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FAME

BEFORE LIFE PROJECT

What Earth probably was, and most likely was not, in the earliest times

Stephen Mojzsis

University of Colorado at Boulder

Department of Geological Sciences

as amended and presented by:

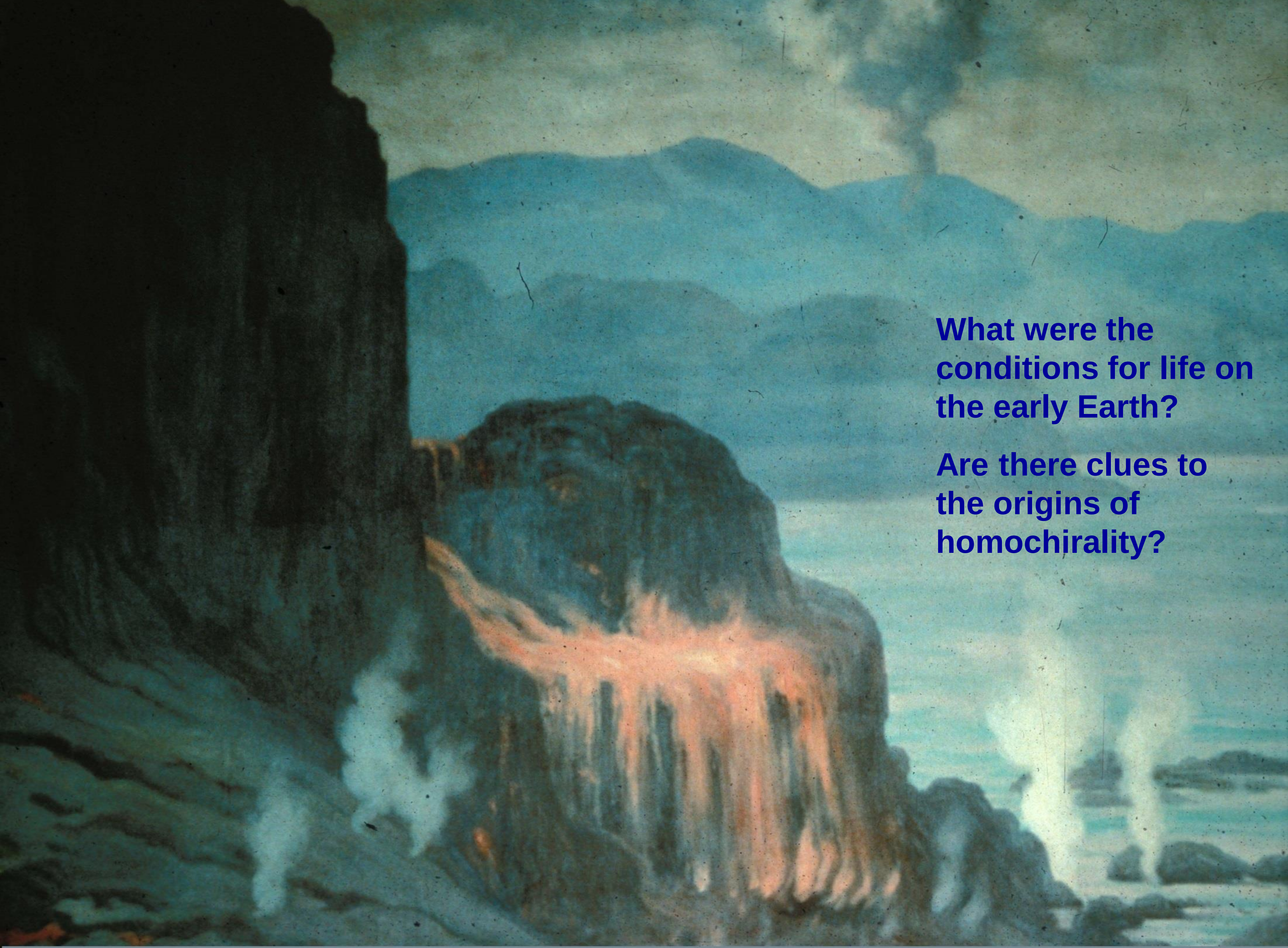
Stephen Macko

University of Virginia

University of Colorado 1876 · Magyar Tudományos Akadémia 1825 · CRiO · NASA · ELSI Earth - Life Science Institute

Events that Shaped the Earth
The Origin Life

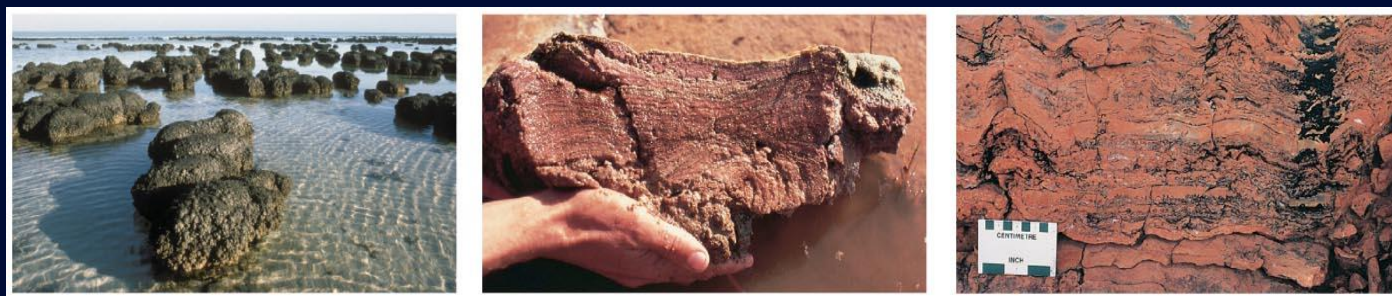
Stephen Macko
University of Virginia

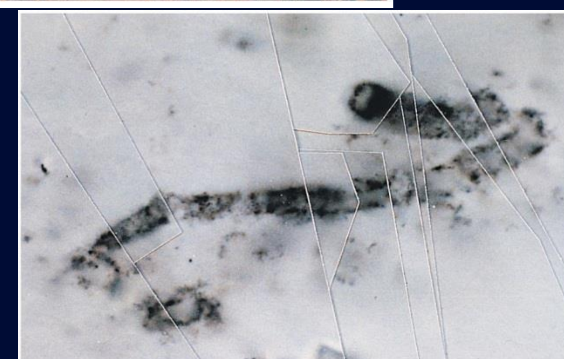


What were the conditions for life on the early Earth?

Are there clues to the origins of homochirality?

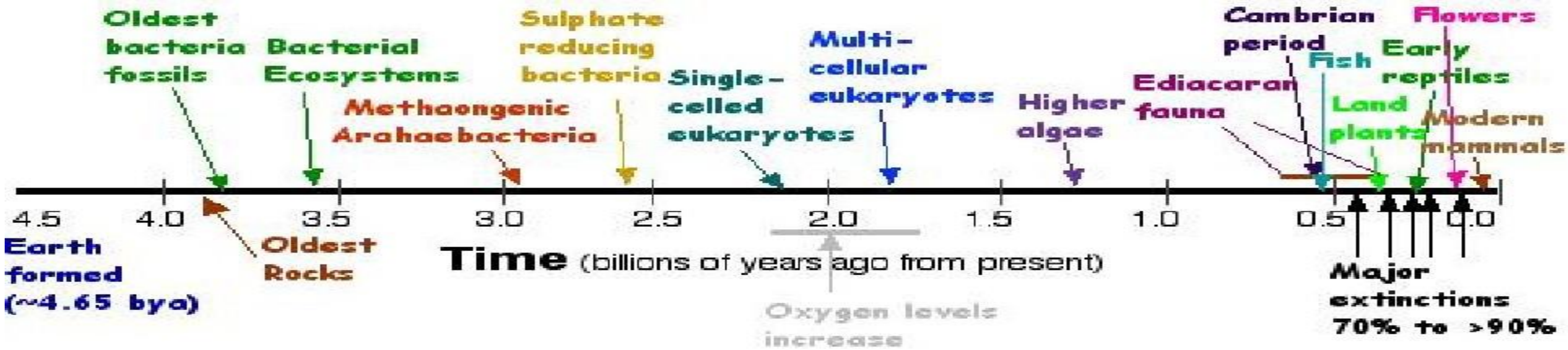
- Stromatolites
  - Living: colonies of bacteria living in outer layer of sedimentary rocks
  - 3.5 Byr old rocks: almost identical layered structure
  - Inconclusive evidence: sedimentation layering may mimic stromatolites

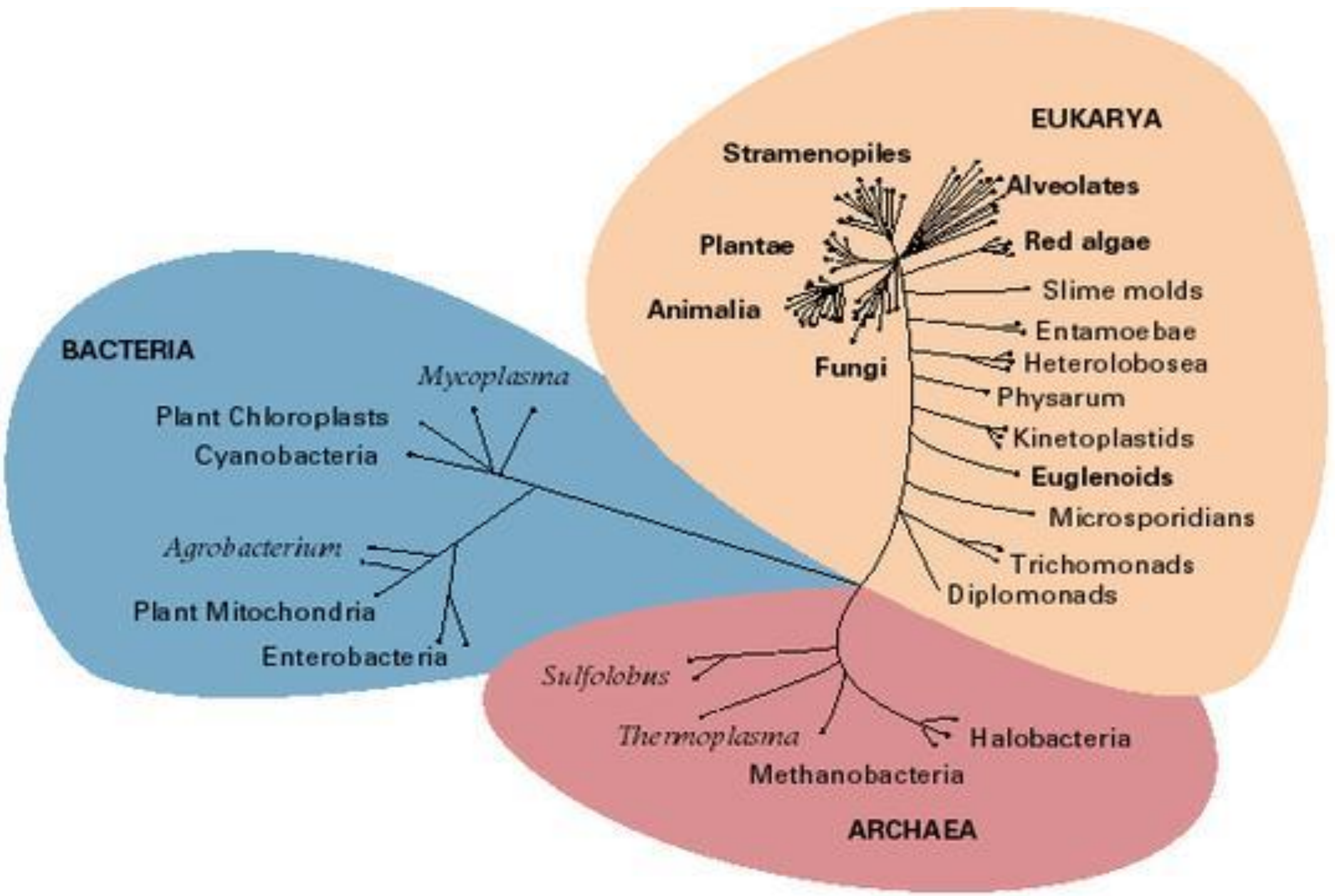




- Fossil evidence
  - 3.5 Byr old Australian rock shows “cells”
  - Could this form naturally from minerals?
  - Younger sites: at least two more (3.2-3.5 byr old)
  - Older sites: sedimentary rock too altered to be useful

- $^{13}C/^{12}C$ ratio
  - Normal abundance ratio 1/89
  - Living tissue and fossils show less ^{13}C
  - Some rocks older than 3.85 Gyr show the low ^{13}C abundance





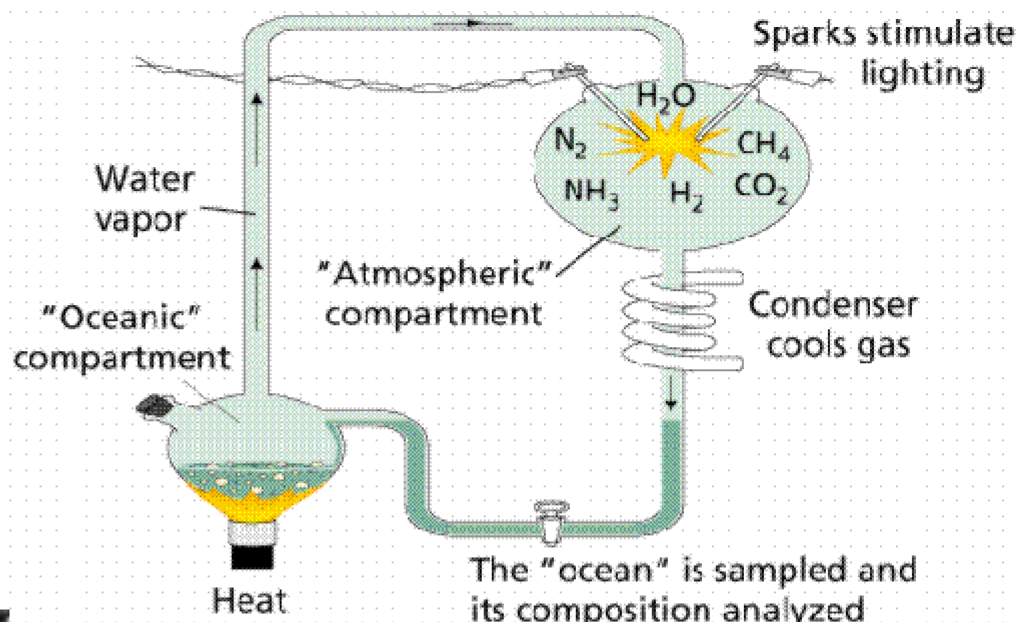
Charles Darwin 1809-1882 Hot Ponds

The Origin of Life on Earth

"primordial soup"

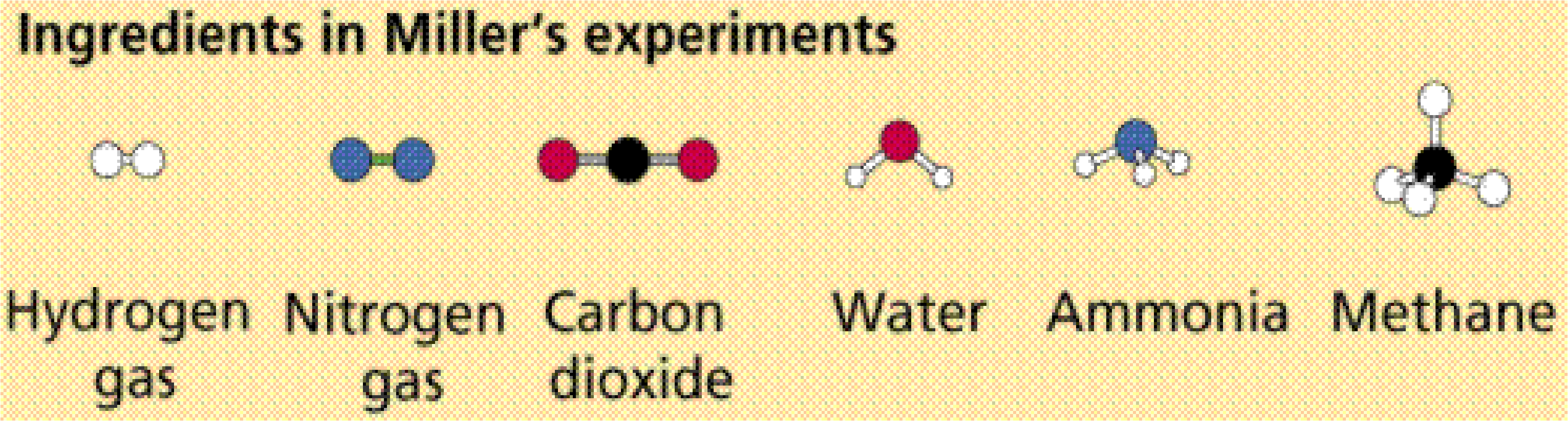
1924

The Miller Urey Experiment



SL Miller

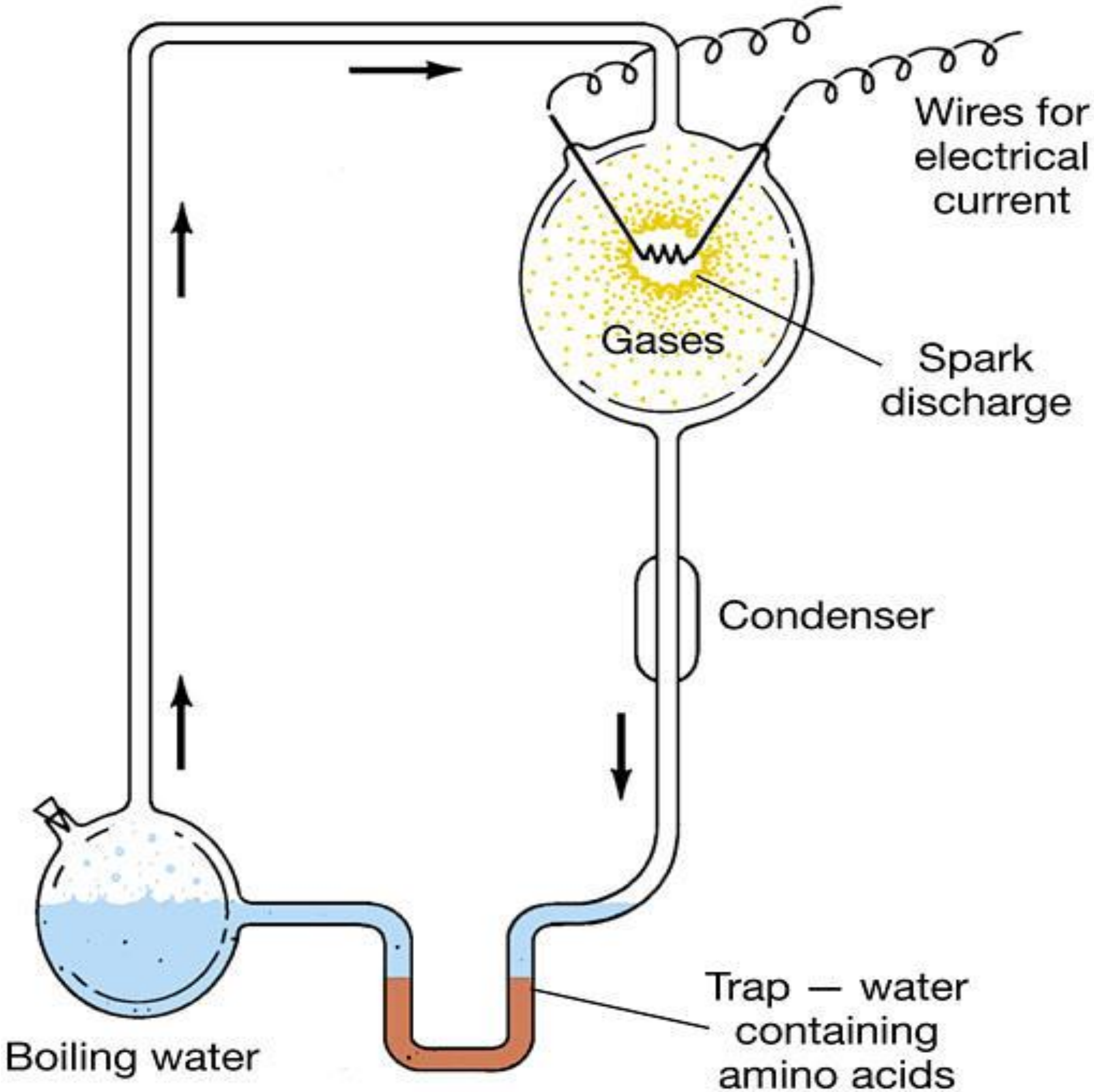
HC Urey



No Oxygen !

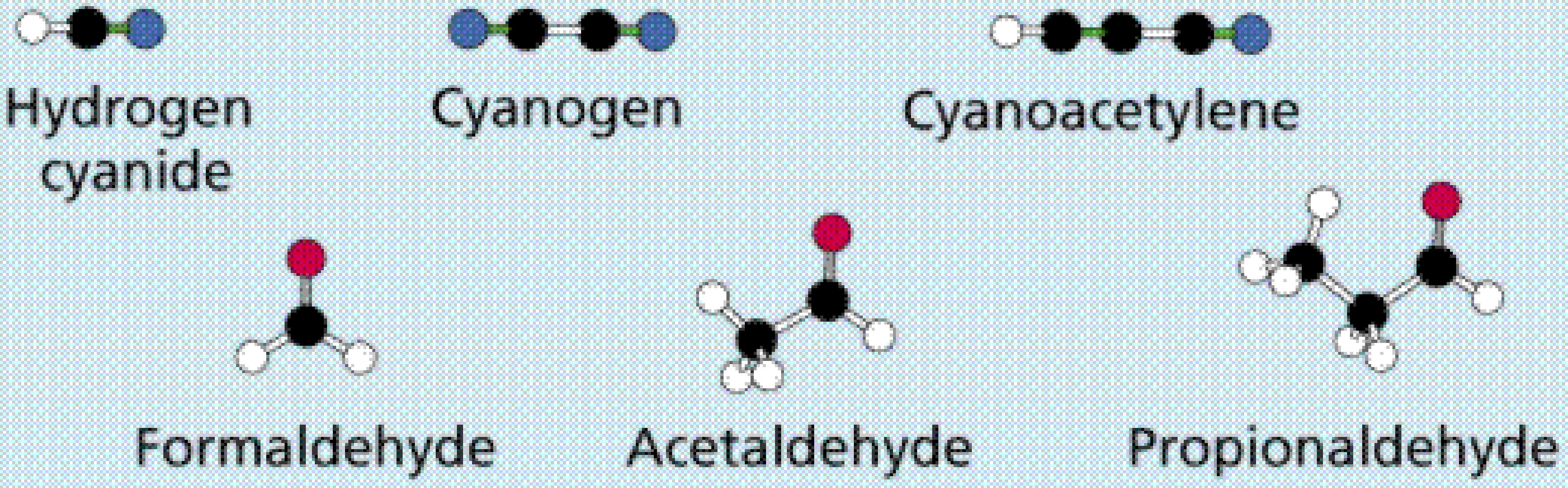
(Not in the Early Earth's Atmosphere)

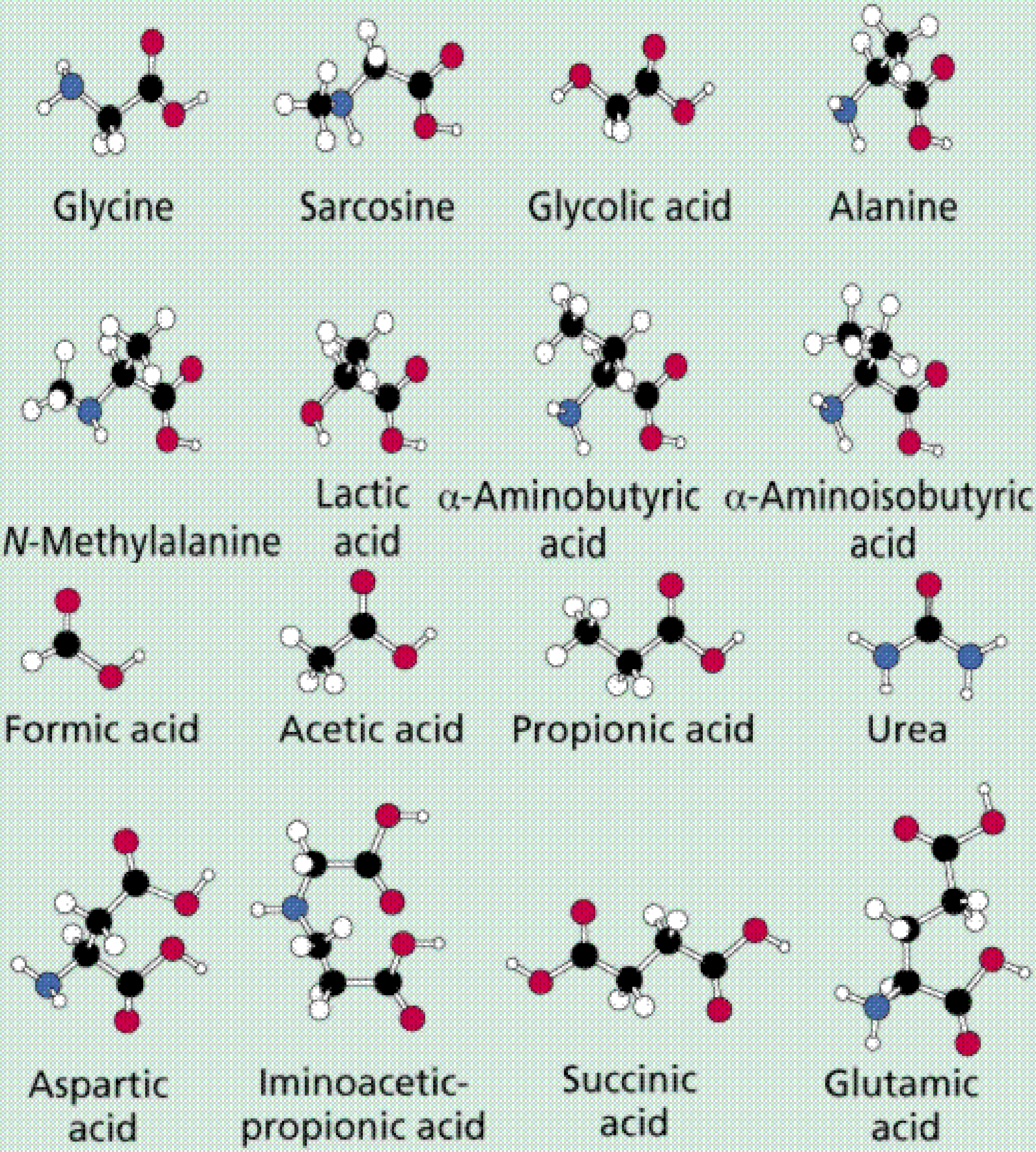
http://www.ucsd.tv/miller-urey/



Chicago
1953

Primitive molecules



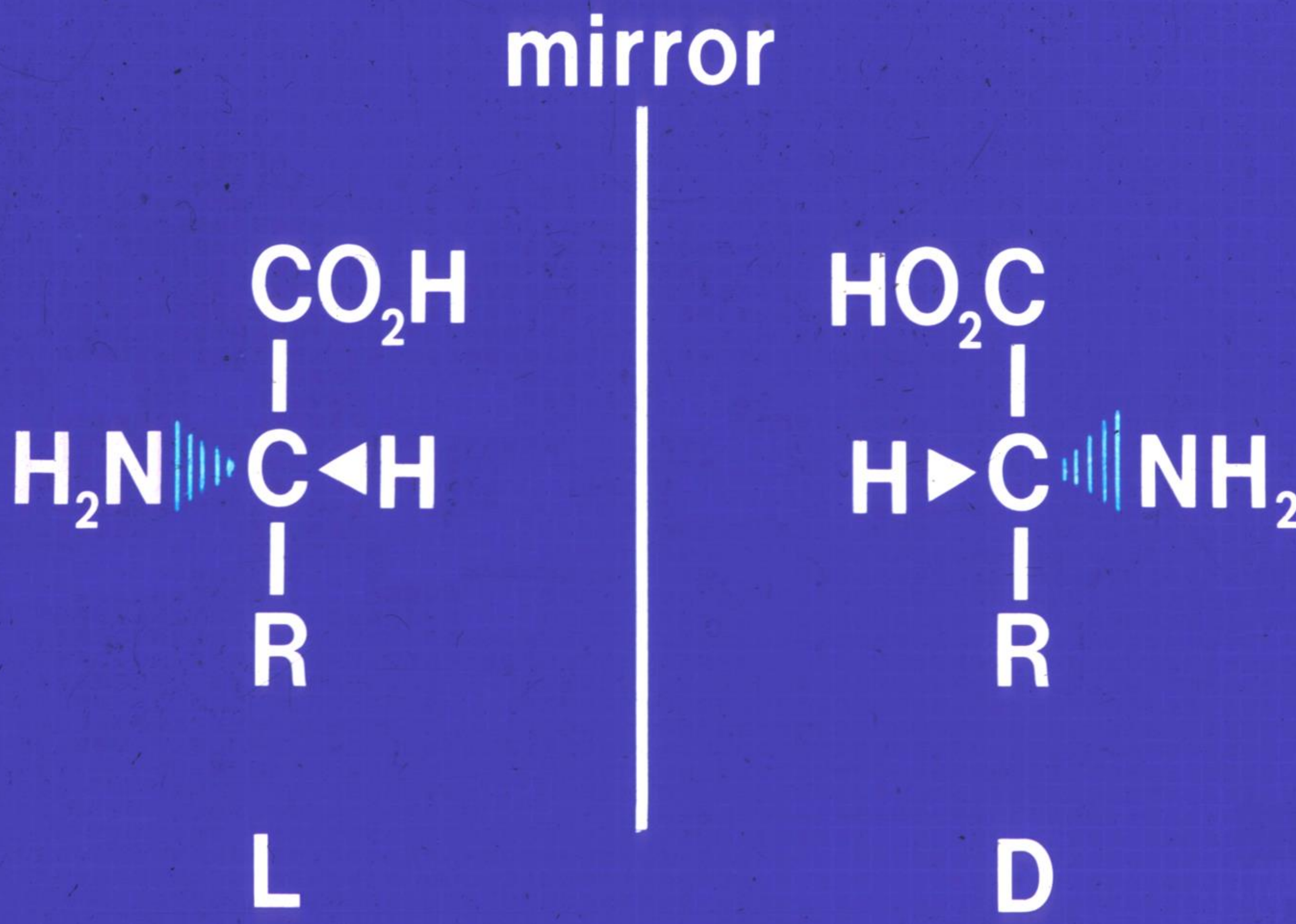


More complex molecules

NOT nucleotides

So…Is it *Right*?

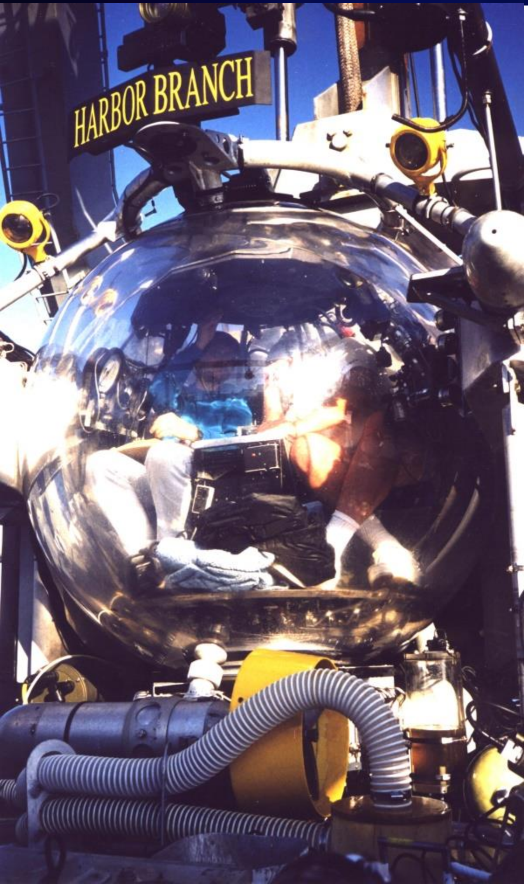
- Rocks don’t reflect such a strange atmosphere (hydrogen, ammonia, methane)
- Chemistry of products don’t reflect LIFE in the amino acids (L-amino acids)
- So where to look for “Origins”?



Stereoisomers of amino acids

Mammoth Hot Springs

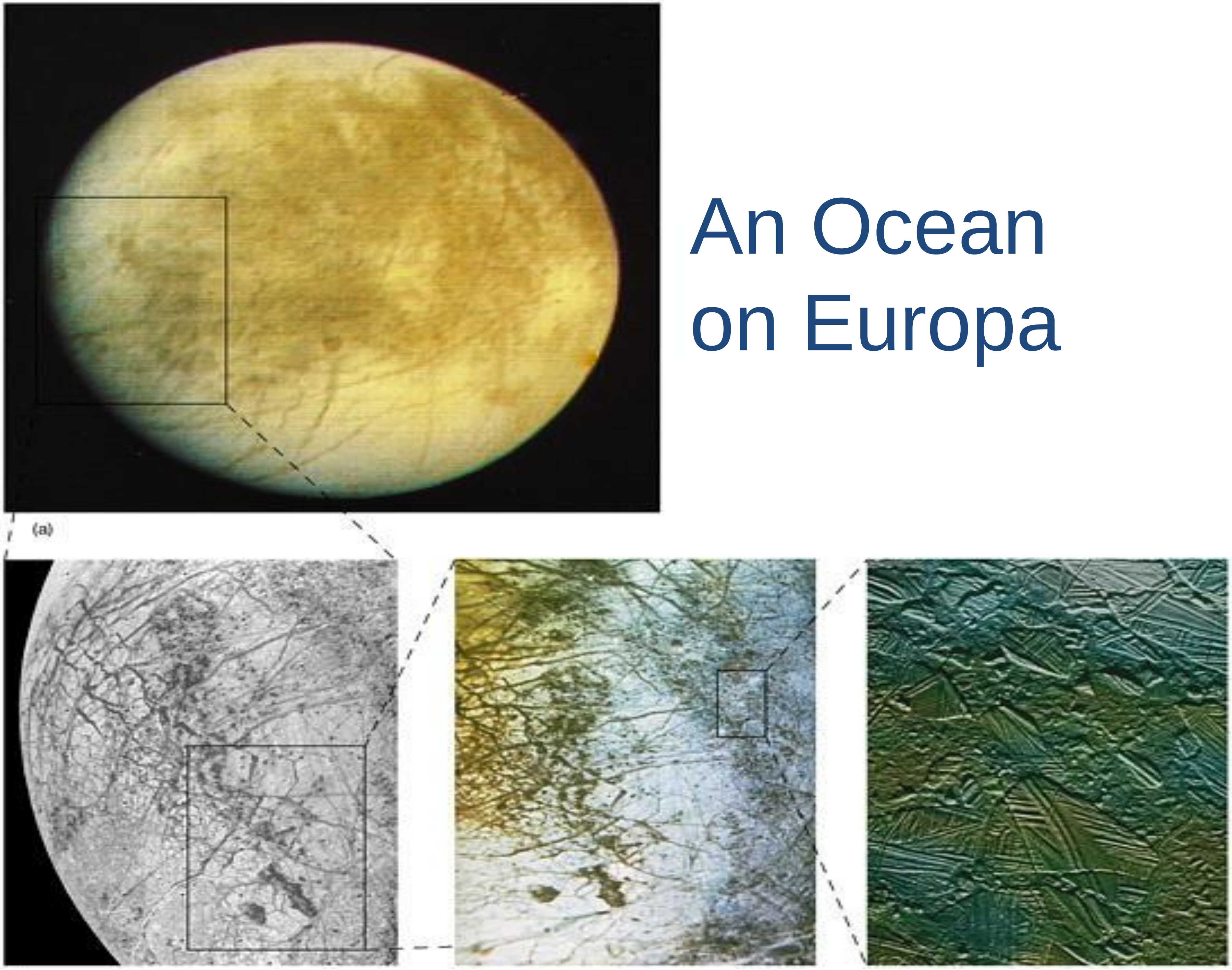
Alvin



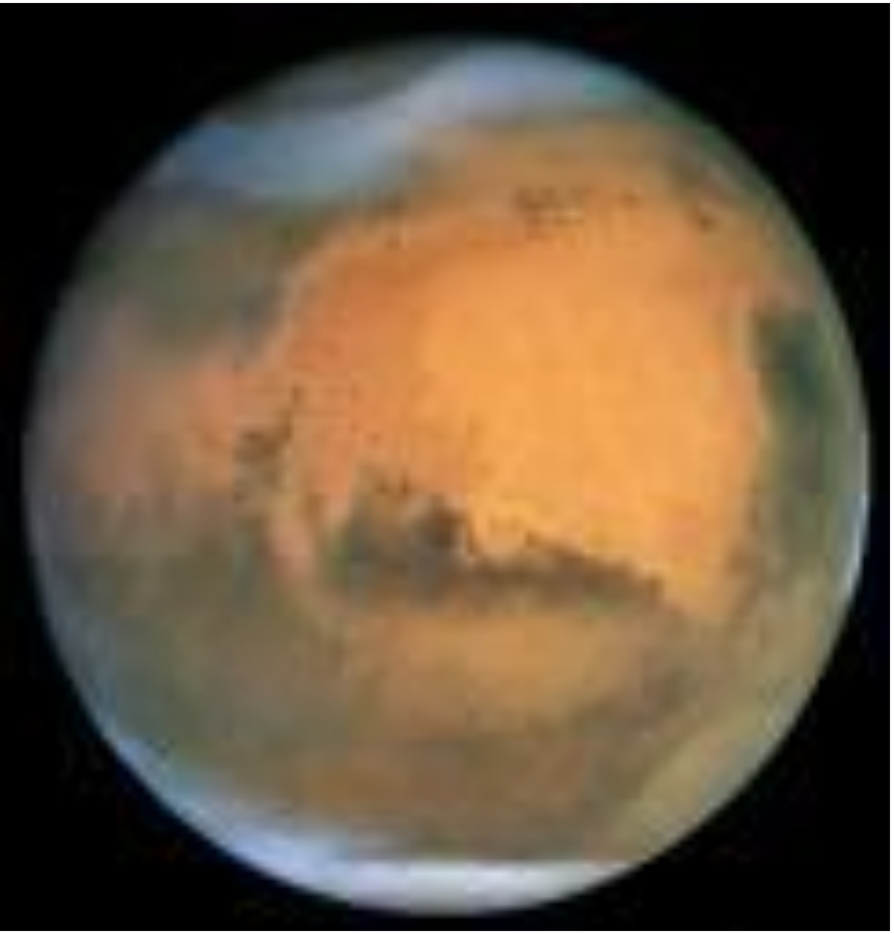
Sea Link

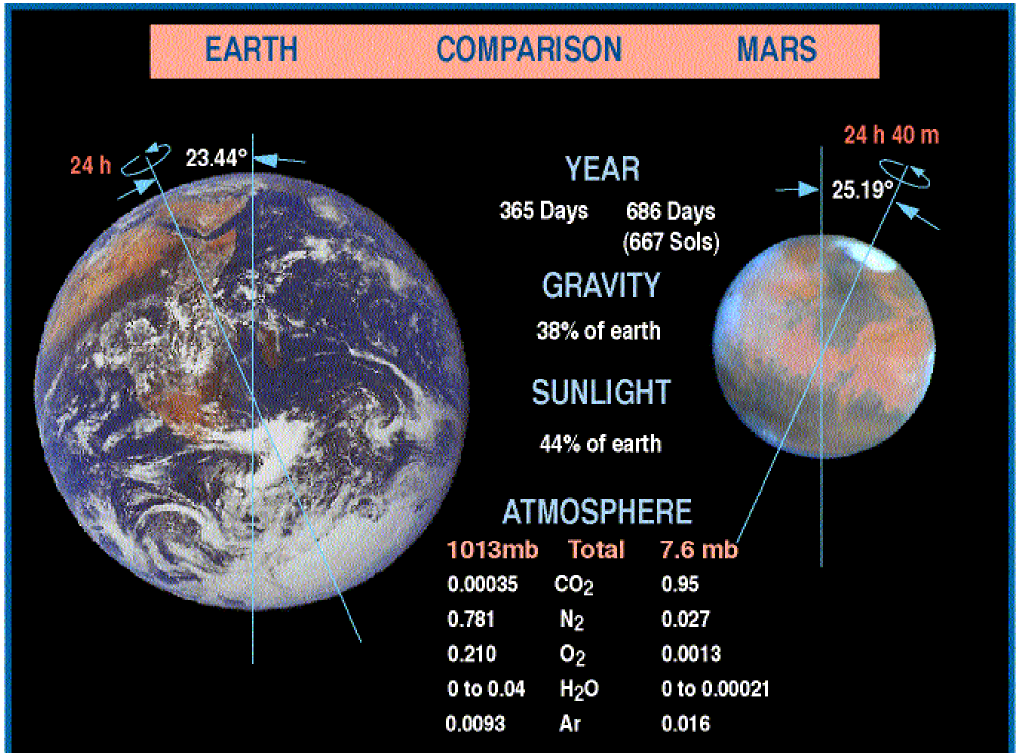
Hot Vents 250 C

An Ocean on Europa



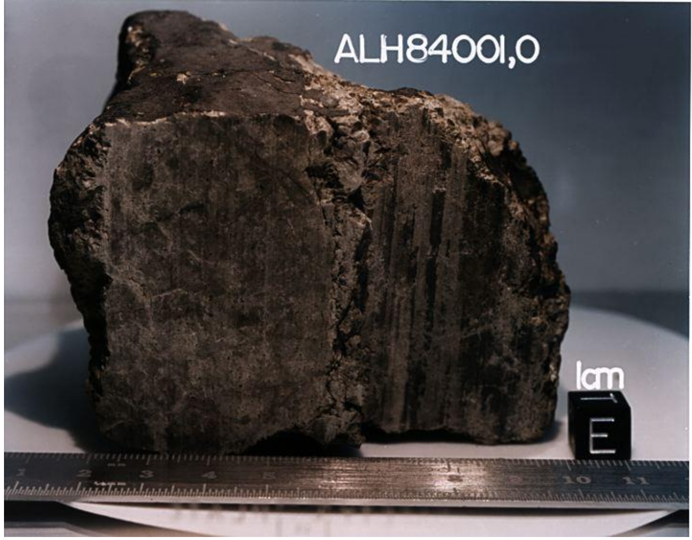
Mars

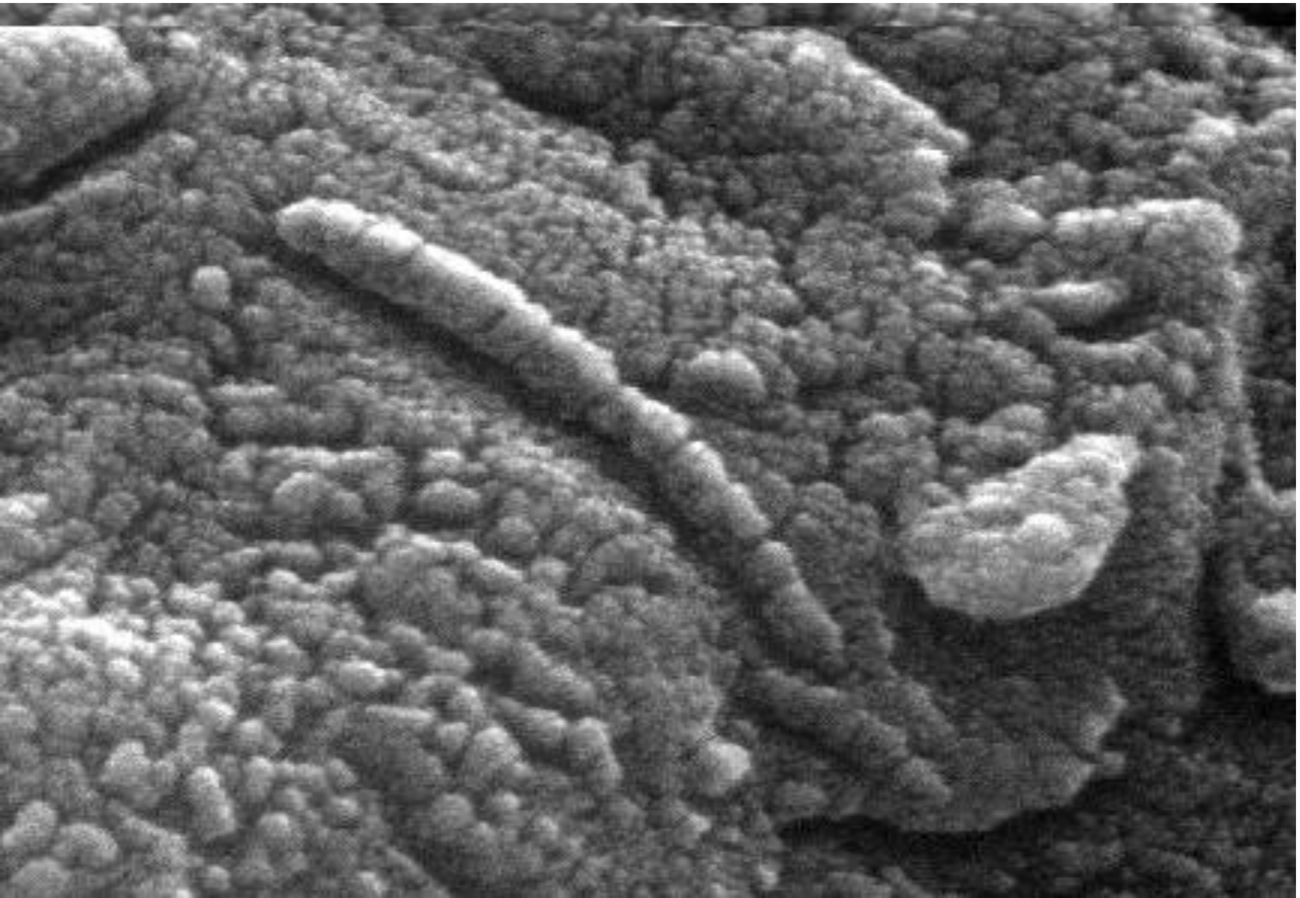



EARTH
COMPARISON
MARS
24 h
23.44°
24 h 40 m
25.19°
YEAR
365 Days
686 Days
(667 Sols)
GRAVITY
38% of earth
SUNLIGHT
44% of earth
ATMOSPHERE
1013mb Total 7.6 mb
0.00035 CO2 0.95
0.781 N2 0.027
0.210 O2 0.0013
0 to 0.04 H2O 0 to 0.00021
0.0093 Ar 0.016

Meteorite Impacts

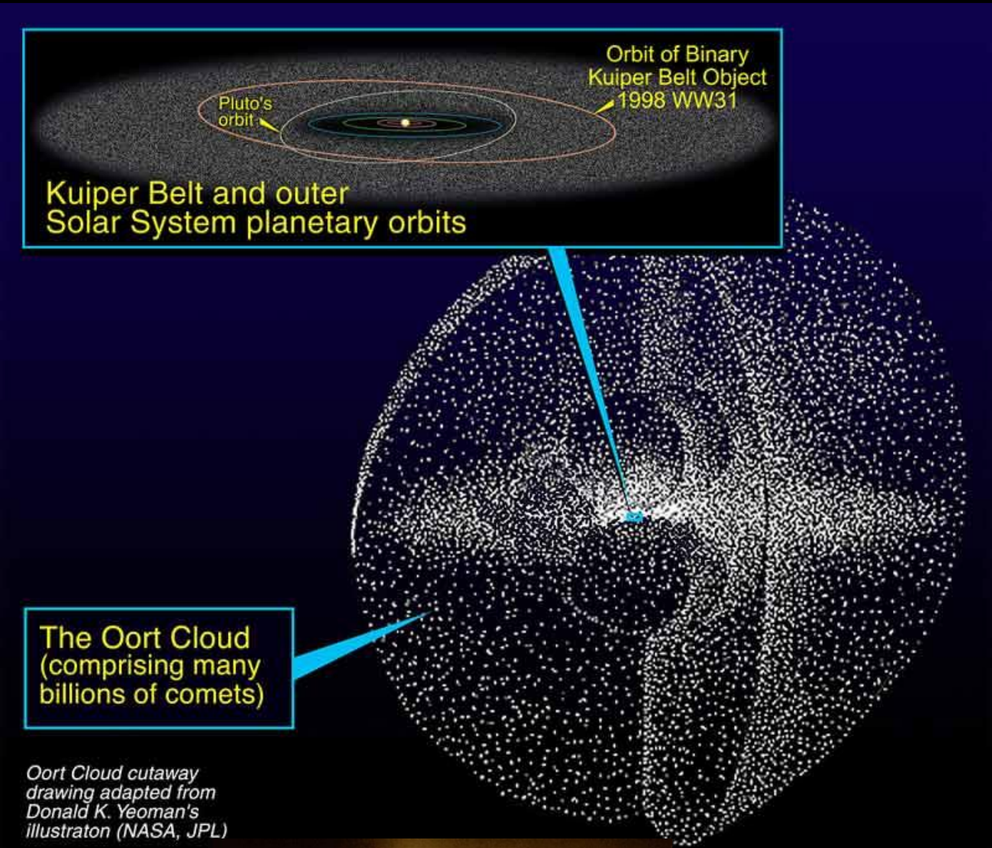
Meteorites from Mars

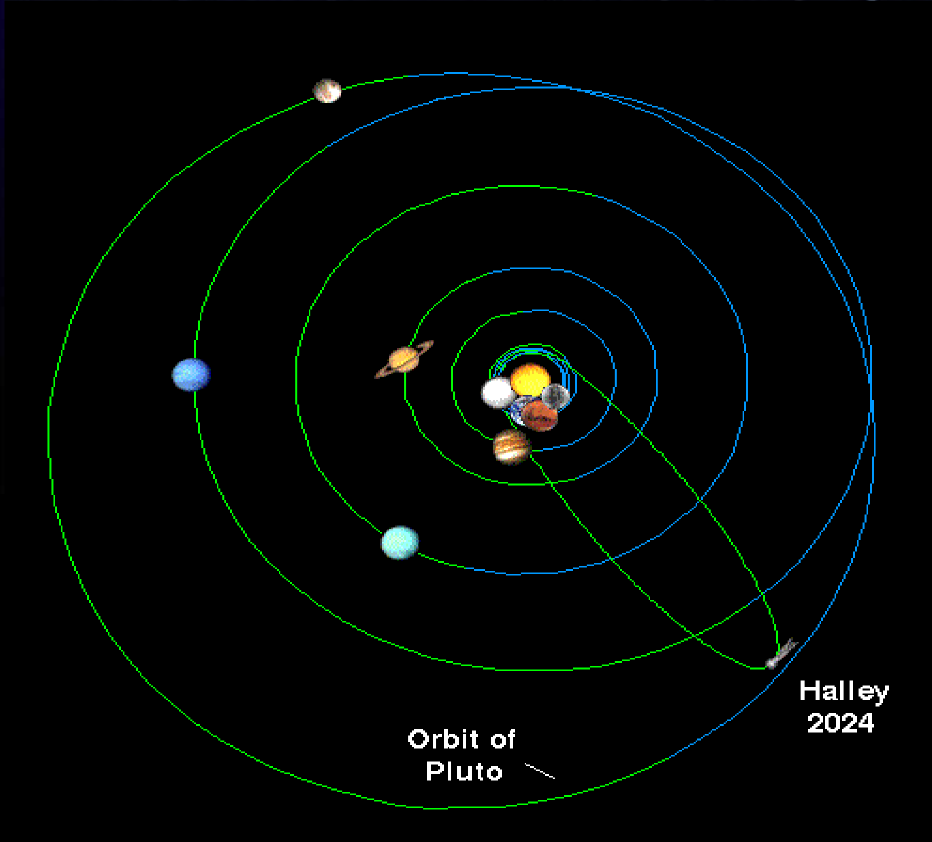




Organized microstructures

Comets


Orbit of Binary
Kuiper Belt Object
1998 WW31
Pluto's
orbit
Kuiper Belt and outer
Solar System planetary orbits
The Oort Cloud
(comprising many
billions of comets)
Oort Cloud cutaway
drawing adapted from
Donald K. Yeoman's
illustraton (NASA, JPL)


Halley
2024
Orbit of
Pluto

Still looking

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Department of Geological Sciences

Collaborative for Research in Origins (CRiO)

isotope.colorado.edu

crio.space

UNIVERSITY OF COLORADO · 1876 · LET YOUR LIGHT SHINE

MAGYAR TUDOMÁNYOS AKADÉMIA 1825

CRiO

NASA

EARTH - LIFE SCIENCE INSTITUTE

A short glossary for a diverse audience

Hadean (eon; from 4.56 – 3.85 billion years ago)

Oxygen fugacity (fO_2) – a measure of redox

Zircon ($Zr(SiO_4$) – a very useful mineral!

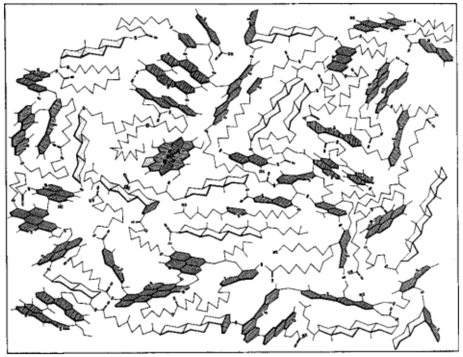
Granite (composed of ≥10% quartz, feldspar, +other minerals)

(Basalt, komatiite, peridotite, andesite, etc.) – different rocks expected on the early Earth

Closure temperature – retentivity of a mineral

Chemical partitioning – how a mineral gets its composition

Organic raw materials



*"Free Energy" from disequilibria**

Liquid water

Time

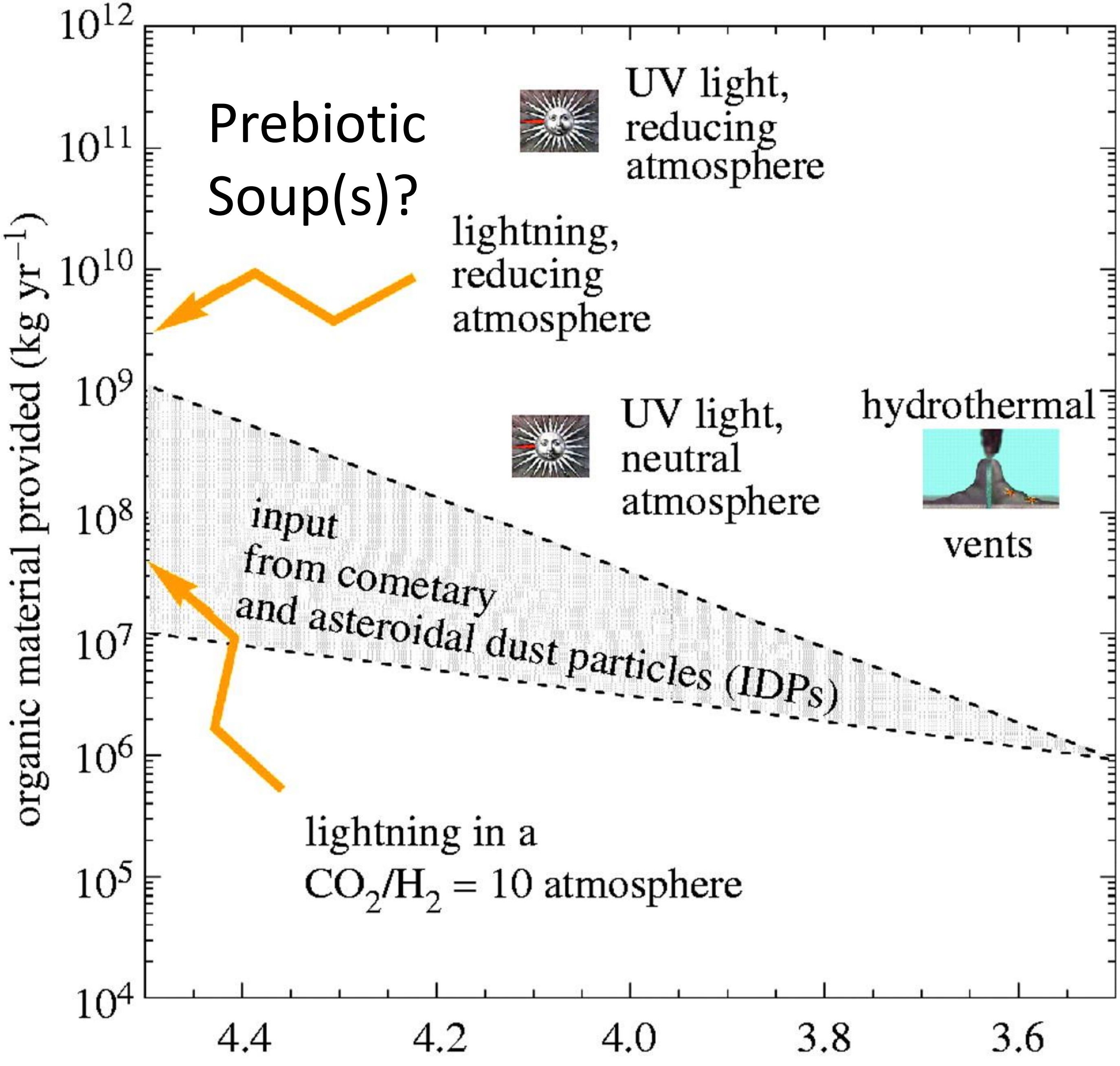
Hypothesis: Life will arise when the above conditions are met

"but the first steps are the hardest" (Mike Russell, 2014)

CAN WE MODIFY OUR FOUR CRITERIA FOR "PLANETS AS CRADLES OF LIFE"?

**E. Branscomb*

A visual representation summarizing the relative contributions of some major sources of organic molecules.

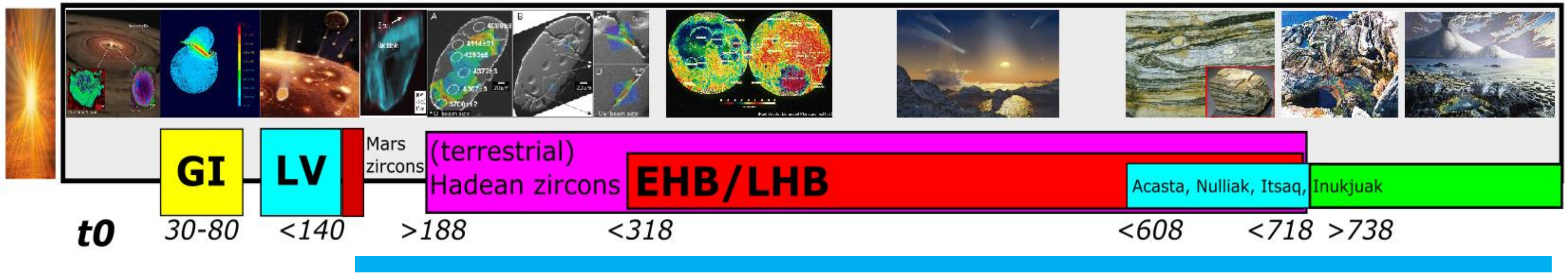


Time before present (Ga)

S.L. Miller


artwork: Cosmographica

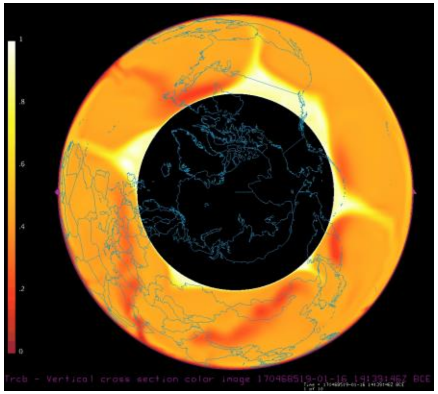

artwork: Don Dixon

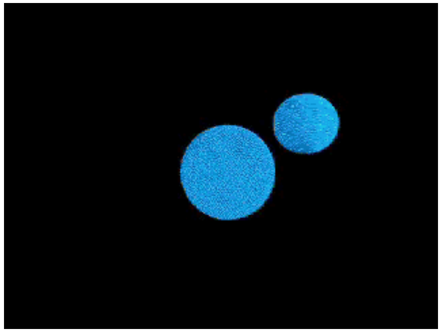


2 themes to this presentation

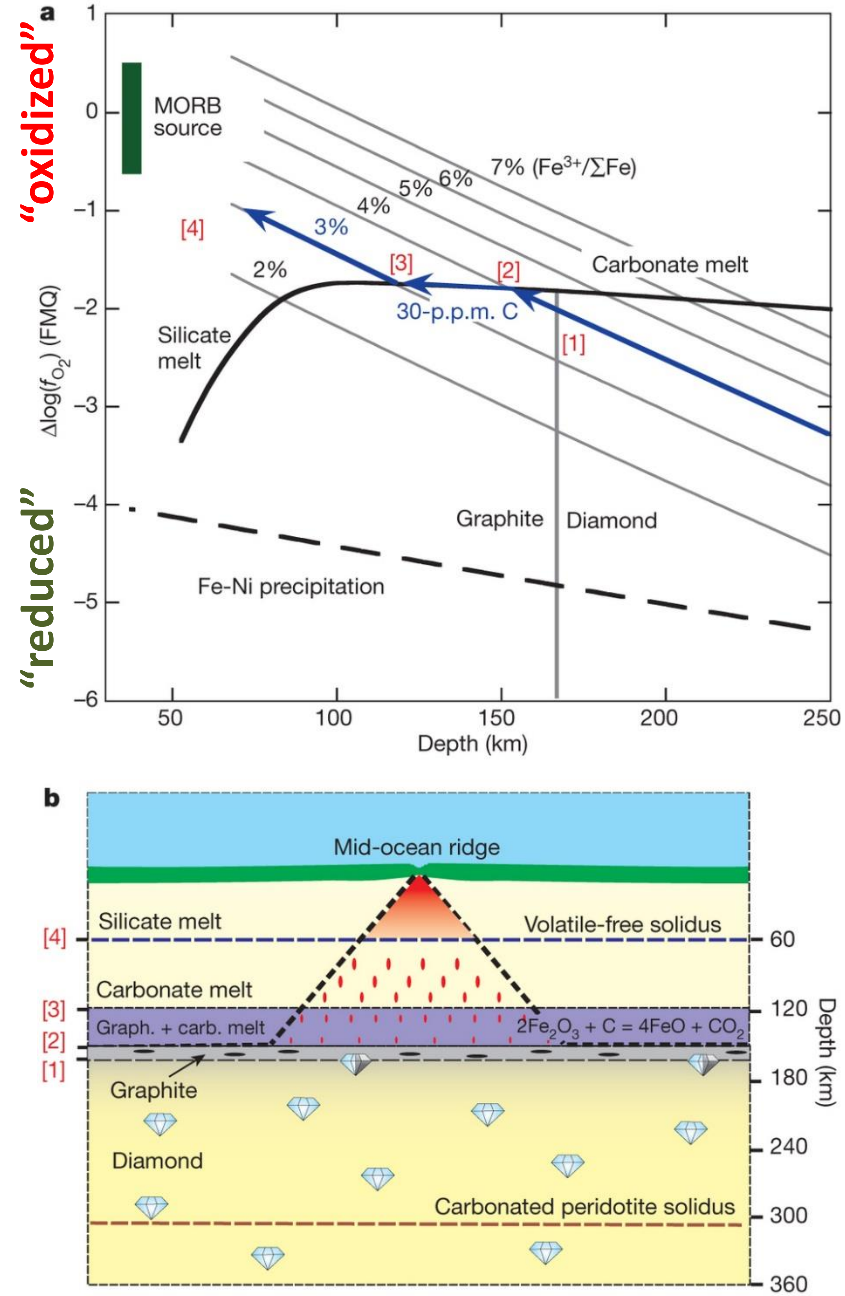
1. Evolution of mantle redox state and what this means for the origin of life

2. The crust as a platform for early life – its antiquity, volume and complexity





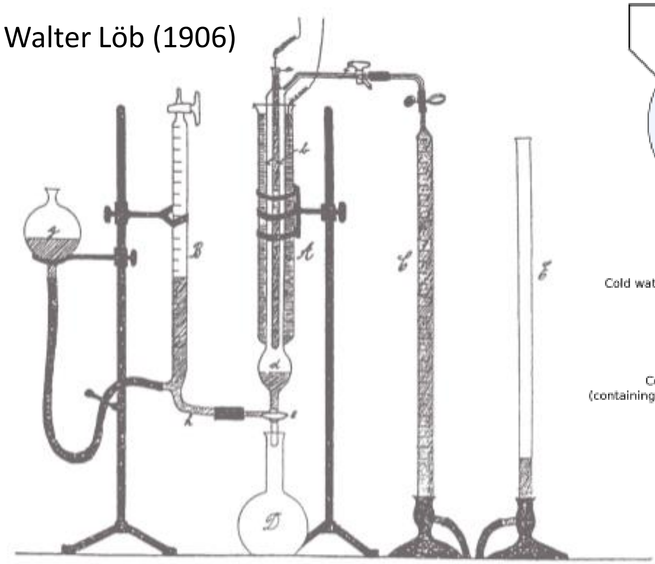
1. Mantle redox evolution

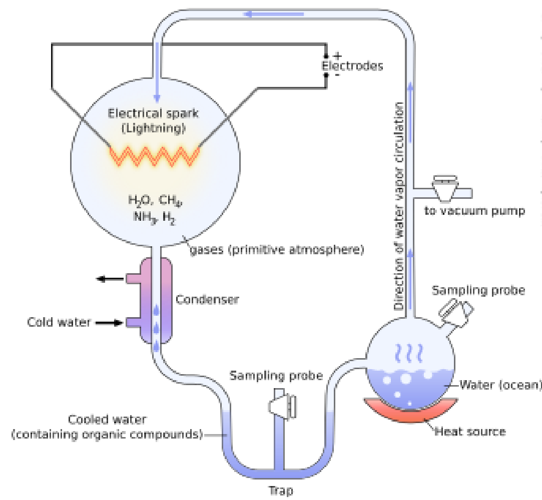


Stagno et al. (2012)

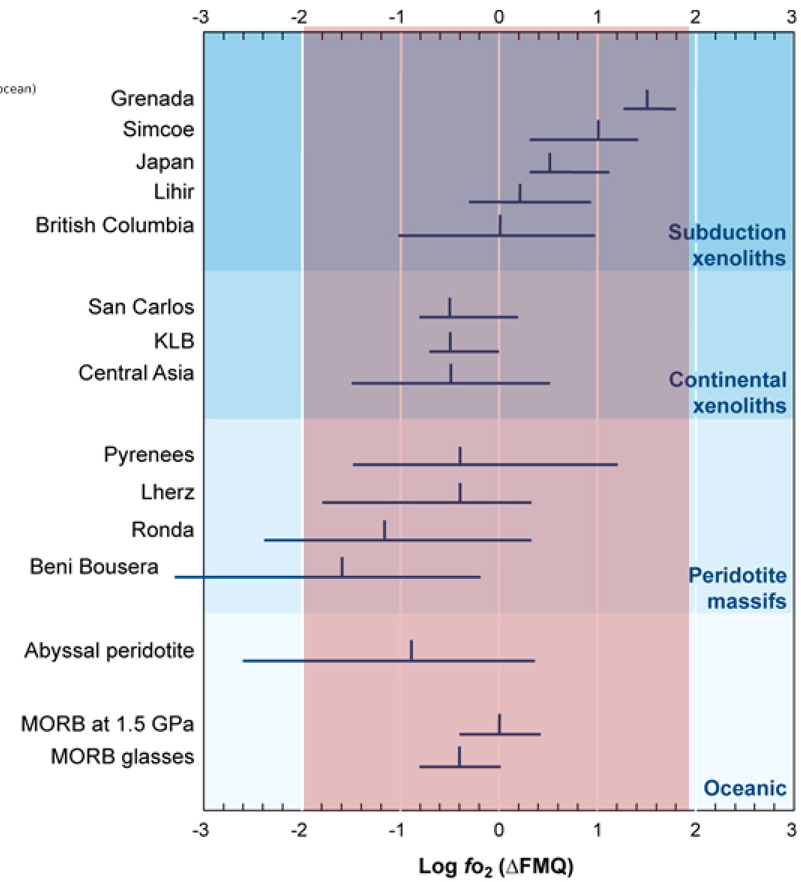
The evolution of oxygen fugacity in Earth's silicate mantle affects the speciation and mobility of volatile elements in the interior and has controlled the character of degassing species from the Earth since the planet's formation.

Walter Löb (1906)





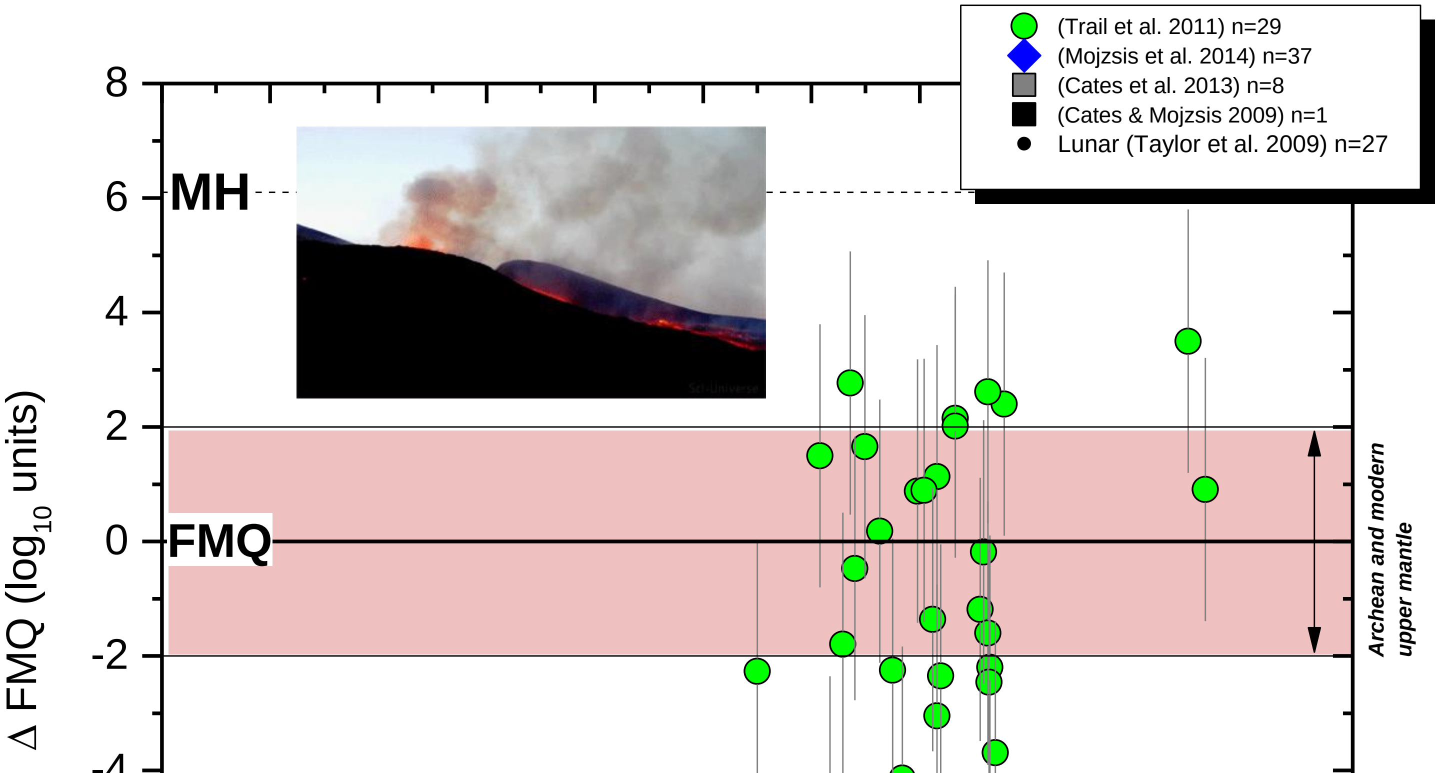
S. Miller & H. Urey (1952)

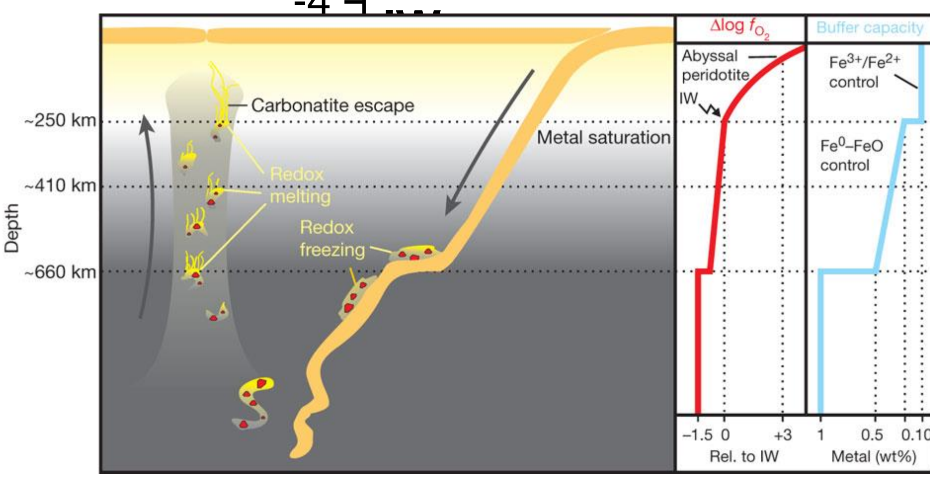


V/Sc ratios of peridotites and basalts from the Archean cover a similar range to present-day samples, with the inference that upper mantle fo_2 could have risen by no more than 0.3 log units over the last 3.5 Gyrs of Earth's history (Li & Lee 2004). Delano (2001) reached a similar conclusion by studying Cr.

SOME IMPORTANT RECENT PROGRESS

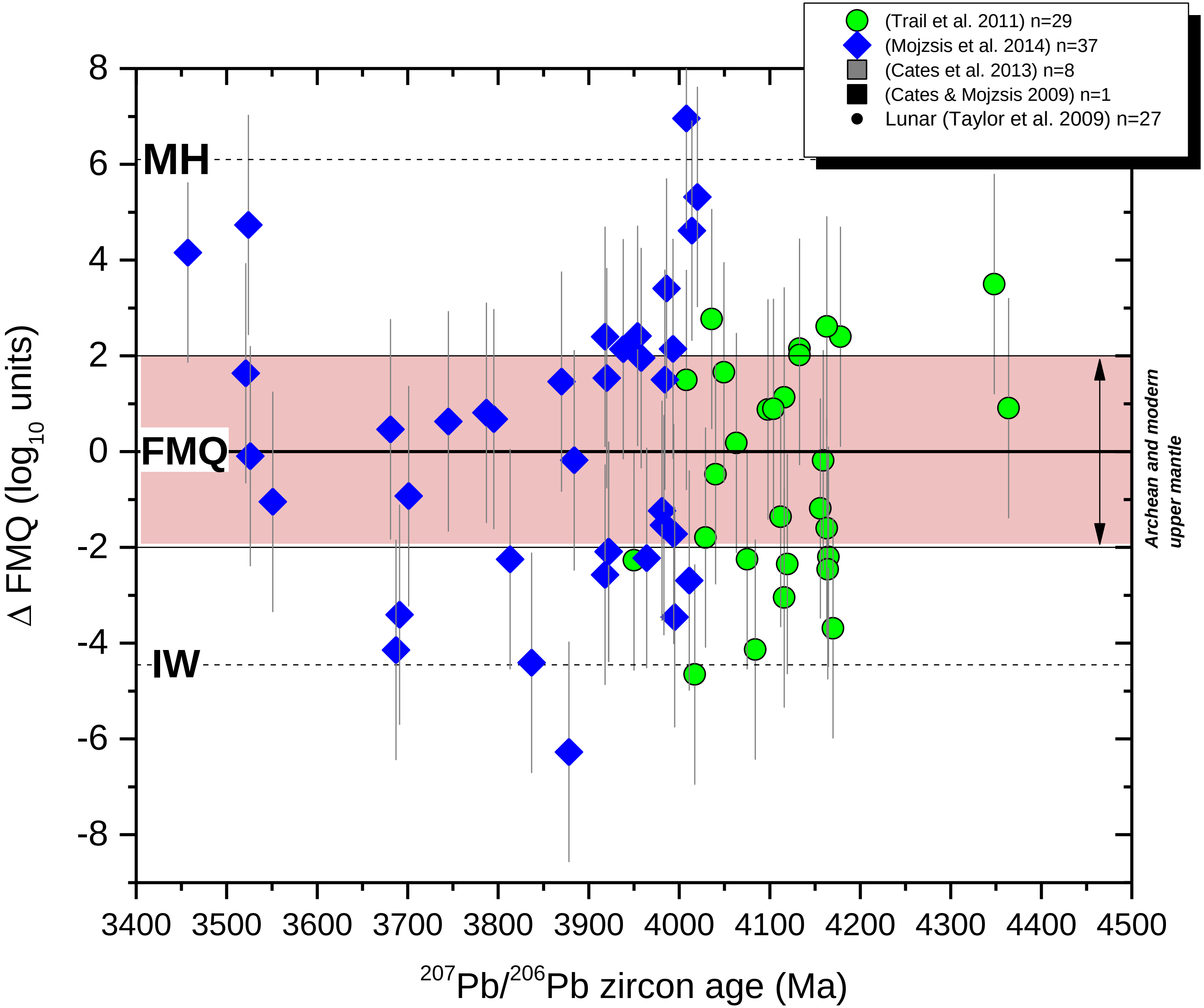
Evolution of terrestrial mantle oxygen fugacity from $[Ce/Ce^*]_{zircon}$





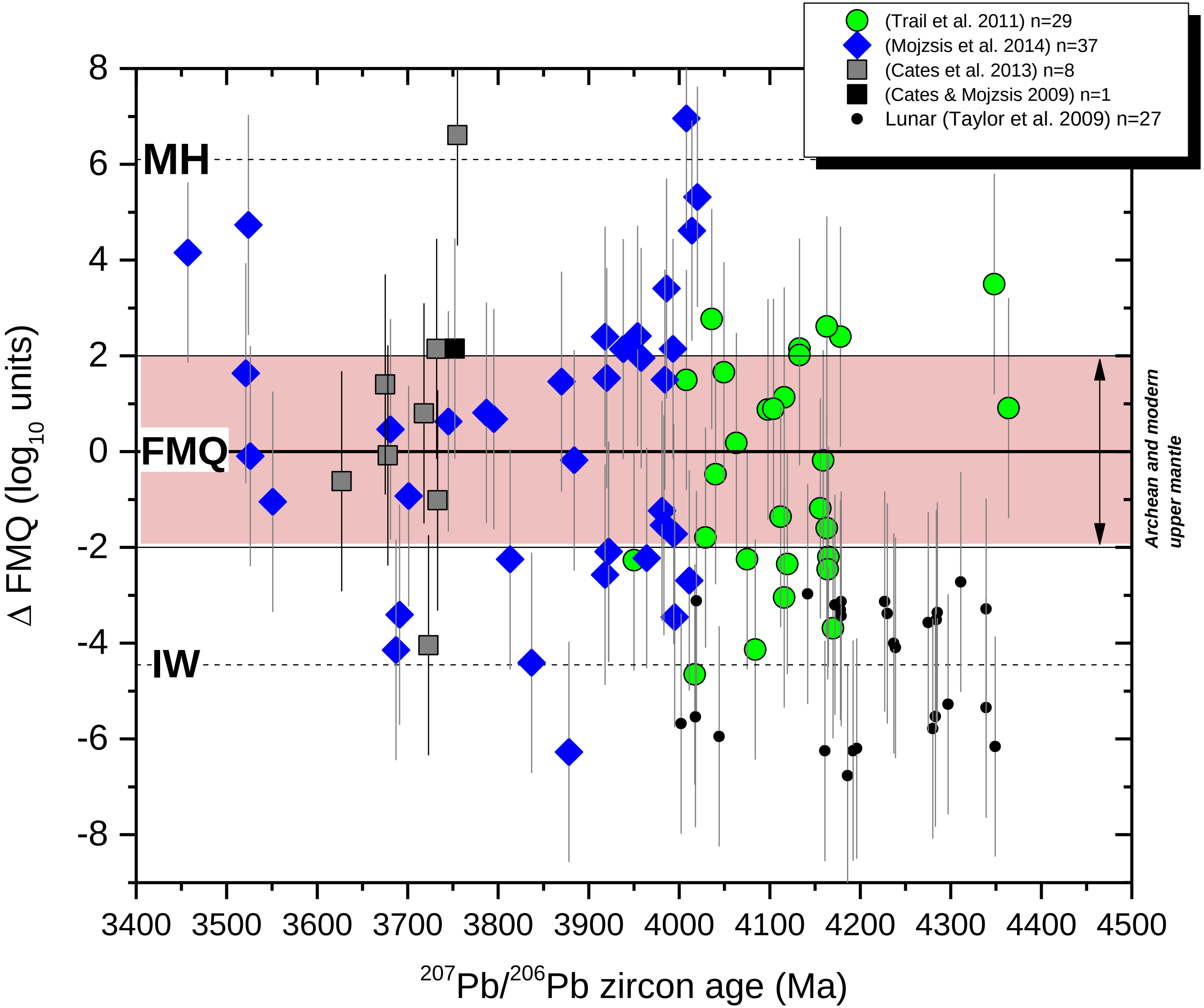
Rohrbach & Schmitt (2011)

Evolution of terrestrial mantle oxygen fugacity from $[Ce/Ce^*]_{zircon}$



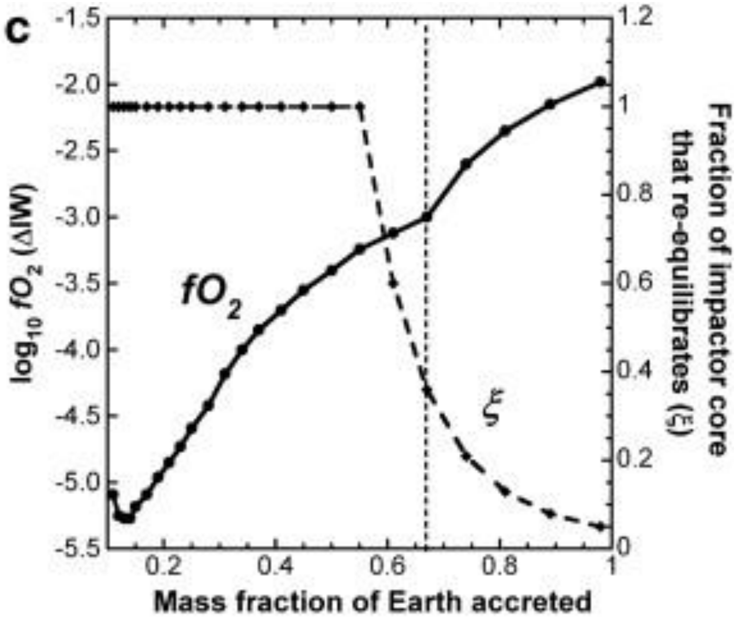
Mojzsis (2018)

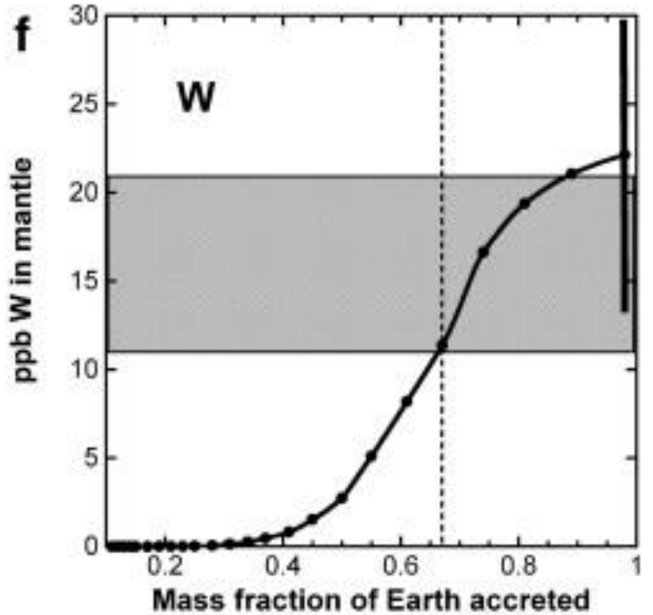
Comparative mantle oxygen fugacities (Earth vs. Moon)

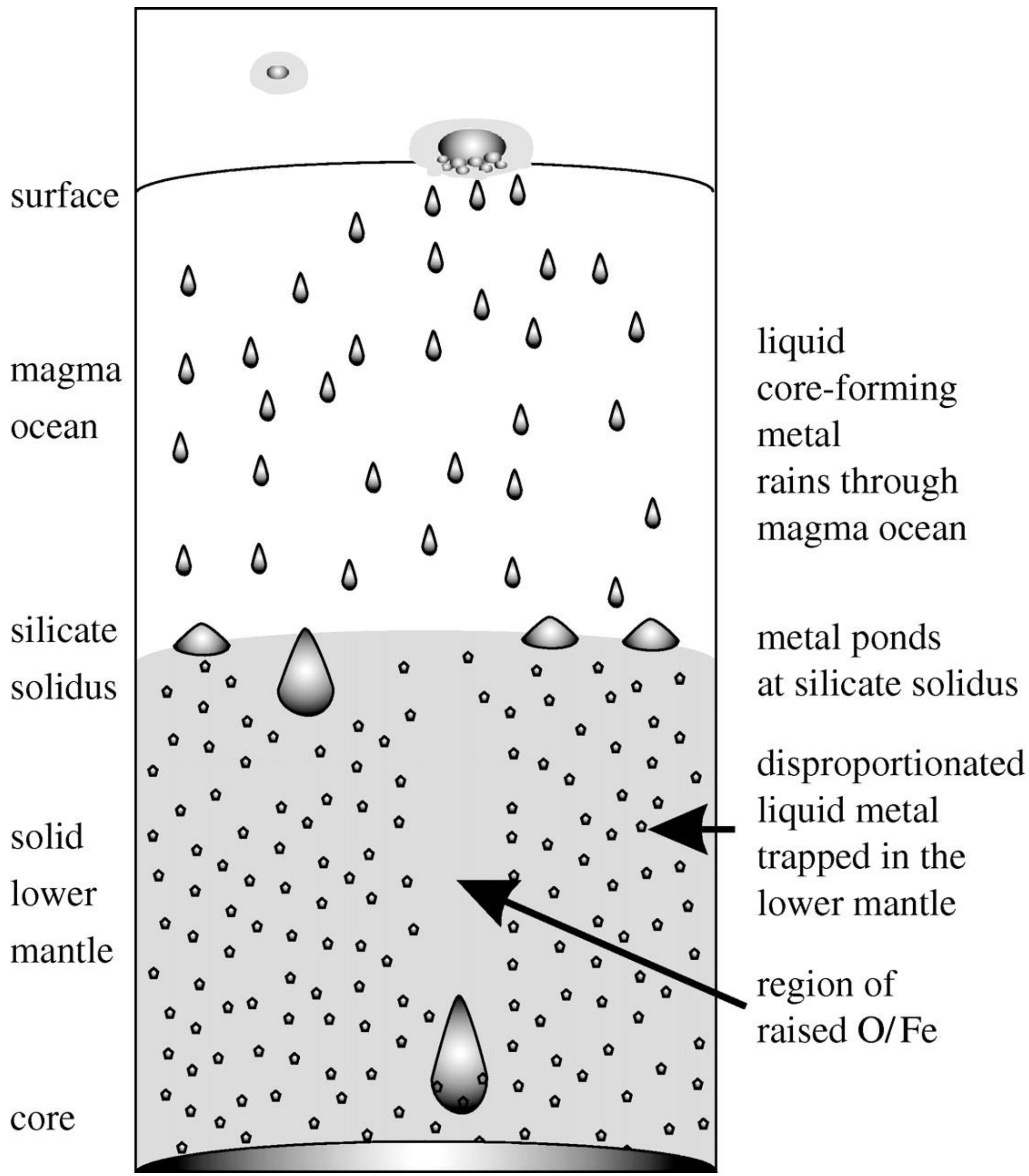


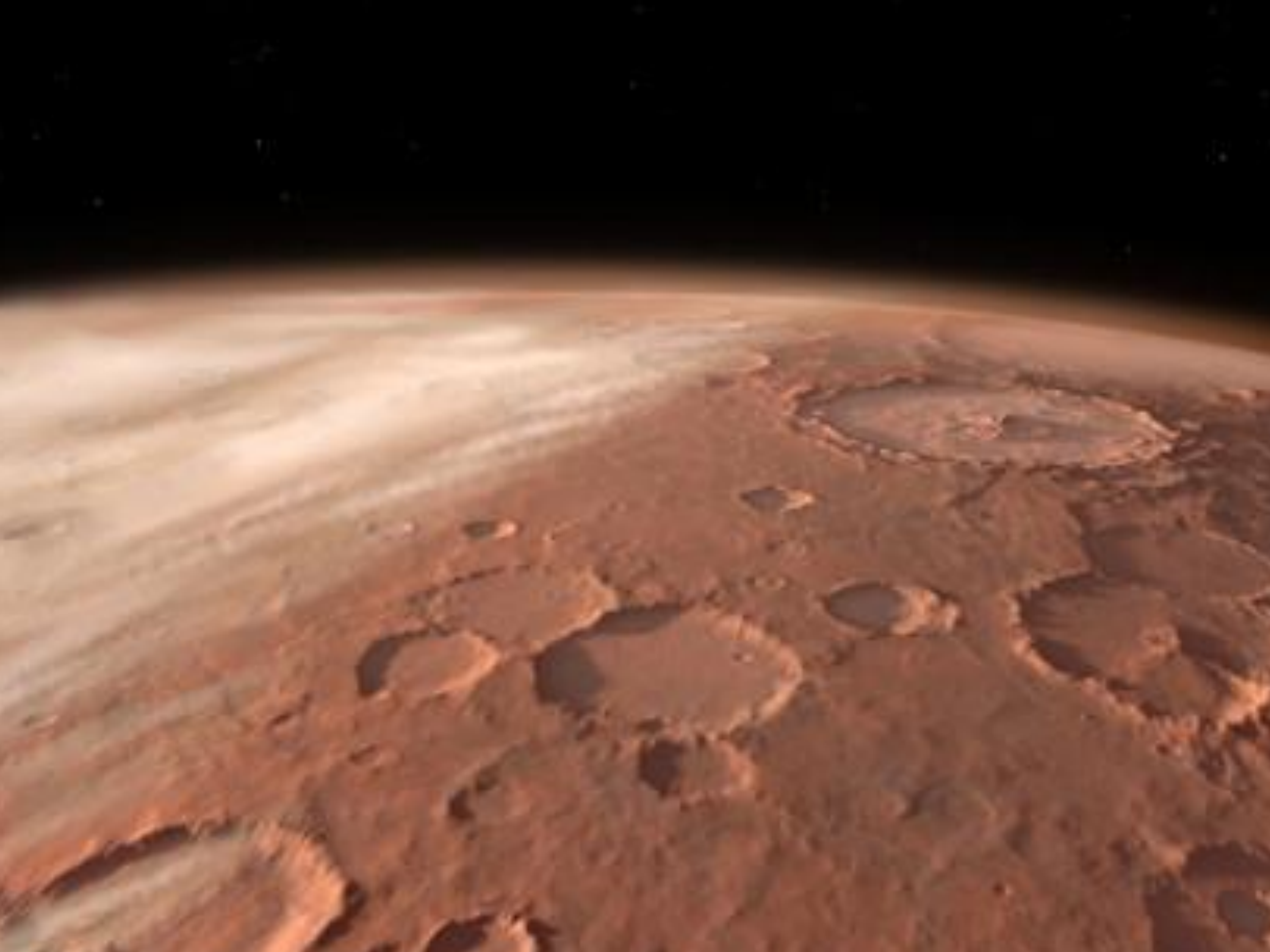
Mojzsis (2018)

Frost et al., 2008



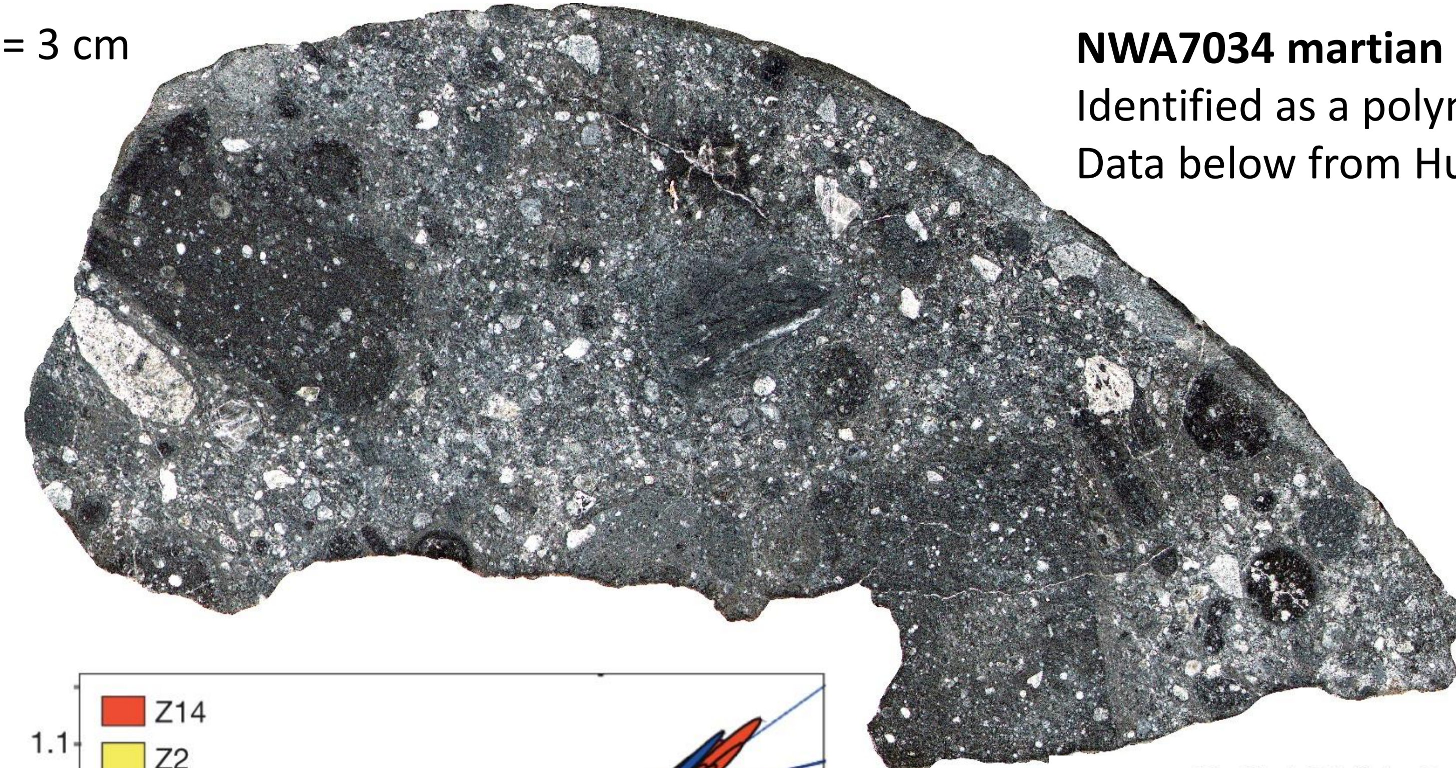


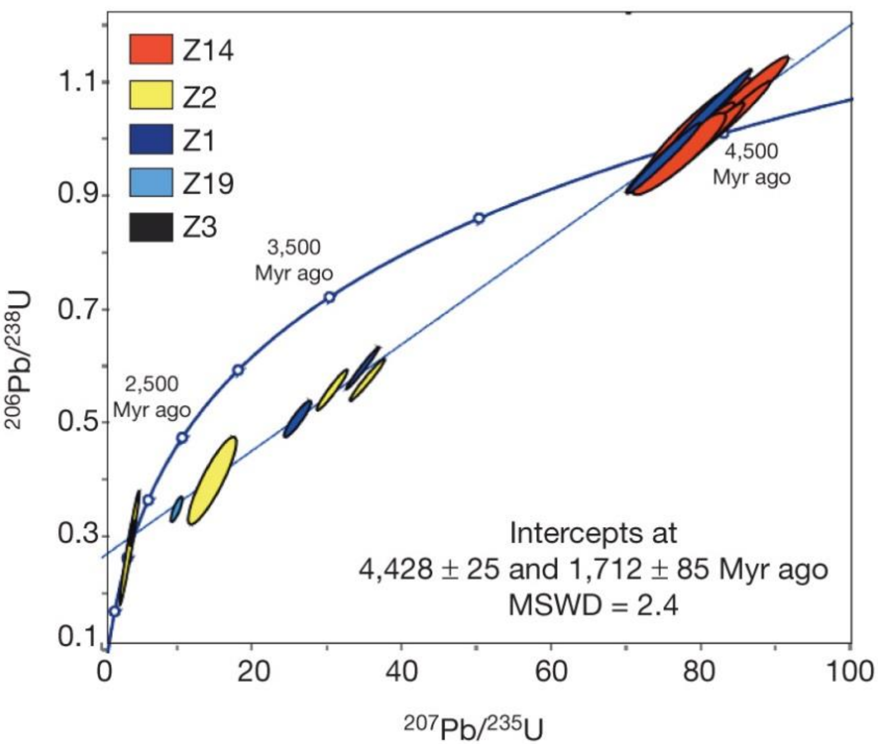


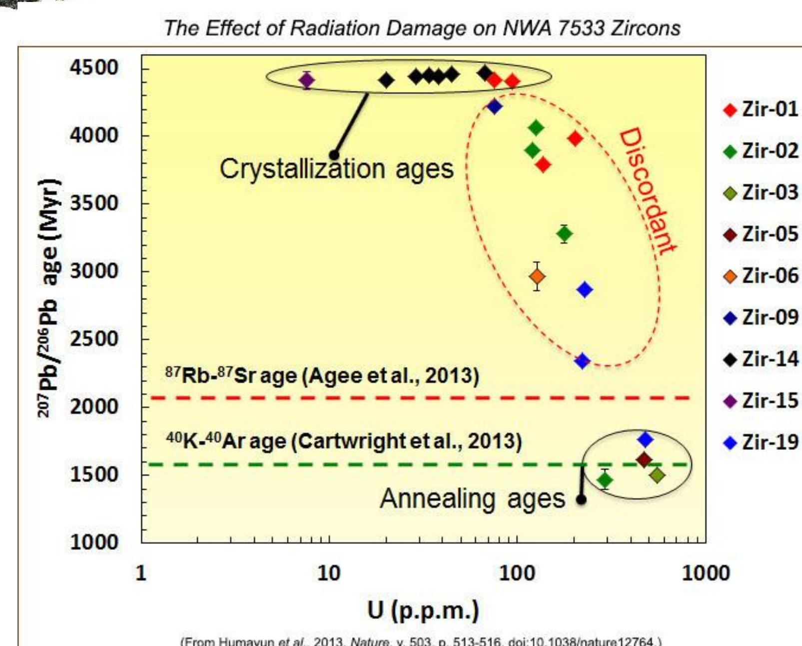


l = 3 cm

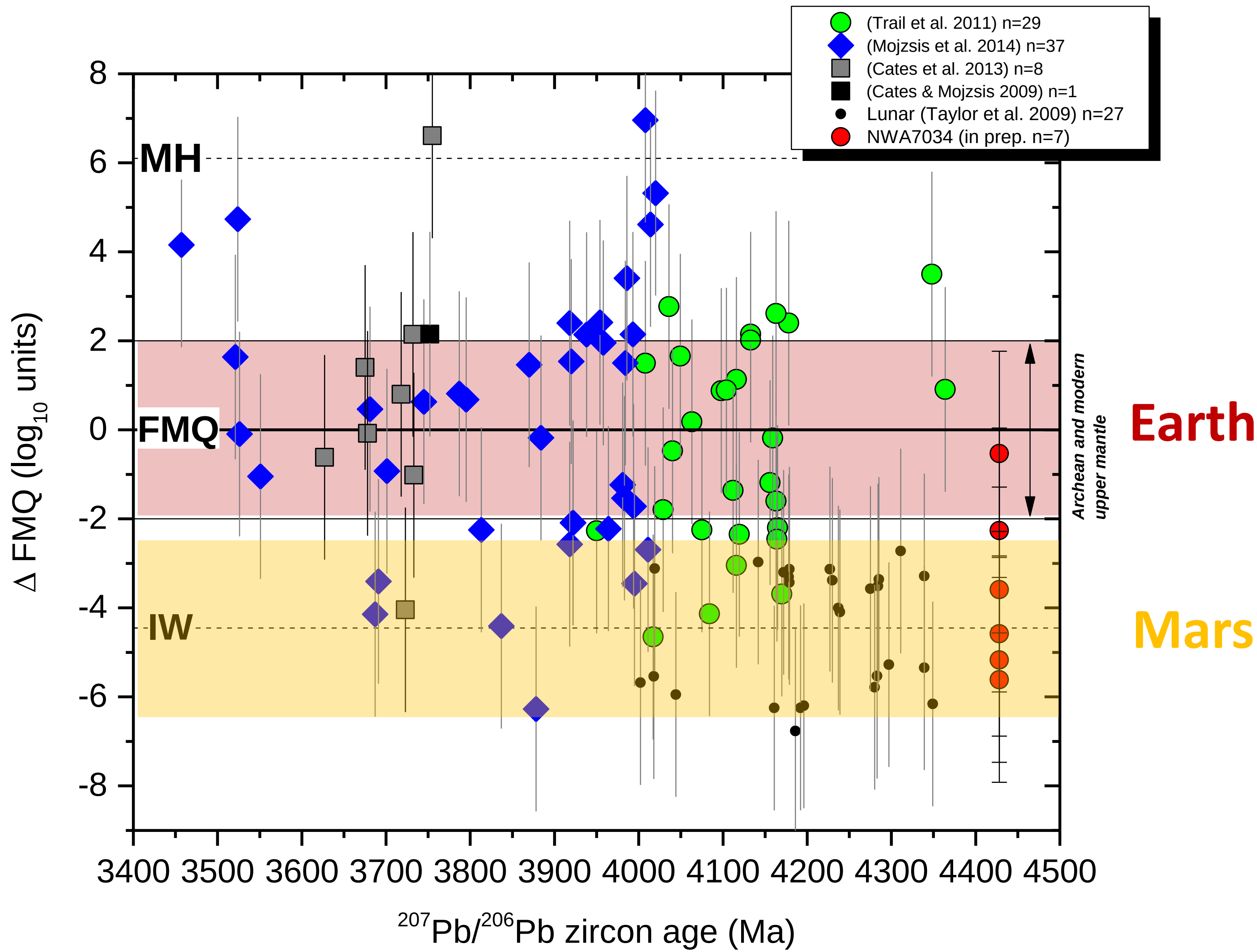
NWA7034 martian meteorite
Identified as a polymict regolith breccia
Data below from Humayun et al. (2013)





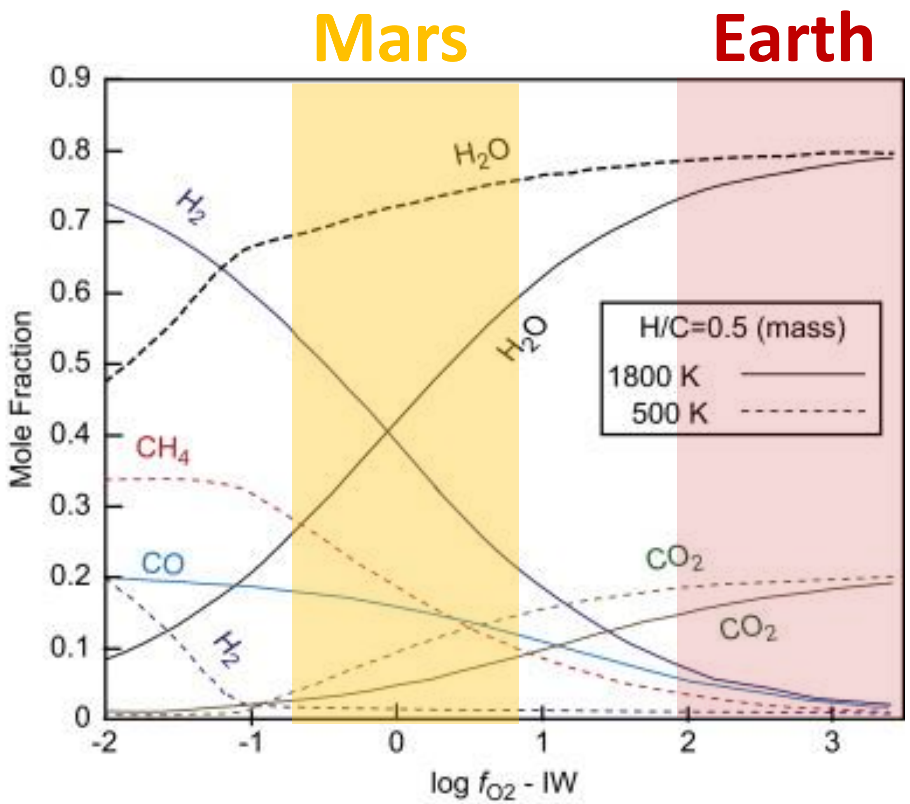


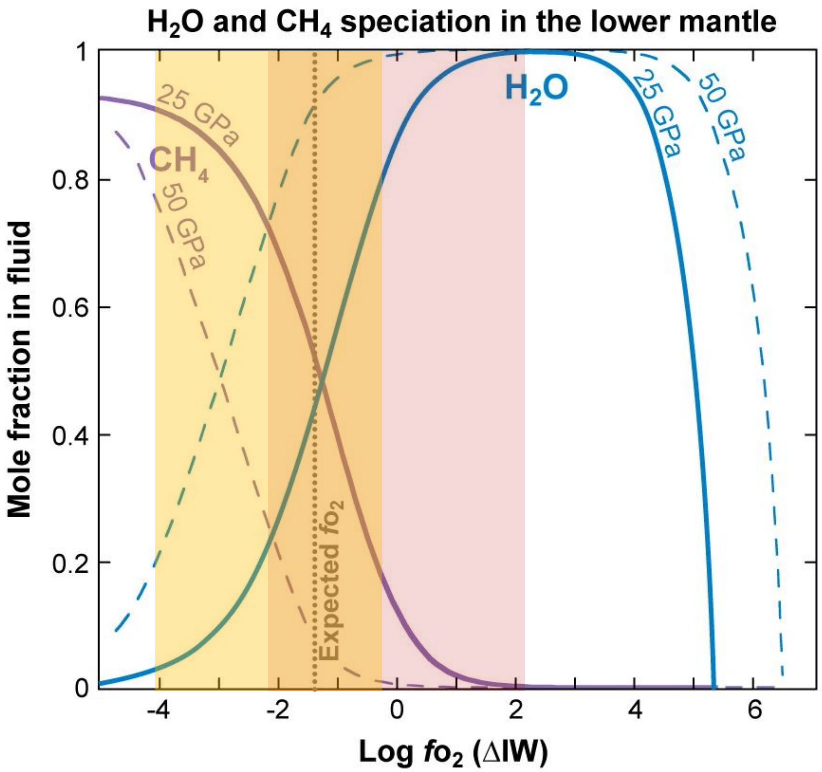
Comparative mantle oxygen fugacities (Earth vs. Moon vs. Mars)



Mojzsis (2018)

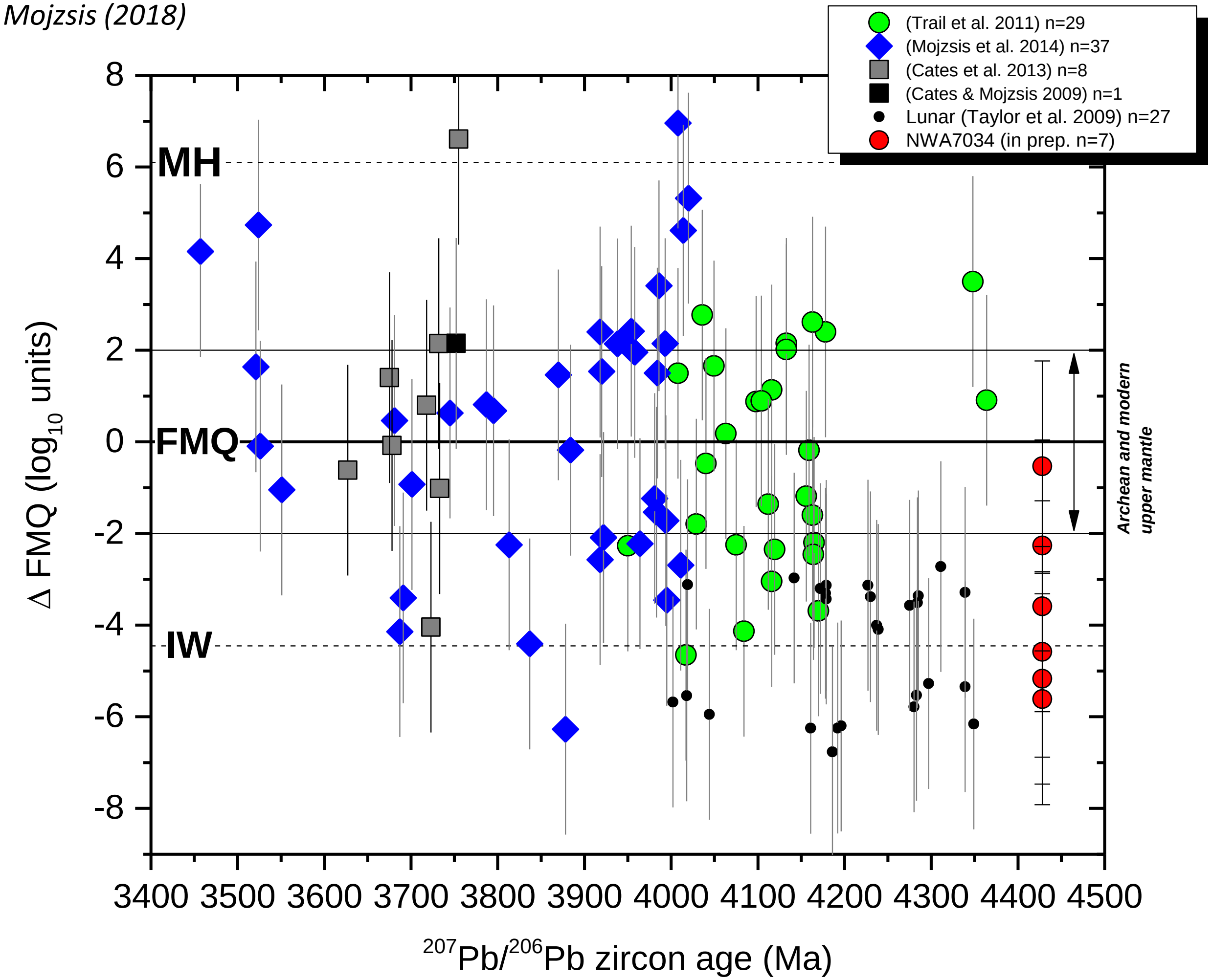
Speciation of volcanic gases on early Earth and early Mars



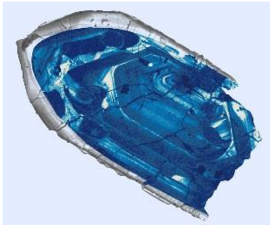


Hirschmann (2012); Frost & McCammon (2008)

Mojzsis (2018)

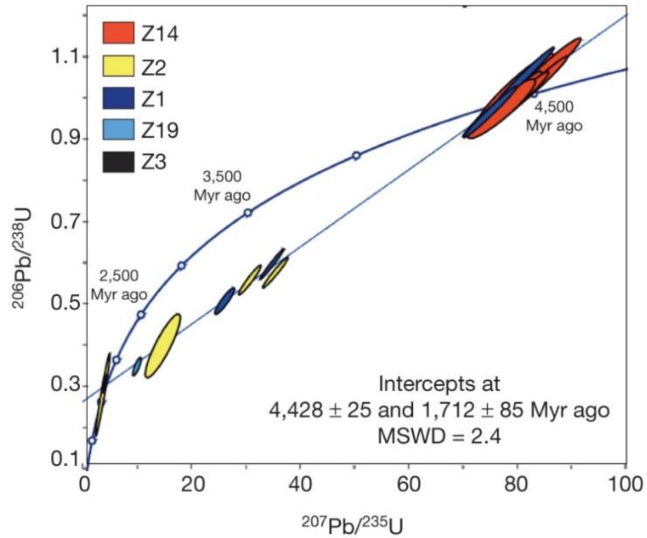


Valley et al. 2014



Mojzsis et al. 2016

Nemchin et al. 2010



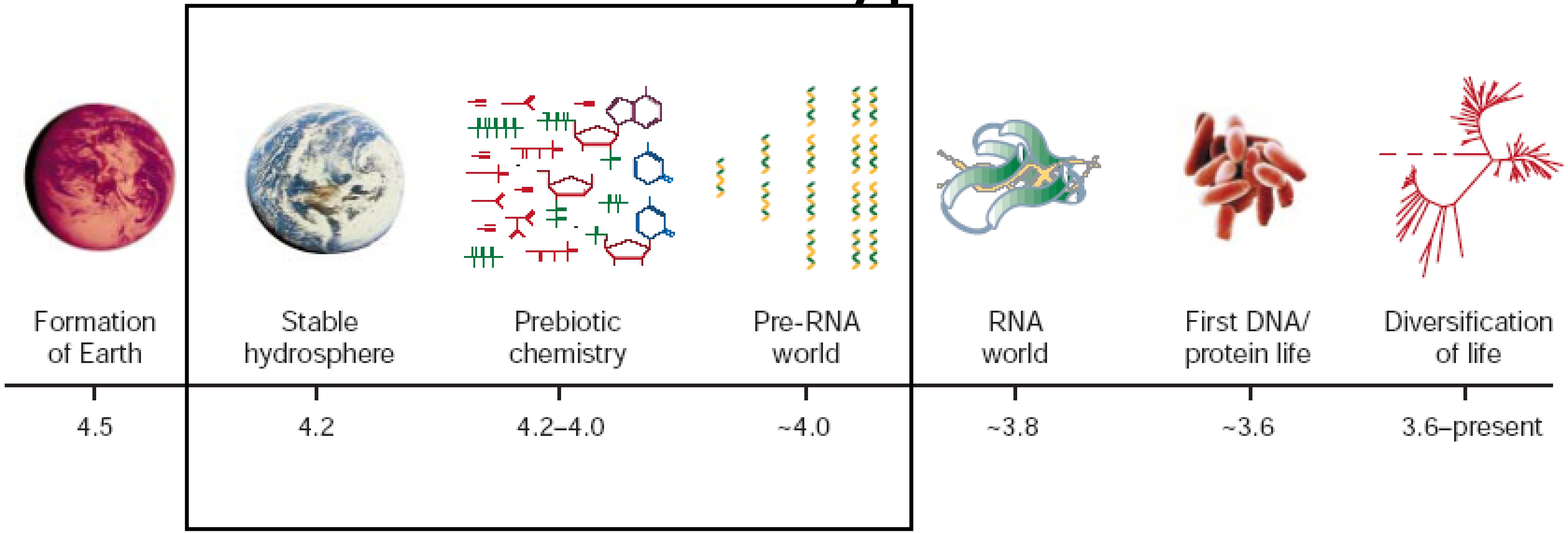
Humayun et al. (2013)

Oldest terrestrial zircon (n=210,000) is 4.38 Ga

Oldest martian zircon (n=15) is 4.43 Ga

Oldest lunar zircon (n=300) is 4.40 Ga

Putting aside highly reduced global geochemical scenarios actually *leads* to the RNA World hypothesis

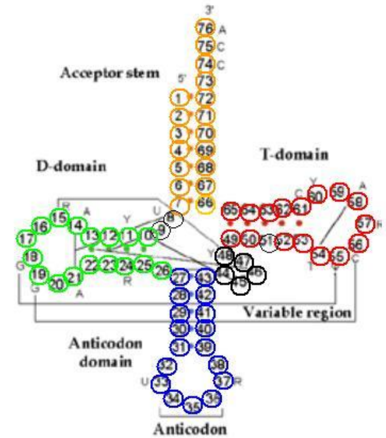


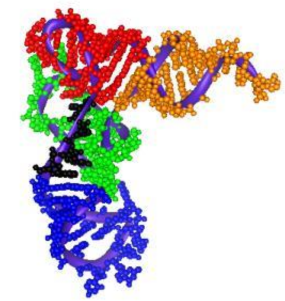
Joyce, G.F. (2002) *Nature* **418**, 214-221.

Prebiotic chemistry: synthesis of biological molecules necessary for the birth of the first living cell
The above time-line is a little arbitrary, <u>everything from 4.2 to 3.6 Ga on it could be pushed back and squashed into a smaller time span.</u>

THIS IDEA IS GEOCHEMICALLY COMPELLING for a number of reasons

What is the RNA World?





1. catalytic - react with one another
2. templating - copy each other

→ RNA viruses have RNA genomes

→ have very high mutation rates (10^5-10^6× bacteria)

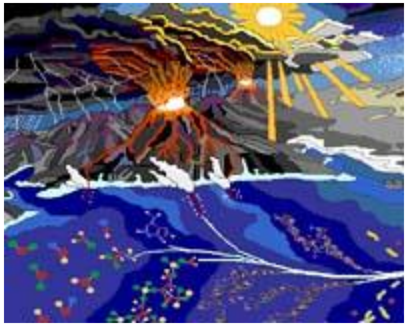
→ RNA viruses not found in Hyperthermophiles

→ use nucleotides from some source

3. Sugars are fundamentally more oxidized chemistry

4. Does not require a Miller-Urey (highly reduced) atm

Problems with The RNA World



1. RNA is not very stable
   -breaks down with heat (>50˚C)
   -breaks down in the presence of Mg^{2+}, Ca^{2+}, Mn^{2+}, Fe^{2+}

(stabilized with phosphate; did RNAs need endorheic or lacustrine environments?)

2. The reactions RNA can catalyze are limited

(but that might just be because of our limited experimental space)

3. Has to have some external source of nucleotides

(same problem with all sugar scenarios, also requires selection of sugars)

4. RNA world would have eventually given rise to *The DNA/Protein world*.

(WHY? Was it an evolutionary innovation to resist heat and salts?)

DNA is much more stable.
   -less sensitive to heat
   -stable in the presence of Mg^{2+}, Ca^{2+}, Mn^{2+}, Fe^{2+}

Proteins with 20 amino acids can catalyze a much larger variety of chemical reactions

The RNA world hypothesis is a temporary phase in the origin of life.

"You were right, sir. It was dishwater. The chef regrets the error."
(Apr 26, 1952) by Syd Hoff

Parochial conclusion #1

IN ANY SCENARIO, THE ‘PREBIOTIC SOUP’ ON EARTH WAS ALWAYS FANTASTICALLY DILUTE IN A RELATIVELY OXIDIZED SETTING

Earth's water and other volatiles

Hydrogen:

Two major terrestrial reservoirs of water: Hydrosphere & Mantle (see review paper by Mike Mottl on this!)

1.4×10^{24} g of water in the hydrosphere

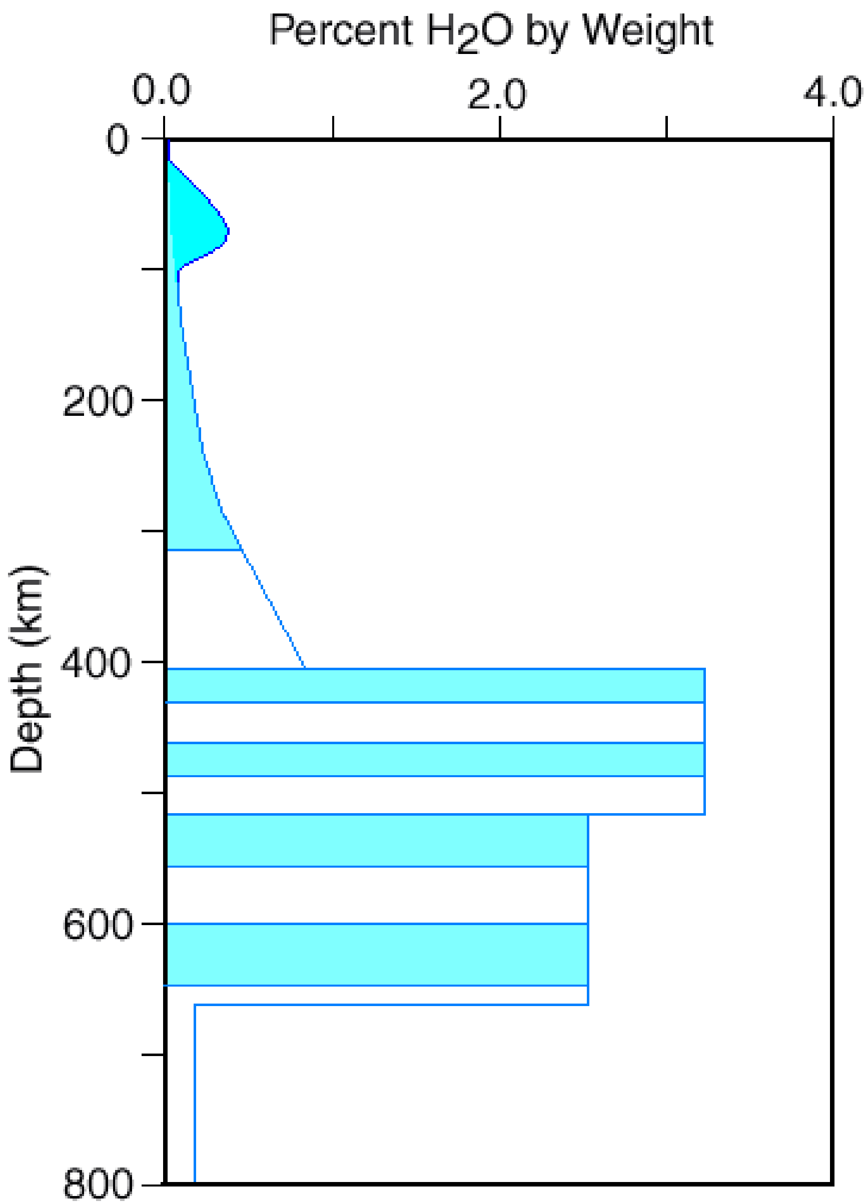
Bulk D/H of this water is 1.557×10^{-4}

The depleted mantle appears to have a water content between 100 and 500 ppm, with the lower value preferred (Sobolev and Chaussidon, 1996) and consistent with measurements of mantle xenoliths (Bell and Rossman, 1992).

The DM estimate corresponds to $0.4\text{-}2 \times 10^{24}$ g of water, with D/H = 4 – 8‰ lighter than SMOW

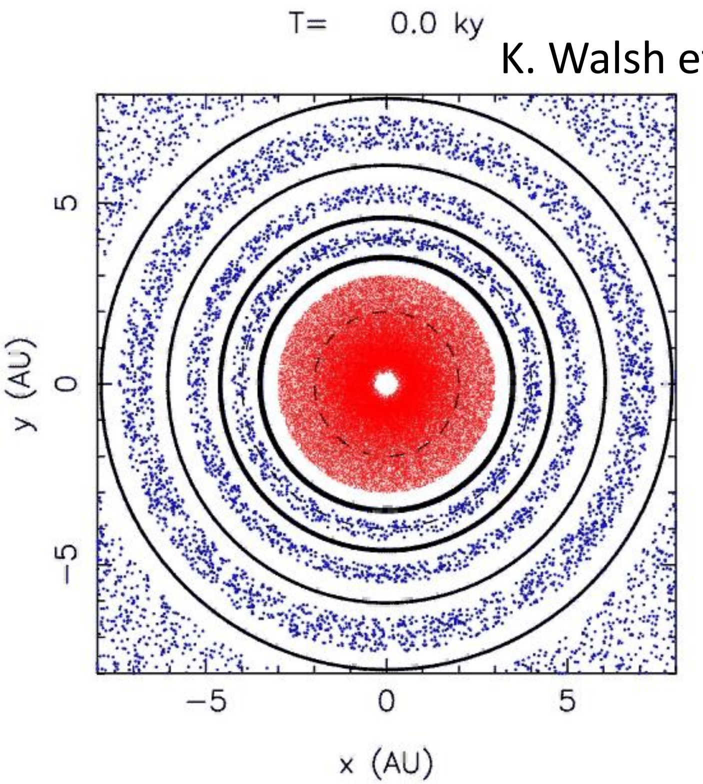
By these estimates, present-day water for the bulk Earth is <u>at least</u> 2.6×10^{24} g with D/H = 1.5×10^{-4}
Or about 4.4×10^{-4} Me

Water storage capacity (Ocean units)



Nominally Anhydrous Minerals (NAMs) can incorporate up to 10 times the total Ocean mass if saturated.

Courtesy: J. Smyth



K. Walsh et al.

The “Grand Tack” hypothesis can explain this

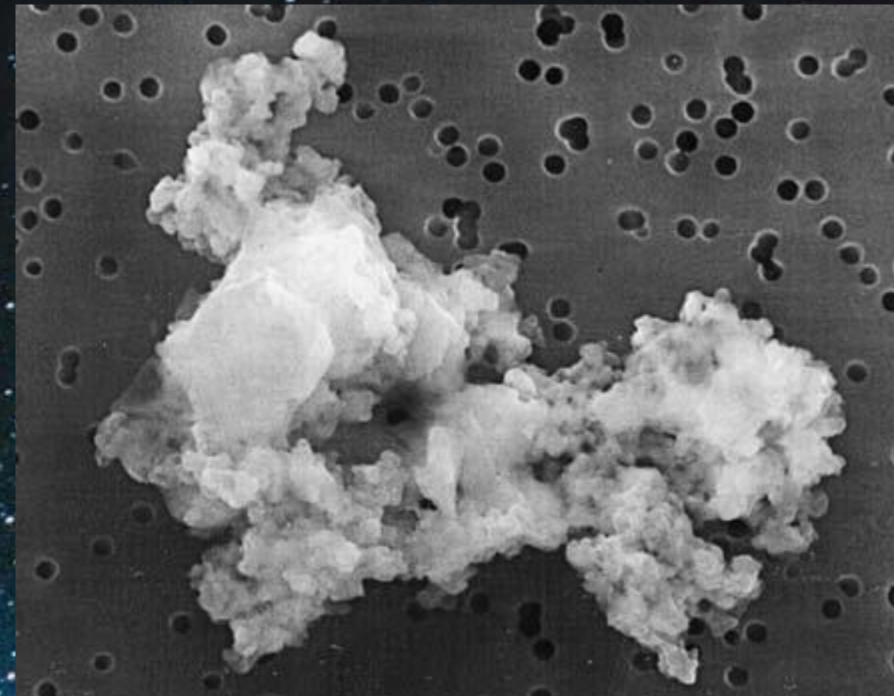
Water delivery in Grand Tack

- Planets > 0.5 Earth mass accrete median value of ~1% Earth mass of C-type material (2-3% is not rare)
- Assuming 10% water by mass (consistent with carbonaceous chondrites), this gives ~1×10^{-3} Earth masses of water
  - Earth has (low estimate) ~$5\text{-}20 \times 10^{-4}$ Earth masses of water

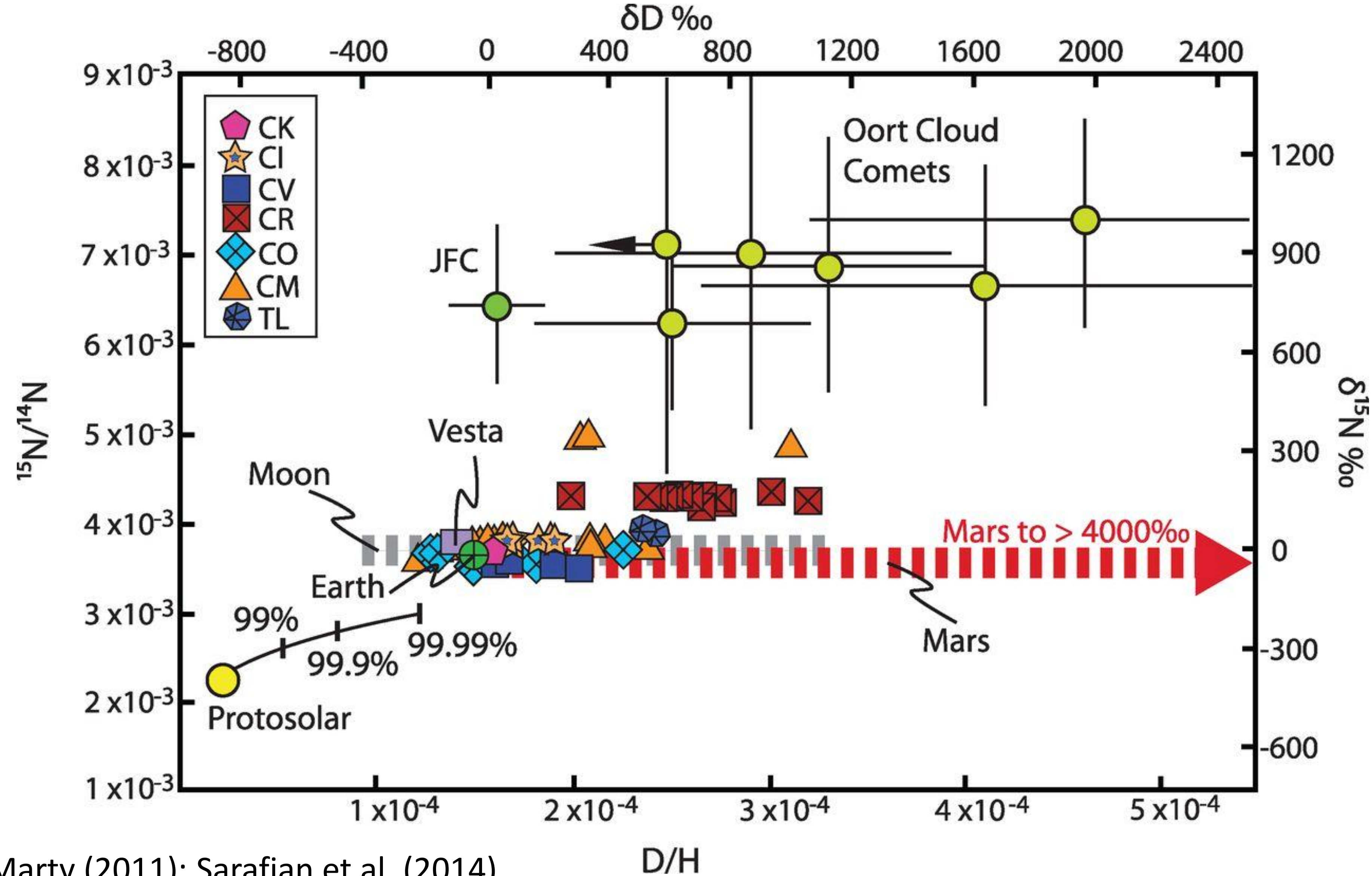
Additional water may be delivered through more massive embryos that were not included in the simulations

Murchison
(CM meteorite)

What about comets?



Stable isotopes suggest that terrestrial planets' volatiles are mainly chondritic



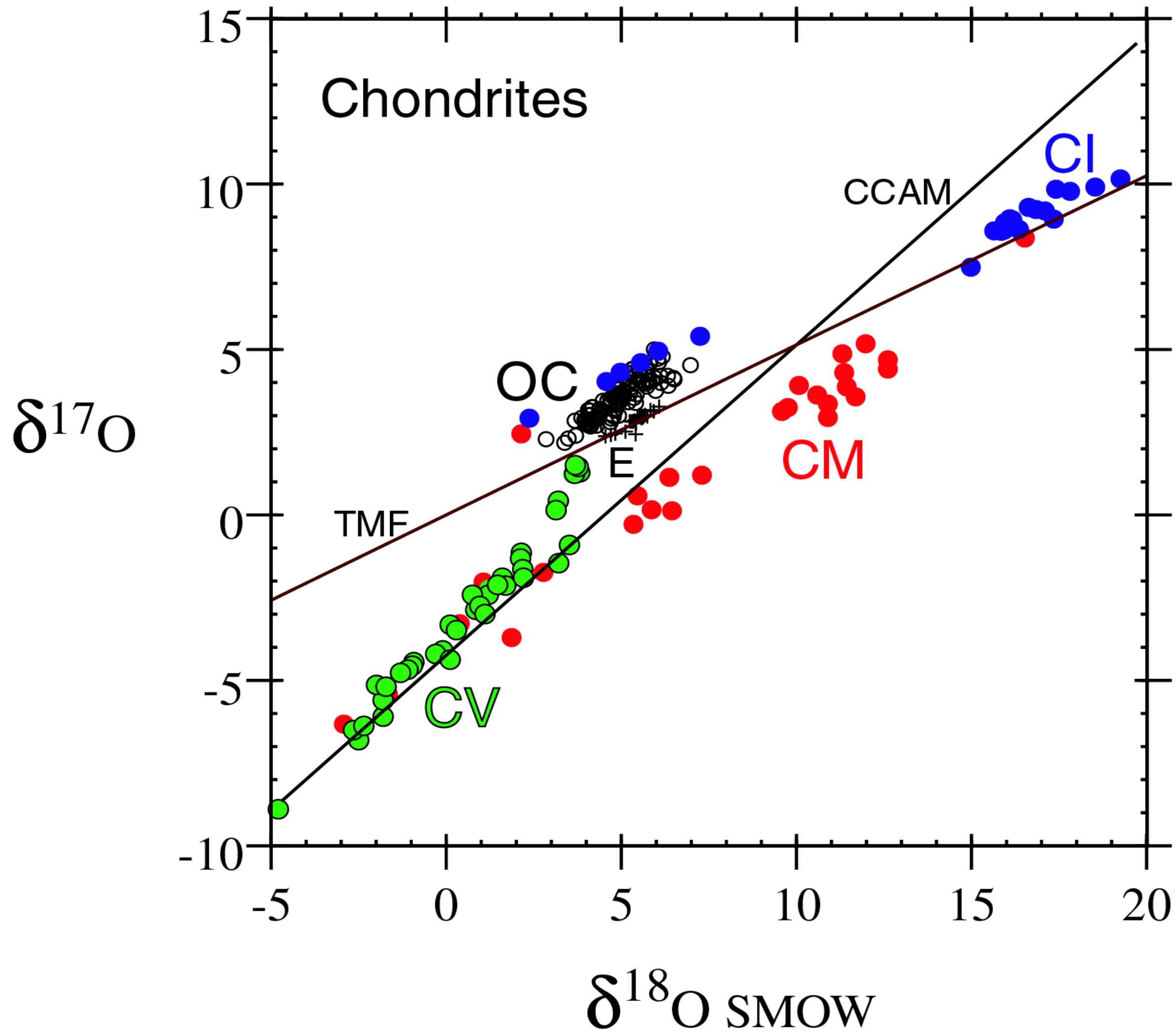
Marty (2011); Sarafian et al. (2014)

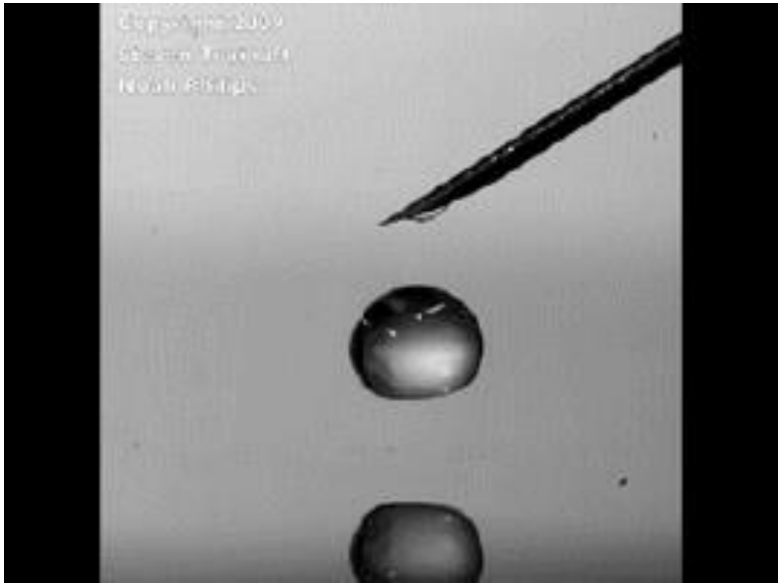
Timing of water/volatile accretion

The Earth and the Moon have indistinguishable oxygen isotope composition.

All carbonaceous meteorites (with the exception of CI) have clearly different Oxygen isotope composition

The delivery of water AFTER the Moon forming event (in something like a "Late Veneer") would have made the Earth and the Moon easily distinguishable in oxygen isotopes!





Water (and volatile elements) argue for an heterogeneous accretion of the Earth. This is well-accepted.
Volatiles were delivered towards the end of the Earth accretion, not by comets and as we will see, not in a Late Veneer fashion, and not in a late heavy bombardment.

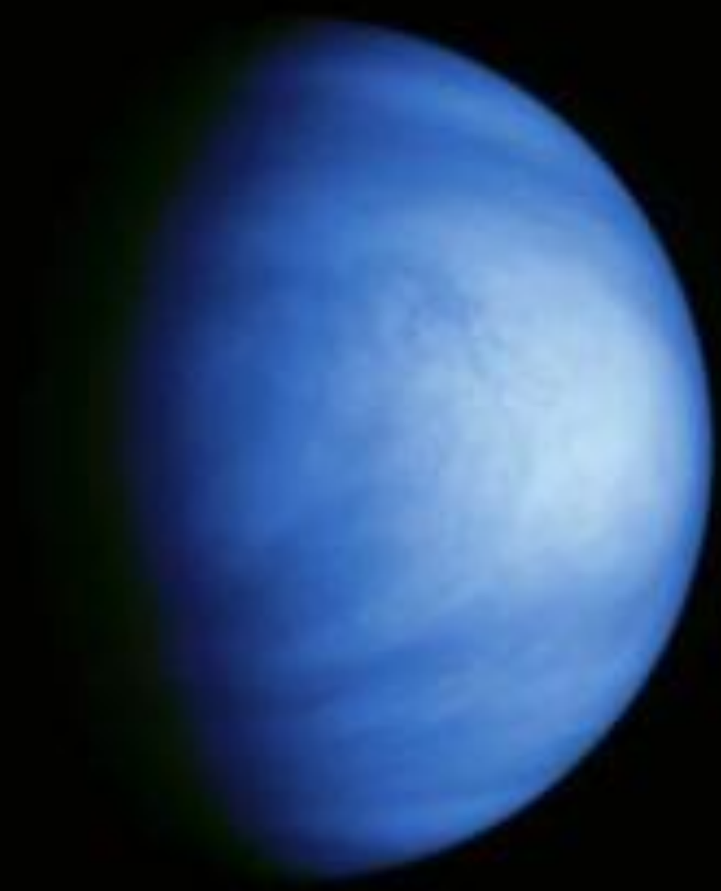
All of this is consistent with the latest dynamical models. But we have to know the DIFFERENCE between the Late Veneer and LHB.

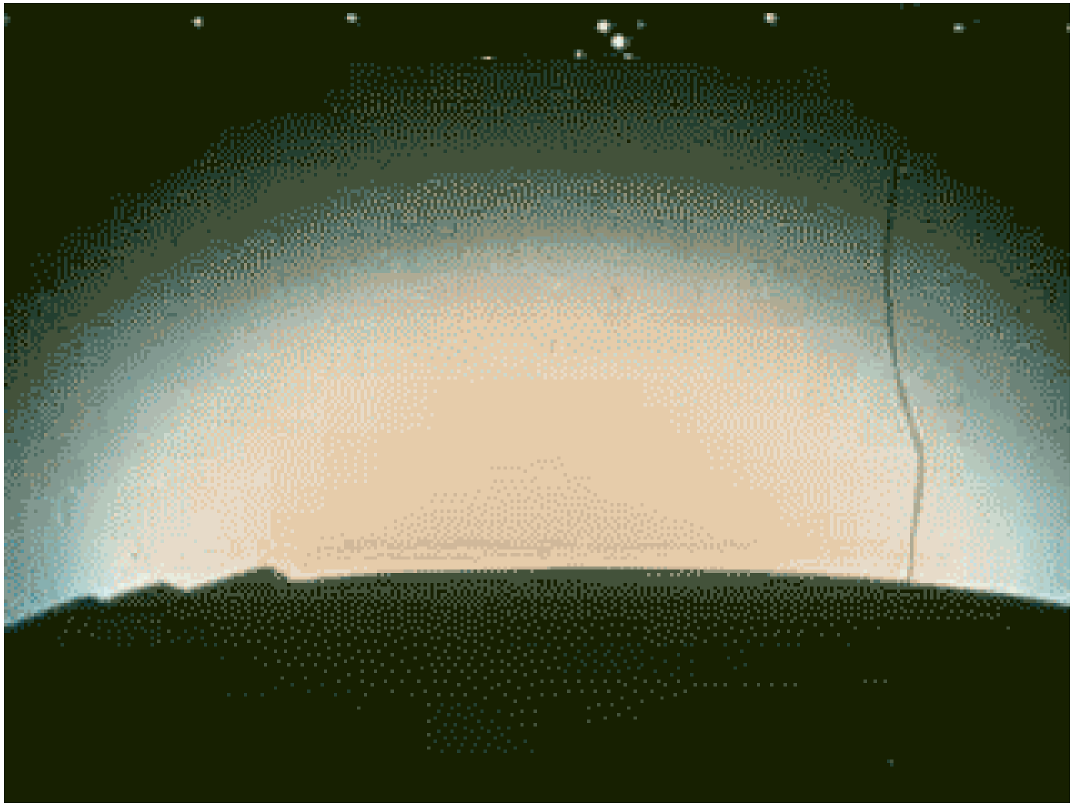
Parochial conclusion #2

WATER WAS MOSTLY DELIVERED AT TIME OF PLANET FORMATION, NOT BY COMETS AND NOT IN BOMBARDMENT

WHEN DID THE CRUSTAL PLATFORM FOR LIFE APPEAR?

Hadean Earth as a Water Planet?





Last part of the talk, with a heavy dose of radiogenic isotope geochemistry

WHEN DID ALL OF THIS HAPPEN?

A word (or two) about isotopic systems

- ^{176}Lu-^{176}Hf

$\tau_{1/2}$ = 37.8 Ga

Lu → mantle, Hf → crust

Principally in felsic rocks

MAFIC ROCKS = things like basalt

FELSIC ROCKS = things like granite

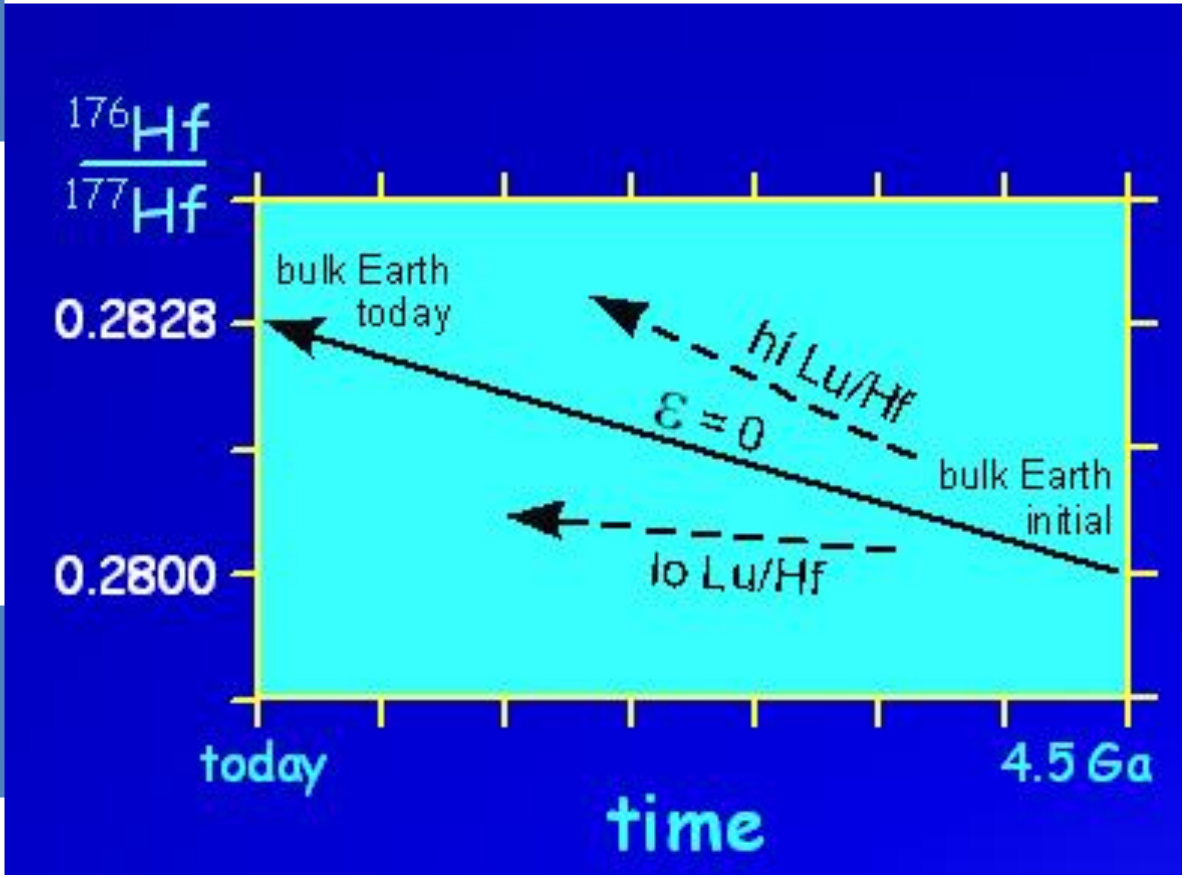
Lu/Hf zircon studies - concepts

^{176}Lu decays to ^{176}Hf with $\tau_{½}$ = 37.8 Ga

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

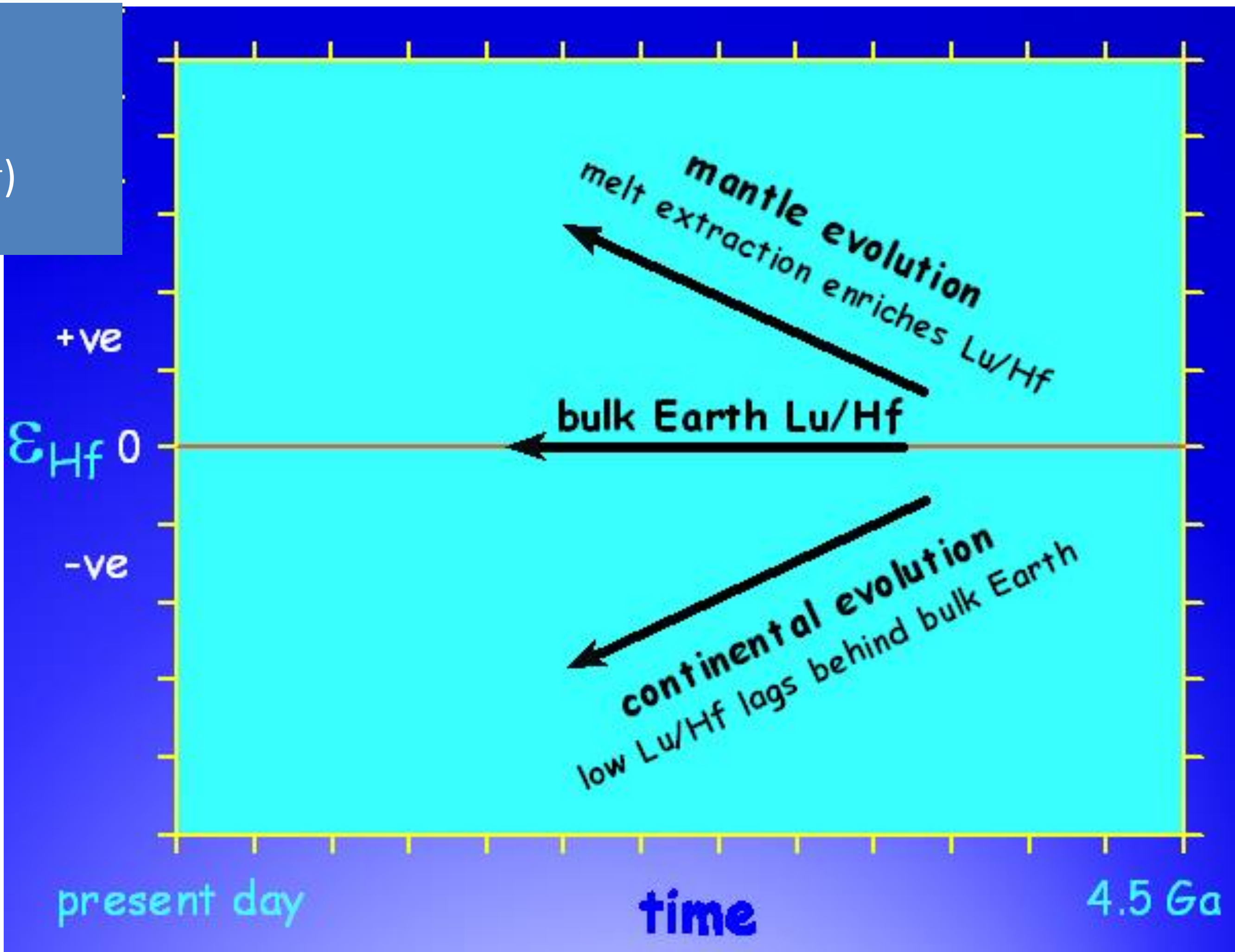
^{177}Hf is the stable reference isotope

Conventionally expressed relative to epsilon



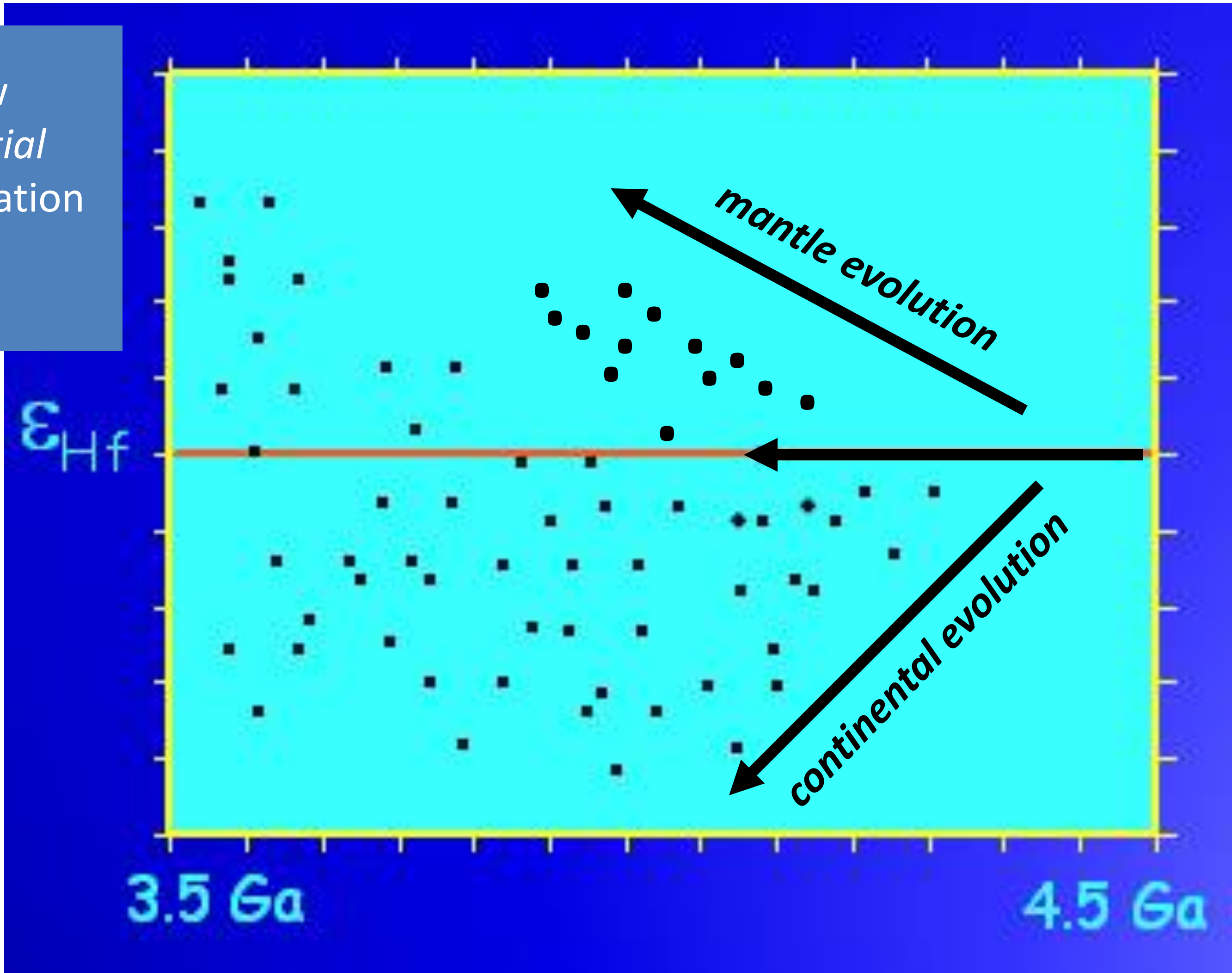
Lu/Hf studies tell us about the origin and evolution of the crust

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



Lu/Hf studies lead us to…

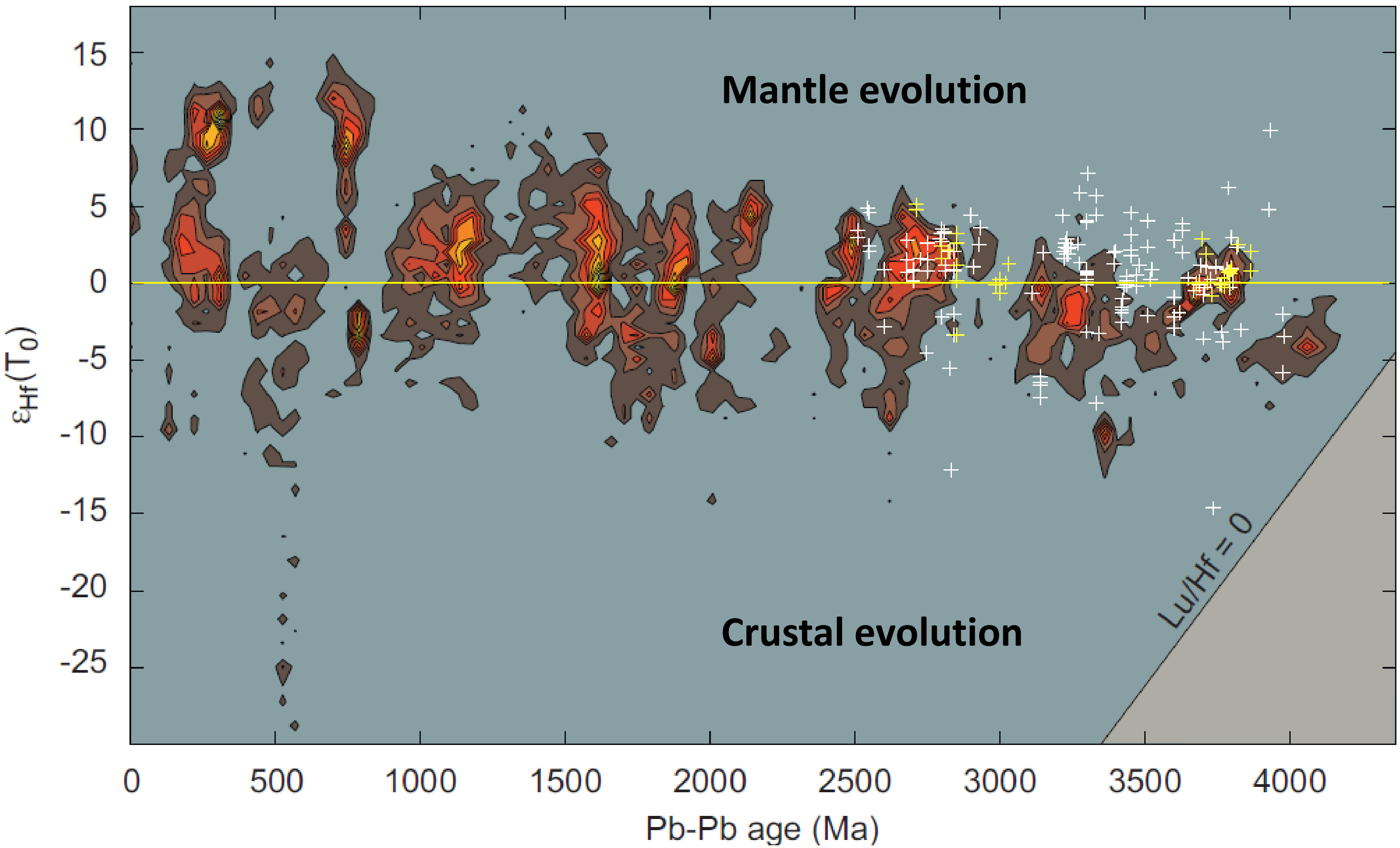
Zircons have extremely low Lu/Hf, thus they record *initial* $^{176}Hf/^{177}Hf$ at time of formation established by Pb ages



Guitreau et al. (2012)

When did crust recycling begin?

Very early. Lu-Hf isotope systematics allows us to “see” back to about 4500 Ma.

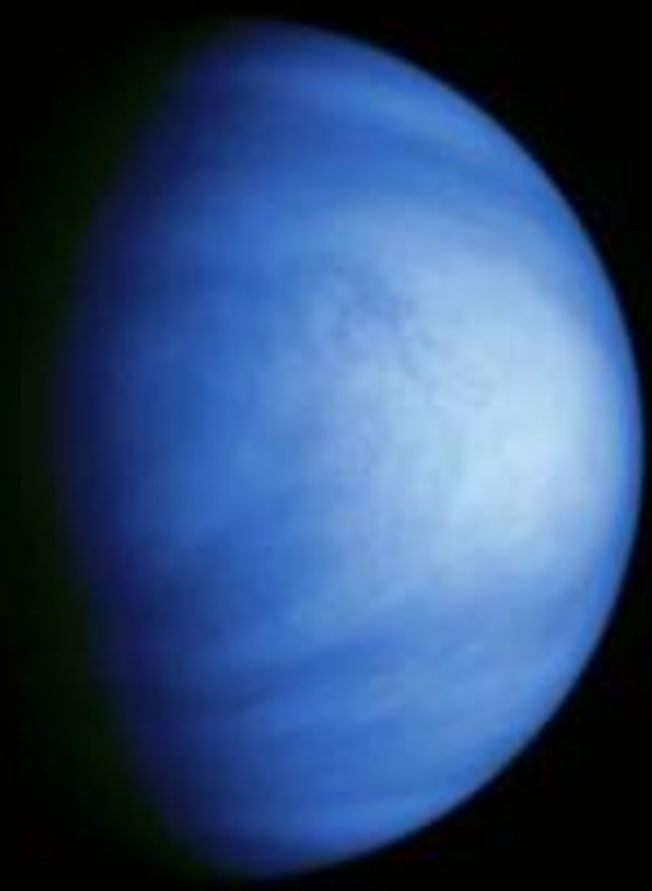


This result means that Earth’s mafic (ocean crust) & felsic (continental crust) has grown in “pulses” since the earliest times, and probably is a reflection of **crust-hydrosphere** interactions since the beginning

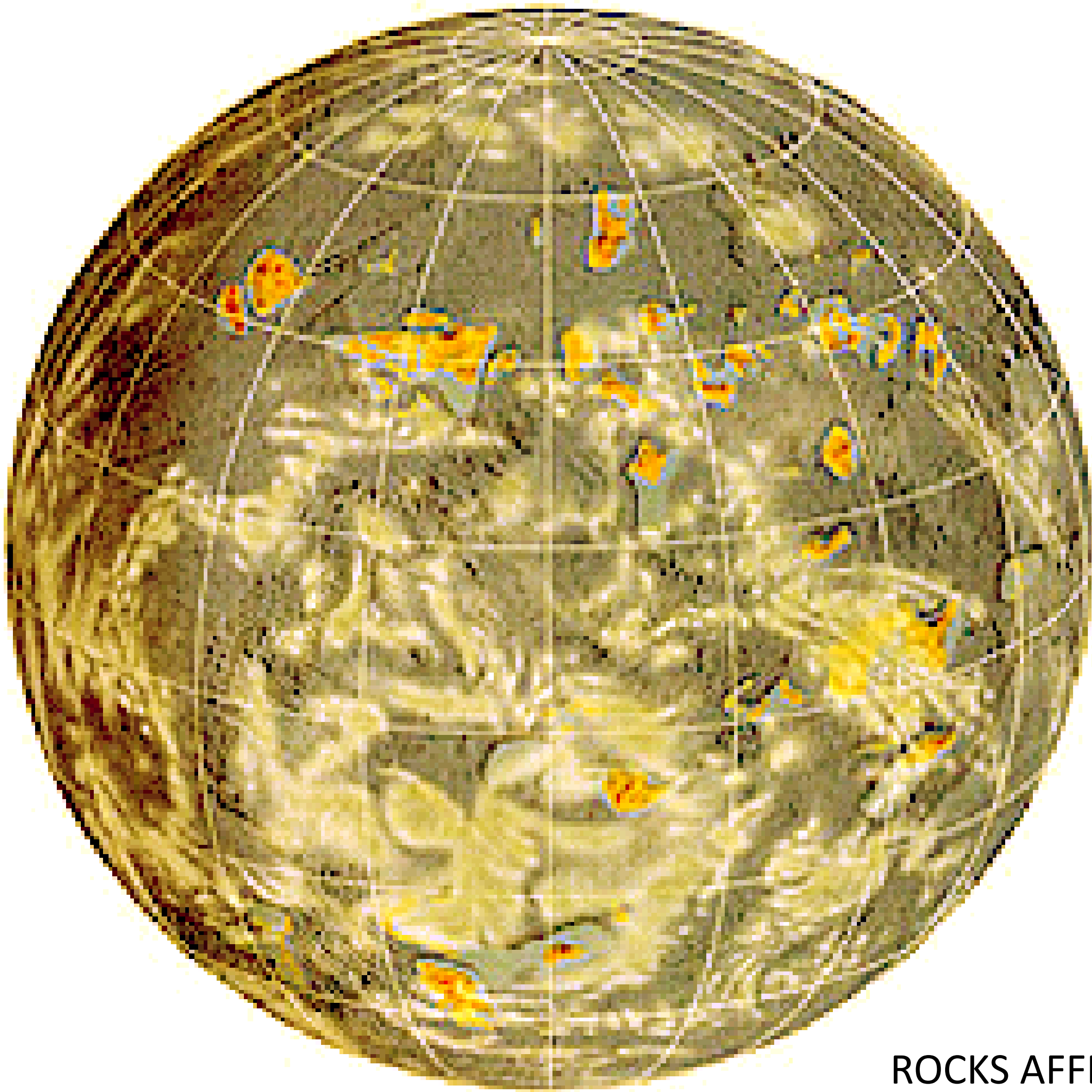
Continental volume estimates

5% of present continental area ≈ 0.9 Australia

Hadean Earth as a Water Planet?



A conceptual model of the Hadean Earth

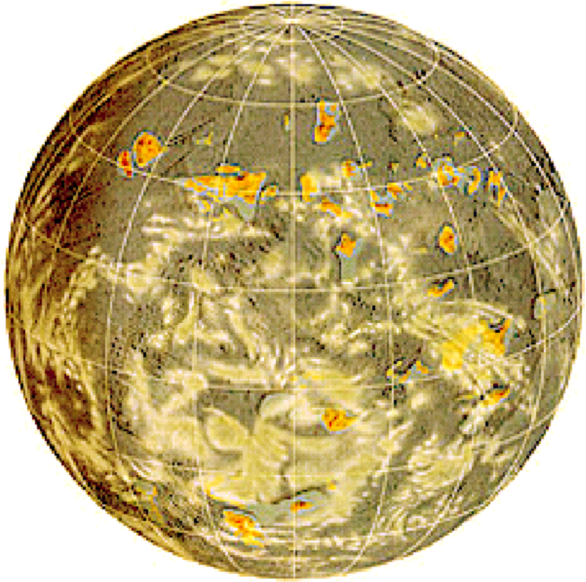


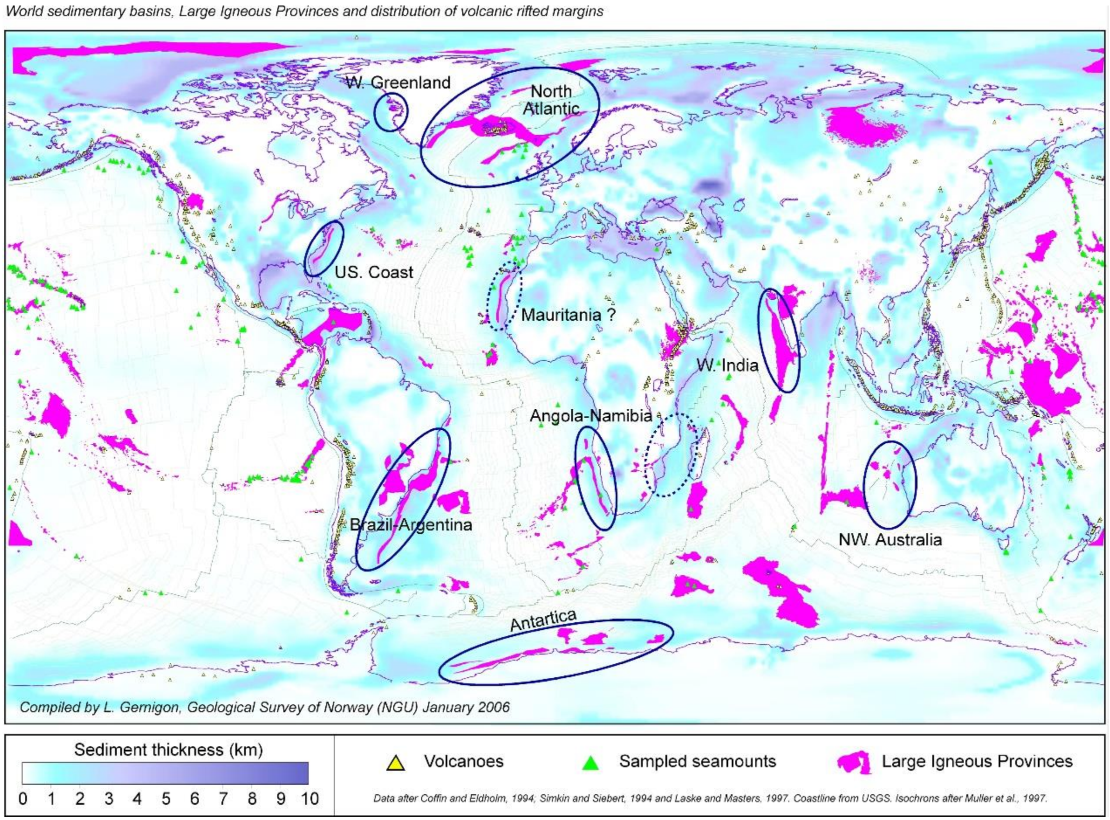
Abundant small proto-continental masses, akin to immature-to-mature island arcs at ocean-ocean subduction zones and plume-related edifices.

(What happens with an Exo-Earth that has 100 oceans? Into core?)

ROCKS AFFECTED BY WATER = Dry land

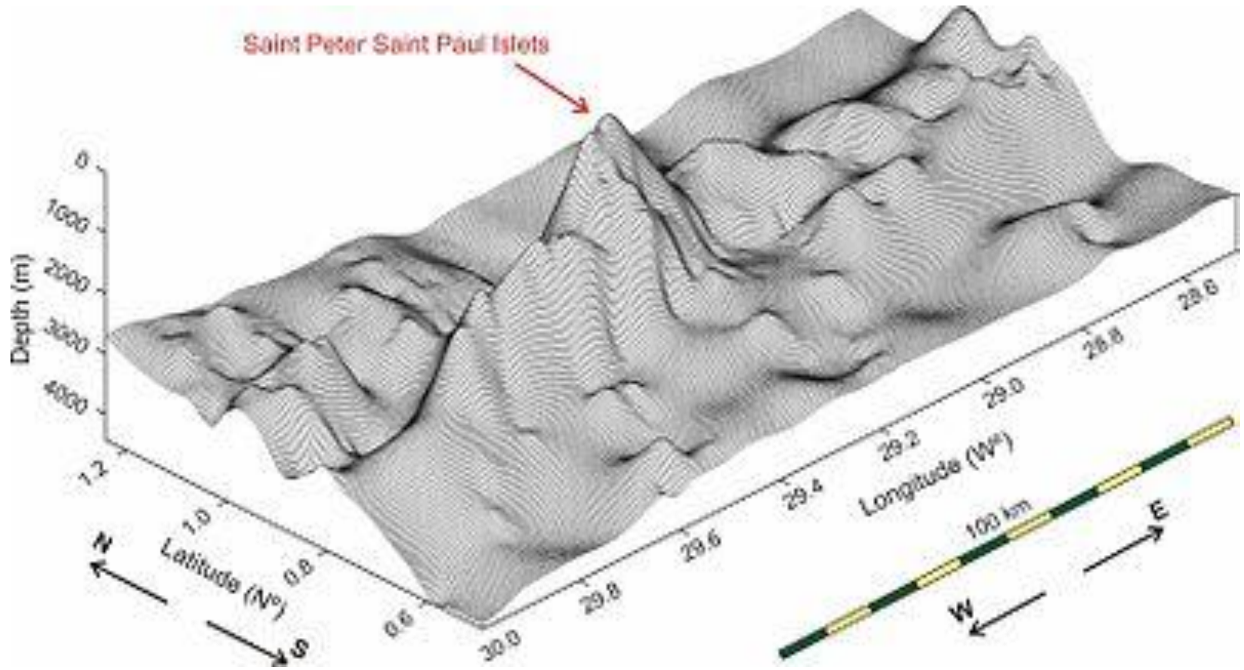
Figure modified from one that appeared in Cassell's "Atlas of Evolution" (2001)





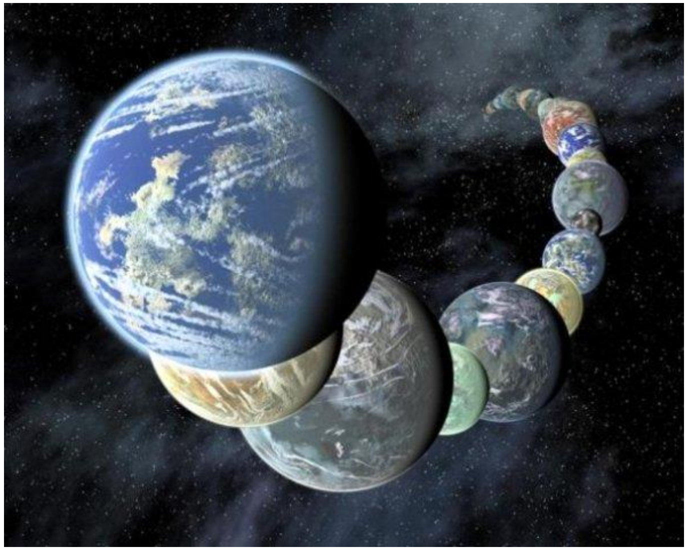
NO: IT IS HIGHLY LIKELY THAT EMERGENT LAND EXISTED IN THE HADEAN

Motoki et al. (2007)



Some conclusions to discuss & debate

- **The first habitats for life could have been a mere 50-100 Myr after solar system formation.**
- **Cosmochemically Earth-like planets tend to have oxidized mantles.**
- **Liquid water is primordial to Earth; hardly any was supplied later by comets. Primary accretion source.**
- **GI>>LV>>>LHB; only magma ocean-forming events matter in the historical continuity of the biosphere.**
- **Planets form hot. Any time hot rock interacts with liquid water = hydrothermal alteration of that rock.**
- **Disequilibrium is maintained over geologic timescales by melting rock, and an atmosphere is probably necessary (planetary oxidation – reduction couple)**



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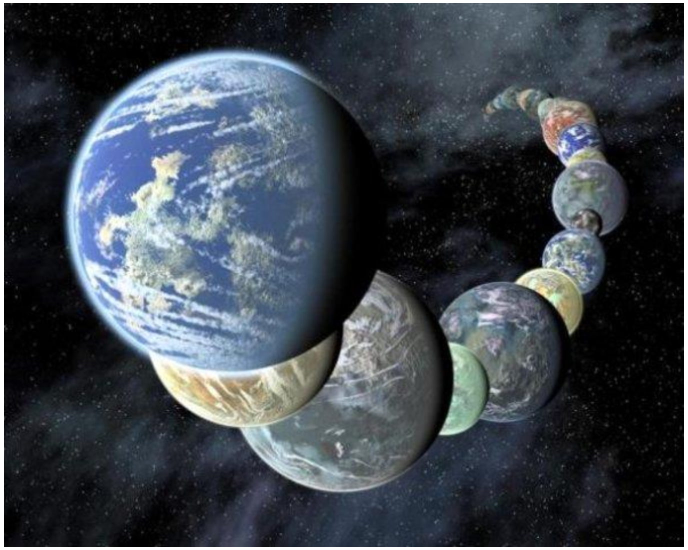

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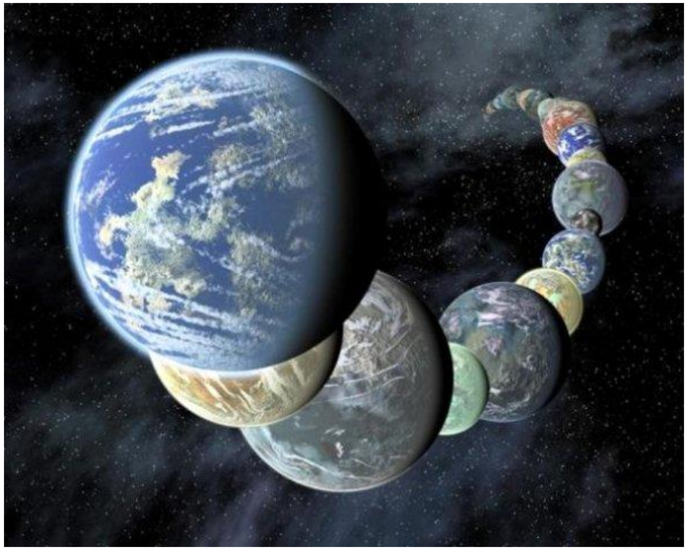

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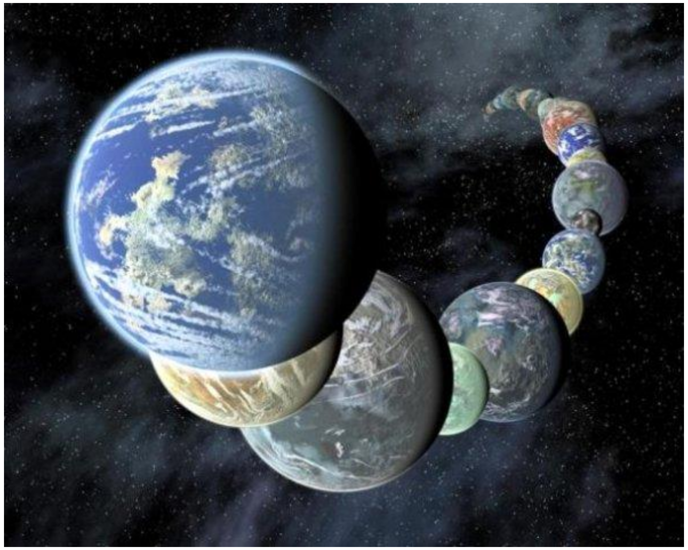

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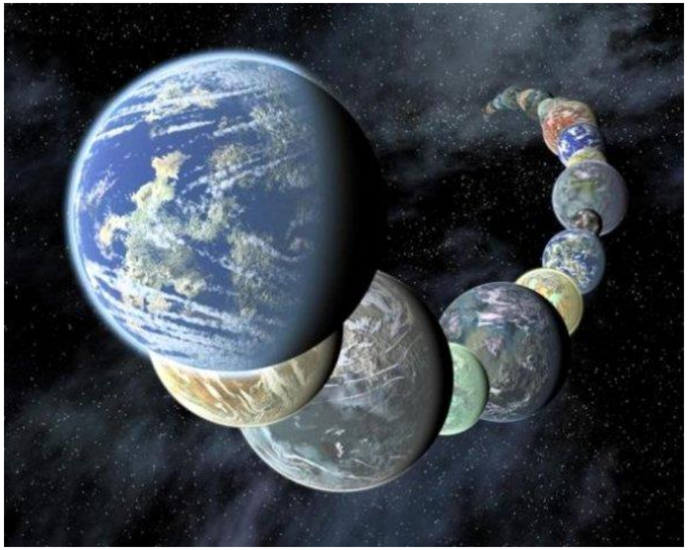

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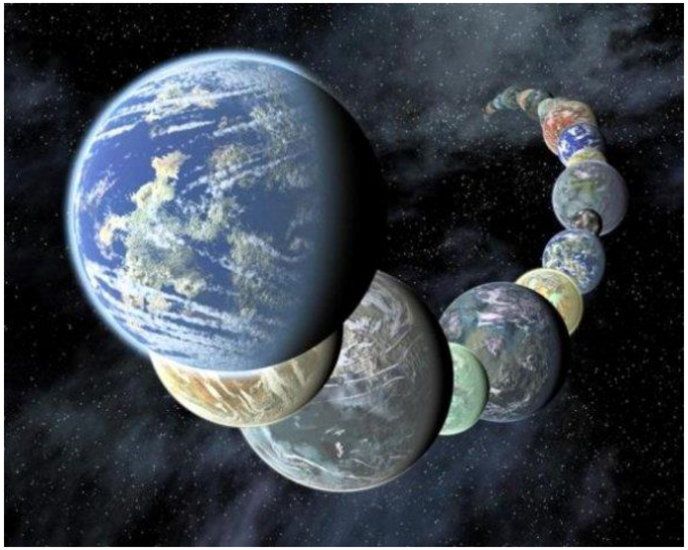

Thank you!

With apologies to Stepen Mojzsis

Still looking

Thank you!

CRiO

MAGYAR TUDOMÁNYOS AKADÉMIA 1825

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