The origin of life in the primitive Earth

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Origin of life

- The origin of life is a central topic of astrobiology
  - To predict if life can originate in remote astronomical environments we need to understand which conditions led to the origin of life on Earth
  - The habitability of an environment does not guarantee the presence of life because the requirements for the origin of life could be different (probably tighter) than the requiremens of habitability
- The scientific approach
  - The origin of life is assumed to be the result of as a <u>sequence of spontaneous processes that leads to the formation of the first living cells starting from non-biological chemical compounds</u>
- Abiogenesis
  - The transition from the abiotic world to life is called *abiogenesis*

Origin of terrestrial life:
the “in situ” hypothesis

- We can constrain the chronology and physico-chemical conditions of abiogenesis by assuming that terrestrial life originated on Earth (“in situ”)
  - Strictly speaking, this is only a working hypothesis
  - According to a few authors, terrestrial life originated outside Earth and was somehow transported to Earth (“panspermia” hypothesis)

- At present time, there is no evidence of life being delivered on Earth
  - However, we do have evidence of organic material delivered on Earth, including relatively complex molecules of prebiotic interest

- We do not consider here the panspermia hypothesis
  - By assuming the existence of panspermia we would shift the problem of the origin of life to an unknown epoch with unknown ambient conditions

Chronology of the origin of terrestrial life

- By assuming the ”in situ” hypothesis we can set <u>temporal limits</u> on the epoch of life formation by:
  - dating the epochs of the development of habitability conditions in the primitive Earth

    ➔ *habitability boundary*
  - dating the oldest evidence of life found in the terrestrial crust

    ➔ *biosignature boundary*

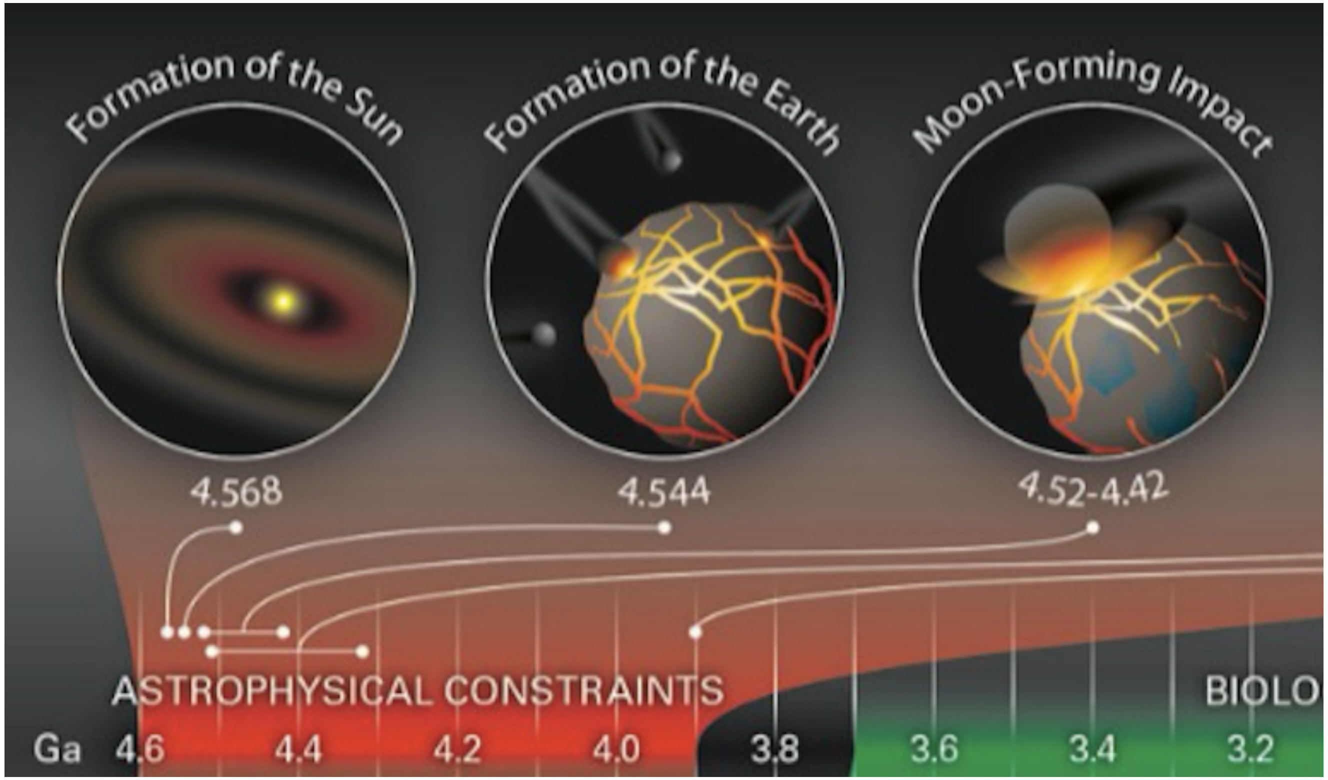
- By comparing the chronology of these events, we can estimate:
  - the <u>epoch of life formation</u>
  - the <u>time interval available for life formation after the onset of habitability conditions</u>

Age of formation of the Earth

- The age of formation of the Solar System can be dated with accuracy from the analyis of meteorites
- Date of the oldest objects in the Solar System:

  4.57×10^9 yr
- After the formation of the Solar System the Earth and Moon formed in less than 10^8 yr

The scenario for the formation of the Moon is uncertain, yet the Moon plays an important role in stabilizing the climate conditions of the Earth



The oldest terrestrial rocks

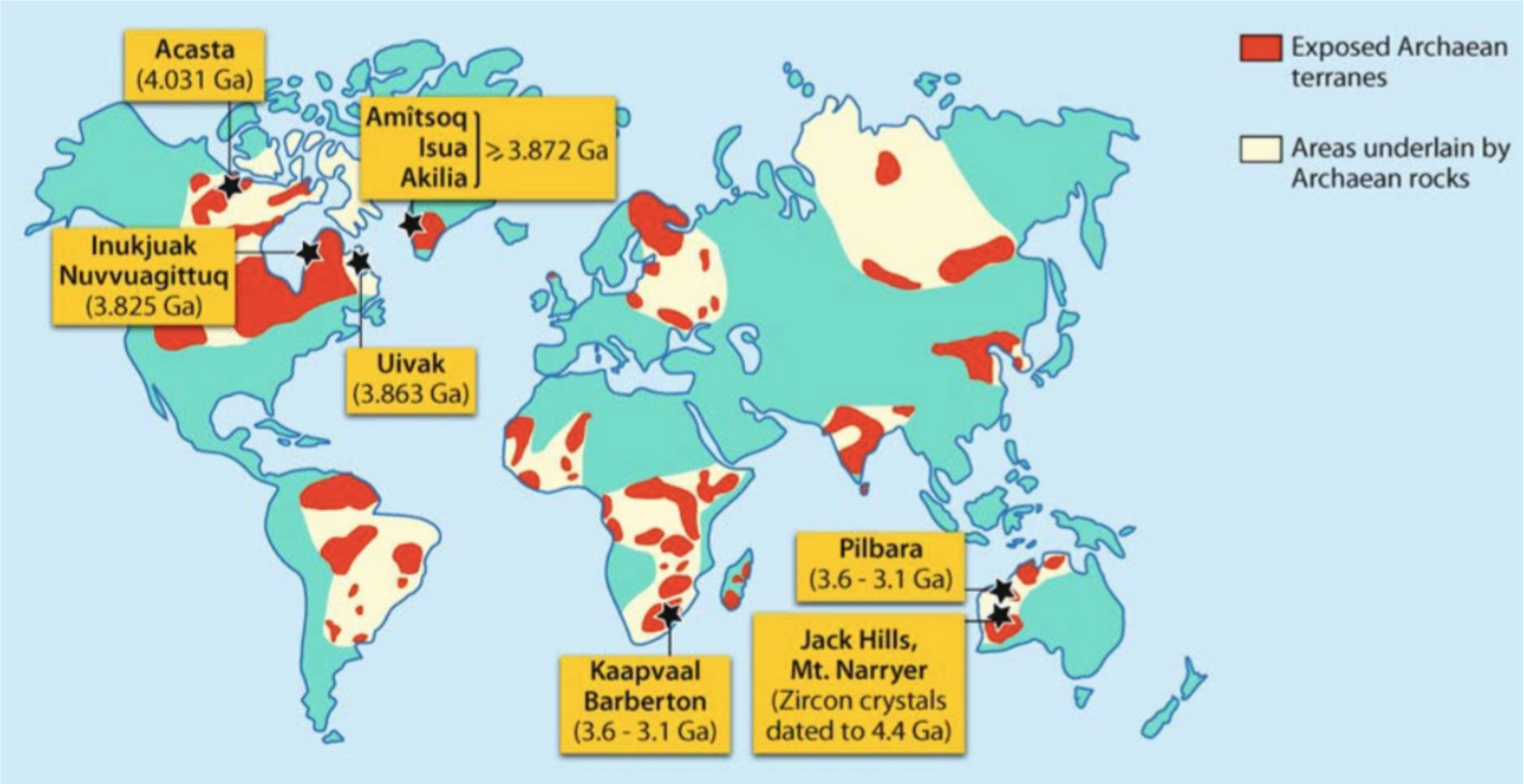
- It is extremely difficult to find terrestrial rocks with ages close to the epoch of Earth formation and early evolution
  - This makes very hard dating the origin of life
- The main reason for this difficulty is tectonic activity, which is constantly recycling the Earth's crust

- As a result of the tectonics, the oldest, well preserved crust material has ages of about 3.2 – 3.5 10^9 Ga

- Older material is also found, embedded in younger strata
  - Typically with ages of 3.5-4.0 Ga, but sparse and quite altered

- The oldest material:
  - Zircon minerals with ages up to 4.4 Ga
  - These minerals show evidence of processing by liquid water

The oldest terrestrial rocks



From Gargaud et al. (2012)

Impacts and delivery of volatiles on the primitive Earth

- The impact craters on the bodies of the inner Solar System indicate a <u>long history of impacts</u>, starting from the epoch of Solar System formation

- Due to tectonics, the oldest impact craters are not visible on Earth
- Clear evidence for the impacts comes from the study of the Moon craters
- Evidence is also accumulating from other bodies of the Solar System

- The impacts were likely the result of episodes of dynamical instability in the early evolutionary stages of the Solar System
- Dynamical instability led to the migration of small bodies from outer regions, richer in volatile material, to the inner regions, where planets rich of rocky material were formed

<u>The impacts of astronomical bodies rich in volatiles may have delivered water and organic material on the primitive Earth</u>

The hypothesis of a "Late heavy bombardment" (LHB)

- An episode of heavy meteoritic impacts may have taken place on Earth well after the formation of the Solar System
- This episode, known as the "Late Heavy Bombardment" is supported by the analysis of Moon samples, but the evidence is weak
  - According to this hypothesis, the frequency and intensity of meteoritic impacts drastically decays between 4.1 e 3.7 x 10^9 Ga
  - The energy of the strongest impacts was sufficient to evaporate a present-day ocean
  - The cumulative effect of the impacts may have delayed the habitability until the end of the LHB

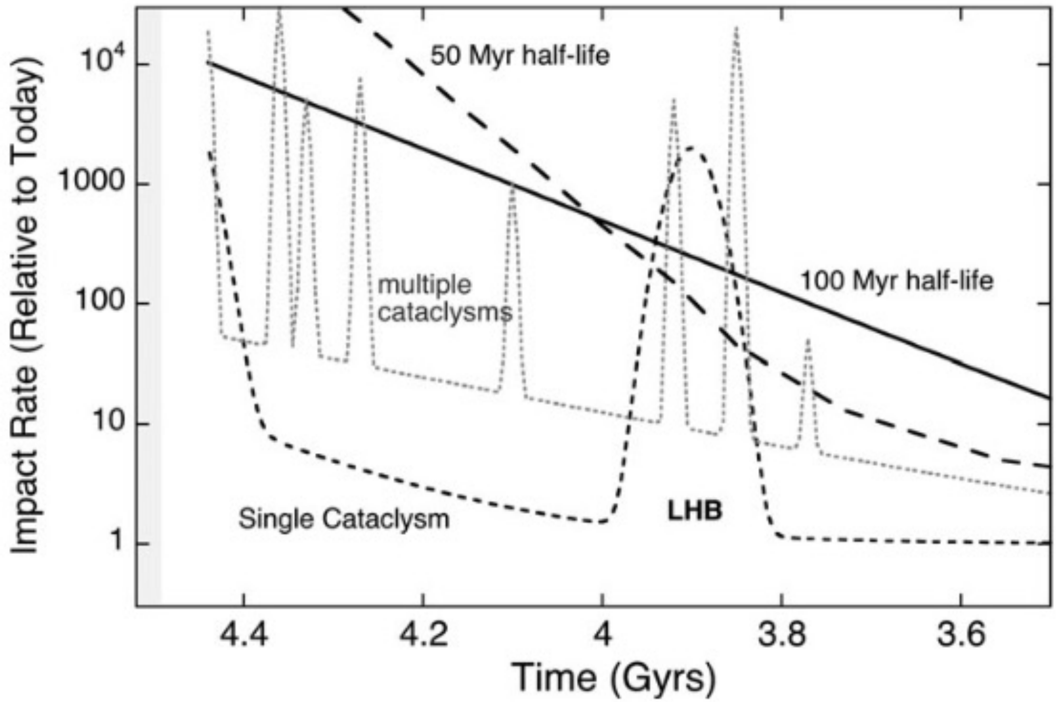


FIG. 2. Four possible scenarios for the LHB, calibrated to crater counts and surface ages at the Apollo landing sites. All scenarios except the 50 Myr half-life model are supported by the available data. Reprinted by permission from Springer Nature: Zahnle *et al.* (2007).

Summary of the habitability boundary

- The zircons with age 4.4 Ga show evidence of having been processed by liquid water
- Therefore the Earth could have been already habitable at that epoch, after the solidification of an early magma ocean

- If the LHB did not interrupt the habitability, the temporal boundary for habitability conditions is ~4.4 Ga
- If the LHB did interrupt the habitability of the Earth, the upper boundary of continuous habitability is ~3.9 Ga

Searching for the oldest traces of life on Earth

- Different types of experimental techniques are used to search for traces of ancient life in the oldest terrestrial rocks
  - Study of isotopic ratios that can be altered biologically

    Example: $^{12}C/^{13}C$
  - Morphological evidences of microscopic forms of life

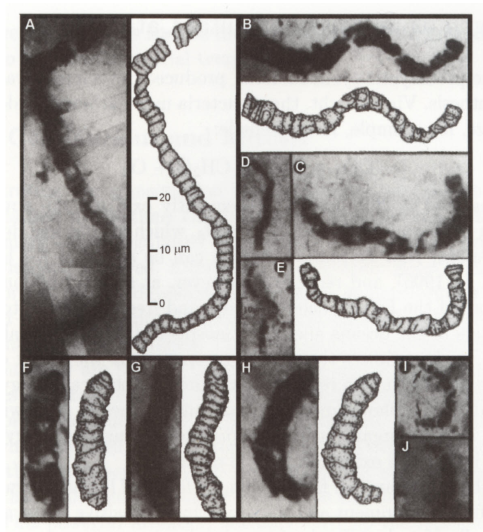
    Microfossils can be preserved thanks to the mineralization of organic matter of biological origin
  - Geological layers of biological origin

    Examples: sedimentary layers similar to present-day "stromatolites"
- These methods only offer indirect evidences
  - Results should be taken with caution
  - However, convincing evidence can be obtained by the combination of different methods

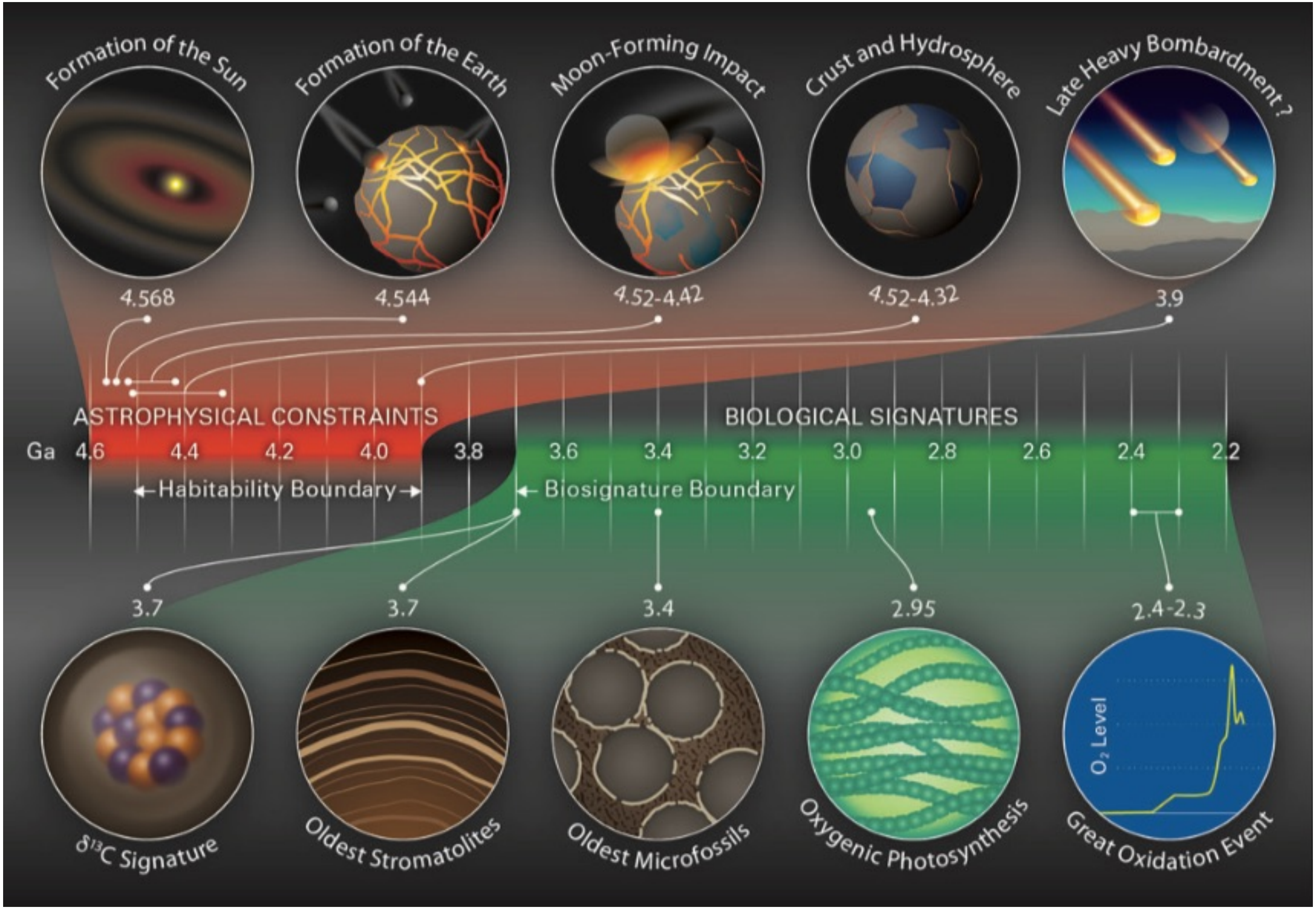
Oldest evidence for life on Earth

- The oldest, tentative, evidence are dated at about 3.8 Ga
  - –Sedimentary rocks in the south-east of Greenland (Isua, Akilia)
    - Based on the isotopic ratio $^{12}C/^{13}C$

- The oldest, more convincing, evidence are dated at about 3.2 - 3.5 Ga
  - –"Greenstone belts" in Australia (Pilbara) and South-Africa (Barbeton)
    - - Isotopic ratios
    - - Microfossils
    - - Stromatolites: sedimentary layers suggesting the presence of diffuse life in shallow water, close to the litoral



Summary of chronology relevant for studies of the origin of life on Earth



Summary of temporal constraints on the origin of terrestrial life

- Assuming that the LHB did exist and interrupted the habitability
  - If we consider the oldest, tentative evidence of life, the origin of life should have taken place around 3.8 - 3.9 Ga, on a relatively short time scale (~10^8 yr)

    This argument is used by supporters of the panspermia theory to claim that there was not sufficient time for life to emerge on Earth
  - If we take the more robust evidence for the oldest trace of life, the origin of life should have taken place between 3.5 and 3.9 Ga, on a time scale of a few hundred millon years
  - Even if we consider the more robust evidences at 3.5 Ga, life must have originated <u>before 3.5 Ga , when it was already widespread</u>

- Assuming that the habitability was not interrupted by the LHB
  - The time scales can be relaxed by several hundred millon years
  - The Earth could have been habitable for almost 1 Gyr before life was able to emerge

Properties of the Earth at the epoch of the origin of life

- In the “in-situ” hypothesis, the physico/chemical conditions of the early Earth set the reference frame for studying which chemical pathways may have lead to the origin of life
  - This does not exclude that organic material, with already formed molecules of biological interest may have been delivered from space

- Here we mention only a few aspects of the early Earth conditions relevant to the origin of life:
  - Early atmospheric composition of the Earth
  - Early climate of the Earth
  - Origin of Earth’s oceans

The early atmosphere of the Earth

- The primary atmosphere of the Earth must have been lost
  - This is deduced from the low abundances of rare gases (^{20}Ne, ^{36}Ar, ^{84}Kr) in the present-day atmosphere, compared to the cosmic abundances of the same elements
- The expected composition of the secondary atmosphere of the early Earth depends on the formation models of our planet
  - Slow formation models (old models, probably not realistic)

    The Earth's interior is cold and rich of volatiles

    Volatiles from the interior are gradually heated and released to the atmosphere

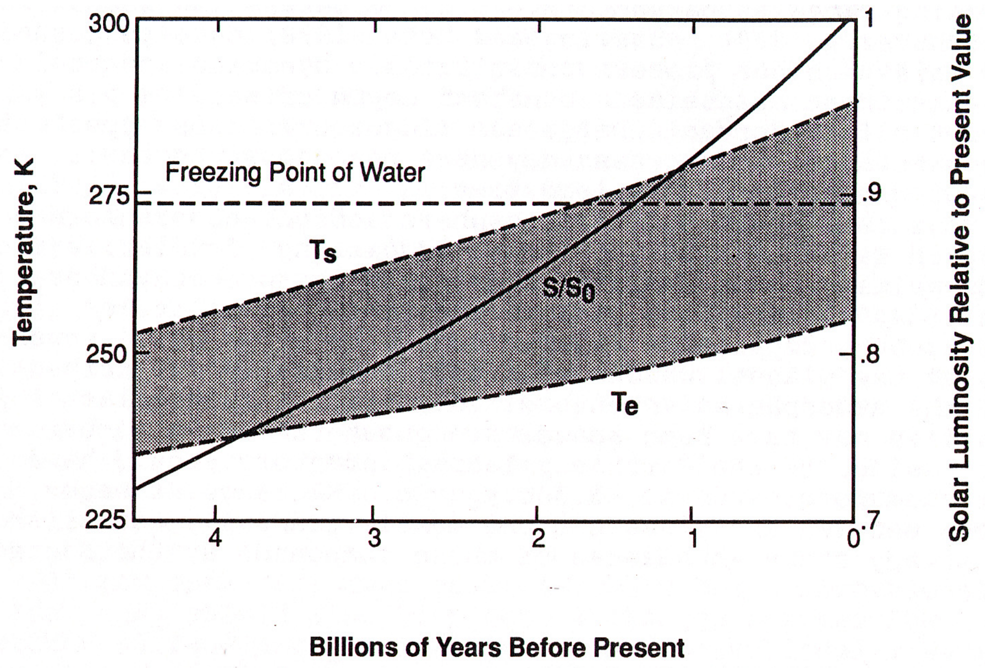
    These volcanic emissions produce a "reducing" atmosphere (rich of hydrogen), with a high content of H_2, CH_4, and NH_3
  - Fast formation models (10-100 millon years; more realistic)

    Because of the impacts with accreting planetesimals, the interior is hot and does not retain significant amounts of volatiles

    By the end of the accretion process, the atmosphere is "weakly reducing", being dominated by CO_2 e N_2 with traces of CO and H_2

The early climate of the Earth:
the "Faint Young Sun paradox"

- The standard model of evolution of the Sun indicates that the solar luminosity at the epoch of the origin of life was about 25% fainter than today
- With a lower level of insolation, models of Earth climate indicate that the Earth should have been completely frozen
  - Assuming an intensity of the greenhouse effect similar to the present-day one
- We know that this was not the case, since there are evidences of liquid water at the same epoch of Earth's history
- This contradiction is known as the "faint young Sun paradox"



Te – Effective temperature of the Earth
Ts – Mean surface temperature of the Earth
The shaded region indicates the greenhouse effect

Possible solutions of the "Faint Young Sun paradox"

- Most commonly adopted explanation:
  - Larger efficiency of the greenhouse effect in the primitive Earth
- Classic explanation:
  - Atmosphere rich in CO_2 and/or CH_4

    Problems: the early amount of atmospheric CO_2 is limited by geochemical constraints
- Recent hypothesis (TBC):
  - Creation of N_2O, a strong greenhouse gas, in the upper atmosphere by energetic protons generated by the strong activity of the young Sun (Airapetian 2018)

    Subsequent decline of solar activity would be compensated by the rise of solar luminosity

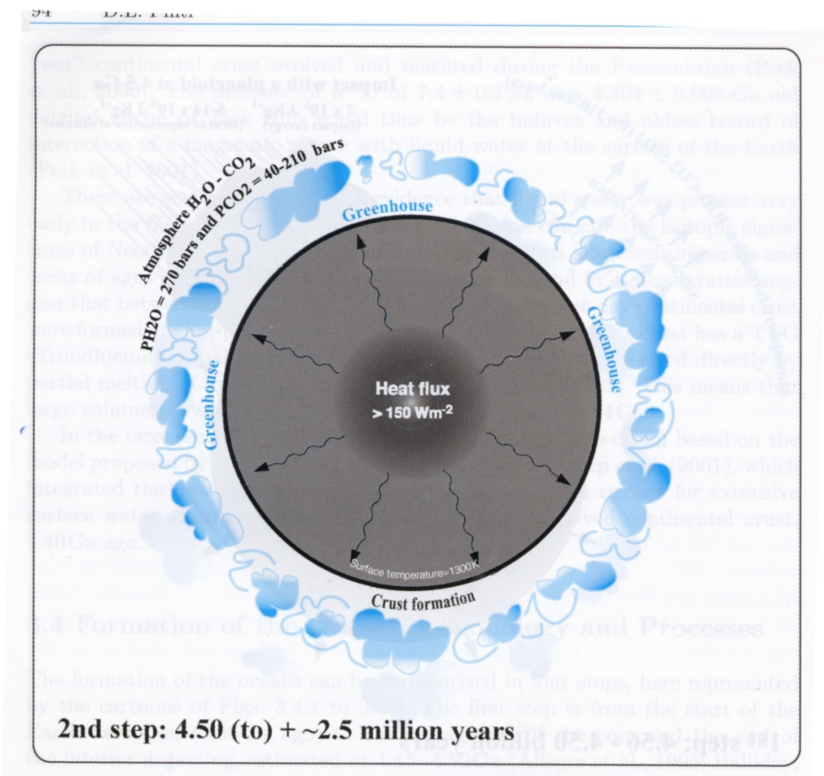


Fig. 3.4.2. Ibid

The origin of Earth's water

- Understanding the origin of Earth's water is best done within the context of the standard model of accretion of terrestrial planets
- According to this model, terrestrial planets accreted from a swarm of planetesimals and planetary embryos
- Therefore, Earth's volatiles, including water, are likely to have been delivered from their planetesimal precursors and their chondritic building blocks
- Specifically, the most likely sources of Earth's volatiles could have been the outer asteroid belt, the giant planet regions, and the Kuiper belt
  - (Morbidelli et al. 2000)
- Gases in the solar nebula were probably not an important source of volatiles
  - the extreme solar wind associated with the T-Tauri phase of stellar evolution is likely to have blown the solar gas away

Testing the origin of Earth's water

- The possibility that water has been delivered on Earth by impacts of minor bodies (asteroids and comets) is tested with studies of the isotopic ratio D/H
- The oceanic D/H ratio is compared with measurements performed in meteorites and comets

- So far, asteroids appear to be favoured, whereas comets have a significantly higher D/H ratio

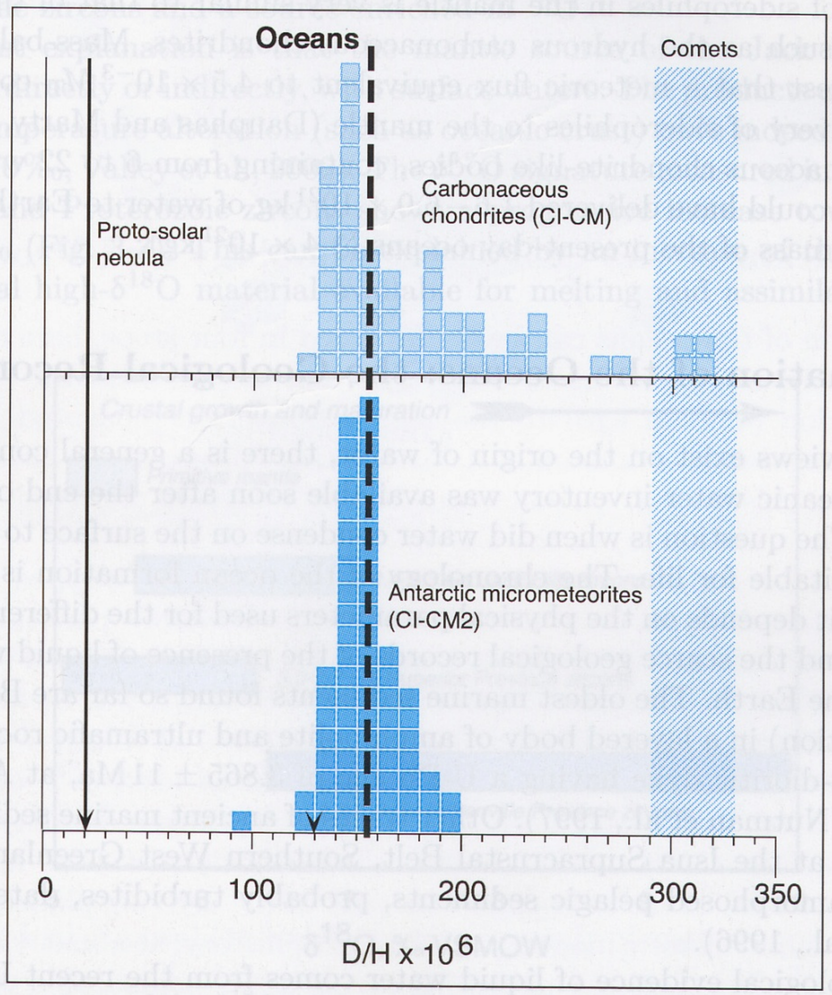


Fig. 3.2. Frequency distribution of the D/H ratios measured in carbonaceous chondrites and Antarctic micrometeorites compared to values for the PSN, Earth oceans and comets. Data: Déloule et al., 1991; Engrand et al., 1999; Maurette et al., 2000; Robert et al. 2000