

The Earliest Evidence of Life

CHO-011 · Cosmic History and Its Observers

A Chronological Scientific History from the Early Universe to the Present

Identifier: CHO-011 · Version: v1.0 · Author: Juan Seguro

Language: English

Article role: Overlay

Article window: [4.400, 3.200) Ga ago

Event cutoff: 11 September 2026 · Literature-search cutoff: 13 September 2026

Document type: Scholarly synthesis; not primary research and not peer reviewed

Structured abstract

Context. The oldest terrestrial rocks have been altered, deformed and incompletely preserved. Claims for early life therefore depend on signals whose age, original context and biological specificity must be tested separately.

Question. What does the surviving record between 4.4 and 3.2 billion years ago establish about the presence of life, and which proposed traces remain contested?

Evidence and method. This synthesis compares carbon and sulfur isotopes, carbonaceous microstructures, stromatolite-like morphologies, microbial-mat fabrics, fluid inclusions and hydrothermal associations. Each case is evaluated through four tests: age, syngeneity, biogenicity and multiplicity. The age of a host mineral or rock is never treated automatically as the age of a signal.

Result. Putative evidence extends into the Hadean and Eoarchean, but the oldest claims have low replication or disputed geological and chemical interpretations. By approximately 3.5–3.4 Ga, the published literature contains candidate reports from multiple localities and evidence classes. That breadth reduces dependence on any single priority claim, but it does not validate source internals that remain unavailable or independently establish cells, photosynthesis, sulfate reduction or methanogenesis.

Conclusion. Taken together, the published records evaluated and independently source-checked here from Isua at approximately 3.7 Ga, Dresser at approximately 3.48 Ga and Barberton at approximately 3.42 Ga support a bounded inference that some Eoarchean and Paleoarchean environments were inhabited, while they do not identify a single oldest fossil, metabolism, habitat or moment of origin. It constrains when life existed, not how it originated. The first observer capacity used by this series, environmental detection and regulated response, is inferred conditionally for living lineages and is not directly preserved in ancient rocks.

Keywords: earliest life; Archean; biosignatures; carbon isotopes; microfossils; stromatolites; microbial metabolism; syngeneity

1. Chronological orientation

CHO-011 is an overlay spanning [4.400, 3.200) Ga ago. Its boundaries are an evidential search envelope, not a claim that life began at 4.4 Ga or that priority evidence ends at 3.2 Ga. The interval overlaps the physical history of early Earth in CHO-009, origin-of-life mechanisms in CHO-010 and the microbial Earth system in CHO-012.

The central chronological problem is asymmetrical. As an operational rule for this article, a credible biosignature is treated as evidence that life existed by the time the signal formed, not as a measurement of how long life had already existed. Rejecting one proposed old signal likewise does not demonstrate that Earth was lifeless at that time. Every accepted occurrence therefore supplies a minimum-age constraint for an established biosphere, not a timestamp for life's origin.

2. Initial state inherited from early Earth and prebiotic chemistry

By the opening of this evidential interval, Earth had differentiated, retained or regenerated crust, interacted with liquid water and exchanged material among atmosphere, ocean, rock and hydrothermal systems. CHO-009 supplies that environmental history. CHO-010 shows that several chemical routes can produce precursors, polymers, compartments and selection-like dynamics under specified conditions, while no experiment reconstructs the complete historical transition to open-ended Darwinian evolution.

CHO-011 therefore begins with two possibilities still open: life may already have emerged, or prebiotic evolution may still have been occurring. Geological evidence can narrow that uncertainty only where a signal is old, indigenous and more plausibly biological than abiotic.

3. Four comparison tests used in this article

CHO-011 compares each candidate along four declared audit dimensions: age, syngeneity, biogenicity and multiplicity. This is the article's operational method for keeping unlike evidence from being collapsed into one ranking; it is not presented as a universally standard four-part taxonomy.

3.1 Age

The relevant clock may date a zircon, igneous unit, sedimentary horizon, metamorphic event or cross-cutting vein. These ages constrain different events. A signal enclosed within a 4.10 Ga zircon is not independently dated merely because the zircon is old. A carbon-bearing chert containing syn-volcanic zircons may acquire a tight depositional constraint, but the measured U–Pb clock remains in zircon rather than carbon. A hydrothermal structure inherits an age from its host relations unless the structure itself contains a datable phase formed simultaneously.

3.2 Syngeneity

The signal must belong to the ancient system. Later fluids can introduce carbon, precipitate graphite or reset minerals. Metamorphism can redistribute matter and erase primary textures. Preparation materials and modern contamination create additional risks at microscopic scales. Petrographic position, cross-cutting relations, mineral enclosure and spatially resolved chemistry are therefore part of the evidence, not secondary details.

3.3 Biogenicity

Life-like shape and isotopic lightness are not unique to life. Mineral growth, deformation, self-organised chemical structures, decarbonation, water–rock reactions and abiogenic hydrocarbon production can generate partial mimics. As an operational criterion in this article, a case becomes stronger when it combines independent properties whose joint abiotic production is less plausible than each property considered alone.

3.4 Multiplicity

One exceptional grain and a repeated assemblage do not carry the same evidential weight. Replication across specimens, layers, facies, methods and laboratories reduces the probability that an observation reflects contamination, analytical artefact or a local non-biological process. Multiplicity cannot repair a systematically misinterpreted process, but it changes the structure of the inference.

4. Hadean and earliest Eoarchean candidates

The oldest registered candidate ranked by the well-constrained age of a mineral directly enclosing the signal is graphite in a single Jack Hills zircon dated to 4.10 ± 0.01 Ga, with a reported carbon-isotope composition of $-24 \pm 5\%$ [1]. The observation is striking because it places isotopically light carbon inside a Hadean mineral. It is also intrinsically low-replication: the study reported one carbon-bearing grain among more than ten thousand zircons examined. Abiotic carbon fractionation and the geological history of the inclusion remain relevant. The responsible conclusion is that this is a potentially biogenic carbon candidate, not evidence sufficient to declare a 4.1 Ga biosphere.

The Nuvvuagittuq Supracrustal Belt in Canada contains hematite filaments, tubes and associated mineral and carbon features interpreted as possible remains of hydrothermal-vent organisms [2,3]. The proposed fossil-bearing unit has been placed within a broad approximately 3.75–4.28 Ga host-unit range. Its 4.28 Ga endpoint is not a directly measured age of an enclosing mineral or of a putative fossil and therefore does not displace the differently defined Jack Hills ranking. A 2025 host-age update is registered [4] but is not used to rank the putative fossils in this

version because its complete text remains unavailable for claim-level ranking. Some structures may have biological analogues; some also admit abiotic formation. The age of the rocks, the age of the structures and their origin must therefore remain separate propositions.

These Hadean and early Eoarchean cases matter even when unresolved. They test how far the record can be pushed before metamorphism, sparse sampling and non-unique signals dominate the inference.

5. Carbon in Labrador and Greenland

Graphite in metasedimentary rocks of the Saglek–Hebron complex was reported as evidence for organisms older than 3.95 Ga [5]. Subsequent studies challenged both the age attributed to some samples and the assumption that all graphitic carbon had the same origin. Petrographic, spectroscopic and geochemical work assigned graphite in marble to abiotic decarbonation, while fluid-deposited graphite in banded iron formation was interpreted as deriving from metamorphic transformation of syngenetic organic matter [6]. Geochronological reassessment separately questioned the true antiquity of the chemofossil attribution [7]. The family remains a candidate, but its priority status is actively contested.

Mojzsis et al. interpreted isotopically light carbon associated with apatite in Akilia and Isua rocks as evidence for life before 3.8 Ga [8]. Van Zuilen et al. later published a reassessment attributing important parts of the association to metasomatic and abiotic processes [9]. CHO-011 records the opposition between these published interpretations without treating either causal account as established from the accessible abstracts alone. Operationally, an isotope ratio is therefore evaluated together with its mineral, texture and reaction history.

Isua also preserves carbonaceous particles and graphite associated with metasedimentary horizons at or above approximately 3.7 Ga [10,11,12]. Recent spatially resolved work distinguishes sediment-associated carbon from vein graphite and examines alteration at the scale of particular mineral hosts [12]. The sediment-associated population has a narrower carbon-isotope distribution than the vein-associated population, while both record metamorphic modification. Such separation strengthens the geological argument without making every graphite occurrence biological. A 2026 study further interprets carbon, sulfur and iron relations in a drill-core succession as evidence for diverse anaerobic metabolisms [13]. That interpretation tests abiotic and metamorphic alternatives but remains a causal reconstruction rather than a direct observation of metabolism.

6. Morphology at Isua

Nutman et al. described conical and domal structures in approximately 3.70 Ga rocks at Isua as stromatolites and presented them as evidence for rapid emergence of life [14]. Allwood et al. later published a three-dimensional reassessment favouring a deformation-related, non-biological interpretation [15]. CHO-011 therefore retains this as a dispute between attributed published claims; it does not adjudicate the unavailable internal three-dimensional evidence.

The dispute illustrates why morphology must be reconstructed in three dimensions and embedded in regional geology. A structure can resemble a younger stromatolite in one surface while failing tests of growth direction, lamination or environmental context. The proper result is not a vote between images but an explicit account of which observations each model explains.

7. Convergence by approximately 3.5–3.4 Ga

The record becomes denser in the Paleoarchean. In Western Australia, the Dresser Formation preserves textures and minerals interpreted as evidence for terrestrial hot-spring microbial communities at about 3.48 Ga [16]. A corrigendum to that study identifies a previously omitted thesis as the detailed sedimentological and stratigraphic support for interpreting the deposits as fluvial rather than marine; it does not withdraw the hot-spring or biosignature interpretation. The Apex chert contains filamentous objects historically described as microfossils [17]. Their geological setting and morphology were challenged as hydrothermal artefacts [18], while later in-situ carbon-isotope analyses supported biological differentiation among the objects [19]. The later measurements do not erase the geological dispute; they add another evidential layer to be adjudicated.

Allwood et al. reported reef-scale stromatolite morphologies in the Strelley Pool Chert at approximately 3.43 Ga [20]. Wacey et al. later reported carbonaceous microstructures associated with sulfur and interpreted them as cellular and metabolic evidence near 3.4 Ga [21]. These are independent, differently scaled published candidates;

CHO-011 does not treat the unavailable internal evidence as verified, and their taxonomic and metabolic specificity remains open.

South Africa supplies an independent locality. Tice and Lowe interpreted carbonaceous material in the 3.416 Ga Buck Reef Chert as photosynthetic microbial mats deposited in a marine environment rather than directly by hydrothermal processes [22]. This sentence reports their published interpretation and does not claim that the inaccessible internal evidence has been independently verified. Carbonaceous microstructures in approximately 3.42 Ga Barberton rocks have also been interpreted as cellular remains from a subseafloor hydrothermal environment [23]. Independence of locality and environment broadens the candidate record beyond one craton or preservation pathway. It does not make morphology or carbon uniquely biological.

In India, Chaudhuri et al. report carbonaceous matter in Bhitardari chert of the Singhbhum Craton, a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3497 ± 5 Ma from associated syn-volcanic zircons, and a bulk-carbon $\delta^{13}\text{C}$ value of approximately -30.9‰ [24]. Their title describes “direct dating” of biogenic carbon, while the published abstract identifies zircon as the U–Pb analyte. CHO-011 therefore records the result as an attributed, tightly linked host-age claim rather than as a radiometric analysis of carbon itself. The unavailable full methods and the biogenic interpretation remain unverified here.

Taken together, the literature contains candidate records from several regions and depositional settings by approximately 3.5–3.4 Ga. Their geographical and evidential diversity makes the comparison less dependent on any isolated priority claim, but does not independently validate an interpretation whose internal evidence remains inaccessible. The resulting synthesis is deliberately less specific than declaring a unique oldest fossil or habitat.

8. Metabolic priority claims

Shen et al. interpreted sulfur-isotope fractionations associated with approximately 3.47 Ga Dresser Formation barites as evidence for microbial sulfate reduction [25]. Ueno et al. later published quadruple-isotope analyses framed as new evidence for the same metabolism [26]. CHO-011 records these as attributed metabolic interpretations, not as direct observations of sulfate reduction, and keeps volcanogenic or abiotic sulfur pathways open until the internal isotope-system arguments can be verified.

Ueno et al. reported methane from fluid inclusions in approximately 3.5 Ga Pilbara hydrothermal precipitates and interpreted its isotope composition as evidence for methanogens older than 3.46 Ga [27]. Horita and Berndt reported experimental abiogenic methane formation and isotope fractionation under hydrothermal conditions [28]. These published claims establish a biological interpretation and a relevant counterpathway; they do not by themselves verify inclusion syngeneity, exclude younger fluids or determine which pathway produced the ancient signal.

Cavalazzi et al. interpreted approximately 3.42 Ga Barberton filaments as the oldest direct evidence for subsurface methane-cycling microorganisms and as methanogens and/or methanotrophs [23]. Within the chronological comparison registered here, that source-specific priority claim is younger than Ueno et al.’s claim for methanogenesis older than 3.46 Ga [27] and therefore does not displace it. Both remain model-dependent biological interpretations rather than direct observations of metabolism.

Photosynthesis, sulfate reduction and methanogenesis are not interchangeable claims. Each identifies a different metabolism, proxy and set of alternatives. None should be inferred merely because microbial life existed somewhere else at the same time.

9. Evidence base, dating methods and resolution limits

The evidence classes resolve different questions:

Evidence class	Principal strength	Principal limit
U–Pb zircon geochronology	Precise crystallisation age of zircon	Dates zircon; linkage to sediment or carbon requires geological interpretation
Carbon isotopes	Tests fractionating carbon pathways	Biological and abiotic ranges can overlap; alteration changes context
Sulfur isotopes	Constrains sulfur reservoirs and fractionating processes	Metabolic attribution depends on substrates, pathways and later exchange
Morphology	Preserves spatial organisation at cellular to reef scale	Mineral growth, deformation and preparation can mimic biological shapes
Sedimentology and petrography	Tests environment, order and syngeneity	Ancient rocks may be incomplete, metamorphosed or structurally repeated
Fluid inclusions	May retain ancient fluids and gases	Inclusion generation, leakage, reopening and contamination must be established

Numerical precision must follow the dated object. A ± 5 Myr zircon result does not give every carbon particle in a rock a ± 5 Myr independent age. A broad host-unit range should not be collapsed to its oldest endpoint. Approximate ages used in this article orient comparisons; claim-level uncertainty is bounded by the source-verification limits stated for each case.

10. Observer capacity at the origin of the biological record

CHO uses OC1 for environmental detection and regulated response: a living system detects a difference and changes state through an evolved regulatory pathway. Ancient rocks do not preserve receptor dynamics, gene-regulatory circuits or observed behaviour. A biosignature alone therefore cannot demonstrate a named sensing mechanism.

If a candidate is accepted as evidence of life, OC1 is inferred only at lineage level from the minimal functional organisation required for living populations and from comparative biology. This is a conditional reconstruction, not a direct fossil observation. It implies neither cognition nor consciousness. Prebiotic chemical selectivity remains outside OC1 unless it is embedded in an evolved living system.

11. Contingency and contemporaries

Early life, if present, inhabited a planet undergoing crustal recycling, impacts, hydrothermal circulation, changing atmosphere–ocean chemistry and strong solar ultraviolet exposure. Multiple habitats may have coexisted: marine photic zones, sediments, subseafloor fractures, volcanic pools and hydrothermal systems. Preservation favoured some environments and destroyed others.

The surviving record is therefore not a census. A famous locality may be prominent because its rocks escaped erosion and metamorphic obliteration, not because life began there. Entire lineages, metabolisms and habitats may have left no recognisable trace. Conversely, a structure resembling a modern biological product may result from a pathway no longer common on Earth.

Nothing in the record requires one inevitable route. Early communities could have remained locally restricted, diversified, exchanged genes or disappeared without descendants. The existence of present life reveals survival somewhere in the lineage, but not the number of failed origins or extinct early branches.

12. Competing interpretations and unresolved questions

Several questions remain open:

1. Are the oldest carbon signals syngenetic and biological, or products of later metamorphic and abiotic reactions?
2. Which Nuvvuagittuq structures require biology after mineral growth and deformation are modelled?
3. Can Isua graphite populations be connected to particular organisms or metabolisms without overinterpreting isotope distributions?
4. Do Paleoarchean morphological, sedimentological and chemical signals converge within the same samples and depositional events?

5. Can sulfur and methane isotope systems exclude abiotic hydrothermal pathways quantitatively?
6. How much older than the first robust evidence was the origin of life?

The last question may remain underdetermined. The earliest preserved record is limited jointly by biology, geology, sampling and analytical resolution.

13. Claim classes, boundaries and exclusions

Measured or observed: mineral ages, isotope ratios, textures, mineral associations, spatial distributions and cross-cutting relations reported by cited studies.

Reconstructed: depositional environment, syngeneity, biological origin, metabolic pathway and the existence of a regional biosphere.

Model-dependent: transformations by metamorphism and deformation, abiotic reaction pathways and the probability that several signals share one cause.

Actively contested: Hadean graphite, Nuvvuagittuq structures and ages, Saglek graphite antiquity and origin, Akilia carbon, Isua stromatolite morphology and Apex microfossils.

Speculative: no origin scenario or claim of consciousness is adopted as an established result.

Open: on the evidence bounded and evaluated in this article, the exact time, place and frequency of life's origin remain unresolved; so do direct ancestry between any candidate community and present organisms, and cognition or consciousness in early microbes. This is a conclusion from the limits of the registered record, not a claim that no future evidence could resolve those questions.

CHO-011 owns priority biosignature adjudication. It does not reconstruct the origin mechanism, which belongs to CHO-010, or provide the full history of Archean ecosystems and photosynthesis, which belongs to CHO-012. Evidence at exactly 3.200 Ga passes to CHO-012 under the half-open boundary.

14. Closing state

By the end of the interval, the literature no longer consists only of isolated ancient-carbon reports or a single disputed morphology. Multiple Paleoproterozoic localities have generated attributed reports of microbial mats, stromatolite-scale structures, carbonaceous microstructures and metabolic isotope signals. This breadth makes the reconstruction less dependent on any single priority claim; it does not convert every candidate into verified biological evidence, and each interpretation remains conditional on its own tests.

CHO-012 inherits an Earth that was plausibly and increasingly well documented as inhabited by microbial life. It will examine how those organisms participated in Archean environments, diversified metabolisms and altered planetary chemistry. The transition from evidence of presence to history of ecosystems must not erase the uncertainties established here.

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Disclosure

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