

Oxygen Transforms Earth

CHO-013 · Cosmic History and Its Observers

A Chronological Scientific History from the Early Universe to the Present

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Structured abstract

Context. Between 2.500 and 1.800 billion years ago, oxygen ceased to be only a locally produced reactive by-product and became a persistent, though variable, component of Earth's surface system. This transformation altered atmospheric chemistry, continental weathering, ocean redox structure, nutrient cycles and climate.

Question. What changed during the Great Oxidation Event and its aftermath, and how can the transition be reconstructed without treating different proxies, basins and environmental compartments as if they recorded one synchronous global switch?

Evidence and method. This synthesis keeps sulfur-isotope signals, detrital minerals, chromium and molybdenum records, thallium and vanadium isotope mass balances, iron speciation, sulfate archives and carbon-isotope excursions distinct until their spatial and temporal scales can be compared. A published terrestrial-red-bed proposal is retained only as an attributed bibliographic claim because its internal evidence is not independently available here. Measured ages and proxy observations are separated from atmospheric reconstructions and causal models. The 2.500-Ga and 1.800-Ga boundaries are ownership seams, not claimed event dates.

Results. The available record supports an extended and locally complex transition rather than an instantaneous irreversible rise. The disappearance of mass-independent sulfur-isotope signals was asynchronous or episodic among successions; atmosphere-scale accumulation, coupled atmosphere–ocean oxygenation and persistent surface-ocean oxygenation need not have occurred simultaneously. Oxidative weathering and the marine sulfate reservoir expanded unevenly. Paleoproterozoic glaciations overlap the oxygenation interval, but methane-collapse, nutrient, volcanic and deep-carbon mechanisms remain competing explanations rather than a single demonstrated cause. Carbonates attributed to the Lomagundi–Jatuli excursion record a major carbon-cycle disturbance, yet its global synchronicity, duration, magnitude and relation to an oxygen overshoot remain disputed. Later records indicate declining sulfate and redox conditions in many basins, with important persistence counterexamples.

Conclusion. Oxygen transformed Earth through a sequence of coupled but non-identical thresholds. By 1.800 Ga, the planet inherited by CHO-014 had a permanently altered atmosphere, spatially stratified oceans and expanded aerobic biogeochemical opportunities, but not uniformly oxygenated seas or a monotonic path toward complex life. Observer status remains limited to microbial OC1 environmental detection and regulated response; oxygen availability alone establishes neither eukaryotic priority nor cognition.

Keywords: Great Oxidation Event; Paleoproterozoic; oxygen; sulfur isotopes; oxidative weathering; Huronian glaciation; Lomagundi–Jatuli excursion; ocean redox; aerobic biogeochemistry

1. Chronological orientation and inherited state

CHO-013 owns the chronological spine interval [2.500, 1.800) Ga ago. Exactly 2.500 Ga belongs here; exactly 1.800 Ga and younger belong to CHO-014. Neither boundary is asserted as a measured event. Ages in Ga denote billions of

years before the present, while quoted radiometric ages retain the precision and uncertainty reported by their sources.

CHO-012 passes forward a planet in which oxygenic photosynthesis was operating somewhere, local or transient oxygenated environments could develop, and reduced volcanic gases, dissolved iron, sulfur species, organic matter and crustal minerals still consumed much of the oxygen produced. Near the seam, the disputed 2.5-Ga “whiff” record illustrates why local geochemistry cannot simply be promoted to a global atmospheric state. A full-text reassessment supports an anoxic ocean for the studied interval, while the original interpretation, technical comment and response preserve an active evidential dispute [1,2,3,4].

The transformation addressed here is therefore not the origin of oxygenic photosynthesis. It is the reorganisation of source–sink balances that allowed oxygen to affect the atmosphere, surface ocean, weathering system and biosphere at larger and more persistent scales. The phrase “Great Oxidation Event” is retained as a historical name, not as a claim that one instantaneous event occurred everywhere.

2. Reading oxygen through different archives

No rock directly preserves a complete global atmospheric time series. Reconstruction depends on proxies that respond to different processes and thresholds. Mass-independent fractionation of sulfur isotopes, or S-MIF, arises from atmospheric photochemistry and is commonly used to track an atmosphere and ozone system with very low oxygen [45]. Selected Archean records have supported an oxic interpretation [46], while other records have been interpreted as evidence for anoxia and changing atmospheric sulfur chemistry [47]. Its disappearance can indicate a threshold change, but deposition, basin history, recycling and analytical scale intervene between atmospheric production and the measured sediment.

Other archives answer different questions. Detrital pyrite and uraninite test whether reduced minerals survived continental transport. A 2024 paper identifies its subject in the published title as terrestrial red beds and presents them as evidence for the GOE [20]; CHO-013 records that attributed proposal without adjudicating the inaccessible internal evidence, age control or priority comparison. Chromium and molybdenum systems track aspects of oxidative weathering and marine transport. Thallium and vanadium isotope mass balances have been used to infer changes in the geographical extent or persistence of oxygenated marine settings. Iron speciation distinguishes ferruginous, euxinic and oxygenated water masses under stated calibrations. Sulfate minerals and sulfur isotopes constrain the size and cycling of the marine sulfate reservoir. Carbon isotopes record carbon-cycle imbalance, not atmospheric oxygen concentration directly.

Agreement among these archives is a synthesis result. A proxy threshold in one basin cannot be converted without a model into a global oxygen percentage, a whole-ocean state or a unique date. Conversely, disagreement does not automatically mean one proxy is wrong: the atmosphere, shallow ocean, deep ocean, continents and restricted basins could change at different times.

3. The Great Oxidation Event as an extended transition

Classic stratigraphic work explicitly framed the problem as dating the rise of atmospheric oxygen [5]. Because only its bibliographic manifestation is controlled here, CHO-013 does not use that paper to establish a numerical onset. Complete-text studies described rapid disappearance of S-MIF around 2.33 Ga [6], while palaeomagnetic and geochronological constraints related oxygenation to glacial deposits over a broader interval [7]. These results helped replace an unconstrained transition with dated stratigraphic brackets, but they did not establish one globally synchronous onset.

Regional comparisons indicate that S-MIF/S-MDF transitions may be asynchronous [8]. Grain-scale and bulk measurements show that preservation and analytical scale can complicate apparently simple trajectories [11], while later work has attempted to reconcile divergent records rather than assuming that every difference represents atmospheric oscillation [12]. New Re–Os geochronology from the Transvaal succession gives a 2443 ± 33 Ma depositional constraint and has been interpreted as evidence for discrete oxygenation episodes, including repeated S-MIF disappearances [13].

The safest account is an interval of threshold crossings, reversals and regional expression. A published bracket from 2501.5 ± 1.7 Ma to 2434 ± 6.6 Ma crosses the 2.500-Ga seam at its older end and remains a source-specific strati-

graphic constraint, not a universal beginning [9]. The central value 2501.5 Ma lies in CHO-012, while its younger uncertainty tail reaches 2499.8 Ma and therefore straddles this article's ownership interval.

Permanence is a further question. Evidence has been interpreted as showing a delay of roughly 200 million years between early oxygenation and permanent atmospheric accumulation [10]. Recent syntheses and models likewise describe prolonged fluctuation rather than immediate stabilization [17,43]. Thus “first atmosphere-scale accumulation”, “last S-MIF recurrence” and “permanent oxygenation” are distinct targets and may require different dates.

4. Atmosphere and ocean did not oxygenate as one compartment

The ocean was vertically and geographically structured. Oxygen generated in surface waters could coexist with ferruginous deep water, euxinic margins and an atmosphere near a proxy threshold. A 2024 thallium-isotope study places the onset of coupled atmosphere–ocean oxygenation near 2.3 Ga [14]. A 2025 vanadium-isotope study interprets shales spanning approximately 2.32–2.26 Ga as recording persistent expansion of oxygenated surface-ocean conditions [15]. These are related but not identical propositions: coupling, spatial expansion and persistence describe different features of the transition.

Other records preserve extensive suboxia during the same broad episode [25]. Complete-text iron and sulfur data have been used to reconstruct shifts from oxygenated deep waters to widespread euxinia between approximately 2.15 and 2.08 Ga [26]. A separate published title reports a transition to a sulfidic ocean at approximately 1.84 Ga [28], but CHO-013 does not use the unavailable internal evidence to establish the timing, extent or mechanism of that transition. A counterexample from around 2.0 Ga has been interpreted as evidence for continued oxygenated oceans after the Lomagundi–Jatuli interval [27].

The resulting picture is not a uniformly oxygenated ocean. It is a redox topology: oxygenated surface and shelf habitats expanding and contracting above deep waters that remained commonly ferruginous or became sulfidic, with basin-to-basin differences. The distinction is ecological as well as geochemical because the availability of oxygen, nitrate, sulfate, iron and sulfide determines which metabolisms are energetically possible in each habitat.

5. Continents weather, sulfate expands

Once oxygen affected continental surfaces more persistently, minerals and solutes delivered to the ocean changed. Chromium isotopes have been interpreted as recording fluctuations in atmospheric oxygenation [18]. Pyrite oxidation by aerobic bacteria has been linked to acid drainage and changing iron delivery during the GOE [19]. A 2024 paper is titled “Earth's oldest terrestrial red beds as direct evidence for the Great Oxidation Event ca. 2.3 Ga” [20]. CHO-013 records that wording as an attributed published proposition only; it does not independently confirm the superlative, age control, comparison set or depositional interpretation. A molybdenum record from black shales has likewise been interpreted as evidence for oscillating early Paleoproterozoic oxygen levels [21].

These archives do not describe complete oxidation everywhere. Detrital and sulfide-weathering evidence published in 2025 supports long intervals of incomplete oxidation and low atmospheric oxygen during the wider transition [16]. The proper conclusion is heterogeneous expansion of oxidative weathering, not a sudden conversion of every continental surface to modern conditions.

Marine sulfate responded to weathering and sulfur cycling. Evaporites near 2.0 Ga preserve evidence of a substantially changed sulfate system [22]. Multiple-sulfur-isotope records indicate expansion of the seawater sulfate reservoir near the GOE and contraction near the end of the Lomagundi interval [23,24]. Sulfate abundance matters because it links continental oxidation to microbial sulfate reduction, sulfide production, pyrite burial and ocean redox structure. Yet the size of the reservoir, the rate of its turnover and its spatial representativeness remain model-dependent.

6. Glaciation during a changing atmosphere

The early Paleoproterozoic includes severe glaciations traditionally grouped within the Huronian. Correlations between the Transvaal and Huronian supergroups use dated volcanic layers and stratigraphy to relate glacial deposits across cratons [38]. Sulfur-isotope and geochronological work places atmosphere-scale oxygenation before at least one major Paleoproterozoic “snowball Earth” interval [9]. The sequence is scientifically important, but temporal ordering alone does not identify one cause.

One influential hypothesis proposes that oxygenic photosynthesis raised oxygen, oxidised atmospheric methane and weakened greenhouse warming enough to trigger global glaciation [37]. Global-glaciation syntheses extend the proposed climatic and biological consequences [39]. Methanogenesis may nevertheless have persisted through sulfide-weathering feedbacks [40], while nutrient recycling, volcanic forcing, albedo and the deep carbon cycle offer additional controls [41,42].

CHO-013 therefore treats methane collapse as a model family, not a demonstrated single trigger. The oxygenation interval and glaciations overlap; their causal connection depends on source and sink fluxes, background carbon dioxide, methane production, haze, ice–albedo feedback and event ordering. Nor does this article call the Paleoproterozoic episode Earth’s first glaciation: older candidate glacial evidence belongs to CHO-012.

7. The Lomagundi–Jatuli problem

Karhu and Holland’s published title links carbon isotopes with the rise of atmospheric oxygen [29]; CHO-013 retains that historical framing without using the unavailable internal text to establish a quantitative oxygen history. A second published title explicitly presents “oxygen overshoot and recovery” as a model for the early Paleoproterozoic [30]. Here it is retained only as an attributed model family, not as independently verified internal evidence. Complete-text carbon and sulfur records, changing marine sulfate and expansion of aerobic iron cycling provide separate evidence for major Earth-system reorganisation [23,33–35].

The apparent simplicity of one global curve is now under direct challenge. A synthesis of roughly 9,400 measurements questions whether the Lomagundi–Jatuli excursion was globally synchronous and emphasises local expression, stratigraphic completeness and depositional alteration [34]. Sample-level studies also show that local preservation and later processes can influence the recorded carbon signal [49]. A 2026 compilation revises the timing, magnitude and global-versus-local decomposition [35]. A separate 2025 study reports a Pb–Pb isochron age of 2194 ± 5 Ma for black shales from the Francevillian FB Formation in Gabon within a volcanic-forcing reconstruction [36]; that value dates a component of that model, not the excursion as a whole.

Accordingly, CHO-013 does not convert a positive carbonate value into one global atmospheric oxygen curve. The excursion is retained as an actively contested carbon-cycle phenomenon whose onset, duration, magnitude and synchronicity remain source- and basin-dependent. Oxygen overshoot, variable carbon inputs, authigenic reservoirs, local processes, nutrient feedbacks, volcanic forcing and deep-Earth degassing remain competing or potentially interacting explanations.

8. Decline, recovery and the end of a simple rise

If oxygen rose during the GOE, it did not simply remain at a peak. Sulfur records indicate contraction of the marine sulfate reservoir near approximately 2.05 Ga [23,24]. Chromium, iron-speciation and basin-redox studies have been interpreted as recording falling surface oxidation and wider euxinia after the positive carbon-isotope interval [18,26,28]. Oxidation of organic matter during the Shunga event adds another major carbon-cycle perturbation [31].

At the same time, evidence from some successions supports persistence of substantial oxygenation [27]. These observations can coexist if atmospheric oxygen, marine sulfate and ocean redox varied across compartments and basins. “Post-Lomagundi decline” is therefore a comparative synthesis, not a return to the Archean state and not evidence that oxygenic photosynthesis stopped.

A triple-oxygen- and sulfur-isotope study has been modelled as indicating a large productivity decline near 2.018 Ga [32]. The result is an inferred change in global primary productivity, not a directly observed mass extinction or a taxonomic census. This distinction prevents a biogeochemical flux model from silently becoming a claim about the disappearance of organisms.

9. Aerobic biogeochemistry expands

Oxygen altered metabolisms before it produced uniformly oxic habitats. Nitrogen-isotope evidence has been interpreted as showing pervasive nitrate availability and aerobic nitrogen cycling near 2.31 Ga [44]. Chromium, molybdenum, selenium, iron and sulfur systems likewise register changes in oxidative weathering and marine redox under their respective calibrations [18,21,25,26,33]. These changes expanded ecological opportunities for respiration and oxidative nutrient cycles while preserving anoxic niches.

Oxygen accumulation reflects a balance, not production alone. Candidate mechanisms include burial of reduced carbon and pyrite, changes in volcanic and metamorphic reductant fluxes, phosphorus recycling, weathering feedbacks and deep carbon cycling [30,37,40–43]. No single mechanism is treated here as sufficient. A planet can host oxygenic photosynthesis for a long interval while sinks prevent atmosphere-scale accumulation, and it can later retain oxygen even as productivity fluctuates if sinks change.

The GOE consequently transformed habitability by increasing the spatial and temporal availability of high-energy aerobic metabolism and by changing nutrient and trace-metal cycles. It did not make all environments oxic. Anaerobic metabolisms remained essential in sediments, euxinic waters, ferruginous basins and the interior of microbial communities.

10. Observer capacities present

CHO uses “observer” as an operational biological category, not as a claim that observation is required for physical reality. The only capacity assigned in CHO-013 is OC1: evolved environmental detection coupled to regulated response. Microbial populations can sense redox gradients, oxygen, light, nutrients and toxic species and can alter movement, gene expression or metabolism accordingly.

No named sensing mechanism is directly fossilised in a Paleoproterozoic rock. OC1 is therefore a conditional lineage-level inference from living systems and from the ecological requirement to persist in variable environments. The expansion of oxygenated habitats enlarges the environmental gradients to which organisms could respond; it does not by itself establish cognition, consciousness, multicellularity or eukaryotic identity.

Organismal priority is deliberately excluded. Eukaryotes, endosymbiosis and complex organisation are owned by CHO-014, including evidence earlier than the 1.800-Ga spine seam under that article’s thematic overlay. CHO-013 supplies environmental context only.

11. Evidence, dating and resolution limits

Radiometric ages may date volcanic ash beds, depositional intervals or later events; their geological relationship to the proxy-bearing sediment must be checked before they constrain oxygenation. A central age and its analytical uncertainty do not automatically date a global atmospheric transition. The 2501.5 ± 1.7 Ma seam case demonstrates why uncertainty intervals must be handled explicitly rather than rounded into an owner.

Proxy records also have different spatial supports. The published record that labels the disputed red beds “terrestrial” is used here only as a land-surface proposal, never as a marine oxygen measurement [20]. A shelf shale does not represent the whole ocean. S-MIF disappearance is not a direct oxygen percentage. A carbon-isotope excursion is not an oxygen gauge. Models can connect these observations, but the model assumptions then become part of the claim.

Complete claim-bearing text was consulted for 37 of the 49 registered sources; access to the remaining 12 was limited to abstracts, metadata or bibliographic pages. Those limited records support only the explicitly attributed propositions they contain and clearly bounded non-entailments. They do not supply unavailable methods, numerical details, comparison sets or body-level causal claims.

12. Contingency and contemporaries

The transition was not inevitable. Oxygen-producing ecosystems could remain limited by nutrients or geography. Reduced volcanic gases, ferrous iron, sulfide and crustal minerals could consume oxygen faster than it accumulated. Methane feedbacks could warm or cool the planet depending on production, oxidation and haze. Organic burial could raise net oxygen, while later oxidation could reverse part of that effect.

Different worlds existed at the same time: glaciated surfaces and open water, oxidising terrestrial environments and reduced sediment pores, oxygenated shelves and ferruginous or euxinic deep basins. Local oxygenation could expand while another basin retained S-MIF-bearing sediment. A global label should not erase these contemporaries.

Preservation was also contingent. Hiatuses, metamorphism, alteration, authigenesis and uneven basin survival shape the apparent chronology. The Lomagundi dispute shows that a smooth composite curve can hide local stratigraphy and incomplete sections. The rock record is a filtered archive of a heterogeneous Earth system.

13. Competing interpretations and unresolved questions

Several questions remain open:

1. Which dated succession best constrains the first atmosphere-scale threshold crossing, and how globally synchronous was it?
2. How should regional S-MIF reversals and grain-scale preservation be separated from true atmospheric oscillations?
3. When did oxygenated surface-ocean conditions become geographically widespread and persistent?
4. Which continental weathering proxies can be quantitatively related to atmospheric oxygen, and over what spatial scale?
5. How were oxygenation and Paleoproterozoic glaciations causally connected, if at all?
6. Was the Lomagundi–Jatuli signal one globally synchronous excursion, overlapping regional excursions, or a composite of local and global processes?
7. How large was any oxygen overshoot, and which carbon, sulfur, nutrient, volcanic or deep-Earth mechanisms produced it?
8. How far did oxygen and sulfate decline after the excursion, and why did some basins preserve more oxygenated conditions?
9. What biological changes followed from expanded aerobic habitats without importing organismal priority from CHO-014?

A 2026 review is useful for mapping current terminology and disputes [48], but recency and breadth do not allow it to close primary quantitative or priority claims. Those remain attached to the underlying evidence.

14. Claim classes, boundaries and exclusions

Measured or observed: radiometric ages, stratigraphic relationships, isotope ratios, mineral survival, elemental abundances and sedimentary redox indicators reported by the cited complete-text studies. The red-bed paper is represented only by its published bibliographic proposition and is not included in this measured-or-observed class.

Reconstructed from evidence: atmosphere-scale threshold crossings, the spatial extent of oxygenated water, oxidative weathering, sulfate-reservoir expansion and contraction, and changes in biogeochemical cycling.

Model-dependent: oxygen percentages, permanent-state definitions, methane-driven glaciation, source–sink balances, oxygen overshoot, productivity magnitude and deep-carbon forcing.

Actively contested: synchrony and tempo of S-MIF loss; the timing of permanent atmospheric oxygenation; the spatial coupling of atmosphere and ocean; the global synchronicity, duration and magnitude of the Lomagundi–Jatuli excursion; and the size and cause of post-excursion redox decline.

Speculative or open: a unique GOE trigger, one global atmospheric curve derived from local carbonate values, direct taxonomic consequences from oxygen availability, and any claim of Paleoproterozoic cognition or consciousness.

CHO-012 owns pre-2.500-Ga environmental evidence except where an uncertainty interval straddles the seam. CHO-013 owns atmosphere, ocean, weathering, glaciation and carbon-cycle consequences inside [2.500,1.800) Ga. CHO-014 owns exactly 1.800 Ga and younger and all eukaryote, endosymbiosis and complex-organisation priorities under its authorised overlay.

15. Closing state passed to CHO-014

By the exclusive 1.800-Ga boundary, oxygen had permanently changed Earth's surface system, but the inherited state was not modern. Atmospheric oxygen had crossed thresholds that altered sulfur photochemistry and continental weathering. Surface and shelf waters could be persistently oxygenated in some regions, while deep oceans remained commonly ferruginous or euxinic. Marine sulfate and nutrient cycles had expanded and contracted. Glaciation and carbon-cycle perturbations demonstrated strong coupling among biology, atmosphere, oceans, continents and the solid Earth.

The central result is not a single rising line. It is a new planetary regime capable of sustaining oxygen over long times while retaining large anoxic reservoirs and pronounced spatial variability. This mixed redox world provides CHO-014 with environmental opportunity and constraint. It does not predetermine eukaryotic emergence, endosymbiosis, multicellularity or later consciousness.

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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.