UIMP 10th International School of Astrobiology
June 18-22, 2012

The transformation(s) of primordial crust(s) – talk #1

Steve Mojzsis

LGL: ENSL & UCBL1, France

My colleagues and collaborators:

Outline for talk #1

- Solids in Nature
- Radioactivity: time and temperature (short and long-lived isotopes) captured in solids
- Input-output of ancient horrors to the planets: planetary growth from geochemical perspective
- Thermal events in the early solar system
- The first possible environments for life
- Transformations of the primordial crust

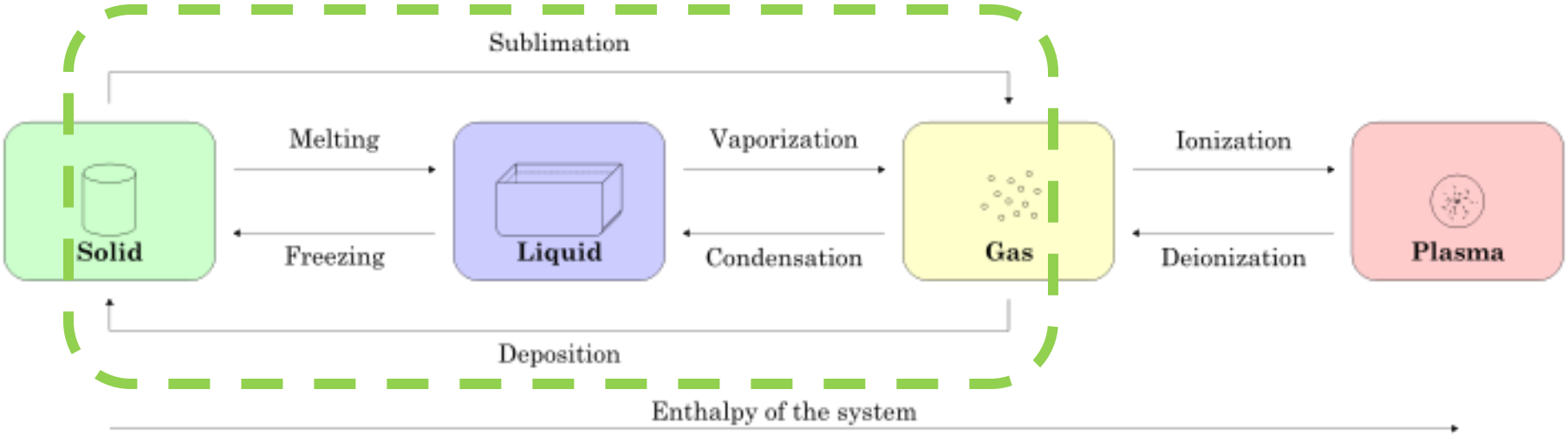
- Introduction to talk #2 (“Physico-chemical conditions at the time of life’s emergence”)

Solid bodies are needed to accumulate ingredients for life

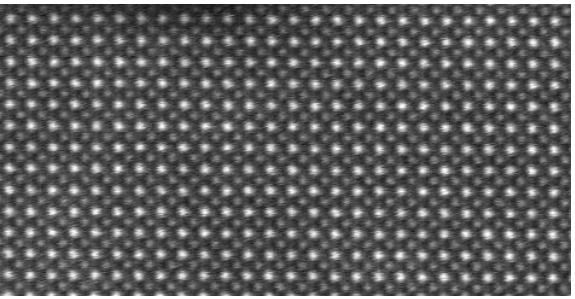
But as we heard yesterday, the early solar system was a dangerous (promising!) place

Solids in Nature

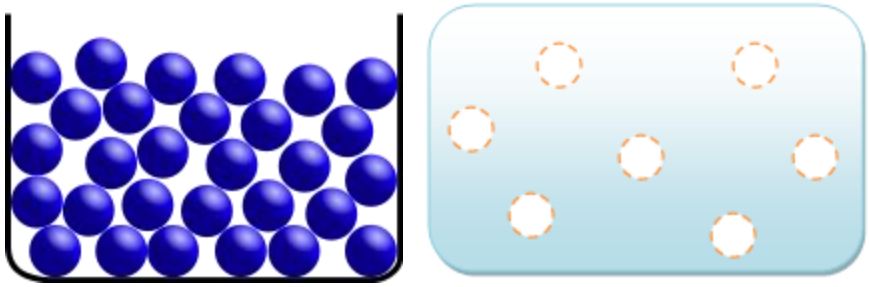
4 states of baryonic matter (~5% of the mass of the Universe; WMAP survey)



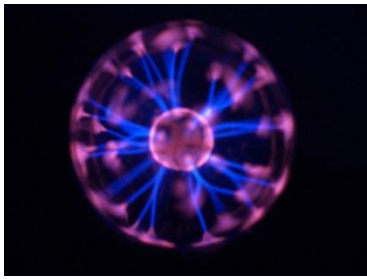
It is from solids that we get information about past times



$SrTiO_3$

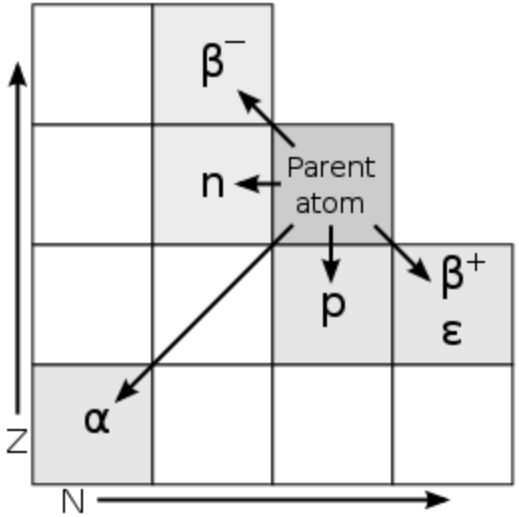


"Classical" monatomic liquid & gas

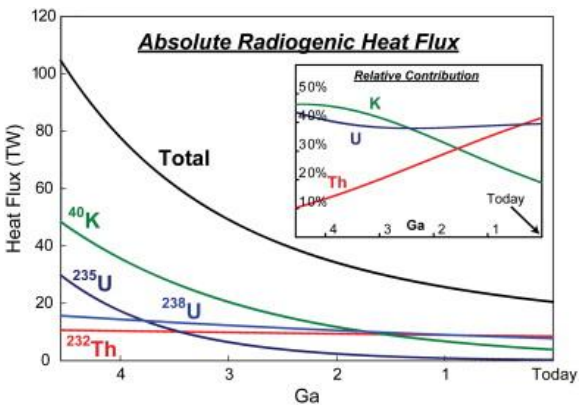


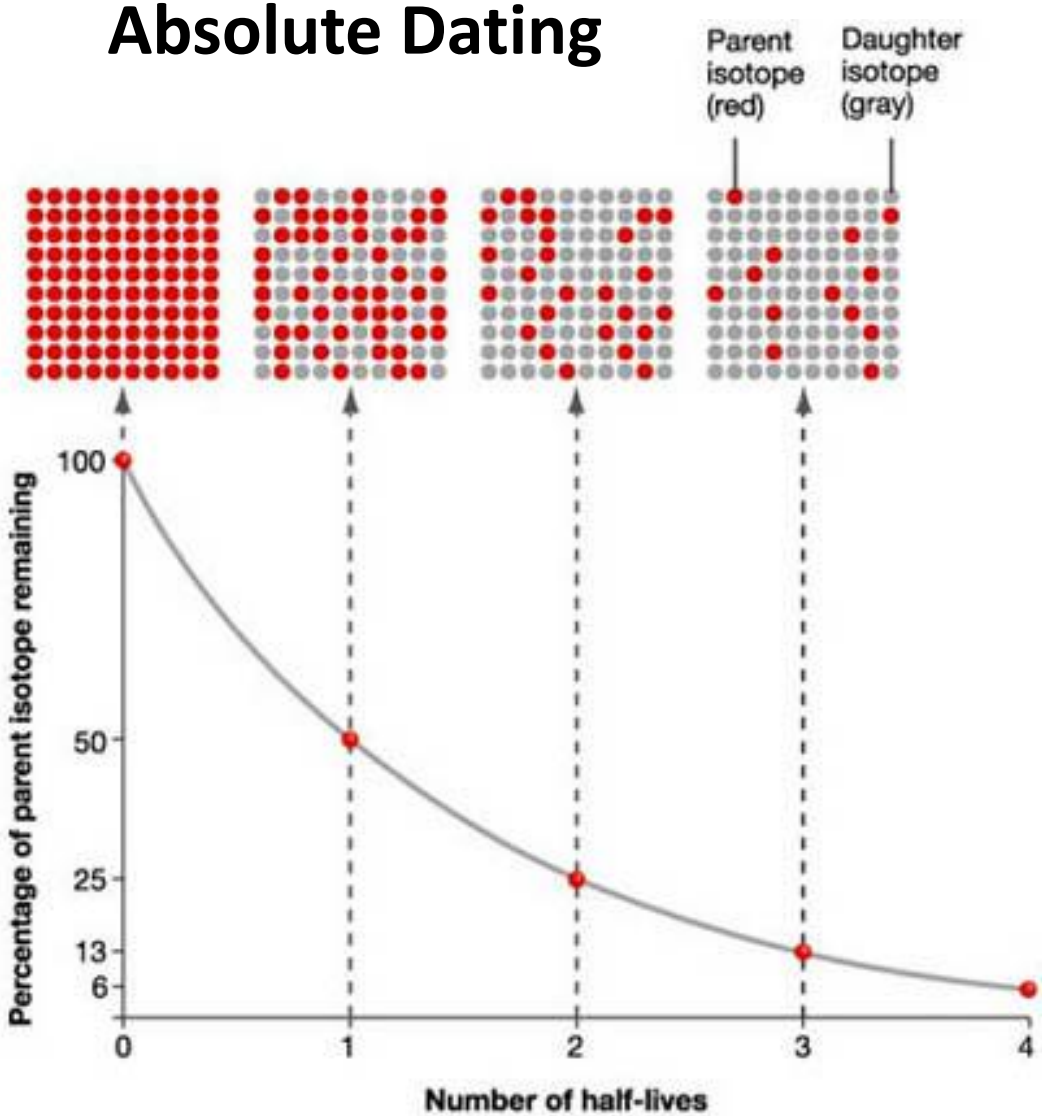
plasma

How does radioactivity work?

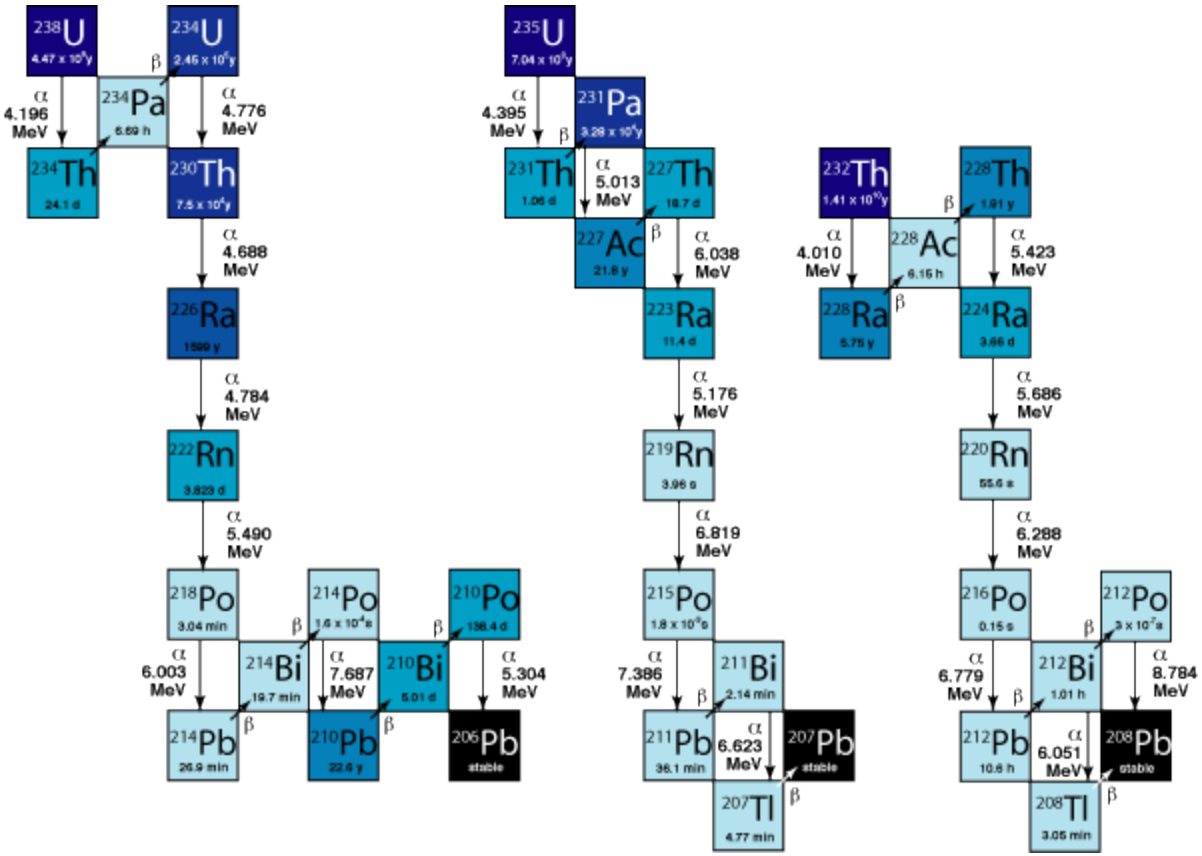


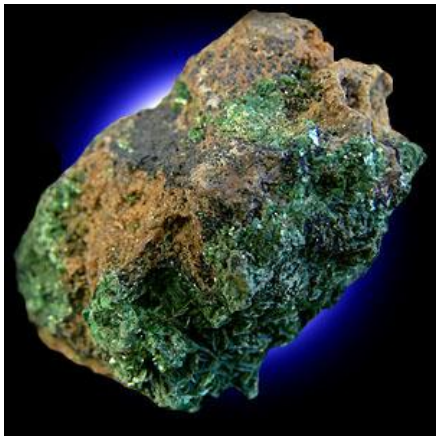
Absolute Dating





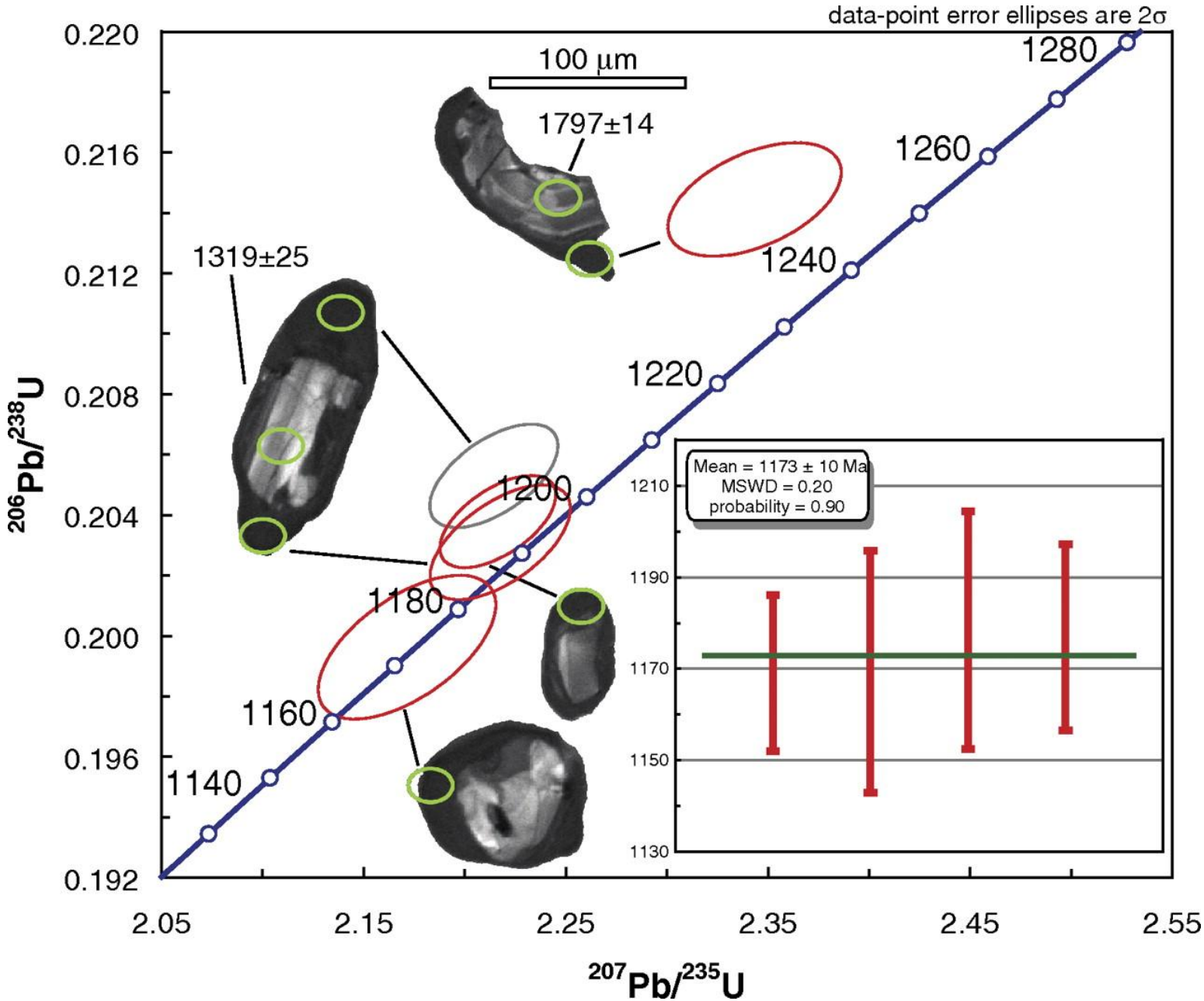
One key example worth understanding: Uranium to Lead





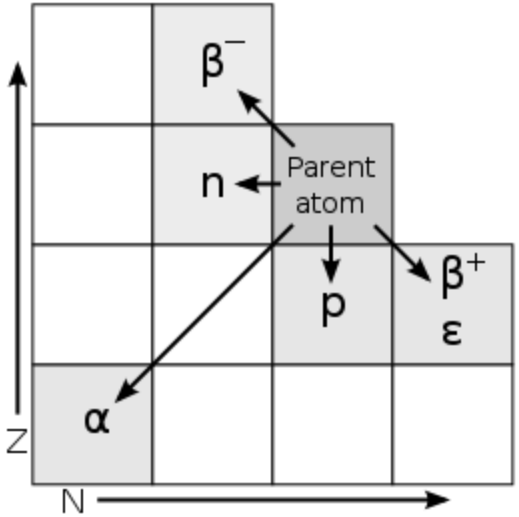
chembase.com

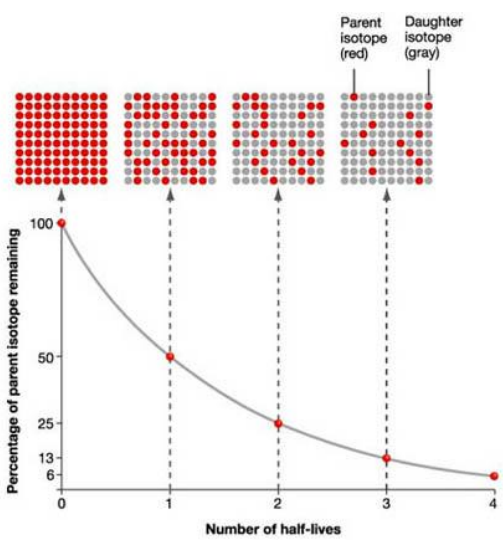
zmescience.com

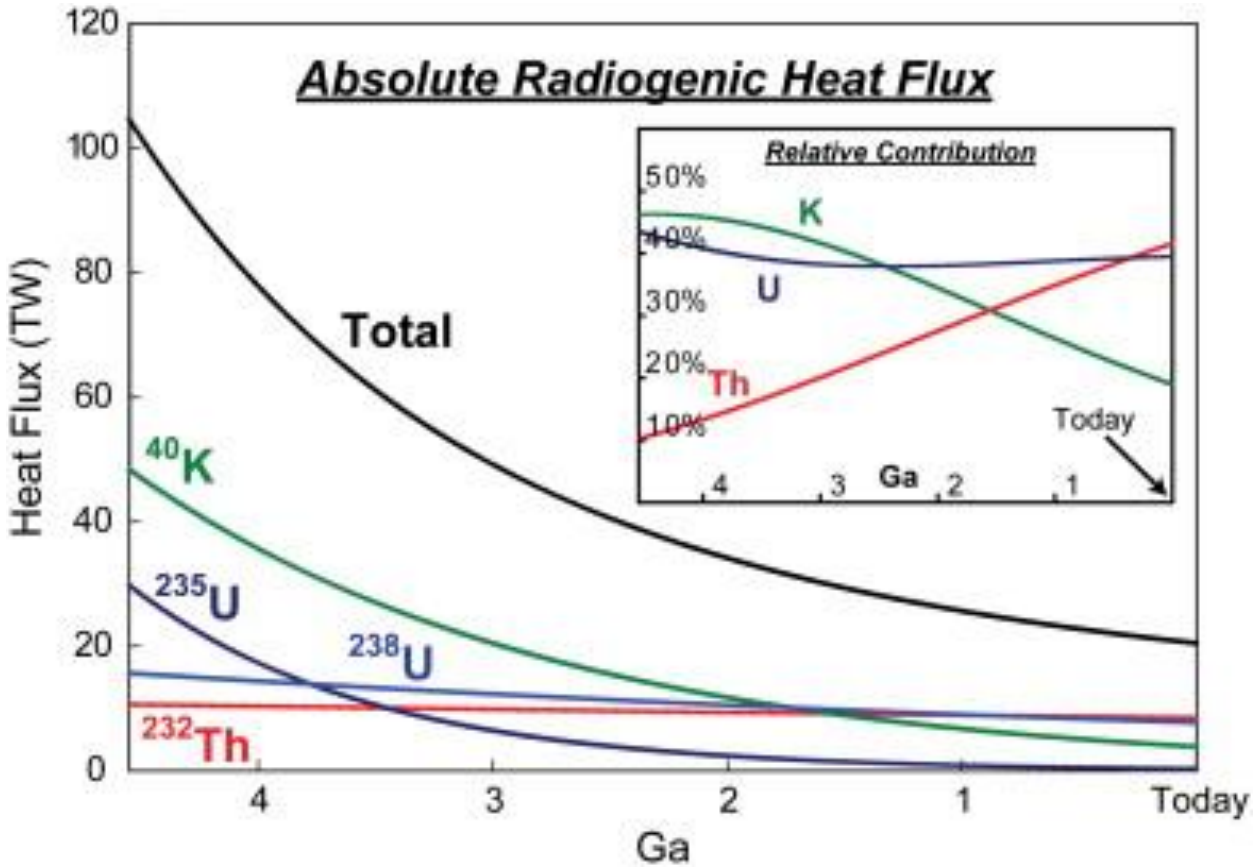

data-point error ellipses are 2σ
100 μm
1797±14
1319±25
1280
1260
1240
1220
1200
1180
1160
1140
Mean = 1173 ± 10 Ma
MSWD = 0.20
probability = 0.90
1210
1190
1170
1150
1130
0.220
0.216
0.212
0.208
0.204
0.200
0.196
0.192
2.05
2.15
2.25
2.35
2.45
2.55
206Pb/238U
207Pb/235U

How does radioactivity work?

Heat production

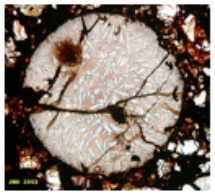


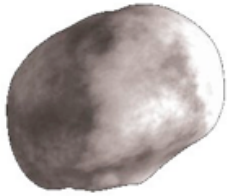


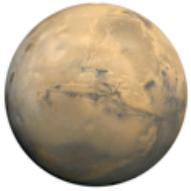


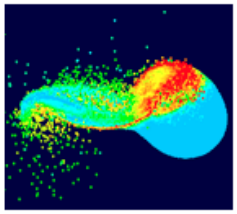
A timeline of crust transformations

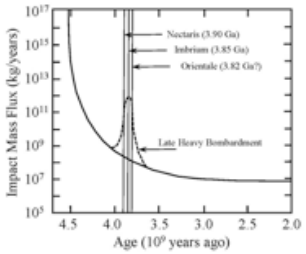
Understanding the timing of these things is important with regards to Origin of Life

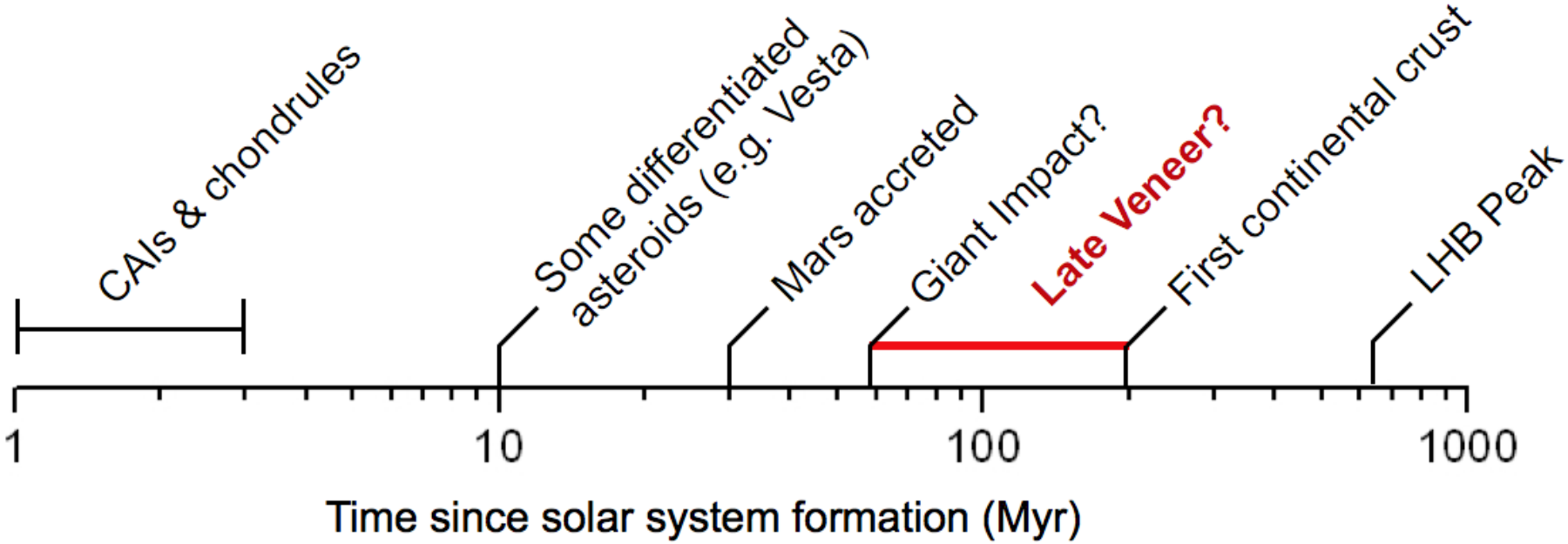












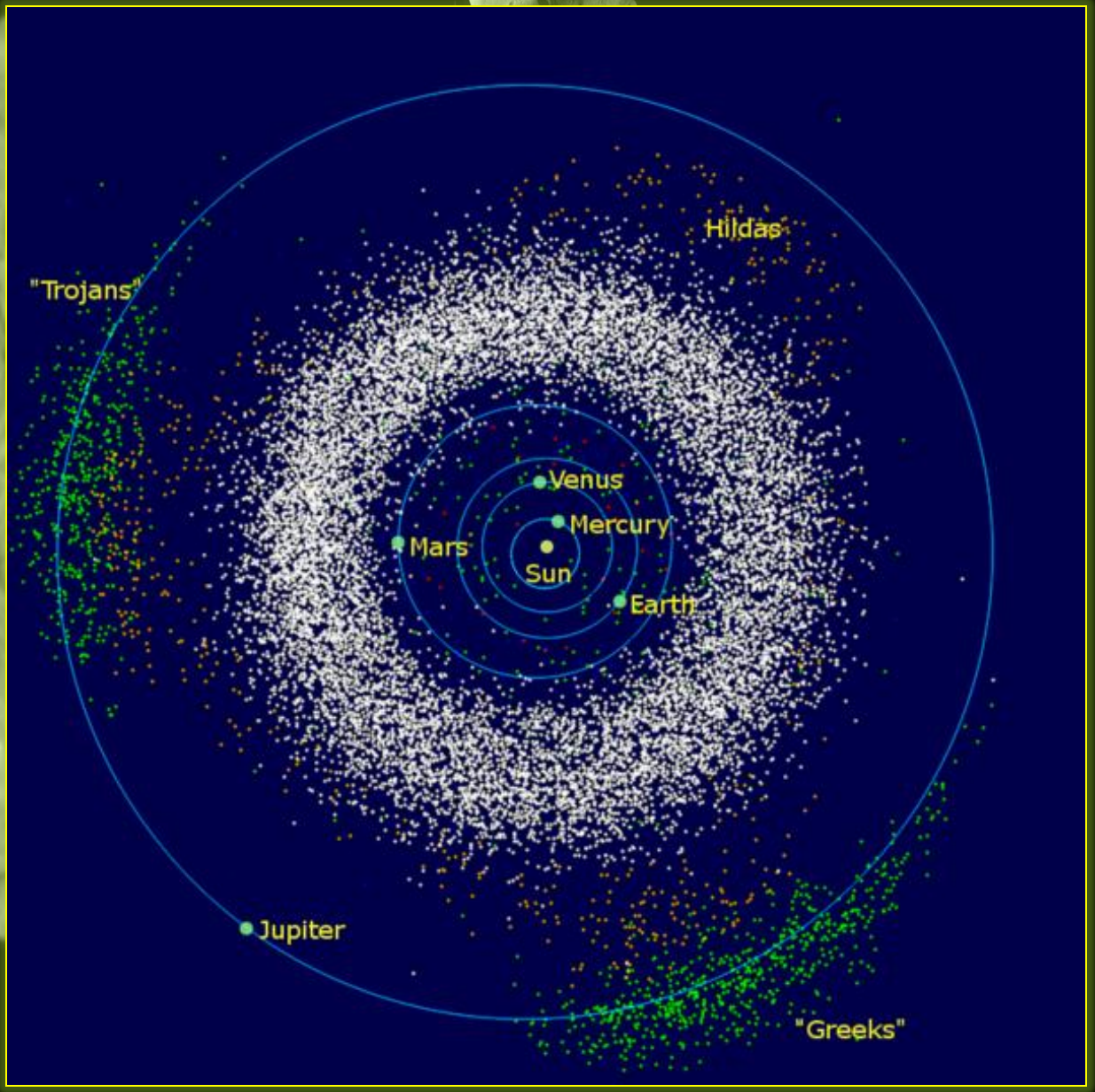
Source: Elizabeth Frank

Asteroids

THE FIRST ENVIRONMENTS FOR LIFE IN THE SOLAR SYSTEM?

Asteroids

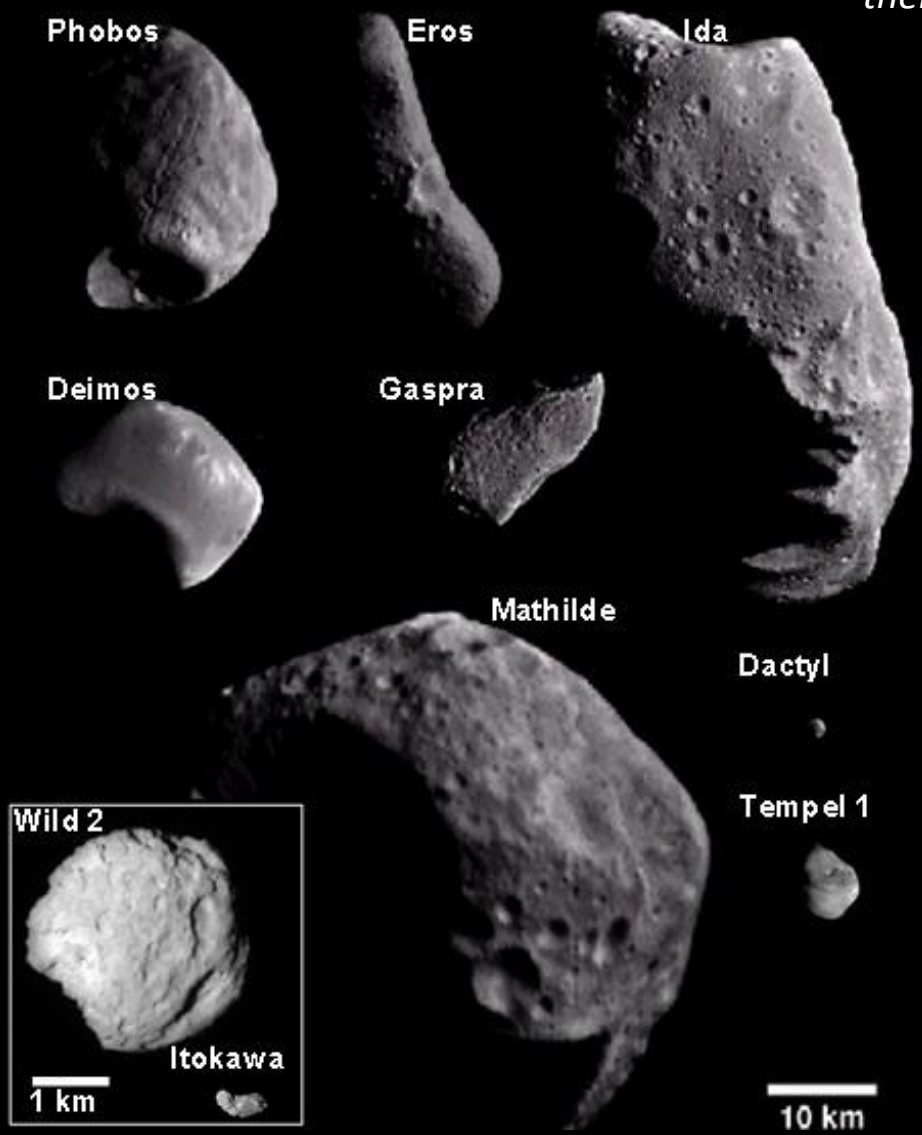
~50,000 meteorites from ~21 parent bodies

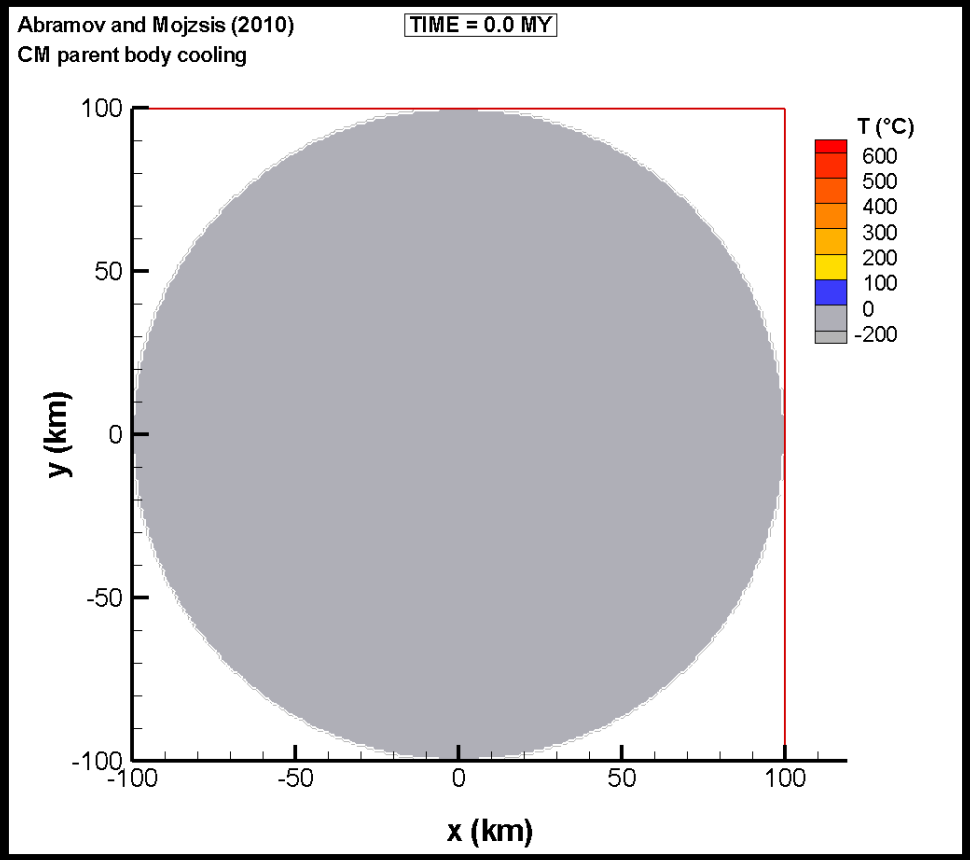


NASA-JPL/Caltech

Watery regimes for prebiotic chemistry inside asteroids – the first 30 Myr

**We are working to establish numerical simulations of thermal fields in asteroids and trans-Neptunian objects*

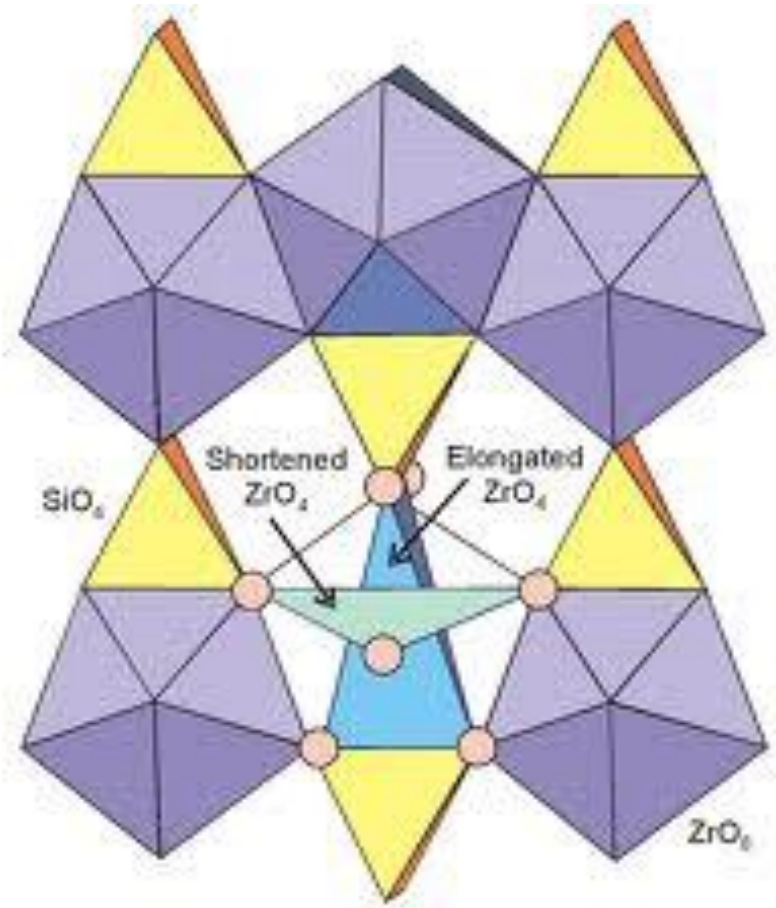




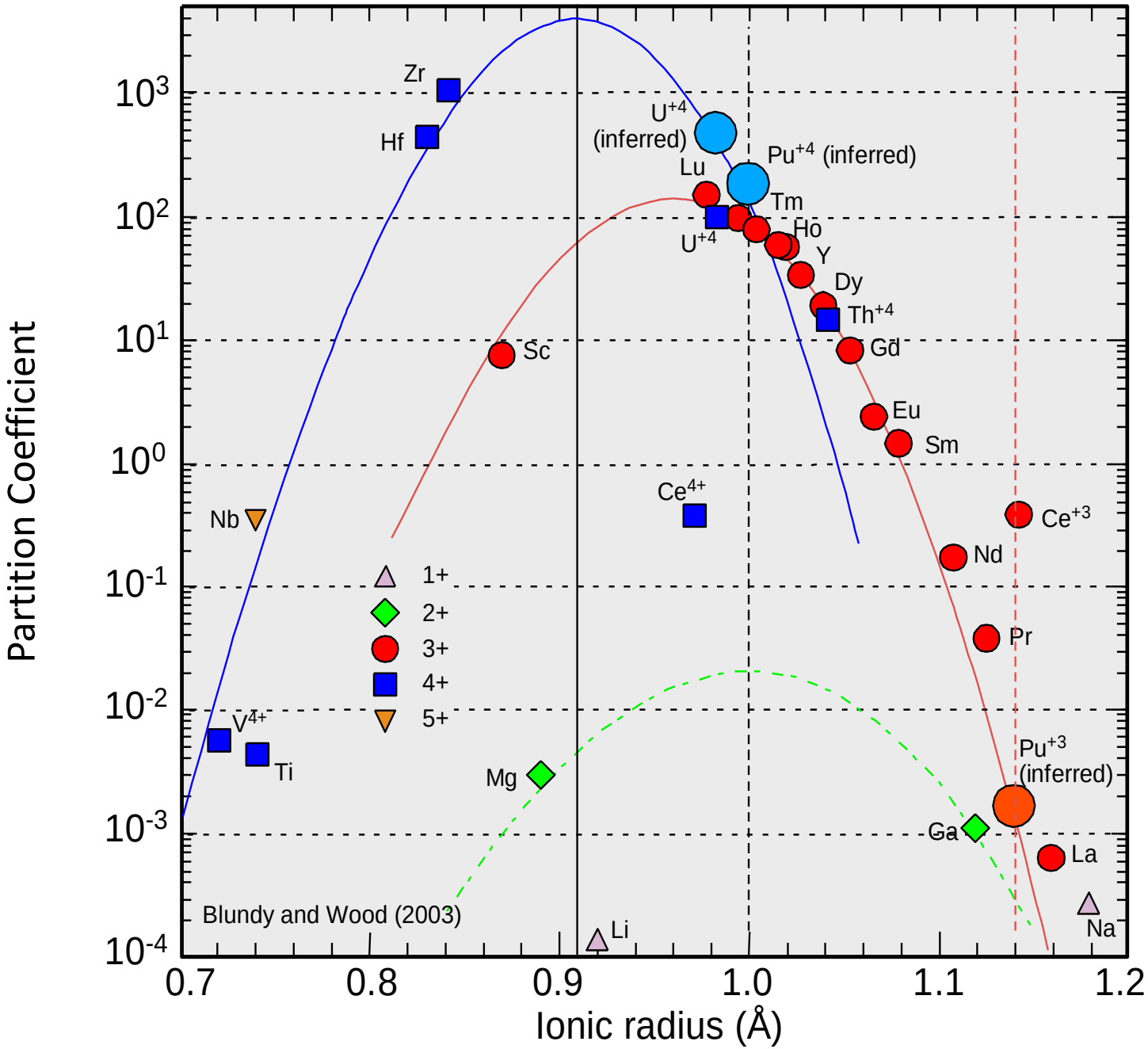
Model of P-T-X stability regimes for liquid water in CM asteroids with time

From Abramov & Mojzsis (2011) *Icarus*

Remember what I said about solids?



Crystalline solids are what they eat



COMPOSITION

$ZrSiO_4$

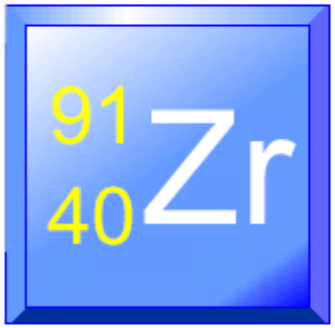
Hf: typically 1 - 1.5%

U: 10 - 1000s ppm

Th: 10 - 1000s ppm

Pb: ~ 1 ppb - 100s of ppm (depends on age!)

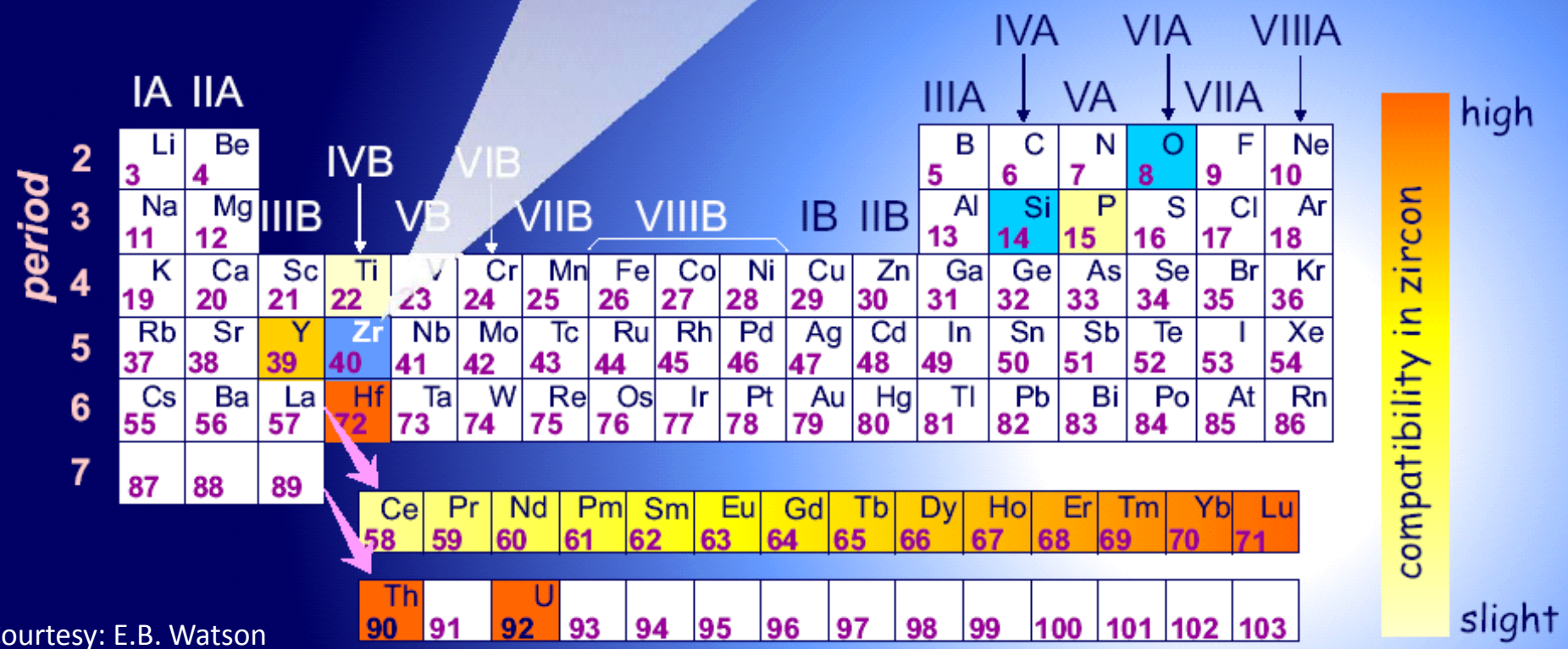
Σ rare earths (+Y): 10s of ppm to 10%



abundance: (silicate Earth) ~10 ppm

valence state: +4

ionic radius: 0.92Å

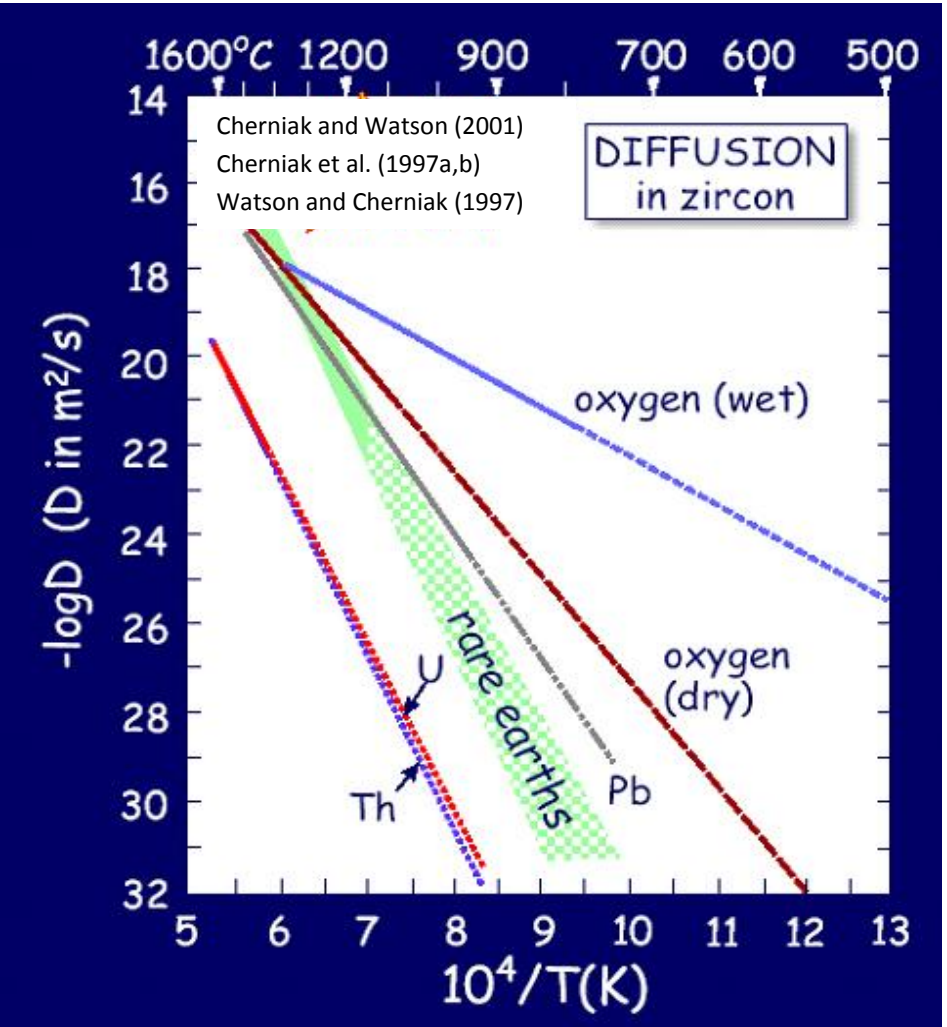


Courtesy: E.B. Watson

Zircon retention

- why is information preserved?

- Diffusion in zircon is unimaginably slow for most elements*



DIFFUSIVE LENGTH SCALES

$$D \sim (D \cdot t)^{1/2}$$

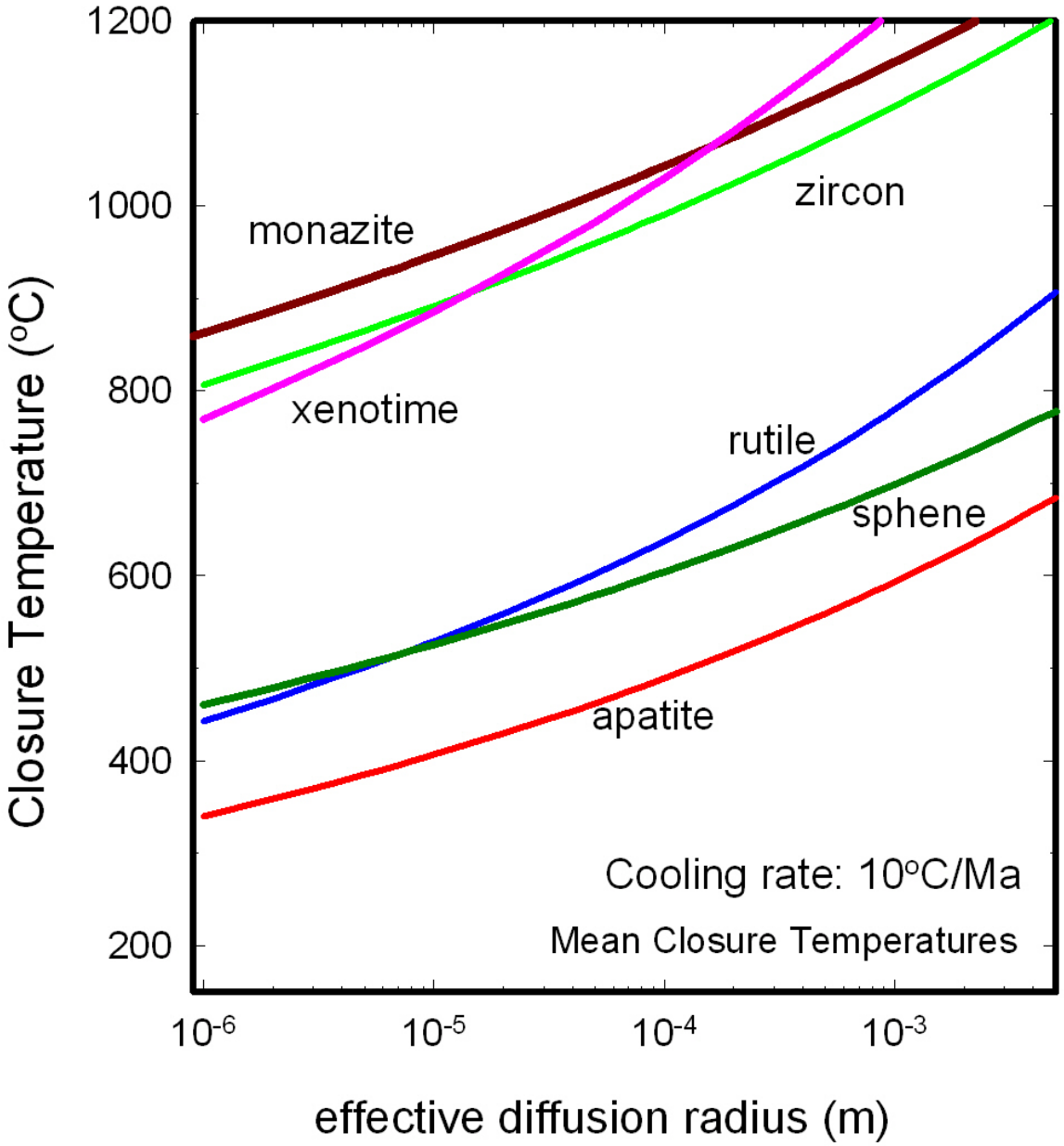
900°C

element	X (1 Ma)	X (1 Ga)
O (wet)	250µm	8000µm
O (dry)	7 µm	225µm
Pb	**1 µm**	**35µm**
REE	100nm	3µm
U&Th	**0.4nm**	**10µm**

500°C

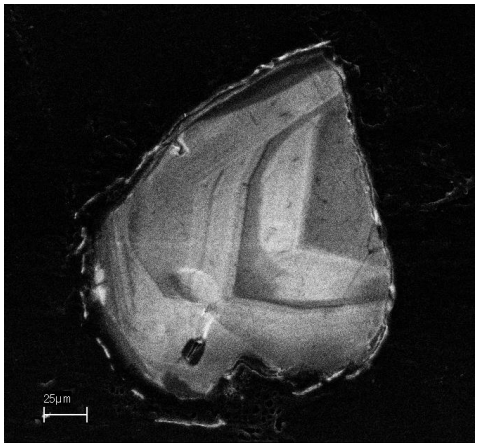
element	X (1 Ma)	X (1 Ga)
O (wet)	1µm	33µm
O (dry)	0.05nm	1.5nm

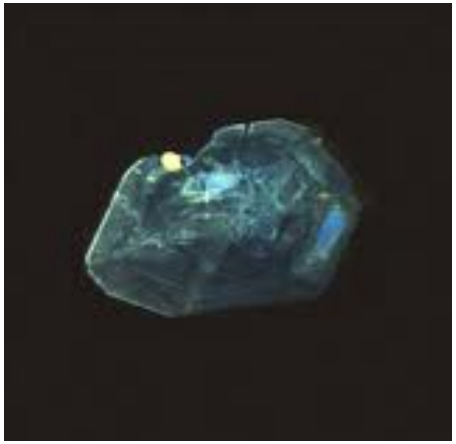
***as long as radiation damage has not caused significant lattice disruption**

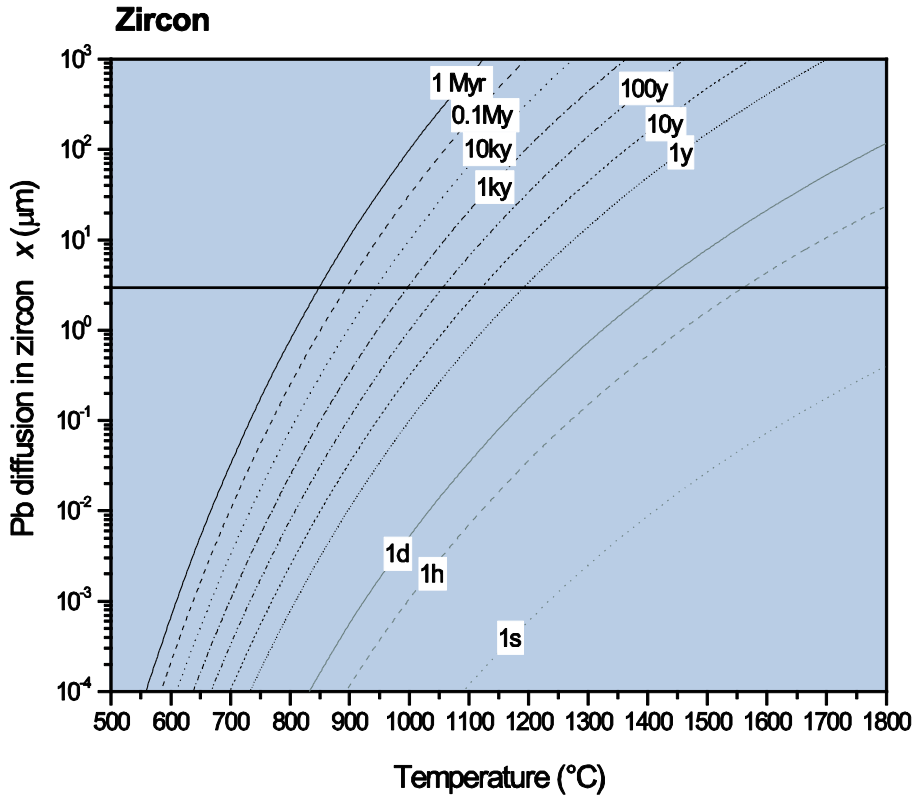

1200
1000
800
600
400
200
Closure Temperature (°C)
monazite
zircon
xenotime
rutile
sphene
apatite
Cooling rate: 10°C/Ma
Mean Closure Temperatures
10-6
10-5
10-4
10-3
effective diffusion radius (m)

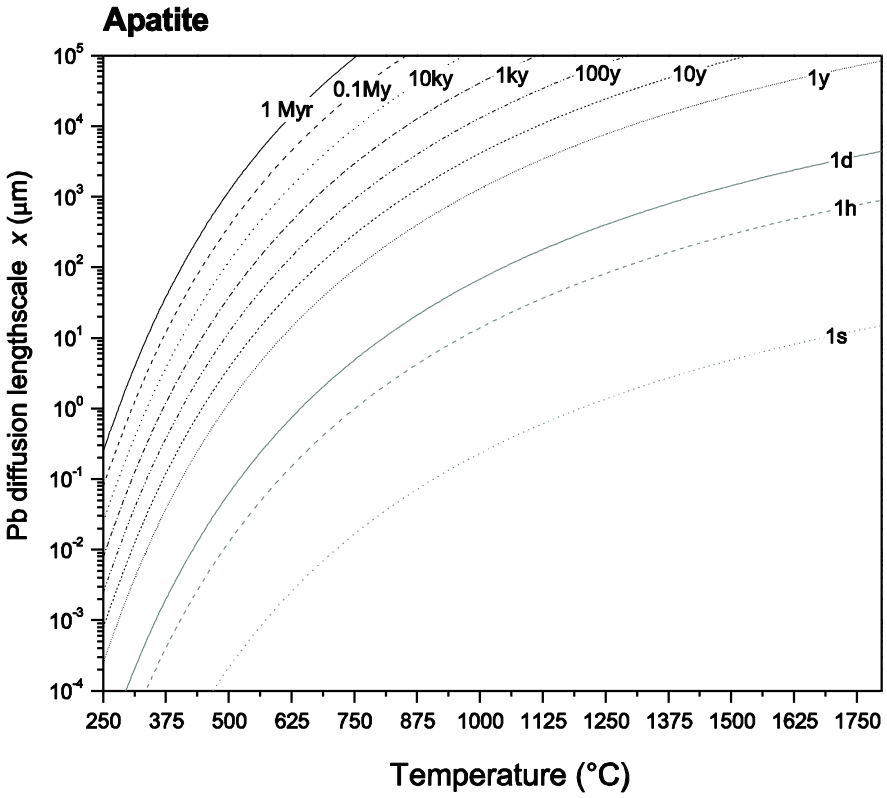
What do we mean by “Thermochronometry” in this case?

Exploitation of different Pb closure temperatures of minerals in ancient rocks & meteorites





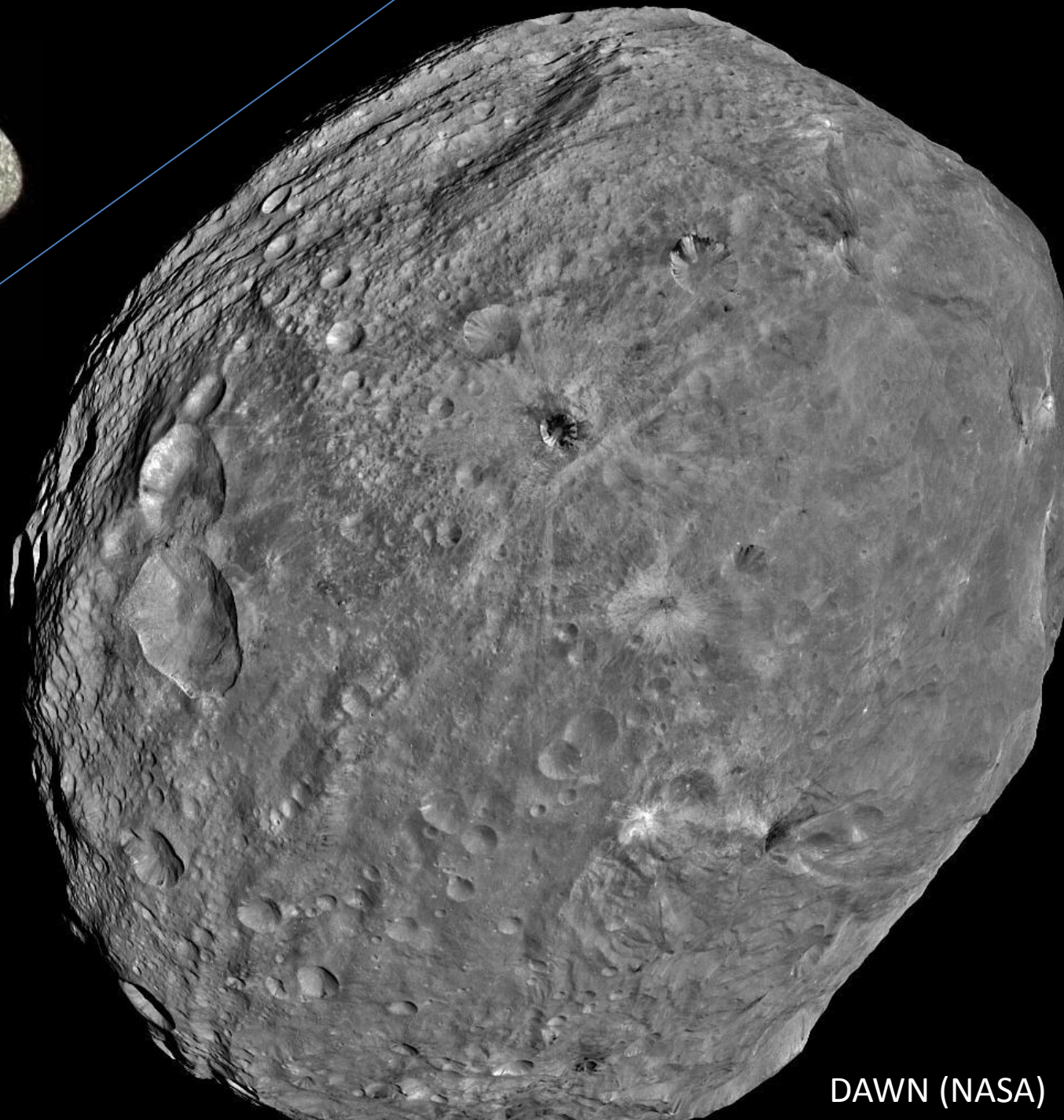




NWA2784 polymict eucrite

2.5 cm

~ 900 samples in meteorite collections
Vesta = HEDs?



~25 km

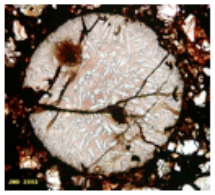
DAWN (NASA)

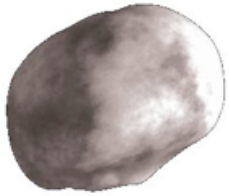
What happened to Earth in the early days?

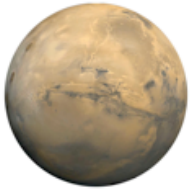
WHAT WAS THE FATE OF THE FIRST CRUST?
IT WAS DESTROYED OVER AND OVER AGAIN BEFORE 3.8 BILLION YEARS AGO

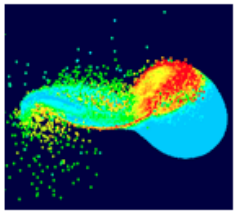
A timeline of crust transformations

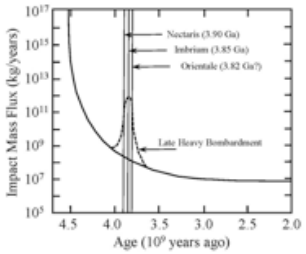
Understanding the timing of these things is important with regards to Origin of Life

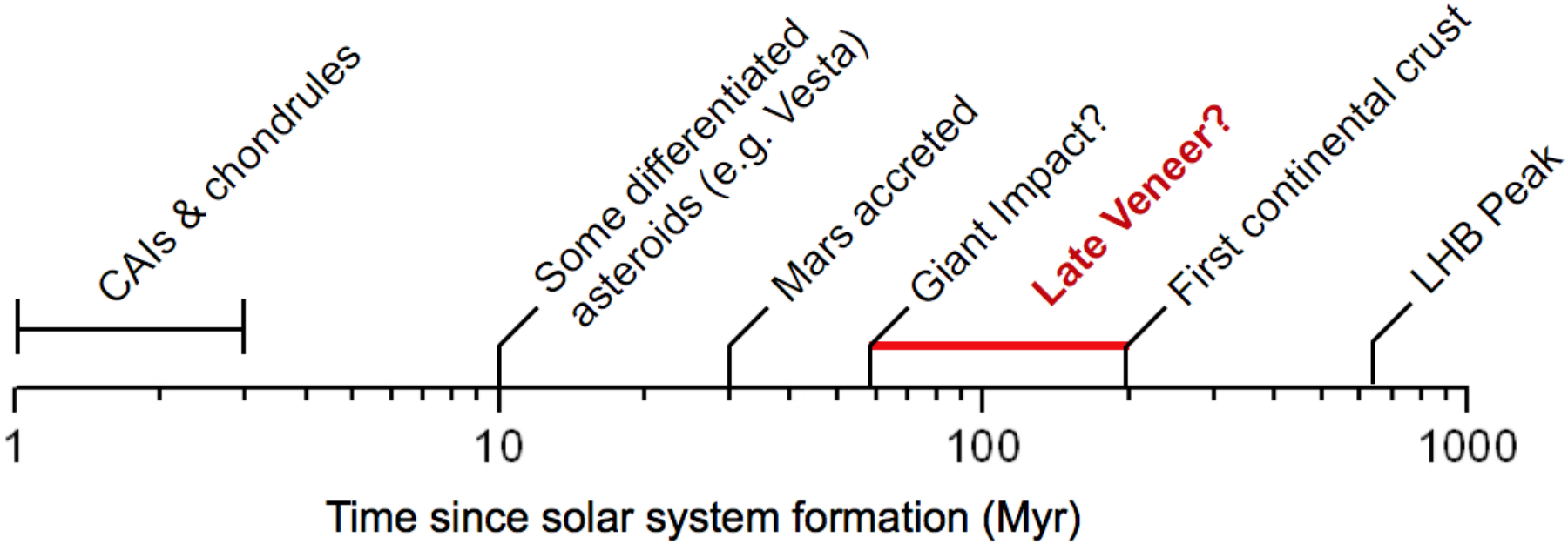




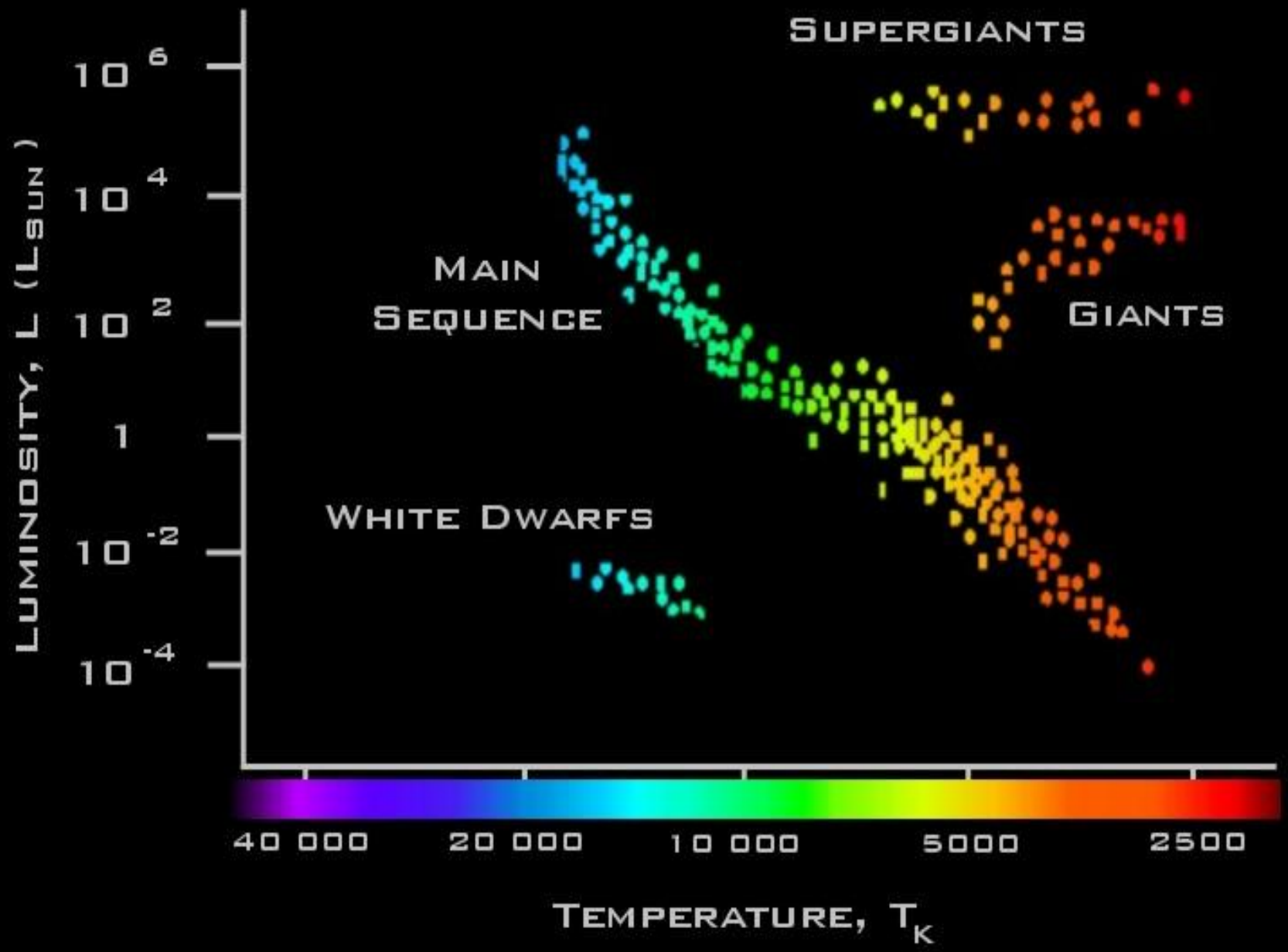






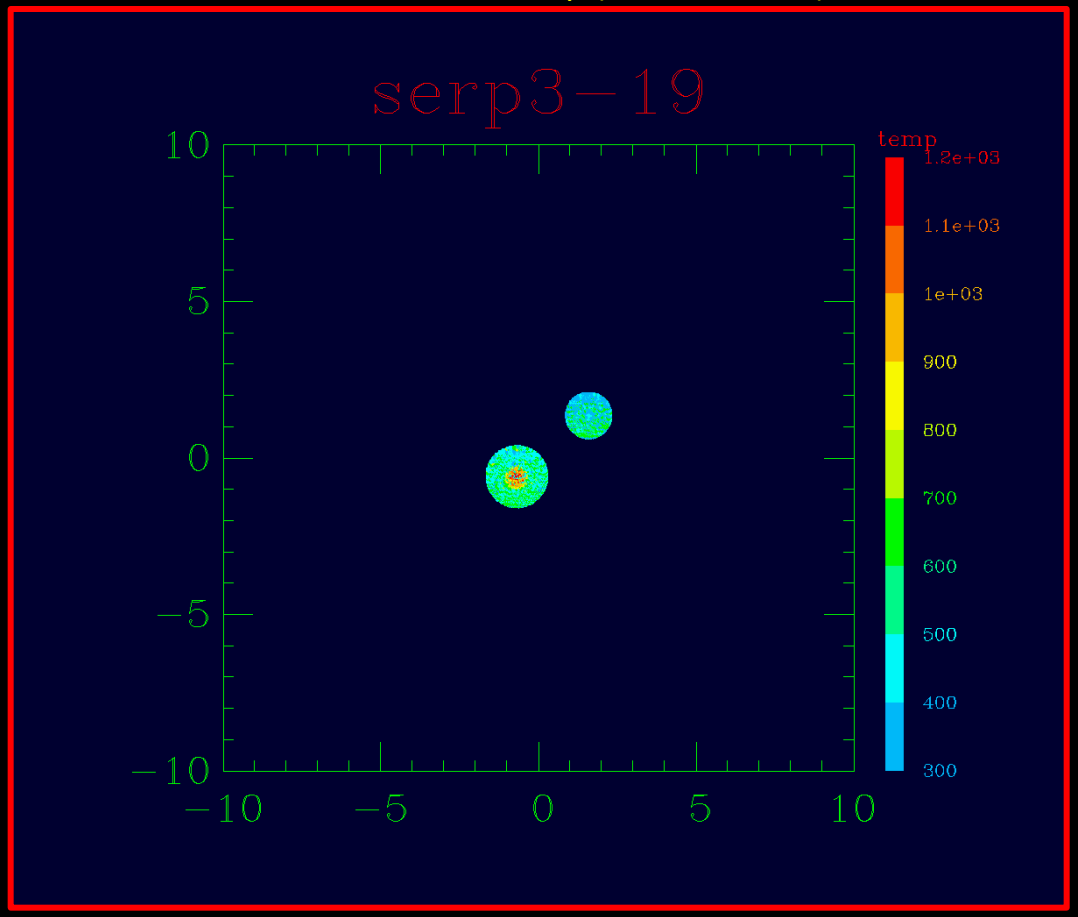


Source: Elizabeth Frank


Supergiants
Main Sequence
Giants
White Dwarfs
Luminosity, L (L_SUN)
10^6
10^4
10^2
1
10^-2
10^-4
40 000
20 000
10 000
5000
2500
Temperature, T_K

But as you have heard, there's more. Other Giant Impacts: Example: formation of Pluto's Moon, Mercury & Earth's Late Veneer

Animation from Robin Canup (SwRI, Boulder)



Charon also likely made by a giant impact. It is ~10% the mass of Pluto. Apparently lots of moons once existed that are now gone.

What happened to Mercury? Earth continued to be hit.

Formation of a cool rind…

- Of ultramafic (>>MgO) composition (evidence seen in ancient supracrustal rocks?)
- Provided a potentially habitable surface at this time
- Convection became "sluggish" because of it
- Collapse of an ultra-greenhouse helped in cooling (removes another t.b.l.)
- 2.7 Myr? to reach clement surface (30ºC)
- Volatile exchange between atm., crust and hydrosphere was enormous
- Planetary hydrothermal system formed with hot water + hot rock on a global scale
- Substantial H_2 and CO followed by methane generated from hydrothermal alteration of the first crust?

A serpentinizing atmosphere !

$$\text{olivine} + H_2O \leftrightharpoons \text{serpentine} + \text{brucite} + \text{magnetite} + H_2.$$

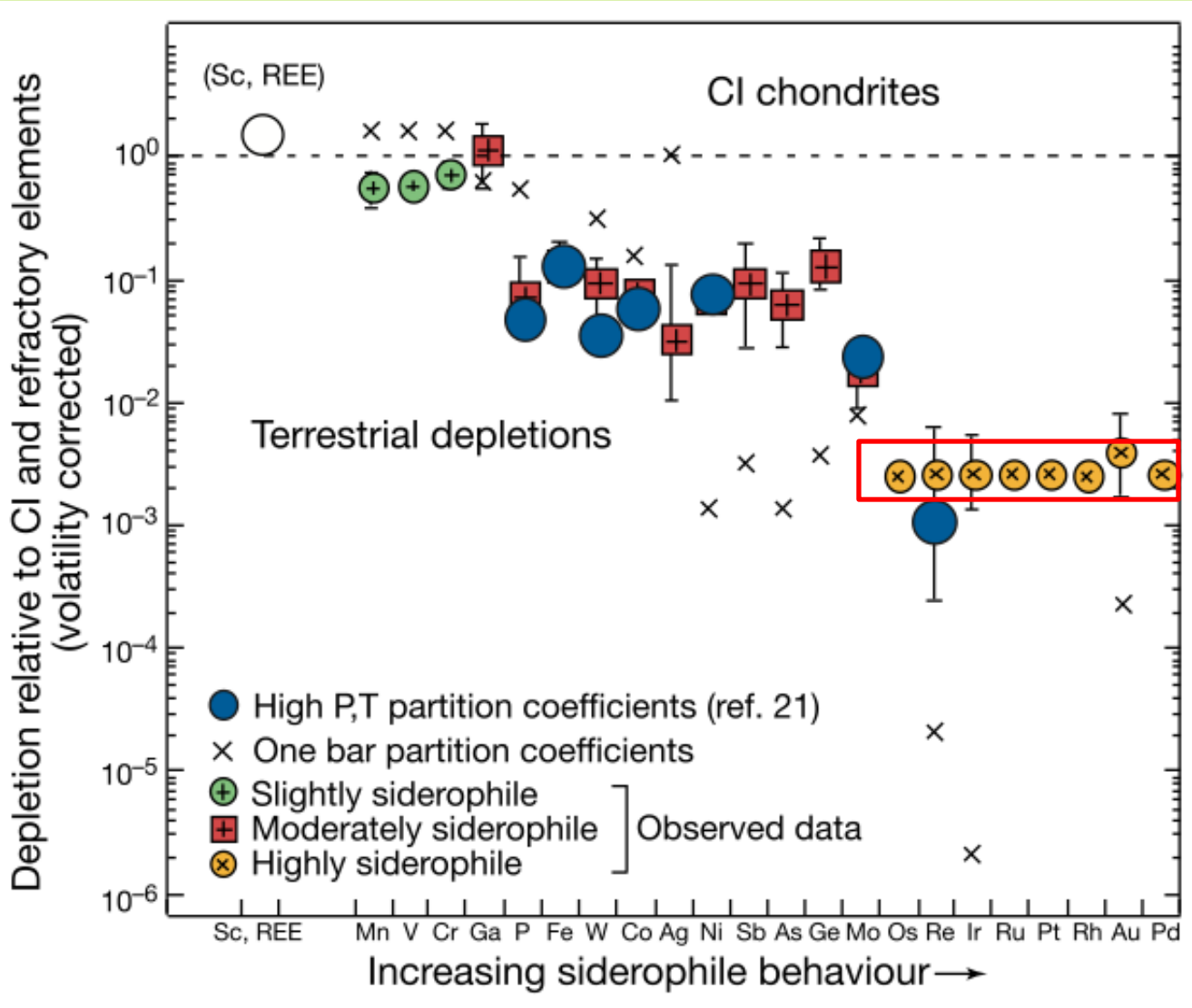
$$CO_2 + 4H_2 \leftrightharpoons CH_4 + 2H_2O$$

Being there vs. getting there

When might Late Accretion have occurred? Lines of evidence

IN THE AFTERMATH OF THE *GIANT IMPACT* <u>AND BEFORE</u> THE *LATE HEAVY BOMBARDMENT*

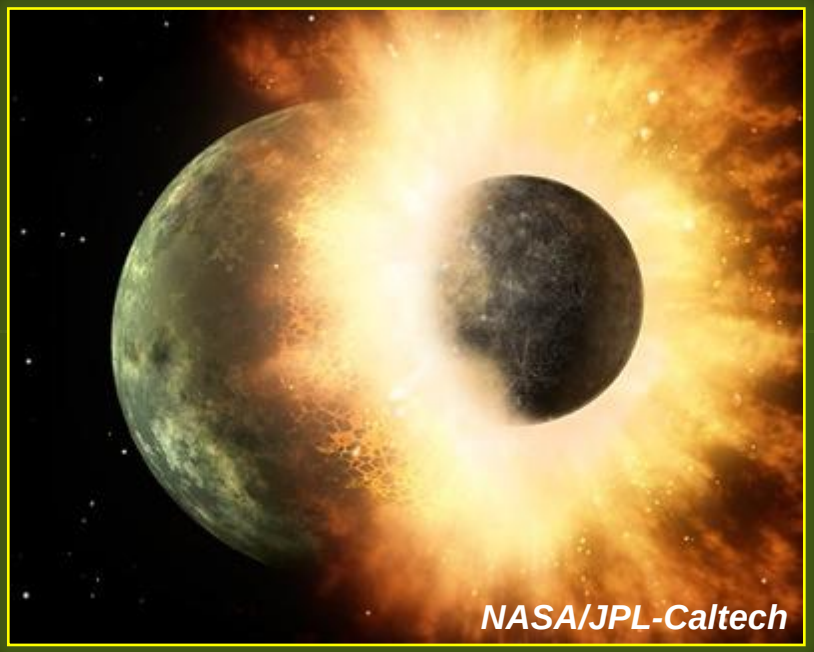
A “Late Veneer” (LV or a.k.a. Late Accretion)

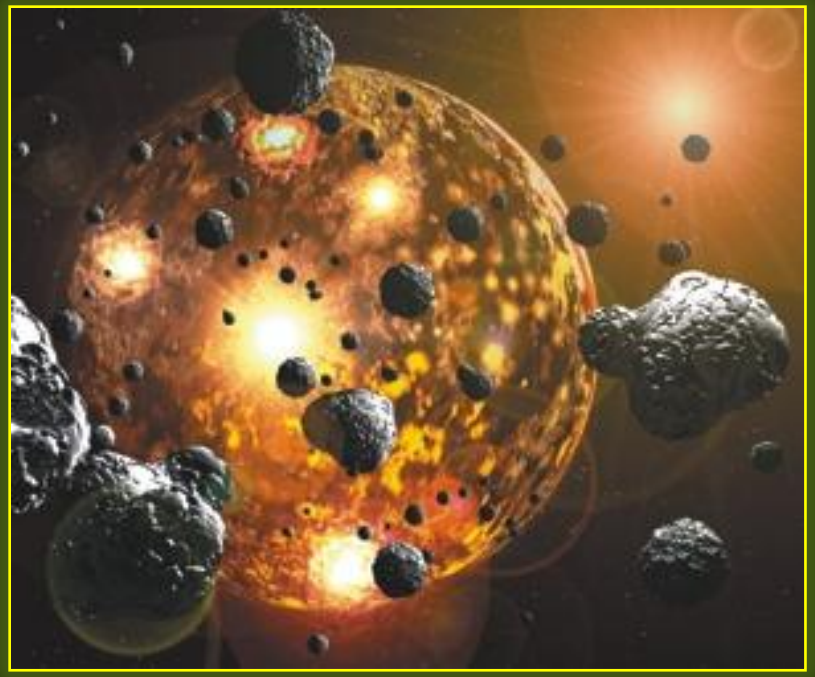


Righter and Drake (2002) (about 1% of Earth’s mass augmented; MUCH more than LHB)

Post-GI: One impactor or an armada in the LV?

one large, differentiated impactor
with *D* =2500-3000 km
(Bottke et al. 2010)

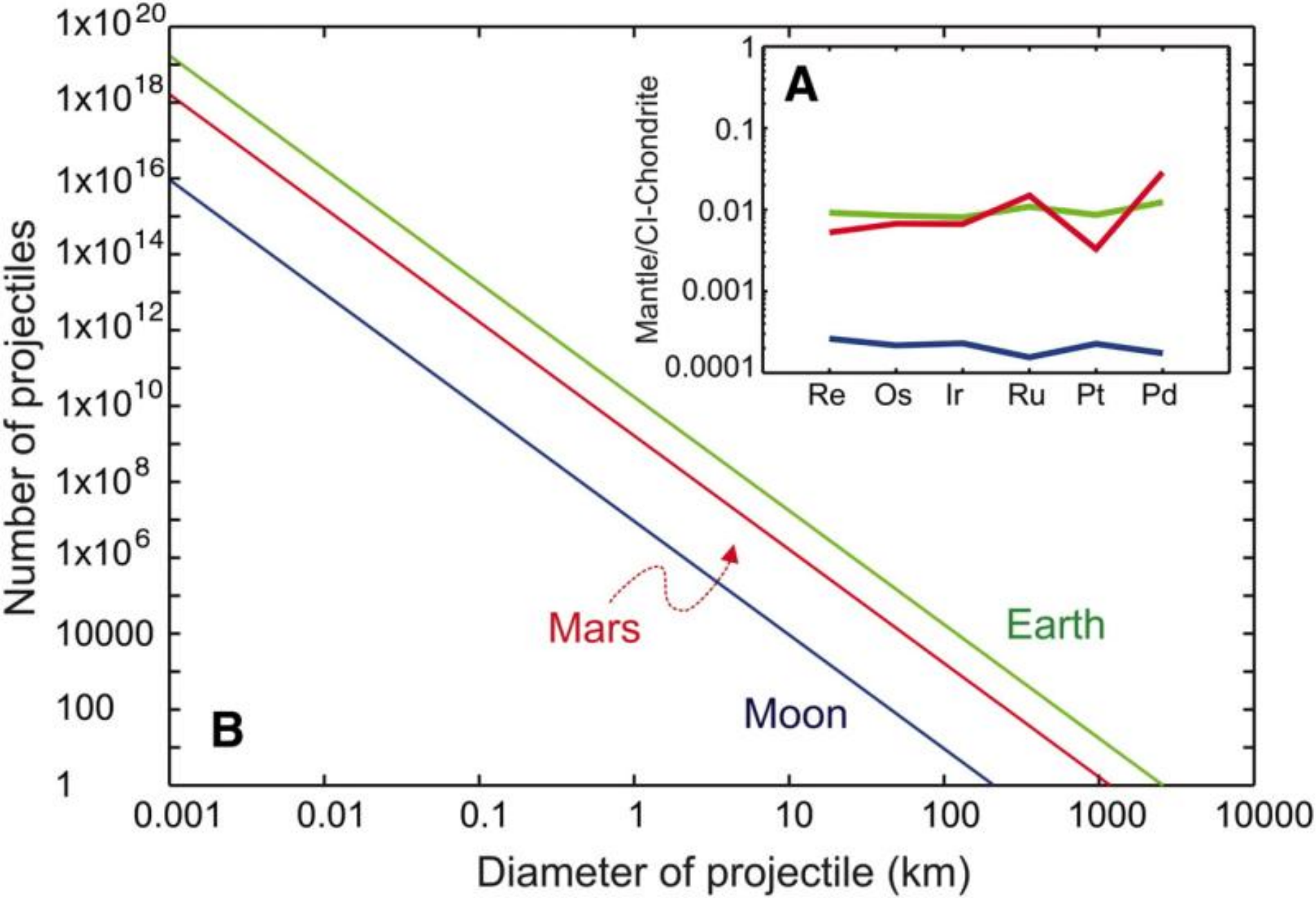


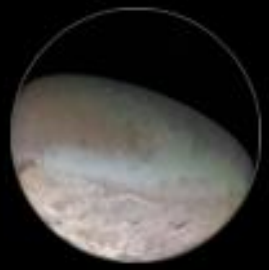


Julian Baum

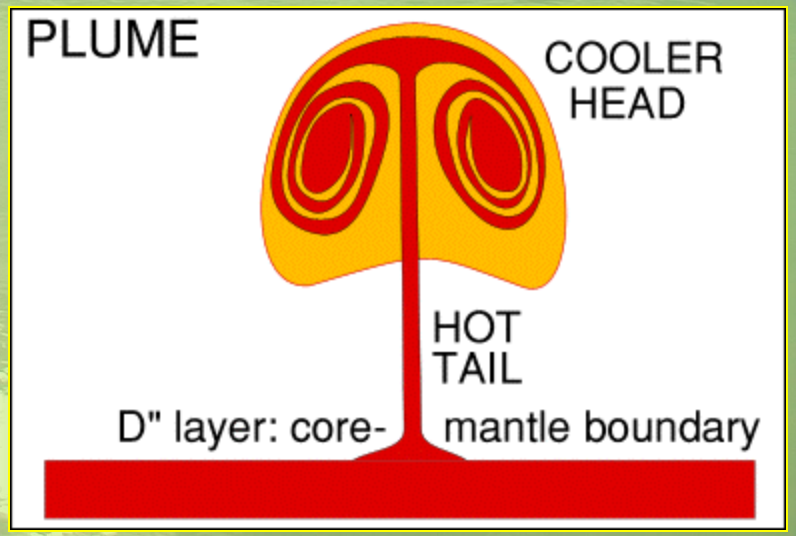
many smaller oxidized impactors
(Rubie et al. 2011)

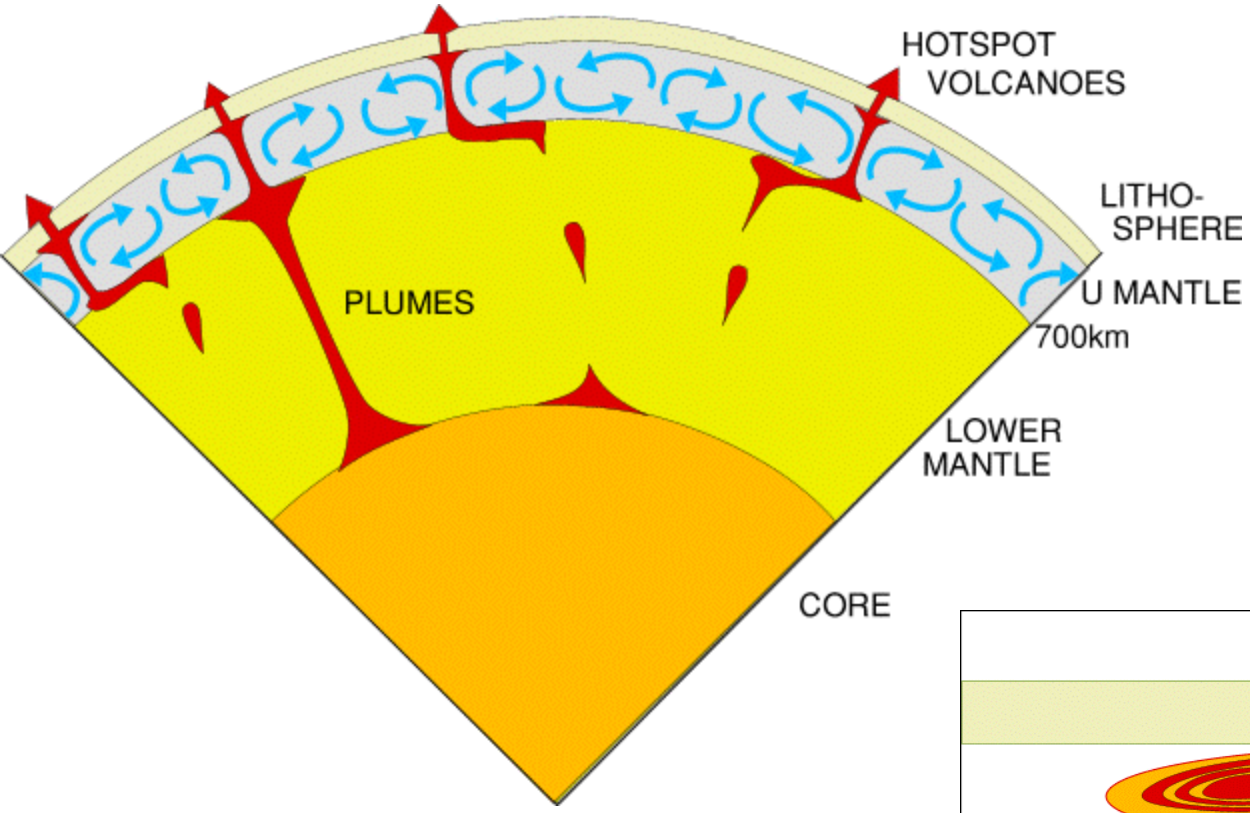
When did Earth's "Late Veneer" (LV) happen?

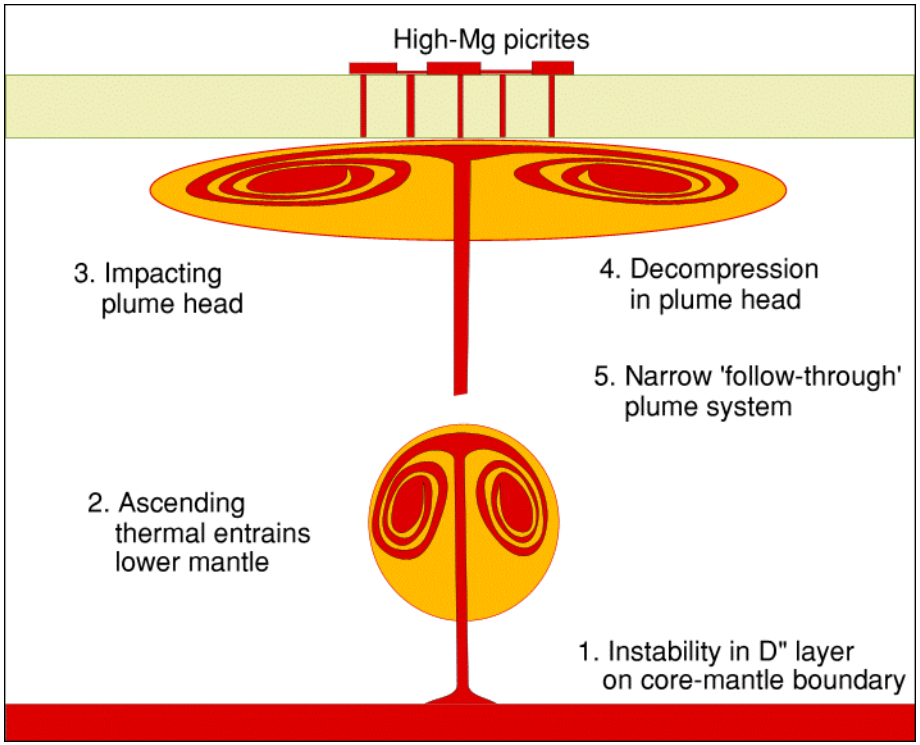




Komatiite HSE composition with time

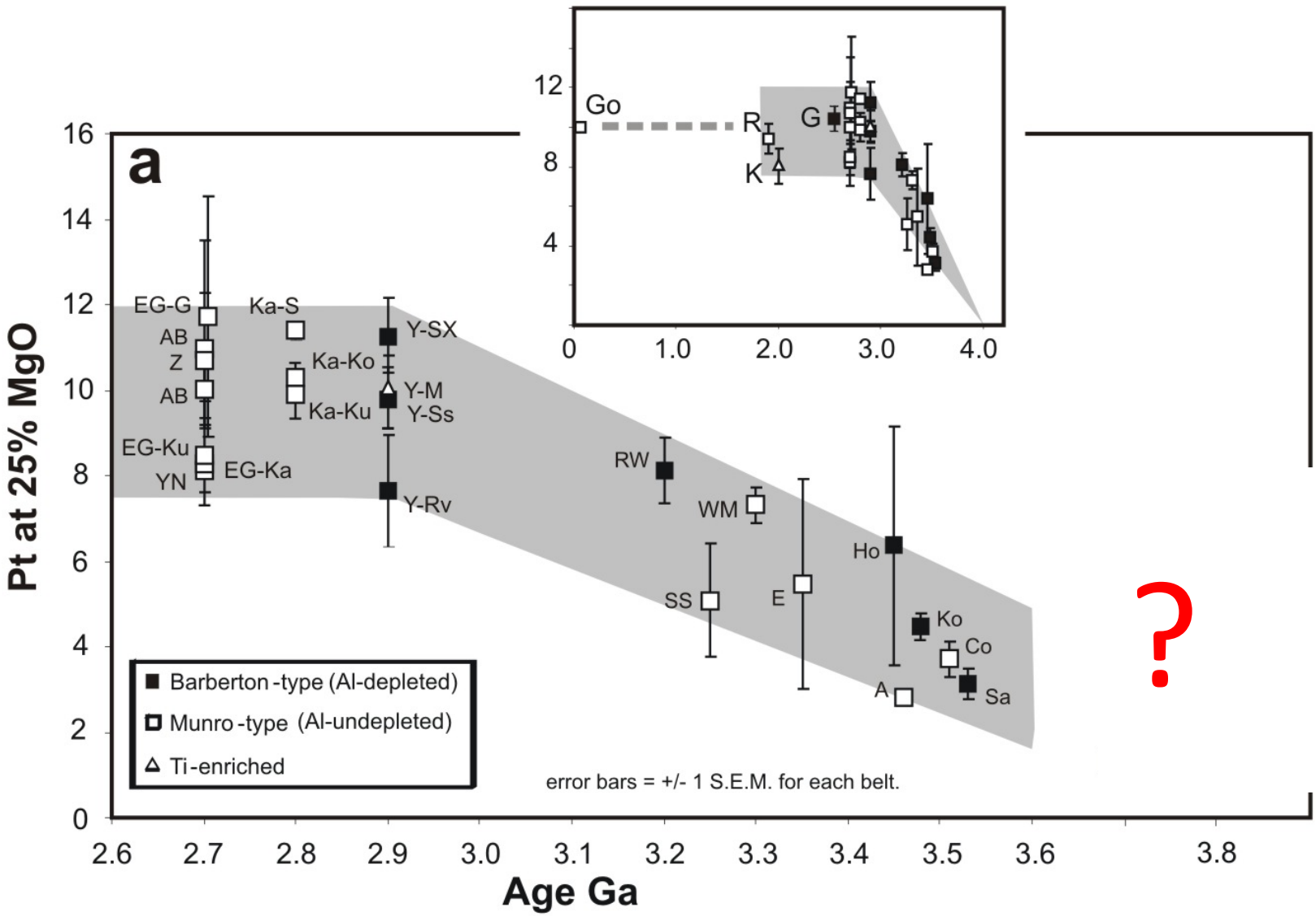




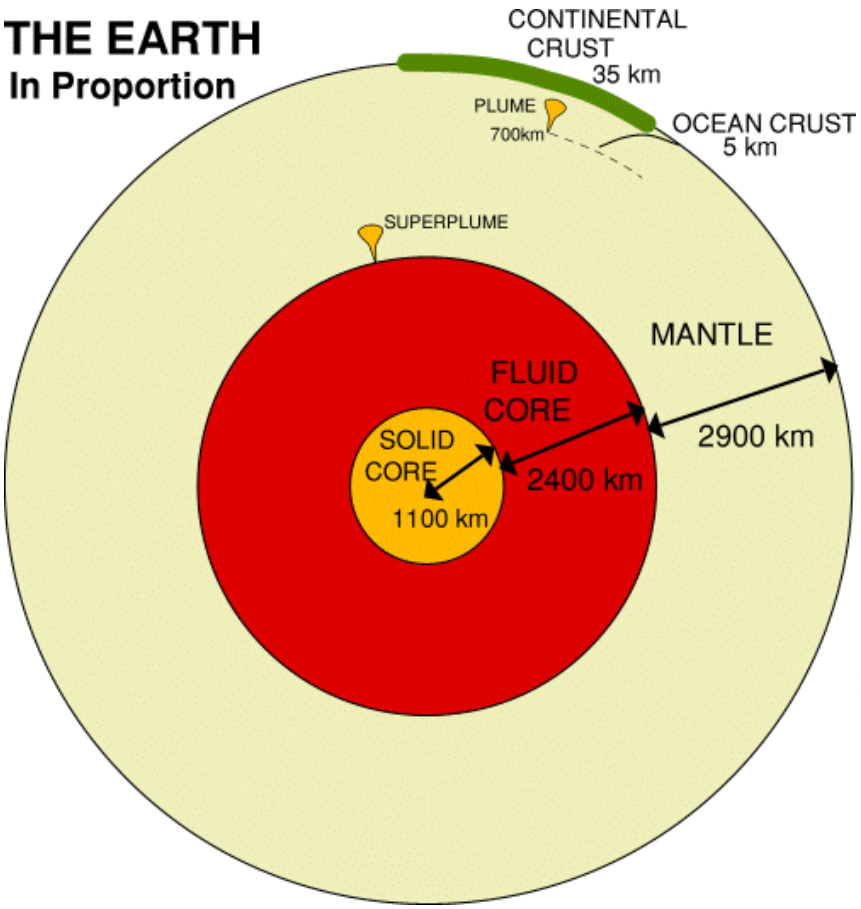


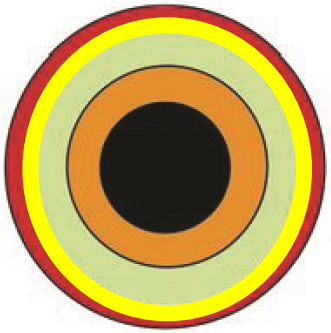
Samples of Earth's mantle composition through geologic time: Plume volcanism

Some clues from evolution of HSE in komatiites



Maier et al. (2009)



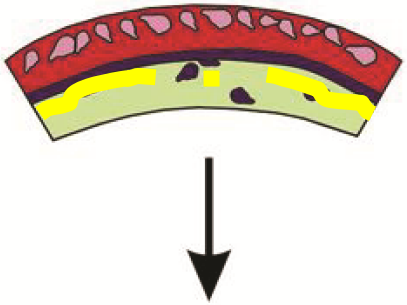


Pollution from an LV

Partial melting of basaltic crust

Gradual accumulation of felsic material and heavy residuum

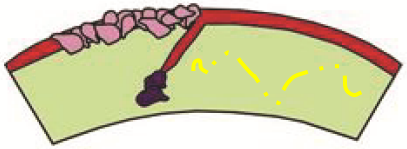
~4.4 - 3.9 Ga



Delamination of residuum

Initiation of subduction

Tonalitic crust

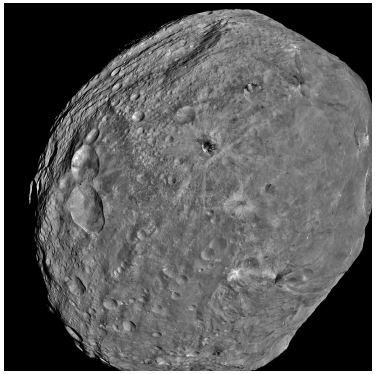


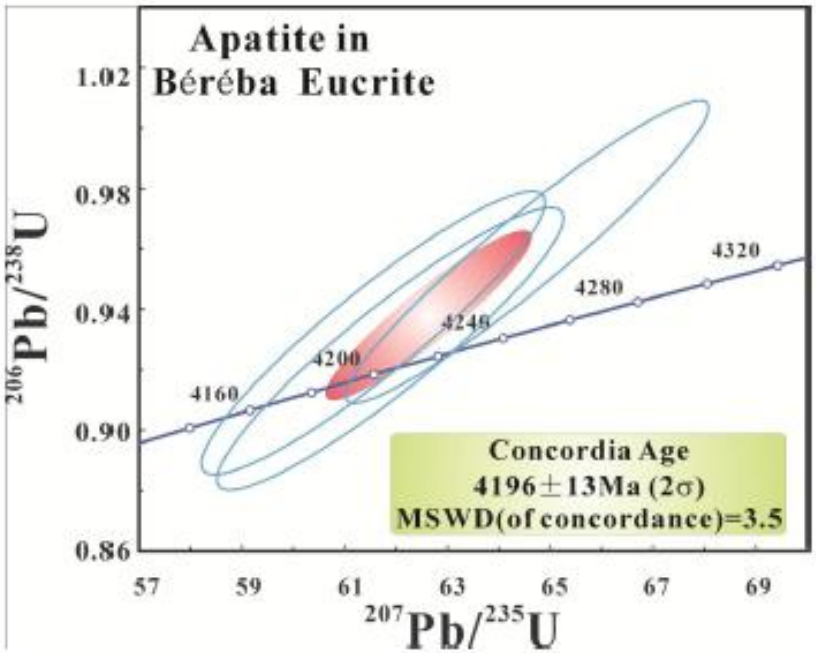
<3.9 Ga

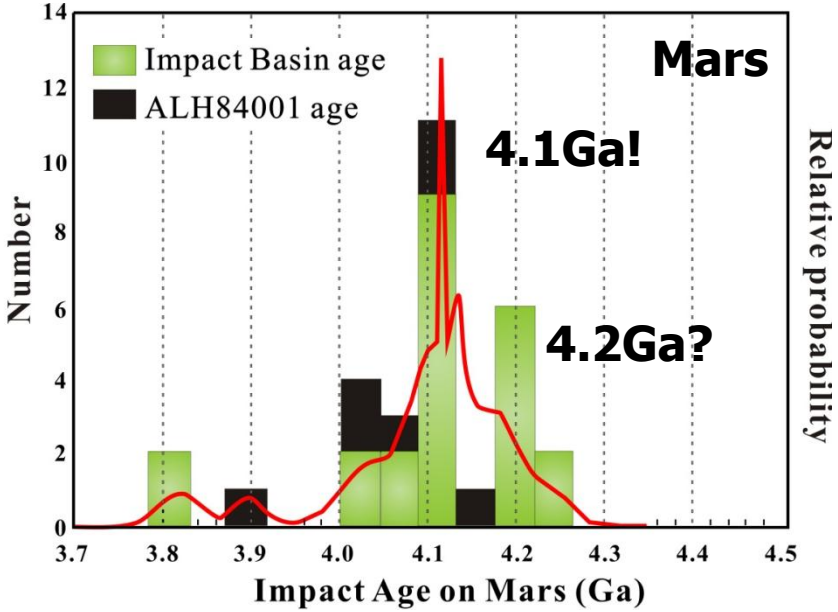
Gradual mixing in of LV

In-between the Late Veneer and the Late Heavy Bombardment

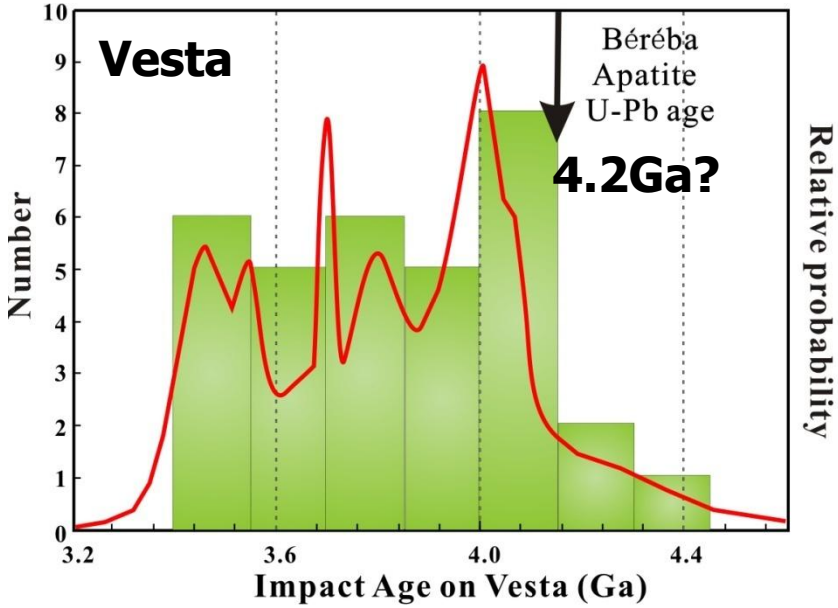
SOME CRYPTIC THERMAL EVENTS







Frey H., (2008); Lapen T.J. et al. (2010)



Bogard D., (1995)

Significance of direct rock samples

- Primordial mafic crust (late state terrestrial magma ocean?)
  - Ought to have formed from initial cooling (after GI)
  - Evidence for this from ^{147,146}Sm-^{143,142}Nd Systematics
  - Lu-Hf, Sm-Nd, U-Pb show evidence for substantial early differentiation
  - This early crust was apparently destroyed by about 3.8 Ga
  - **Indications arise from recent ^{142}Nd results (more in talk 2)**

Black Cat Studios ©

Significance of direct rock samples

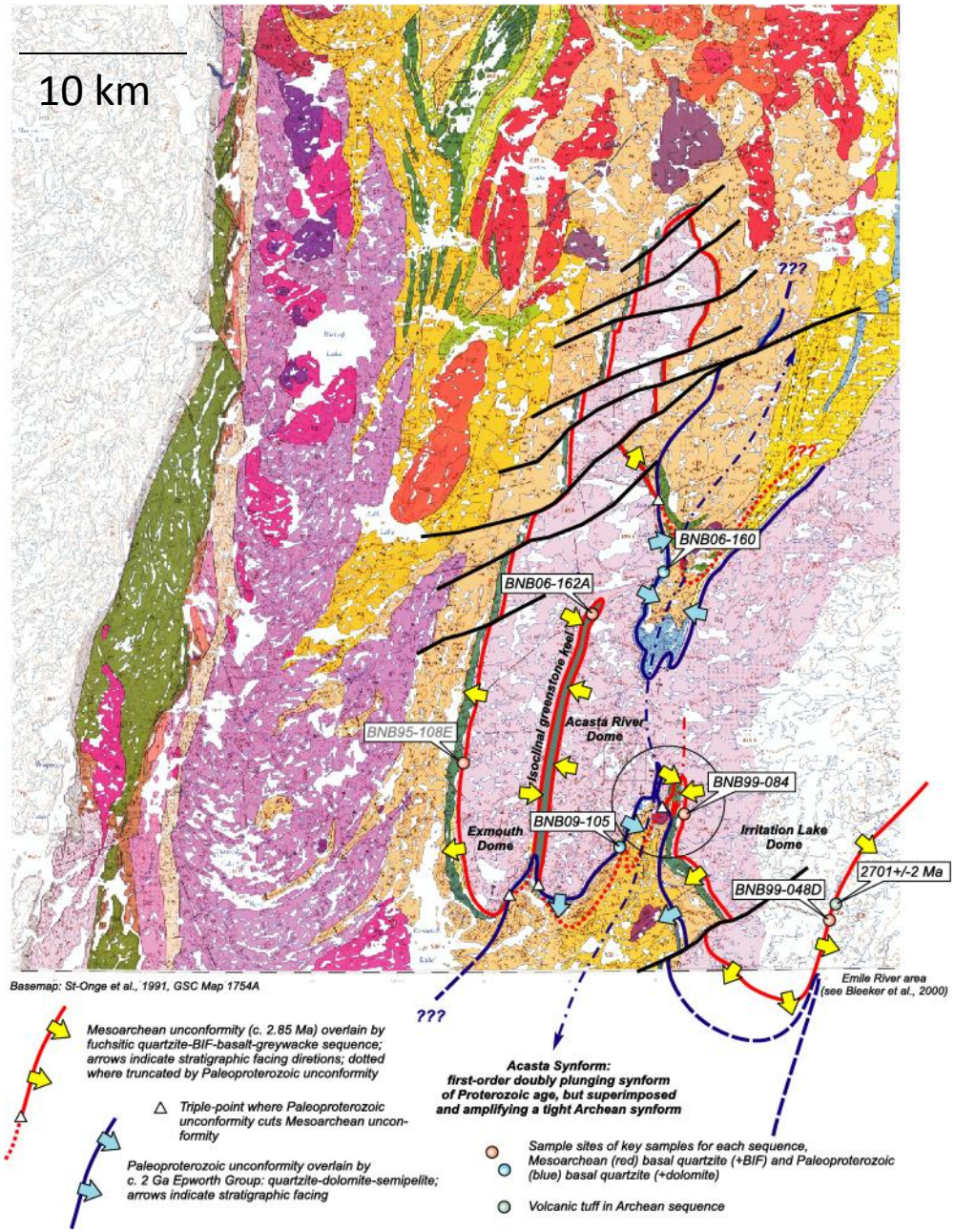
Black Cat Studios ©

- Ancient gneiss complexes

⇨ Are direct samples of the Hadean-Eoarchean Earth

  - **YET**: oldest preserved rocks are dominantly granitoid gneisses locked in younger orogens
  - Separated from everything else by shear zones
  - Oldest terrestrial zircons are derived from low T, high P, hydrous granitic melts → plate tectonics (cf. Kemp et al.)
  - Areal extent is relatively small

World's oldest rocks



300 km N of Yellowknife (NWT, Canada)

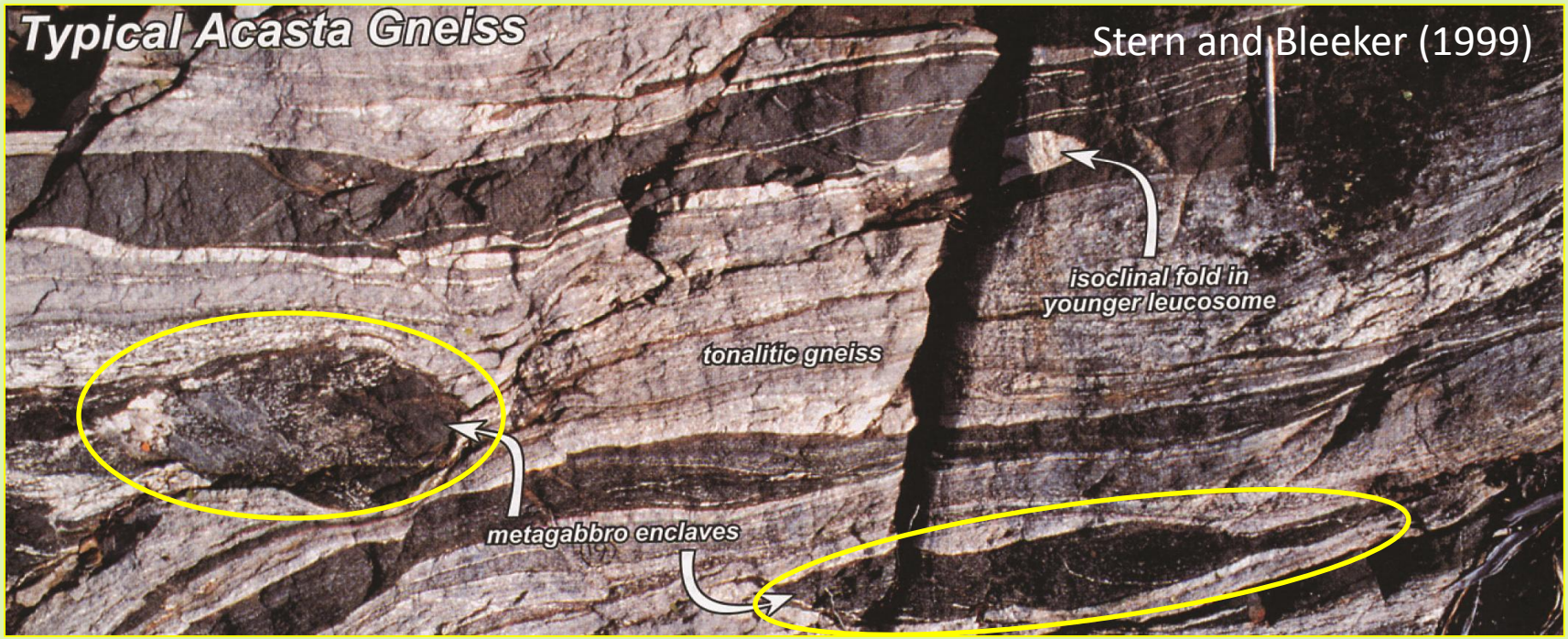
- J.E. King (1985) "Acasta Gneiss Complex"
- Western margin of Archean Slave craton
- Contaminated a wide area (Maier et al. 2011)
- Polydeformed migmatized gneisses
- several hundred sq. kilometers of outcrop?
- amphibolites-orthogneisses-gabbroic schists
- geological relations & geochemistry scant
- Zircon U-Pb geochronology ⇨ 4.05 Ga?
- Uncertainty over the ages of these rocks:

-Prevailing debate over ages

- Our goal is to relate geochronology and composition to geologic history

-These rocks Pre-date the last "major" accretion events

Lithotypes and compositions of AGC



Strongly foliated to gneissic enclaves of hornblende-plagioclase schists ("metagabbro" *s.l.*). Petrologically speaking, these may be termed Leucogabbros.

The Leucogabbros are included within and cross-cut by tonalitic gneisses with core concordant U-Pb ages that span 4.05-3.96 Ga. (pen for scale).

These represent the oldest poly-mineralic rocks on Earth.

Steve's shopping List of known Hadean rock and mineral localities (as of June 2012)

Locality	Age (Ga)[1]	Rock type	References
	HADEAN		
Acasta Gneiss Complex, NWT Canada	4.03-3.94 3.74-3.72 3.66-3.59	orthogneisses,	Iizuka et al., 2006, 2007; Bowring and Williams, 1999; Bowring et al., 1989; and references therein
	(4.20)	inherited zircon	
Napier Complex, Antarctica	3.88-3.85	orthogneisses,	Black *et al*., 1986; Harley and Black 1997
	(>3.9?)	inherited zircon	
Jack Hills, Australia	(4.38-≤3.6)	detrital zircons	Peck *et al*., 2001; Mojzsis *et al*., 2001; Harrison *et al*., 2005; Crowley *et al*., 2005; Trail *et al*., 2007a, 2007b; Cavosie *et al*., 2007; Blichert-Toft and Albarede, 2008; Kemp et al., 2010; references therein
Southern Cross Greenstone, Australia	(4.35)	single detrital zircon	Wyche *et al*., 2004
Mount Narryer, Australia	(4.28-≤3.6)	detrital zircons	Crowley *et al*., 2005; Pigeon and Nemchin, 2006; Trail *et al*., 2007a
Beartooth Mountains, Montana	(3.96-≤3.6)	detrital zircons	Mueller et al., 1992
Thelon Basin, Nunavut, Canada	(3.94)	single detrital zircon	Palmer et al., 2004
Assean Lake crustal complex & Seal River complex, Manitoba, Canada	(3.9-≤3.6)	detrital zircons	Böhm et al., 2003; 2007; references therein
Ameralik fjord, West Greenland	(3.89)	orthogneisses	Naeraa et al. (2012)

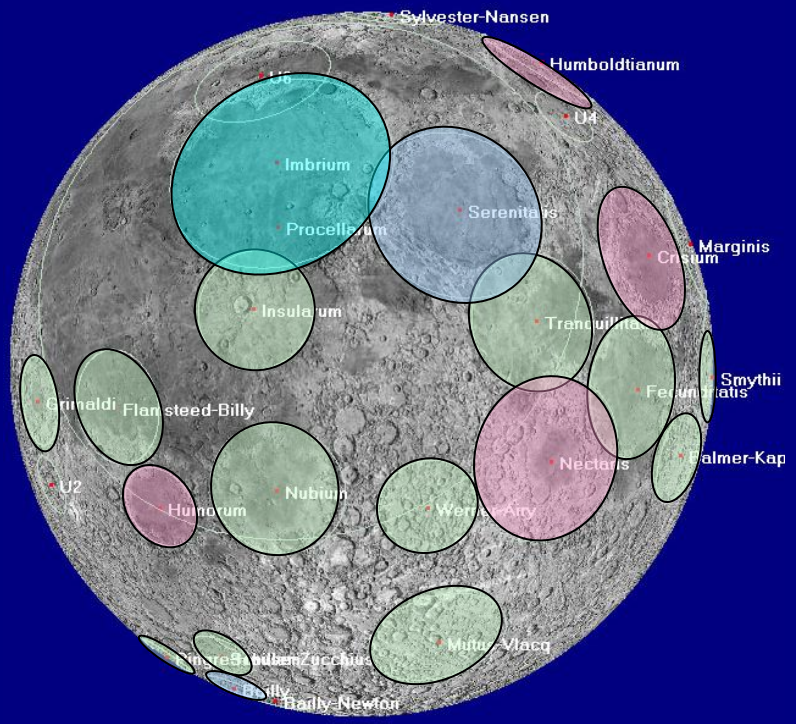
[1]Inherited or detrital zircons indicated by age in parentheses.
HADEAN is defined as the time after planetary accretion and before appearance of first marine sediments at 3.85 Ga

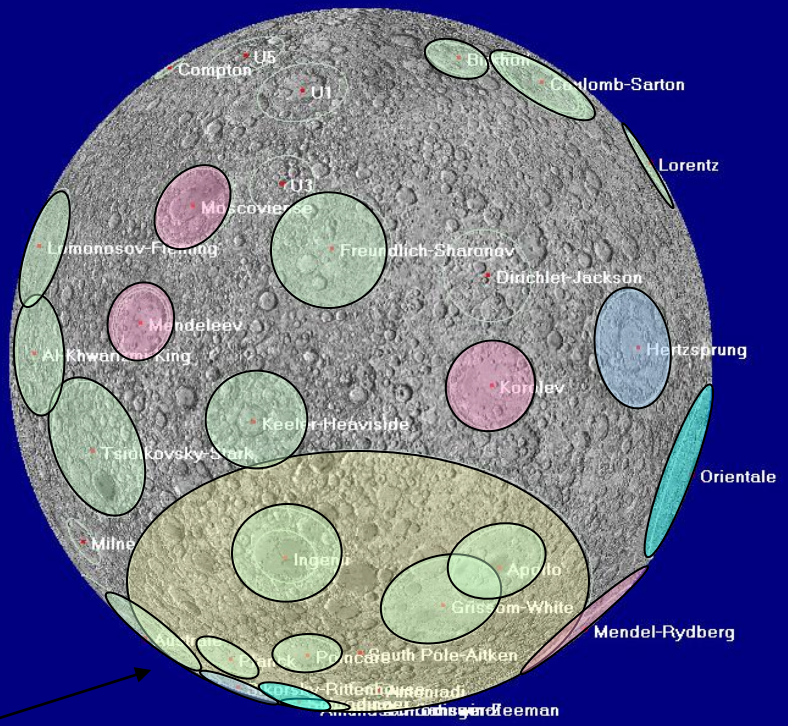
Late Heavy Bombardment

BOREDOM OR HORROR?

Most of the Moon's geology is related directly or indirectly to ~50 big impacts centered at 3.9 Ga

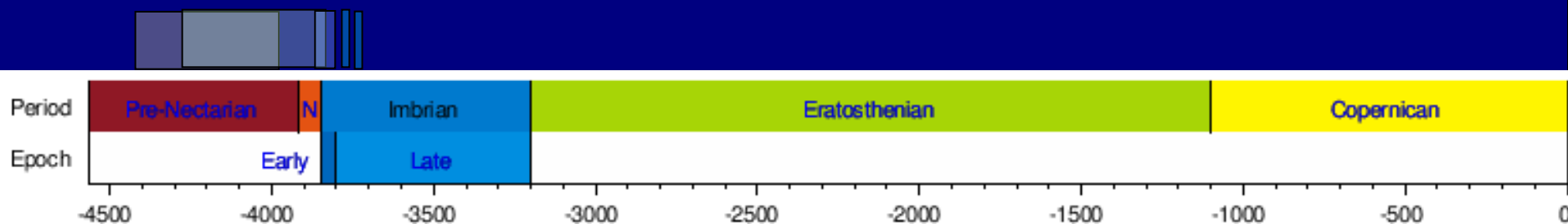
Front





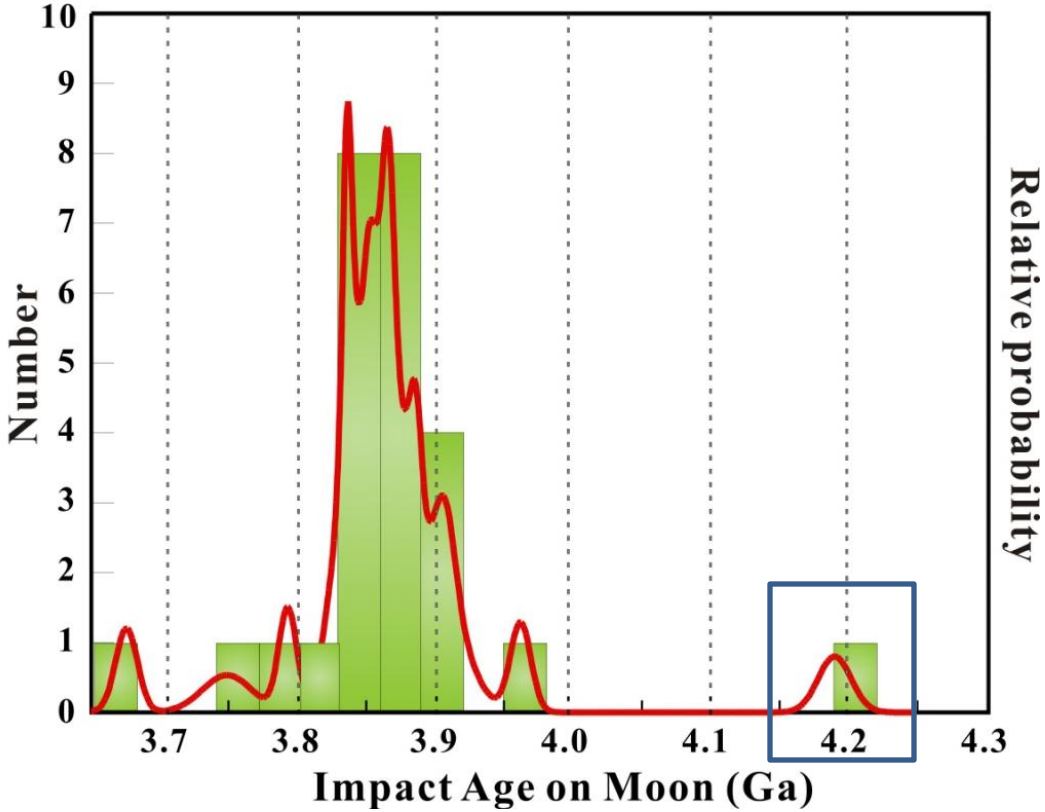
300-1160 km diameter basins
2500 km diameter for SPA

Back

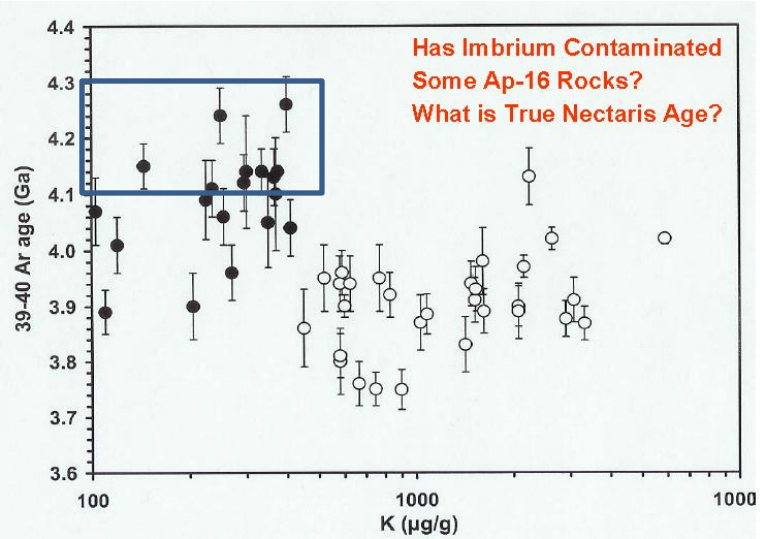


LHB on the Moon (details of geochronology)

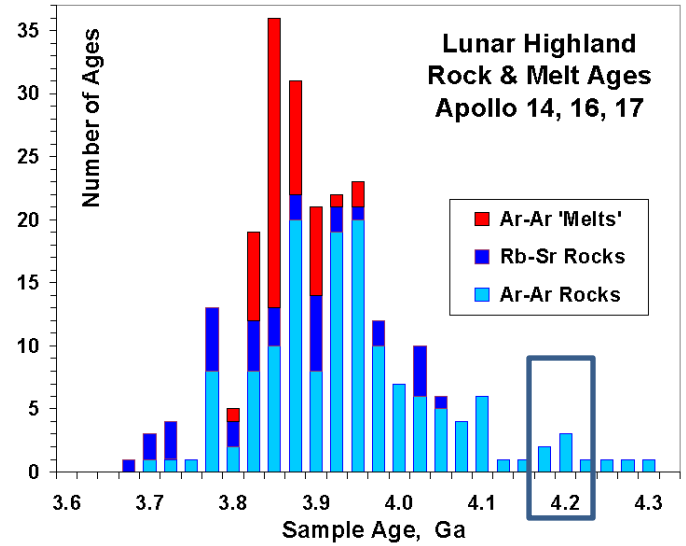
3.85 Ga from Ar ages



Norman et al. (2006)

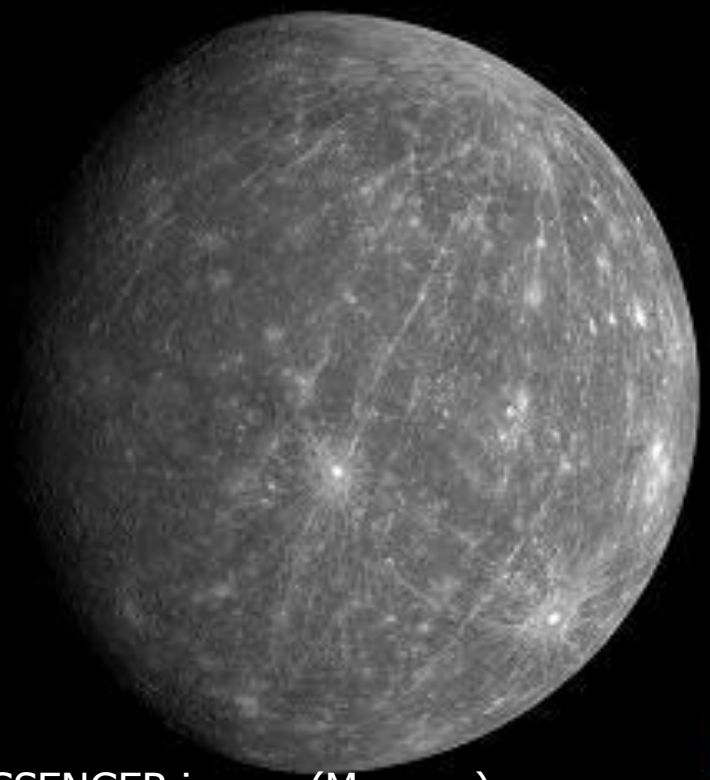


Warren et al. (2003)

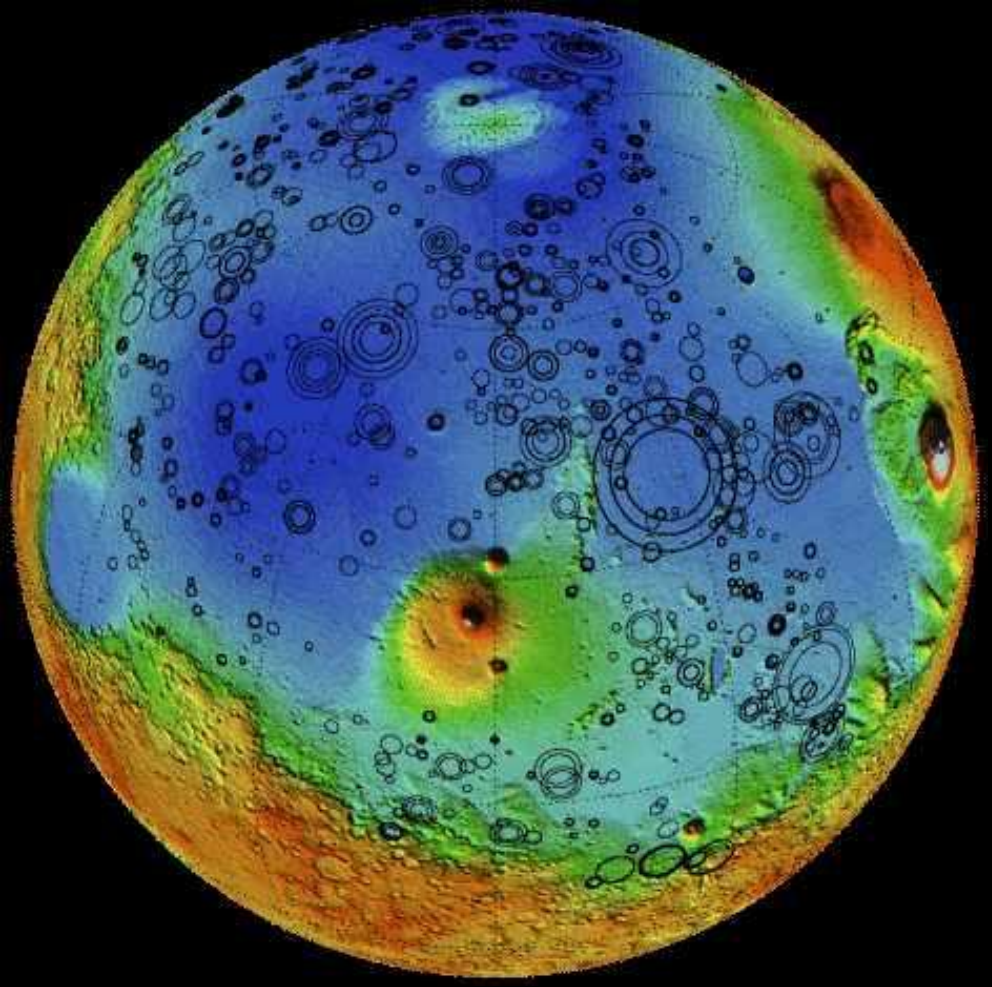


Bogard et al. (2006)

What did the ca. 3.9 Ga Late Heavy Bombardment do for/to early life and the hydrosphere?

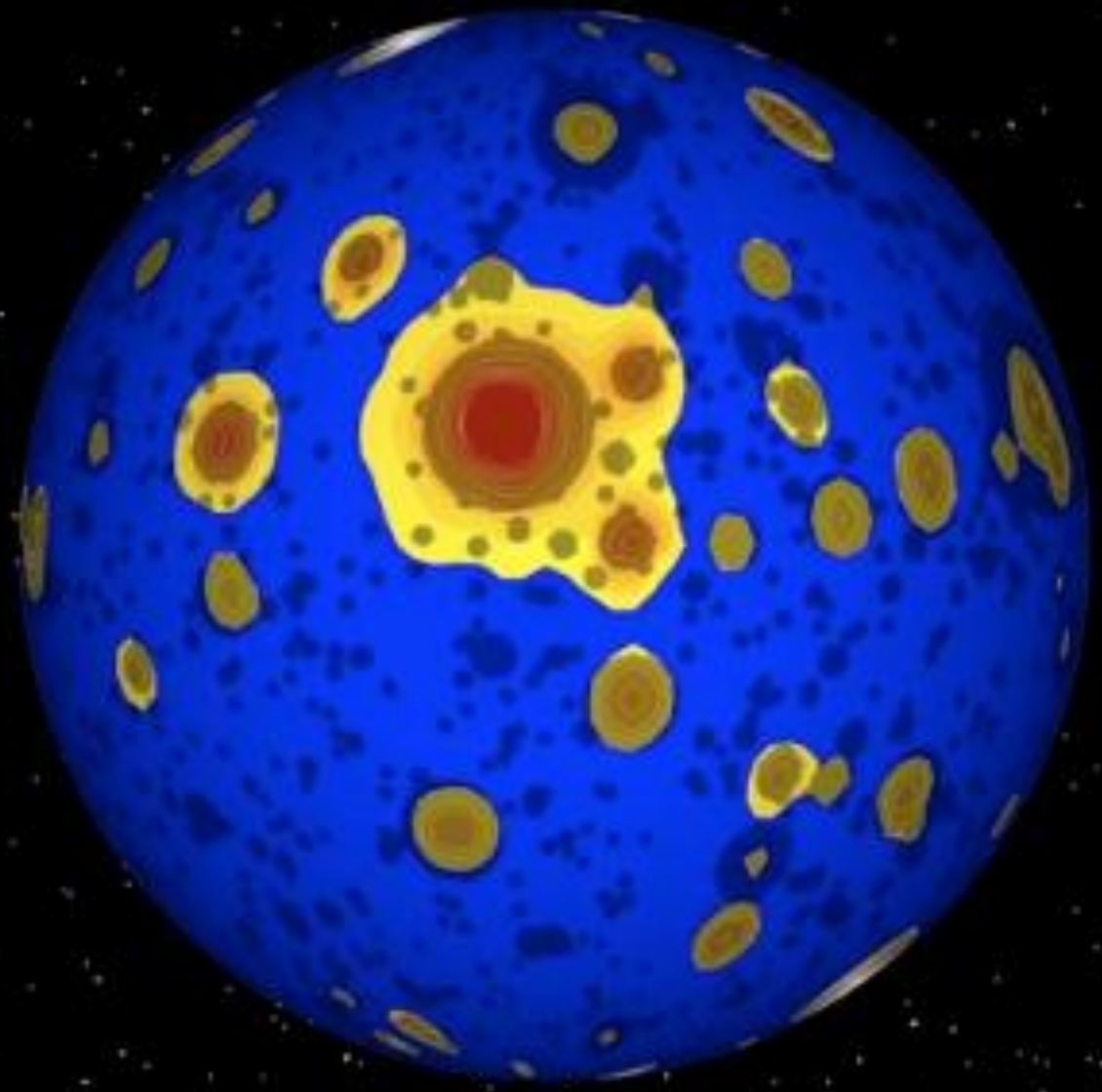


MESSENGER image (Mercury)



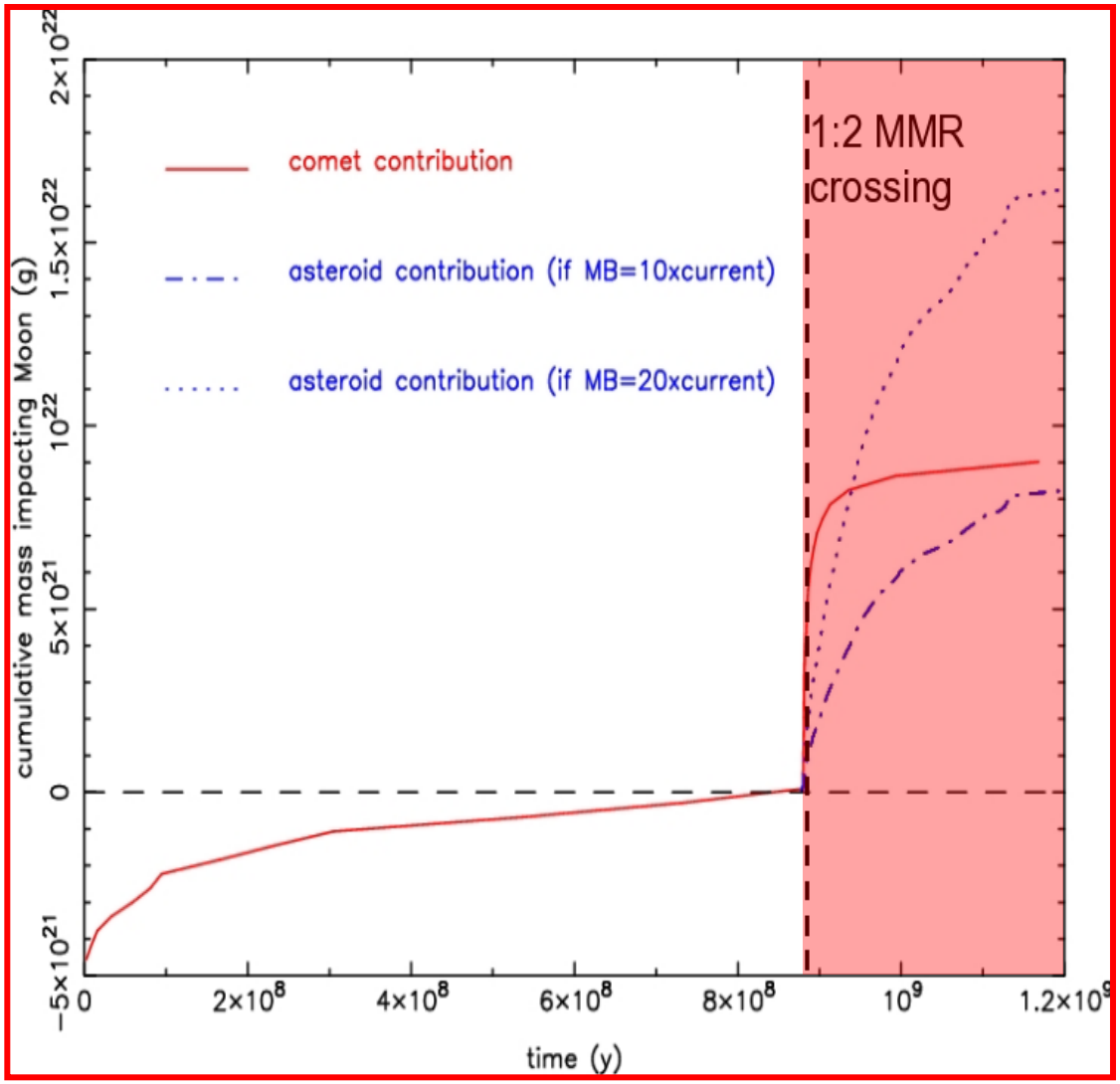
Mars buried cratered terrane: H. Frey (GSFC)

- Life was disrupted
  - No plausible scenario for sterilization, but bad for surface life
- Early crust was partially destroyed
- Oceans were not destroyed

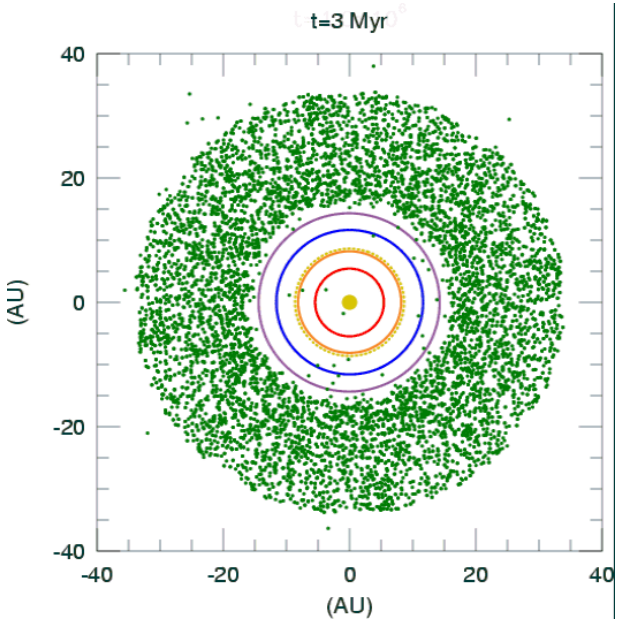


Abramov & Mojzsis (2009)

Exogenous delivery to Earth during the LHB (Note: LHB≠LV! *cf*. Willbold et al. 2011)

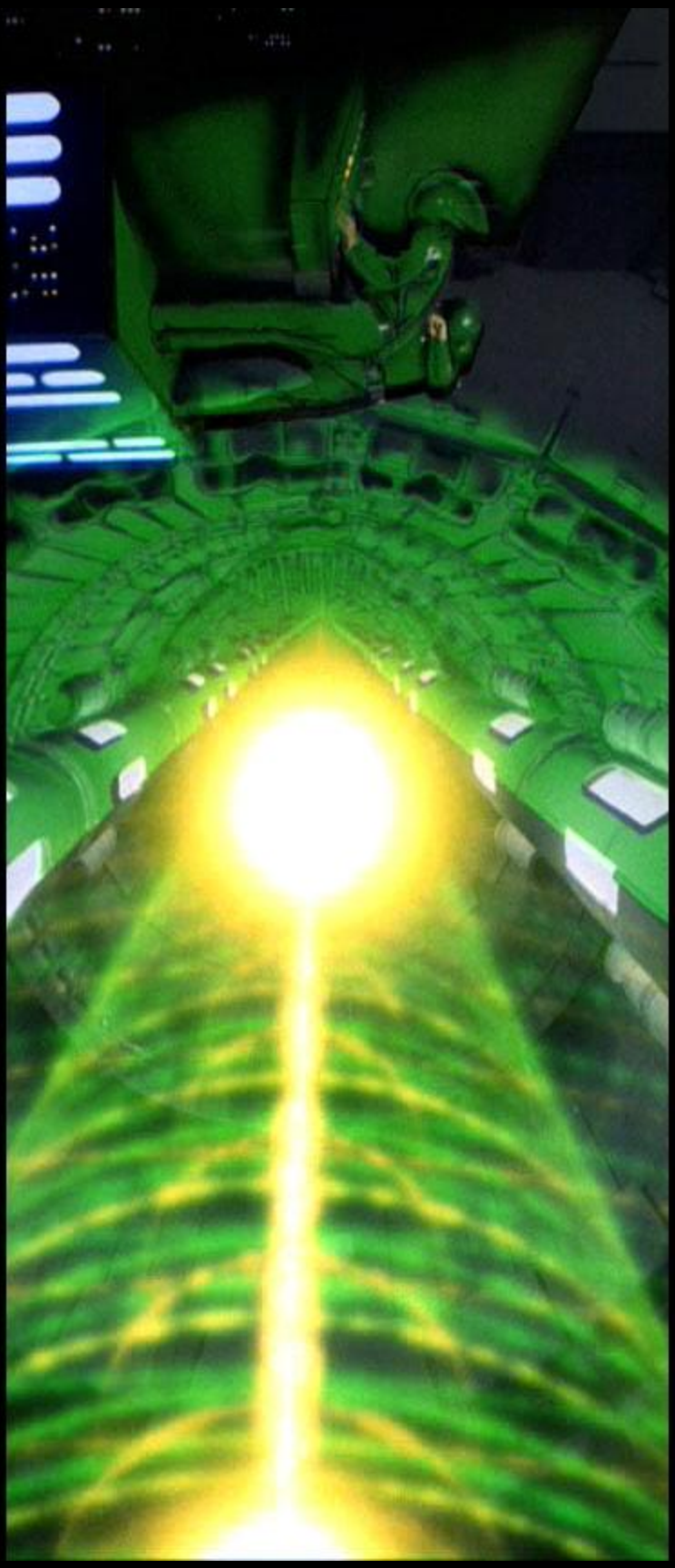


- The Cumulative contribution of these sources would have been significant to the surface zone (little enters the mantle).
- The Earth accretes a small amount of asteroidal and cometary material.



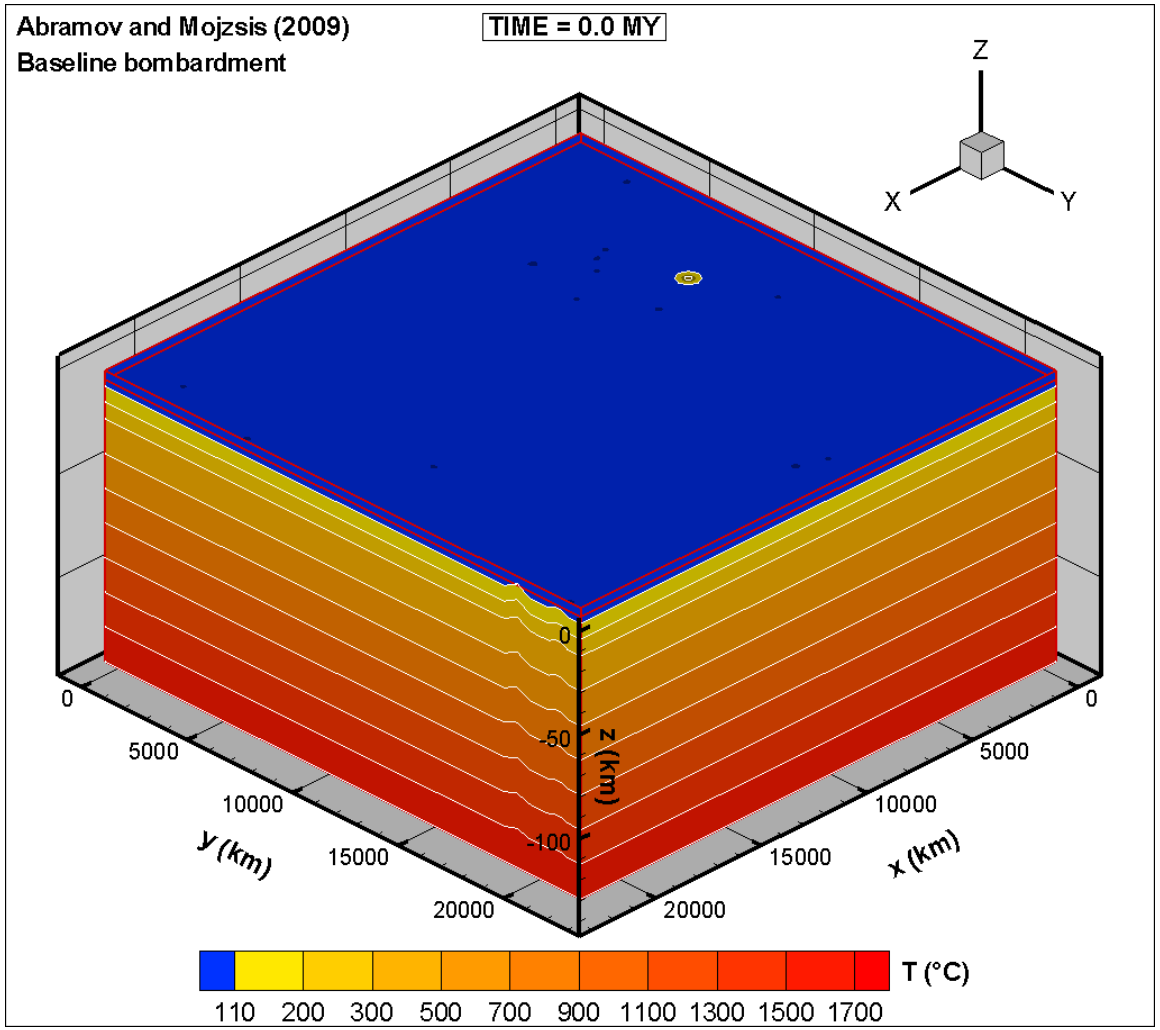
Gomes et al. (2005)

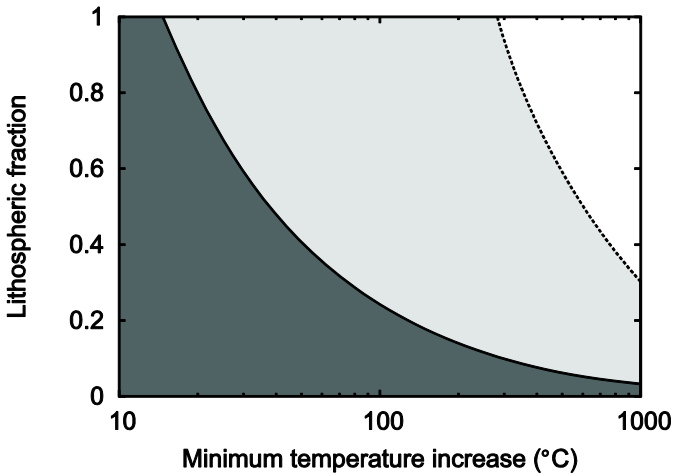
Thanks to Morby (OCA) & Hal (SwRI)



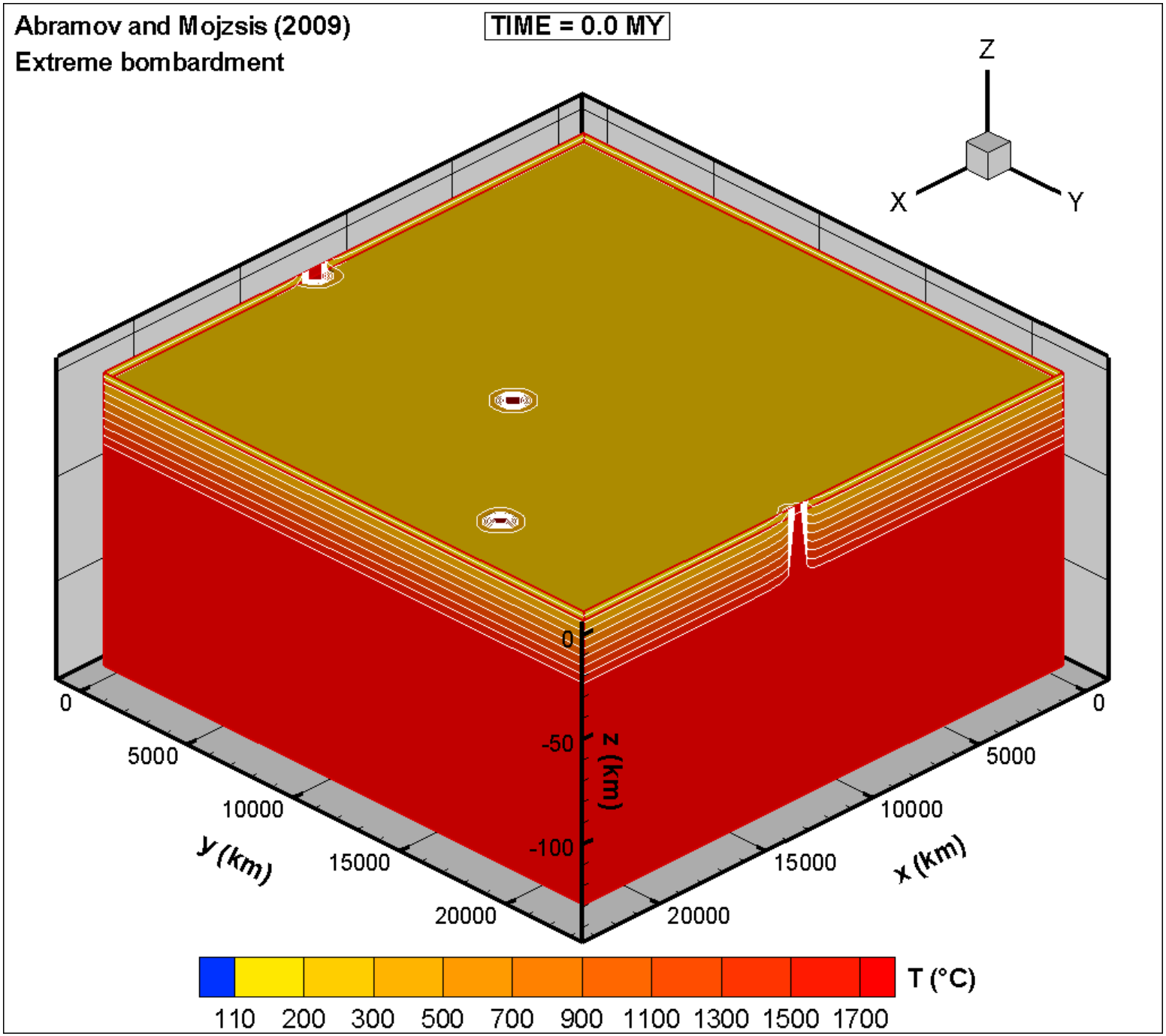
Earth LHB Simulations

- Models allow us to monitor thermal effects to the terrestrial crust.
- But what evidence exists on Earth for these events is cryptic



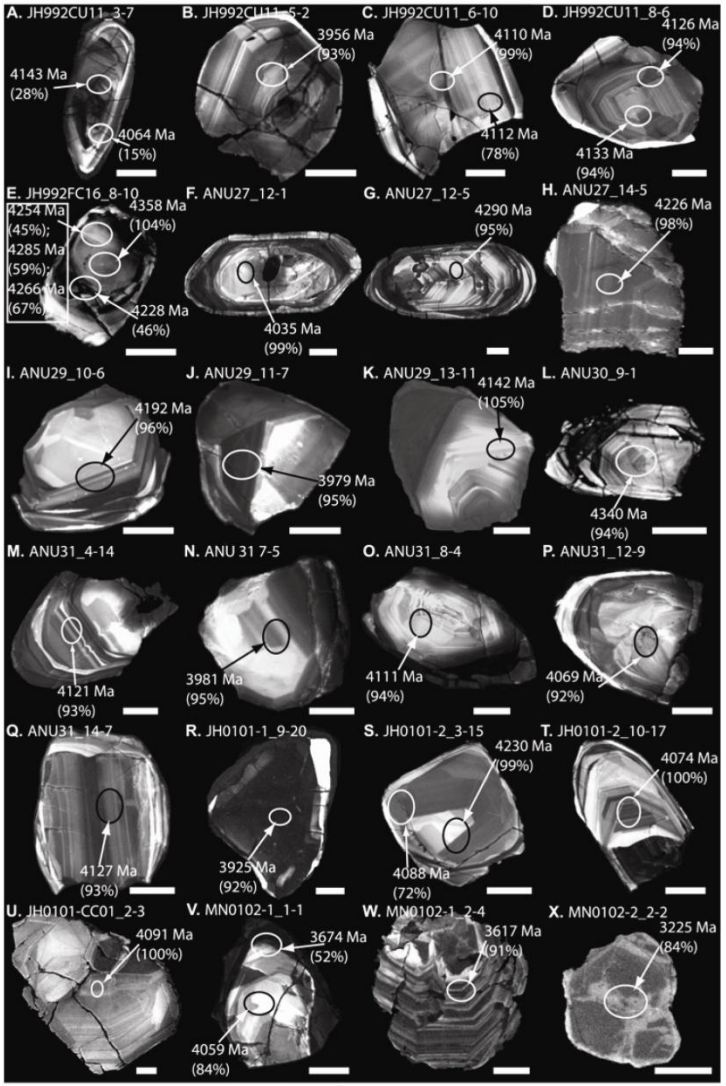


Abramov & Mojzsis (2009)


Abramov and Mojzsis (2009)
Extreme bombardment
TIME = 0.0 MY
Z
X
Y
0
-50
-100
z (km)
0
5000
10000
15000
20000
y (km)
0
5000
10000
15000
20000
x (km)
T (°C)
110 200 300 500 700 900 1100 1300 1500 1700

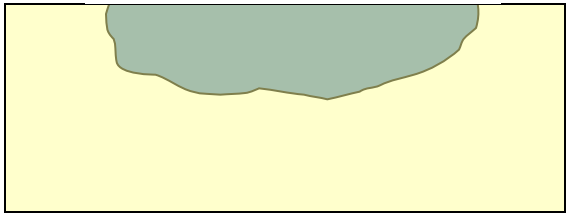
Depth profile analysis

- Hadean zircons are the only dated material on Earth to have gone through the LHB
- Grains chosen for ultra-high resolution depth-profile analysis based on concordant ages (no significant Pb-loss in whole grain)
- Goal: Elucidate a cryptic record of thermal events affecting the crust before the rock record



A word about sample preparation

(1)



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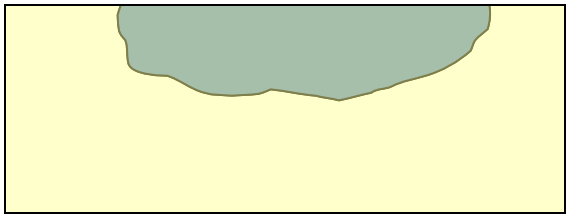

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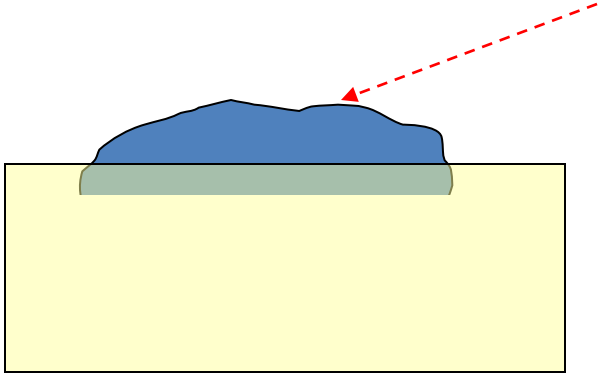
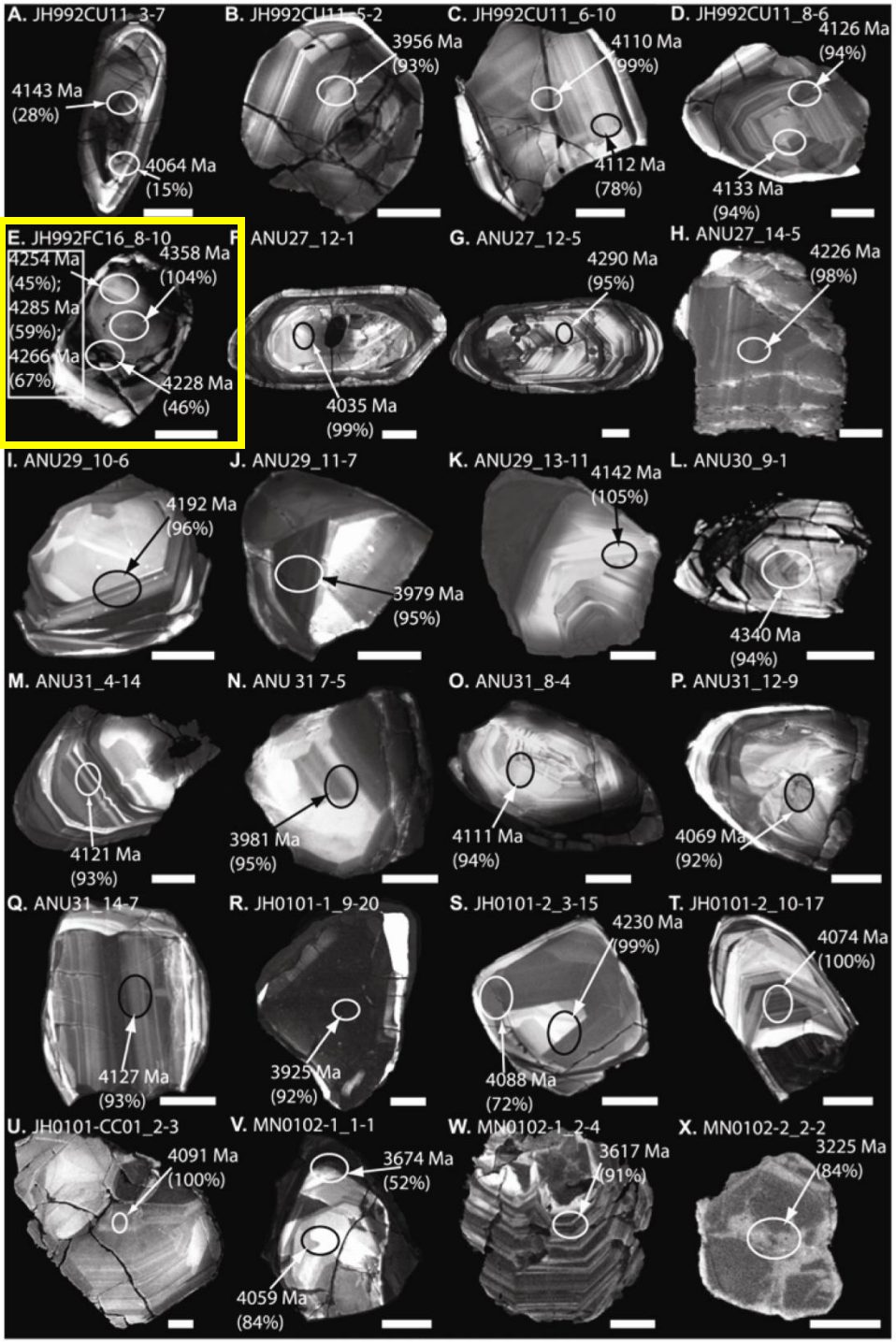
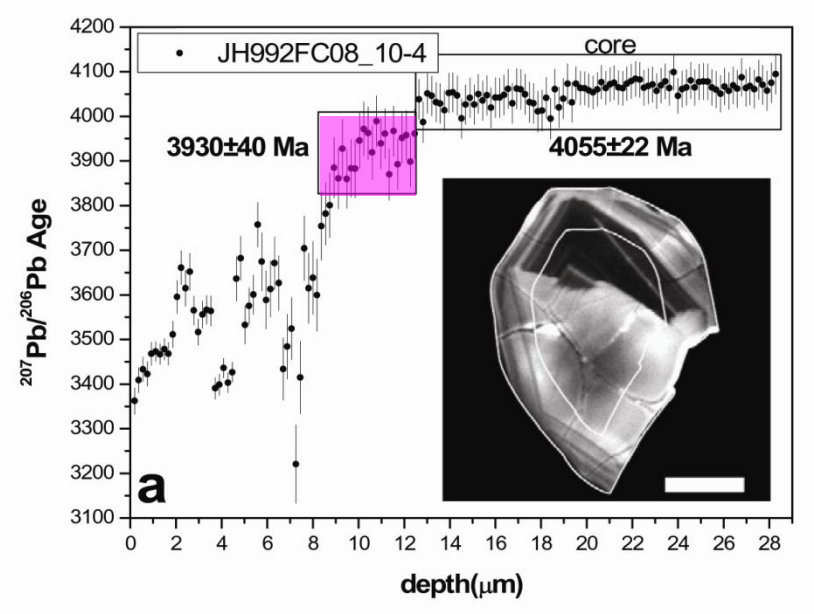
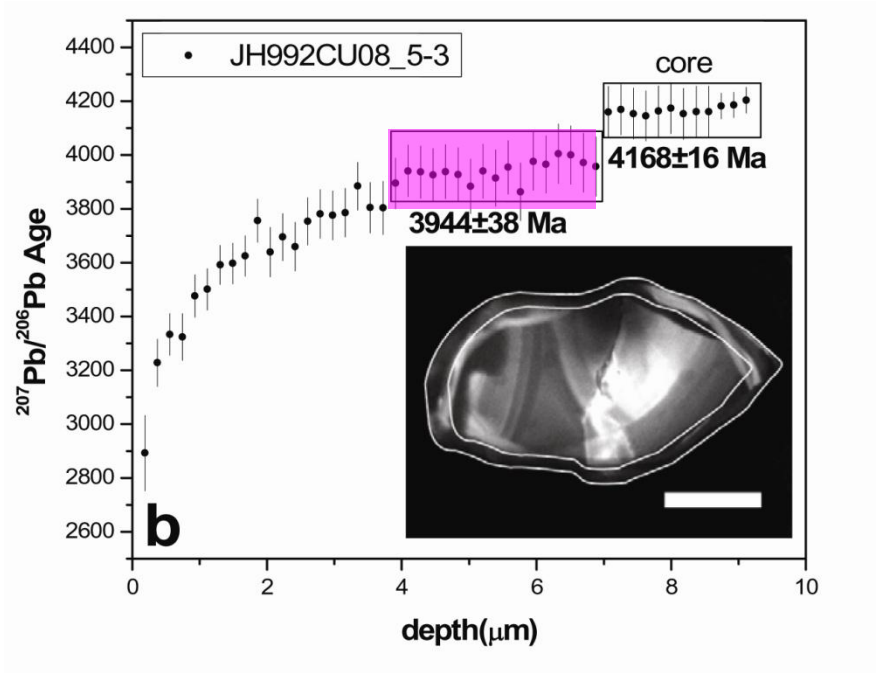
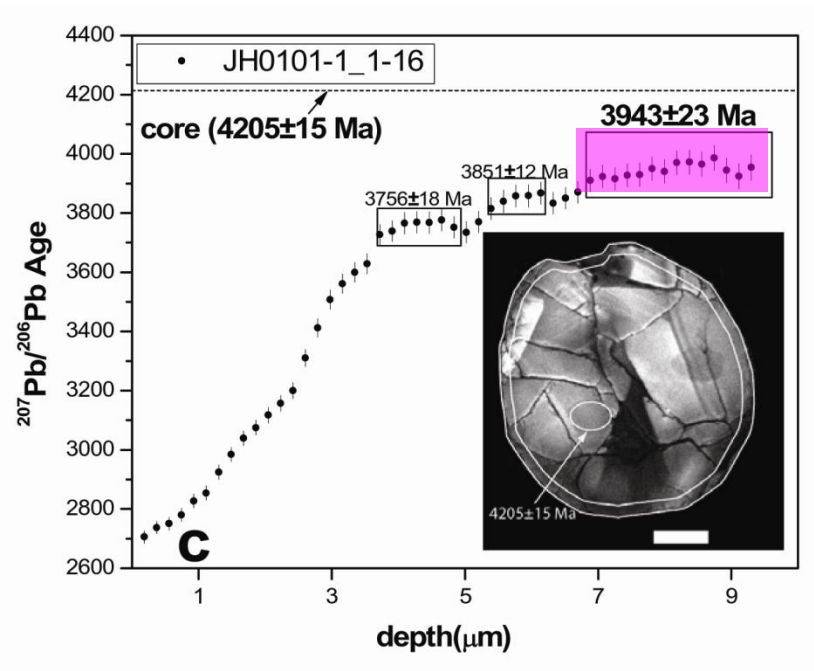
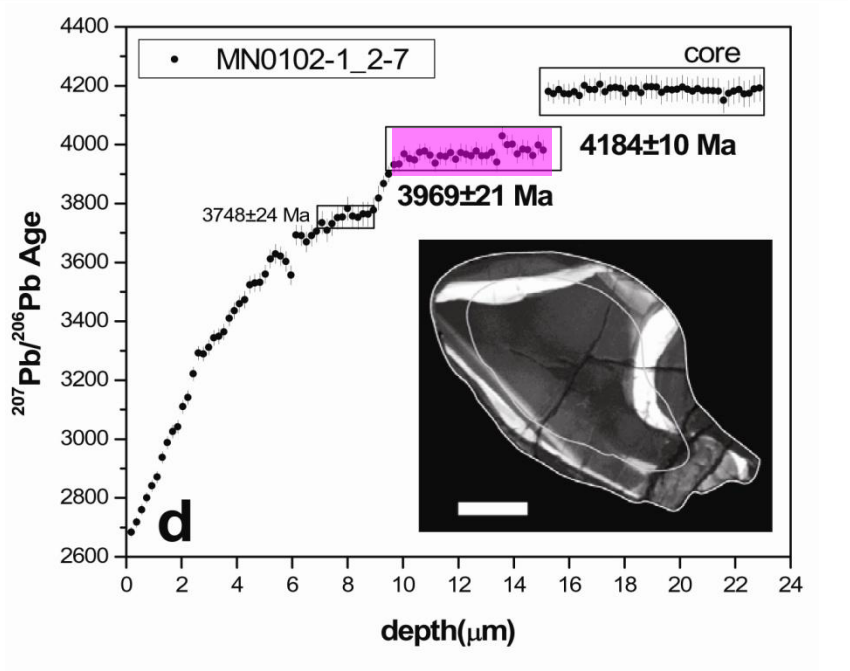




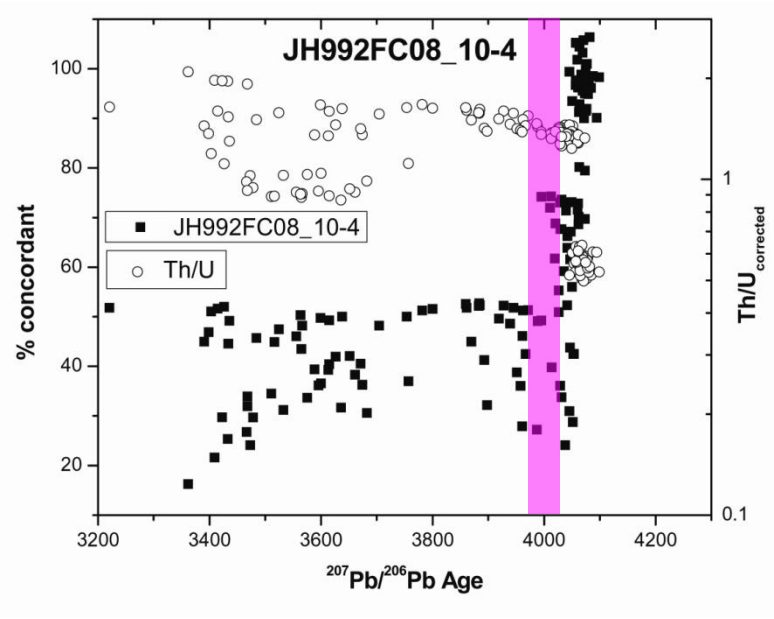


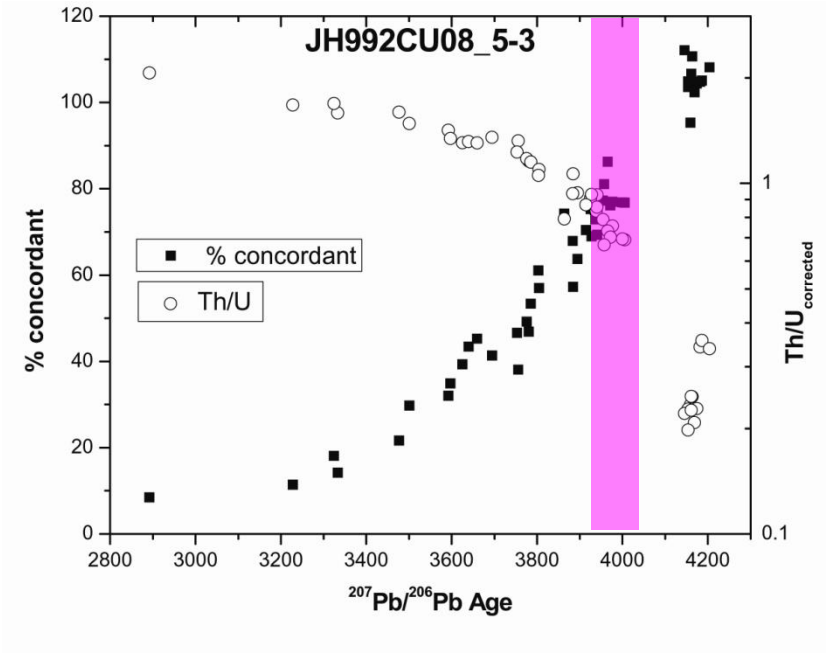






Trail et al. (2007)


JH992FC08_10-4
JH992FC08_10-4
Th/U
% concordant
Th/U corrected
207Pb/206Pb Age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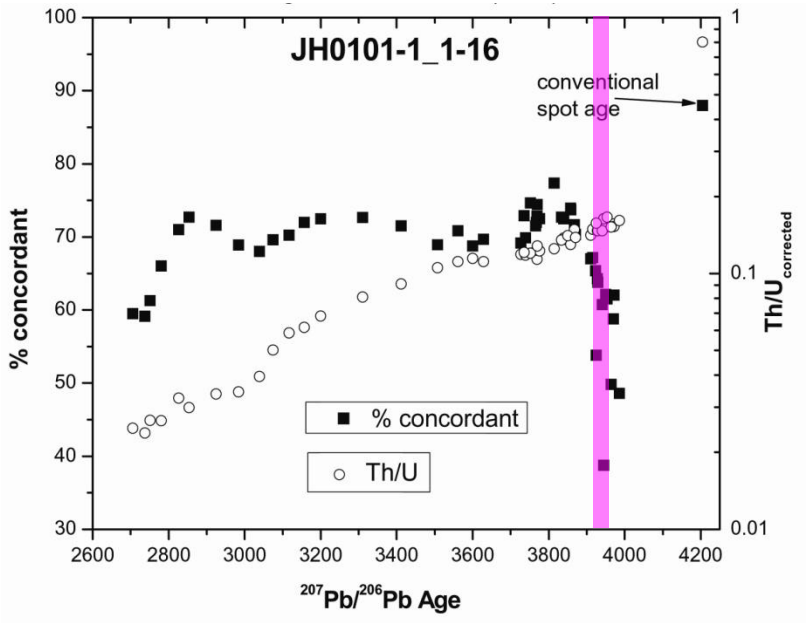
% concordant
Th/U
Th/U corrected
207Pb/206Pb Age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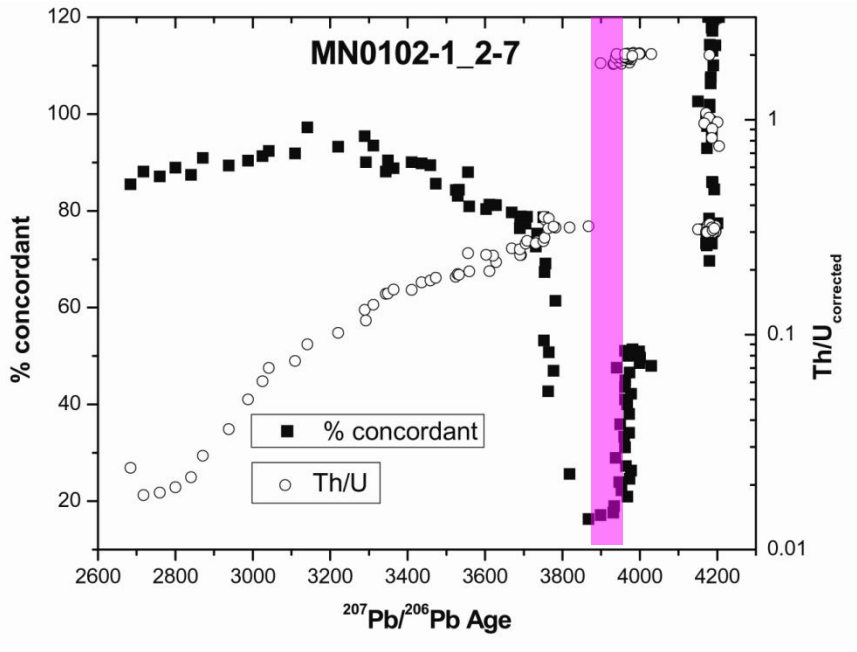
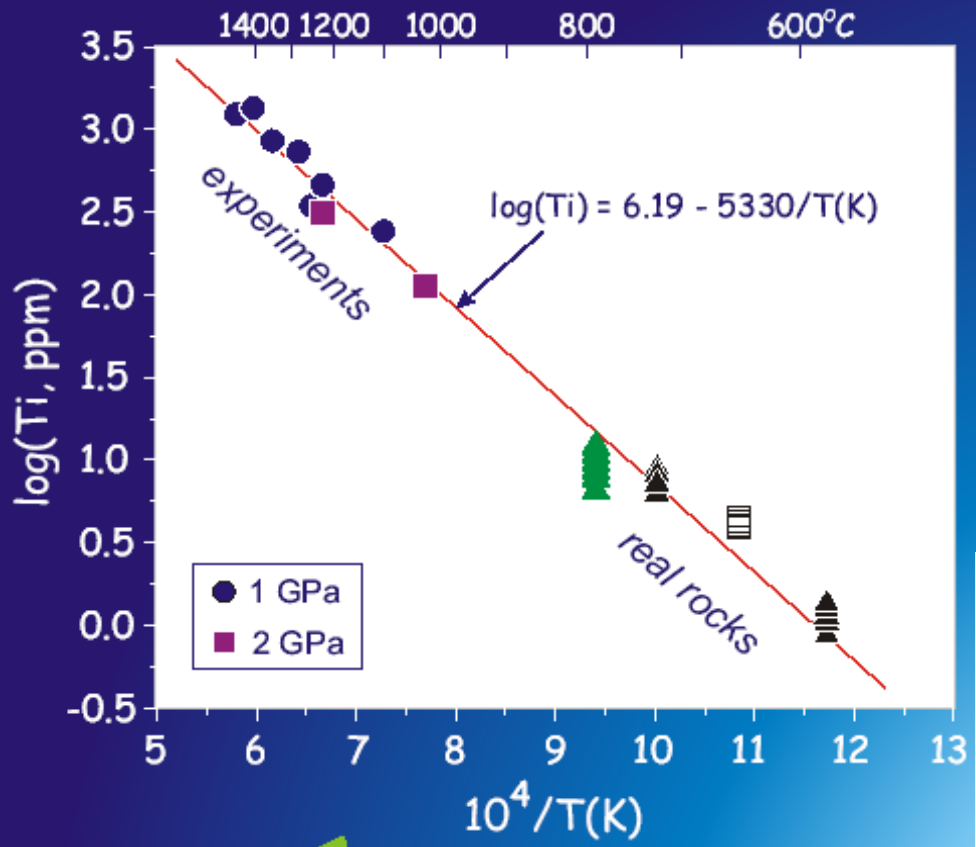
conventional
spot age
% concordant
Th/U
Th/U corrected
207Pb/206Pb Age


MN0102-1_2-7
% concordant
Th/U
Th/U corrected
207Pb/206Pb Age

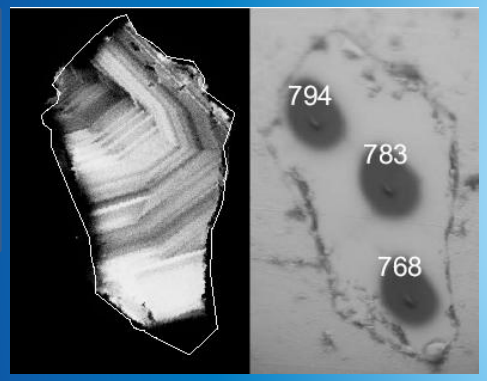
TITANIUM THERMOMETRY of zircons



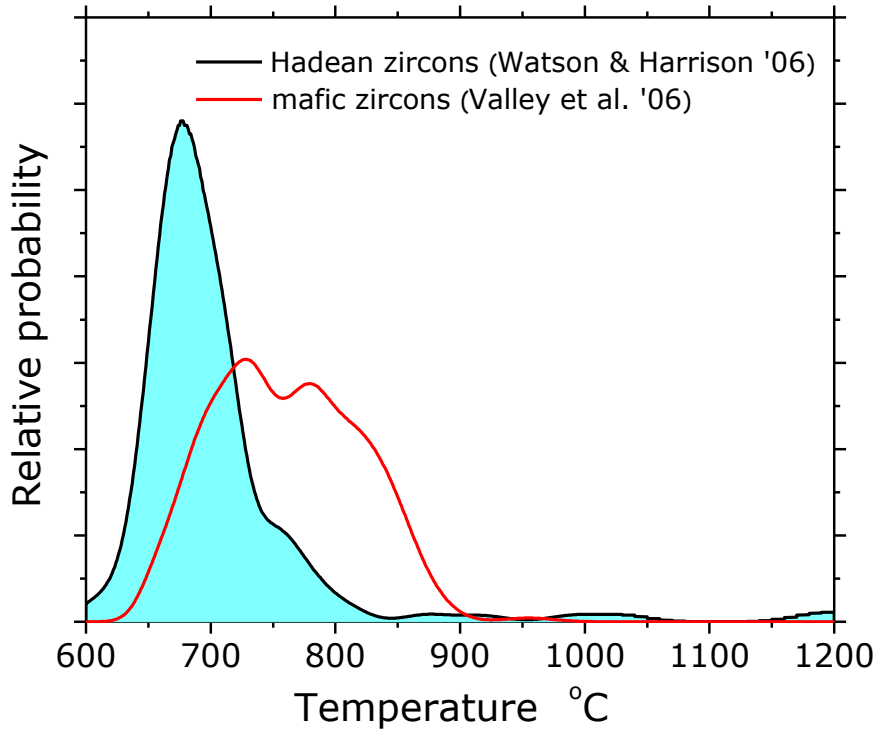
25 calculated temperatures yield 725±35°C

application

Calibration

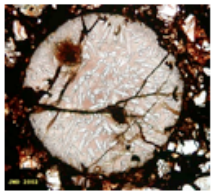


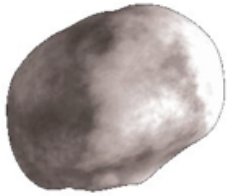
4.2 Ga Jack Hills zircon

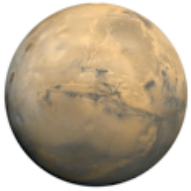


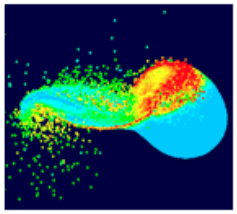
Courtesy: E.B. Watson

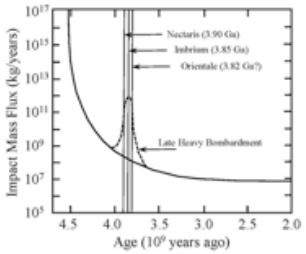
Shedding some light on the “dark ages”

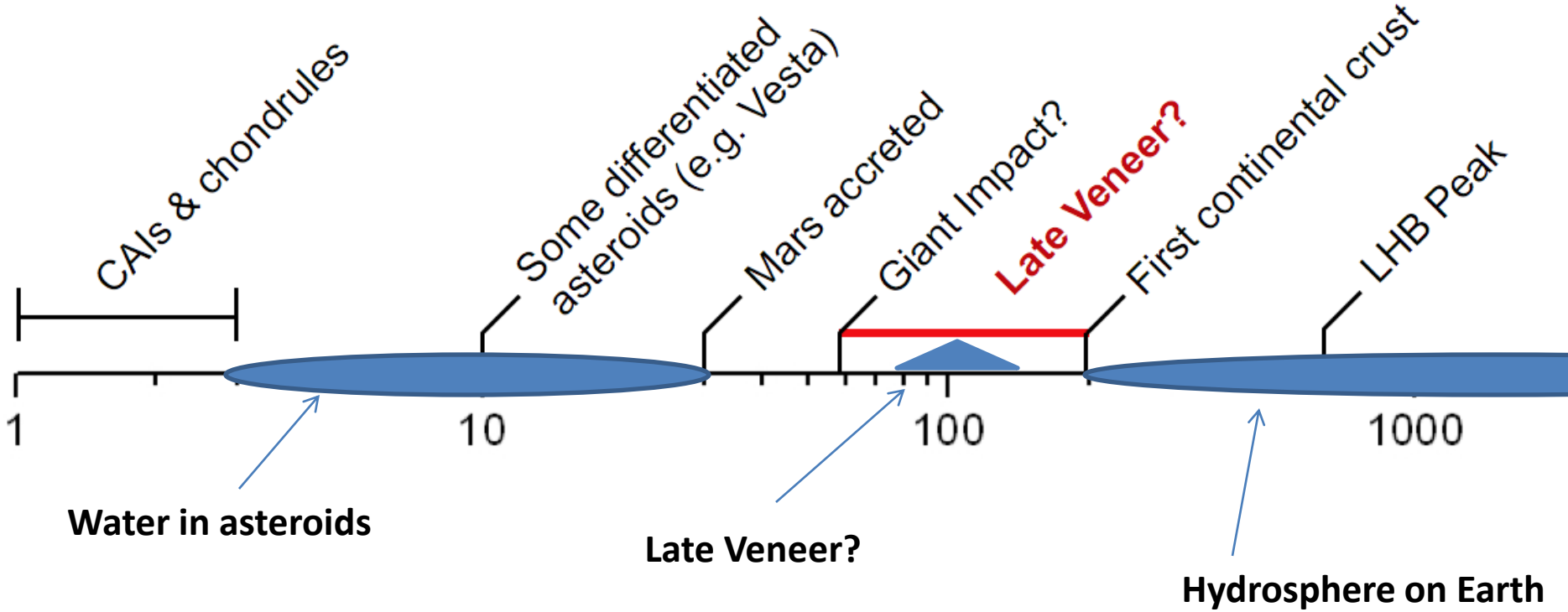












Observations arising…

1. By what time must water on Earth have appeared? **(before 4.4 Ga ago)**

2. Was the origin of life characterized by boredom or terror? **(depends on whether you boil off all the oceans, so probably a little of both)**

3. What was the ultimate fate of the first terrestrial mafic/ultramafic crust? **(reworked into the formation of younger rocks)**

4. What happened in the aftermath of the Moon-forming Giant Impact ("GI") to the Earth? **(One or more Late Veneer(s) that re-melted the crust)**

5. When might Late(r) Accretion have occurred? **(the GI was not the end of the story it seems; Late Accretion/Late Veneer is not the Late Heavy Bombardment; some volatile loss at the GI, but probably not subsequent to the LV(s), LHB; LV happened between 4.5 and 4.4 Ga and may have slightly augmented Earth's water budget)**

Thank you

Nicole Cates, Michelle Hopkins, Analisa Maier, Elizabeth Frank, Dustin Trail, Dominic Papineau, Oleg Abramov, Betsy Swanner, Martin Guitreau, Antoine Roth, Jeff Walker, Jon Adam, Sarah Palaich, Allison Schaiberger & all of my student collaborators

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Steve Mojzsis' talk #2

PHYSICO-CHEMICAL ENVIRONMENTS ON EARTH AT THE TIME OF LIFE'S EMERGENCE (AN "IF/THEN" STORY)

UIMP 10th International School of Astrobiology
June 18-22, 2012

We have seen that the early solar system was dangerous :

1. Probable loss of some atmosphere and volatiles
2. Crust and outer mantle of the Earth eroded (no survival of crystalline rock from before 4.4 Ga)
3. **Magma oceans were formed**
4. Mantle self-oxidized
5. Eventual segregation of different components based on mechanical and chemical properties, final core closure
6. Extinction of any possible pre-existing biosphere
7. What happened afterwards when things settled down?

Key ideas to take with you

Faint Sun, asteroid/comet impacts, extensive hydrothermal systems for life from volatiles that were delivered very early and supplemented by impacts, <0.5 bar atmosphere. For all intents and purposes, Earth could have had life since ca. 4.4 Ga

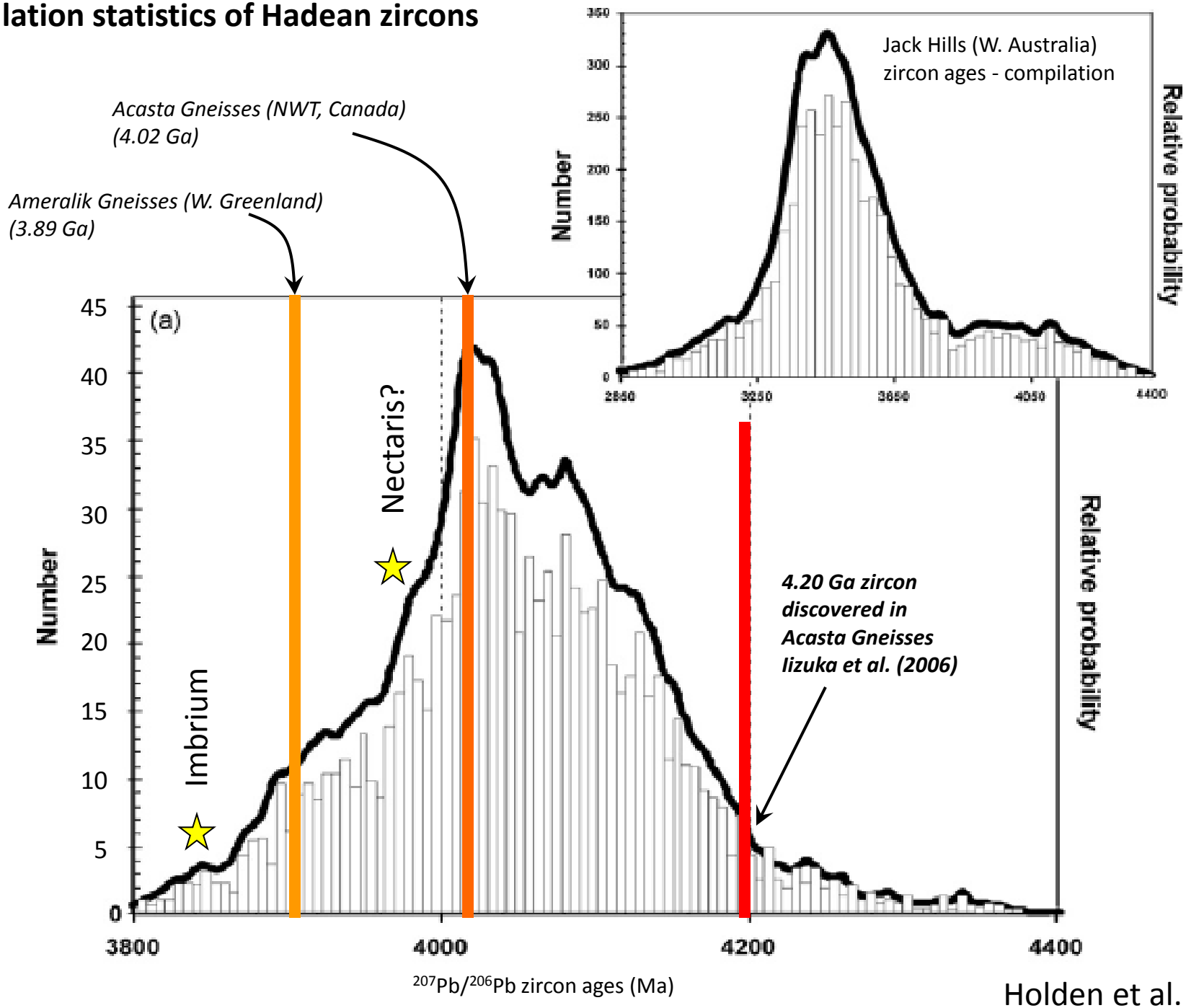
The intense early environment of the solar system seems to have provided a “bouillon” instead of a “coup de grace” for the Origin of Life.

Terrestrial zircon age characterization

Collectively, we have surveyed >**200,000** Jack Hills zircons for $^{207}Pb/^{206}Pb$ age.

The oldest grain so far discovered in this survey is 4.38 billion years old, and quite a few more <4.35 Ga.

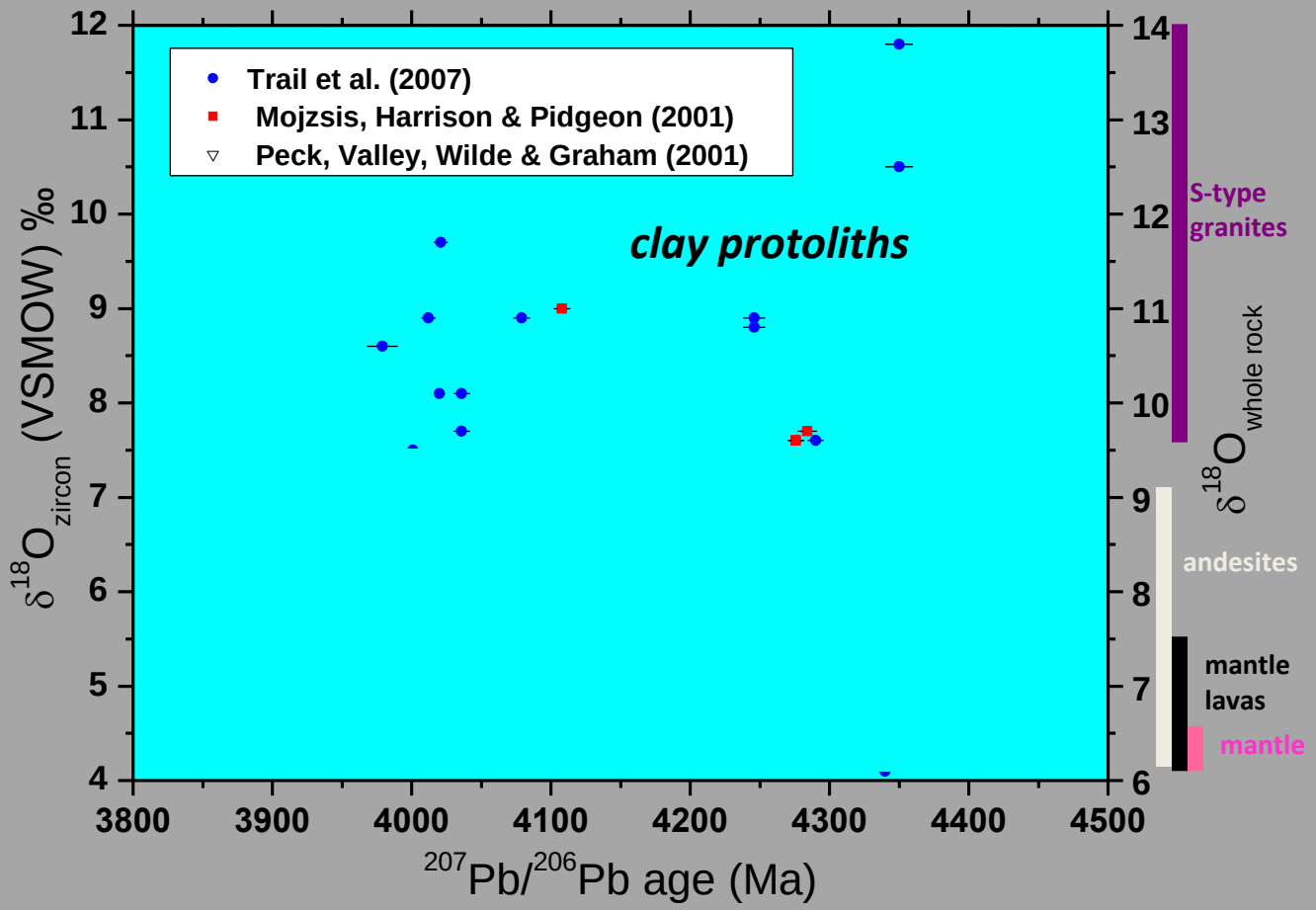
Population statistics of Hadean zircons



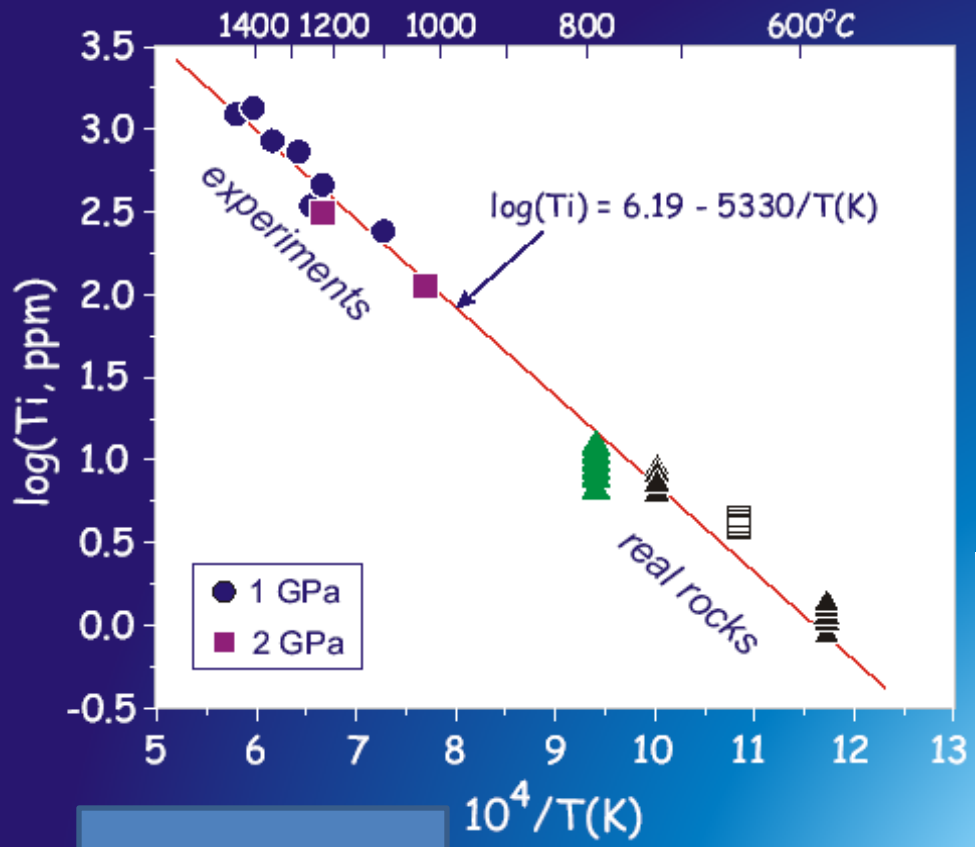
Holden et al. (2009)

Paleo- paleo- paleo-Oceanography

^{18}O enrichments in pre-4.0 Ga zircons = water?

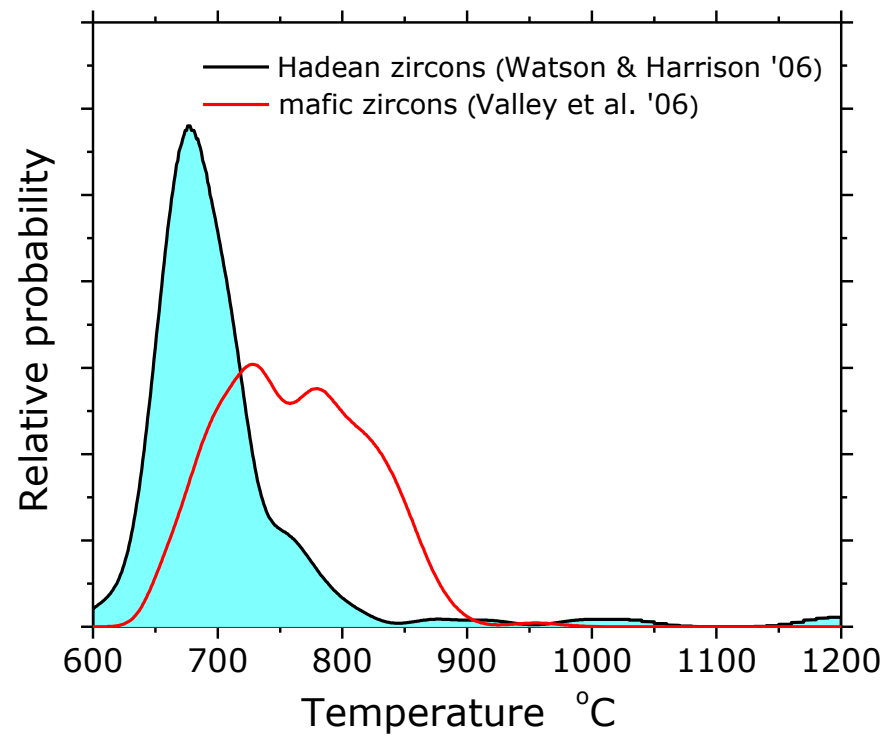


TITANIUM THERMOMETRY of zircons

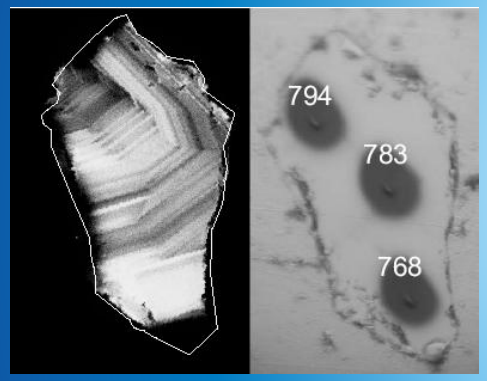


25 calculated temperatures yield 725±35°C

application



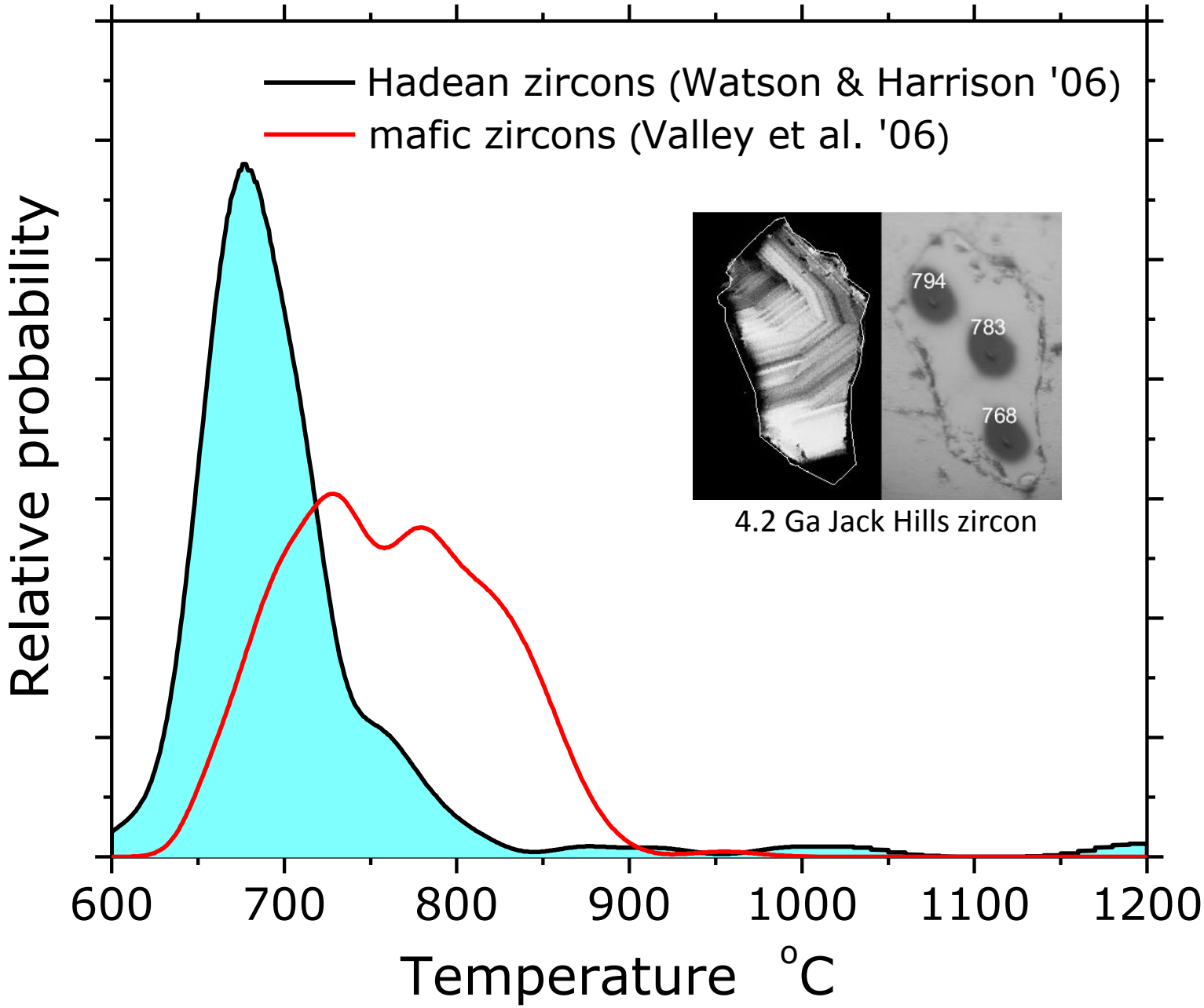
Titanium concentration is sensitive to formation temperature!



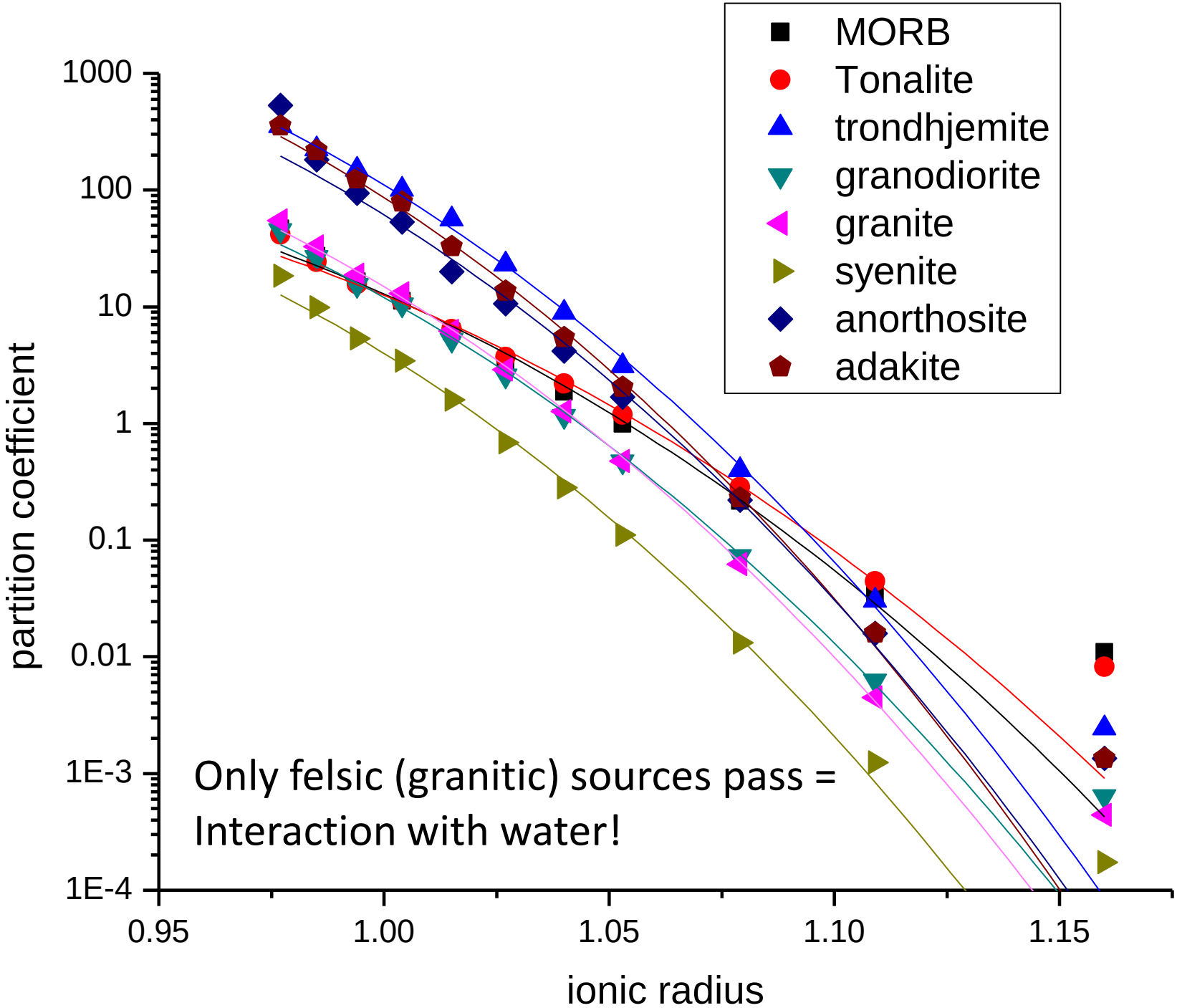
4.2 Ga Jack Hills zircon

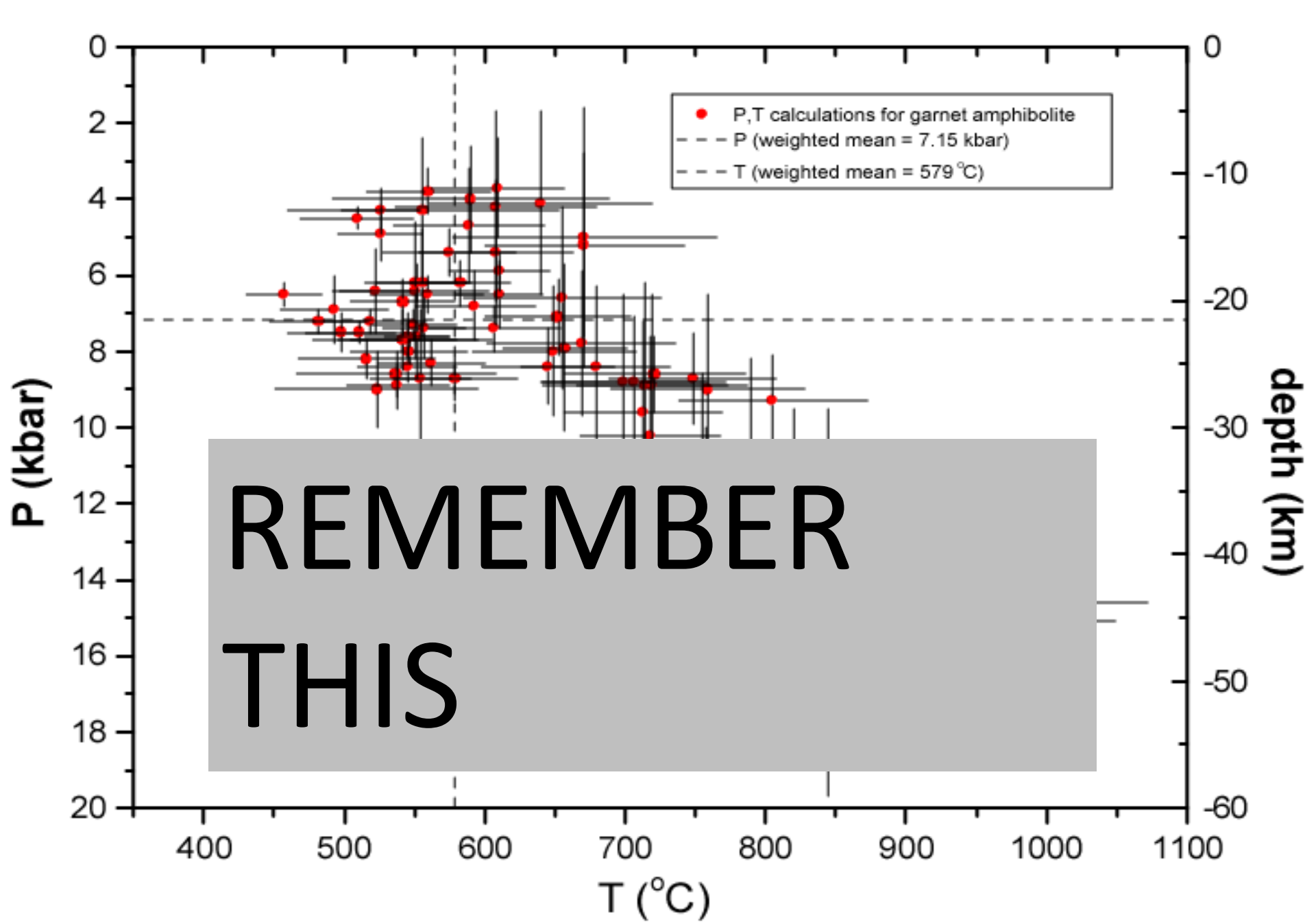
Courtesy: E.B. Watson

Minerals are what they eat

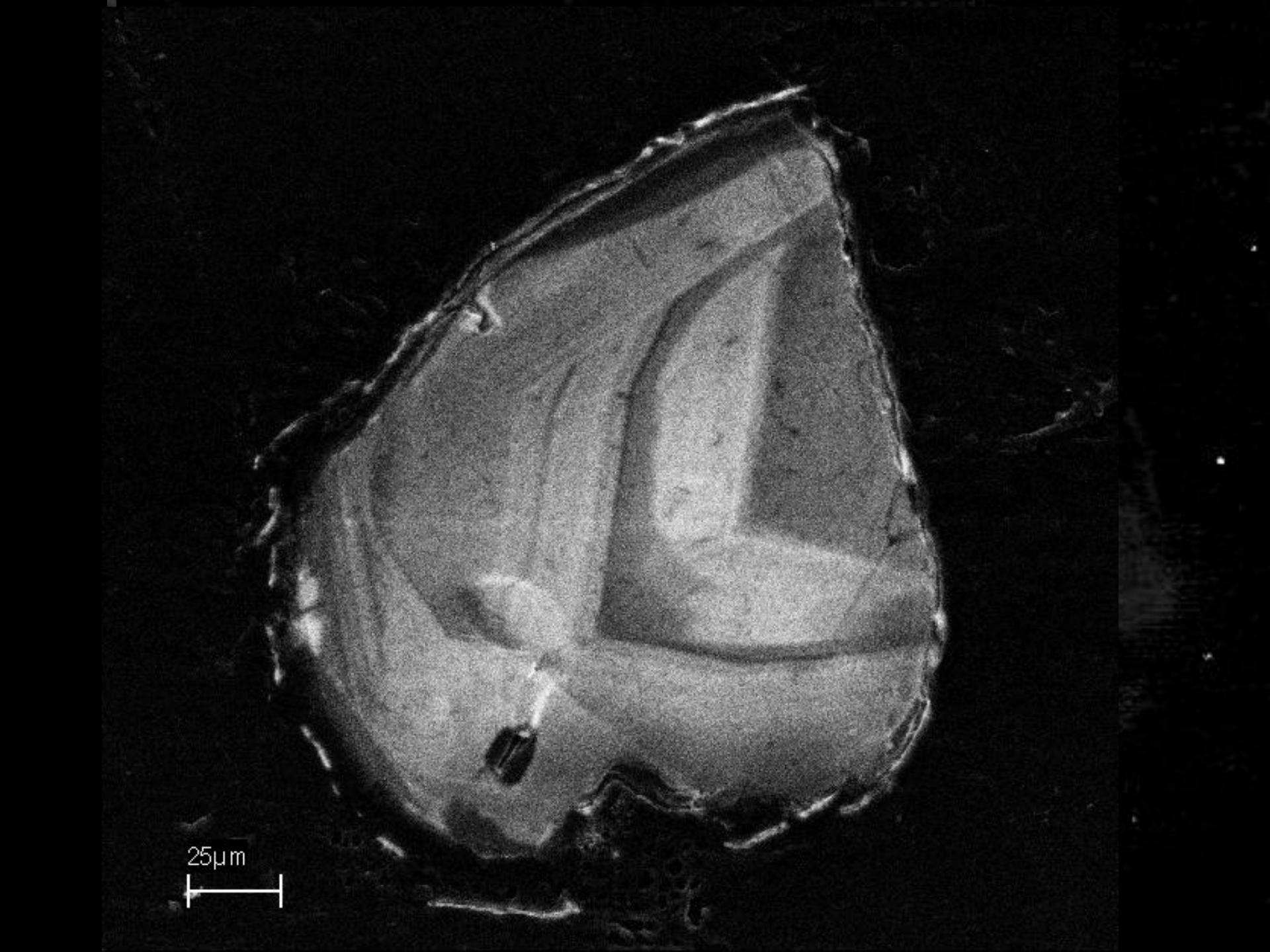


Courtesy: E.B. Watson

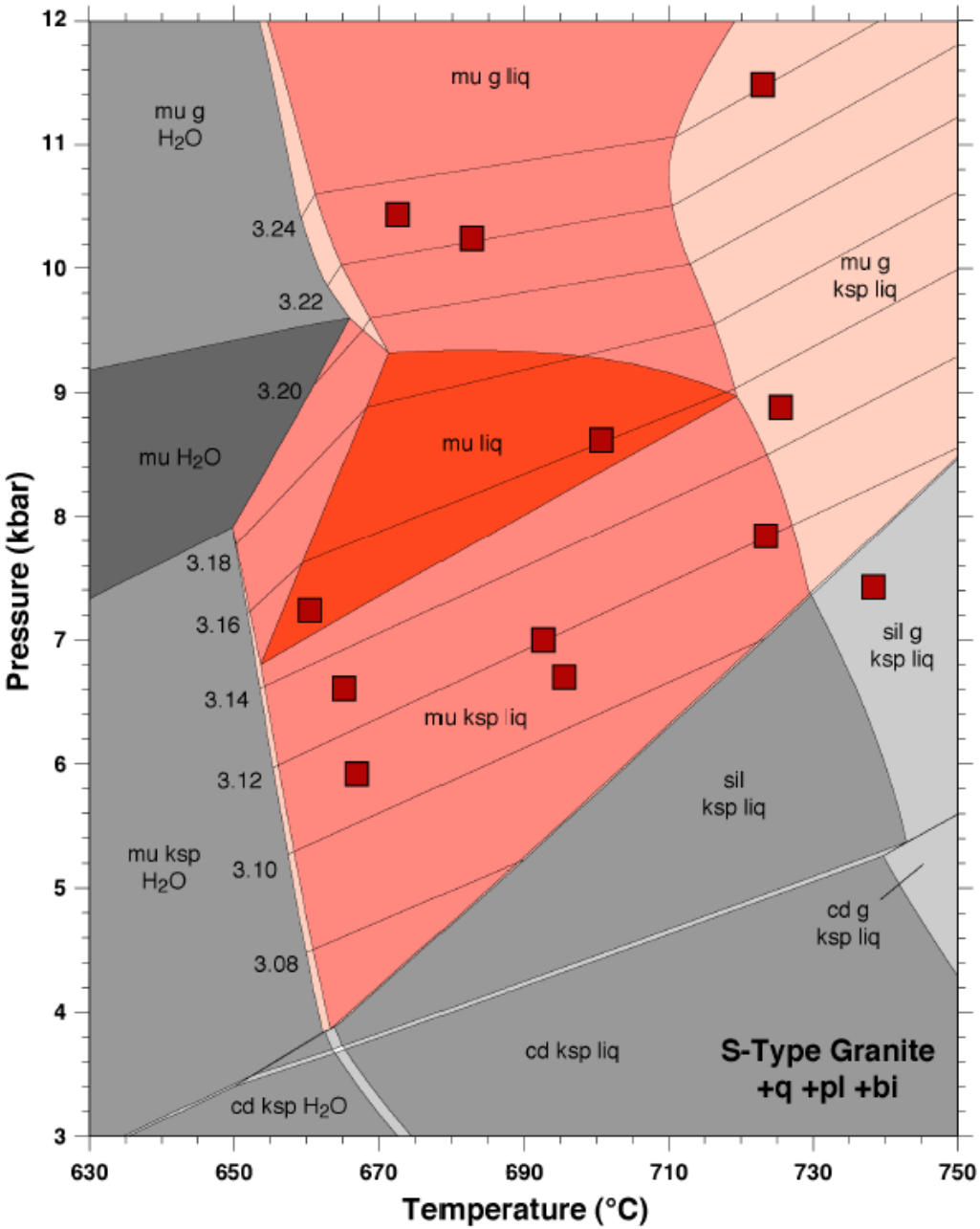

MORB
Tonalite
trondhjemite
granodiorite
granite
syenite
anorthosite
adakite
partition coefficient
1000
100
10
1
0.1
0.01
1E-3
1E-4
0.95
1.00
1.05
1.10
1.15
ionic radius
Only felsic (granitic) sources pass =
Interaction with water!

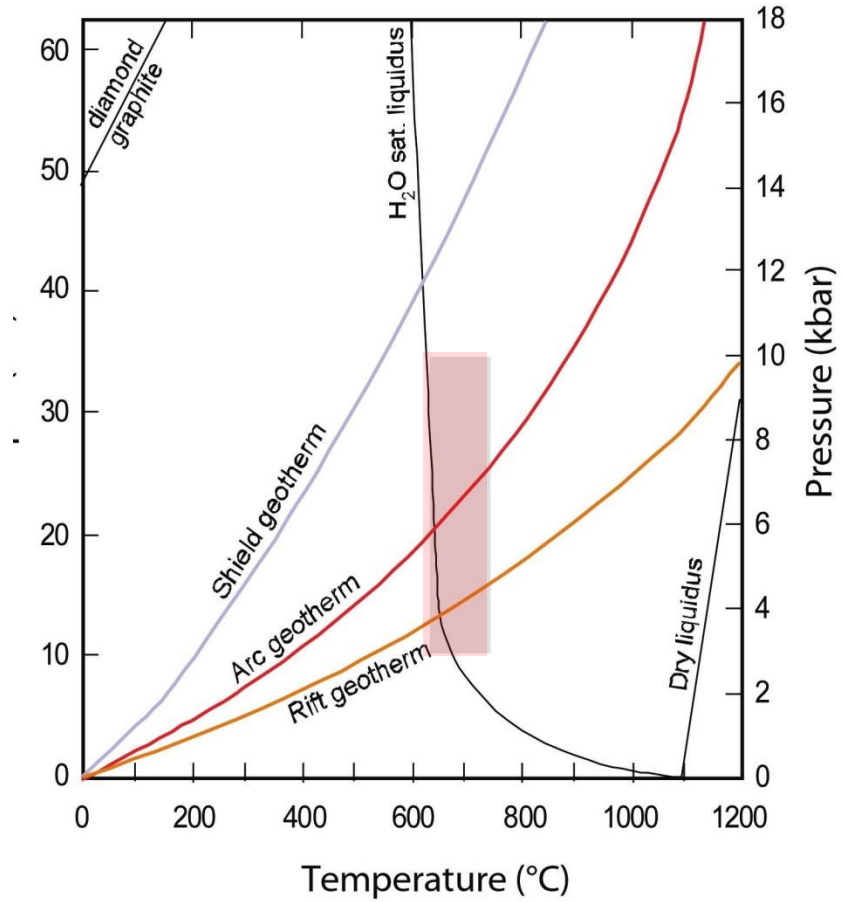


Calibrations of gt-hbl-plag-qtz mineral assemblages (Dale et al. *Contr. Min. Pet.* (2000) 140: 353-362)


25µm

RECALL WHAT I SAID ABOUT GARNET-AMPHIBOLITES and the P-T field



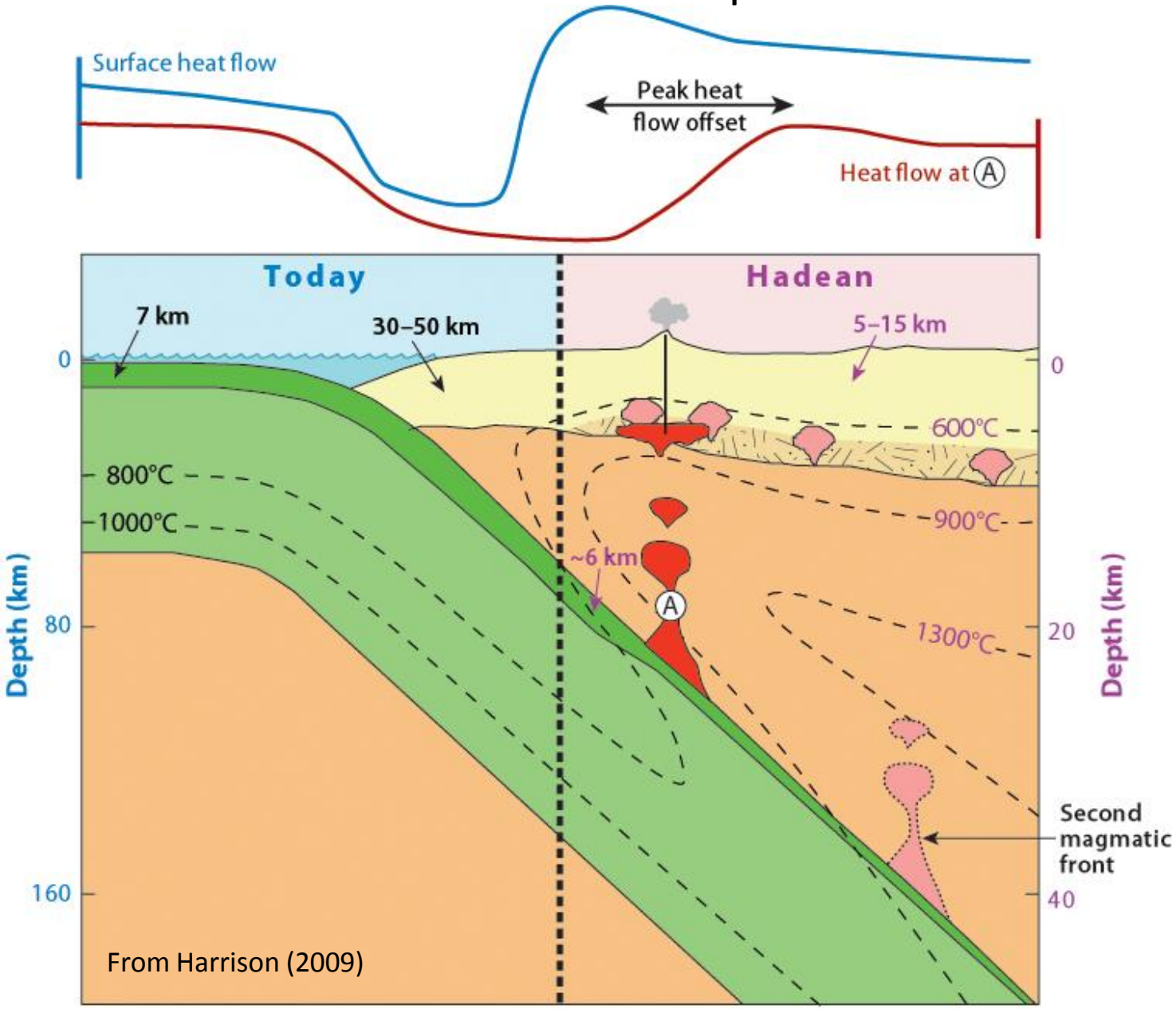


Hadean zircon inclusions

Consistent with plate boundary processes

Hopkins et al. (2008, 2010)

In sum, water – rock interactions are a primordial phenomenon on Earth (These geochemical environments on Earth pre-date bombardment)



COMPOSITION

$ZrSiO_4$

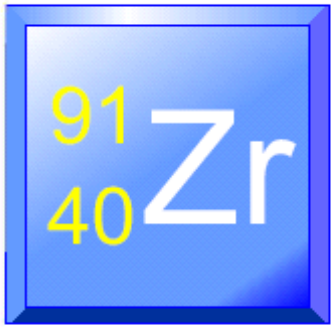
Hf: typically 1 - 1.5%

U: 10 - 1000s ppm

Th: 10 - 1000s ppm

Pb: ~ 1 ppb - 100s of ppm (depends on age!)

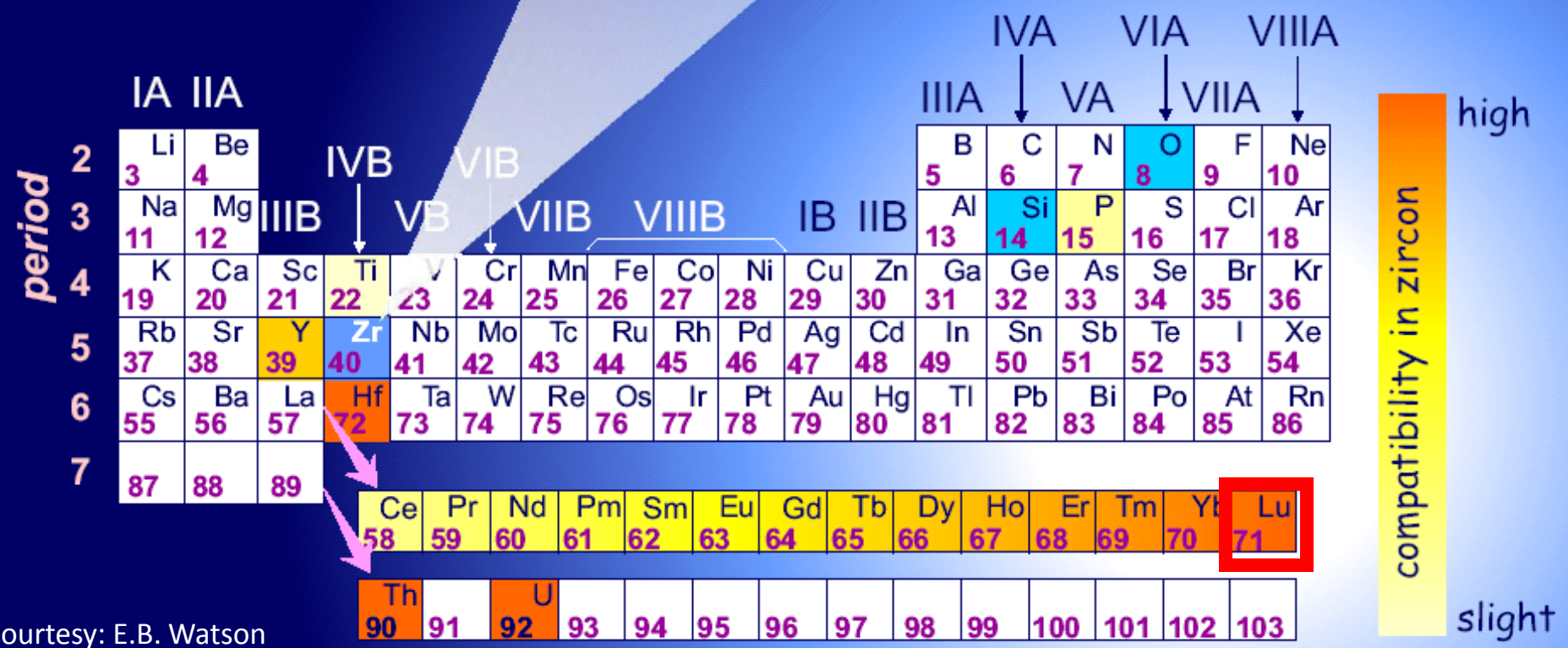
Σ rare earths (+Y): 10s of ppm to 10%



abundance: (silicate Earth) ~10 ppm

valence state: +4

ionic radius: 0.92Å



Courtesy: E.B. Watson

On-going collaborations with J. Blichert-Toft and F. Albarède (ENS Lyon)

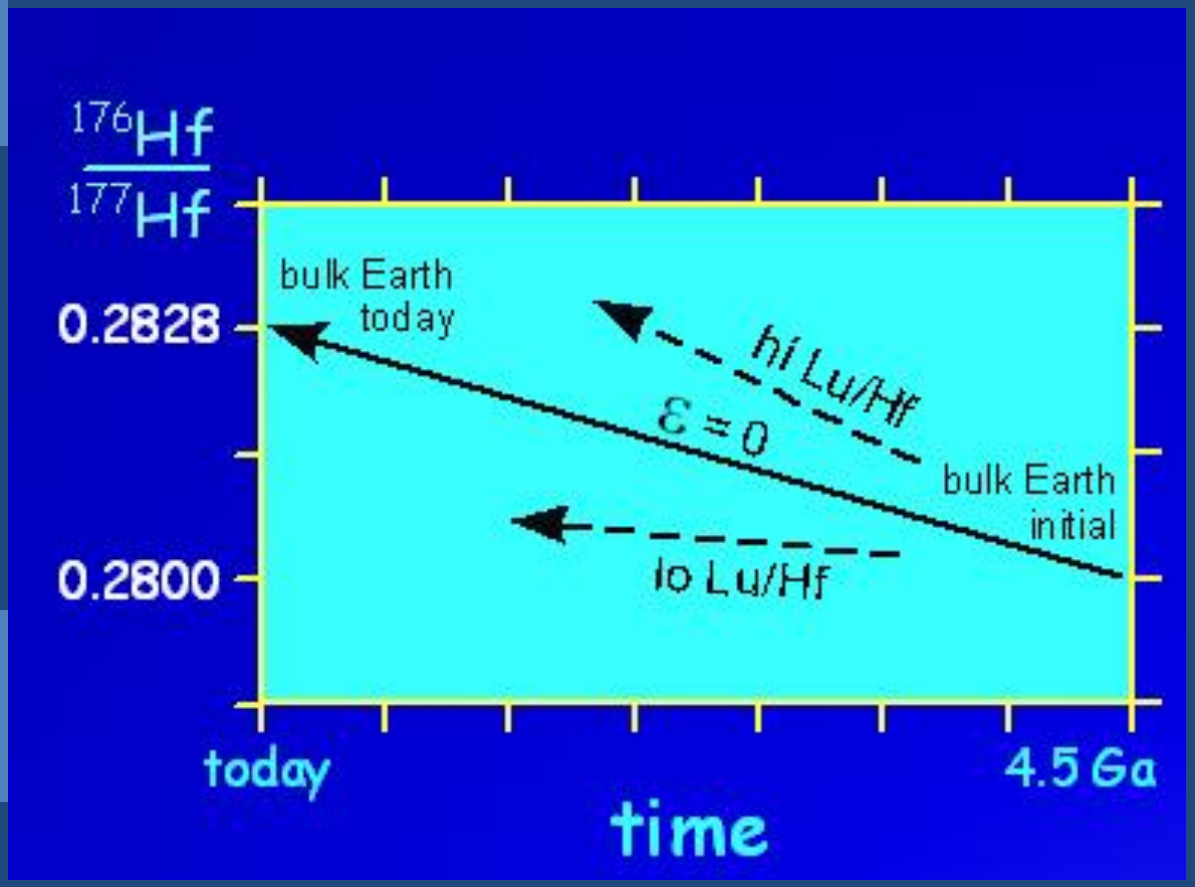
Lu/Hf zircon studies - concepts

^{176}Lu decays to ^{176}Hf with t½ = 37 Ga

e_{Hf} denotes deviations in ^{176}Hf/^{177}Hf from Bulk Earth (in parts per 10^4)

^{177}Hf is the stable reference isotope

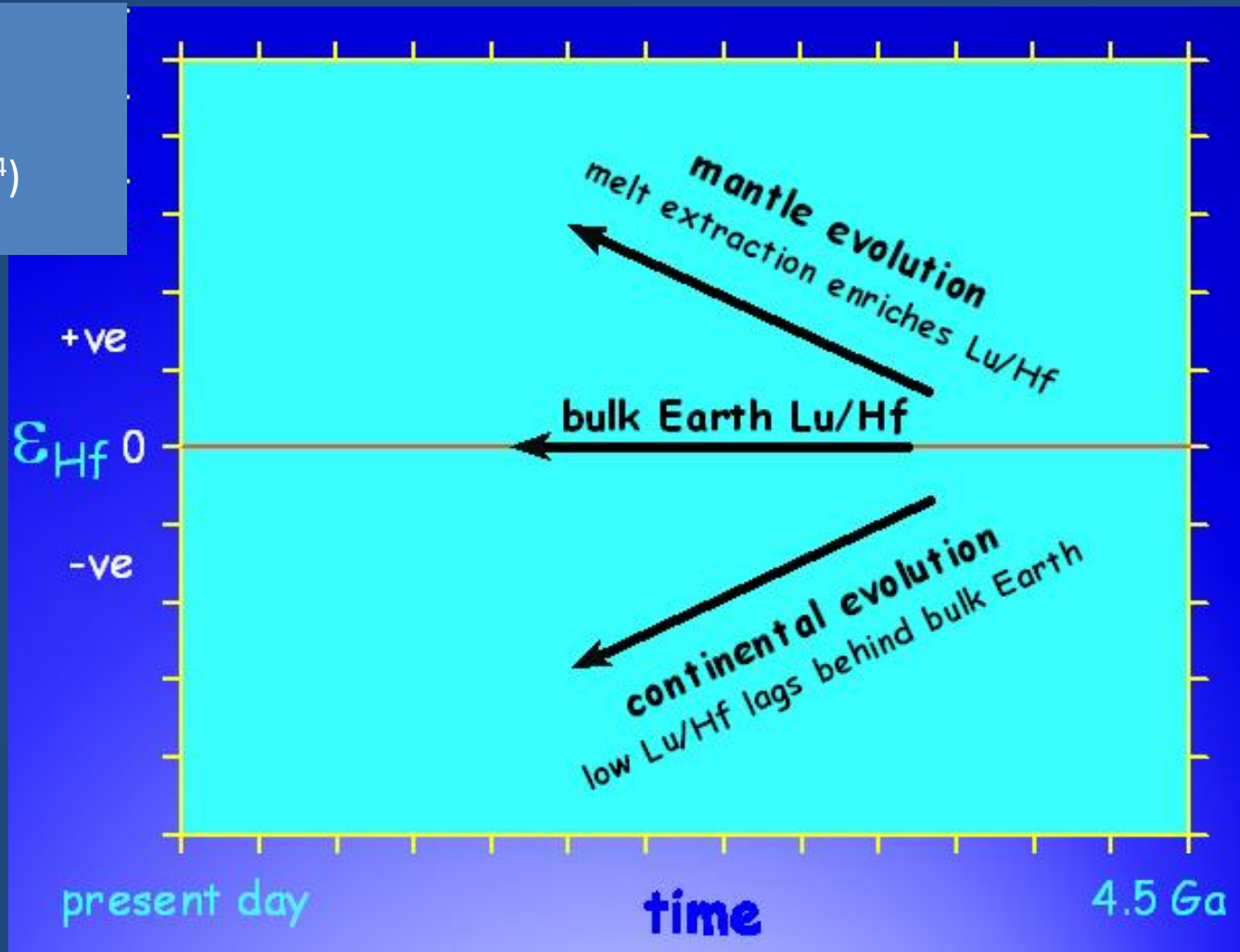
Conventionally expressed relative to epsilon



Lu/Hf studies tell us about the origin and evolution of the crust!

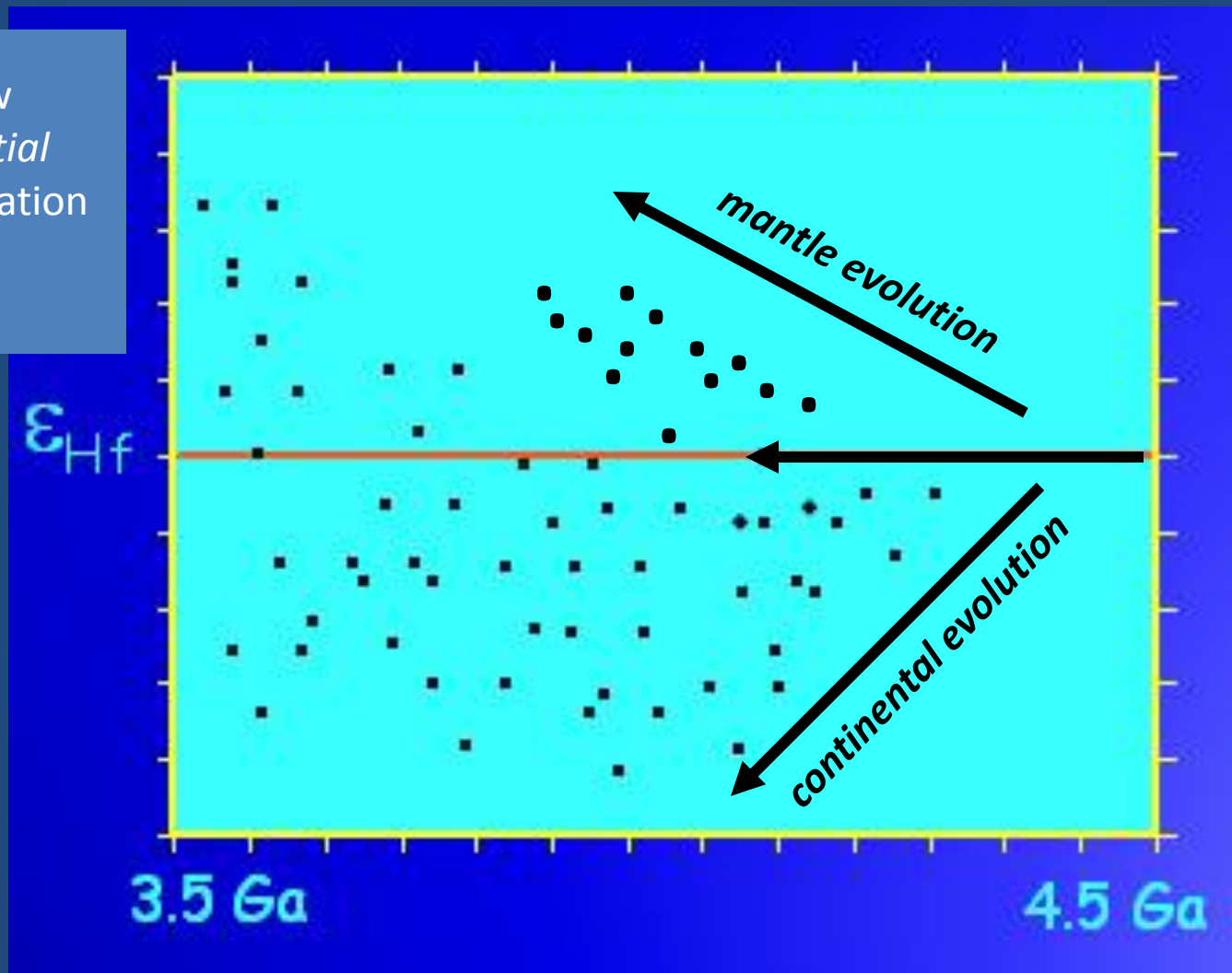
^{176}Lu decays to ^{176}Hf with t½ = 37 Ga

e_{Hf} denotes deviations in ^{176}Hf/^{177}Hf from Bulk Earth (in parts per 10^4)



Lu/Hf studies

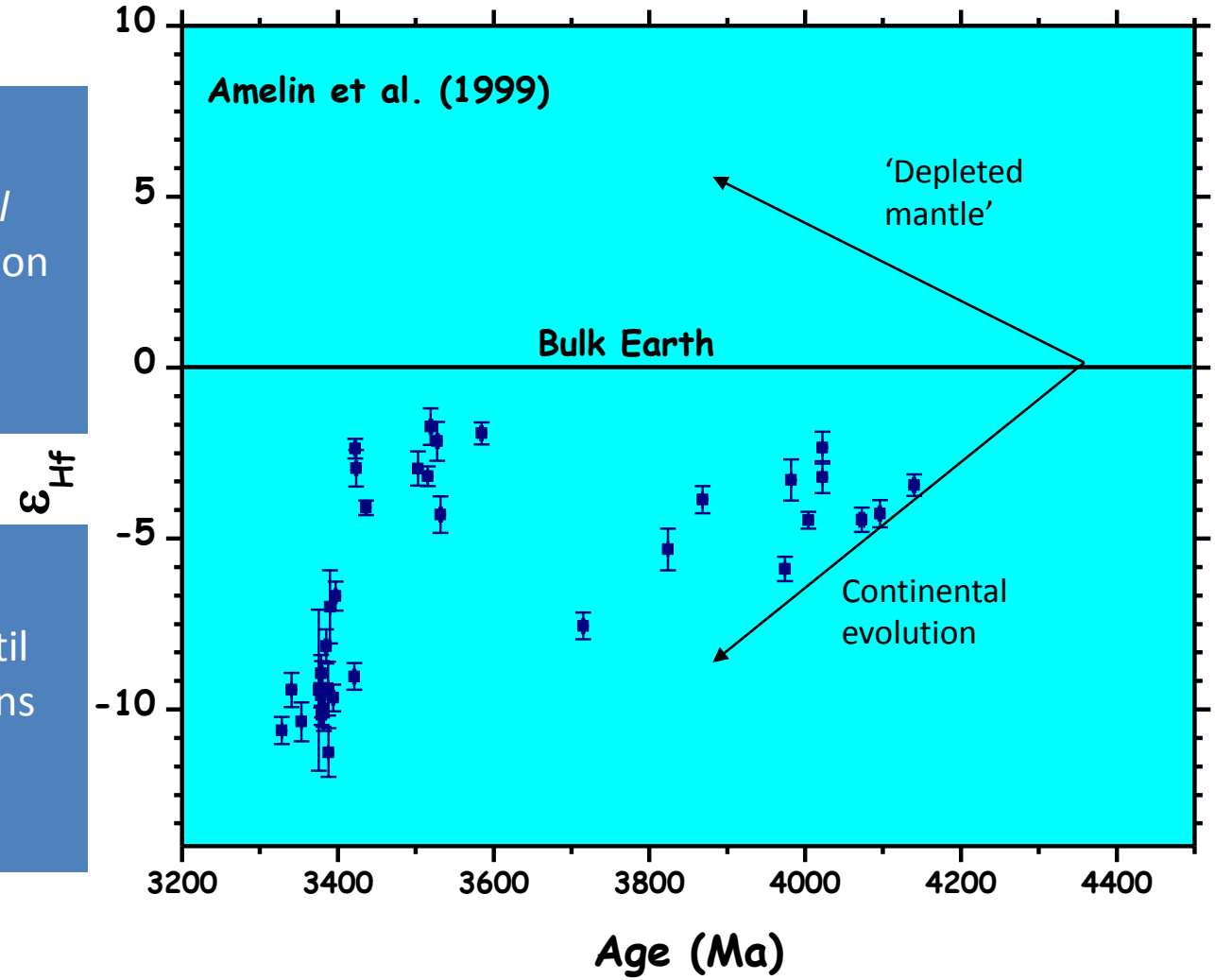
Zircons have extremely low Lu/Hf, thus they record *initial* $^{176}Hf/^{177}Hf$ at time of formation established by Pb ages



Lu/Hf studies

Zircons have extremely low Lu/Hf, thus they record *initial* $^{176}Hf/^{177}Hf$ at time of formation established by Pb ages

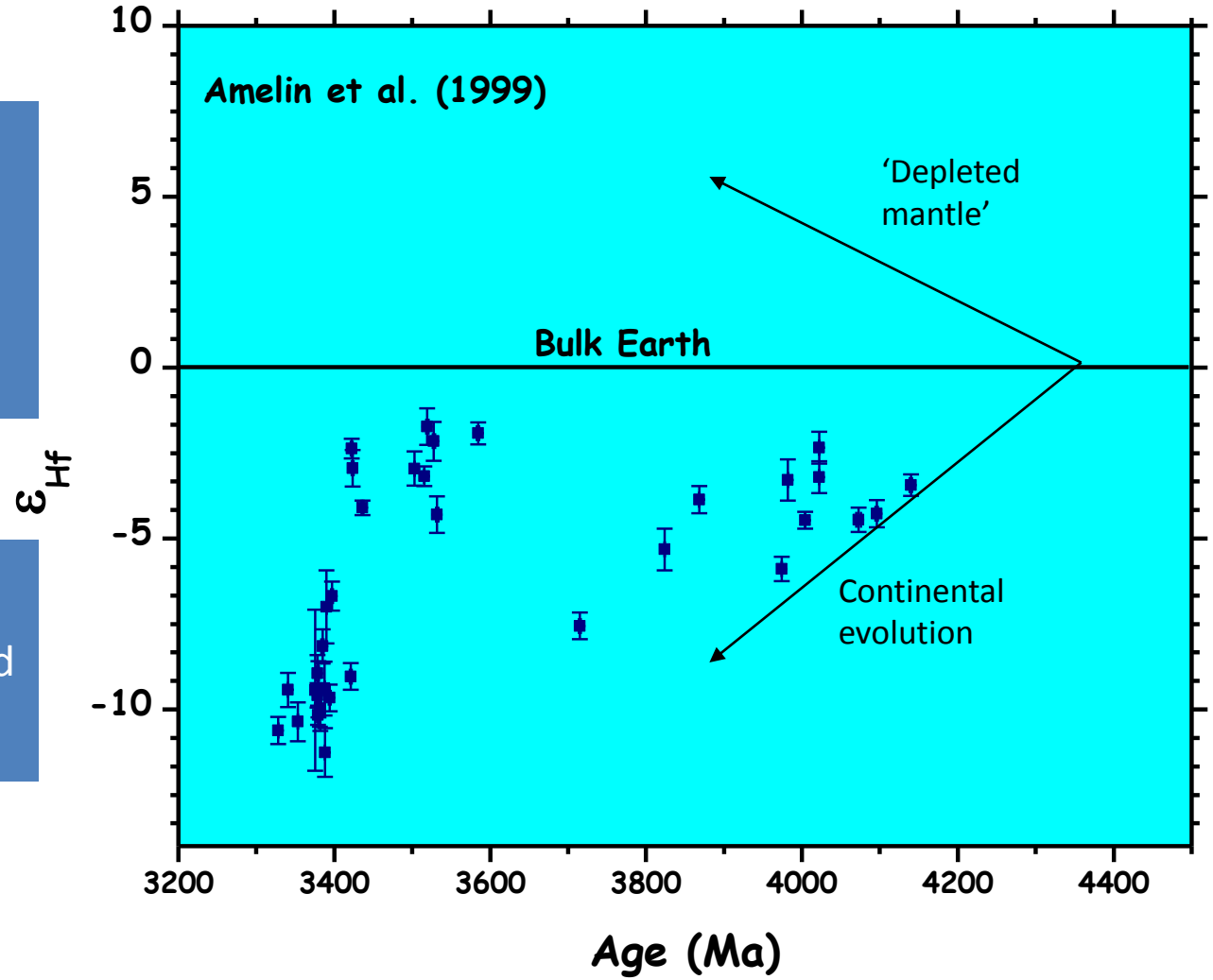
We have long **assumed** that continents didn't emerge until ca. 4 Ga, but earlier depletions may have been remixed



Lu/Hf studies

Jack Hills transcend ambiguity; they are pieces of crust sequestered up to ca. 4.4 Ga

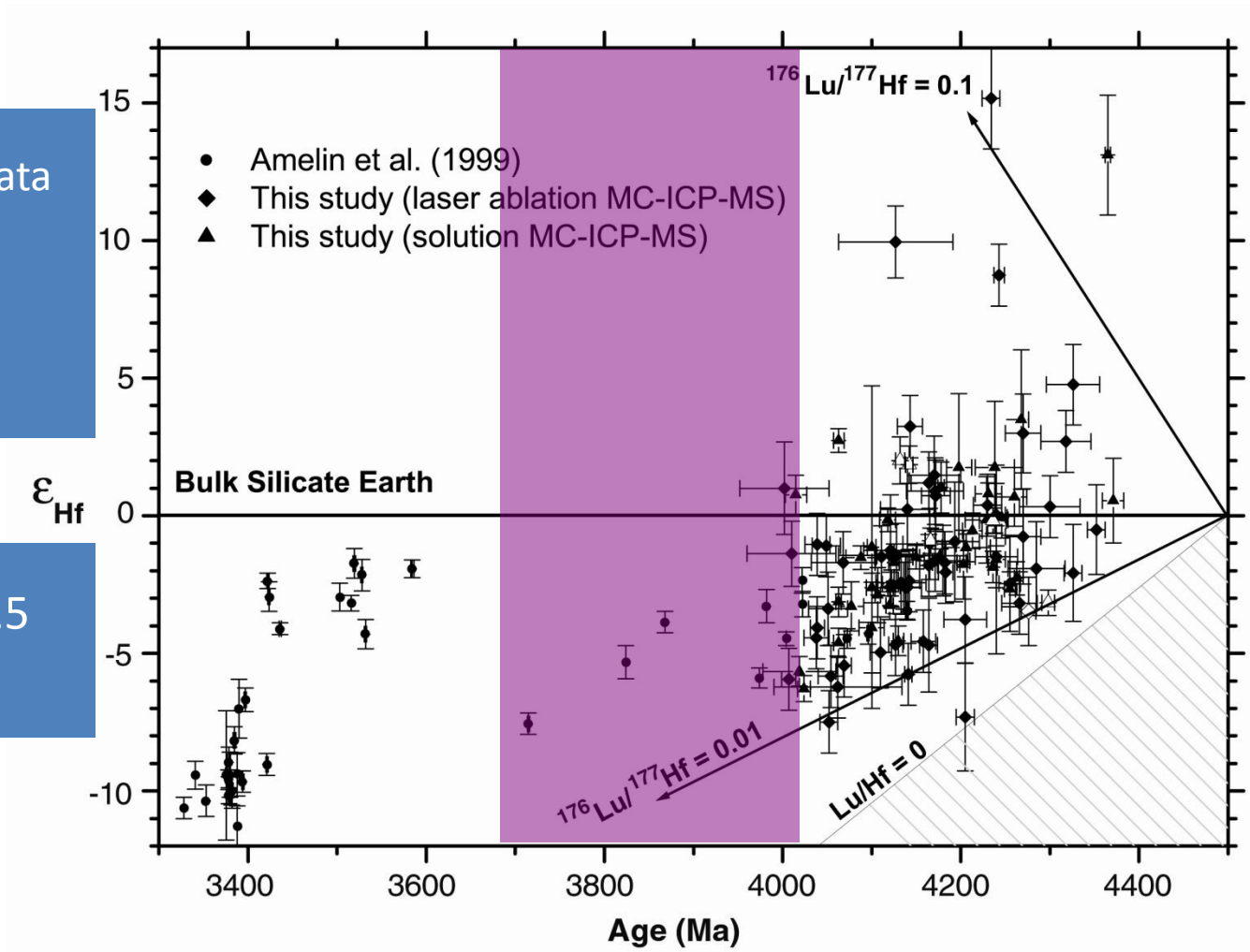
Amelin et al. (1999) data interpreted as re-melting of old crust



Lu/Hf studies

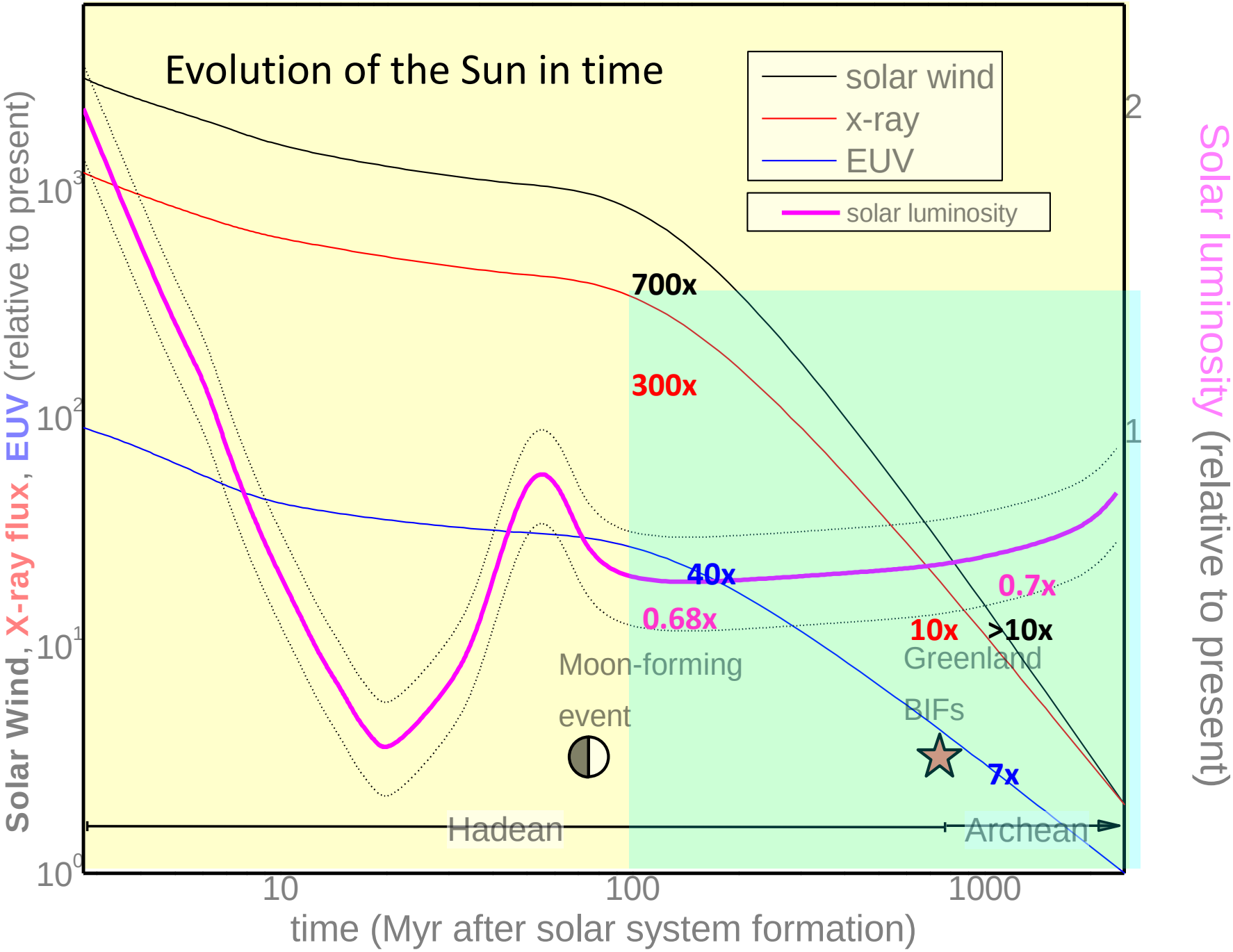
Jack Hills initial $^{176}Hf/^{177}Hf$ data indicate very large negative **AND** positive e_{Hf} deviations from Bulk Earth

Formation of crust by ~ 4.5 Ga

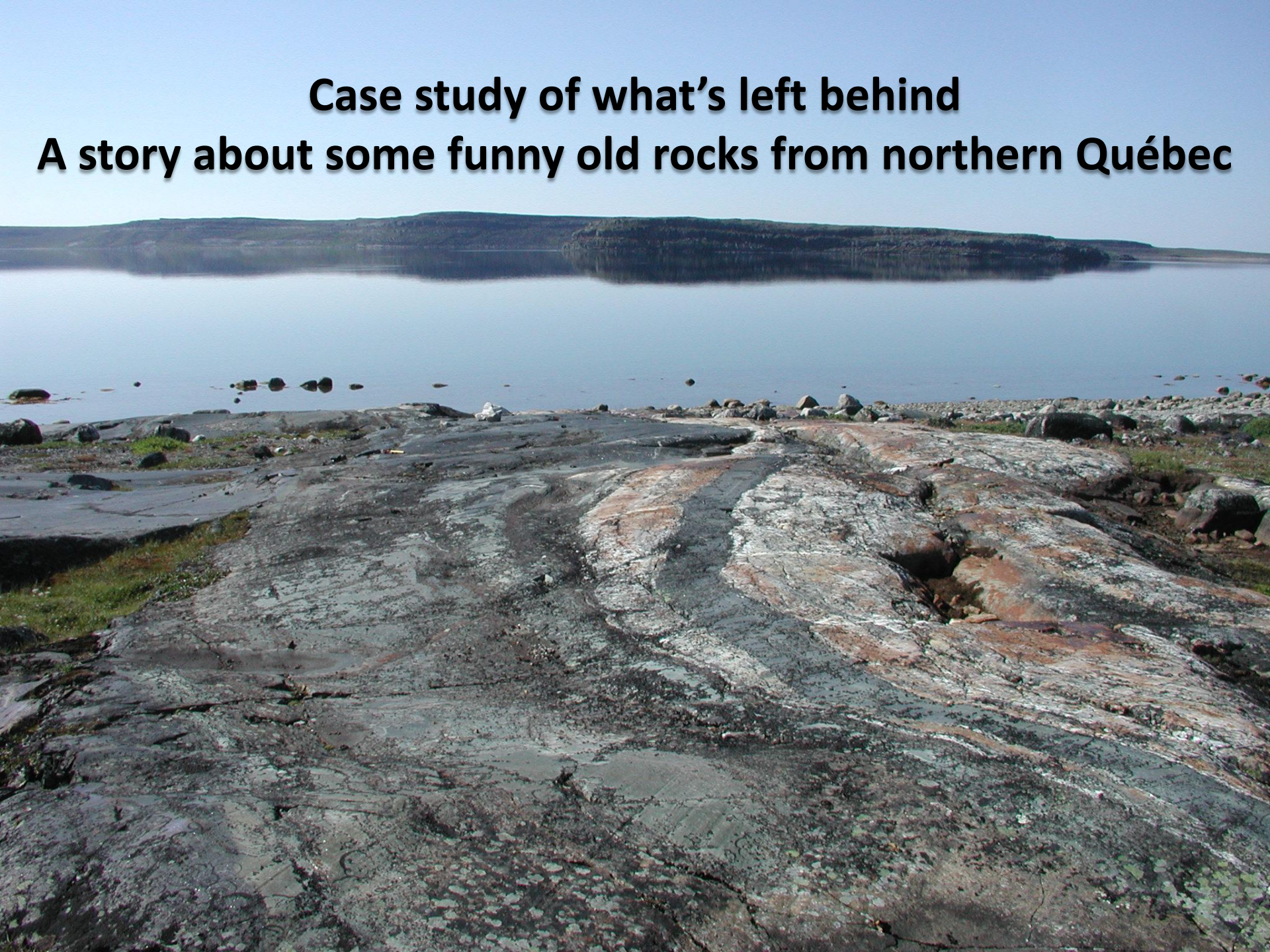


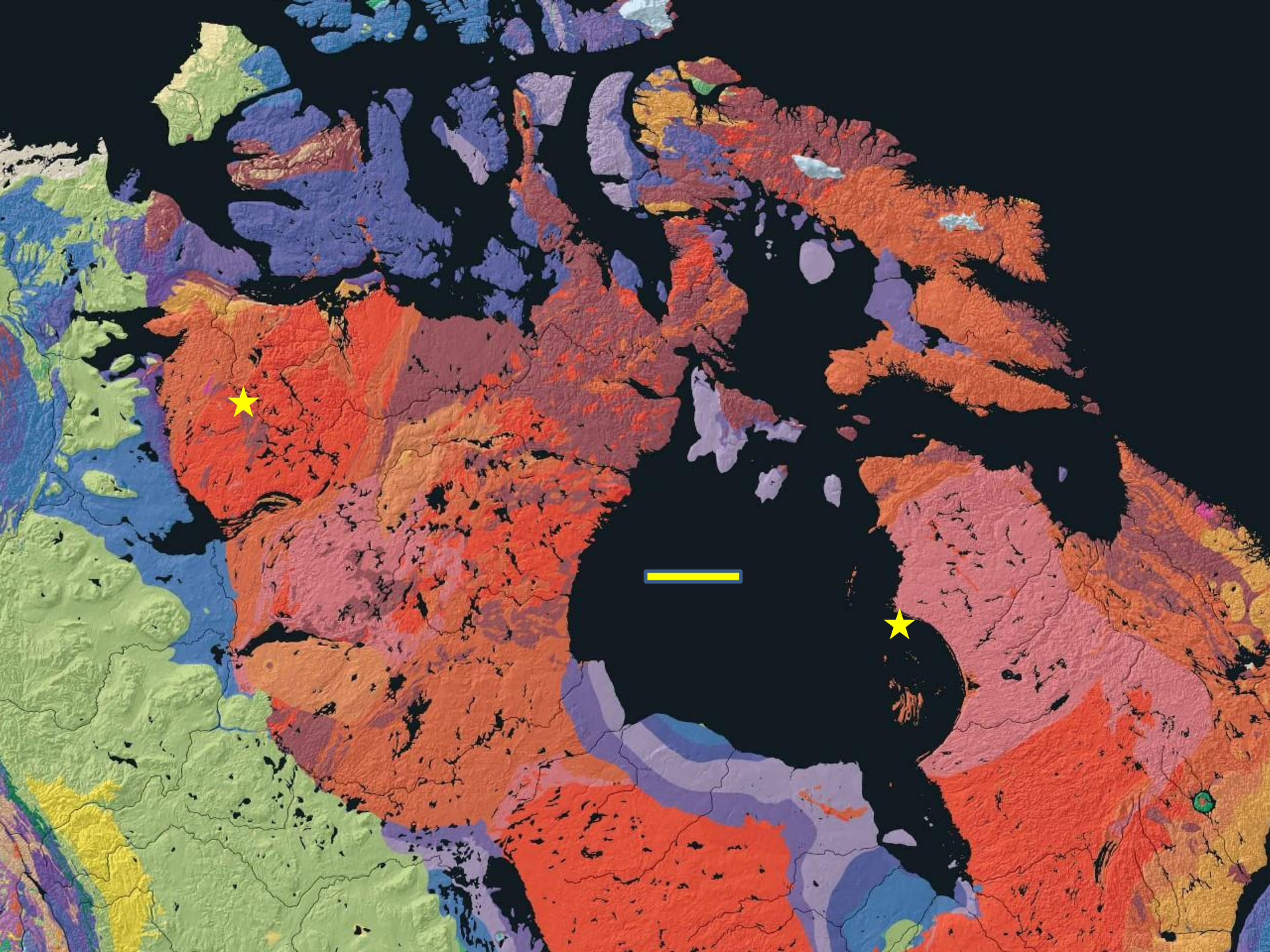
Harrison TM, Blichert-Toft J, Muller W, Albarede, F, Holden, P, Mojzsis, SJ Heterogeneous Hadean hafnium: Evidence of continental crust at 4.4 to 4.5 Ga SCIENCE 310 (5756): 1947-1950 DEC 23 2005

Analytical models of Ribas (2007)



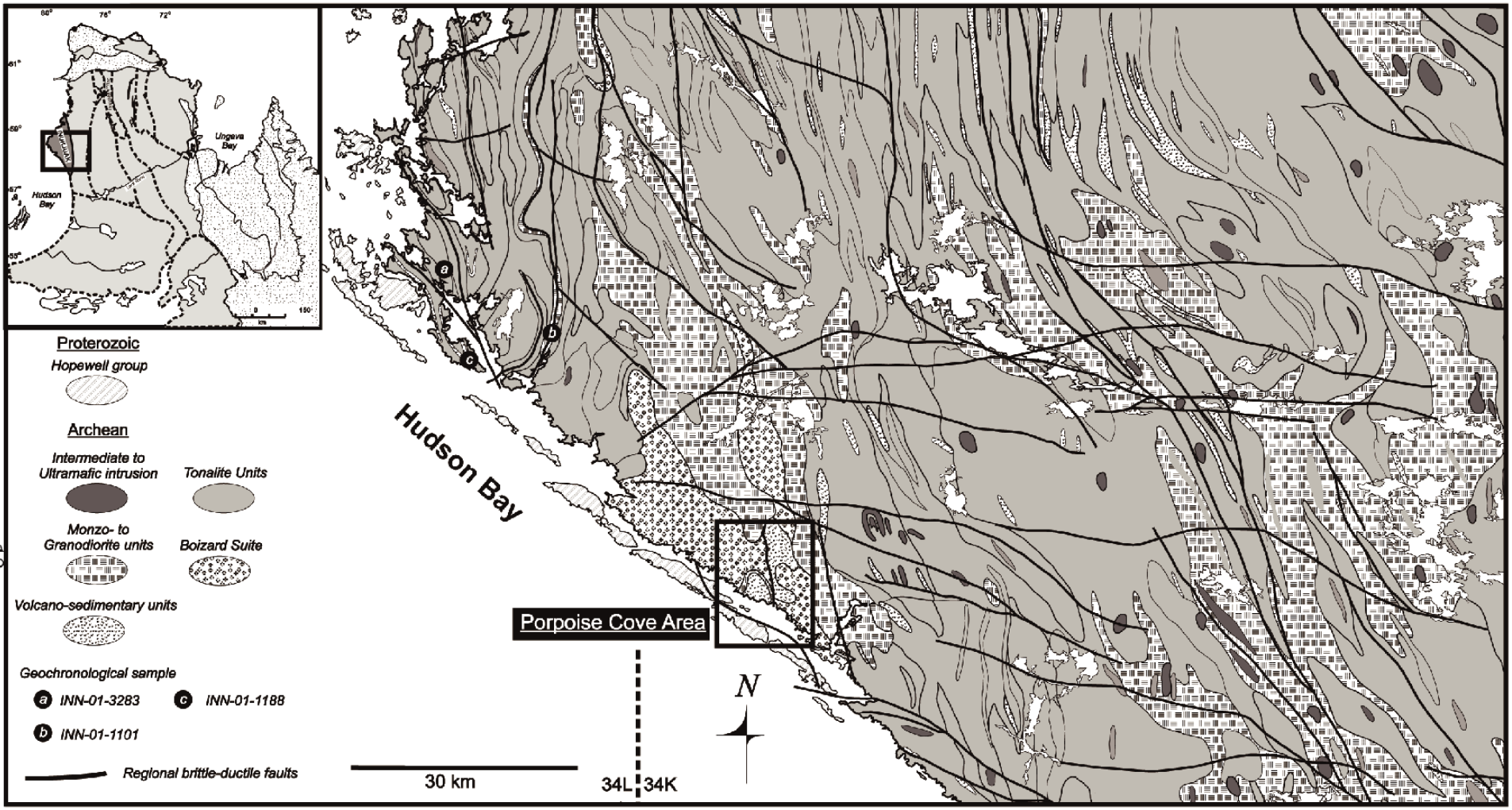
Case study of what's left behind
A story about some funny old rocks from northern Québec





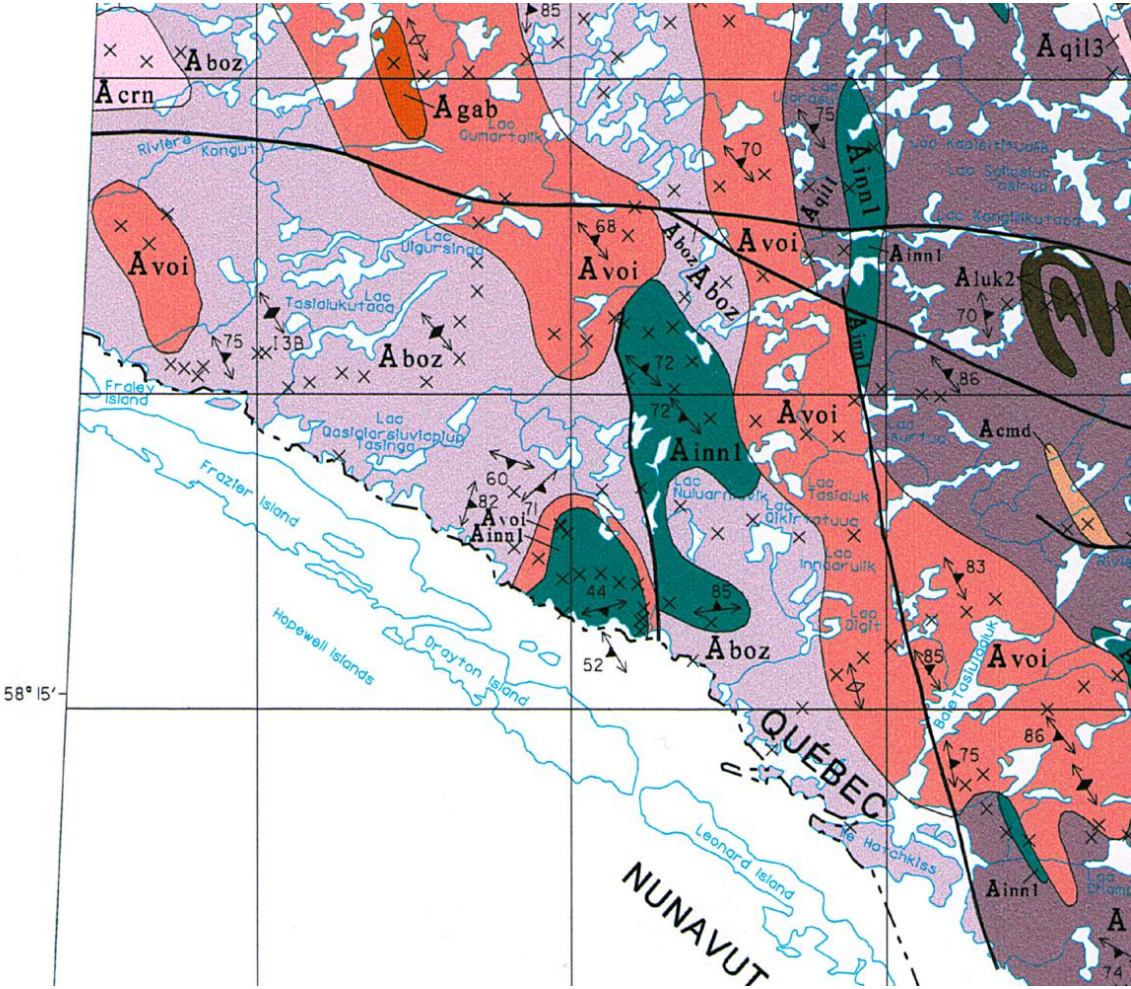
Simard et al. (2001)

Inukjuak Domain: oldest sediments



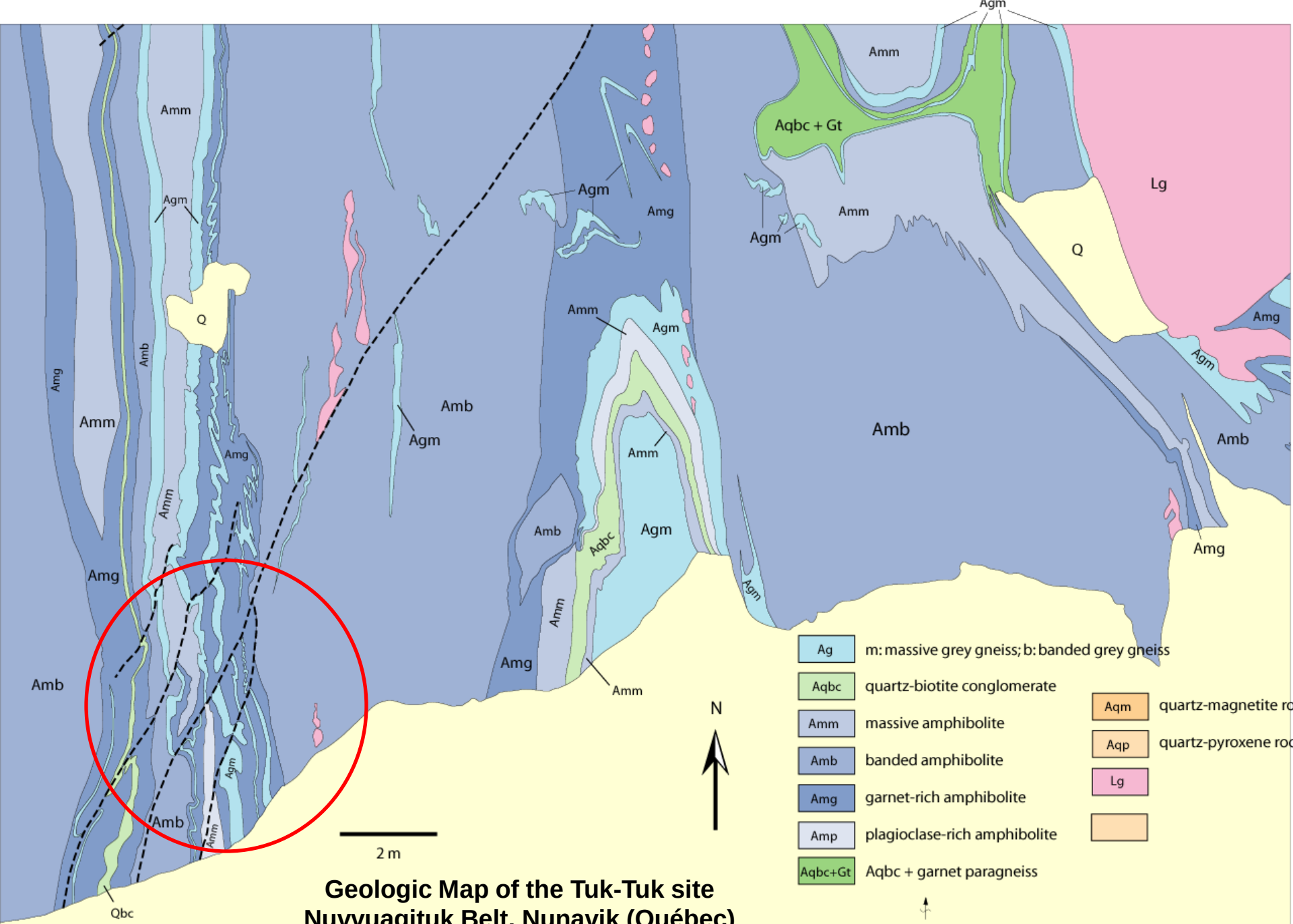
Tour of the locality

- **Excellent exposure**
- **Simple collection of rock types, but they are strongly deformed and metamorphosed**



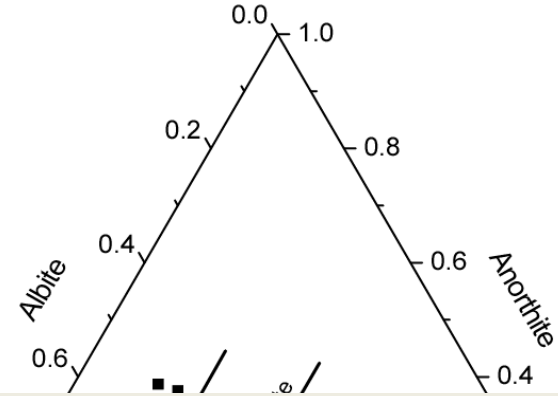
From GEOTOP, 2001

We term this place the: Nuvvuagittuq supracrustal belt or "NSB"

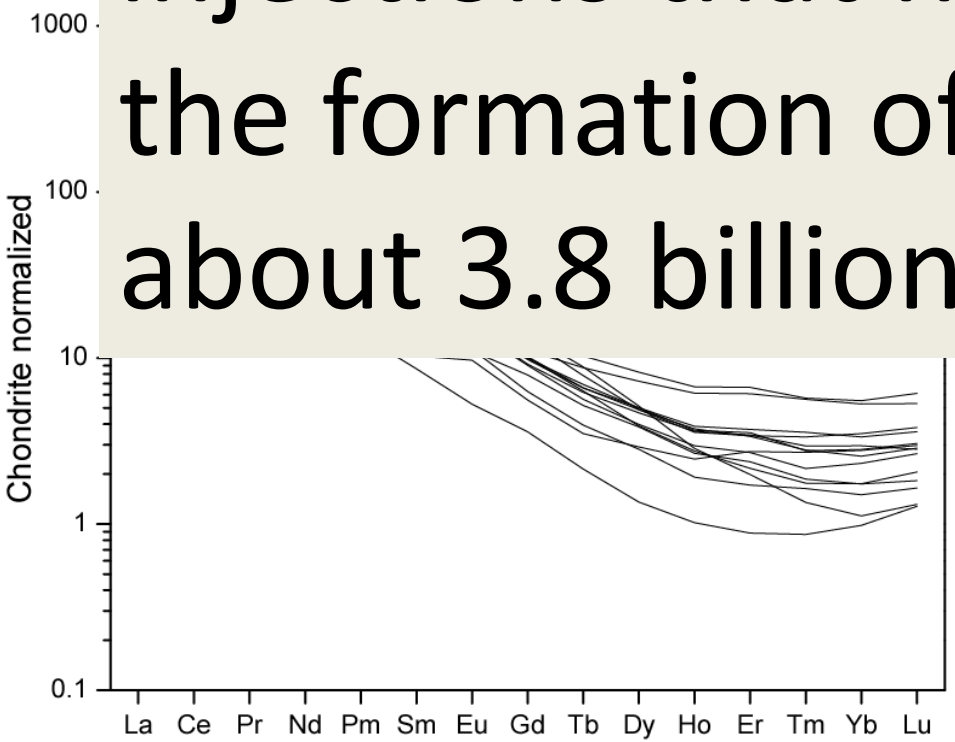


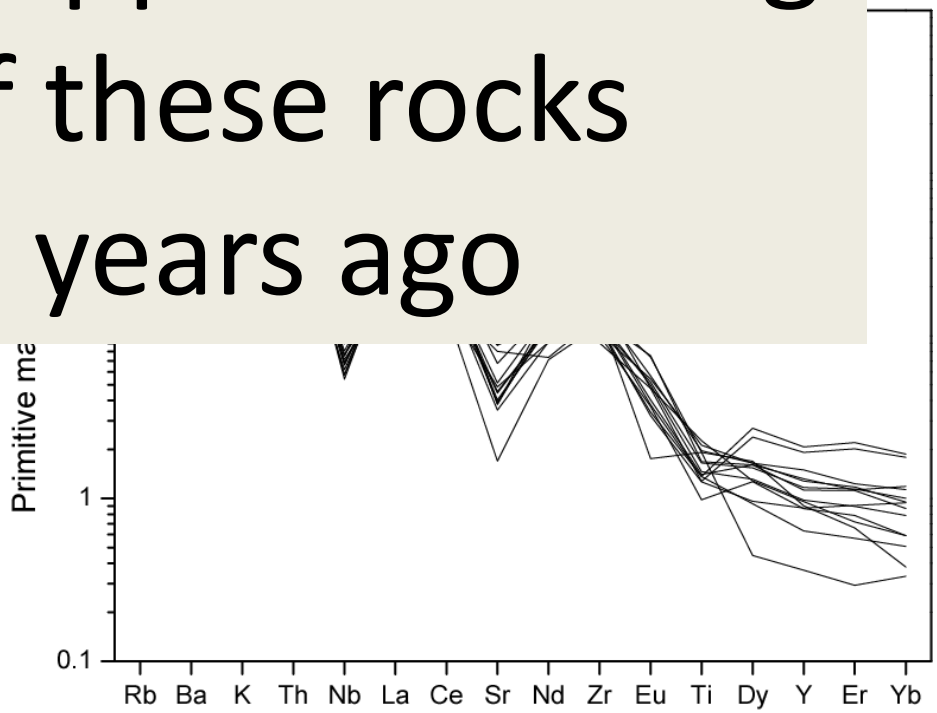
Geologic Map of the Tuk-Tuk site
Nuvvuagituk Belt, Nunavik (Québec)
scale 1:50

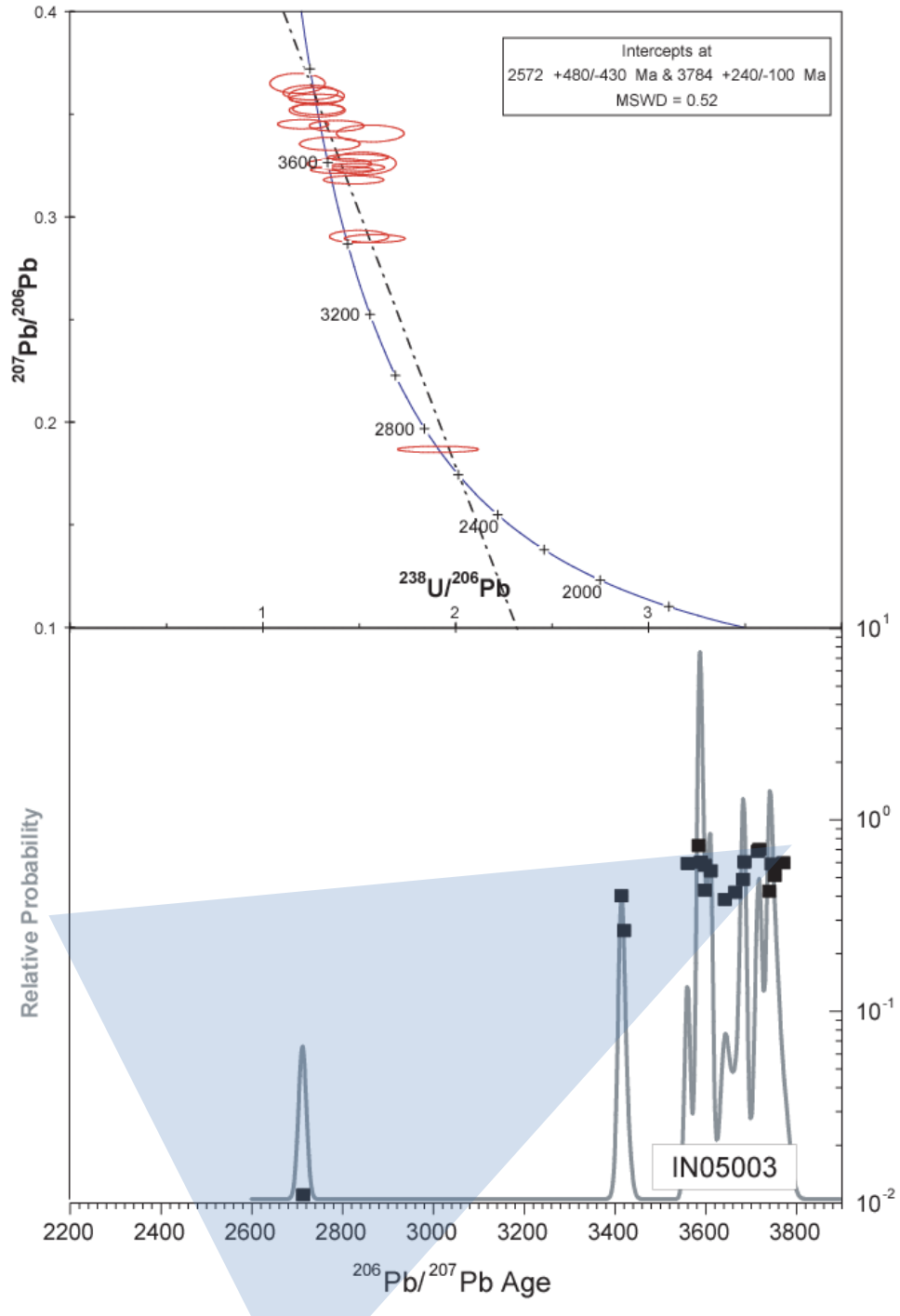
From Cates and Mojzsis, 2007

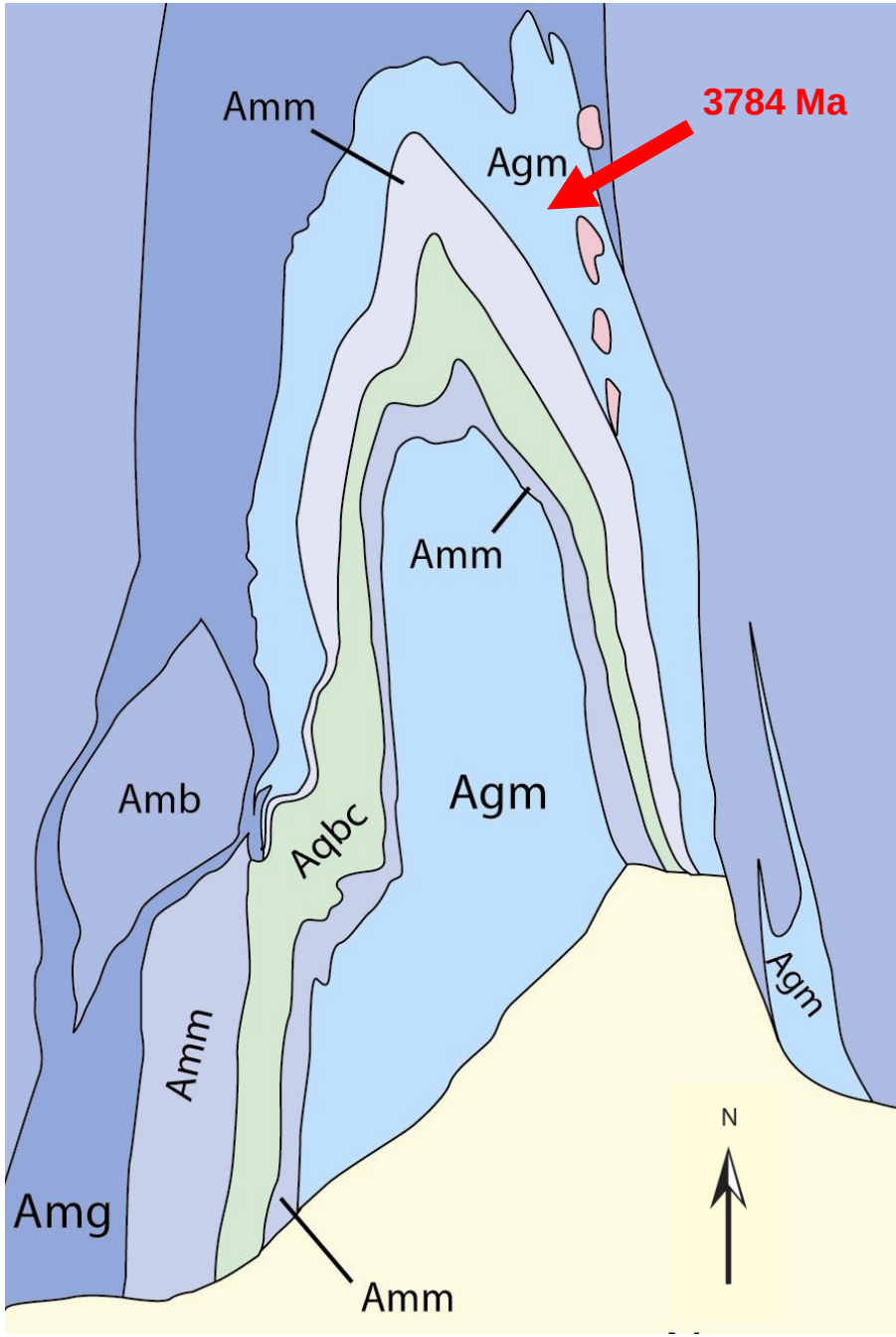


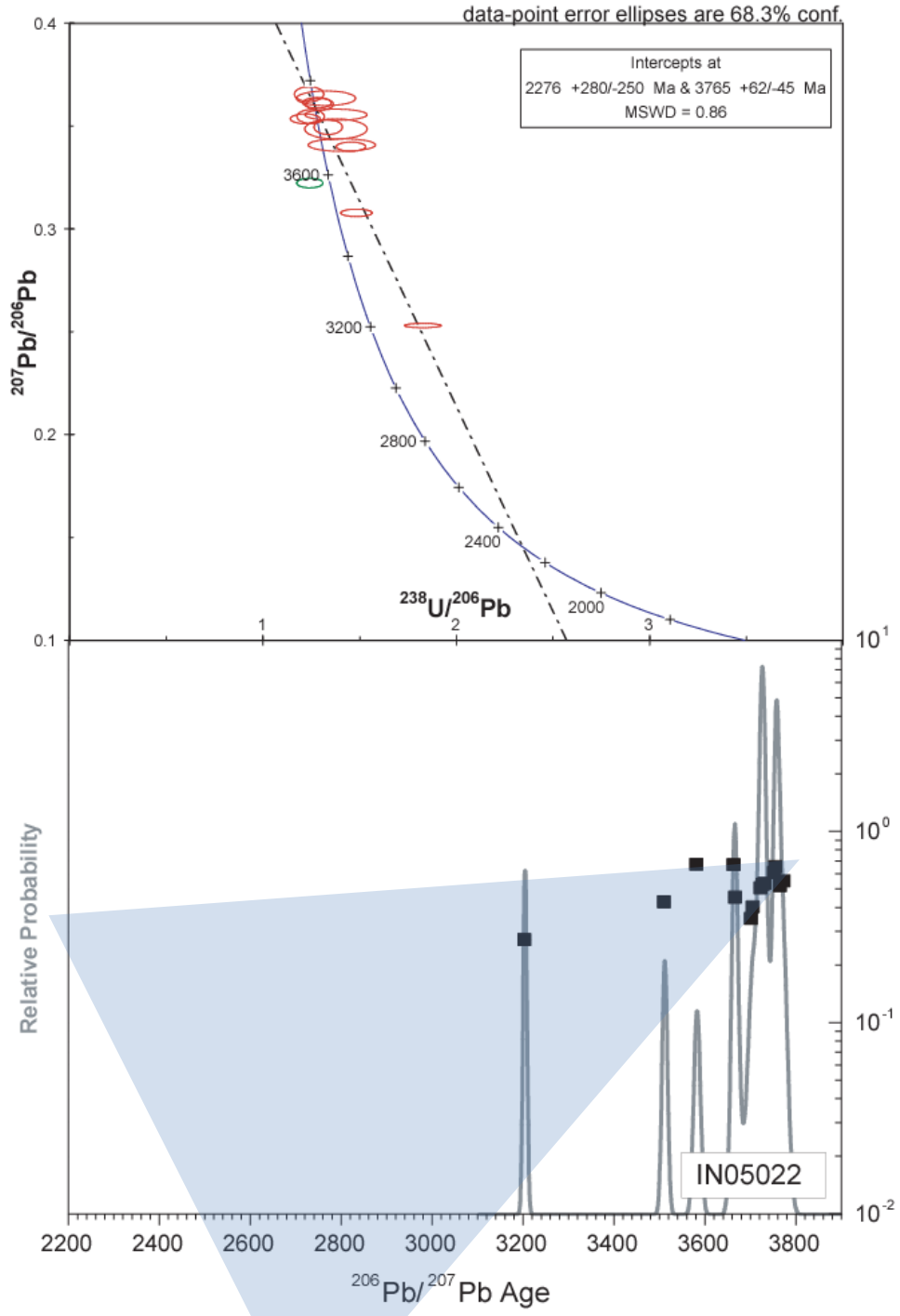
These were small granitic melt injections that happened during the formation of these rocks about 3.8 billion years ago

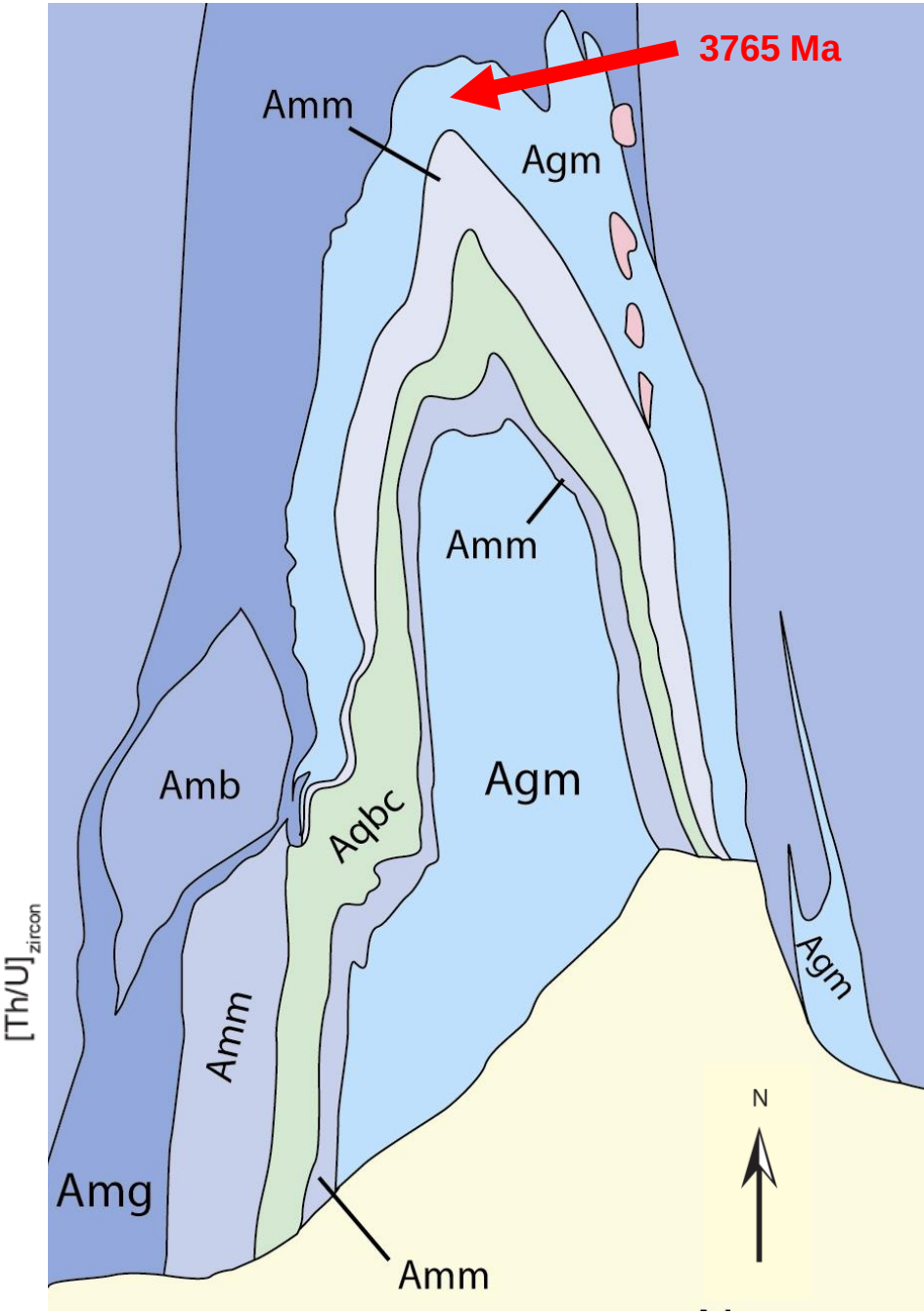


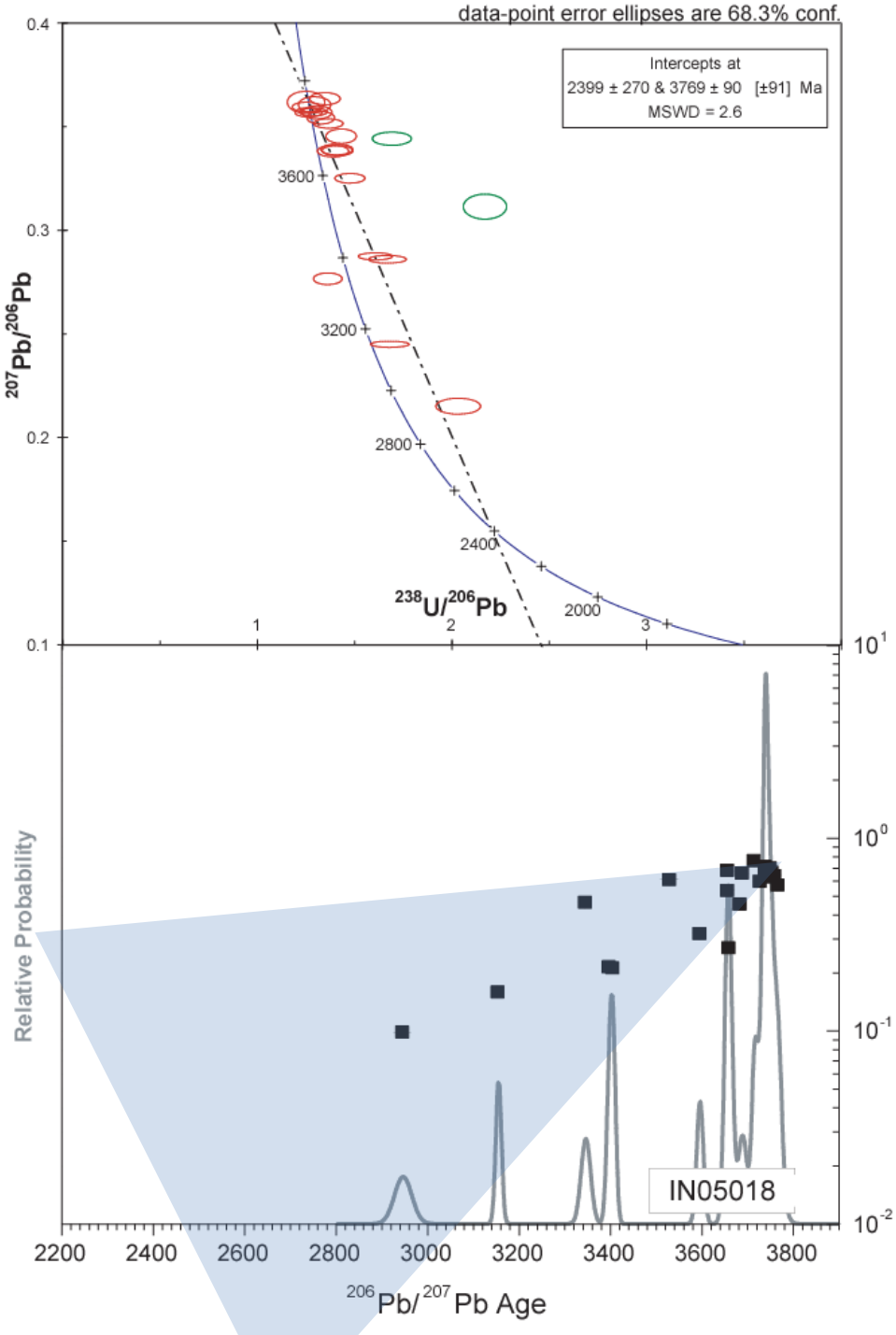


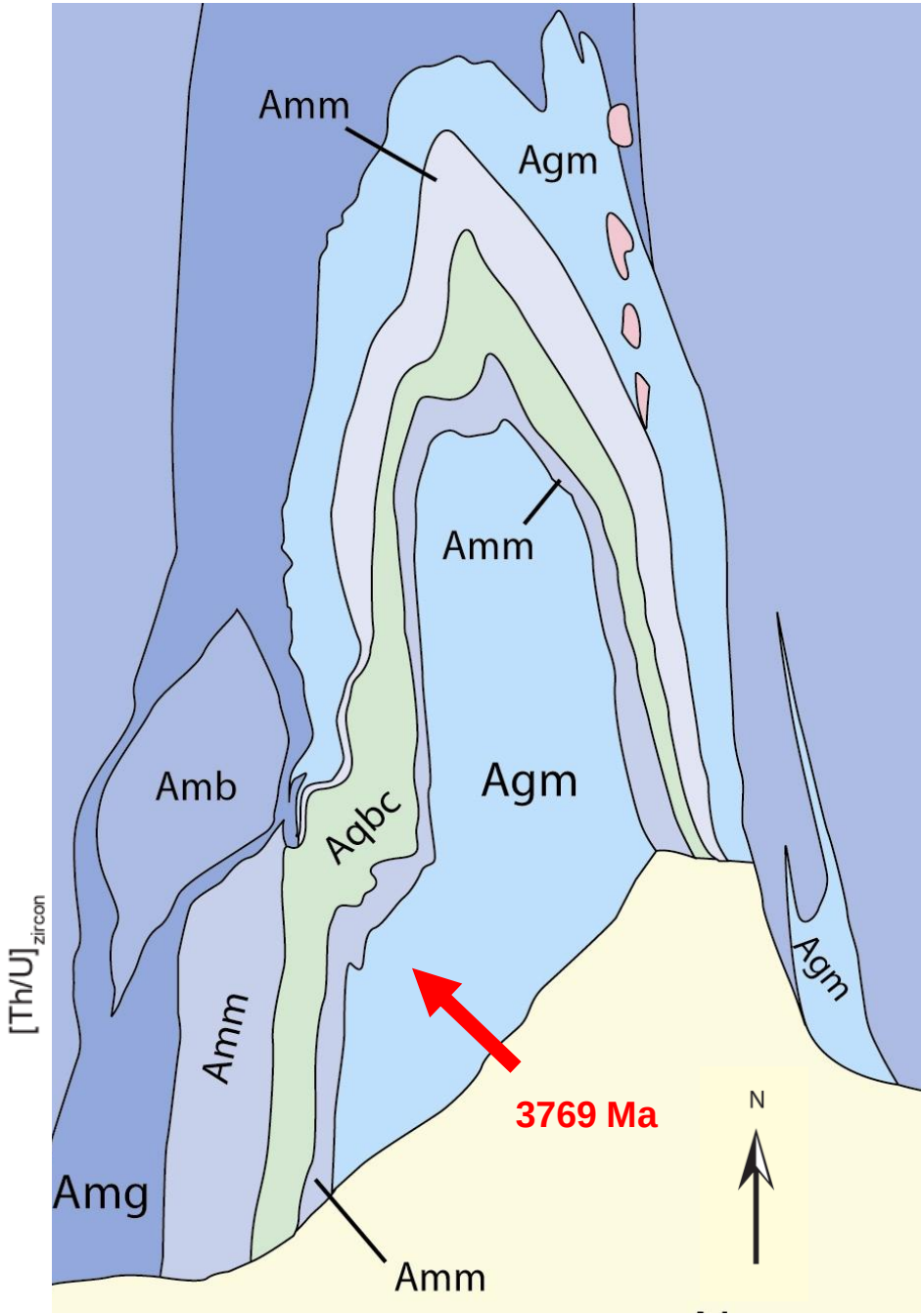

Intercepts at
2572 +480/-430 Ma & 3784 +240/-100 Ma
MSWD = 0.52
3600
3200
2800
2400
2000
$^{238}U/^{206}Pb$
$^{207}Pb/^{206}Pb$
Relative Probability
IN05003
$^{206}Pb/^{207}Pb$ Age

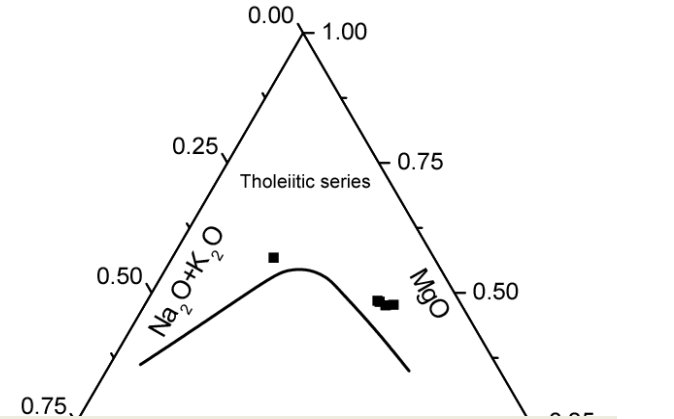

3784 Ma
Amm
Agm
Amm
Amb
Aqbc
Agm
Amm
Agm
Amg
Amm
N


data-point error ellipses are 68.3% conf.
Intercepts at
2276 +280/-250 Ma & 3765 +62/-45 Ma
MSWD = 0.86
$^{207}Pb/^{206}Pb$
$^{238}U/^{206}Pb$
3600
3200
2800
2400
2000
Relative Probability
IN05022
$^{206}Pb/^{207}Pb$ Age

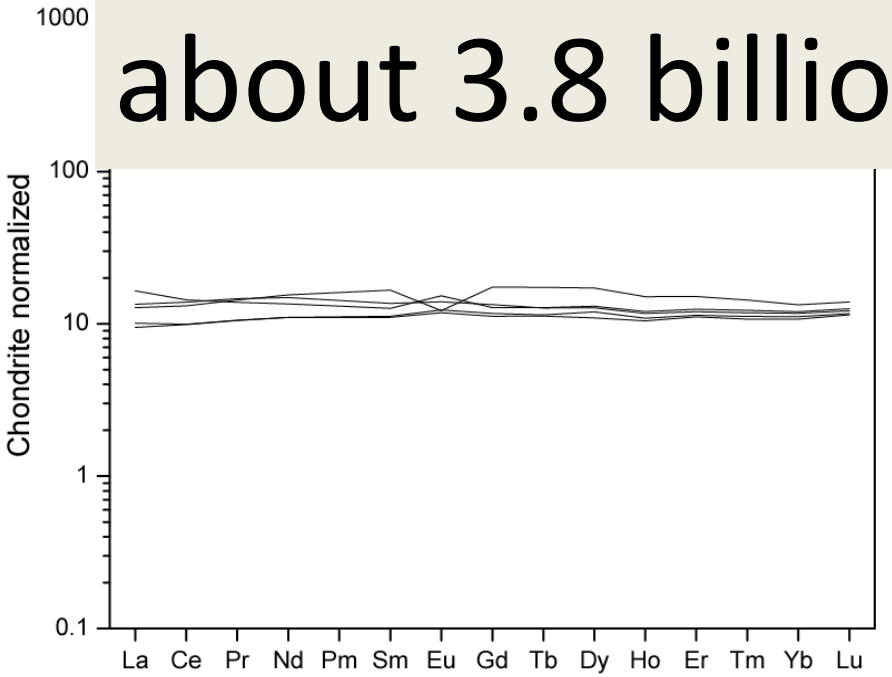

3765 Ma
Amm
Agm
Amm
Amb
Aqbc
Agm
Amm
Agm
Amg
Amm
N
$[Th/U]_{zircon}$

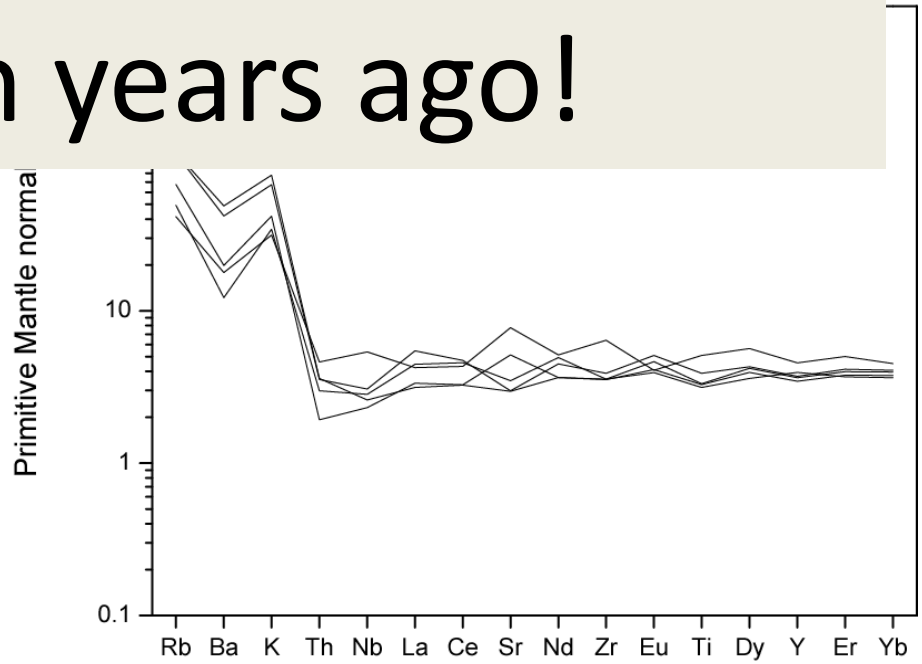

data-point error ellipses are 68.3% conf.
Intercepts at
2399 ± 270 & 3769 ± 90 [±91] Ma
MSWD = 2.6
$^{207}Pb/^{206}Pb$
$^{238}U/^{206}Pb$
3600
3200
2800
2400
2000
Relative Probability
IN05018
$^{206}Pb/^{207}Pb$ Age


Amm
Agm
Amm
Amb
Aqbc
Agm
Amm
Agm
3769 Ma
N
Amg
Amm
$[Th/U]_{zircon}$



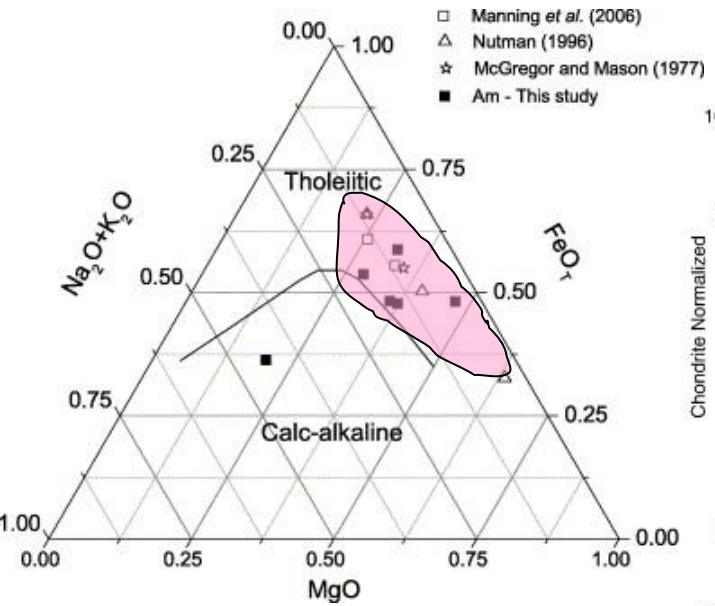
These were basaltic lava flows on the seafloor that erupted about 3.8 billion years ago!

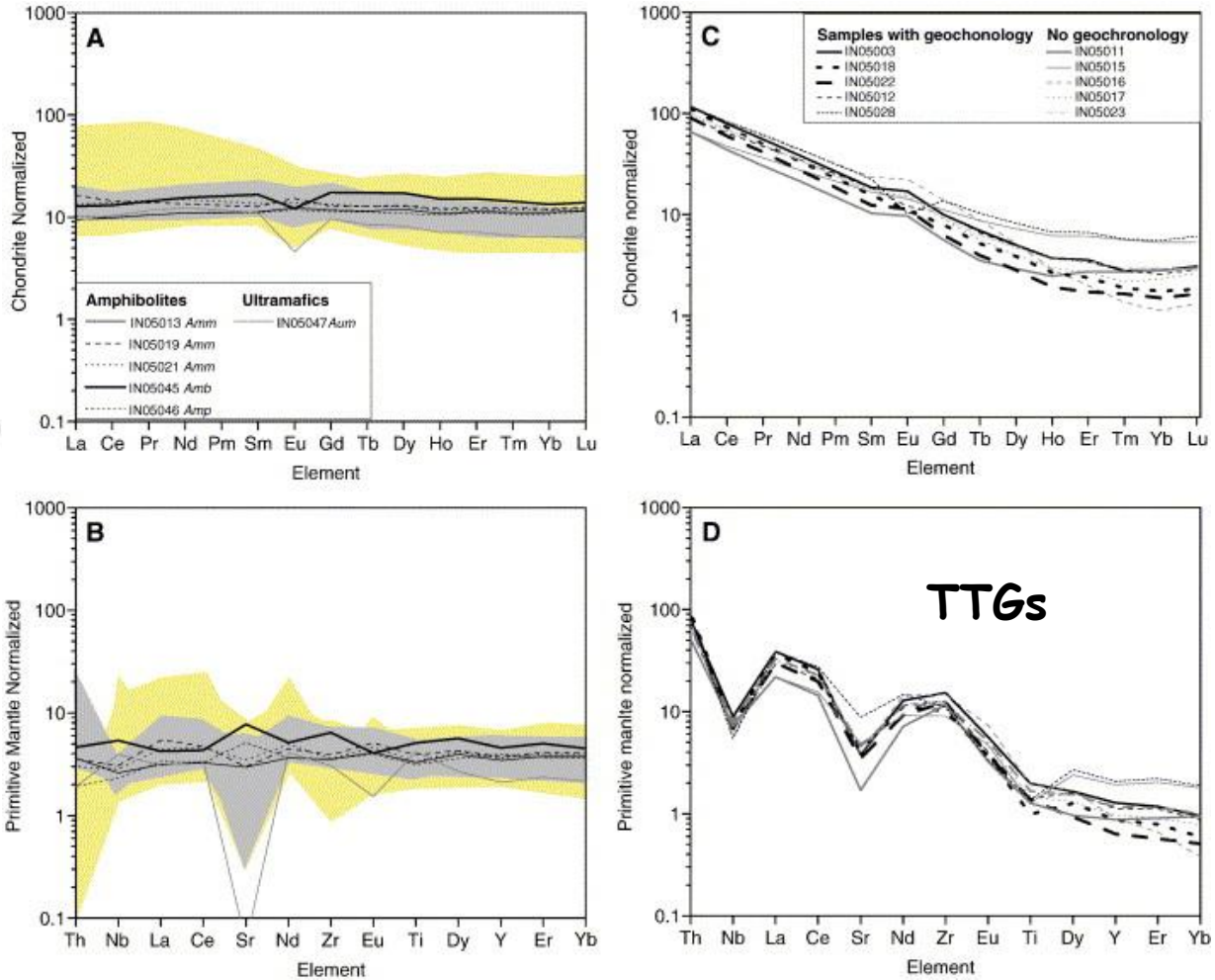




AFM diagram (boundary of Irvine and Baragar, 1971) showing tholeiitic affinity of *Am*-type units in *Akilia association*.

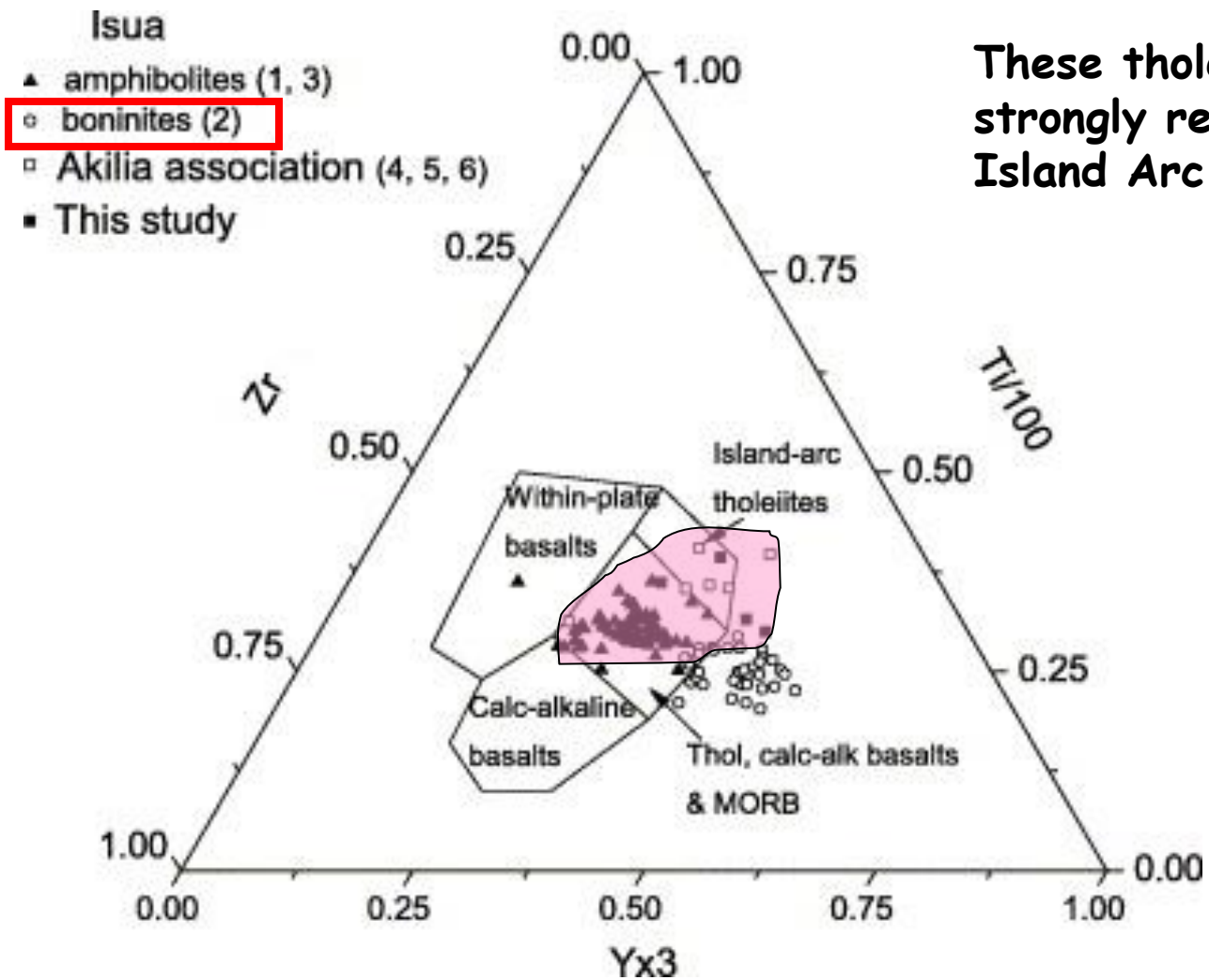
Typical tholeiitic compositions for the amphibolites





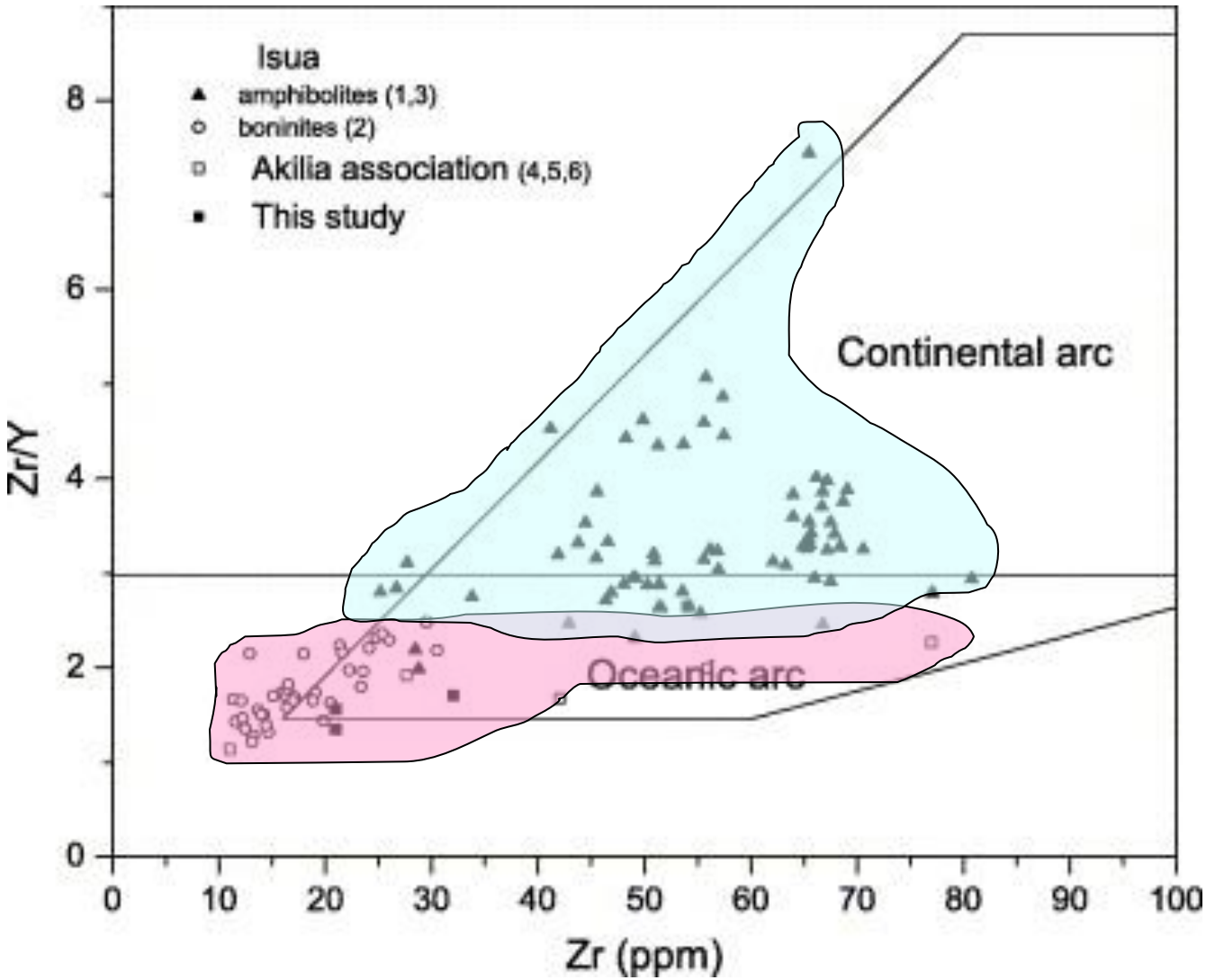
from:
Cates and Mojzsis
(2006, 2007, 2009)

Normalized trace element plots. Least altered amphibolites from the *ISB* (dark field) and the *AA*] (light field). (A) Chondrite normalized REE plot of amphibolites. (B) Primitive mantle normalized multi-element plot of amphibolites. (C) Chondrite normalized REE plot of orthogneisses. (D) Primitive mantle normalized multi-element plot of orthogneisses.



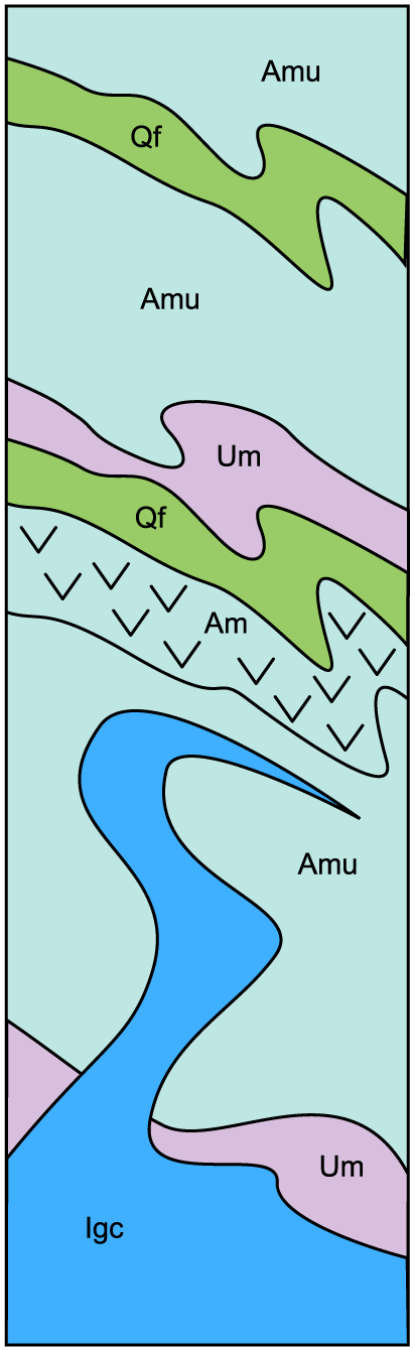
These tholeiites most strongly resemble Island Arc types

Tectonic discrimination diagram of *ISB* (triangles and circles) and *Akilia association* (squares) mafic rocks. Fields of Pearce and Cann (1973). (1) Polat et al. (2003); (2) Polat et al. (2002); (3) Polat and Hofmann (2003); (4) Manning et al. (2006); (5) McGregor and Mason (1977); (6) Nutman et al. (1996).

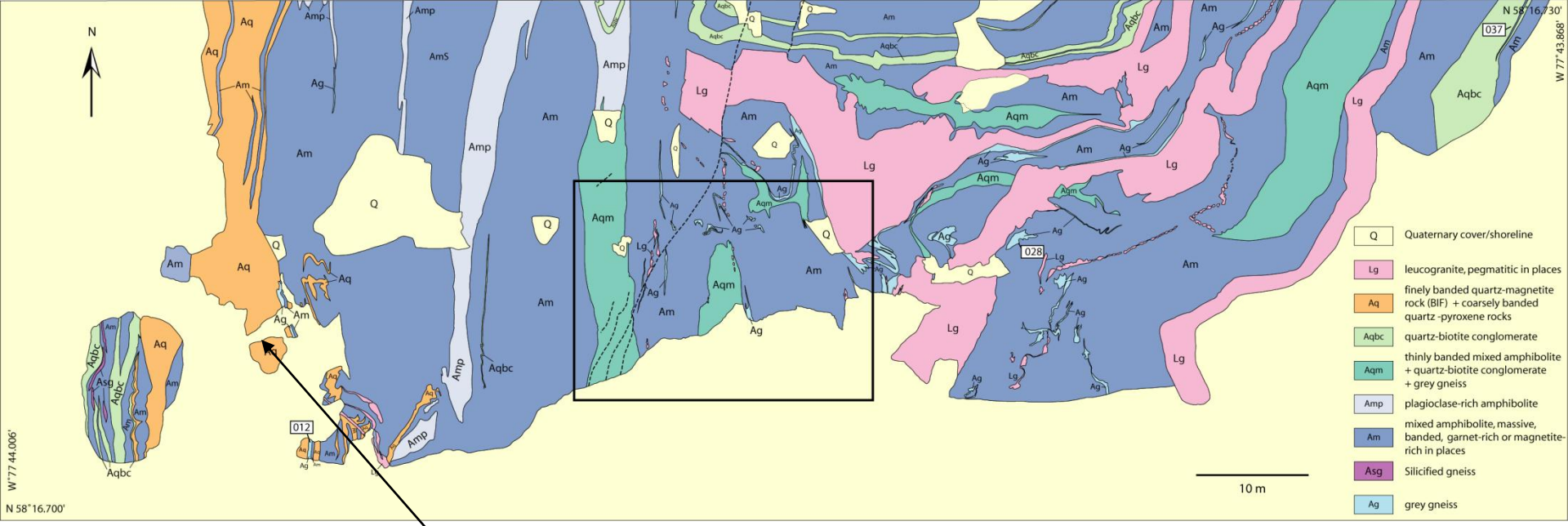


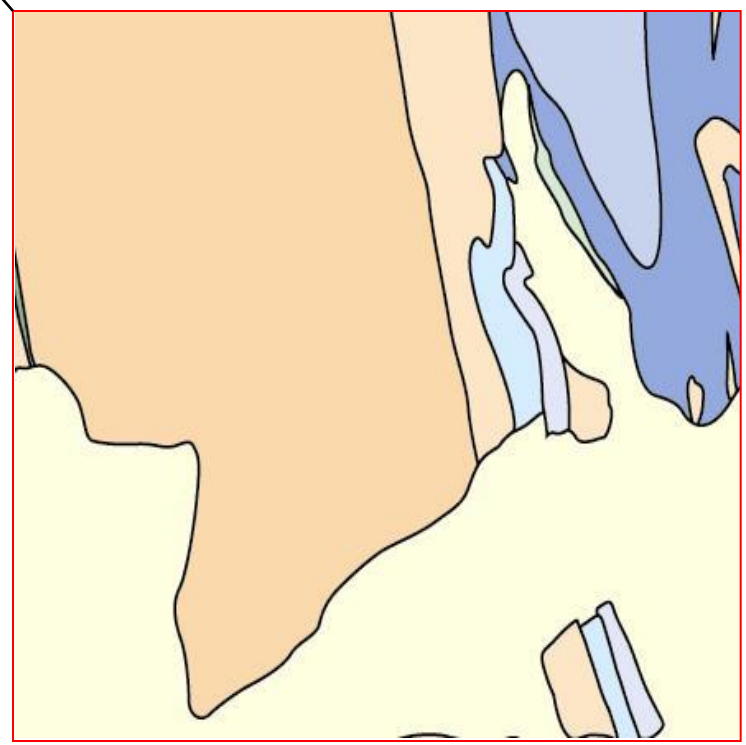
Tectonic discrimination diagram of *ISB* (triangles and circles) and *Akilia association* (squares) mafic rocks showing oceanic arc affinity for *Akilia association* amphibolites. Fields of Pearce (1983).

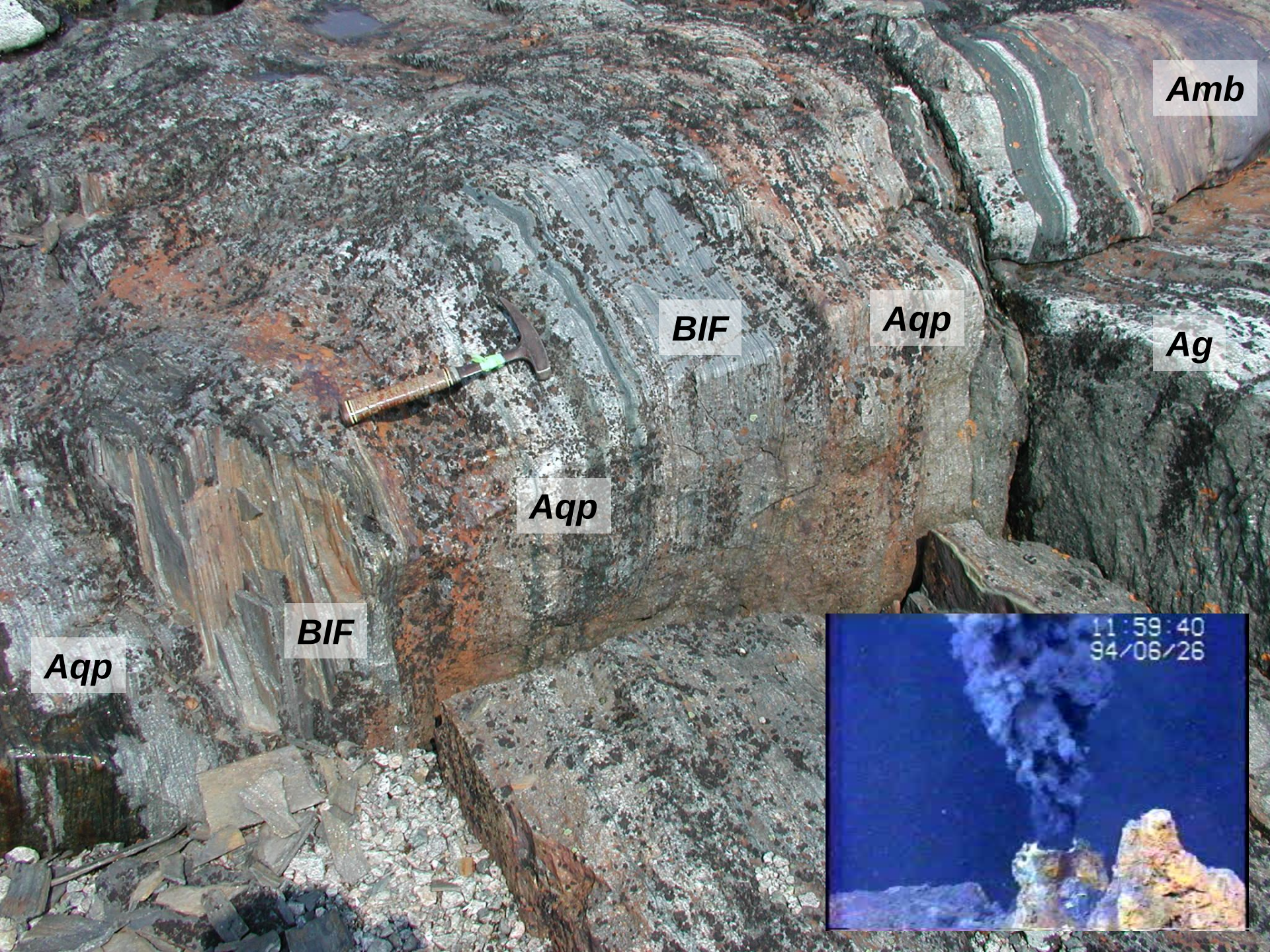
Normal Supracrustal "stratigraphy"



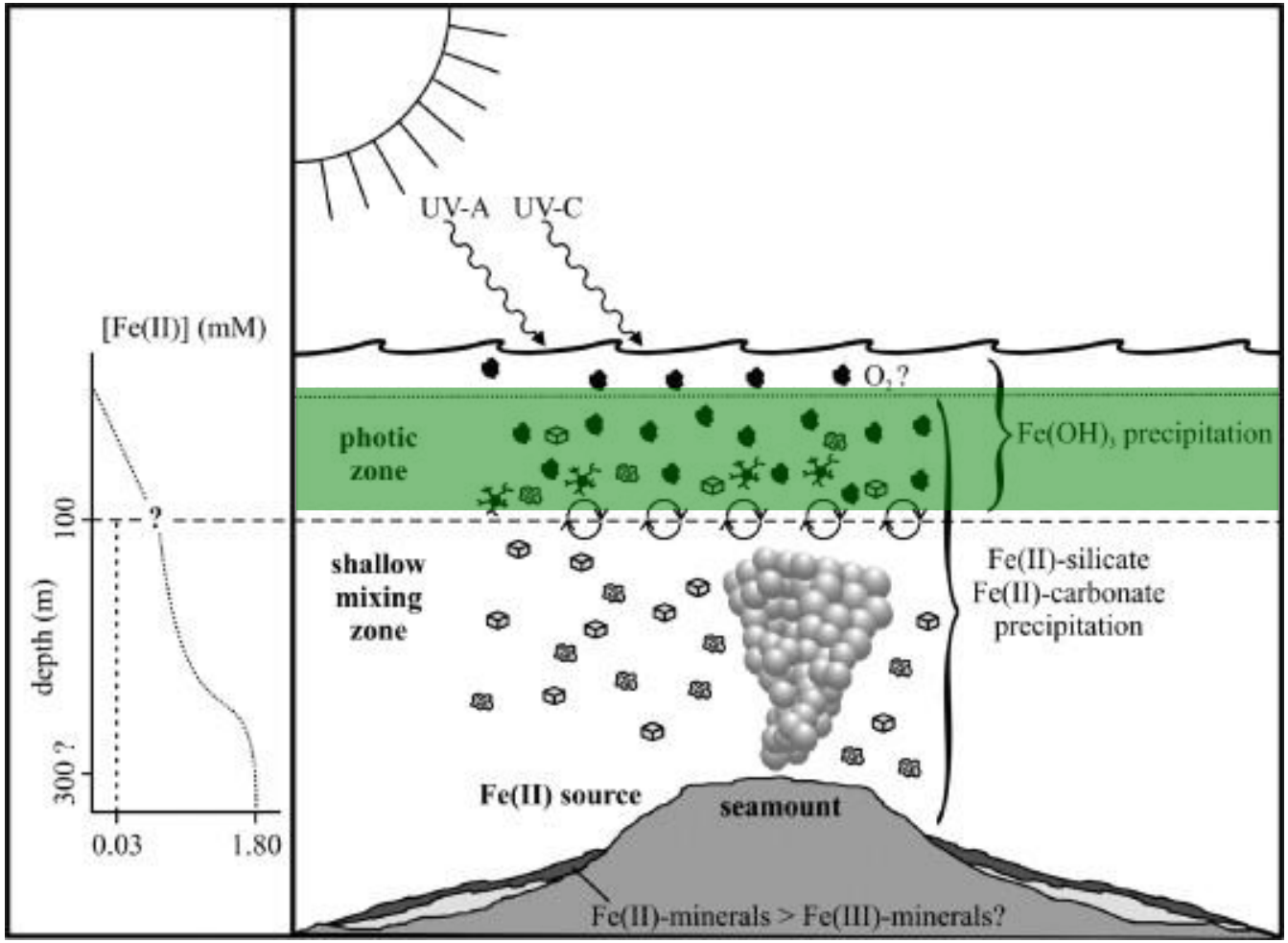
Granitoid dikes crosscut the supracrustal packages during arc evolution


N
N 58°16.730'
W 77°43.868'
N 58°16.700'
W 77°44.006'
037
028
012
10 m
Q Quaternary cover/shoreline
Lg leucogranite, pegmatitic in places
Aq finely banded quartz-magnetite rock (BIF) + coarsely banded quartz -pyroxene rocks
Aqbc quartz-biotite conglomerate
Aqm thinly banded mixed amphibolite + quartz-biotite conglomerate + grey gneiss
Amp plagioclase-rich amphibolite
Am mixed amphibolite, massive, banded, garnet-rich or magnetite-rich in places
Asg Silicified gneiss
Ag grey gneiss



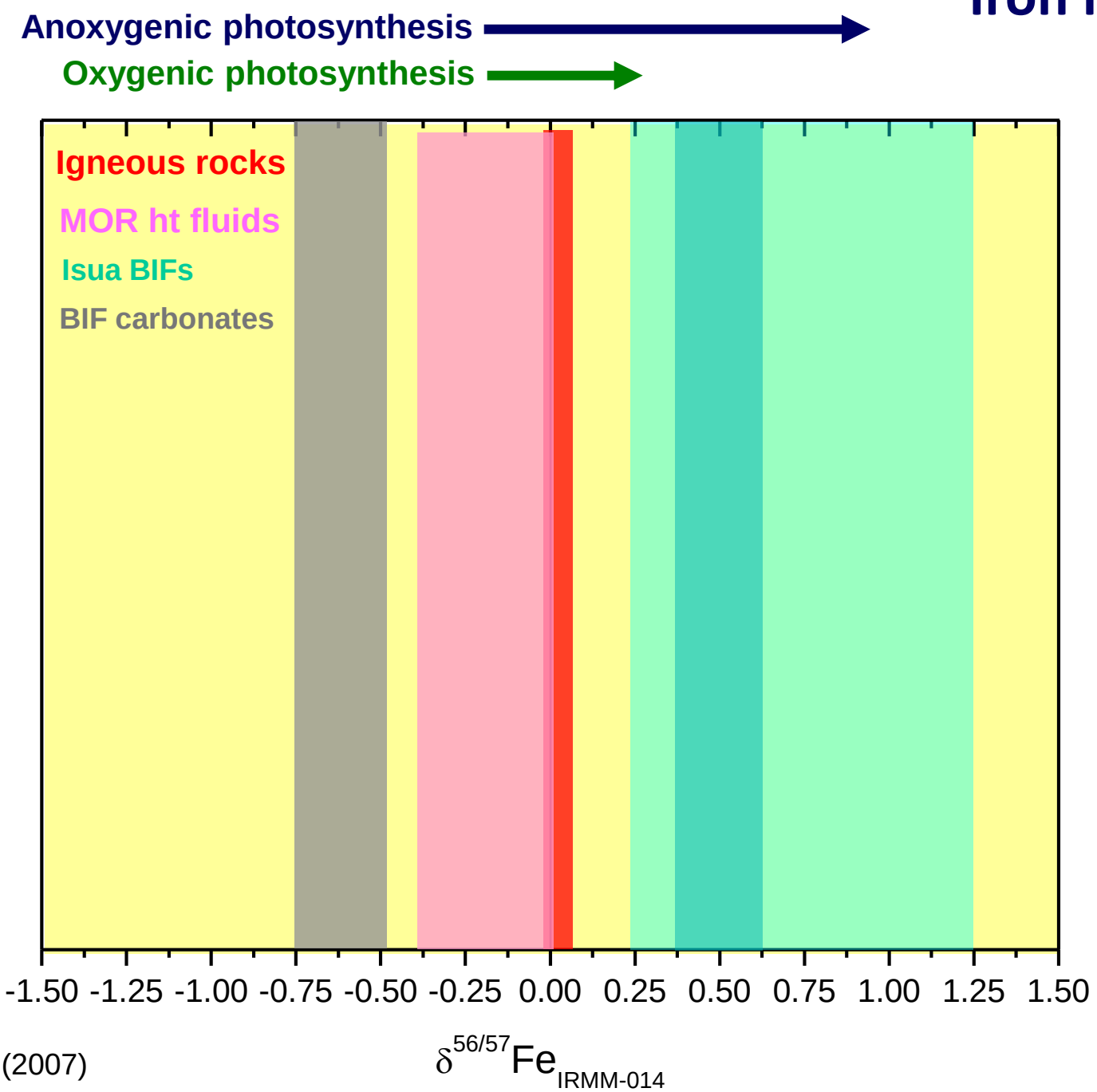

Amb
BIF
Aqp
Ag
Aqp
BIF
Aqp
11:59:40
94/06/26

Genesis of Archean banded iron-formations (BIFs)



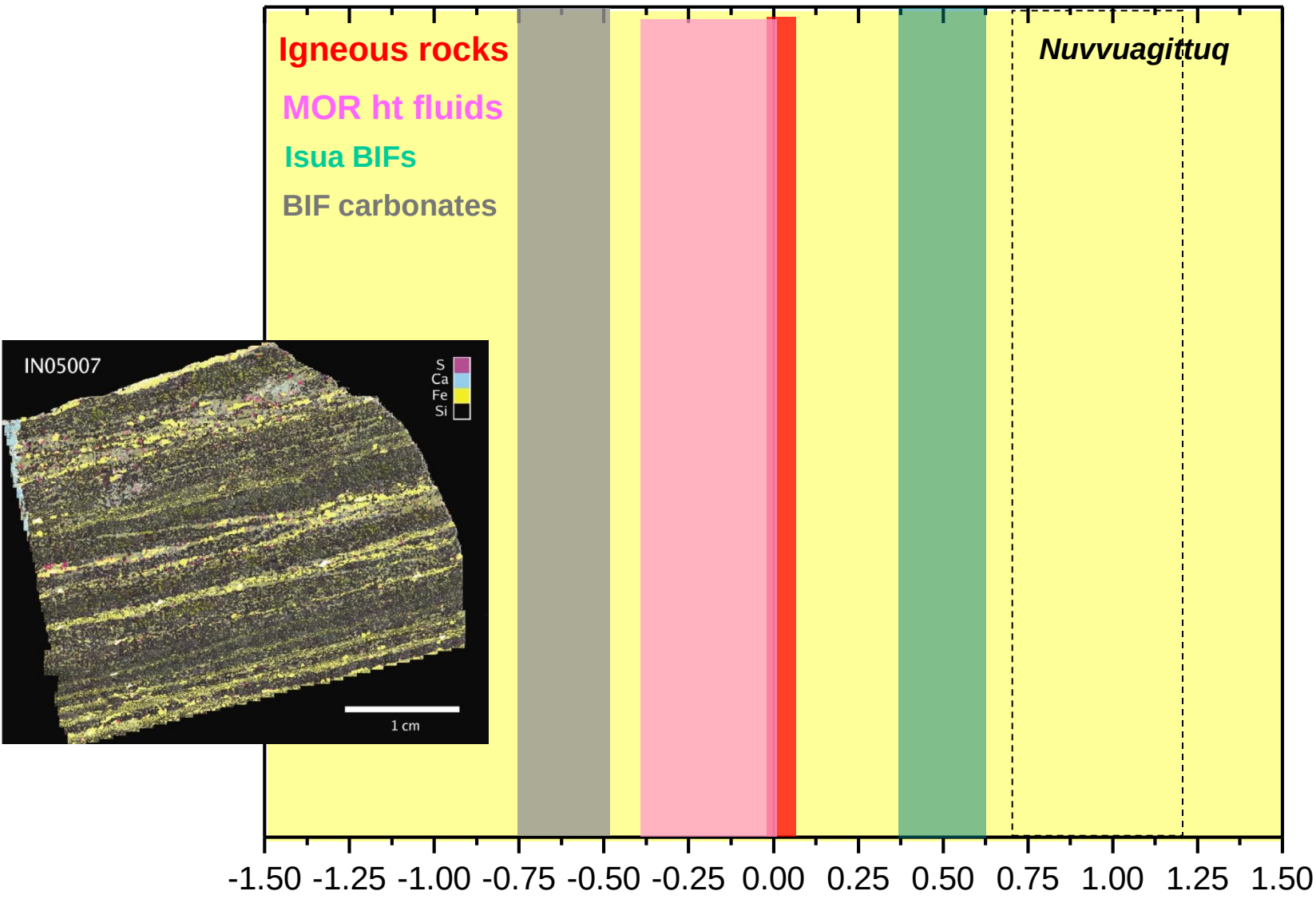
Conceptual model showing Fe(II) effused from a shallow seamount-type system almost directly into the photic zone of the ocean, where its concentration is diminished by a combination of mineral precipitation, photochemical oxidation, anoxygenic photosynthesis, and possibly reaction with dissolved O_2, which could be present in localized 'oases' or in a continuous surface layer. The attainment of equilibrium conditions depends on the relative depth of the seamount vent versus the depth of the photic zone (***from Konhauser et al. 2007***)

Iron isotopes



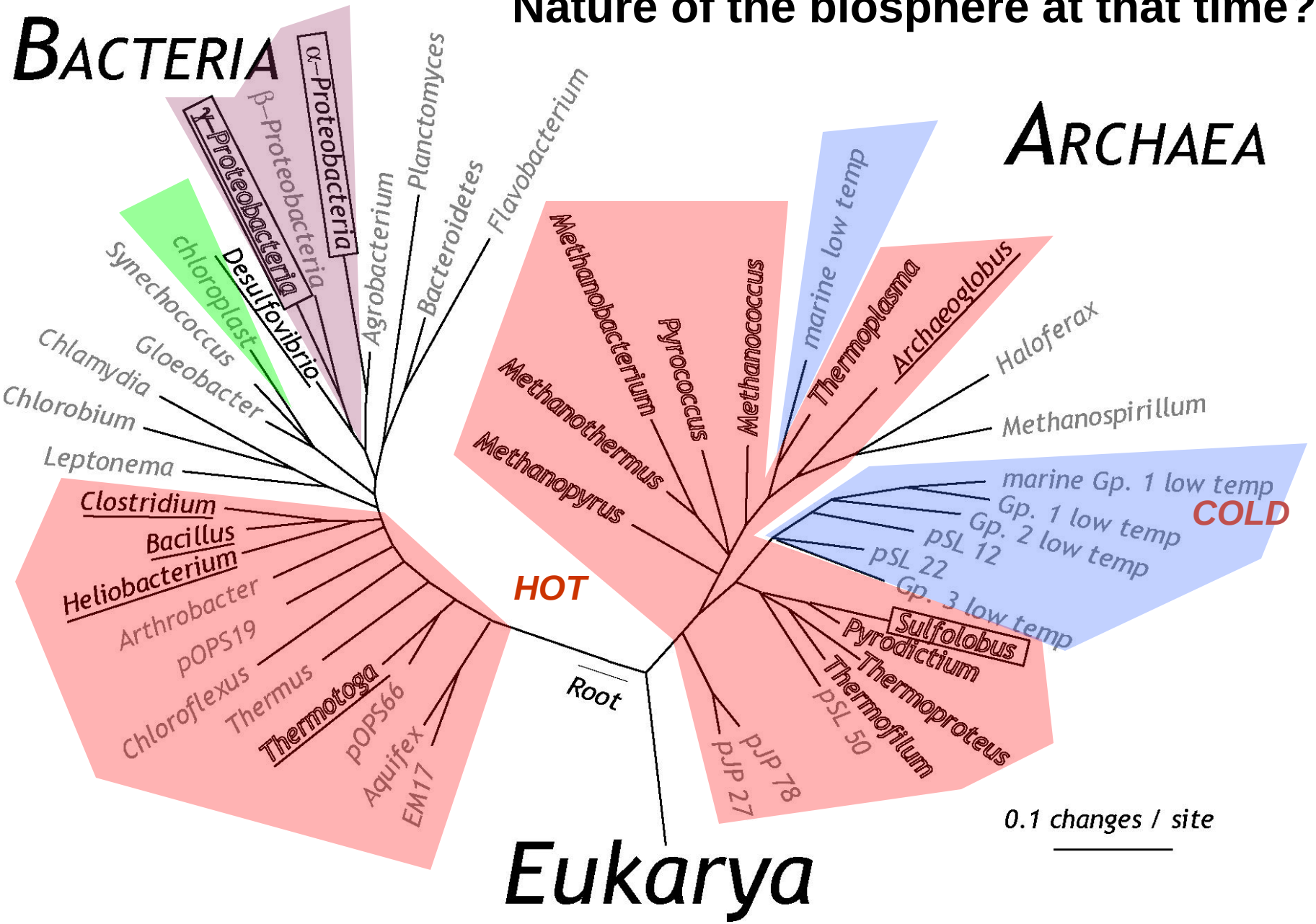
Dauphas et al. (2007)

Iron isotopes



Dauphas et al. (2007)

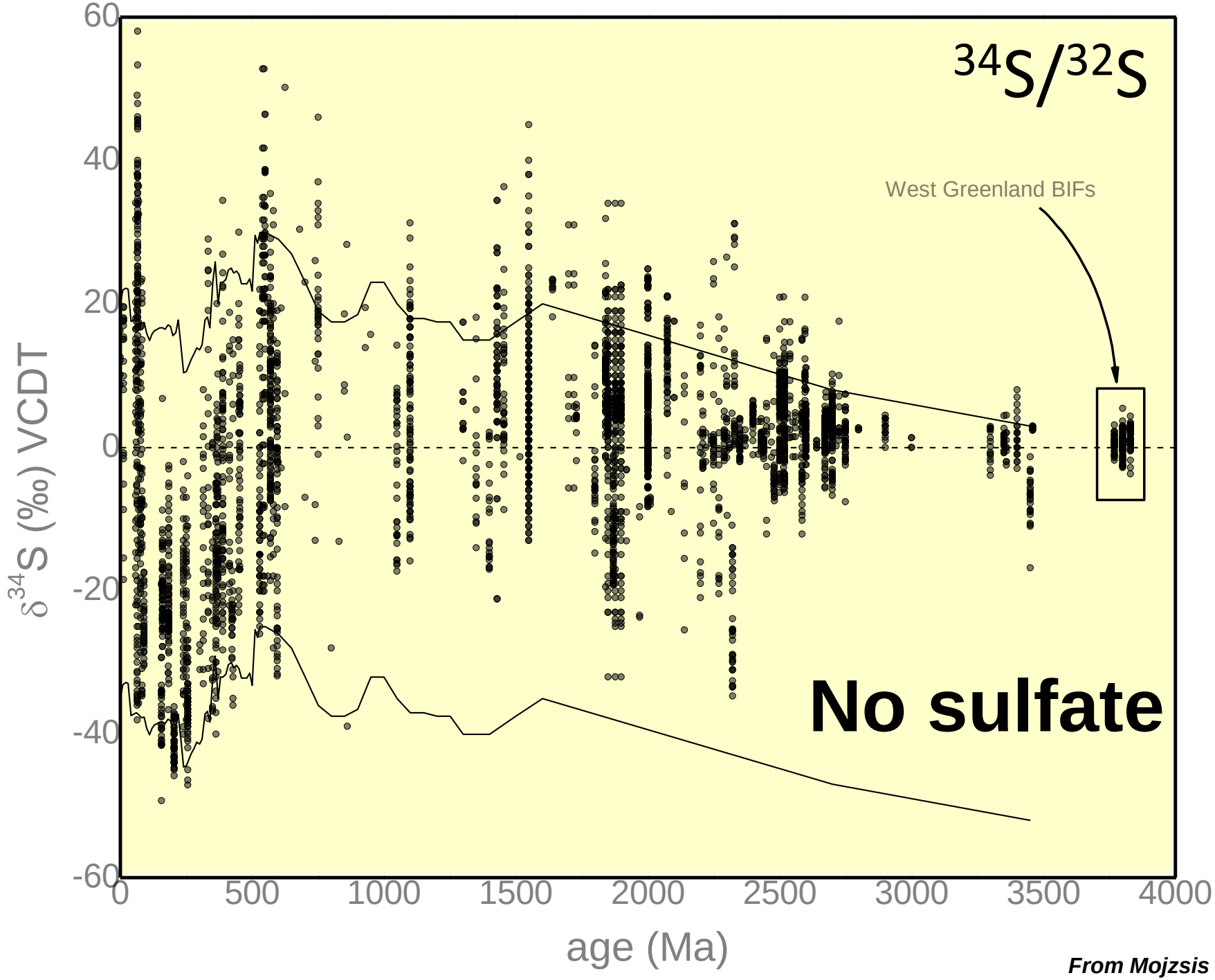
Nature of the biosphere at that time?



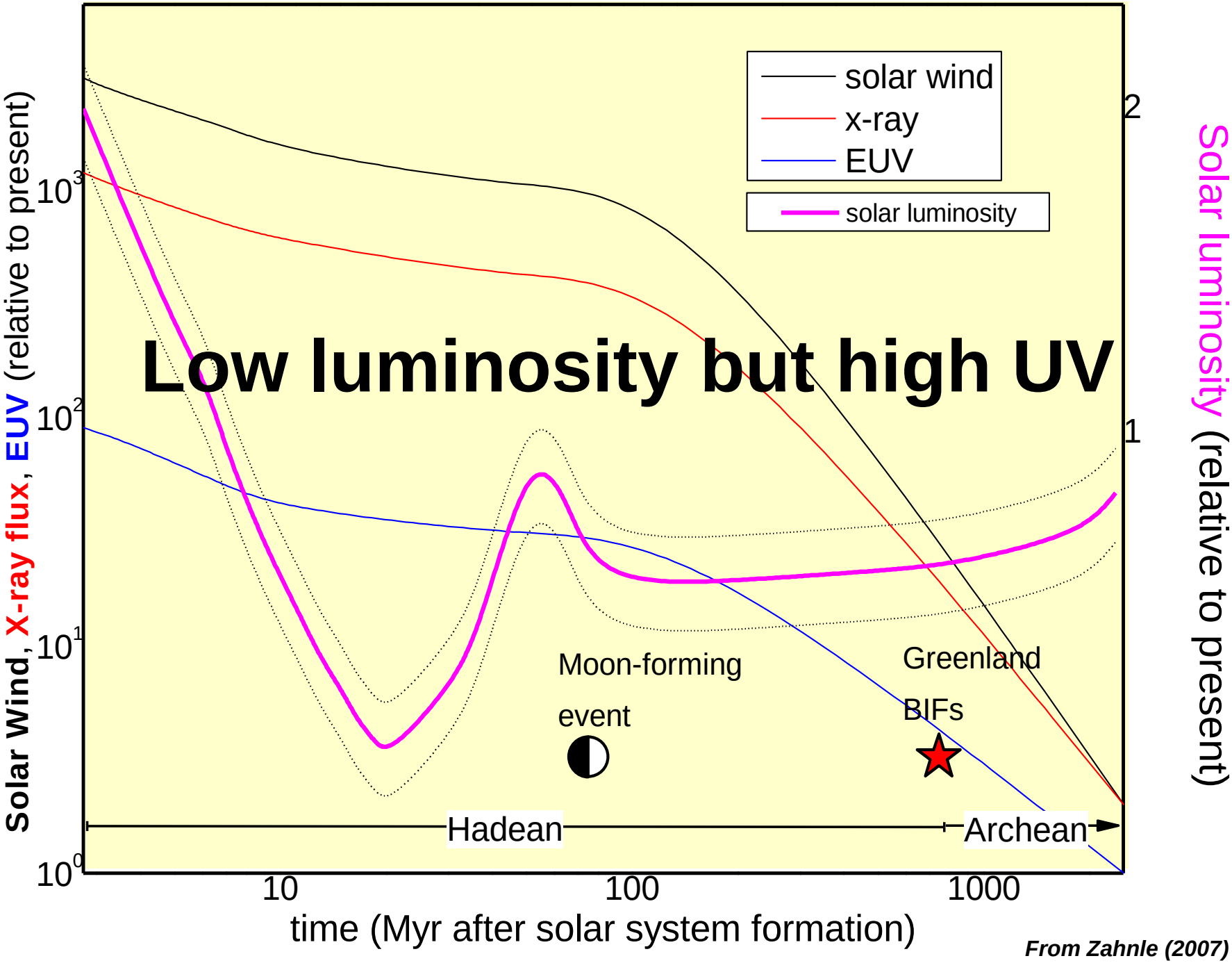
Ages and protolith types established for the oldest known sediments.

What of the hydrosphere and atmosphere?

- Sulfide – sulfate through time
- Evolution of the Sun
- Multiple sulfur isotopes
- Record of photochemistry in S isotopes
- Some constraints on the atmosphere and hydrosphere from « MIF in BIF »

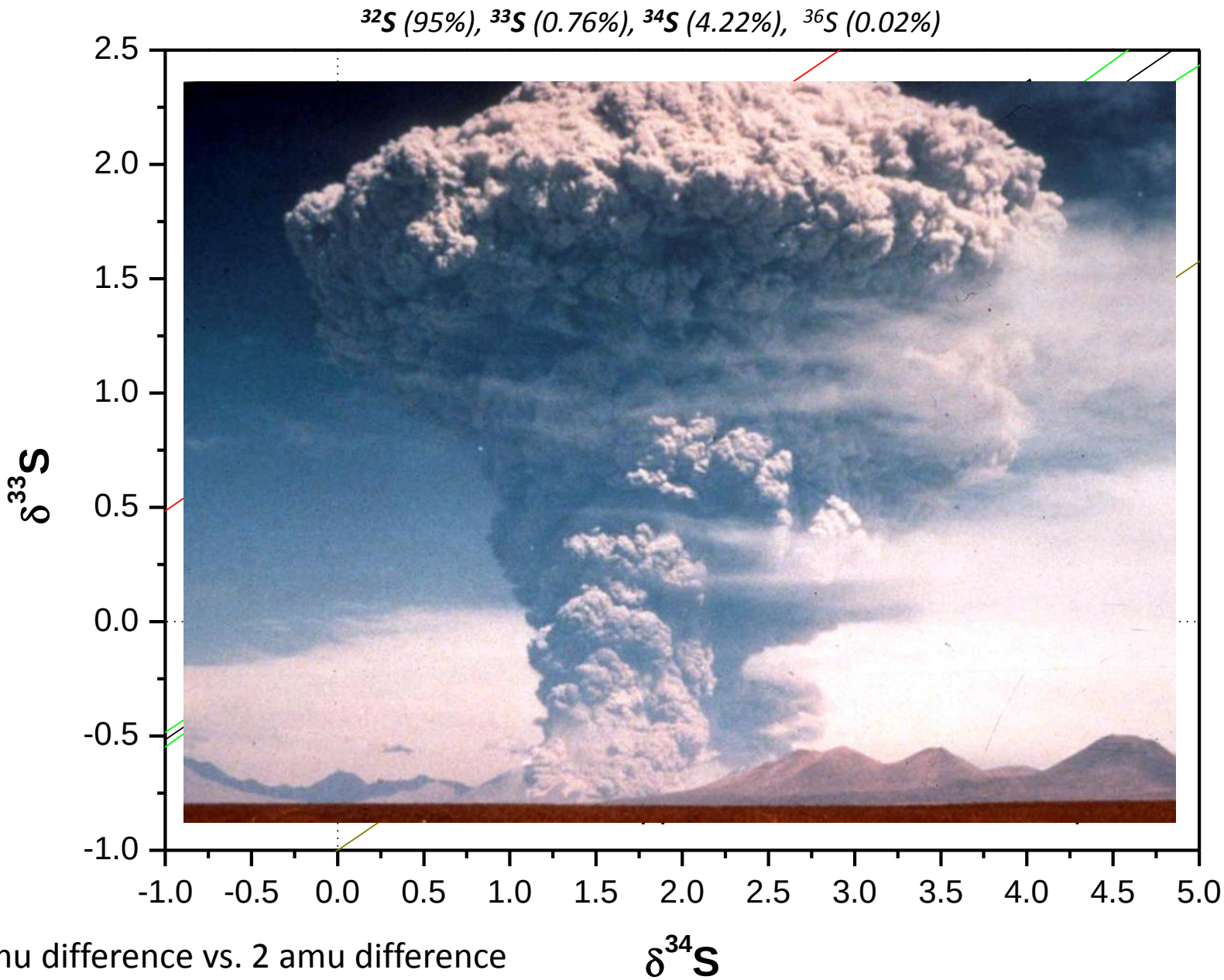


From Mojzsis (2007)

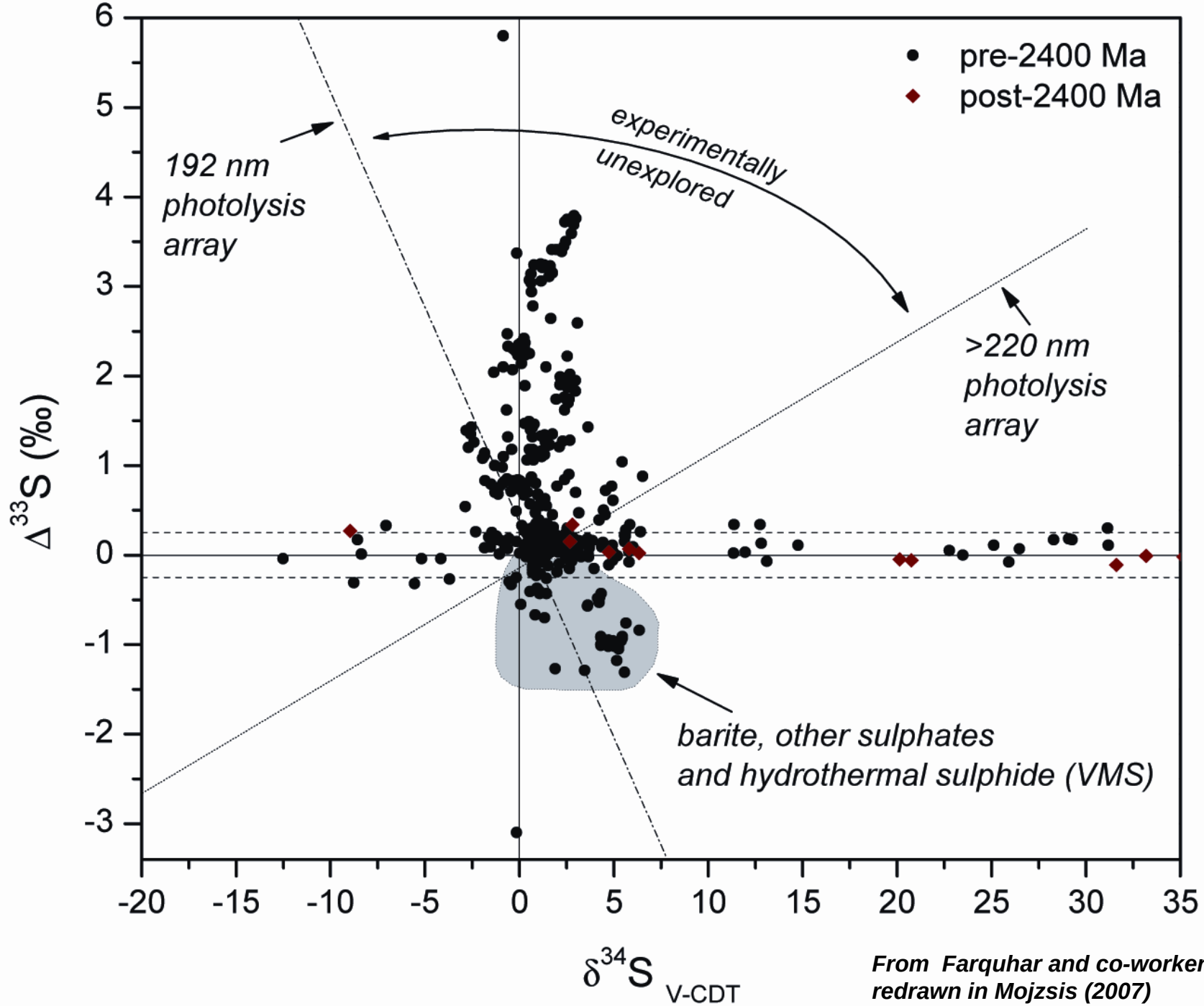


From Zahnle (2007)

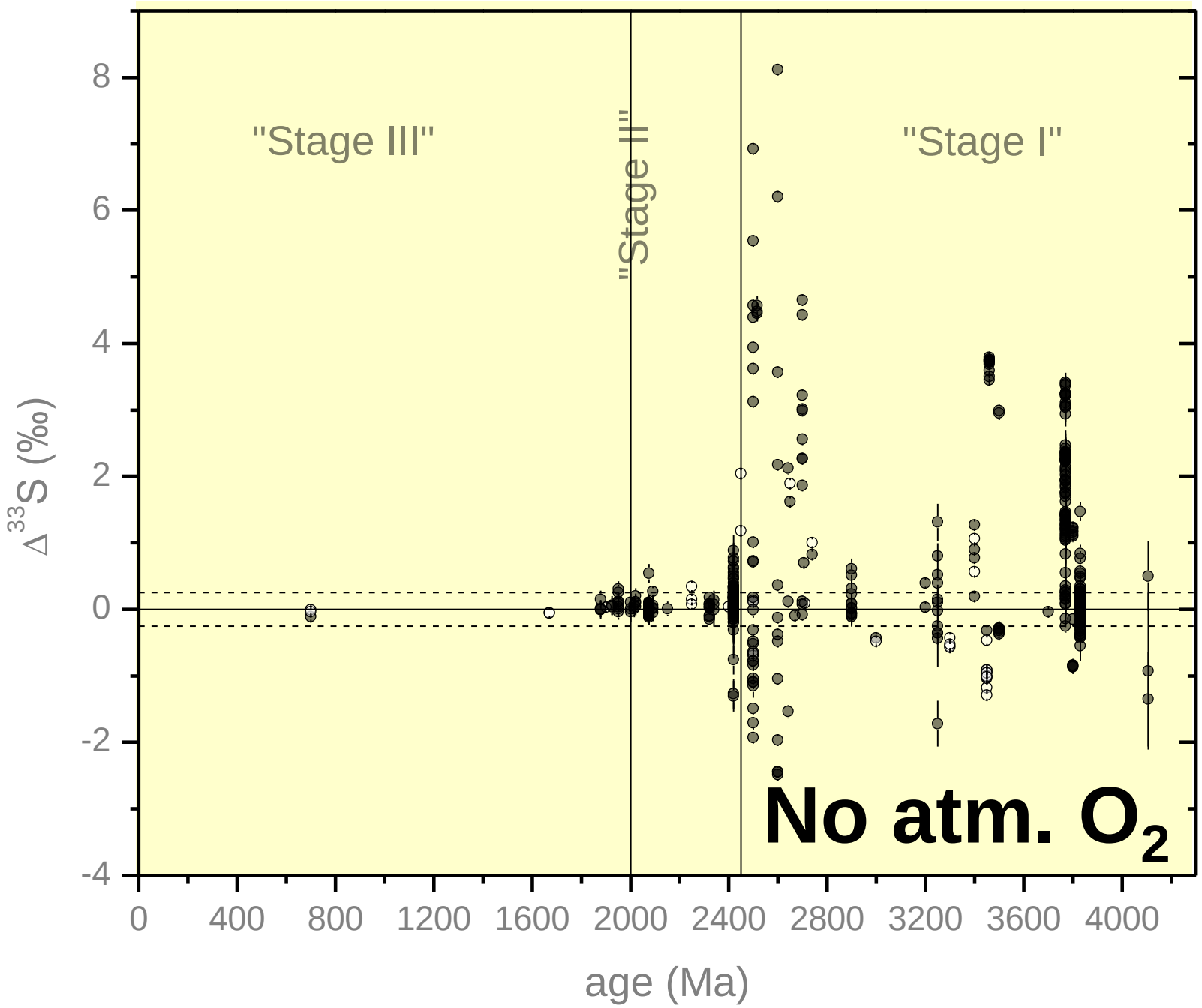
Mass-independent fractionation of S isotopes



1 amu difference vs. 2 amu difference



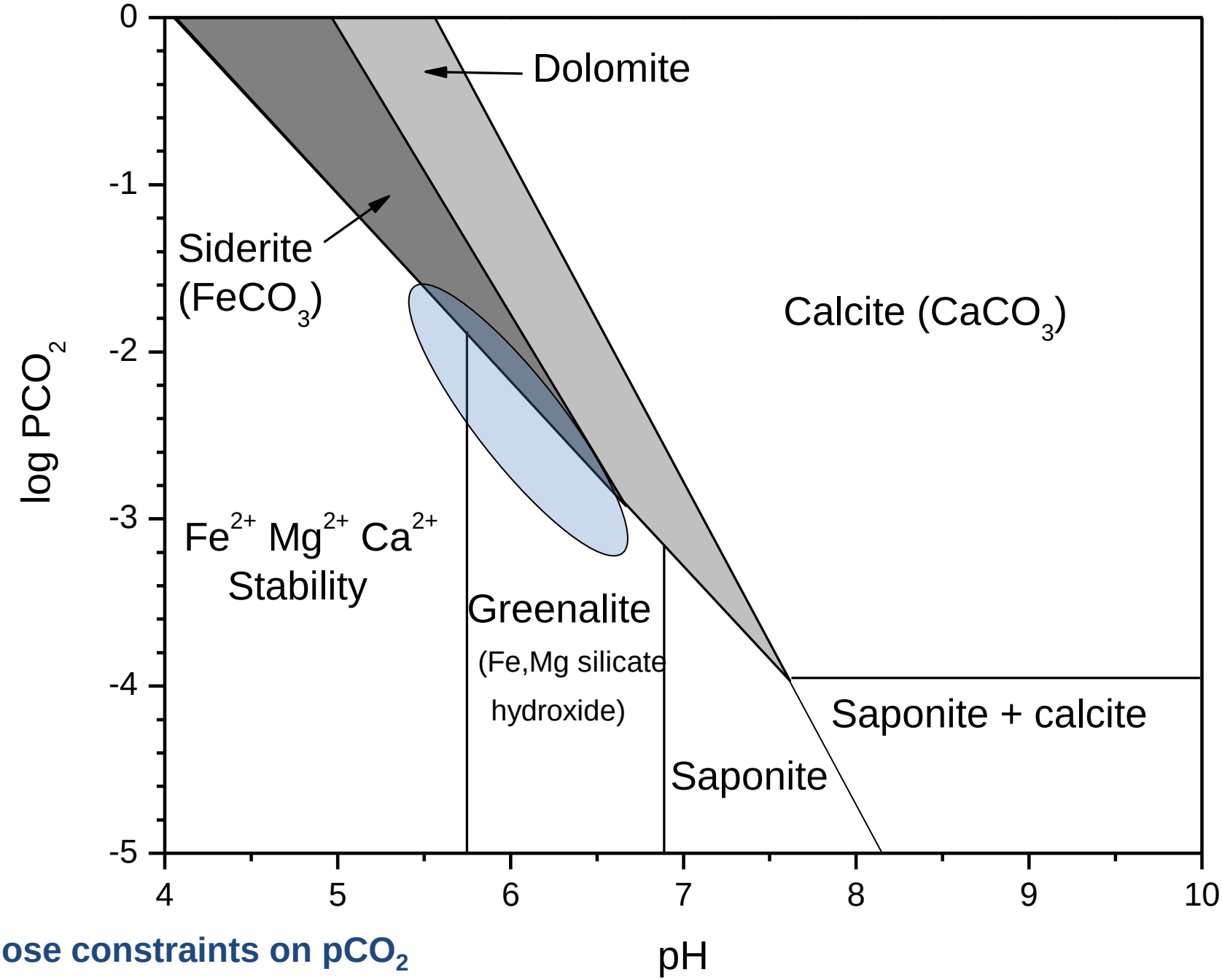
From Farquhar and co-workers, redrawn in Mojzsis (2007)



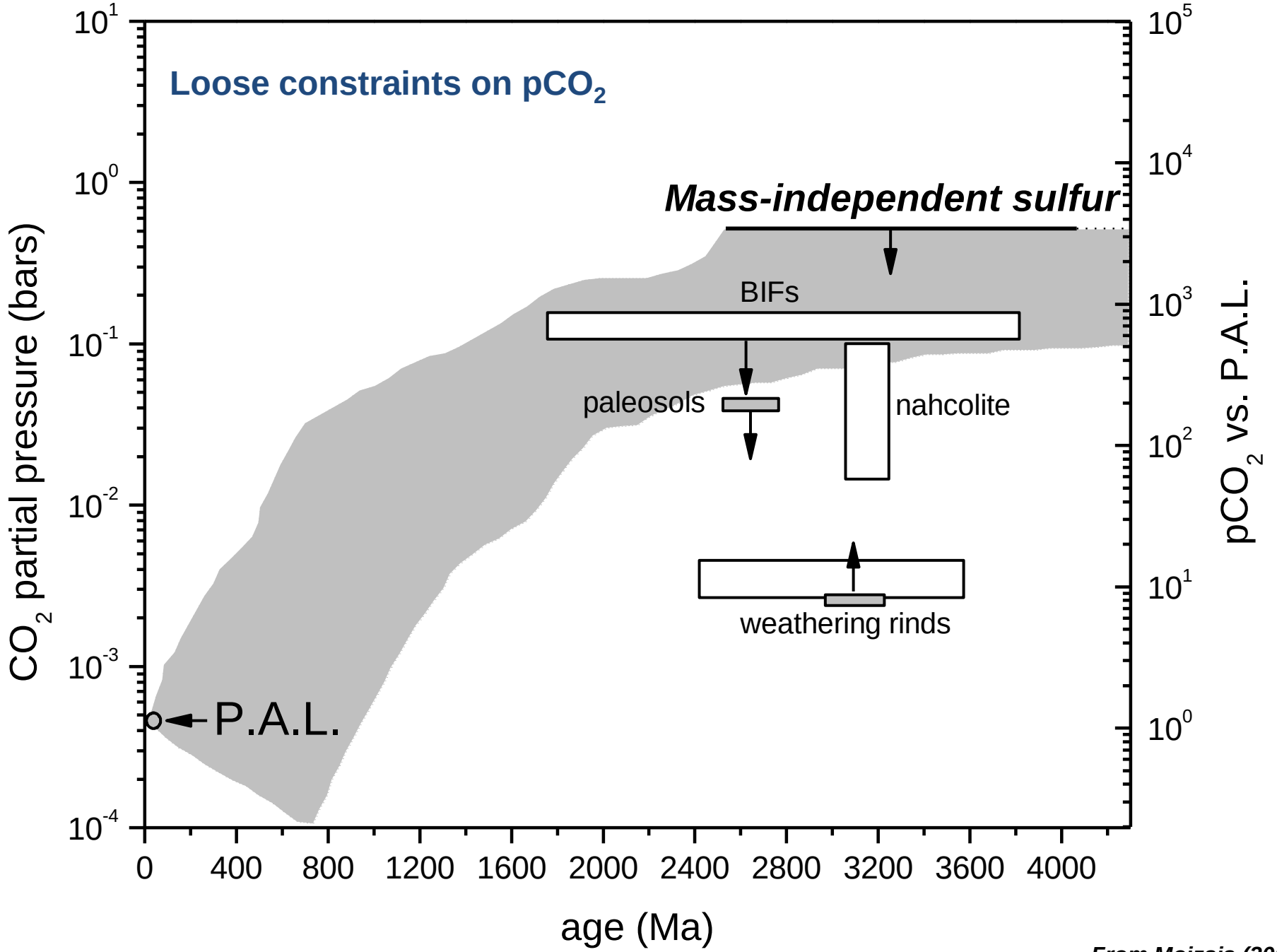
From Mojzsis (2007)

New and old perspective on the early Archean Atmosphere and Hydrosphere:

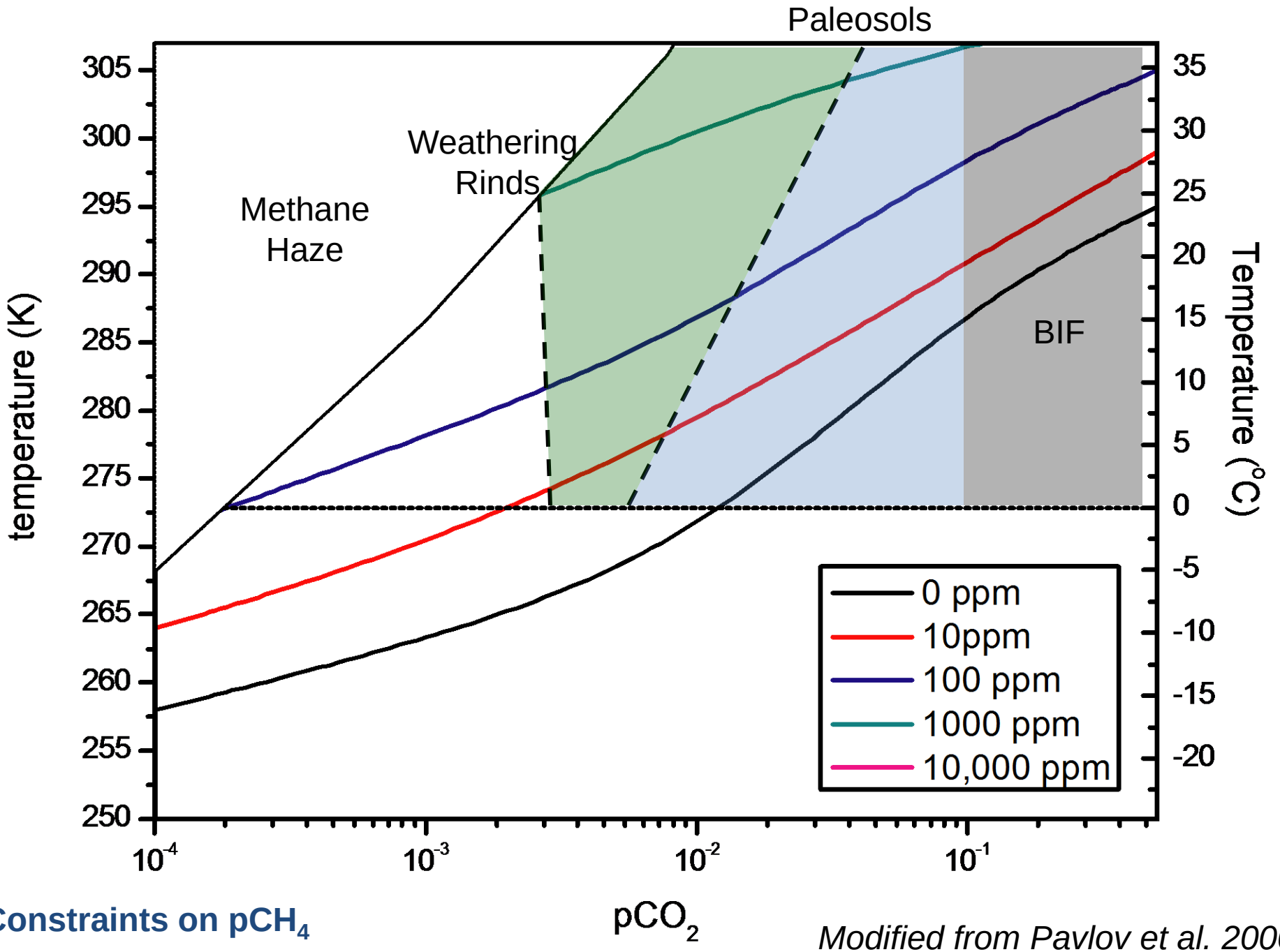
- Oxygen (<<10^{-6} PAL)
- CO_2
- Methane
- Hydrogen
- Seawater temperature and pH



Loose constraints on pCO_2



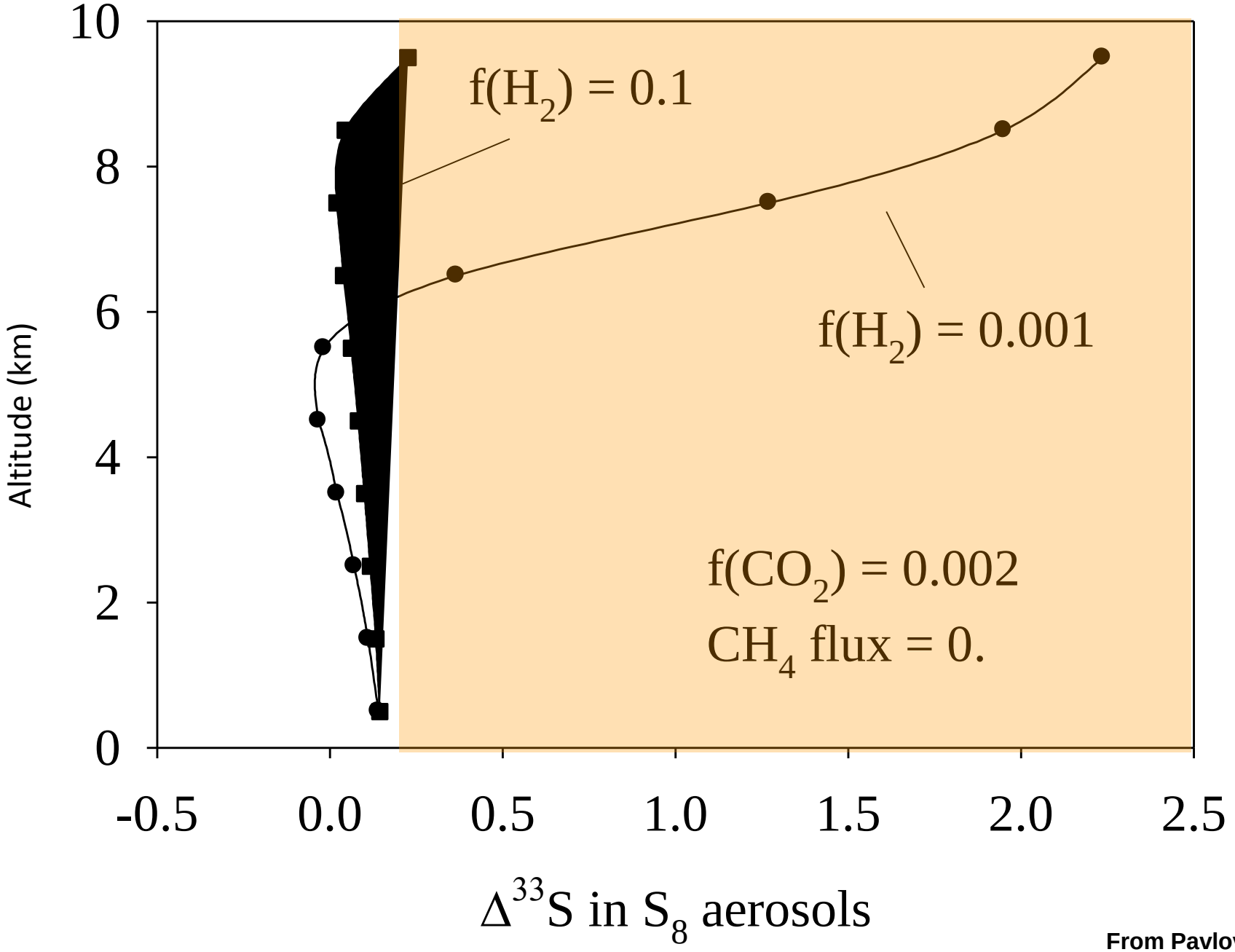
From Mojzsis (2007)



Constraints on pCH_4

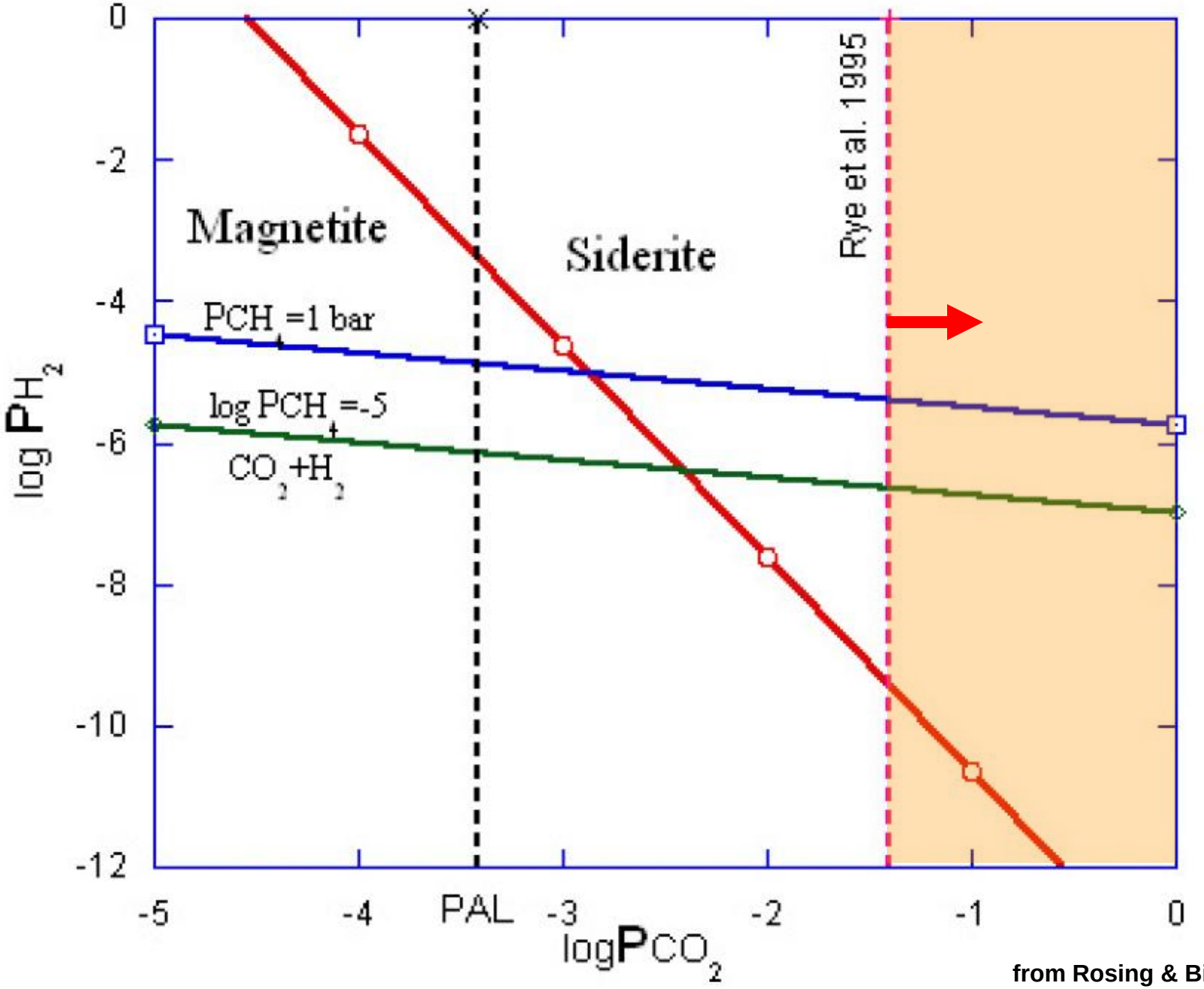
Modified from Pavlov et al. 2000

Constraints on pH_2



From Pavlov (2007)

Independent constraints on pH_2 & pCH_4



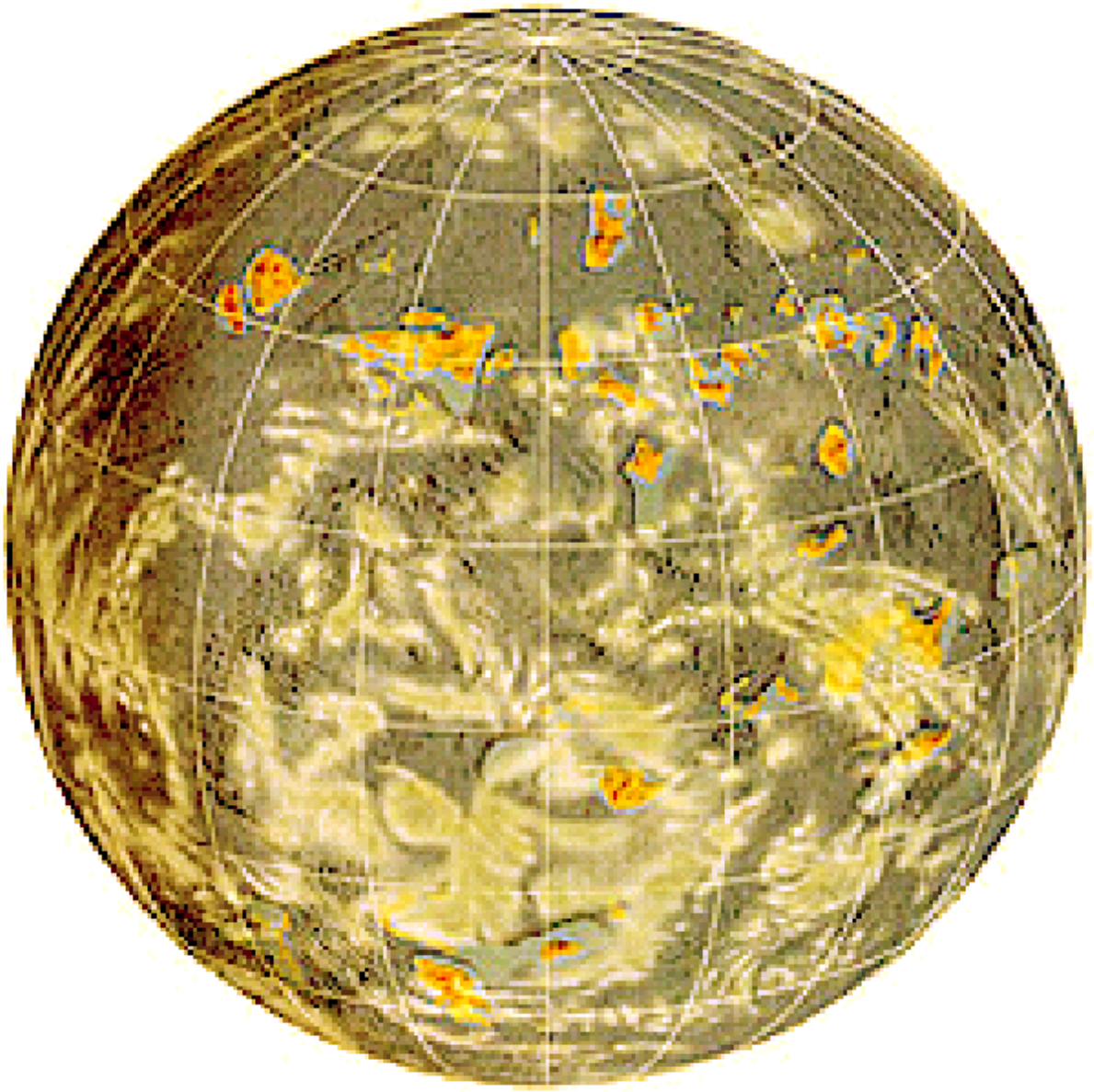
from Rosing & Bird (2007)

Key points for the Earth at about 4 billion years ago

- Abundant (small) continents
- Water rich planet
- Probable biosphere
- Anoxic conditions
- Plate tectonics?
- Certainly plate boundary processes

- Transparent atmosphere
- pCO_2 was $\leq 1.5 \times 10^3 \times$ PAL
- Ocean pH < 7
- pCH_4 was very probably >100 ppm or enough to keep the average surface temperature at ~20ºC or even much less (near freezing?)
- pH_2 was far less than 10^3 ppm or even lower

A conceptual model of the Earth in olden times



Hypothesis:

Abundant small proto-continental masses, akin to immature-to-mature island arcs at ocean-ocean subduction zones.

Figure modified from one that appeared in Cassell's "Atlas of Evolution" (2001)