Astrobiology
Lecture 11

The terrestrial context for the origin of life

University of Trieste, 2023
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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

- With ”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*

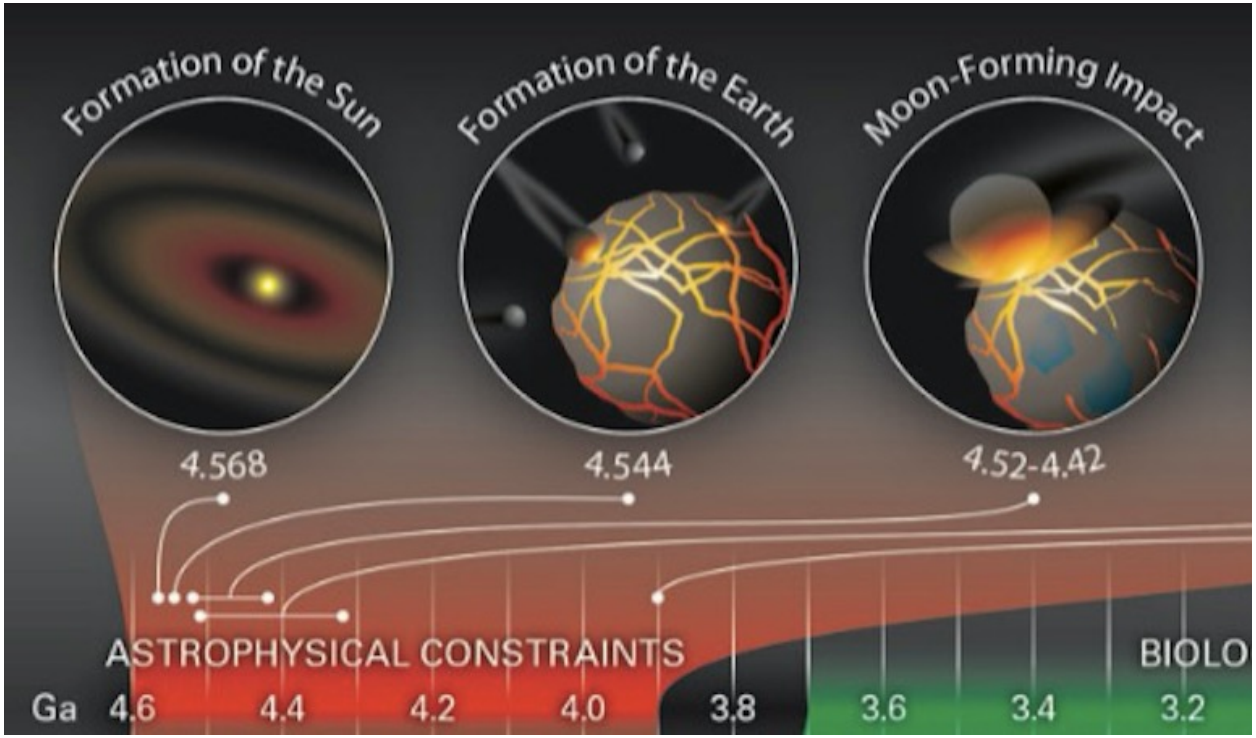
- By comparing the chronology of these events, we can estimate:
  - the <u>epoch of life formation</u>
  - the <u>time interval available for life formation after the onset of habitability conditions</u>

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 x 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

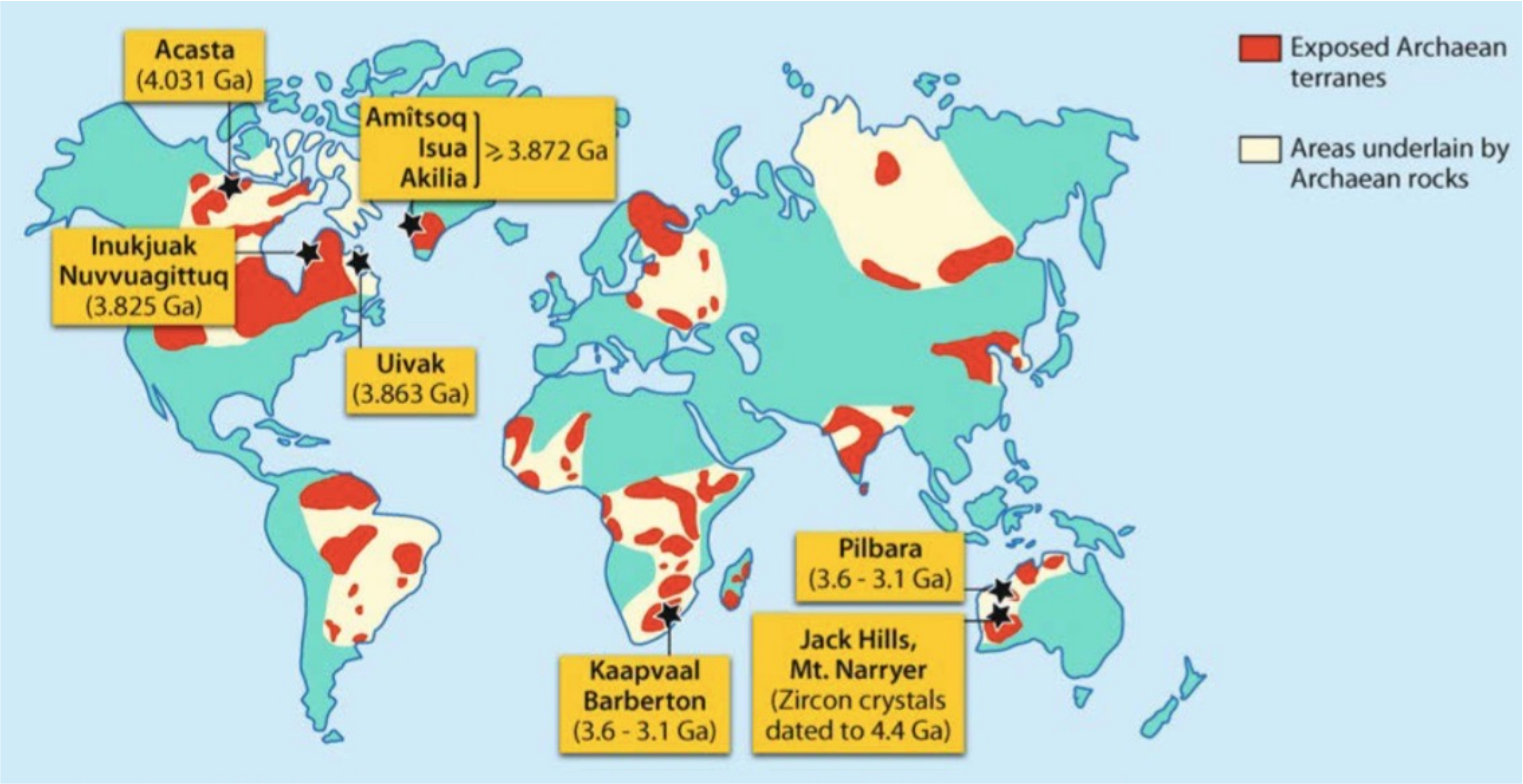
- It is extremely difficult to find terrestrial rocks with ages close to the epoch of the primitive Earth
  - This makes very hard dating the origin of life
- The main reason for this difficulty is tectonic activity, which is constantly recycling the Earth’s crust

- 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 (e.g., Mercury, Moon, Mars) indicate a long history of collisions with minor bodies, 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

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

Minor bodies/meteoritic collisions in the primitive Earth

- Based on the analysis of some Lunar samples, an episode of heavy meteoritic impacts may have taken place on Earth half billon years after its formation
- However, the evidence for this "Late Heavy Bombardment" is quite weak
  - According to this scenario, 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 of the Earth until ~ 3.8 x 10^9 Ga

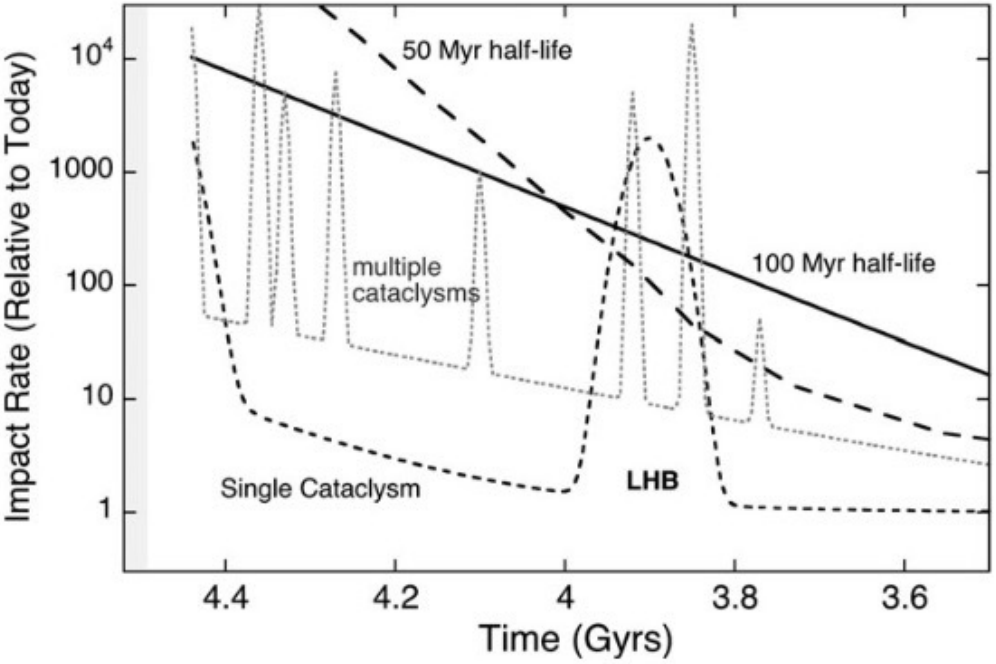


FIG. 2. Four possible scenarios for the LHB, calibrated to crater counts and surface ages at the Apollo landing sites. All scenarios except the 50 Myr half-life model are supported by the available data. Reprinted by permission from Springer Nature: Zahnle *et al.* (2007).

Summary of the temporal boundaries of the onset of habitability conditions in the primitive Earth

- 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

- Should the Late Heavy Bombardment have been so effective to interrupt the habitability of the Earth, the upper boundary of continuous habitability would be ~3.8 Ga
- However, there is no compelling evidence for the LHB, so that the temporal boundary for habitability conditions could be as high as ~4.4 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

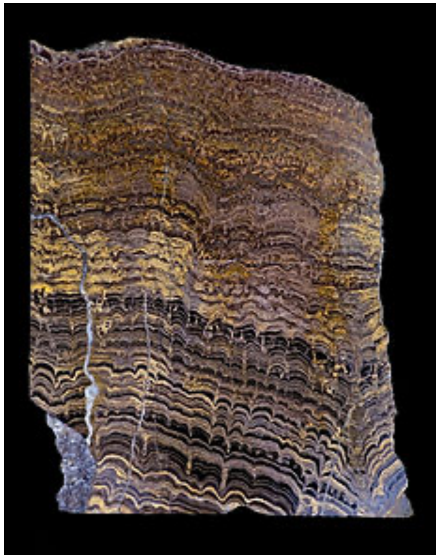
    Examples: sedimentary layers similar to present-day "stromatolites"

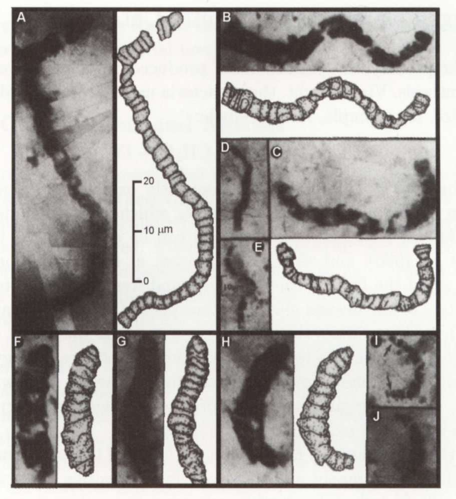
- These methods only offer indirect evidences
  - Results should be taken with caution
  - However, convincing evidence can be obtained by the combination of different methods

Oldest evidence for life on Earth

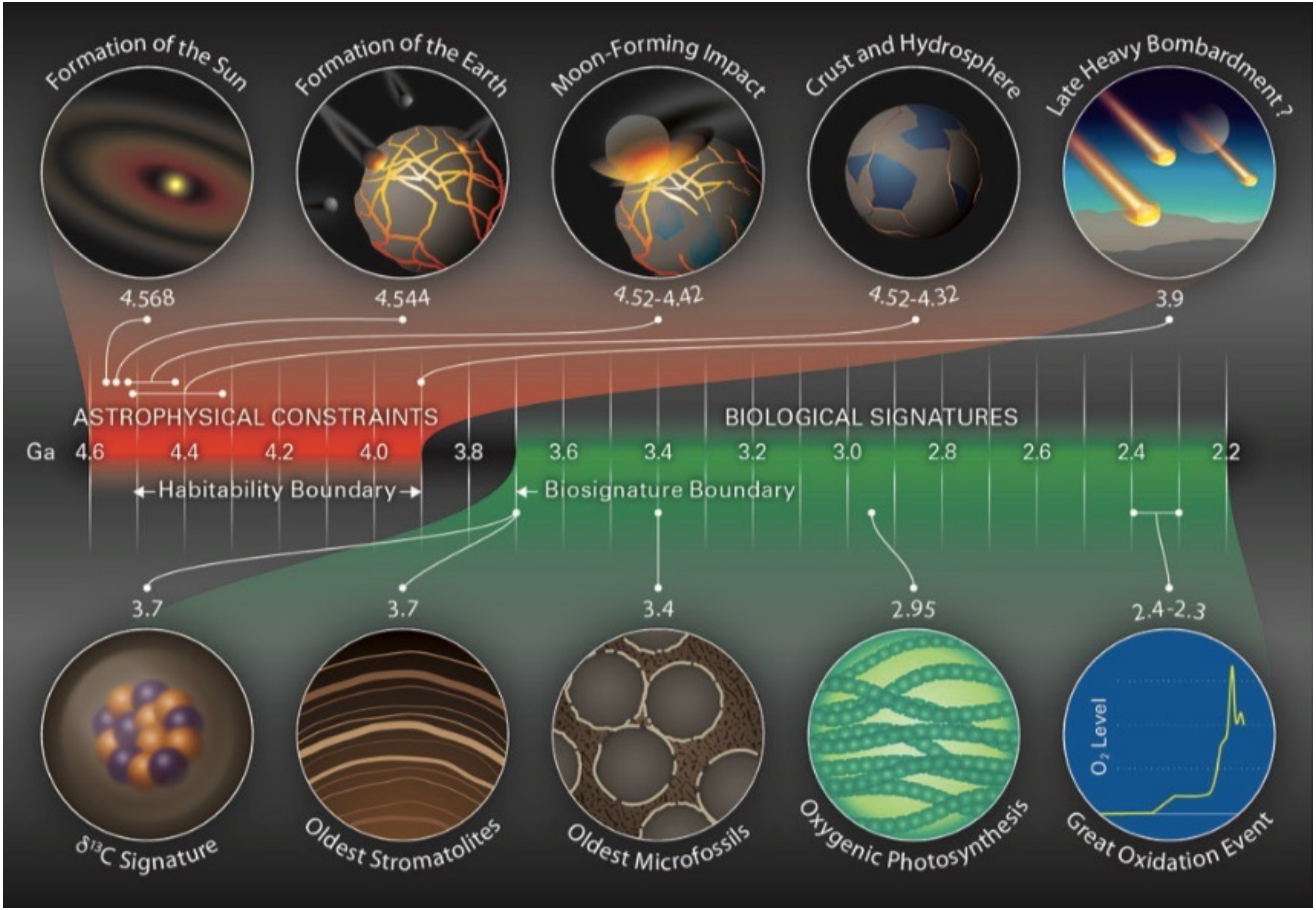
- The oldest, <u>tentative</u>, evidence are dated at about 3.8 Ga
  - Sedimentary rocks in the south-east of Greenland (Isua, Akilia)
    - Based on the isotopic ratio $^{12}C/^{13}C$

- The oldest, <u>more convincing</u>, 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 <u>diffuse life</u> in shallow water, close to the litoral





Chronology relevant for studies of the origin of life on Earth



Summary of temporal constraints on the origin of terrestrial life

Even if we consider the oldest, robust evidence of biological traces at 3.5 Ga, life must have originated before 3.5 Ga , when it was already widespread

- Neglecting the scenario of "Late Heavy Bombardment"
  - The Earth could have been habitable for almost 1 Gyr before life was able to emerge
- 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 oldest, robust evidence of biological traces, 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

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

- 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 a few aspects of the early Earth conditions relevant to the origin of life:
  - Early atmospheric composition
  - Early climate conditions
  - 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

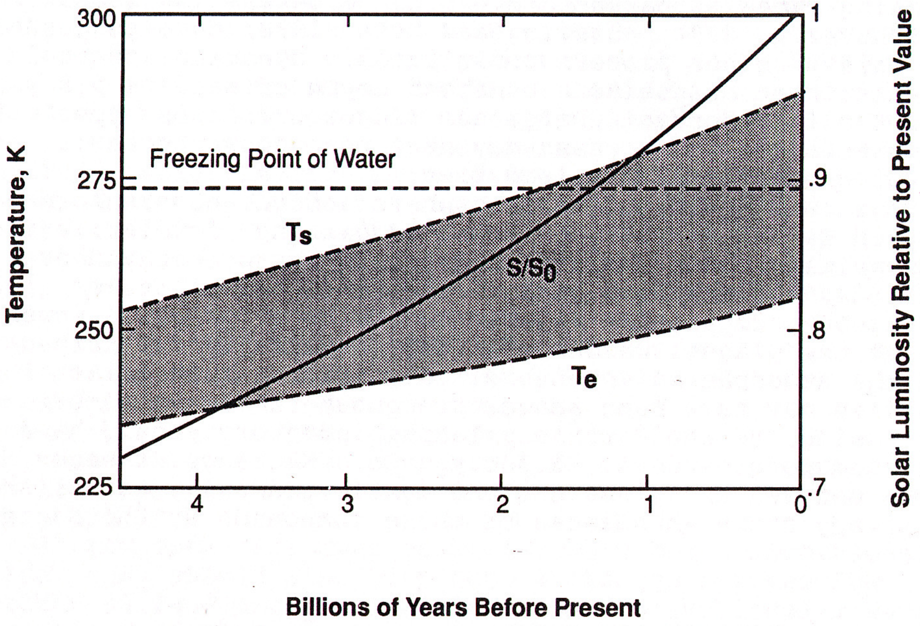
    These volcanic emissions produce a "reducing" atmosphere (rich of hydrogen), with a high content of H_2, CH_4, and NH_3
  - Fast formation models (10-100 millon years; more realistic)

    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 with present-day greenhouse levels indicate that the Earth should have been completely frozen
- 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"



T_e – Effective temperature of the Earth

T_s – 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

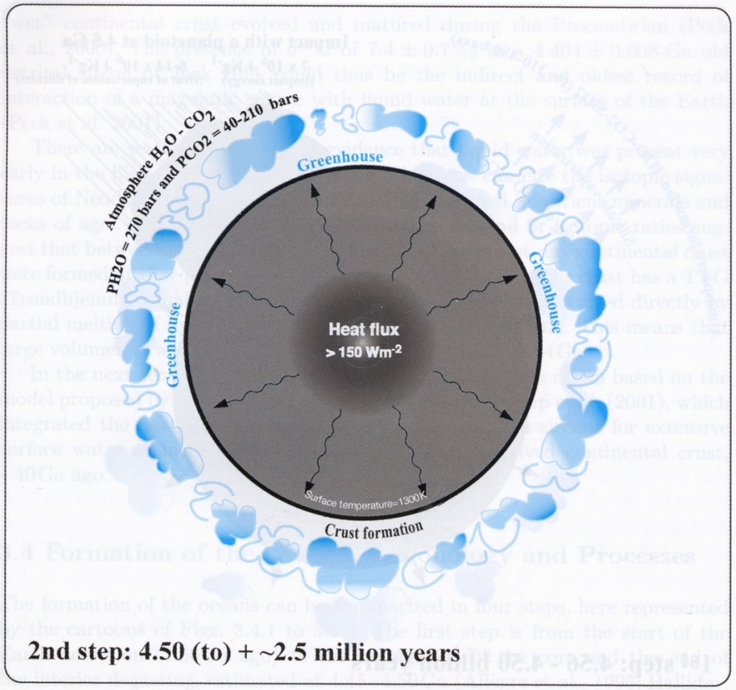
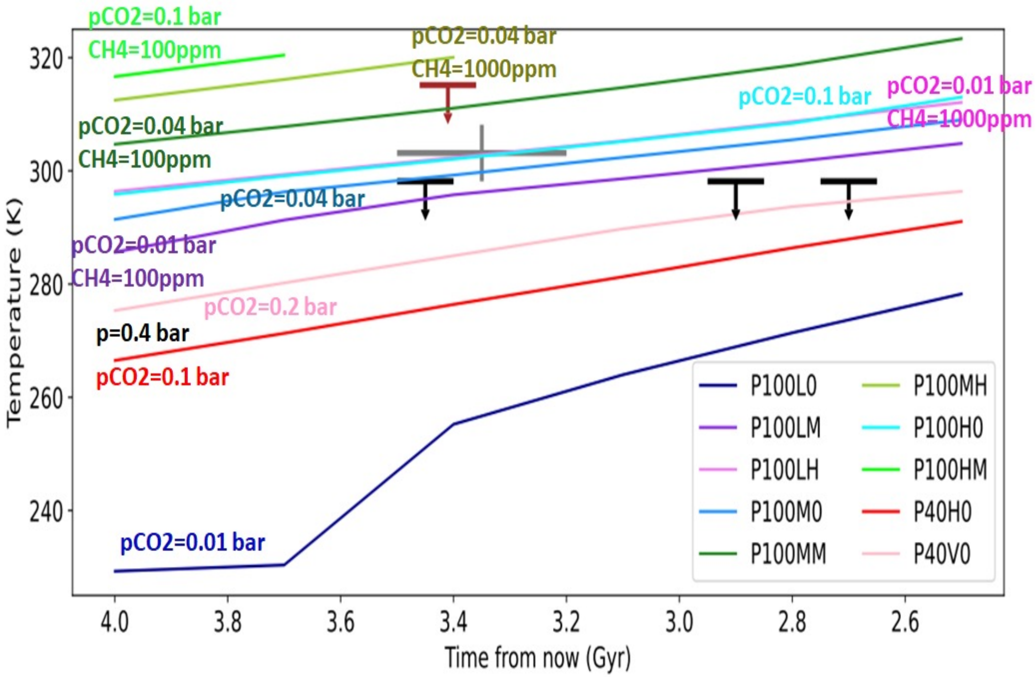


Fig. 3.4.2. Ibid

Studies of the Archean climate at INAF Trieste

Bevilacqua (2022, Thesis); Ivanovski et al., in prep.



Evolution of the mean temperature of the Earth during the. Results obtained with the ESTM climate model. The solar luminosity, rotation period, and continental coverage were changed at each epoch according to specific evolutionary models. Each curve corresponds to a fixed atmospheric composition. Upper limits and cross: experimental constraints.

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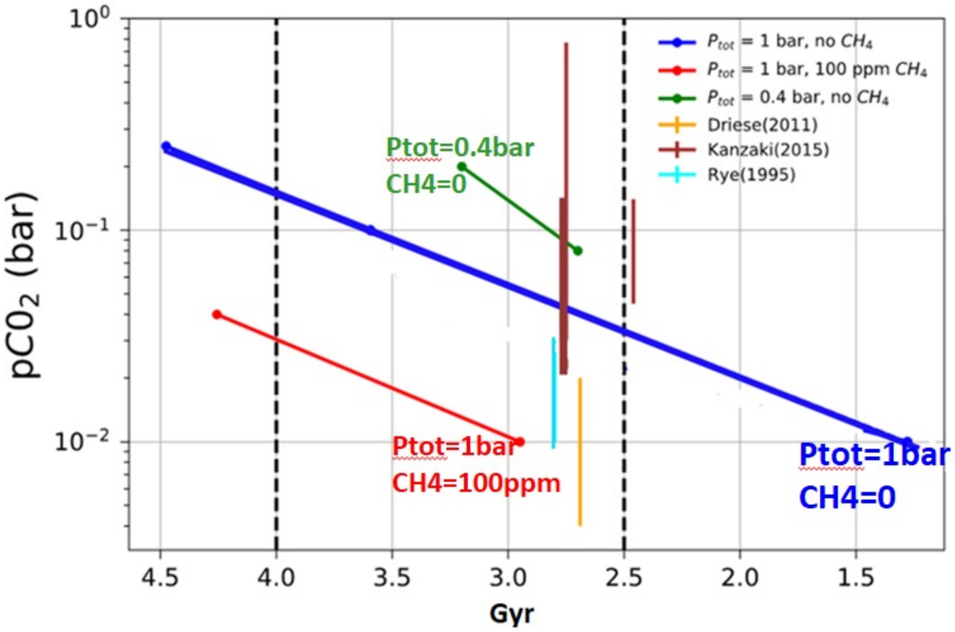


Models of the evolution of atmospheric CO_2 obtained imposing a constant temperature T=300K. Each curve corresponds to atmospheres with different pressures and different content of CH_4. The solar luminosity, rotation period, and continental coverage were changed at each epoch according to specific evolutionary models. Vertical bars: experimental constraints.

Alternative solutions of the "Faint Young Sun paradox"

- Recent hypothesis:
  - 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)

Potential advantages of this hypothesis:

The gradual decline of solar activity would decrease the amount of N_2O and reduce its greenhouse effect

In the meantime the gradual rise of solar luminosity would make unnecessary the presence of a strong greenhouse gas to keep the Earth habitable

  - Work in progress at INAF Trieste: study of the impact of an upper layer of N_2O on the Archean climate of the Earth

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

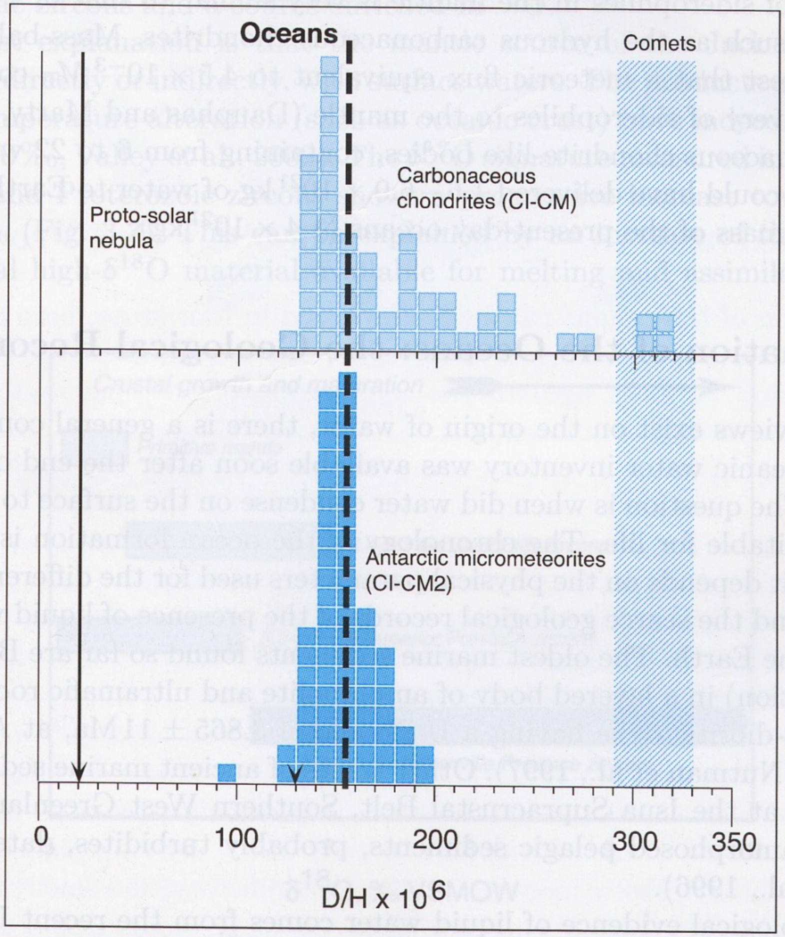
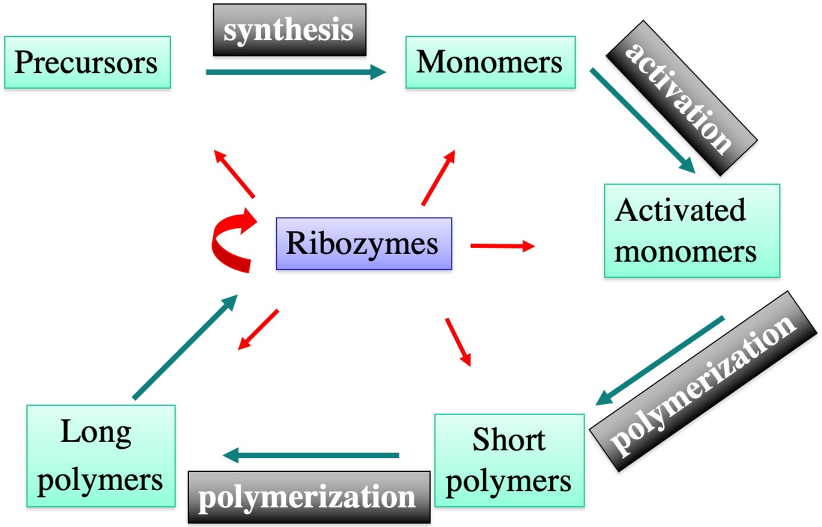


Fig. 3.2. Frequency distribution of the D/H ratios measured in carbonaceous chondrites and Antarctic micrometeorites compared to values for the PSN, Earth oceans and comets. Data: Déloule et al., 1991; Engrand et al., 1999; Maurette et al., 2000; Robert et al. 2000

The emergence of life outside Earth

- The exact conditions for the emergence of life ("abiogenesis conditions") are not clear even for terrestrial life
- However, it is clear that the pathway of spontaneous steps that may lead to the origin of life is quite narrow since it requires the tuning of multiple factors



- The "abiogenesis conditions" are probably narrower than the conditions that allow a planet to be habitable
- The existence of life outside Earth (e.g., in exoplanets) is probably more constrained by "abiogenesis conditions" rather than habitability conditions

- By studying the properties of the Archean Earth we may obtain significant contraints on the conditions suitable for the origin of life
- The conditions of abiogenesis can be applied to search for exoplanets where life may potentially emerge
- From our current understanding of the origins of terrestrial life, planets with subaerial sites (in practice, rocky planets with an atmosphere) offer better conditions of abiogenesis with respect to other planets (e.g. gaseous giants, water worlds)

Scenario of abiogenesis	Variety of sites or conditions	Transfer of prebiotic products	Variations in a given site	Exogenous delivery	Origin of chirality
Subaerial sites (heterotrophic scenario)	Ponds, lakes, beaches, dry areas, volcanoes, geysers, hot springs	PLAUSIBLE (e.g., hydrological system)	**Irradiation** (day-night cycle), **concentration** (dry-wet cycles in ponds/lakes, tidal cycles on beaches)	POSSIBLE	On Earth's surface or from meteorites
Bottom of the oceans (autotrophic scenario)	VERY LIMITED (inside vent system)	VERY LIMITED (inside vent system)	NO (steady conditions)	NO (extremely diluted)	NO