

Archean Earth, Microbial Worlds, and Photosynthesis

CHO-012 · Cosmic History and Its Observers

A Chronological Scientific History from the Early Universe to the Present

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Structured abstract

Context. Between 4.000 and 2.500 billion years ago, Earth acquired long-lived continental nuclei, repeatedly reorganised its crust and oceans, hosted diverse microbial ecosystems, and developed photosynthetic pathways that began altering surface redox conditions. The interval cannot be represented as a smooth ascent toward modern Earth.

Question. How did Archean geodynamics, climate, microbial metabolism and photosynthesis interact, and what does the evidence establish without converting local proxies or model dates into a single global transition?

Evidence and method. This synthesis separates measured rock, isotope and palaeomagnetic observations from geodynamic, climatic, biological and molecular-clock reconstructions. Competing mechanisms are retained where the same proxy admits several interpretations. Oldest-life adjudication remains with CHO-011; the Great Oxidation Event from 2.500 Ga onward remains with CHO-013.

Results. Archean felsic crust formed through several processes, and evidence for mobile plates does not by itself date the establishment of a global modern-style plate network. Climate solutions to the faint-young-Sun problem require coupled greenhouse, albedo, cloud, haze, pressure and hydrological constraints, including evidence interpreted as a glacial interval near 2.90 Ga. Microbial worlds diversified carbon, methane, sulfur and nitrogen cycling. Geological and molecular evidence permits oxygenic photosynthesis in the Archean but does not identify a single origin date. Local or transient oxygenated environments coexisted with an atmosphere for which mass-independent sulfur-isotope records are commonly interpreted as evidence of low oxygen, although that interpretation has been contested.

Conclusion. Approaching the 2.500 Ga ownership seam, Earth was a geologically and biologically coupled planet with stable continental regions, extensive microbial ecosystems and spatially heterogeneous redox conditions. These developments prepared, but did not predetermine, the later planetary oxygenation treated in CHO-013. The observer capacity assigned here is limited to conditional lineage-level environmental detection and regulated response, not cognition or consciousness.

Keywords: Archean; continental crust; plate tectonics; faint young Sun; microbial ecology; metabolism; photosynthesis; oxygen oases; sulfur isotopes

1. Chronological orientation and inherited state

CHO-012 is the chronological spine for [4.000, 2.500) Ga ago. The lower boundary is the conventional Hadean-Archean transition used by this series, not a globally synchronous geological event. The upper boundary is a stratigraphic ownership seam: any datum at exactly 2.500 Ga or younger belongs to CHO-013. Within the article, Ga denotes billions of years before the present.

CHO-009 passes forward a planet with differentiated interior, early crust, liquid-water interaction, atmosphere-ocean exchange and a record repeatedly modified by impact, melting, alteration and metamorphism. CHO-010 supplies multiple experimentally plausible components of chemical evolution without dating a unique origin of life. CHO-011 concludes that selected Eoarchean and Paleoarchean records support a bounded inference that some environments were inhabited, while not identifying one oldest fossil, metabolism, habitat or moment of origin.

The task here is therefore different from finding a first organism. It is to reconstruct the changing Earth system in which microbial populations persisted, diversified and modified their environments. Four transformations organise the interval: production and survival of continental crust; changing modes of tectonic recycling; maintenance of habitable surface water under a fainter Sun; and expansion of microbial metabolisms, including photosynthesis and locally oxygenating ecosystems.

2. Building continents without assuming one tectonic regime

Archean continental crust is dominated in many terranes by tonalite-trondhjemite-granodiorite suites and associated greenstone belts. Their chemistry records melting of mafic precursors, but chemistry alone does not specify one geodynamic mechanism. Hydrated basalt may melt in subduction-like settings, within thickened mafic crust, or during plume-related burial and reworking. Later deformation can juxtapose products of different processes.

Experimental work on East Pilbara compositions supports coexistence of deep, subduction-like melting and shallower intracrustal processes in the early Archean [2]. Conversely, modelling shows that mafic crustal overthickening can generate wet, oxidising magmas without requiring modern-style subduction [8]. A global compilation published in 2025 identifies diverse sources for early felsic crust and interprets a major geodynamic transition near 3.0 Ga [7]. These studies narrow process space; they do not turn every Archean granitoid into a plate-boundary marker.

Continents also had to emerge above sea level and remain stable enough to interact persistently with atmosphere and oceans. Work on the Singhbhum Craton attributes widespread emergence around 3.3-3.2 Ga to magmatic thickening in a non-plate-tectonic setting [1]. This is a regional reconstruction, not a date for Earth's first exposed land everywhere. By the late Archean, passive-margin-like successions and craton stability have been interpreted as creating longer-lived interfaces among weathering, nutrient delivery, sedimentation and atmospheric chemistry [9]. This is a regional crust-surface-system interpretation, not proof that one tectonic transition caused a biological innovation.

The appropriate synthesis is plural. Early crust could grow, founder, melt and be recycled under several coexisting regimes. The geological transition of interest is not the first local occurrence of a subduction-like signature; it is the gradual organisation of long-lived, connected surface mobility and recycling.

3. When did plate tectonics become global?

No single observation uniquely dates the onset of plate tectonics. Candidate indicators include high-pressure metamorphism, arc-like geochemistry, paired thermal gradients, ophiolite-like associations, palaeomagnetic motion, sedimentary basin architecture and evidence of deep volatile recycling. Each records only part of the modern system.

Palaeomagnetic work reports motion of the East Pilbara Craton relative to Earth's rotation axis at rates comparable to modern plate motion around 3.2 Ga [3]. The study does not separate differential plate motion from true polar wander or net rotation of the lithosphere. Geochemical evidence from mantle-derived rocks has also been interpreted as widespread mantle re-enrichment at 3.2 Ga and therefore as a signal of global-scale recycling [4]. These are important constraints, but motion of crustal blocks and recycling of material are necessary rather than sufficient conditions for a continuously connected global plate network.

Other studies place a broader transition later. Greenstone burial-exhumation histories have been interpreted as marking a late-Archean shift toward plate-tectonic behaviour [5], and Neoarchean palaeomagnetic records support relative mobilism without alone specifying the global topology [6]. The evidence may be reconciled if local subduction, episodic mobility and plume-driven recycling preceded stable global operation. It may also reflect genuine disagreement among proxies, regions and definitions.

CHO-012 therefore does not print a unique onset date. It distinguishes four propositions: local subduction-like processing; movement between crustal blocks; deep recycling; and a persistent global network of mobile plates. Evidence for one level cannot silently close the others.

4. Habitable water beneath a faint young Sun

Solar luminosity was lower during the Archean, yet sedimentary and alteration records require persistent liquid-water environments. The apparent contradiction is the faint-young-Sun problem. It is a coupled climate problem rather than a request for one missing greenhouse gas.

Proposed solutions combine carbon dioxide, methane, atmospheric pressure, cloud microphysics, surface albedo, rotation, continental distribution and photochemical haze. Rosing and colleagues argued that reduced cloud condensation nuclei and lower planetary albedo could ease the paradox while geochemical evidence limited carbon dioxide [10]. Dauphas and Kasting challenged the conversion from pore-water chemistry to atmospheric carbon dioxide [11]. Three-dimensional modelling further indicates that ice-albedo feedback and faster rotation can increase the warming required relative to simpler calculations [12].

Methane produced by microbial ecosystems is an efficient greenhouse gas in reducing atmospheres [13], but abundant methane can also generate organic haze whose climatic effect depends on particle distribution, clouds and circulation [14]. Geological constraints remain indispensable. Palaeosol and weathering records have been used to bound carbon dioxide near 3.2 Ga [15], while fossil raindrop imprints constrain air density indirectly rather than measuring an exact atmospheric pressure [16].

Warm settings were not continuous everywhere. Triple-oxygen-isotope work on approximately 2.90 Ga Pongola-Mozaan rocks supports weathering by very cold, high-latitude precipitation and a glacial episode [17]. The source calls this Earth's first glaciation; after full-text review CHO does not adopt that priority phrase, while retaining the colder interval as a model constraint. A successful Archean climate reconstruction must accommodate both liquid-water habitability and the possibility, under this interpretation, of at least one preserved glacial state. Habitability was a distribution across space and time, not a globally uniform temperature.

4.1 Evidence base, dating methods and resolution limits

Archean chronology combines clocks that date different objects. A numerical age must remain attached to the object and process actually dated. Precision is limited by the weakest link among analytical uncertainty, disturbance of the isotopic system, the relation between a dated mineral and its host unit, stratigraphic correlation, and the inference connecting the host to the environmental or biological claim.

Method or evidence class	What it dates or constrains here	Principal resolution limit
U-Pb zircon and other mineral geochronology	Crystallisation or later isotopic resetting of dated minerals; it may bracket deposition when the mineral-unit relation is demonstrated	A precise zircon age is not automatically the age of sedimentation, a carbon particle, a metabolism or a tectonic regime; inheritance, Pb loss and reworking must be tested
Stratigraphic and field bracketing	Relative order and an interval for deposition between independently dated units, ash beds or cross-cutting bodies	The environmental signal inherits the bracket and correlation uncertainty; the oldest endpoint is not an exact event date
Palaeomagnetism combined with independent geochronology	Direction and changes in primary remanent magnetisation through time, used to reconstruct crustal motion relative to Earth's rotation axis; differential motion requires additional constraints [3,6]	Remanence acquisition, overprinting, block rotation and age control affect the reconstruction; true polar wander and net lithospheric rotation must also be distinguished from differential plate motion before inferring tectonic topology
La-Ce geochronology of cerium anomalies	The timing of La/Ce fractionation and therefore, under the source interpretation, syn-depositional Ce oxidation in the studied carbonates [28]	It dates formation of the anomaly in particular deposits, not the evolutionary origin of oxygenic photosynthesis; mixing, later mobility and isochron assumptions must be excluded
Triple oxygen isotopes	Hydrological conditions and the provenance of weathering water recorded by already dated rocks [17]	The isotope system is a climate proxy, not the clock that establishes 2.90 Ga; spatial representativeness and preservation limit the climatic inference
Elemental and stable-isotope proxies, including MIF-S, nitrogen, molybdenum and cerium	Redox, photochemical or metabolic processes associated with a dated sample [21,22,26-28,32-34,42,43]	Proxy production, transport, deposition and alteration intervene; the host age dates occurrence of a signal, not necessarily the origin, duration or global extent of its process
Molecular clocks and horizontal-gene-transfer constraints	Probability distributions for lineage or protein-family divergences [20,29,30]	Results depend on topology, calibrations, rate models, horizontal transfer and sampled descendants; they are not rock ages and should not be printed as point events
Molecular fossils	The depositional age of an indigenous, syngenetic compound only after provenance is established [35-39]	Migration, metamorphism, drilling and laboratory contamination can detach a molecule from the host-rock age and invalidate biological priority claims

Accordingly, 3.2 Ga plate motion dates an inferred movement interval, not the beginning of a global system. The 2.87, 2.85 and 2.78 Ga La-Ce results date formation of particular cerium anomalies, not the first water-splitting lineage. The approximately 2.90 Ga age and the triple-oxygen-isotope climate interpretation are separate links in one argument. Molecular-clock intervals date modelled divergences, while geochemical proxies date preserved environmental expressions. CHO reports no biological or planetary transition more precisely than this complete chain permits.

5. Microbial worlds rather than a single biosphere type

The Archean biological record is filtered through preservation and proxy interpretation. CHO-011 owns claims about the oldest evidence. CHO-012 begins from the narrower proposition that microbial populations existed and asks how ecosystems could have been organised.

Microbial communities exploited chemical disequilibria generated by sunlight, water-rock reactions, volcanic gases, hydrothermal circulation and organic matter. Anaerobic metabolisms must have dominated large parts of the interval: fermentation, methanogenesis, anoxygenic photosynthesis, sulfur transformations and nitrogen fixation could operate without an oxygenated atmosphere. Their relative importance varied among photic waters, sediments, hydrothermal systems, continental margins and restricted basins.

Organic films from the approximately 3.4 Ga Buck Reef Chert preserve geochemical diversity among material subjected to similar metamorphic history [19]. Such within-unit heterogeneity is useful because it reduces the temptation to read all ancient carbon as one biological or alteration product. It still does not identify organisms taxonomically.

Phylogenomic analyses offer a different archive. Horizontal gene transfer has been used to constrain diversification within methanogenic lineages to deep Archean time [20]. Laboratory simulations published in 2025 show that a hydrogen-dependent acetyl-CoA pathway can be fuelled under modelled early-Earth geochemical conditions [23]. A

2026 paper proposes a hydrogen-, methane- and ammonia-rich early biosphere-atmosphere system [24]. These results differ in evidential type: lineage histories, experimental feasibility and thermodynamic reconstruction cannot be collapsed into one dated geological observation.

6. Nitrogen, sulfur and methane cycles

Biological productivity requires accessible nitrogen. A 3.2 Ga nitrogen-isotope record has been interpreted as evidence for molybdenum-nitrogenase-mediated fixation [21]. That interpretation depends on calibration of biological fractionation and exclusion of abiotic or diagenetic alternatives. Experiments with reconstructed ancestral nitrogenases published in 2026 reproduce canonical nitrogen-isotope biosignatures across evolutionary variants [22], strengthening the mechanistic basis of the proxy without retroactively proving every ancient sample.

Methane connected biology and climate. Methanogens could consume hydrogen and carbon compounds in anoxic settings, adding greenhouse forcing while leaving isotope patterns that abiotic hydrothermal reactions can sometimes imitate. The article therefore separates the evolutionary history of methanogenic lineages from priority methane evidence already assessed in CHO-011 and from climate consequences.

Sulfur isotopes constrain both metabolism and the atmosphere. Mass-independent fractionation of sulfur isotopes, or MIF-S, is widely interpreted as a record of gas-phase atmospheric reactions under low oxygen [32]. Mesoarchean records have been used to argue for atmospheric anoxia and changing sulfur chemistry [34]. Yet the absence of MIF-S in selected 2.92 and 2.76 Ga successions has supported competing oxic, fluctuating or diagenetic interpretations [33].

These records require scale discipline. A sedimentary basin can record local oxygen production while the global atmosphere remains sufficiently reducing to preserve MIF-S elsewhere. Conversely, an interval without a MIF-S signal does not by itself prove a permanently oxygenated global atmosphere. Proxy production, transport, deposition, alteration and sampling all lie between atmospheric state and measured rock.

7. Photosynthesis: several innovations, several clocks

Photosynthesis is not one indivisible invention. Anoxygenic systems use light without splitting water and can employ electron donors such as hydrogen, ferrous iron or reduced sulfur. Oxygenic photosynthesis couples two reaction centres to extract electrons from water and releases molecular oxygen. Crown cyanobacteria, the water-oxidising machinery and later plastids are related but chronologically distinct targets.

The 3.416 Ga Buck Reef record has been interpreted as photosynthetic microbial mats [18], but the priority adjudication remains with CHO-011 and the source does not establish oxygenic photosynthesis. A 3.7 Ga uranium-associated signal has been interpreted as evidence of oxygenic photosynthesis [25], while later proxy families provide younger and differently calibrated constraints.

Manganese and molybdenum data have been used to infer oxygenic photosynthesis at least 2.95 Ga [26]. Isotope evidence has also been interpreted as oxygenated Mesoarchean shallow water [27]. La-Ce geochronology published in 2025 directly dates cerium anomalies at approximately 2.87, 2.85 and 2.78 Ga and places the evolution of oxygenic photosynthesis in the Mesoarchean or earlier [28]. These are constraints on oxygen production and redox chemistry, not observations of the originating organism.

Molecular evolution supplies broad, model-dependent intervals. Analyses of Photosystem II diversification support an early Archean history for core water-oxidation machinery [29]. Molecular-clock work separates the Archean origin of oxygenic photosynthesis from the later diversification of extant crown cyanobacterial lineages [30]. Gene-tree topology, calibration choice, rate variation and horizontal transfer widen the uncertainty. Geological proxies and molecular clocks can be mutually informative without being forced to yield one birthday.

8. The biomarker warning

Late-Archean hydrocarbons were once presented as molecular fossils of eukaryotes and cyanobacteria [35,36]. Subsequent work showed why ancient biomarker claims demand exceptional contamination control. Reassessment linked relevant hydrocarbons to younger material or metamorphic contexts [37]. Ultraclean drilling, procedural blanks and multiple laboratories found the previously diagnostic compounds to be contaminants while identifying

indigenous hydrocarbons too thermally mature for the original taxonomic claims [38]. Laboratory air itself can transport trace hydrocarbons [39].

A distinct 2025 approach analysed distributions of fragments released by pyrolysis-gas chromatography-mass spectrometry and classified them with supervised random forests [48]. The authors reported model support for biogenic molecular assemblages in 3.33 Ga Josefsdal rocks and described the combined 2.52 Ga Gamohaan results as suggestive of photosynthesis, while noting that most Precambrian samples of unknown affinity remained indeterminate, intact diagnostic biomolecules were absent and systematic contamination effects require further testing. This pattern-classification result neither restores the rejected sterane and 2-methylhopane claims nor identifies an Archean taxon or the origin date of photosynthesis.

CHO-012 retains this episode as a falsification case, not as positive dating evidence. The discarded cyanobacterial reading belongs here because it once affected claims about photosynthesis. The discarded eukaryotic reading belongs to the CHO-014 priority overlay beginning at 2.800 Ga; it is mentioned here only because both readings arose from the same contaminated evidence class. A molecule's modern biological association does not establish its antiquity, syngeneity or source organism.

9. Oxygen oases before atmospheric accumulation

Oxygenic photosynthesis need not produce immediate atmospheric oxygenation. Oxygen was consumed by reduced volcanic gases, dissolved iron, sulfur species, organic matter and crustal minerals. Production could exceed local sinks in a mat, shallow-water body or continental shelf while remaining below the threshold for sustained global accumulation.

Multiple proxy systems support heterogeneous Archean redox. The 2.95 Ga manganese-molybdenum record, Mesoarchean shallow-water signals and directly dated Meso- to Neoarchean cerium anomalies all point to local oxygen production under their respective interpretations [26-28]. A 2013 study argued for atmospheric oxygenation around 3.0 Ga [31], but this atmosphere-scale conclusion must be tested alongside MIF-S evidence rather than treated as equivalent to a local oasis.

Mesoarchean and Neoarchean studies add temporal variability. In a 2.93 Ga Red Lake drill core, phosphorus recycling has been modelled as enabling pulses of enhanced productivity and spatially limited oxygen oases [40]. Independent Neoarchean work reports transient oxygenation of continental-shelf bottom waters by approximately 2.65 Ga [41]. Nitrogen isotopes have been interpreted as evidence of oxygen-linked nitrogen cycling late in the Archean [42,43]. These records describe ecological networks and local redox states; they do not measure a modern atmospheric oxygen concentration.

The often-cited “whiff of oxygen” near 2.5 Ga illustrates the boundary risk [44]. A 2022 reassessment, using depositional brackets of 2533 ± 6 Ma and 2483 ± 7 Ma, attributed the original bulk signal to postdepositional alteration and argued for an anoxic ocean before the Great Oxidation Event [45]. A 2023 technical comment disputed that reassessment and defended transient pre-GOE oxygenation [46]; the reassessment's authors replied that late-stage pyrite compromised the whiff interpretation and that primary signals instead supported anoxic conditions [47]. This published exchange remains unresolved here. Because this article's interval is half-open, material at exactly 2.500 Ga and younger is CHO-013 evidence. Older samples may provide context only when their dates, alteration histories and ownership are explicit.

10. Observer capacities present

CHO uses “observer” operationally. For microbial life, the only applicable capacity here is OC1: evolved environmental detection coupled to regulated response. Chemotaxis, phototaxis, stress regulation and metabolic switching in living lineages are examples of the general functional class, but no named mechanism is directly fossilised in an Archean rock.

OC1 is therefore a conditional lineage-level reconstruction. If a population was living, maintaining itself and reproducing under variable conditions, regulated interactions with its environment are biologically plausible. This classification does not imply nervous systems, internal models, phenomenal experience or reflective awareness. It also does not classify non-living mineral or atmospheric responses as observers merely because they encode environmental information.

11. Contingency and contemporaries

Archean developments were neither isolated nor inevitable. Continents could grow by several mechanisms, then founder or be reworked. Local mobility could fail to become a persistent global network. Greenhouse warming could be offset by haze or ice-albedo feedback. Nutrient scarcity and redox sinks could limit photosynthetic expansion. Oxygen-producing lineages could remain geographically restricted or disappear without leaving recognisable descendants.

Contemporaneous environments differed sharply. Emergent cratons weathered under the same fainter Sun that illuminated microbial mats; hydrothermal systems supplied reducing power while shallow waters admitted light; anoxic atmosphere-scale chemistry coexisted with possible local oxygen oases. The approximately 2.90 Ga Pongola-Mozaan record, under its published glacial interpretation, shows that a habitable-planet model must permit severe regional or episodic cold.

The geological record is also contingent. Survival of a craton, basin or chert creates an observational opportunity; metamorphism, deformation, erosion and contamination destroy or imitate evidence. Absence from the surviving record is therefore not equivalent to biological absence.

12. Competing interpretations and unresolved questions

Several central questions remain open:

1. When did local, episodic crustal recycling become a persistent global plate network?
2. Which combination of greenhouse gases, pressure, albedo, clouds and haze reproduced the full distribution of Archean climates?
3. How representative are surviving sedimentary basins of global microbial diversity?
4. Which geological proxies require oxygenic photosynthesis rather than non-biological oxidation or later alteration?
5. How should molecular-clock distributions be reconciled with incomplete and locally biased rock records?
6. How often did oxygen oases form, how large were they, and which sinks prevented global accumulation?
7. Which components of nitrogen, sulfur and methane cycling were biologically mediated in each dated setting?

The 2026 hydrogen-methane-ammonia reconstruction [24] and conventional carbon-dioxide-nitrogen frameworks make sharply different assumptions about mantle redox, atmospheric composition and biological feedstocks. CHO retains the newer proposal as a contested alternative rather than treating recency as confirmation.

13. Claim classes, boundaries and exclusions

Measured or observed: rock ages, mineral and elemental distributions, isotope ratios, remanent magnetisation, sedimentary structures and experimentally measured reaction products reported by the cited studies.

Reconstructed from evidence: subaerial emergence, tectonic setting, environmental temperature, biological metabolism, oxygenated water and ecosystem structure.

Model-dependent: global tectonic topology, climate solutions, molecular-clock dates, atmospheric mixing, nutrient feedbacks and the magnitude of biological gas fluxes.

Actively contested: the onset of global plate tectonics; atmospheric carbon-dioxide constraints; the interpretation of selected MIF-S absences; very early oxygenic photosynthesis; late-Archean atmospheric oxygenation; and the hydrogen-methane-ammonia biosphere model.

Rejected as positive dating evidence in this synthesis: Archean sterane and 2-methylhopane priority claims where contamination and syngeneity controls fail.

Speculative or open: a single date for the origin of photosynthesis, direct ancestry between any preserved community and living clades, and any claim of Archean cognition or consciousness.

CHO-011 alone owns oldest-life priority adjudication before 3.200 Ga. CHO-012 may inherit those records as environmental context but may not reopen their ranking. CHO-014 alone owns eukaryote and endosymbiosis priority

within its overlay from 2.800 Ga. CHO-013 owns the Great Oxidation Event and every datum at exactly 2.500 Ga or younger. The disappearance of MIF-S near the Great Oxidation Event is therefore not closed here.

14. Closing state passed to CHO-013

Approaching the exclusive 2.500 Ga boundary, Earth contained stable continental regions and sedimentary basins, though the timing and global organisation of plate tectonics remained debated. Liquid-water environments persisted beneath a fainter Sun and included climatic heterogeneity, with the approximately 2.90 Ga Pongola-Mozaan record interpreted as evidence of glaciation. Microbial ecosystems exploited multiple energy and nutrient pathways. Oxygenic photosynthesis was operating somewhere in the Archean under several independent interpretations, yet its origin remained interval-based and model-dependent.

Oxygen production had begun to restructure selected waters, shelves and nutrient cycles, while atmospheric and sedimentary proxies continued to record extensive anoxia and strong sinks. This is not a failed version of the modern world. It is the inherited state required to explain the next transformation.

CHO-013 begins at 2.500 Ga and asks how oxygen escaped local production-consumption balances, accumulated unevenly in atmosphere and oceans, interacted with glaciation and the carbon cycle, and transformed planetary habitability. The transition was prepared by Archean processes but was not guaranteed by them.

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Disclosure

This document is a scholarly synthesis; it is not primary research and has not been peer reviewed. Juan Seguro is the sole author. He approved the final text and is responsible for its content.