Habitability : Geosciences point of view

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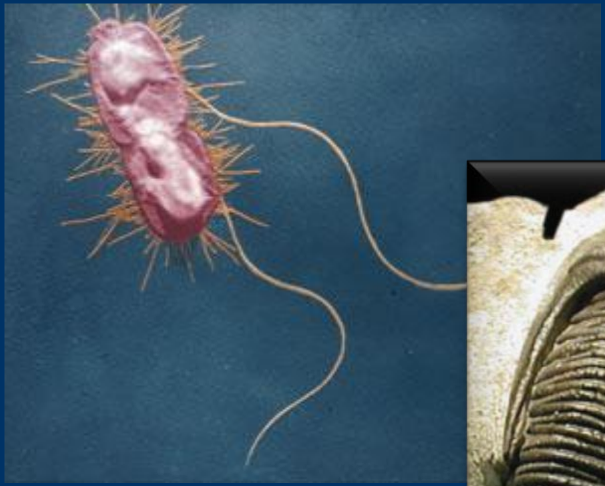
Earth habitability

Consequently, theoretically, it should be easy to establish when Earth became habitable and when Life began to develop on it.

In fact, this appears as being a tricky problem.

On Earth we can take as much samples as we need

Earth is an inhabited habitable planet



Earth is a living planet

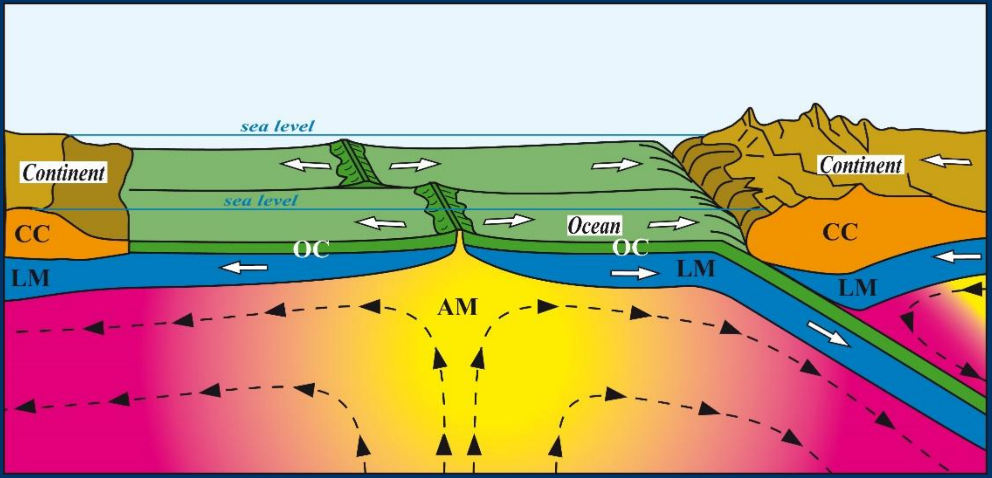
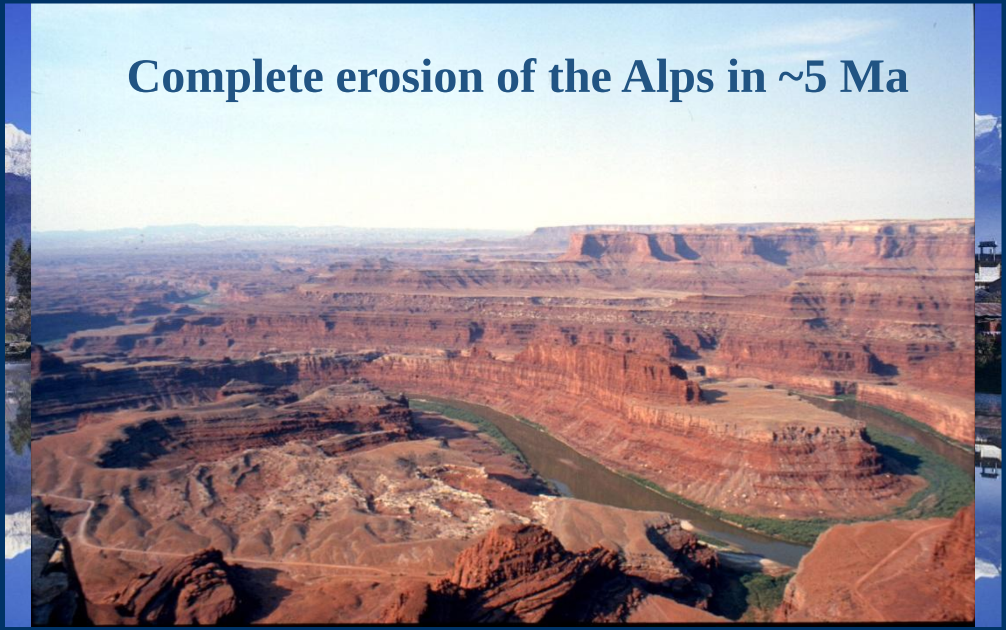


Plate tectonics



Earth is a living planet

4.568 Ga	4.0 Ga	2.5 Ga	0.5 Ga	0.0 Ga
HADEAN	ARCHAEAN	PROTEROZOIC	PHANERO ZOIC	

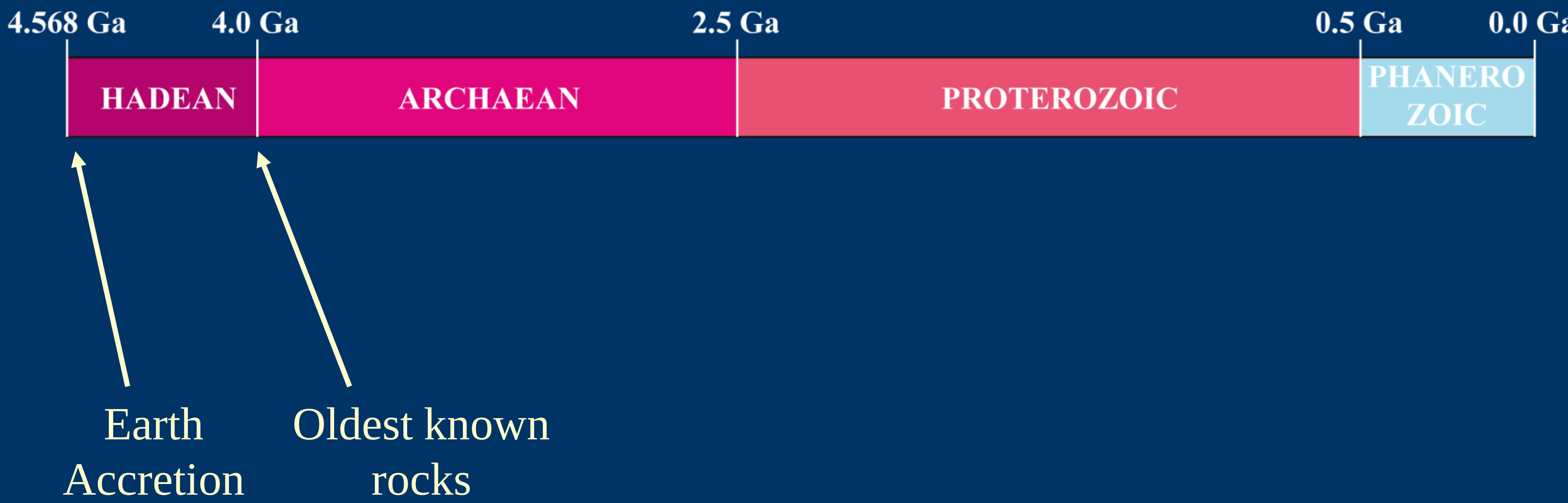
Earth Accretion

Oldest known rocks

Acasta gneisses dated at 4,03 Ga

Alan Brandon / Nature
Photo M. Guitreau

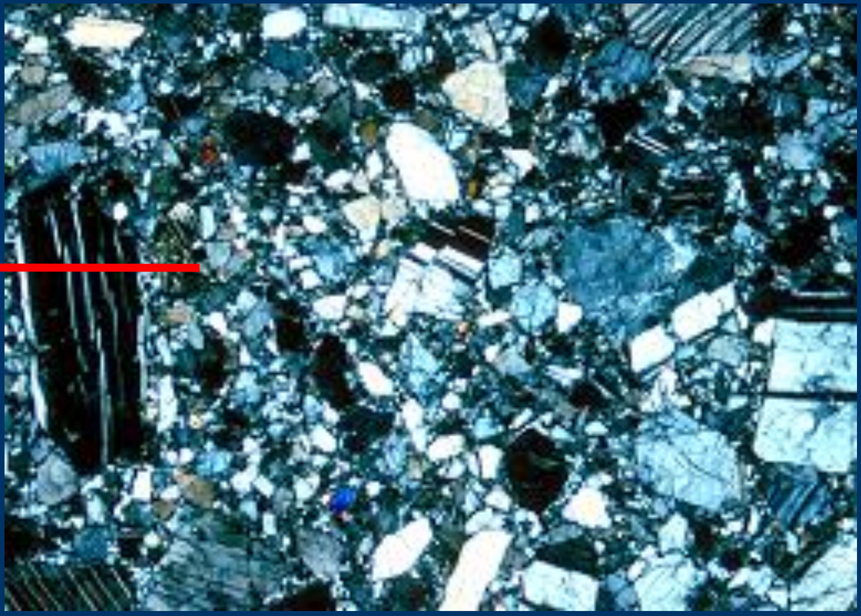
Earth is a living planet

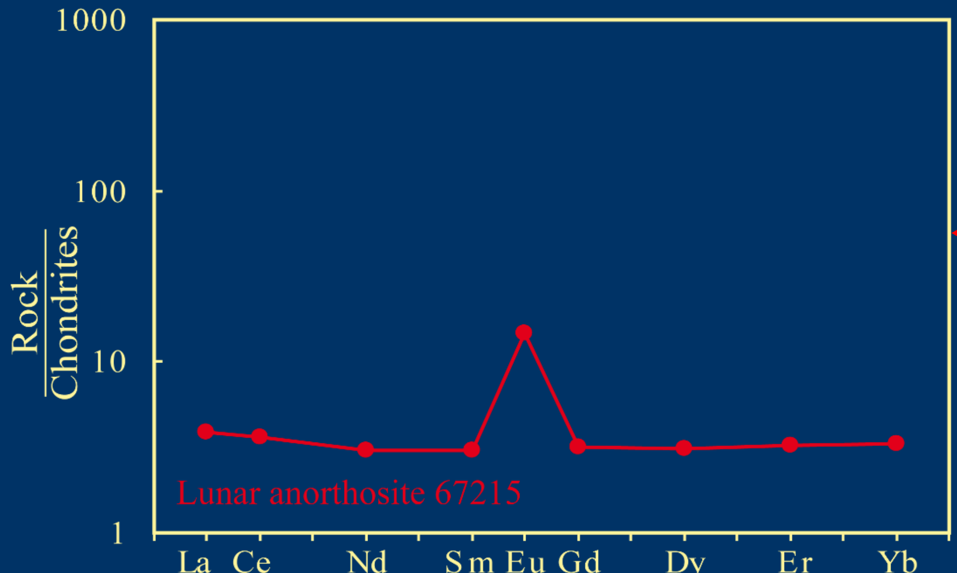


Magma ocean

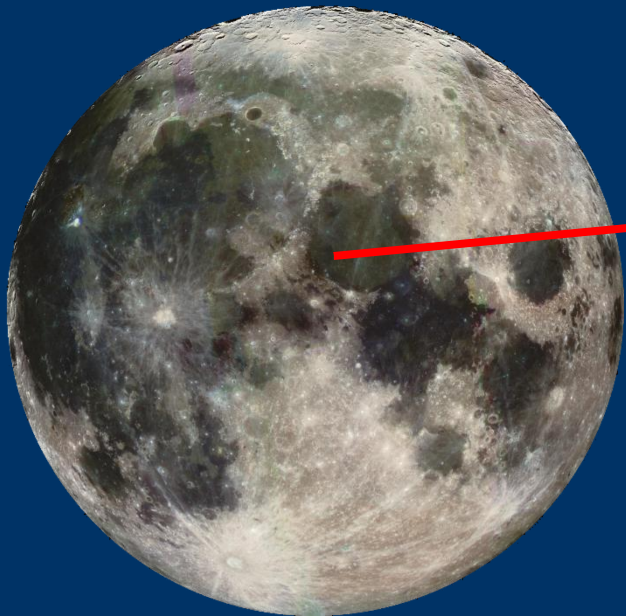
Cool Early Earth

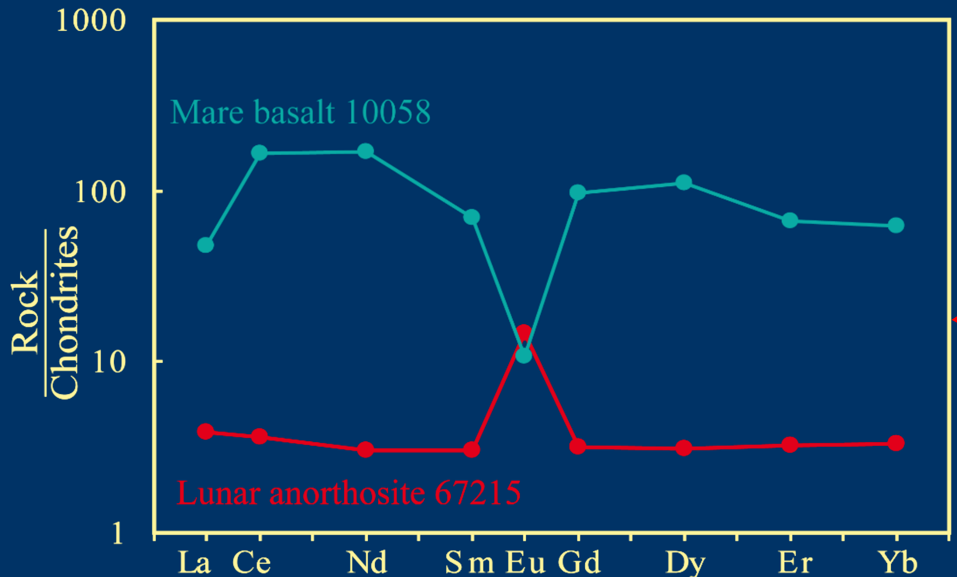
From 4.568 to 4.40 Ga :Earth magma ocean



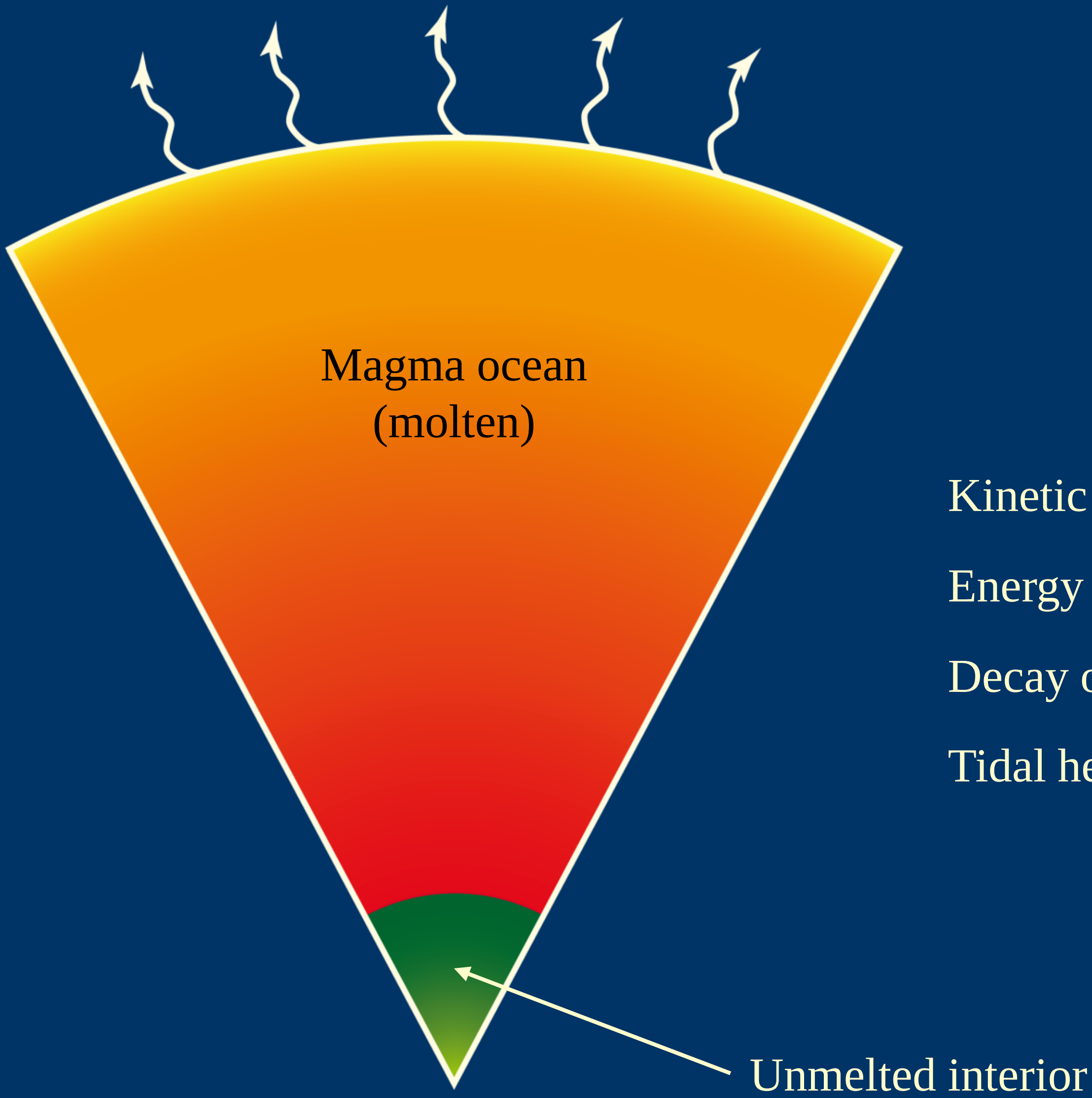


From 4.568 to 4.40 Ga :Earth magma ocean





From 4.568 to 4.40 Ga :Earth magma ocean



Energy sources

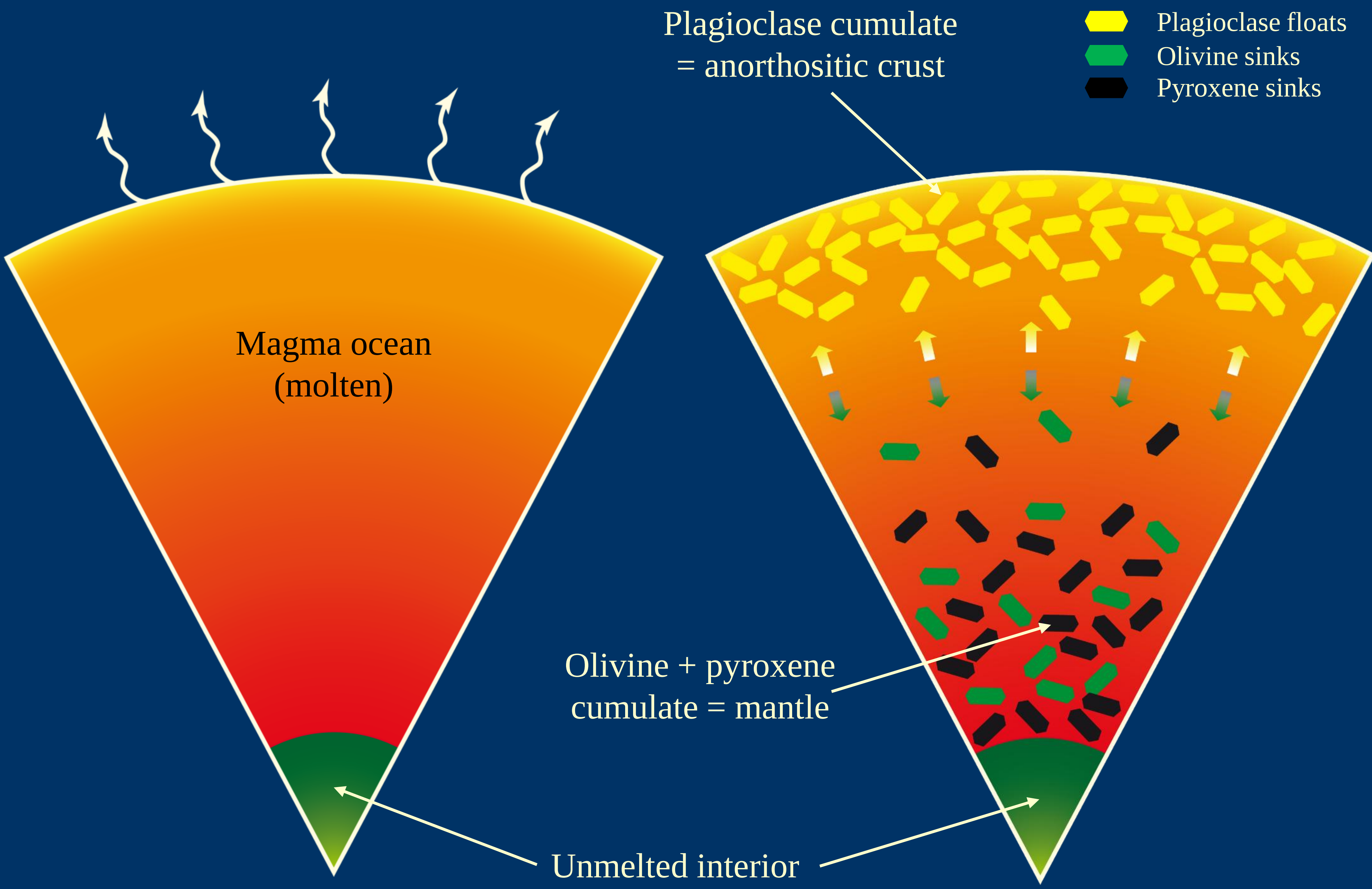
Kinetic energy of planetesimal impacts

Energy of iron-silicate gravitational separation

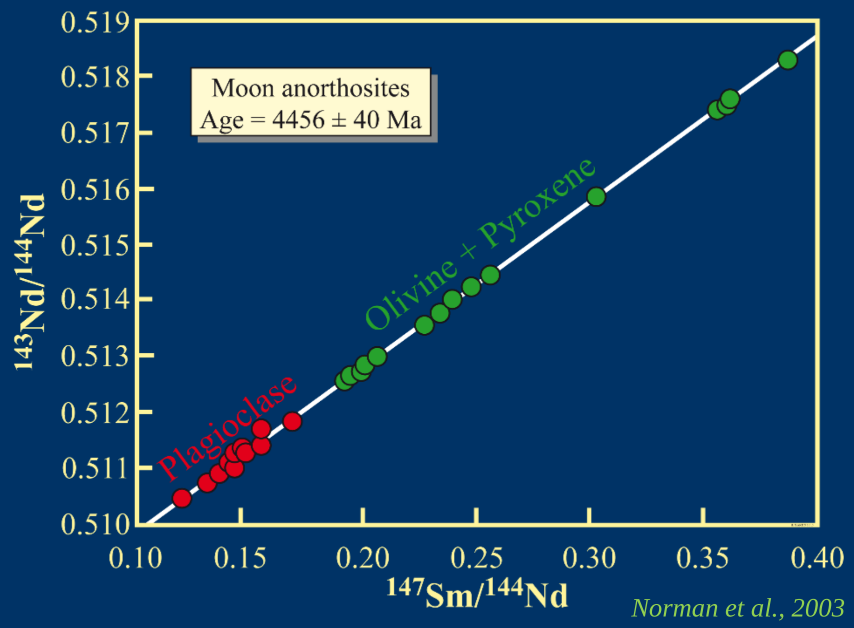
Decay of radioactive sources (K, U, Th…)

Tidal heating

From 4.568 to 4.40 Ga :Earth magma ocean



From 4.568 to 4.40 Ga :Earth magma ocean



Anorthosites cover most of the Moon surface

Their genesis is a planetary scale process

The magma ocean covered the whole Moon

Age of anorthosite crystallization = 4456 Ma

Magma ocean formed early in the planet history

Magma ocean is a very early process that affected the whole planet

From 4.568 to 4.40 Ga :Earth magma ocean

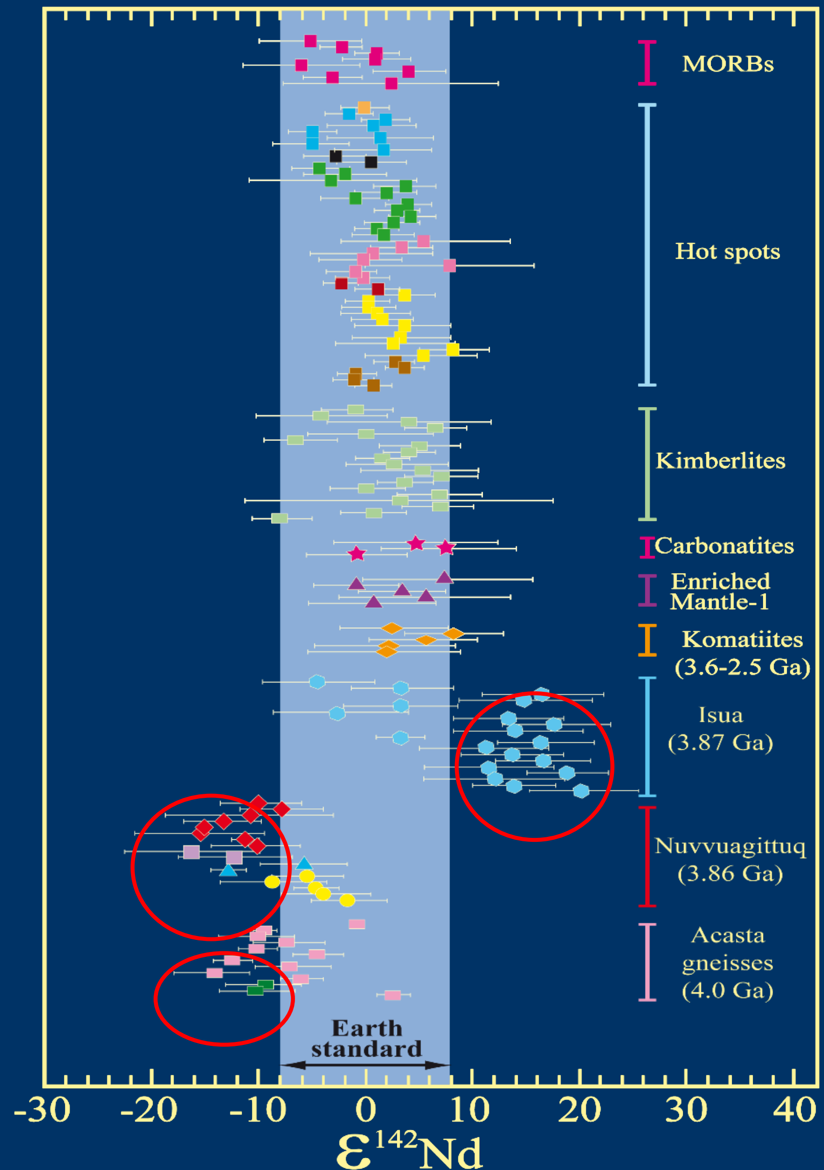
On Earth, plate tectonics and erosion wiped out almost all direct traces of magma ocean

$^{146}Sm \rightarrow ^{142}Nd$ ($T_{1/2}$= 103 Ma)
silicate/silicate fractionation

The oldest known rocks display complementary ^{142}Nd enrichment and impoverishment

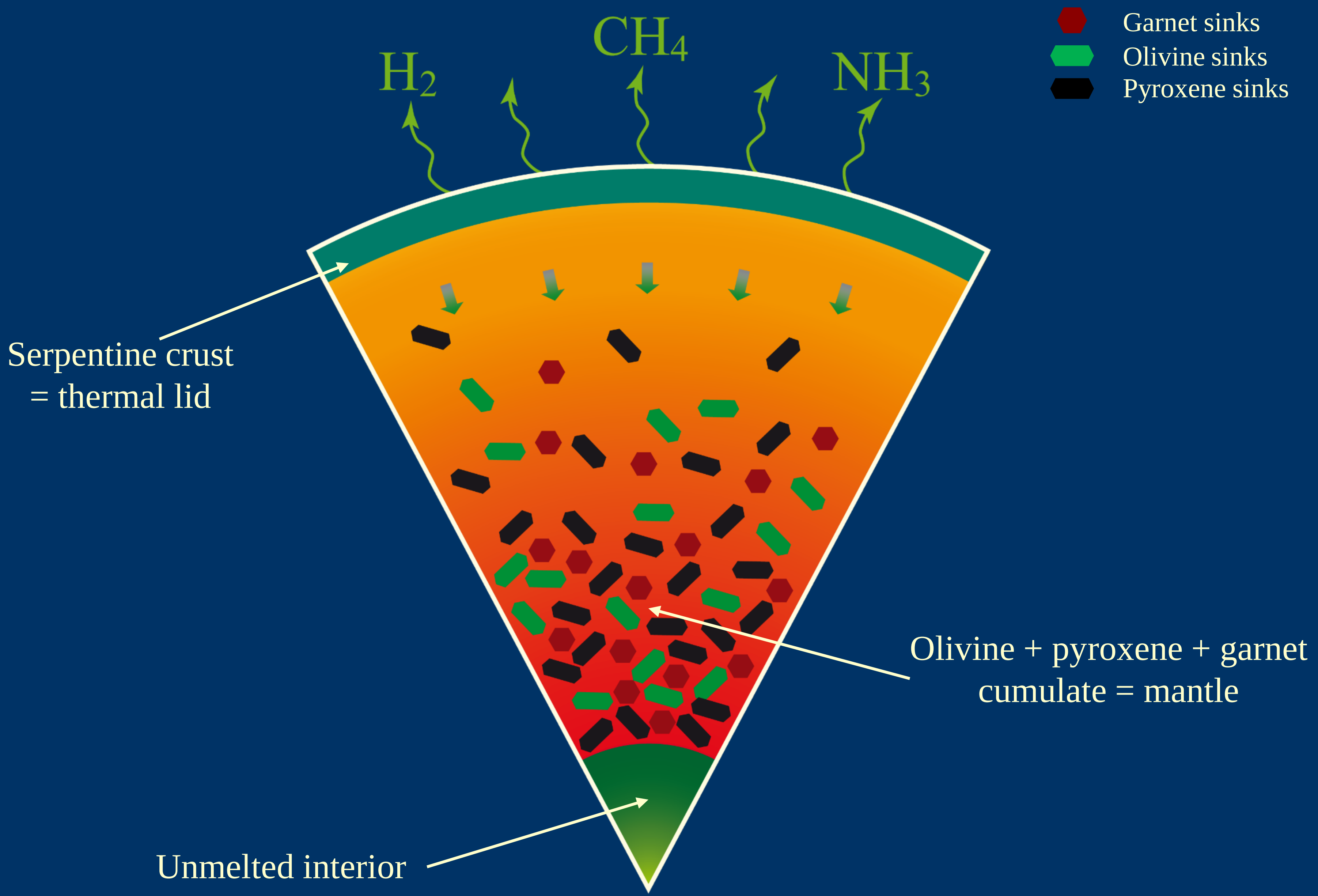
Early Earth's mantle preserved traces of primary differentiation (<500 Ma)

^{142}Nd model ages indicate magma ocean crystallization ages of 4.45 – 4.35 Ga

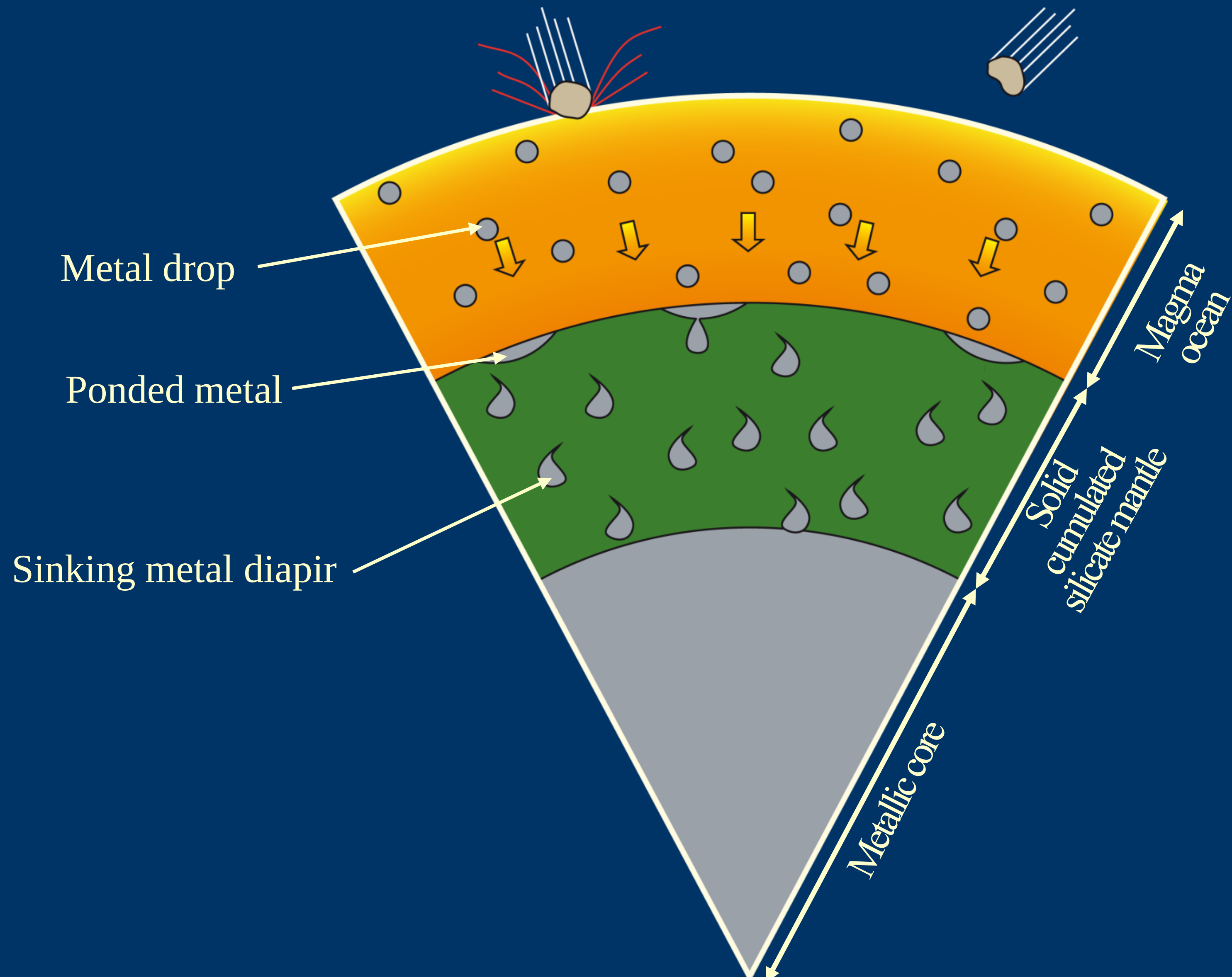


Boyer and Carlson, 2008; Jackson and Carlson, 2012; Roth et al., 2014

From 4.568 to 4.40 Ga :Earth magma ocean



Core-mantle differentiation and magnetic field



Core-mantle differentiation and magnetic field

When did the separation of the metallic core and silicate mantle took place?

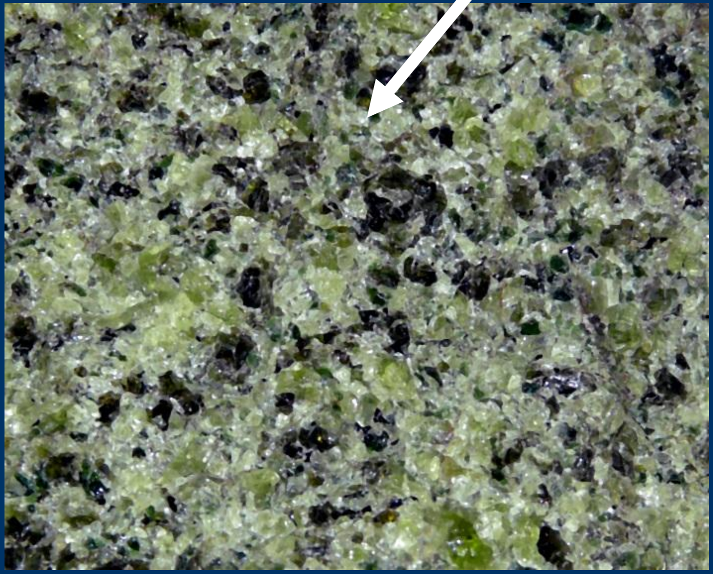
Dating based on extinct radioactivity

$^{182}Hf \rightarrow {}^{182}W$ ($T_{1/2}$= 9 Ma) $\Rightarrow$ all ^{182}Hf disappears for T<60Ma

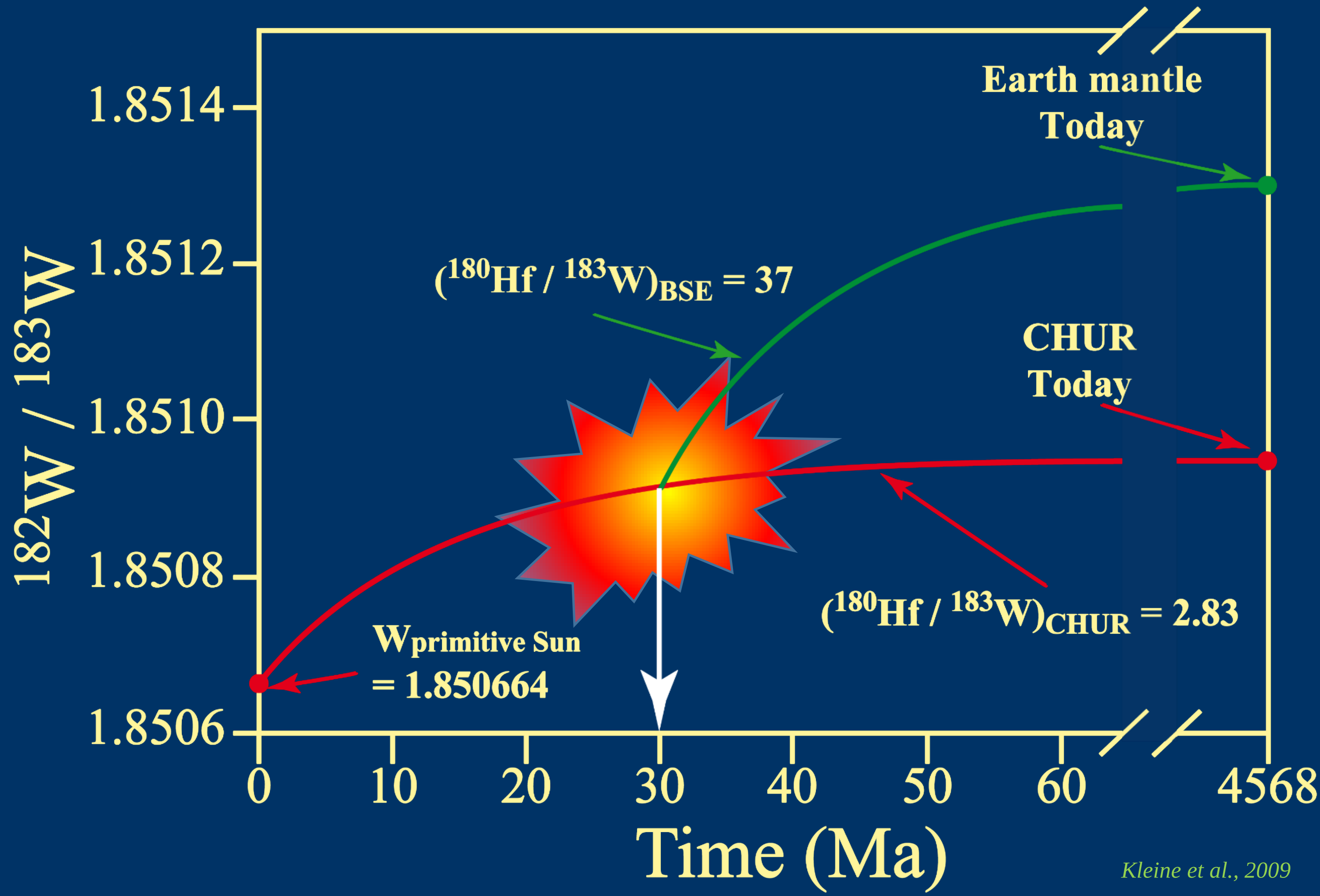
$$^{182}Hf \rightarrow {}^{182}W$$

Hf = lithophile : incorporated in silicates (mantle and crusts)

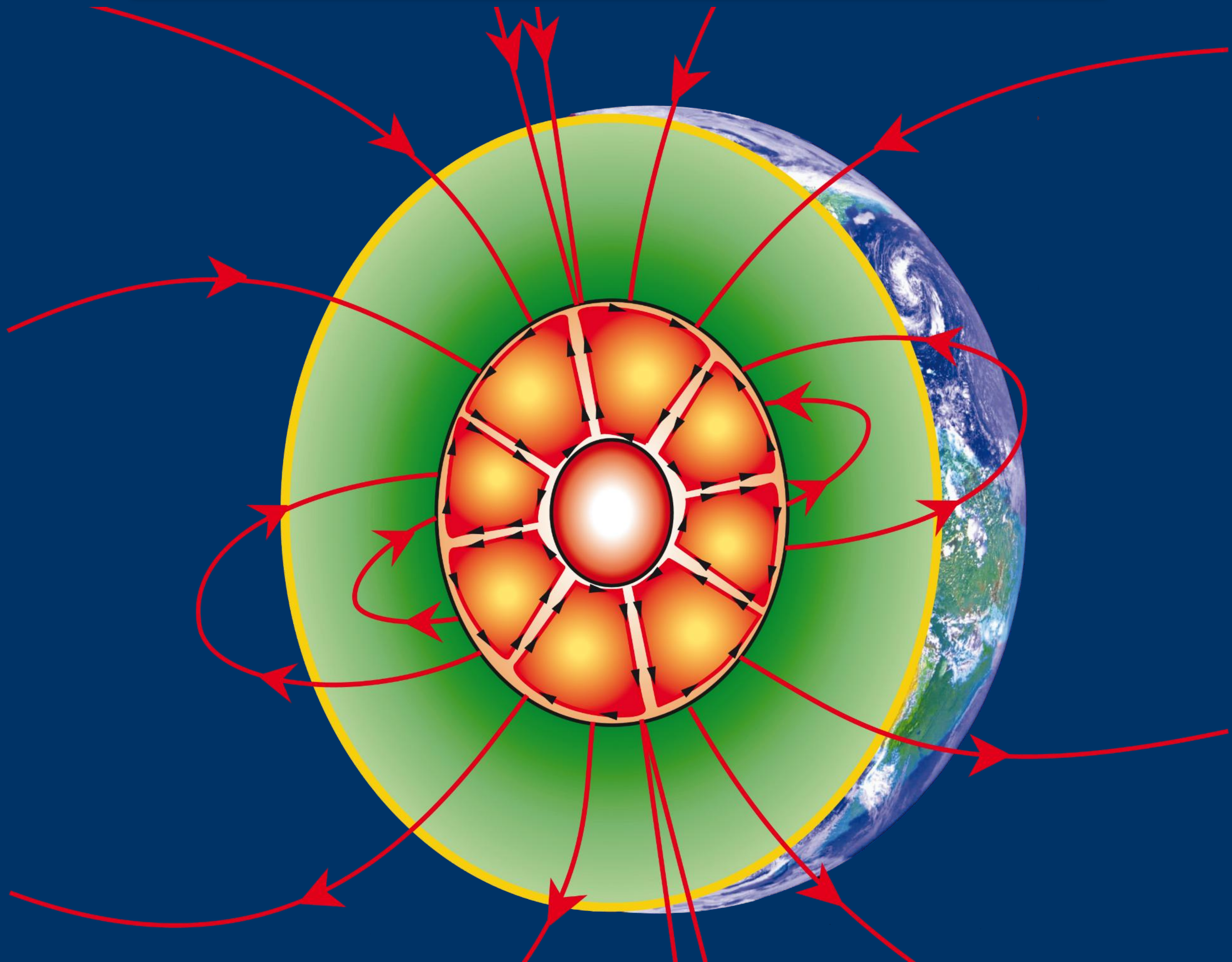
W = siderophile : incorporated in metal (core)



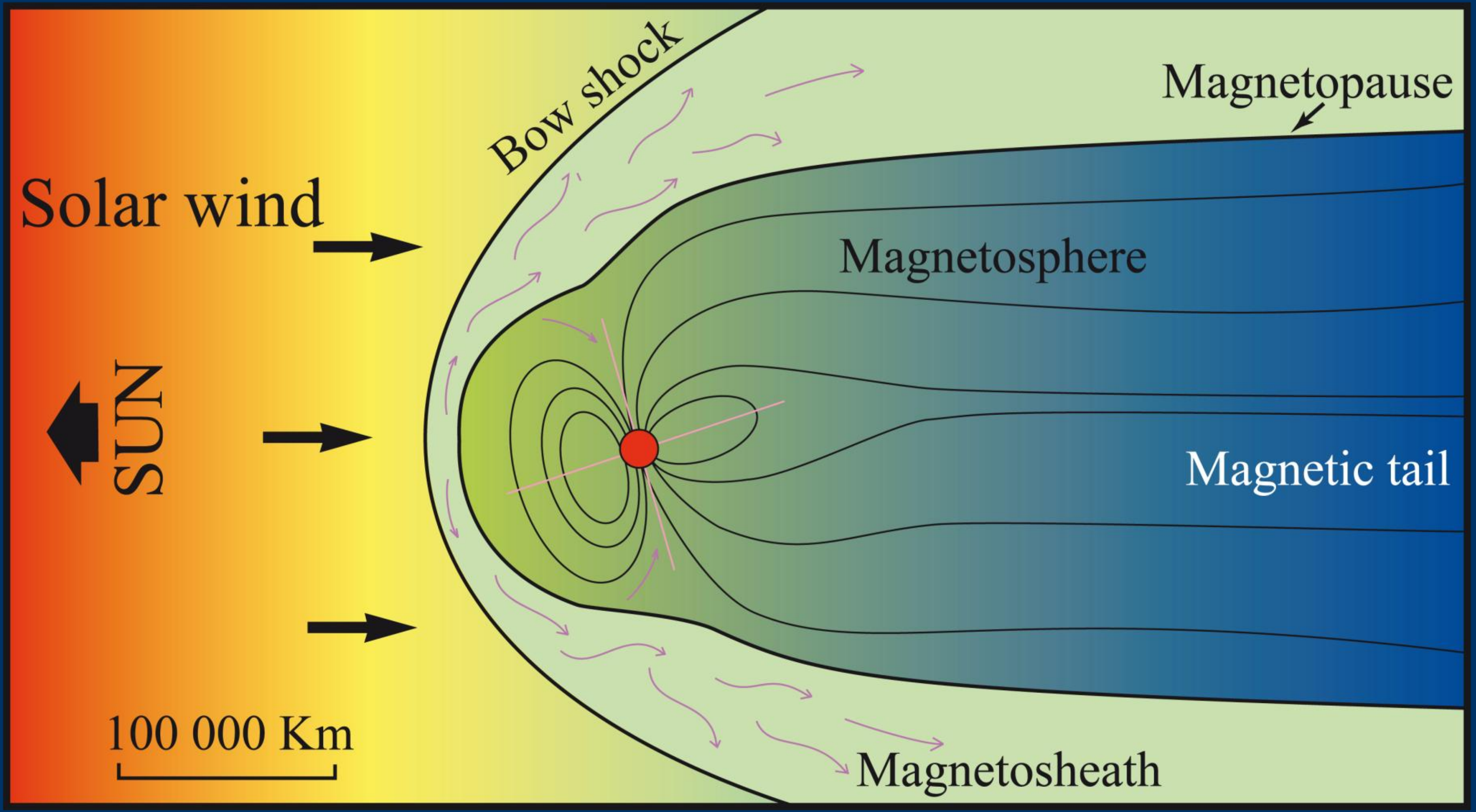
Core-mantle differentiation and magnetic field



Core-mantle differentiation and magnetic field

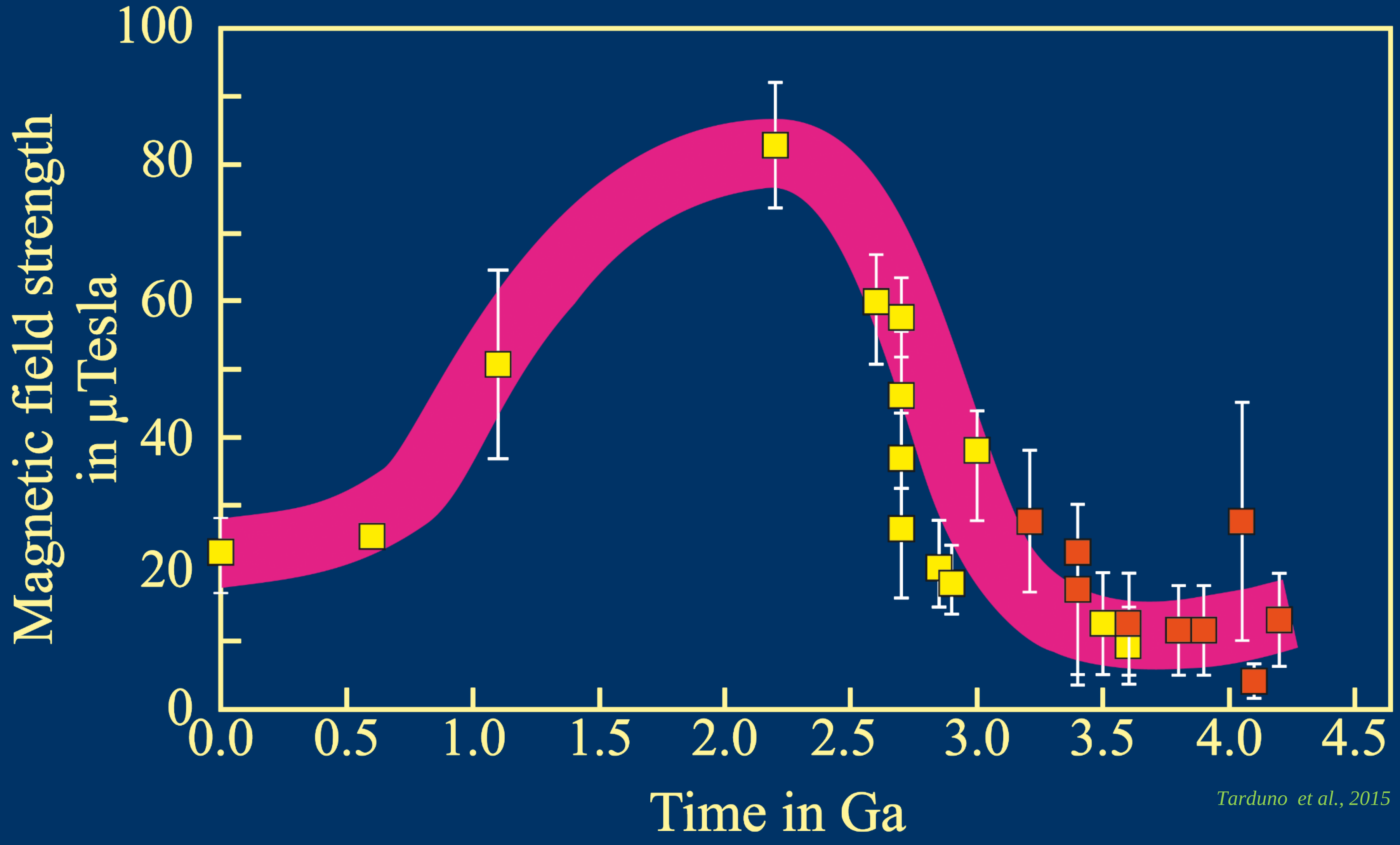


Core-mantle differentiation and magnetic field



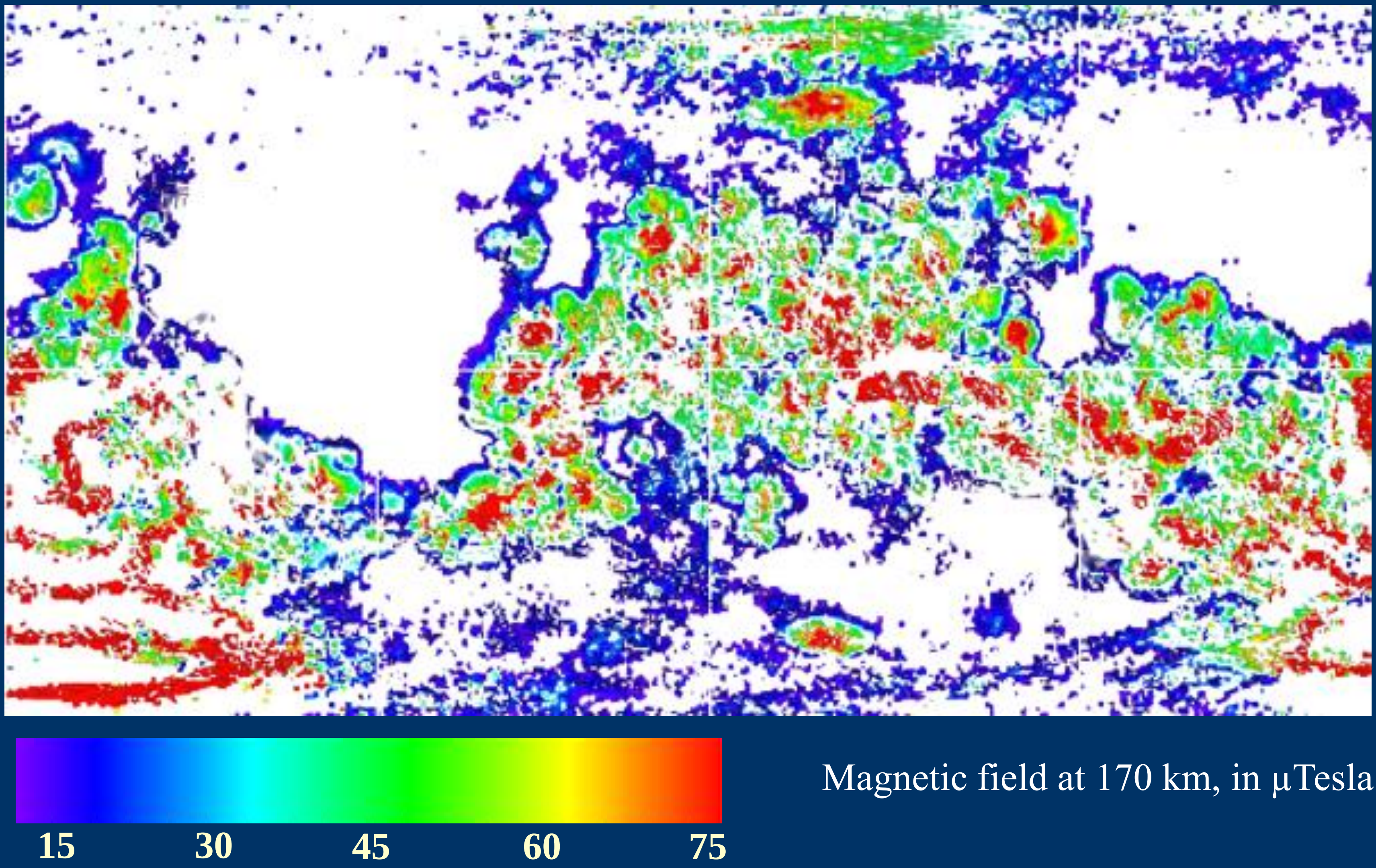
Immediately after the core formation, the conditions for the apparition of the Earth's magnetic field, were fulfilled; which does not necessarily mean that this latter appeared at that time.

Core-mantle differentiation and magnetic field



Tarduno et al., 2015

Core-mantle differentiation and magnetic field



Magnetic field at 170 km, in μTesla

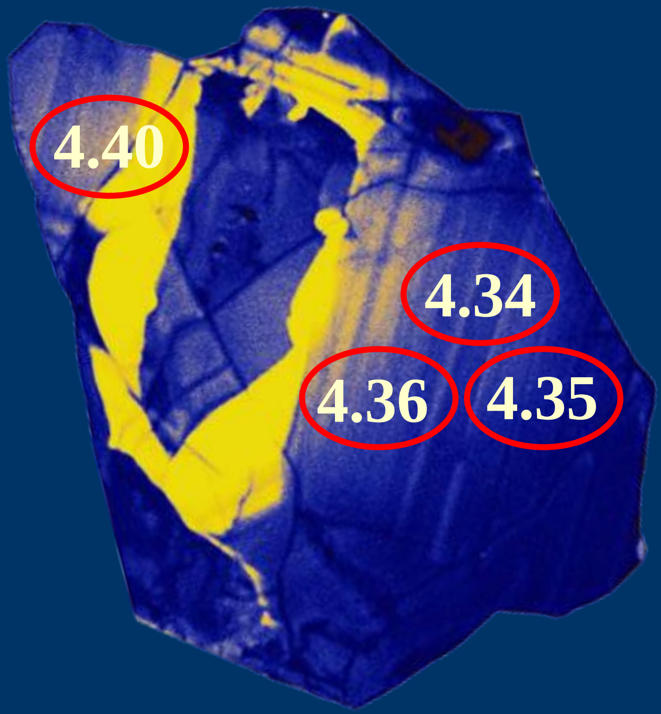
Today Mars has no global magnetic field

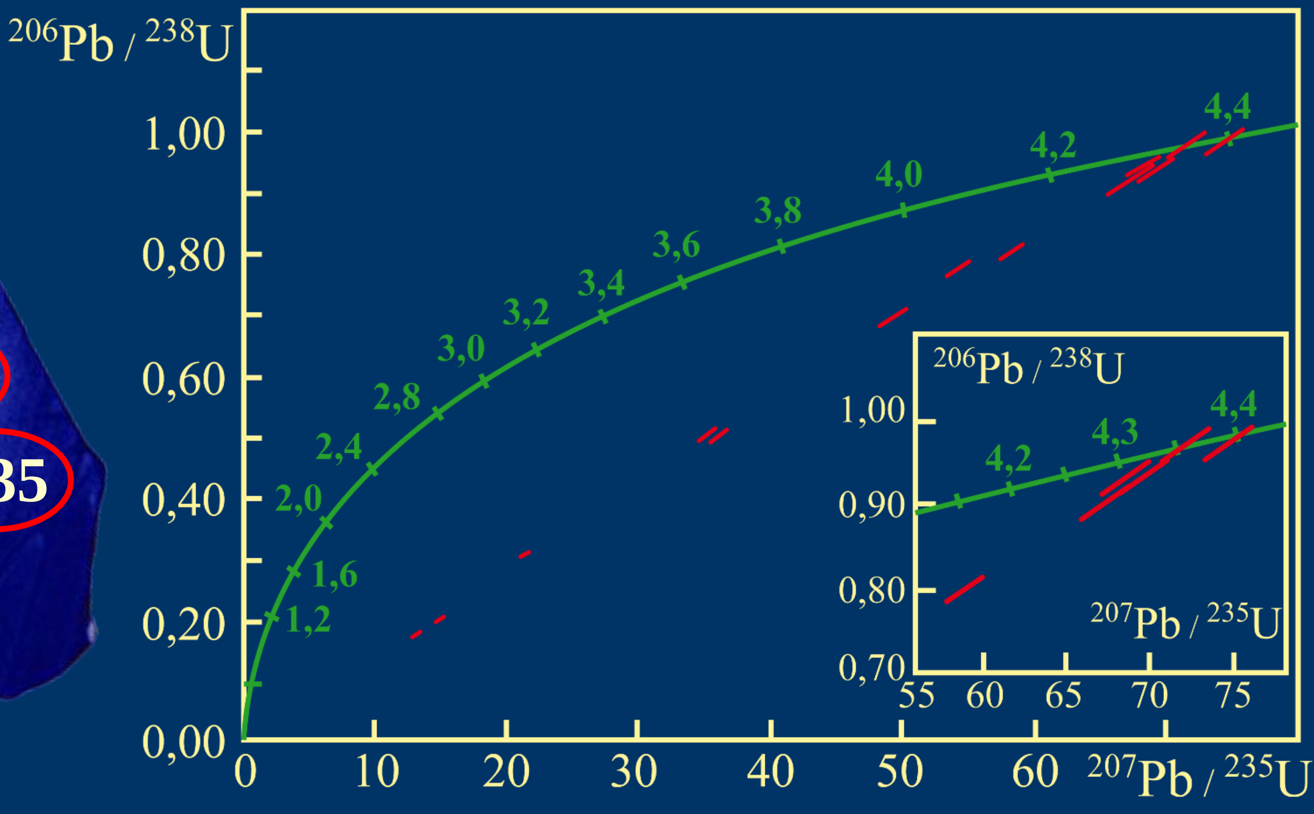
Remnant magnetic field is only recorded in terranes older than 4.0 Ga

From 4.40 to 4.0 Ga :the first continental crust

Jack Hills (Western Australia)

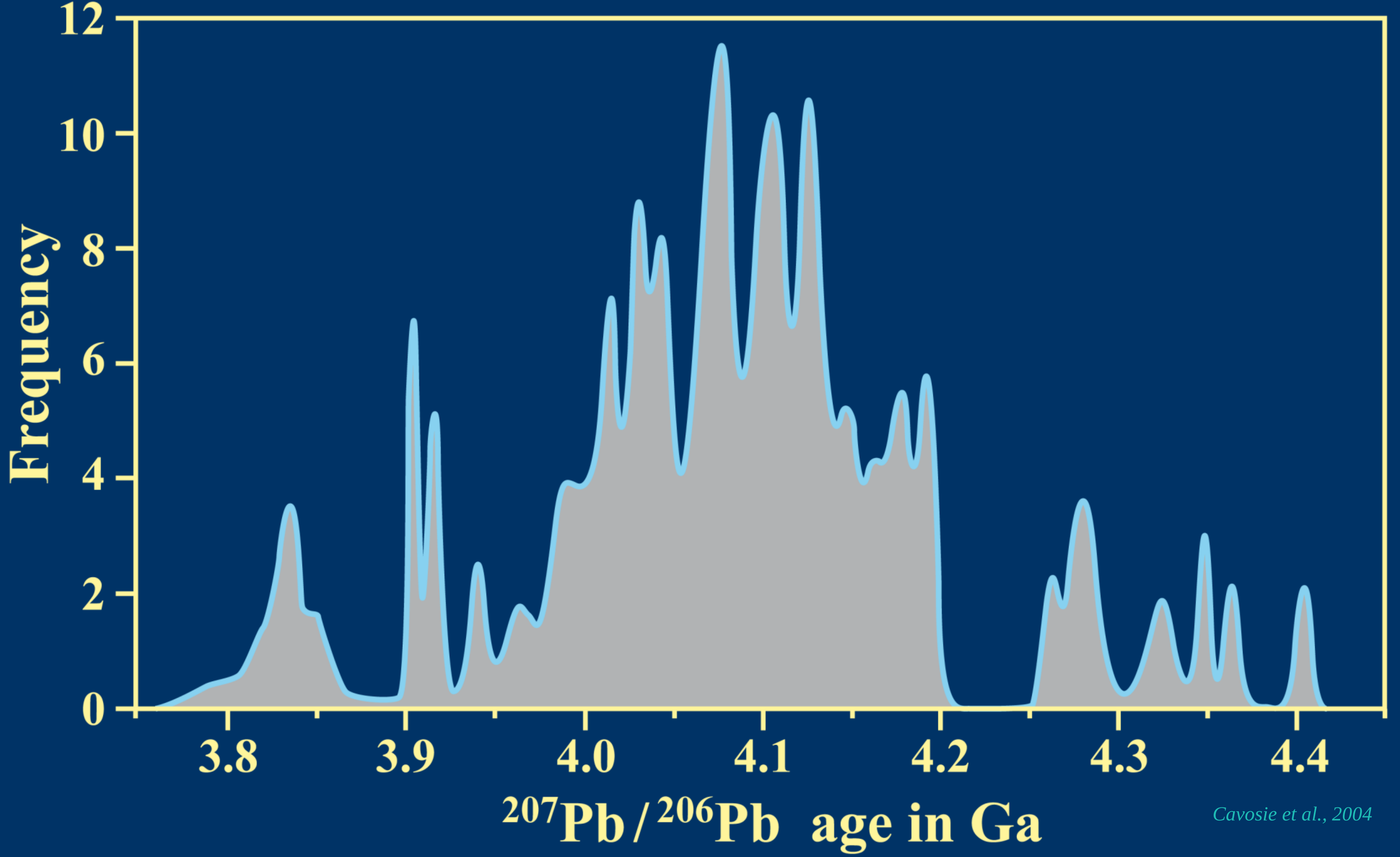
From 4.40 to 4.0 Ga :the first continental crust





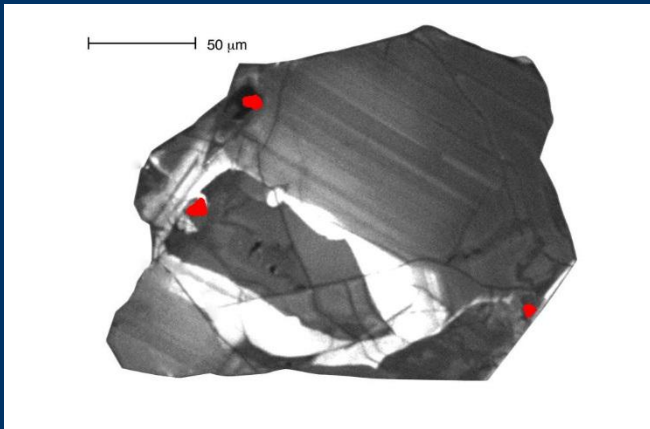
Wilde et al. 2001

From 4.40 to 4.0 Ga :the first continental crust

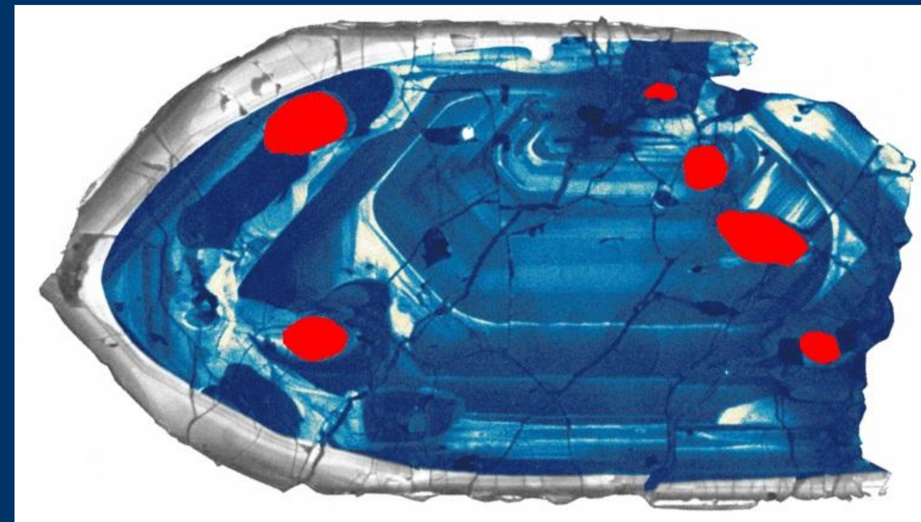


From 4.40 to 4.0 Ga :the first continental crust

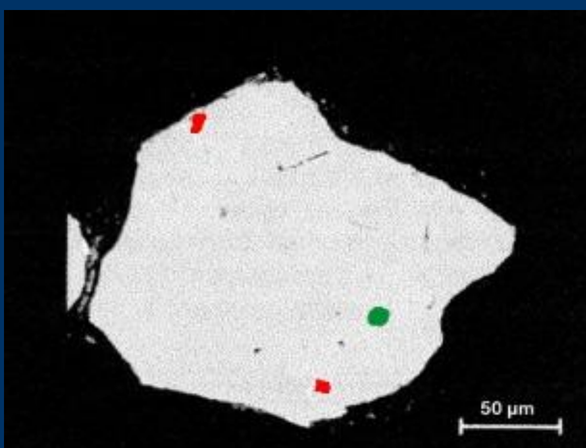
Jack Hills zircon crystals contain inclusions of minerals formed in their host magma



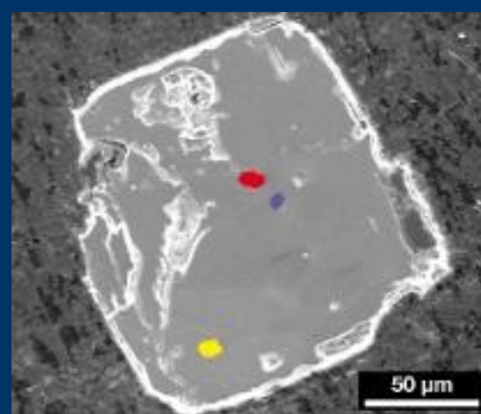
Wilde et al., 2001



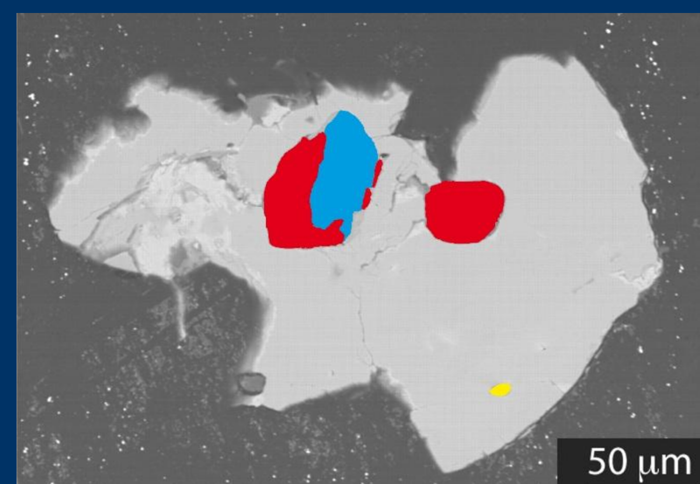
Valley et al., 2014



Wilde et al., 2001



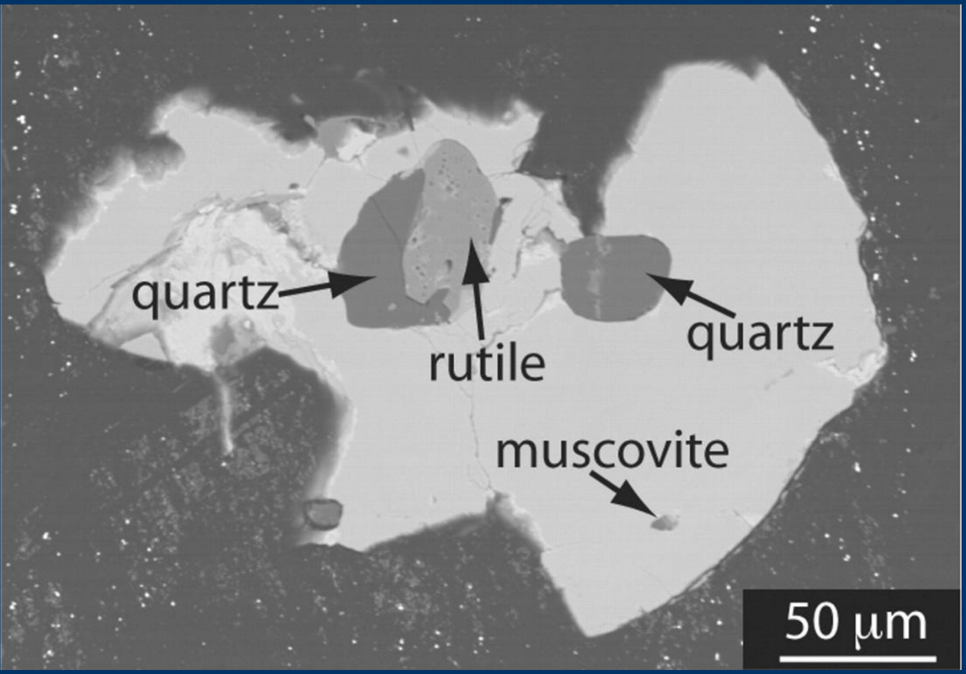
Hopkins et al., 2008



Hopkins et al., 2008

- Quartz
- Plagioclase
- Rutile
- Muscovite
- Biotite

From 4.40 to 4.0 Ga :the first continental crust



Mineral inclusions

Quartz : SiO_2

Plagioclase : $NaAlSi_3O_8$

Orthoclase : $KAlSi_3O_8$

Biotite : $(Fe,Mg)_3K(AlSi_3O_{10}, (OH)_2)$

Muscovite : $(Al)_2K(AlSi_3O_{10}, (OH)_2)$

Rutile : TiO_2

etc……..

Quartz + Feldspars + Micas

=

Granite

=

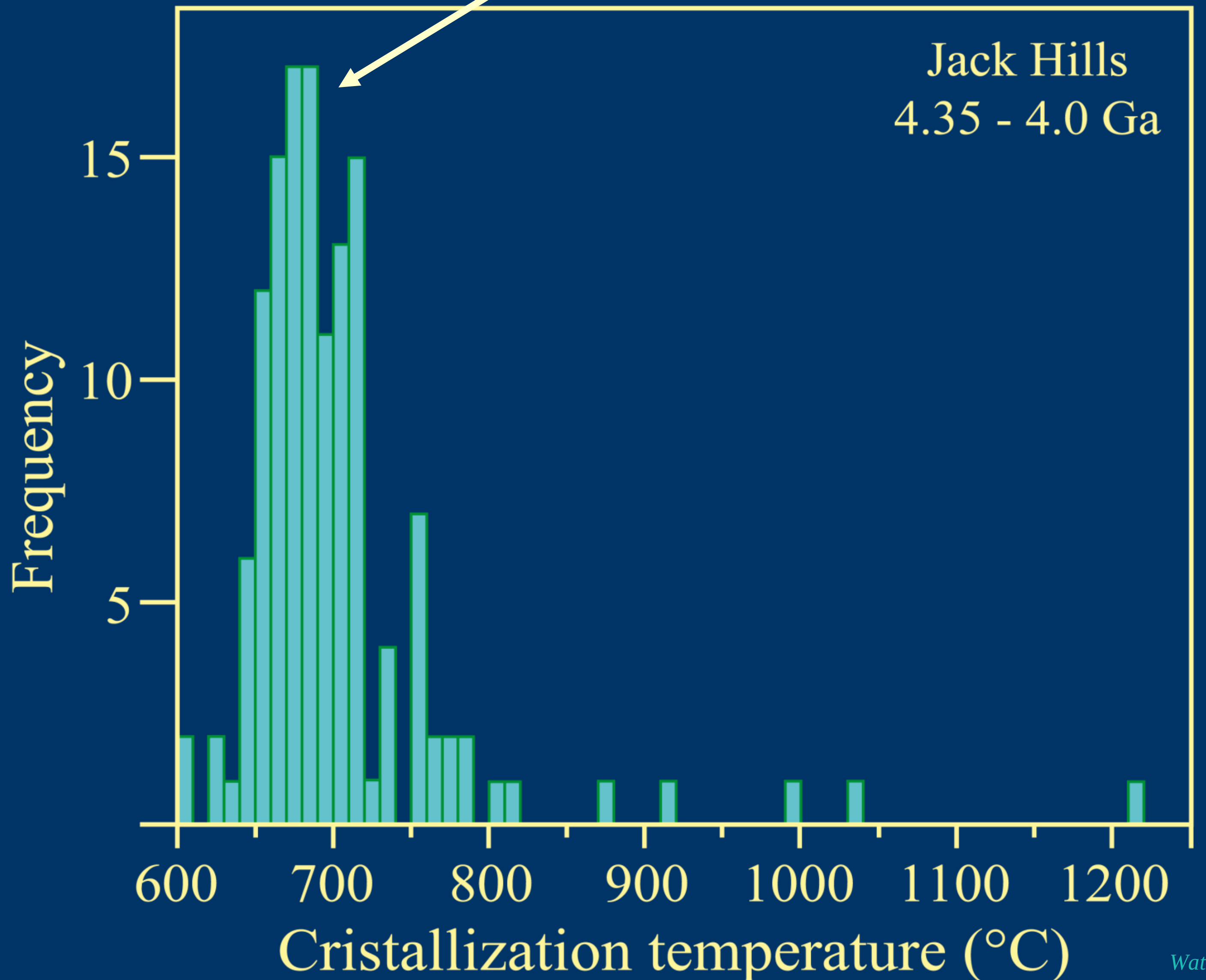
Continental crust

Continental crust existed as early as 4.4 Ga

From 4.40 to 4.0 Ga :the first continental crust

The lattice of zircon crystal is able to incorporate very small amounts of Ti, which amount is temperature-dependant

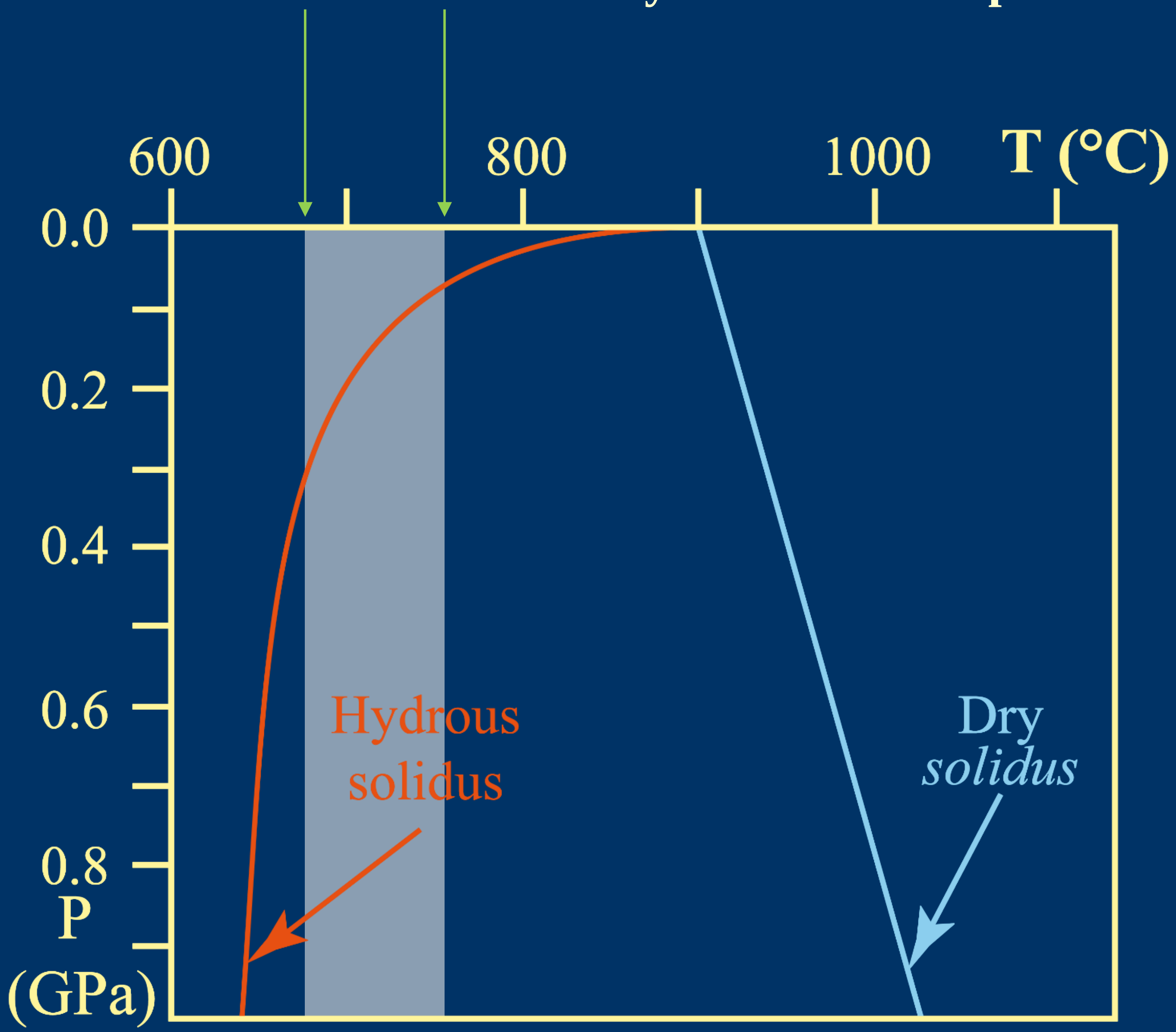
Low crystallization temperature : 680 – 750 C



Watson and Harrisson, 2005

From 4.40 to 4.0 Ga :the first continental crust

680 – 750 C = crystallization temperature



Hydrous melting

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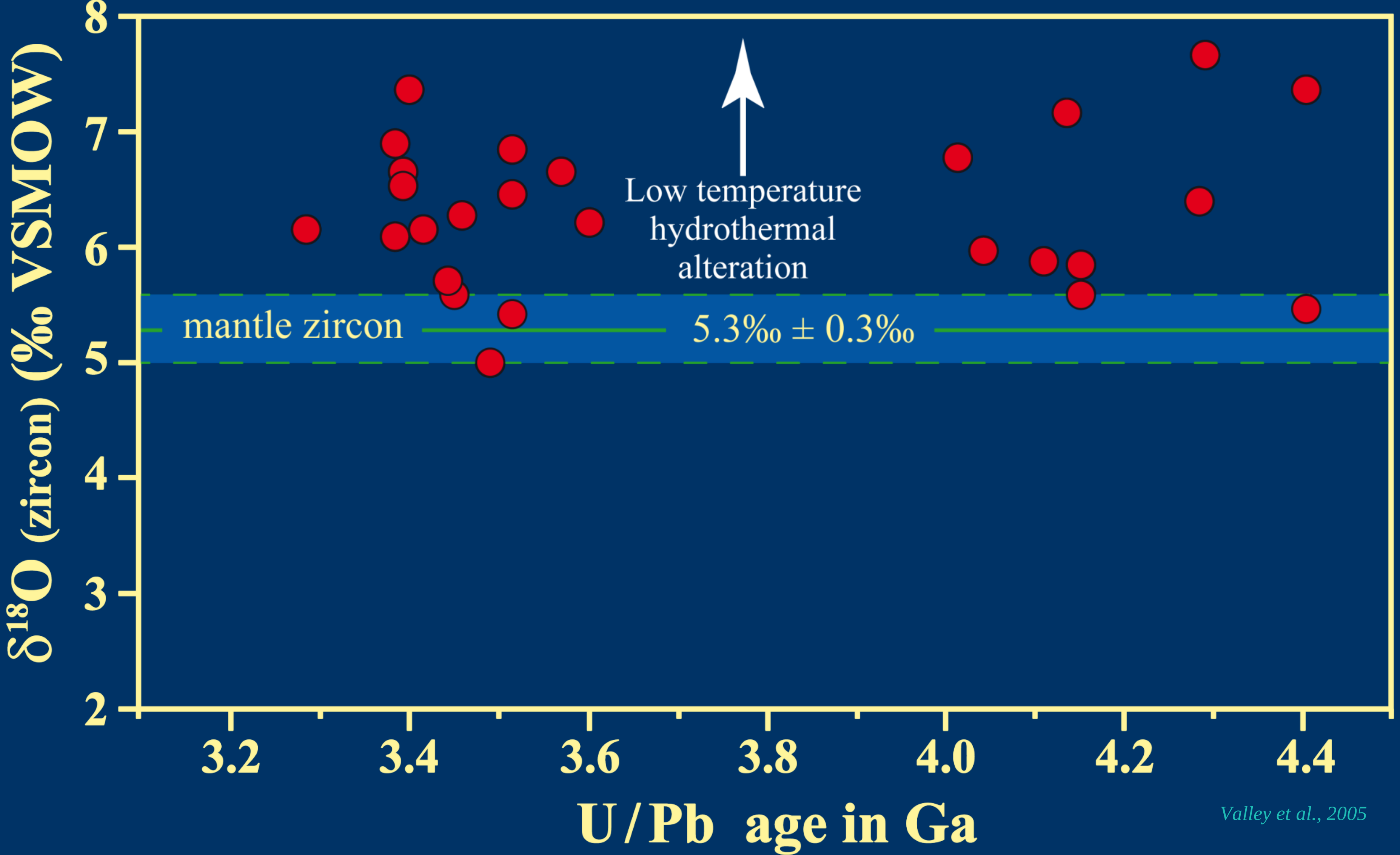
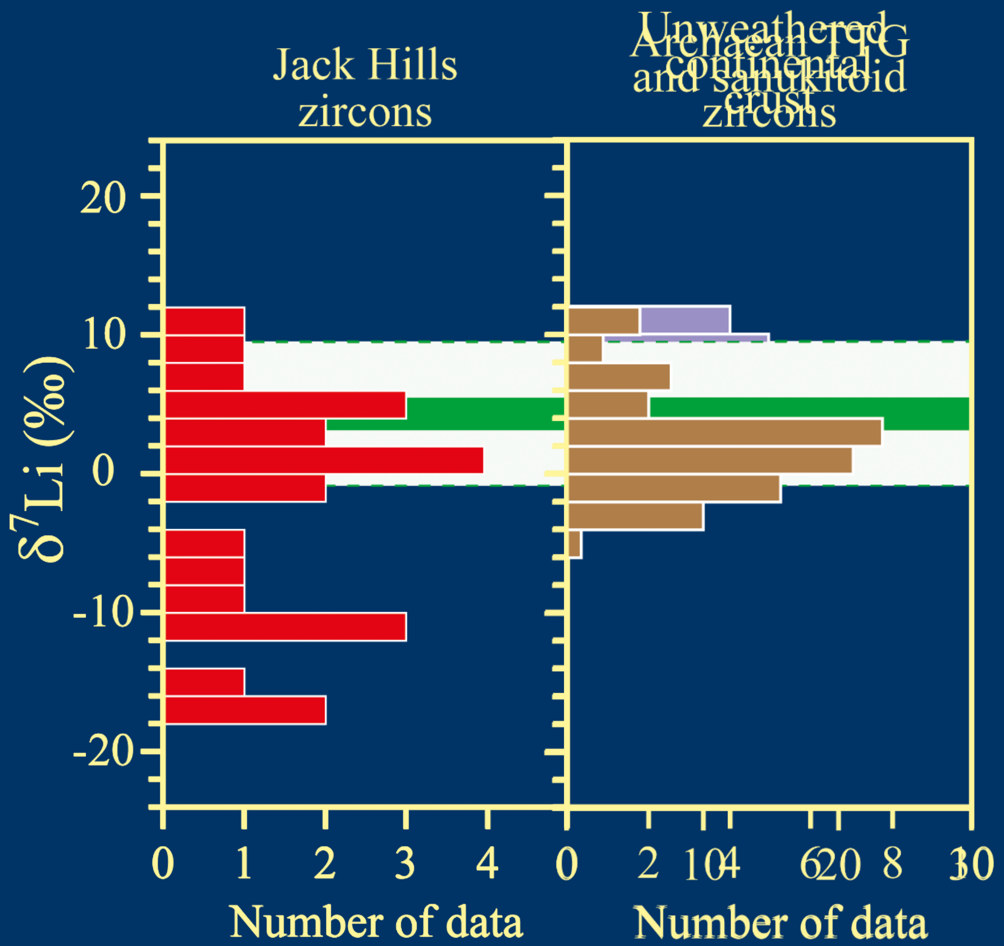
Water available

From 4.40 to 4.0 Ga :the first ocean

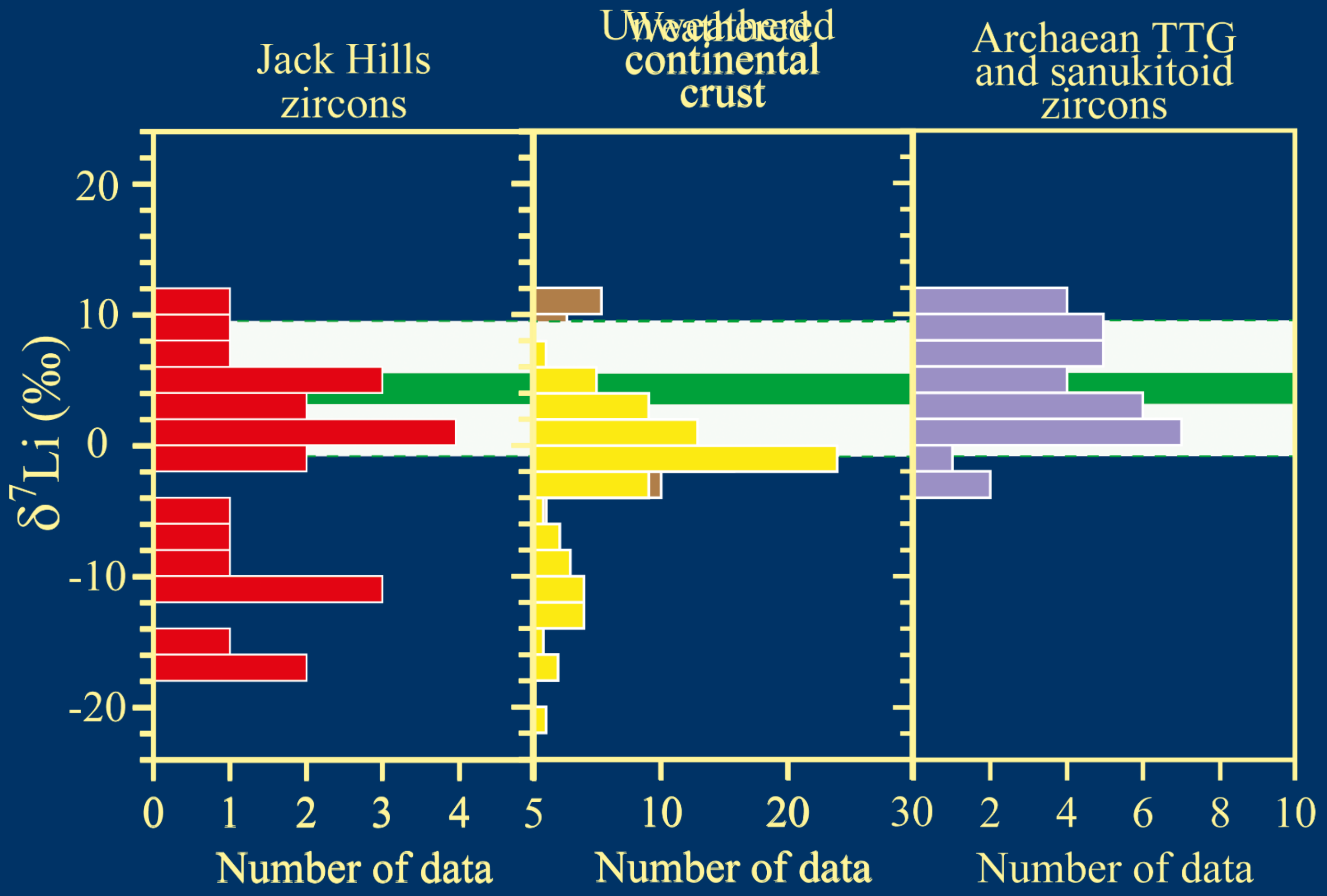


Valley et al., 2005

From 4.40 to 4.0 Ga :the first ocean



From 4.40 to 4.0 Ga :the first ocean



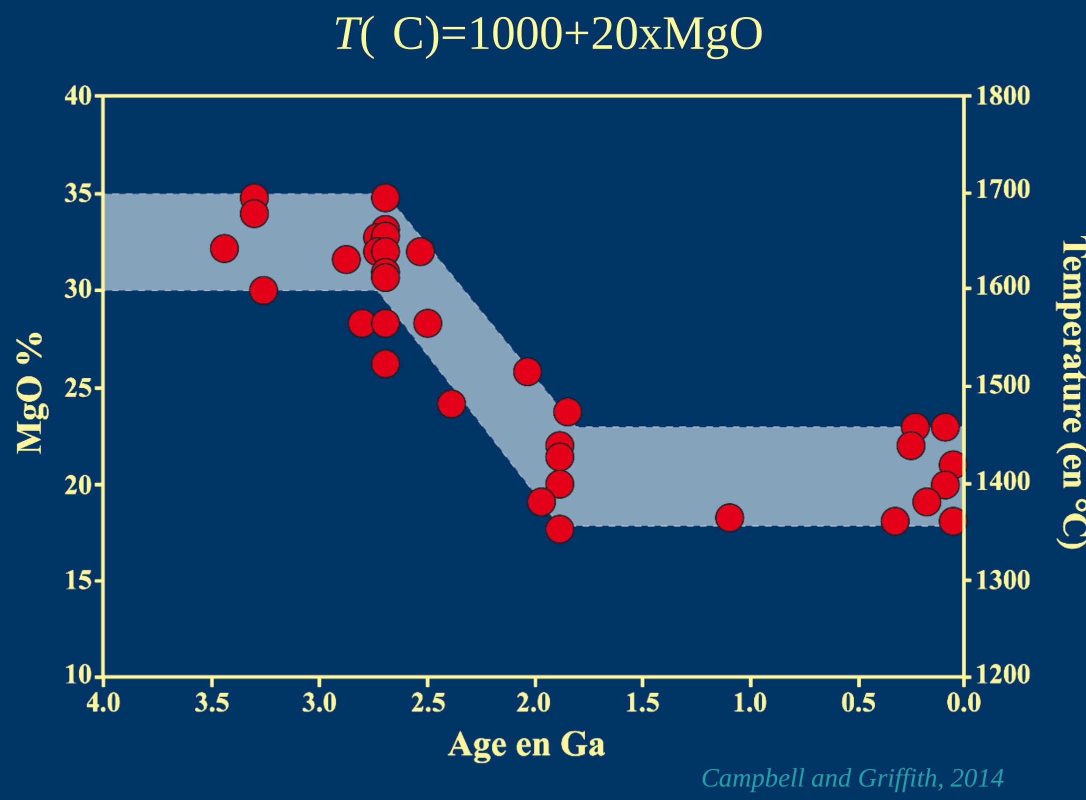
Bouvier et al., 2012

Water induced weathering decreases δ^7Li

From 4.40 to 4.0 Ga :the first ocean

After 4.0 Ga :the Archaean

Komatiite from Pike Hill (Canada)



Archaean internal Earth heat production was greater than today

After 4.0 Ga :the Archaean

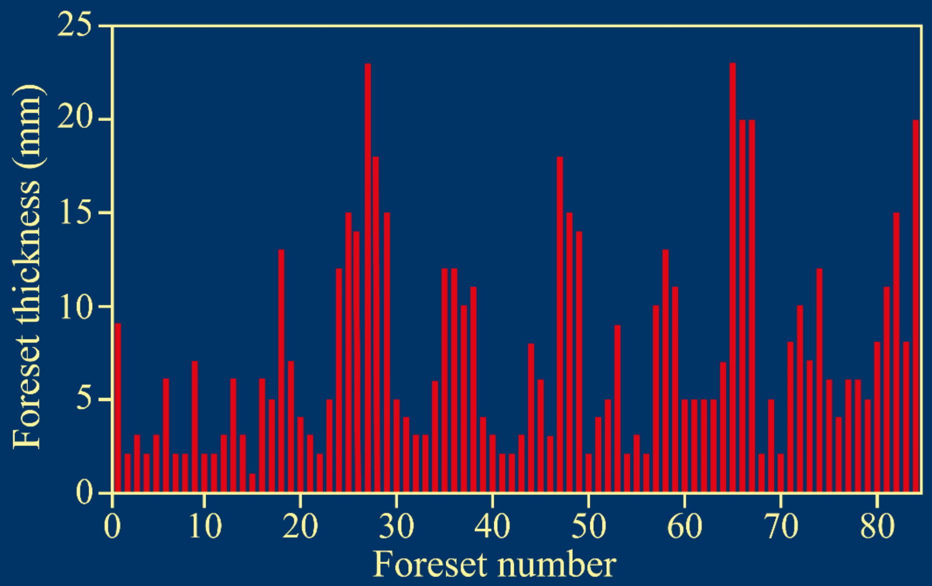
Tholeiitic pillow lavas from Isua (Greenland) :3.86 Ga

Mud cracks from Barberton (South Africa) :3.45 Ga

During the Archaean there were oceans as well as emerged continents

After 4.0 Ga :the Archaean

Moodies sandstone from Barberton (South Africa) :3.2 Ga



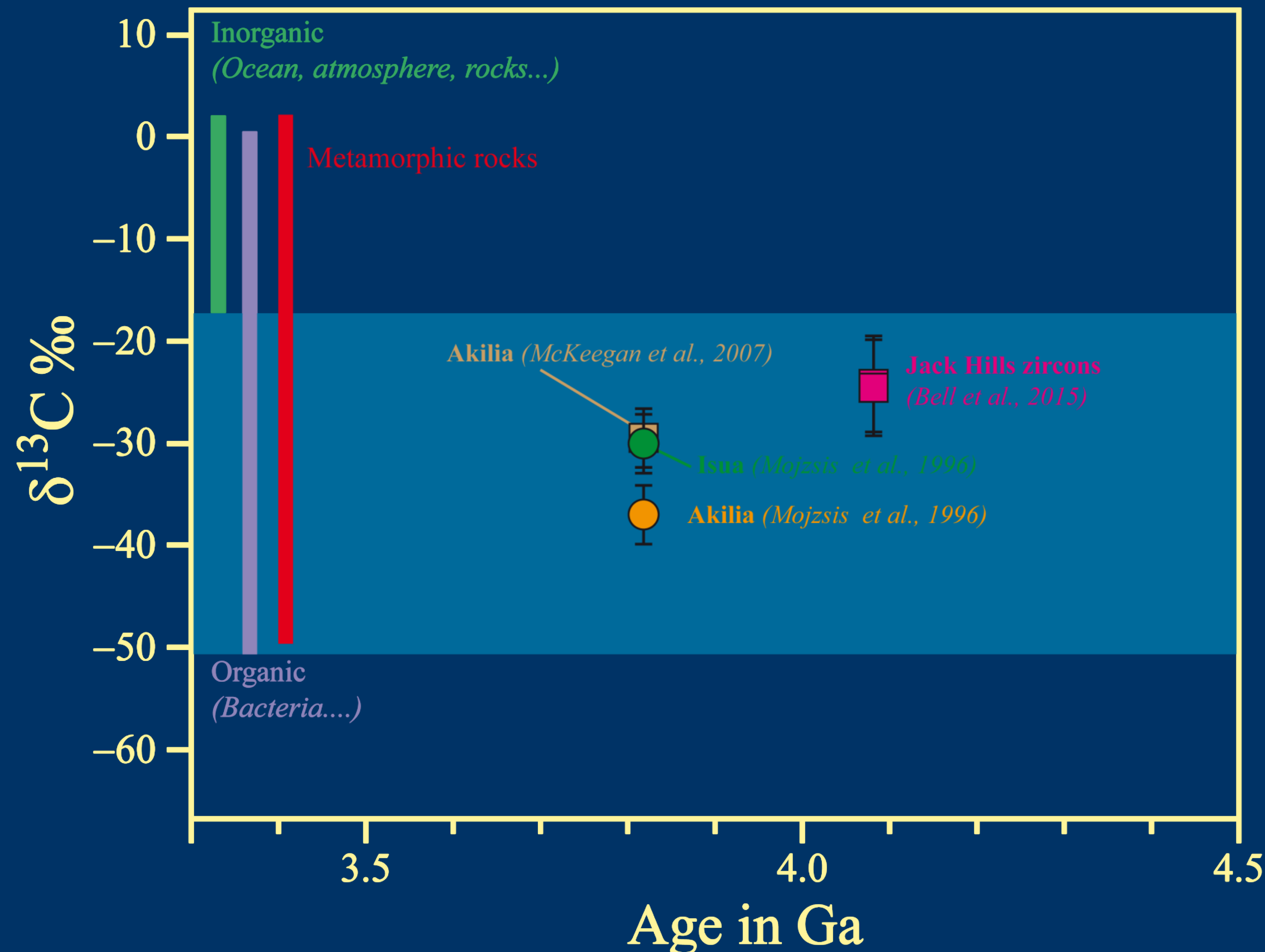
Eriksson and Simpson, 2000

3.2 Ga ago, the anomalistic month was of about 20 days

After 4.0 Ga :the Archaean

North Pole stromatolites (Pilbara, Australia): 3.2 Ga

At least 3,4 Ga ago, Earth was inhabitable and inhabited

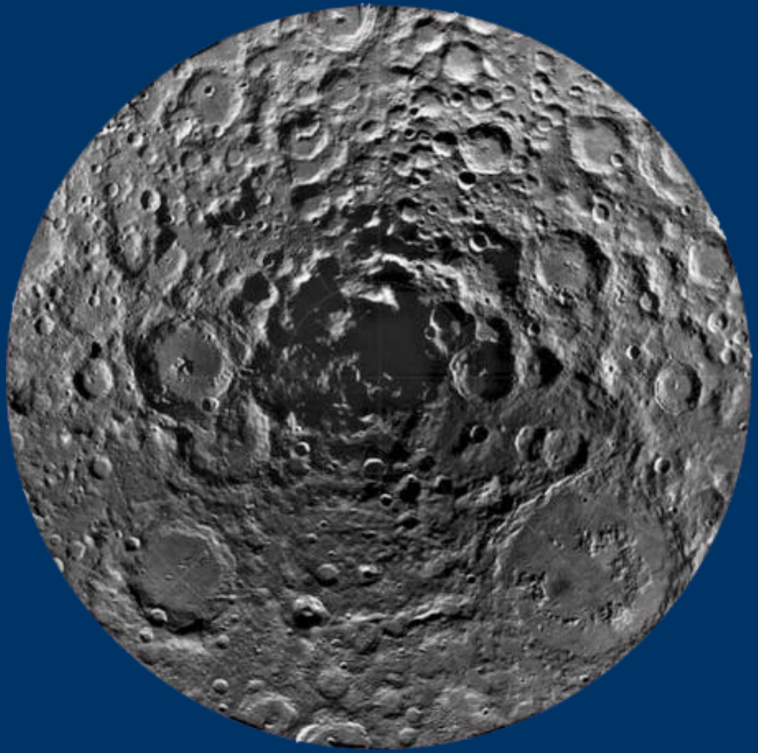


10
0
−10
−20
−30
−40
−50
−60
δ13C ‰
Inorganic
(Ocean, atmosphere, rocks...)
Metamorphic rocks
Akilia (McKeegan et al., 2007)
Jack Hills zircons
(Bell et al., 2015)
Isua (Mojzsis et al., 1996)
Akilia (Mojzsis et al., 1996)
Organic
(Bacteria....)
3.5
4.0
4.5
Age in Ga

From 4,0 to 3,85 Ga: The Late Heavy Bombardment

Mercury

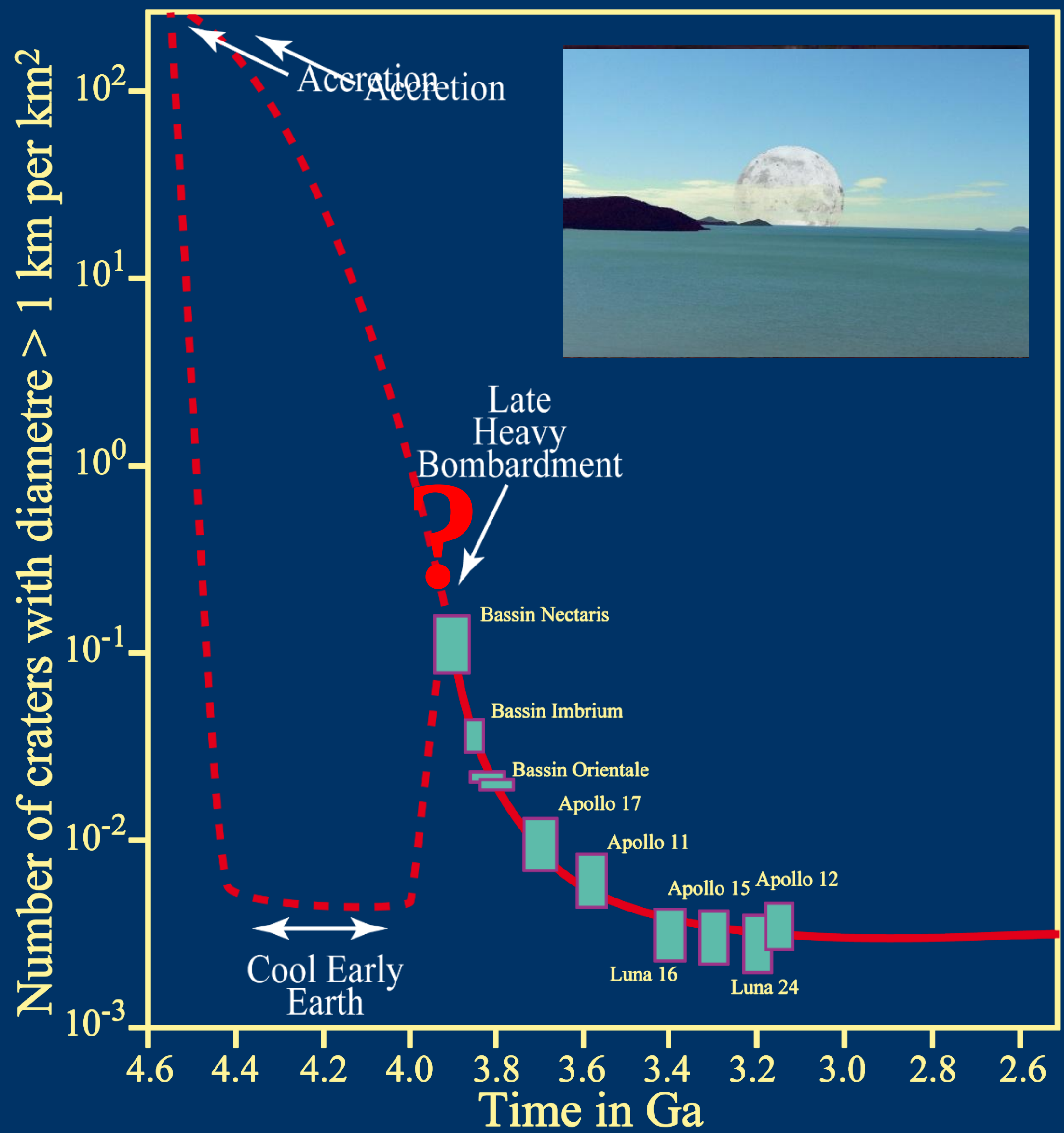
Ganymede



Moon

All the objects, devoid of plate tectonics and erosion,
kept the record of an intense meteorite bombardment

After 4.0 Ga :the Archaean



Implications for Early Earth inhabitability

Early Hadean (4.568 - 4.40 Ga)

Magma ocean, no liquid water, no magnetic field

No possibility for prebiotic chemistry and emergence of life

Late Hadean (4.40- 4.00 Ga)

Continental crust, liquid water (ocean), magnetic field

Environmental conditions favourable for the emergence of life

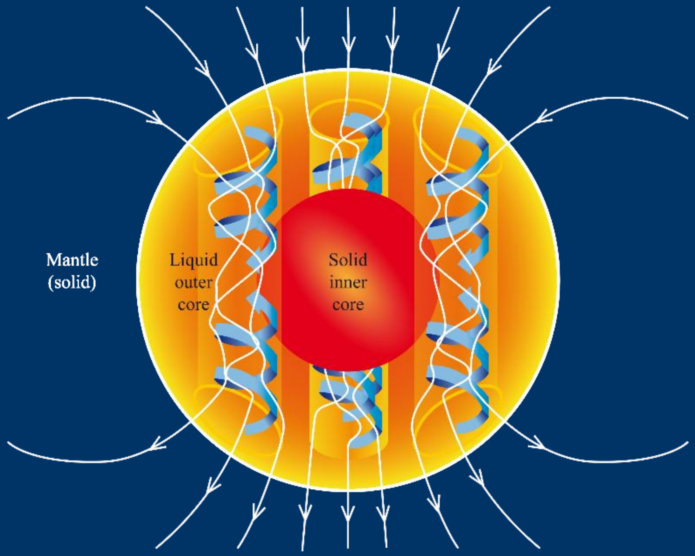
Late Heavy Bombardment ***Sterilising ???***

Archaean (4.00 – 2.50 Ga)

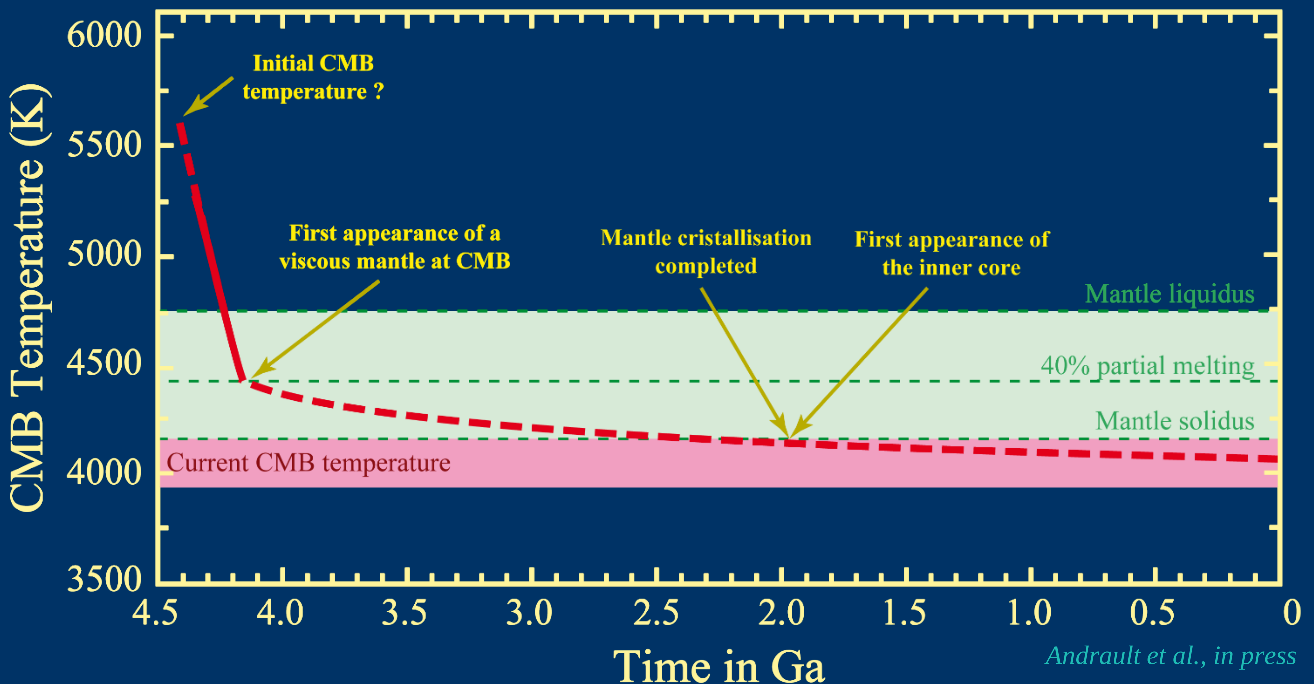
Continents, oceans, plate tectonics, etc.

Environmental conditions favourable for the evolution of life

Additional feature



Core tidal heating = 3.7 TW
Wunsch and Ferrari, 2004



Andrault et al., in press


The end