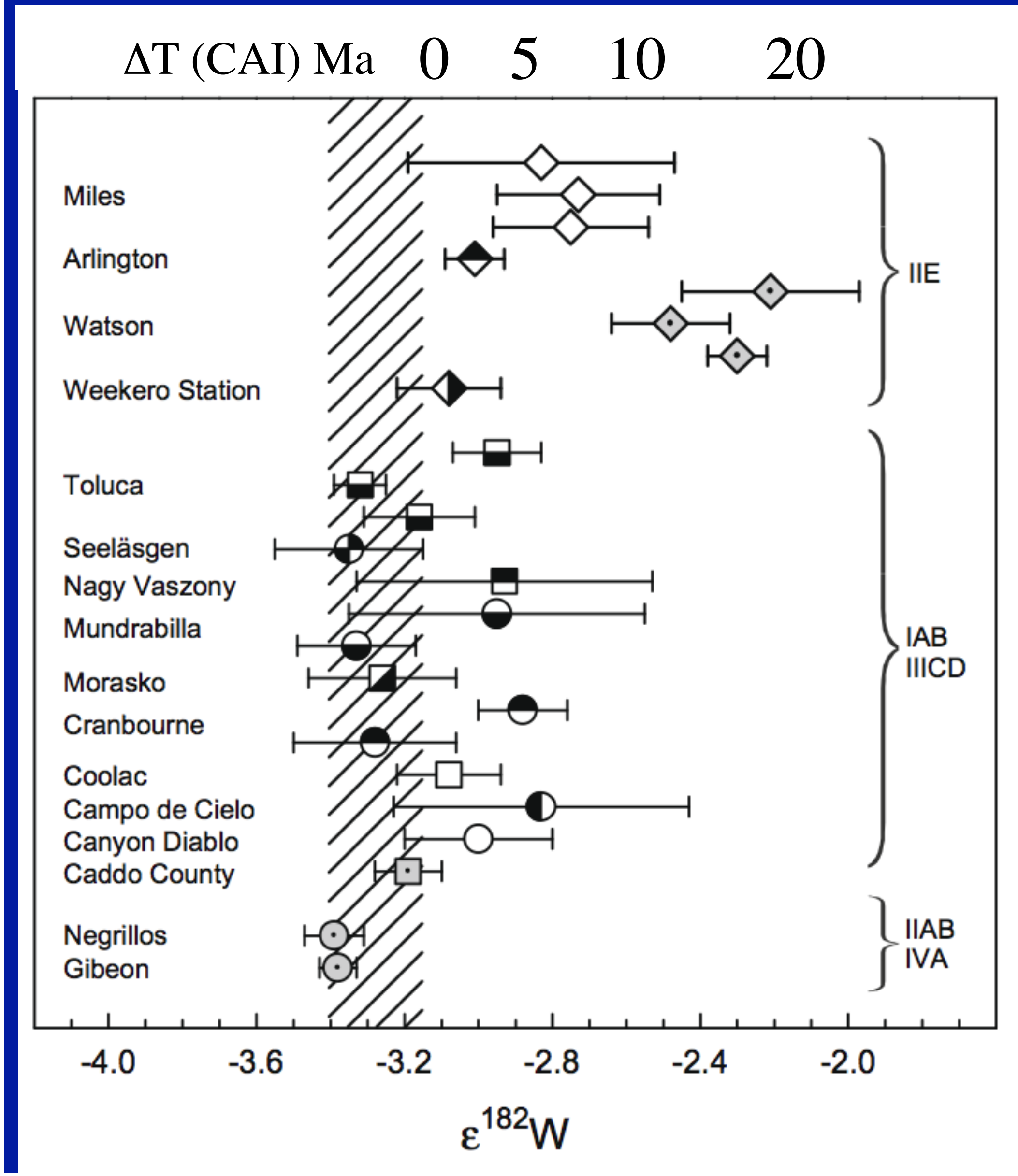
(figure from Palme and O'Neil, TOG, 2013. Data from Trinquier et al., GCA 2008 and Qin et al., GCA 2010)

The Added Complication of Internal Planet Differentiation



Core formation takes metal-soluble (siderophile) elements out of mantle, enriches mantle in metal-insoluble (lithophile) elements by mass balance

Iron Meteorite Tungsten Isotopic Composition Shows that Metal-Silicate Separation Happened Quickly, Even on Small Planetesimals



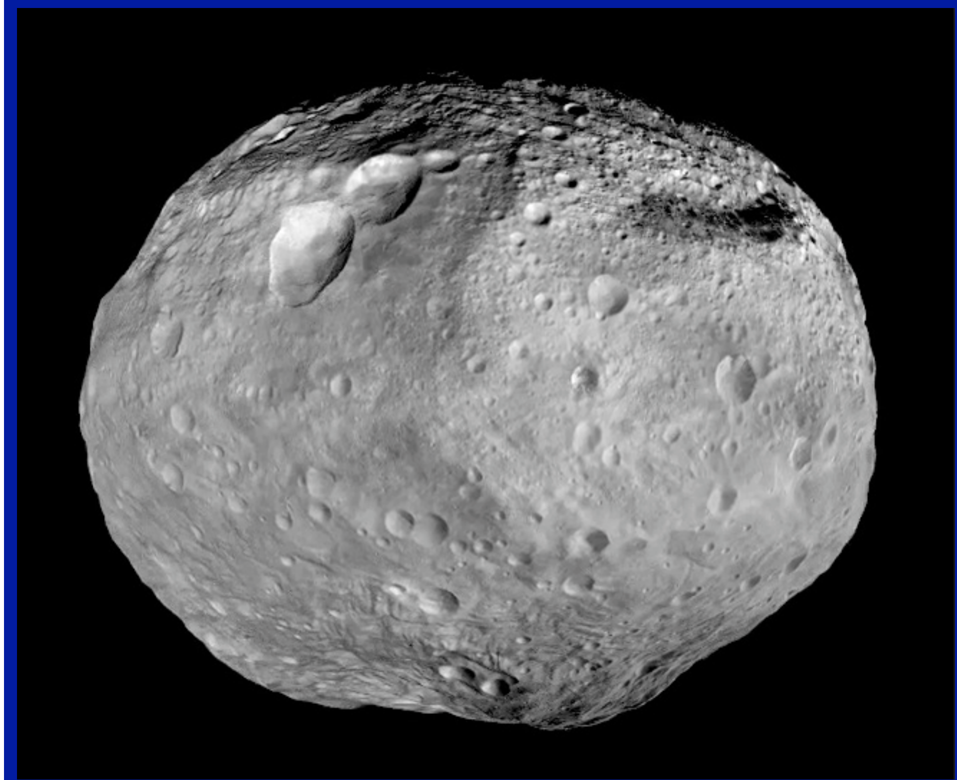
^{182}Hf → ^{182}W (8.9 Ma half life)

Many iron meteorites have ^{182}W / ^{184}W ratios similar to the Solar system initial value determined from CAIs. Others have higher ^{182}W/^{184}W consistent with iron-metal separation times of 20 Ma. The implication here is that core formation occurred very rapidly on small planetesimals and didn't wait until a planet the size of Earth had accumulated.

(Kleine et al., EPSL, 2009)

So What If Earth Formed Out Of:

This: Vesta, a highly differentiated planetesimal that lost its atmosphere and segregrated core, mantle, and crust as the result of a global magma ocean at 4565 Ma (Solar system is 4568 Ma old)



Instead of this: A primitive chondrite with Solar composition in all but the most volatile elements

Orgueil, CI Carbonaceous Chondrite

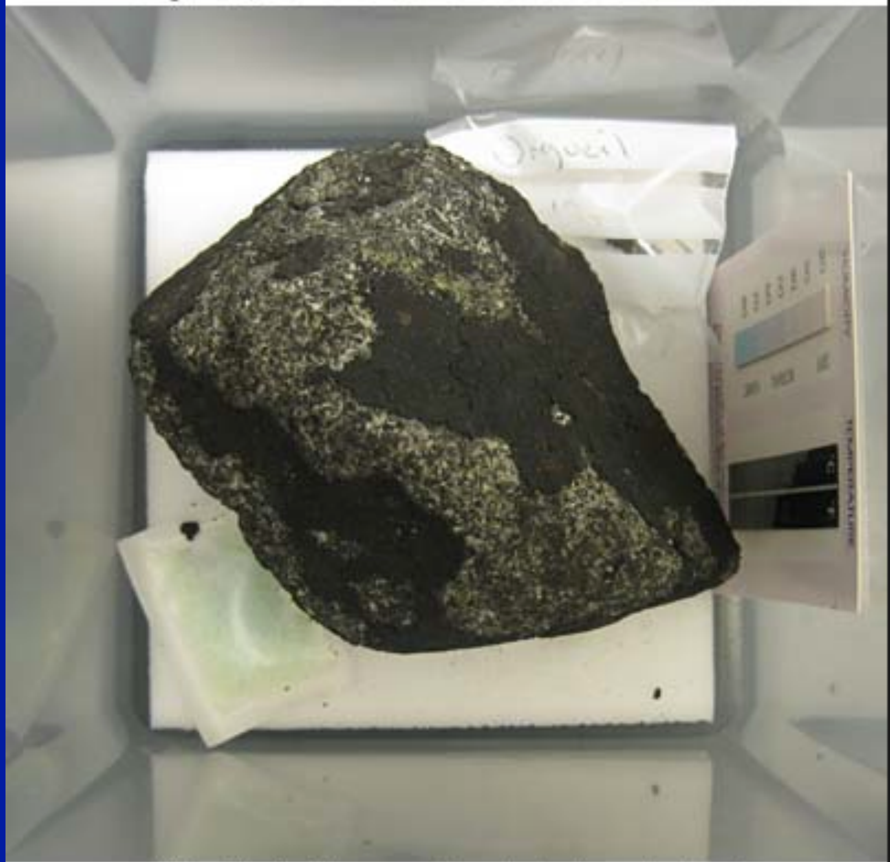
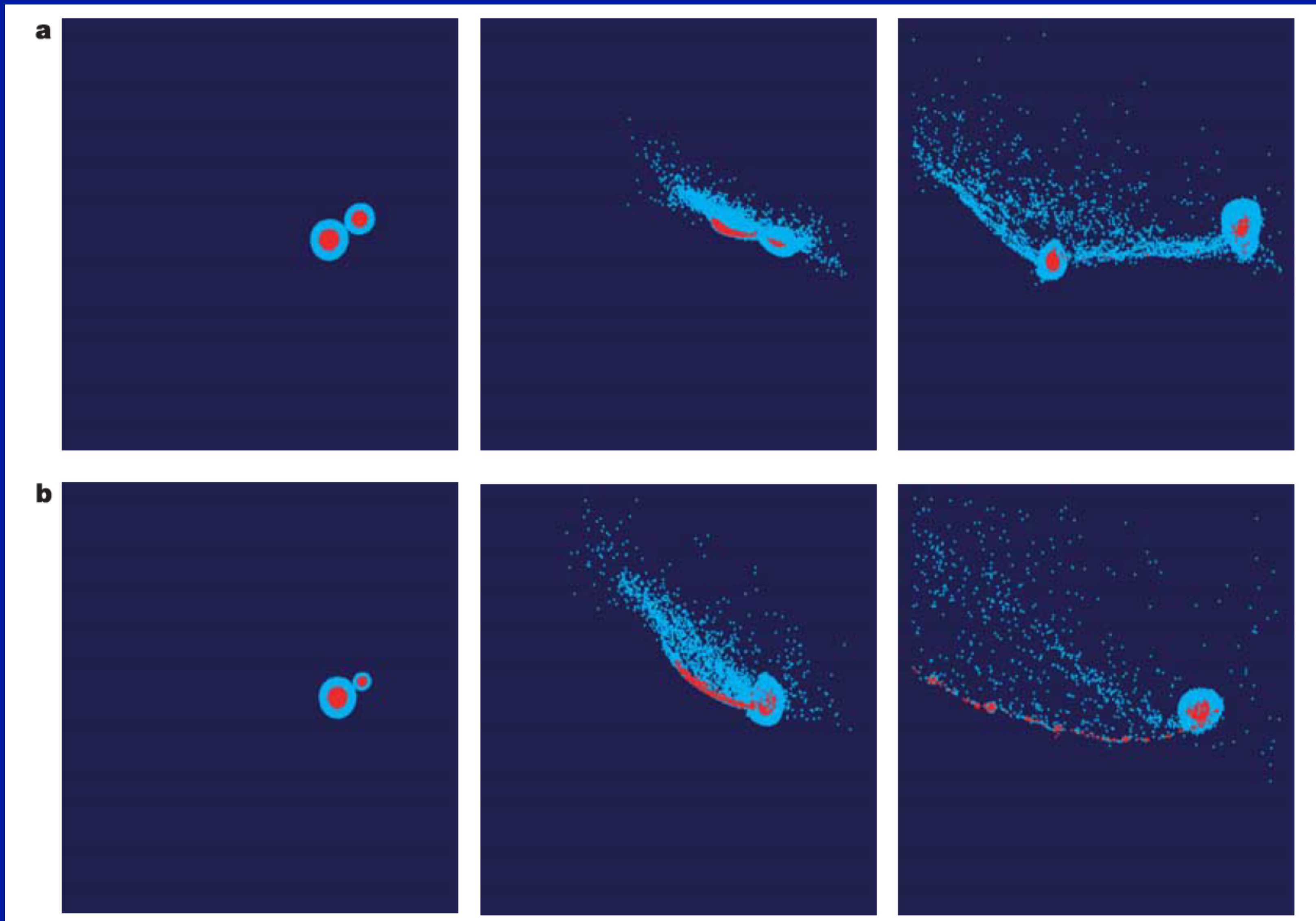


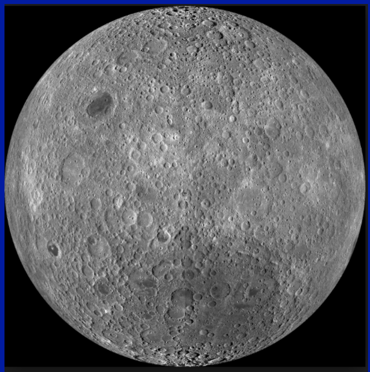
Photo by L. Martel, www.psrd.hawaii.edu with permission of Natural History Museum, London.

The Physics of Planetary Accretion

Imperfect accretion during "hit and run" collisions, e.g. Asphaug et al., 2006



The Lesson from Comparative Planetology



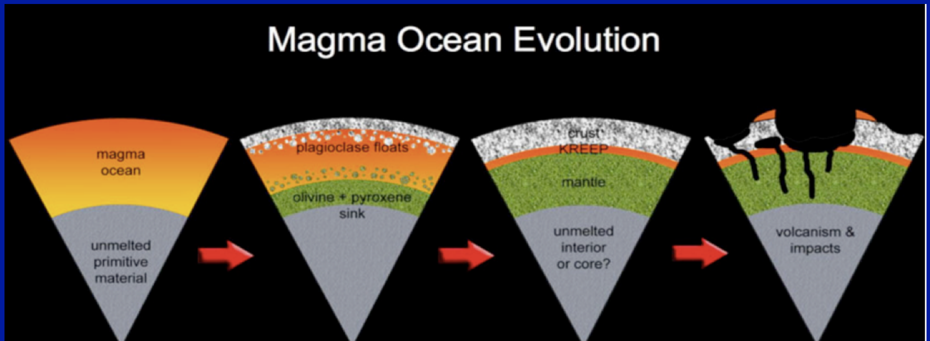
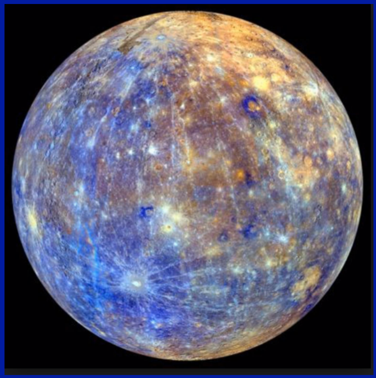


Image from Jeff Plescia in Moon 101

Moon: Crust mostly anorthosite formed by plagioclase flotation from a global magma ocean at 4.4 Ga. Whole Moon iron deficient.

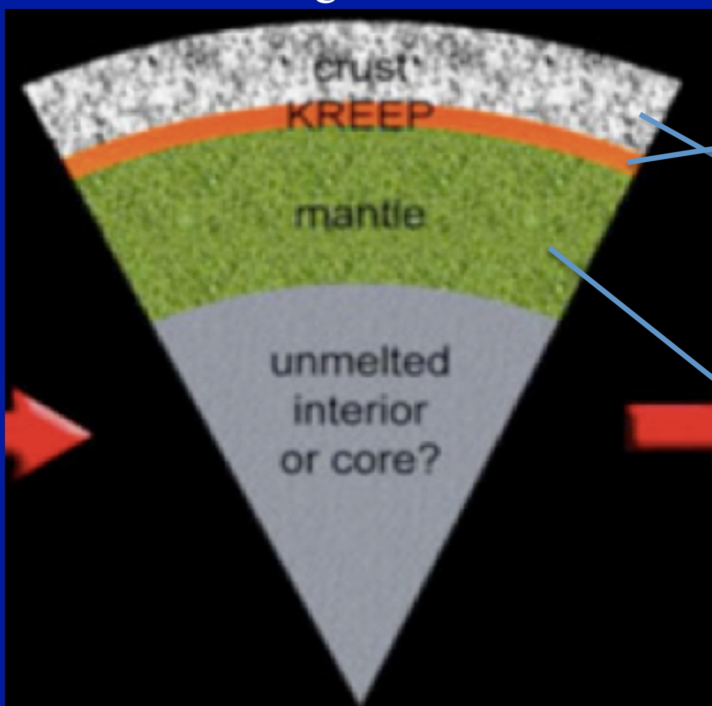
Mars: Crust broadly basaltic. Formed by serial magmatism that continues to recent times though most of the Martian surface may be > 4 Ga. Mantle shows chemical evidence of very early (>4.5 Ga) global differentiation.

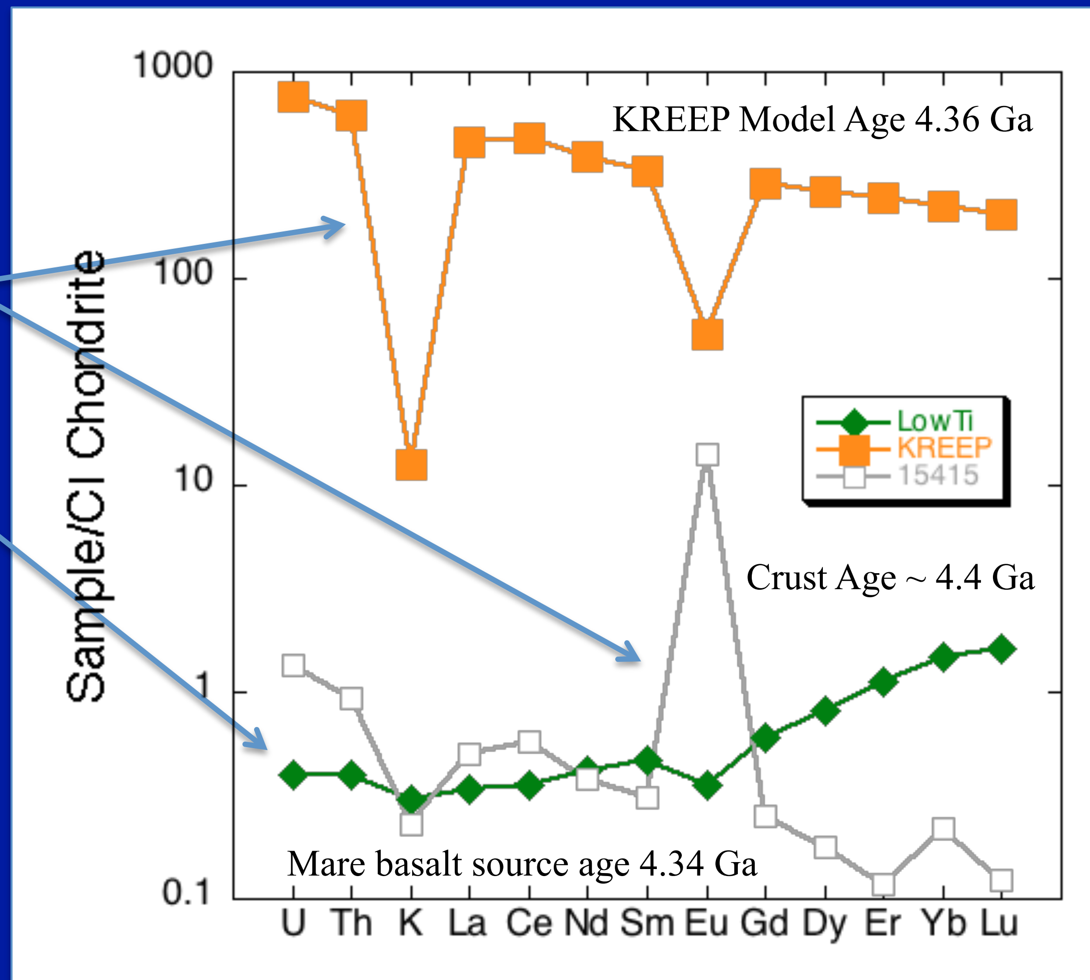


Mercury: Crust broadly basaltic to komatiitic, mostly or entirely volcanic in origin. Enriched in sulfur (up to 3 wt%), sodium and potassium, very low in iron (<2 wt%). Extremely high ratio of core to mantle.

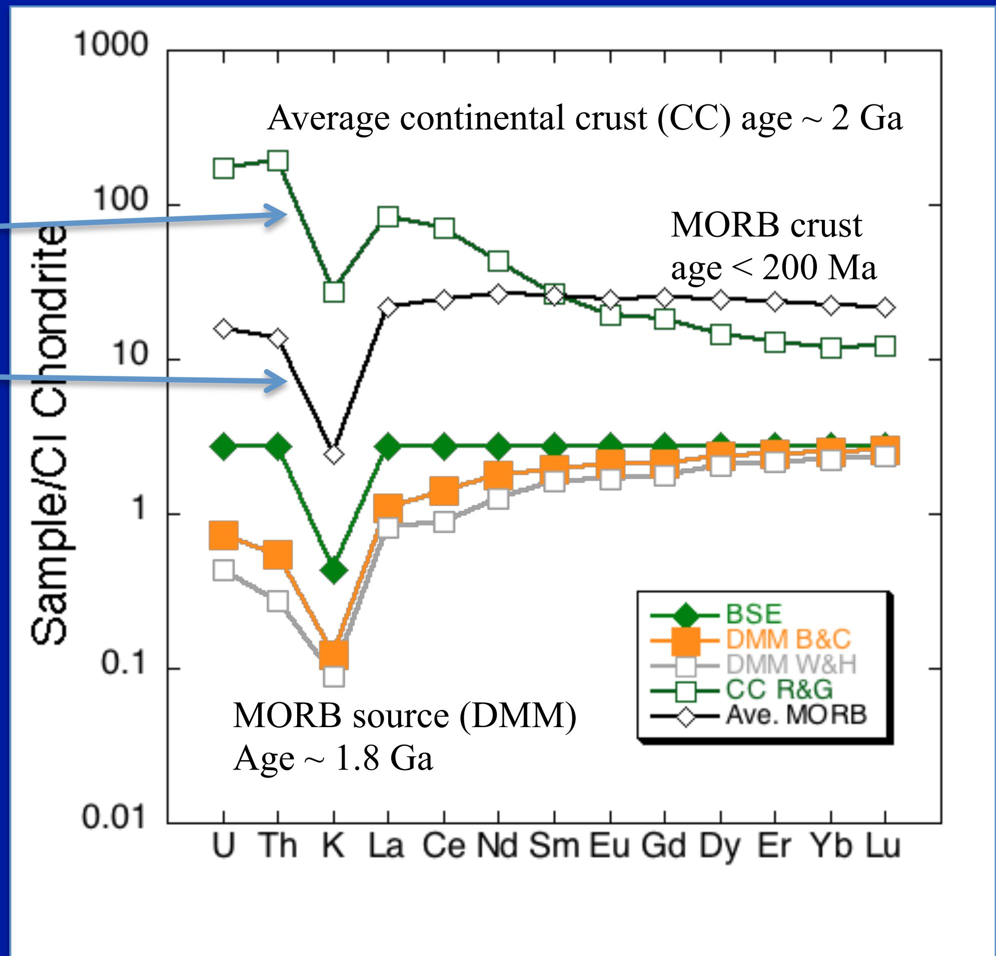
Igneous Differentiation Very Good at Separating U, Th, K from Other Elements

The Post-Magma Ocean Moon





Earth's Crust-Mantle Differentiation, but from what Starting Composition?



^{142}Nd Difference Between Earth and Chondrites

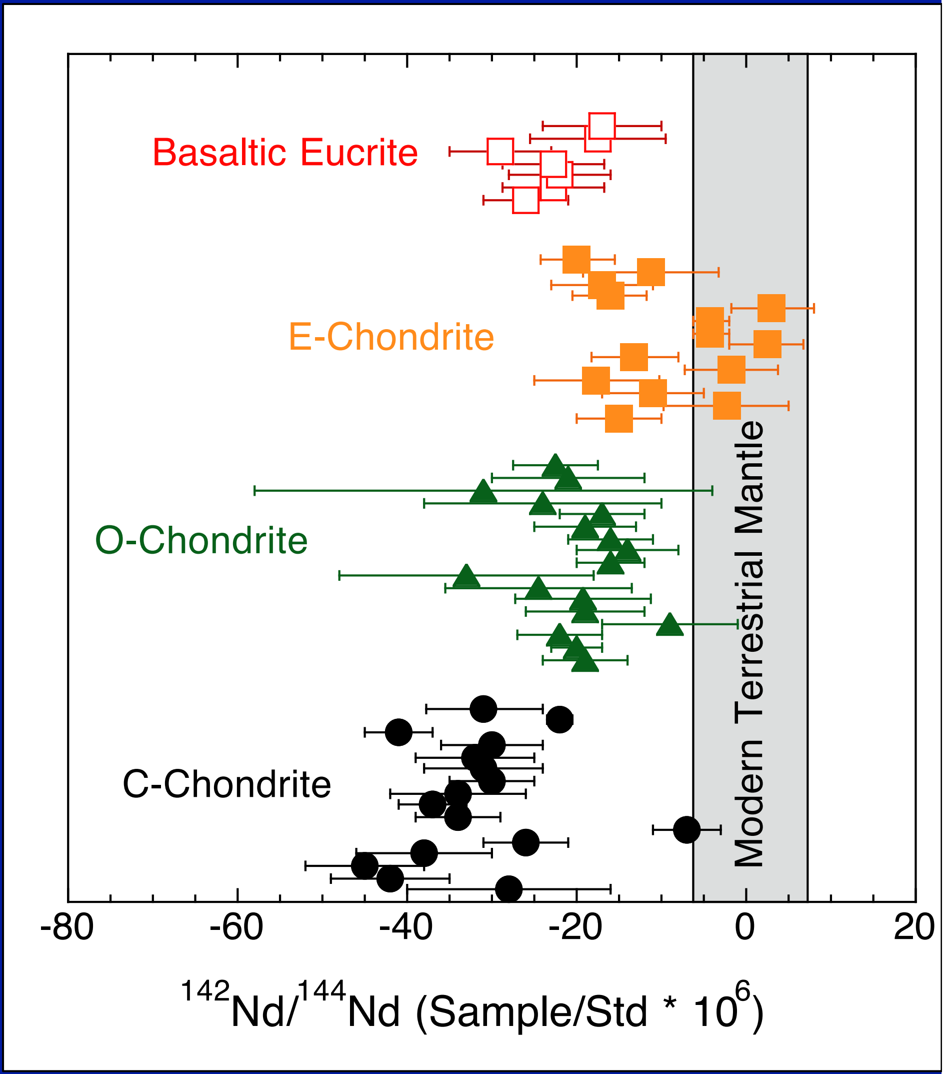
- $^{142}Nd/^{144}Nd$ ratios measured in carbonaceous and ordinary chondrites and basaltic eucrites are lower than all modern terrestrial rocks. Enstatite chondrites overlap both O-chondrite and terrestrial mantle values.

Explanation 1:

- Accessible Earth has a Sm/Nd ratio ~6% higher than O-chondrites. High Sm/Nd ratio results in excess ^{142}Nd from the decay of ^{146}Sm.

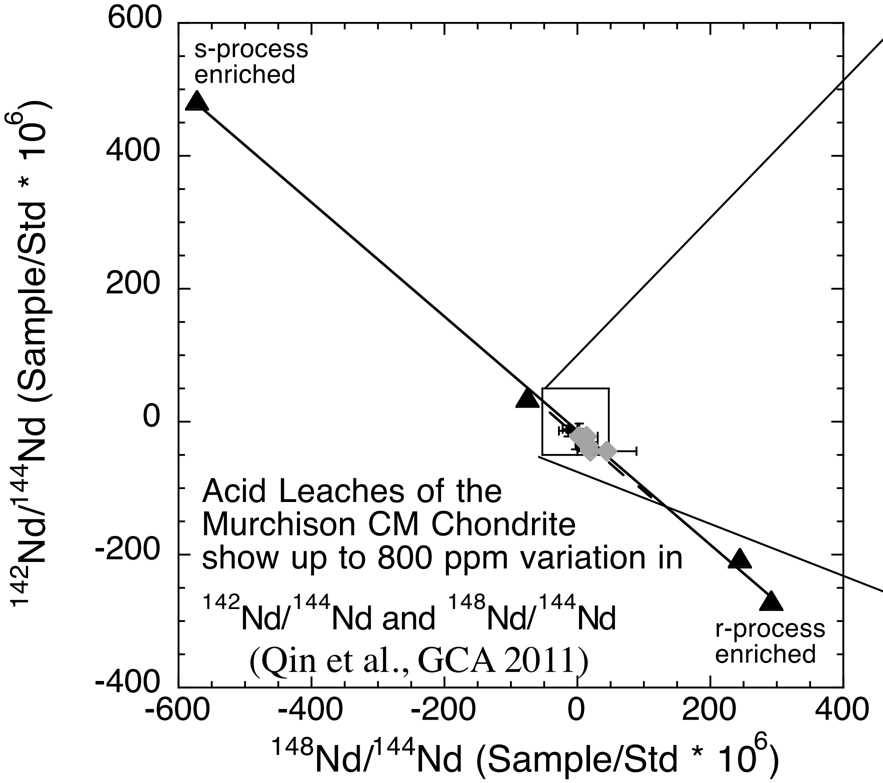
Explanation 2:

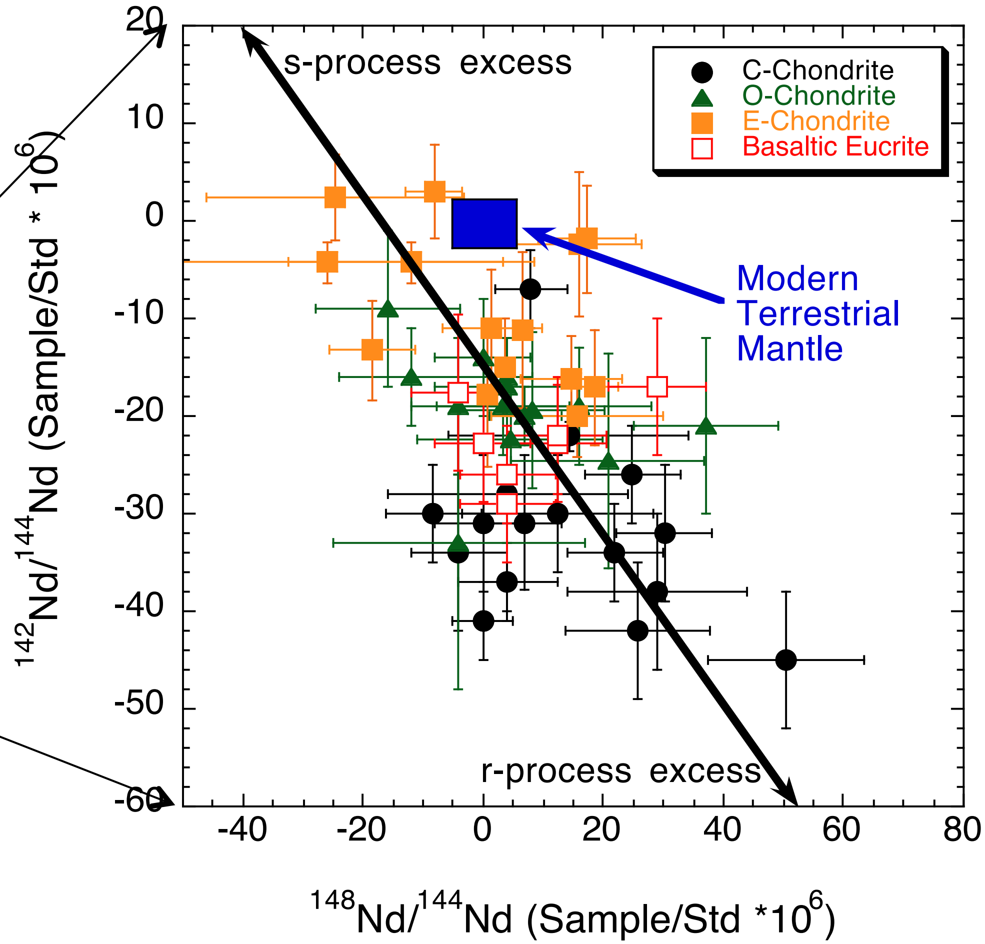
- ^{142}Nd variation due to incomplete mixing nucleosynthetic products. Only E-chondrites sampled a similar mix as Earth. ^{142}Nd variation has nothing to do with ^{146}Sm decay or non-chondritic Sm/Nd ratios.



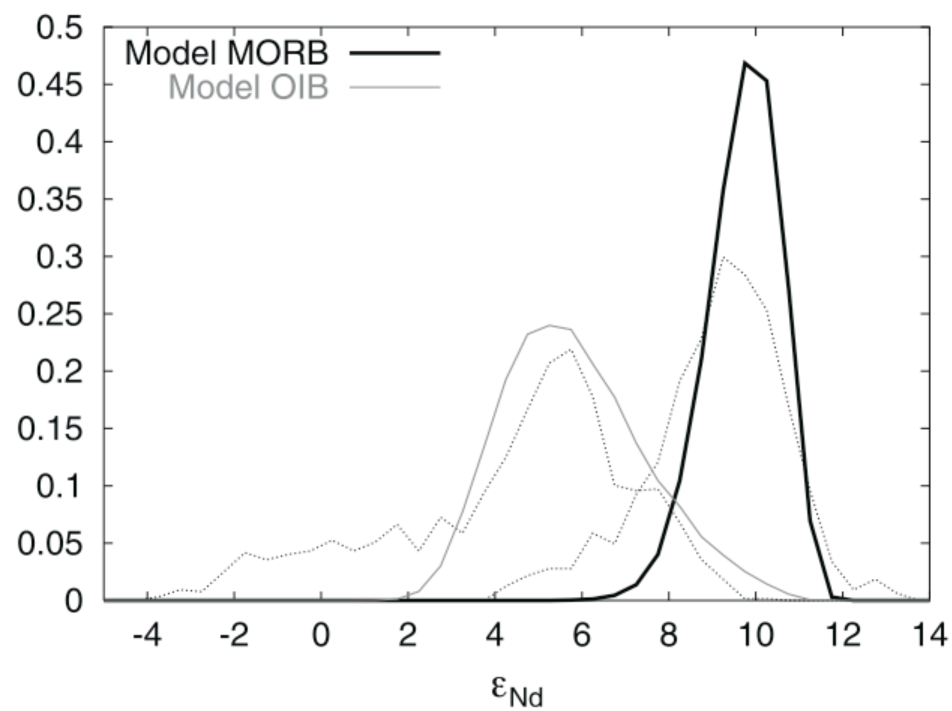
Data from Nyquist et al., 1995; Boyet and Carlson, 2005; Andreasen and Sharma, 2006; Rankenburg et al., 2006. Carlson et al., 2007; Gannoun et al., 2011.

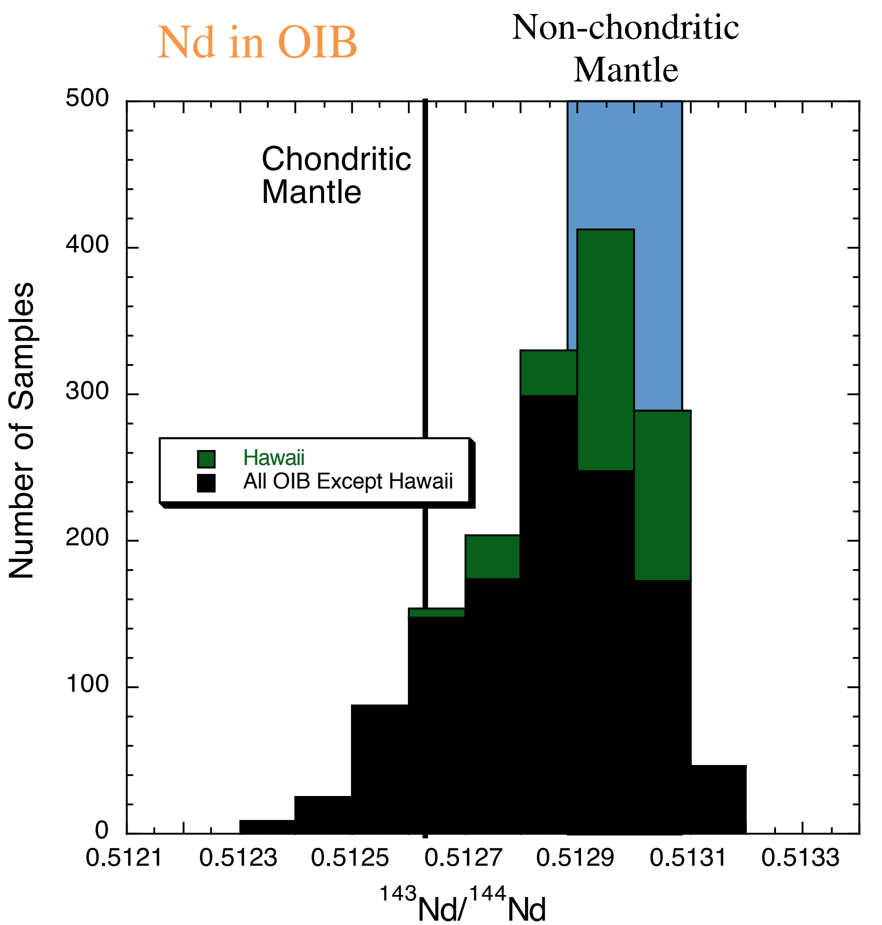
Few meteorites have both $^{142}Nd/^{144}Nd$ and $^{148}Nd/^{144}Nd$ that simultaneously overlap terrestrial values. E-chondrites come closest, but even they show a range of isotopic compositions





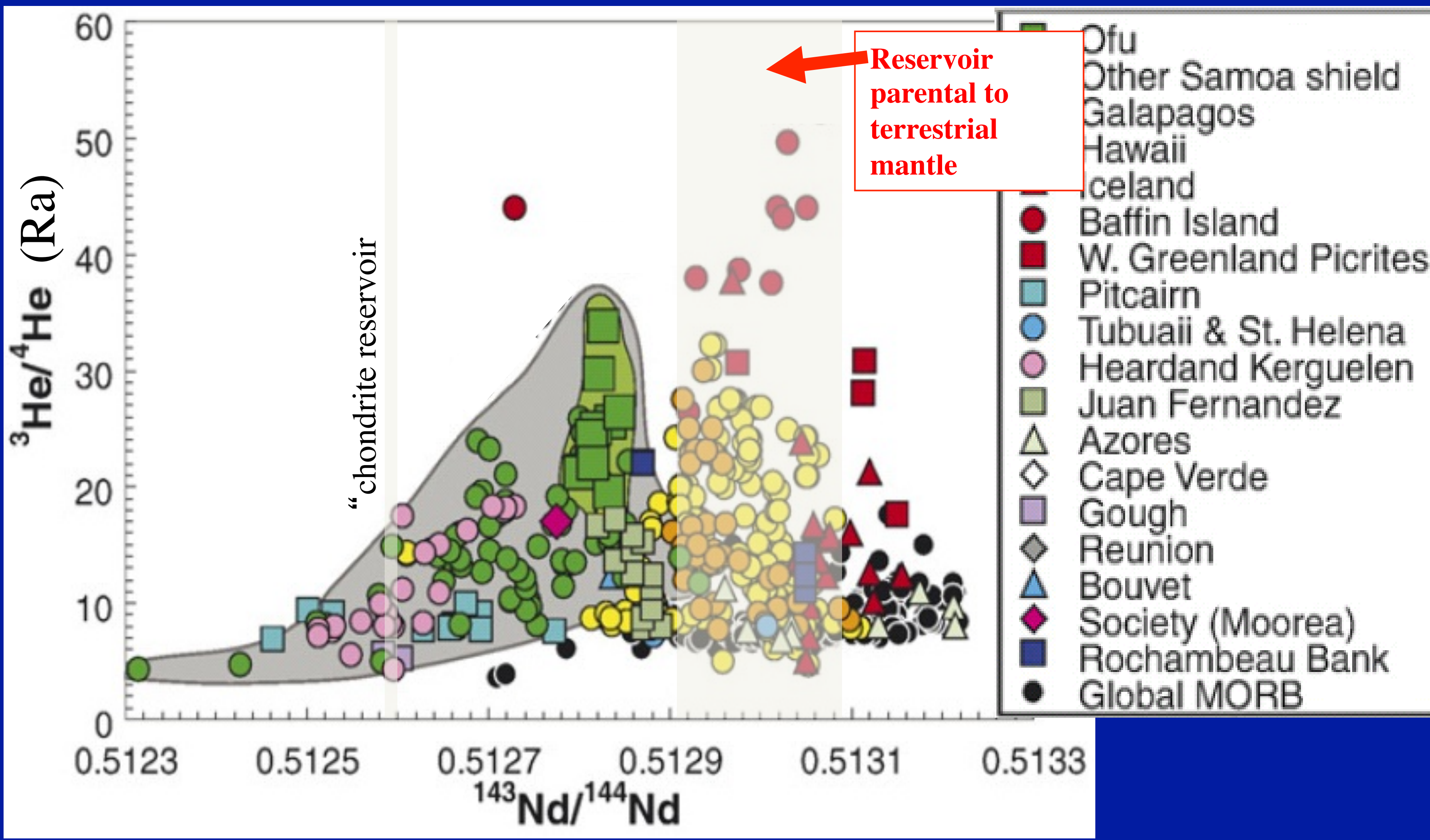
Primitive mantle with $\varepsilon^{143}Nd = 0$ is a very muted component in intraplate volcanism





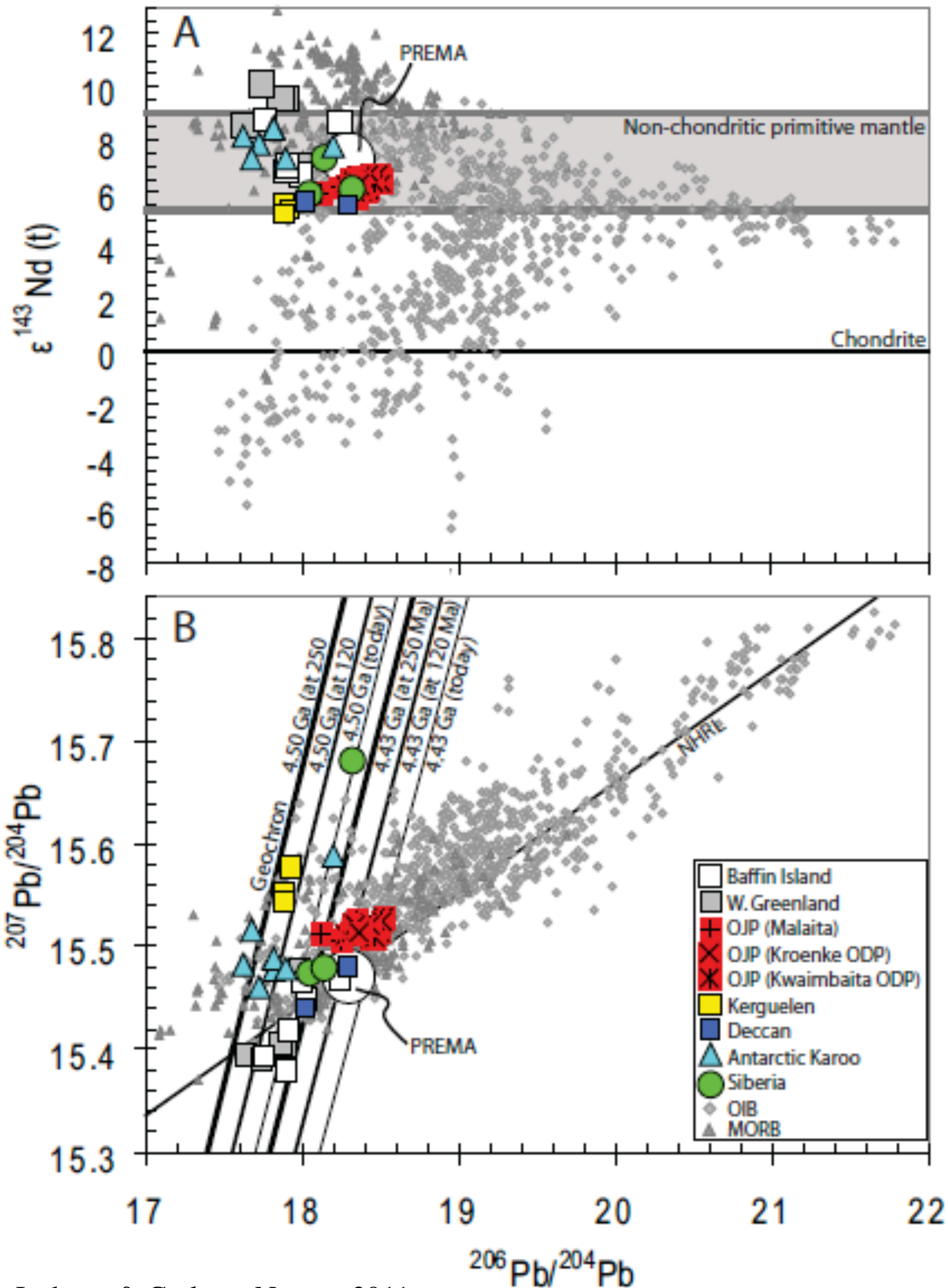
One explanation – regulate mass transfer rates between depleted upper mantle and primitive lower mantle to match erupted compositions, e.g. Kellogg et al., EPSL, 2002

Predicted $^{143}Nd/^{144}Nd$ from ^{142}Nd Excess Overlaps with high $^{3}He/^{4}He$ Reservoir



• Though there are complexities (age corrections, crustal contamination), the Pb isotopic composition of many flood basalt parental magmas plot near circa 4.5 Ga geochrons.

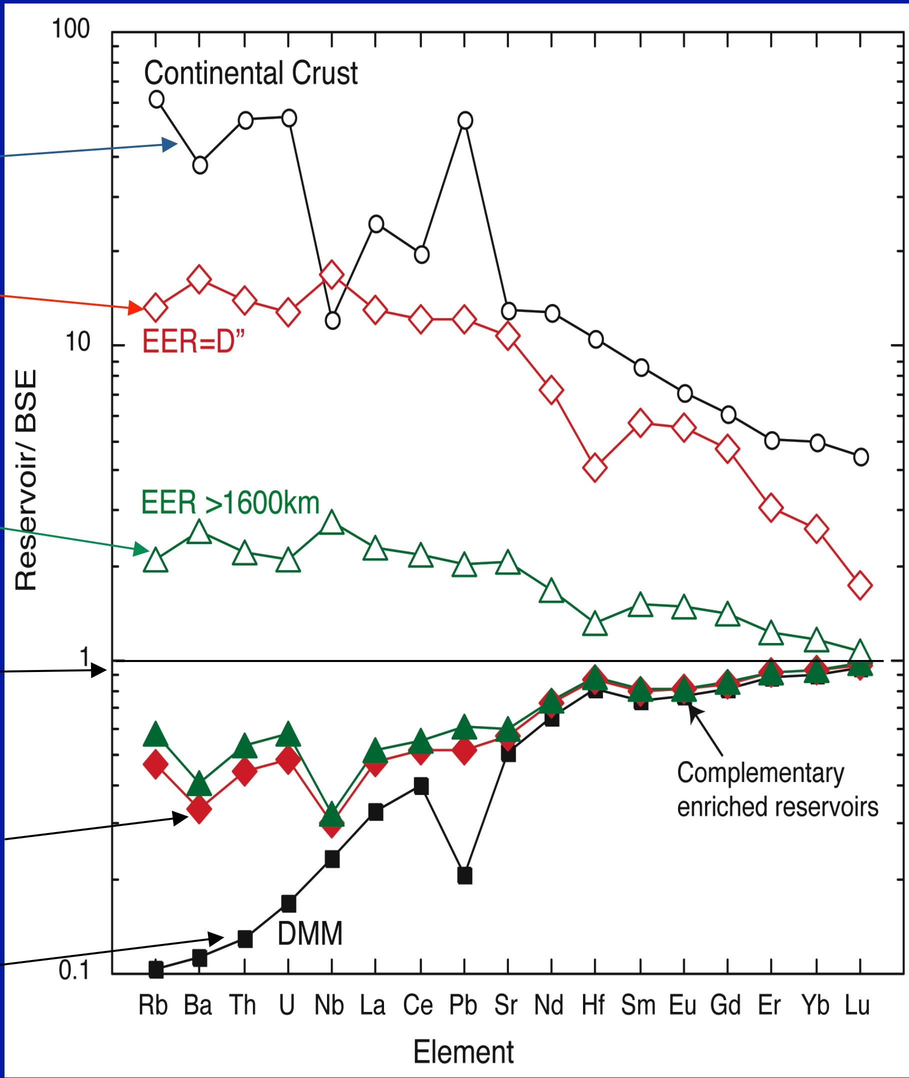
•All the colored symbols on this figure have $\varepsilon^{143}Nd$ between +5.3 and +8 and were selected as those samples least affected by crustal contamination.



Jackson & Carlson, Nature, 2011

If Earth-Chondrite Offset in ^{142}Nd is Reflective of non-Chondritic Sm/Nd, Implications for Bulk-Earth Compositional Estimates

Reservoir	Mass(10^{25}g)	Th(ppb)	U(ppb)	K(ppm)	TW
Cont. Crust	2.26	5600	1300	15000	7.3
Enriched=D”	17	920	230	2650	9.3
Enriched>1600km	111	150	40	440	10.4
Primitive (60%)	242	79	20	240	11.7
Early Depleted	290-390	43-53	11-13	~150	9.5-10.3
MORB Mantle	161	7.9	3.2	50	1.1

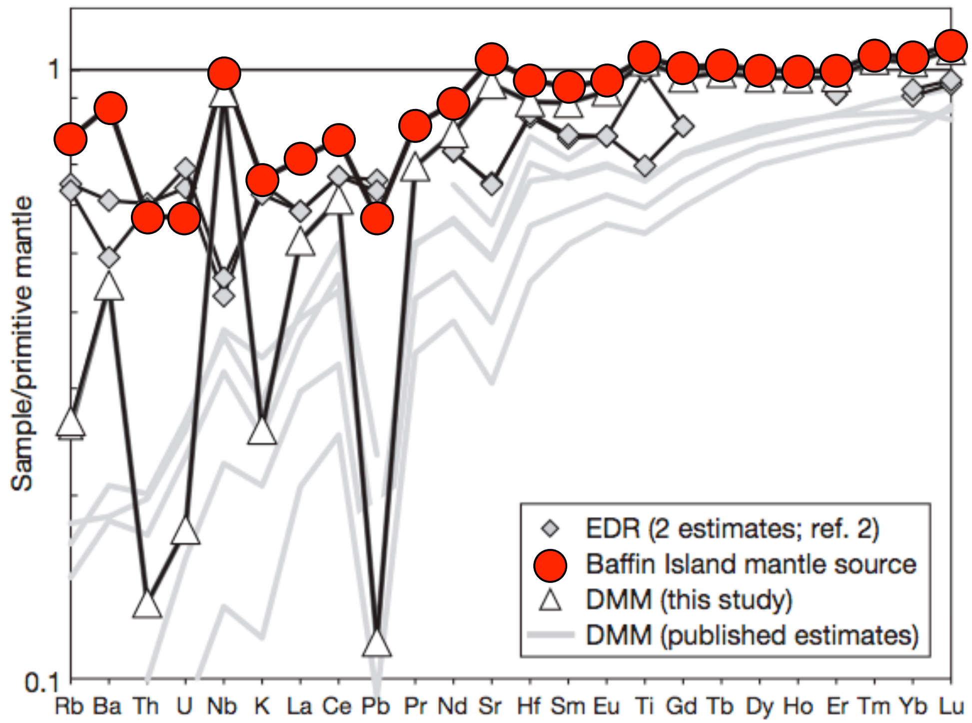


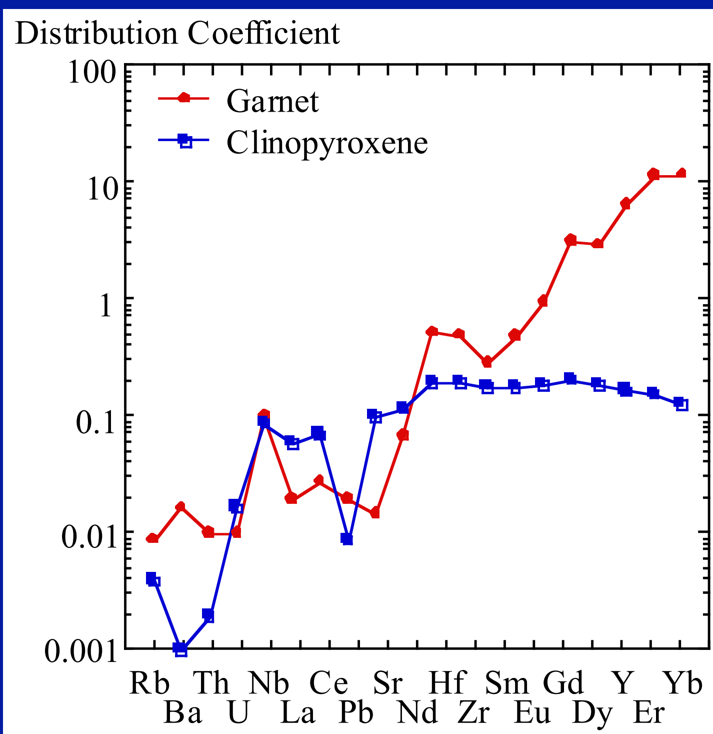
If the bulk silicate Earth is like this early depleted reservoir, then it has half the radioactive heat generating capacity, and half the ^{40}Ar of mantle models based on chondritic refractory lithophile element abundances

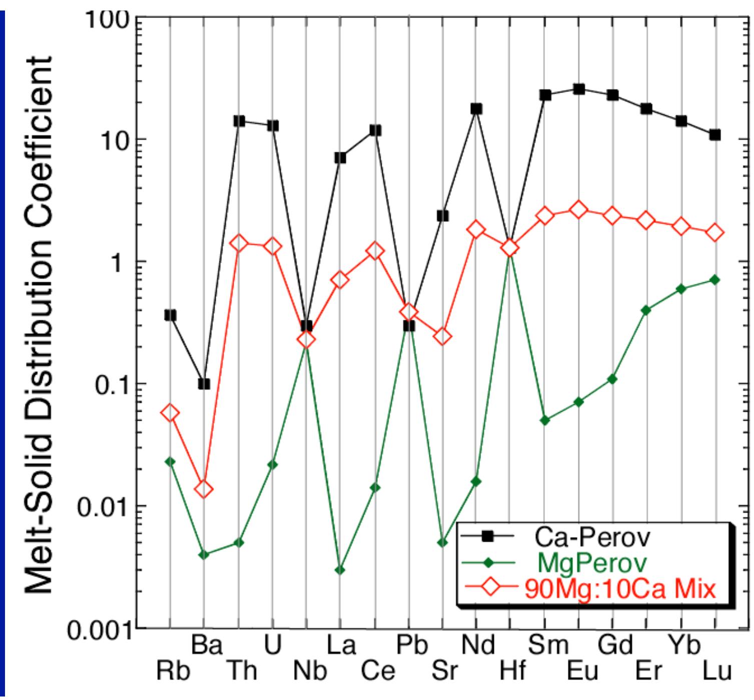
Boyet and Carlson, 2005

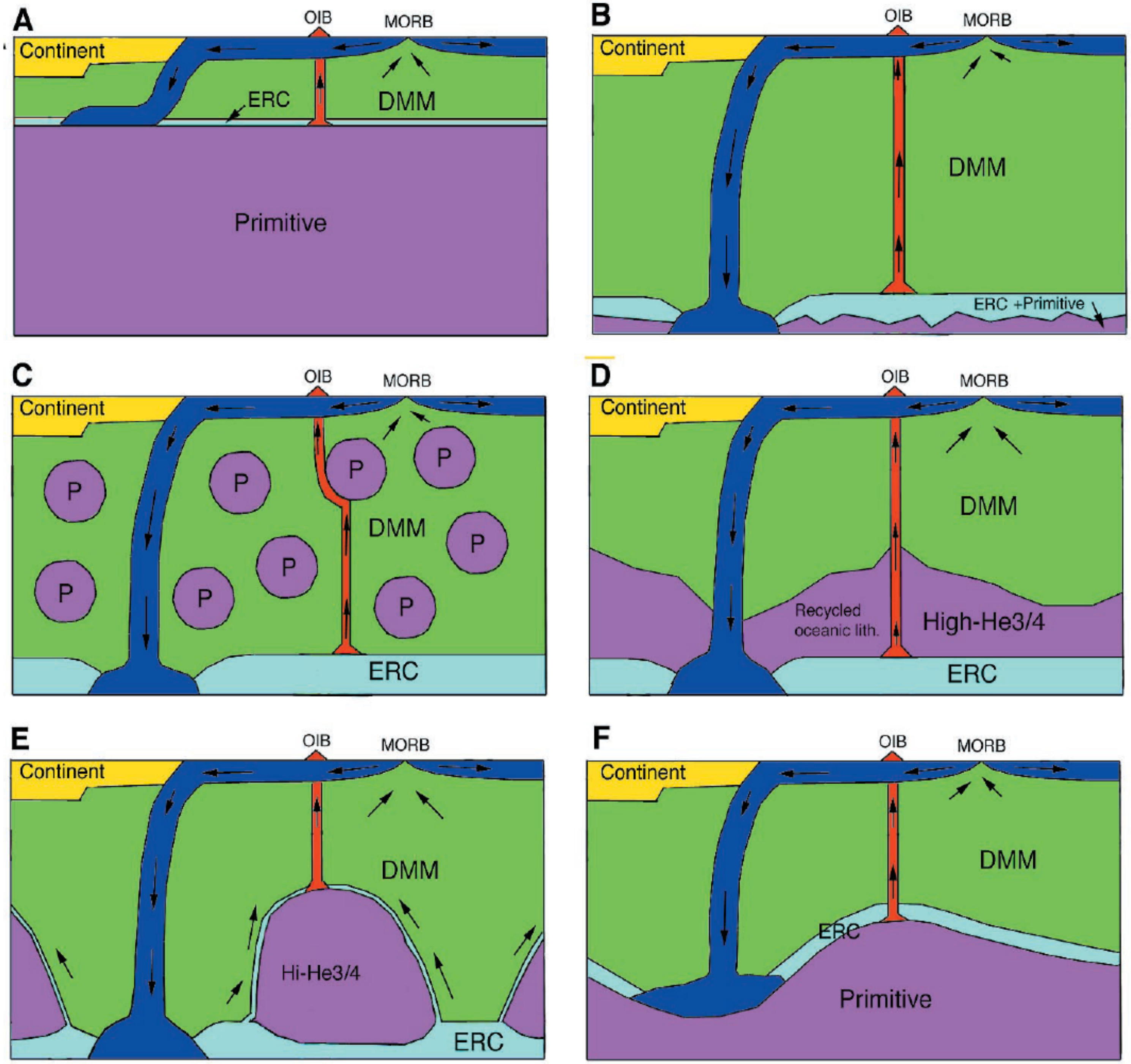
How Did the Non-Chondritic Mantle Form?

Melting is the easiest way to fractionate the lithophile elements, but what were the conditions of melting?



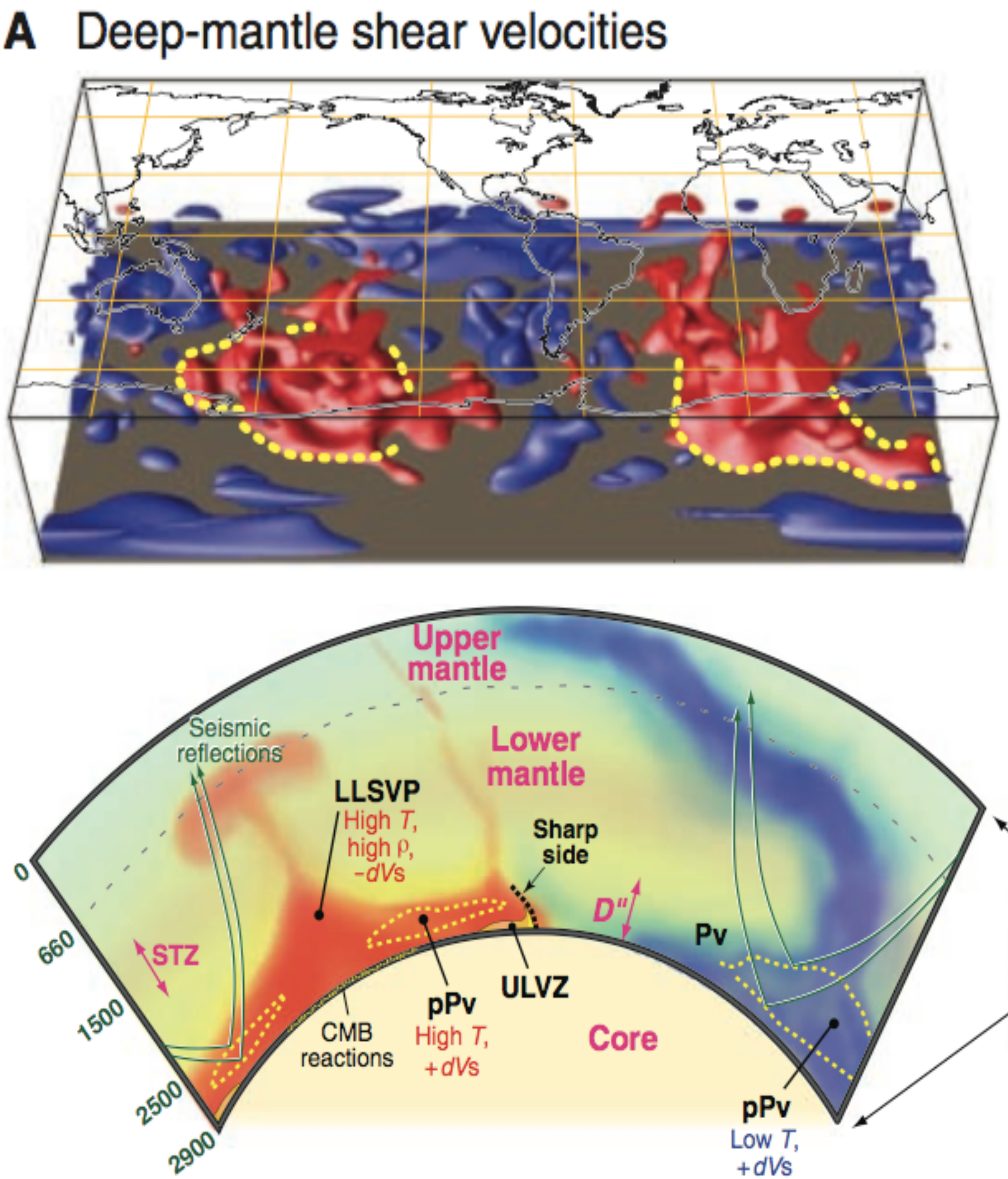






Moving from Cartoons of Mantle Composition

(Tackley, Science 2000)



To Actual Images of Mantle Heterogeneities

Garnero and McNamara, 2008

If the BSE has a Sm/Nd Ratio 6% Higher than Chondritic, the "Primitive Mantle" has εNd = +7 ± 2

Explains:

1) The most common Nd isotopic composition seen in OIB
2) The positive εNd seen even in the oldest mantle-derived rocks
3) Association of high $^{3}He/^{4}He$ mantle with positive εNd
4) The ^{40}Ar "paradox"
    - U, Th, and K abundances in the non-chondritic BSE are 60% those generally assumed
5) Flood basalts preferentially sample the non-chondritic primitive mantle

Implies:

1) DMM is less depleted than if calculated as originating from a chondritic source (e.g. Workman and Hart, EPSL, 2005)
2) DMM occupies most of the mantle

Difficulties:

1) Mantle radioactive heat production 60% that of a chondritic mantle
2) How does one make an Earth with non-chondritic RLE?
    - Is there a missing LIL-enriched reservoir?