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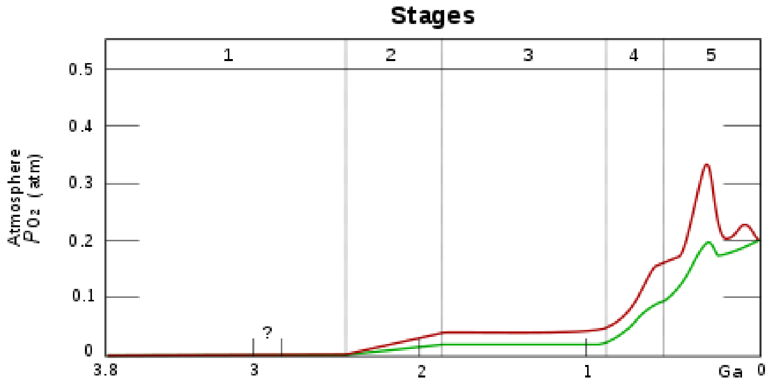
Great Oxidation Event

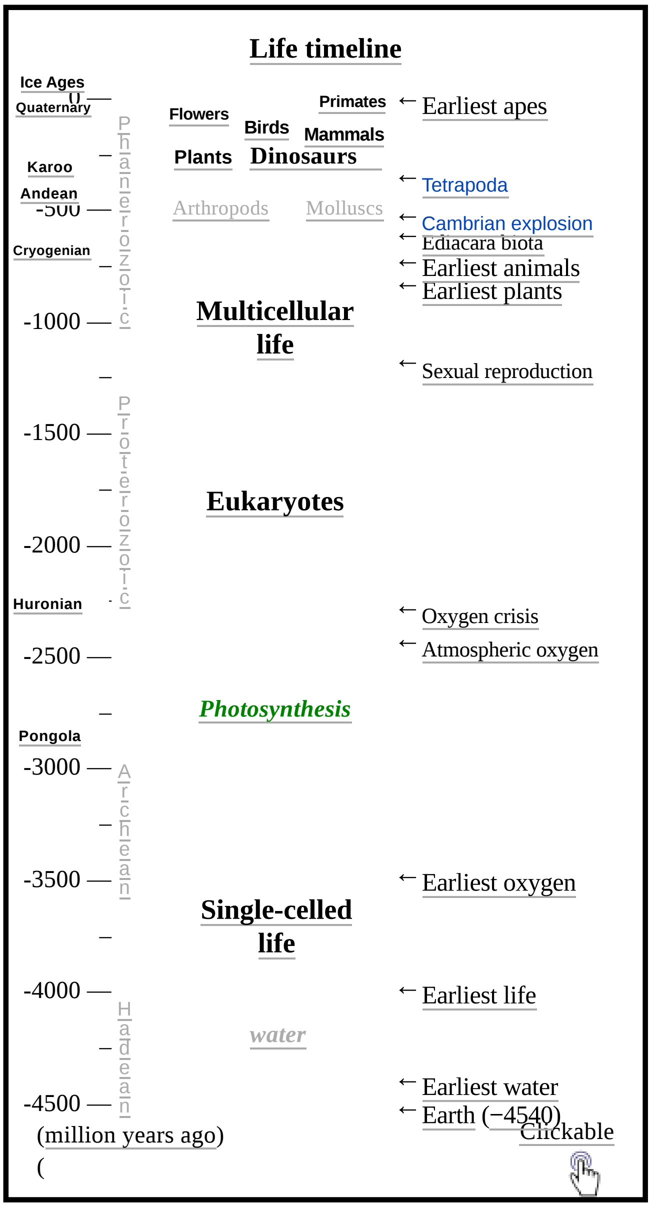
The **Great Oxidation Event** (**GOE**), sometimes also called the **Great Oxygenation Event**, **Oxygen Catastrophe**, **Oxygen Crisis**, **Oxygen Holocaust**,[2] or **Oxygen Revolution**, was a time period when the Earth's atmosphere and the shallow ocean experienced a rise in oxygen, approximately 2.4 billion years ago (2.4 Ga) to 2.1–2.0 Ga during the Paleoproterozoic era.[3] Geological, isotopic, and chemical evidence suggests that biologically induced molecular oxygen (dioxygen, O_2) started to accumulate in Earth's atmosphere and changed Earth's atmosphere from a weakly reducing atmosphere to an oxidizing atmosphere, [4] causing almost all life on Earth to go extinct.[5] The cyanobacteria producing the oxygen caused the event which enabled the subsequent development of multicellular forms.[6]



O_2 build-up in the Earth's atmosphere. Red and green lines represent the range of the estimates while time is measured in billions of years ago (Ga).
Stage 1 (3.85–2.45 Ga): Practically no O_2 in the atmosphere. The oceans were also largely anoxic with the possible exception of O_2 in the shallow oceans.
Stage 2 (2.45–1.85 Ga): O_2 produced, rising to values of 0.02 and 0.04 atm, but absorbed in oceans and seabed rock.
Stage 3 (1.85–0.85 Ga): O_2 starts to gas out of the oceans, but is absorbed by land surfaces. No significant change in oxygen level.
Stages 4 and 5 (0.85 Ga–present): Other O_2 reservoirs filled; gas accumulates in atmosphere.[1]

Contents

Oxygen accumulation



A chronology of oxygen accumulation suggests that free oxygen was first produced by prokaryotic and then later by eukaryotic organisms in the ocean. These organisms carried out photosynthesis more efficiently, producing oxygen as a waste product.[7][8] In one interpretation, the first oxygen-producing cyanobacteria could have arisen before the GOE,[7][9] from 2.7–2.4 Ga and perhaps even earlier.[3][10][11] However, oxygenic photosynthesis also produces organic carbon that must be segregated from oxygen to allow oxygen accumulation in the surface environment, otherwise the oxygen back-reacts with the organic carbon and does not accumulate. The burial of organic carbon, sulfide, and minerals containing ferrous iron (Fe^{2+}) are primary factors in oxygen accumulation.[12] For example, when organic carbon is buried without being oxidized, the oxygen is left in the atmosphere. In total, the burial of organic carbon and pyrite today creates a total of 15.8 ± 3.3 T mol {{{1}}} of O_2 per year. This creates a net O_2 flux from the global oxygen sources.

The rate of change of oxygen can be calculated from the difference between global sources and sinks.[13] The oxygen sinks include reducing gases and minerals from volcanoes, metamorphism and weathering.[13] The GOE started after these oxygen-sink fluxes and reduced-gas fluxes were exceeded by the flux of O_2 associated with the burial of reductants, such as organic carbon.[14] For the weathering mechanisms, 12.0 ± 3.3 T mol of O_2 per year today goes to the sinks composed of reducing minerals and gases from volcanoes, metamorphism, percolating seawater and heat vents from the seafloor.[13] On the other hand, 5.7 ± 1.2 T mol of O_2 per year today oxidizes reducing gases in the atmosphere through photochemical reaction.[13] On the early Earth, there was visibly very little oxidative weathering of continents (e.g., a lack of redbeds) and so the weathering sink on oxygen would have been negligible compared to that from reducing gases and dissolved iron in oceans.

Dissolved iron in oceans exemplifies O_2 sinks. Free oxygen produced during this time was chemically captured by dissolved iron, converting iron $\mathbf{Fe}$ and $\mathbf{Fe^{2+}}$ to magnetite ($\mathbf{Fe^{2+}Fe^{3+}_2O_4}$) that is insoluble in water, and sank to the bottom of the shallow seas to create banded iron formations such as the ones found in Minnesota and Pilbara, Western Australia.[14] It took 50 million years or longer to deplete the oxygen sinks.[15] The rate of photosynthesis and associated rate of organic burial also affect the rate of oxygen accumulation. When land plants spread over the continents in the Devonian, more organic carbon was buried and likely allowed higher O_2 levels to occur.[16] Today, the average time that an O_2 molecule spends in the air before it is consumed by geological sinks is about 2 million years.[17] That residence time is relatively short compared to geologic time - so in the Phanerozoic there must have been feedback processes that kept the atmospheric O_2 level within bounds suitable for animal life.

Eventually, oxygen started to accumulate in the atmosphere, with two major consequences.

- First, it has been proposed that oxygen oxidized atmospheric methane (a strong greenhouse gas) to carbon dioxide (a weaker one) and water. This weakened the greenhouse effect of the Earth's atmosphere, causing planetary cooling, which has been proposed to have triggered a series of ice ages known as the Huronian glaciation, bracketing an age range of 2.45–2.22 Ga.[18][19][20] A fourth glaciation event found in South Africa is ~2.22 Ga in age. Because geological evidence suggests that the ice reached sea-level in some areas and that the South African event occurred at low latitudes, the latter is associated with a so-called Snowball Earth.[21]

- Second, the increased oxygen concentrations provided a new opportunity for biological diversification, as well as tremendous changes in the nature of chemical interactions between rocks, sand, clay, and other geological substrates and the Earth's air, oceans, and other surface waters. Despite the natural recycling of organic matter, life had remained energetically limited until the widespread availability of oxygen. This breakthrough in metabolic evolution greatly increased the free energy available to living organisms, with global environmental impacts. For example, mitochondria evolved after the GOE, giving organisms the energy to exploit new, more complex morphology interacting in increasingly complex ecosystems, although these did not appear until the late Proterozoic and Cambrian[22]

Timeline of glaciations, shown in blue.

Geological evidence

Continental indicators

Paleosols, detrital grains, and redbeds are evidence of low-level oxygen.[13] The paleosols older than 2.4 Ga have low iron concentrations that suggests anoxic weathering.[23] Detrital grains older than 2.4 Ga also have material that only exists under low oxygen conditions.[24] Redbeds are red-colored sandstones that are coated with hematite, which indicates that there was enough oxygen to oxidize iron.[25]

Banded iron formation (BIF)

Iron speciation

The concentration of ferruginous and euxinic states in iron mass can also provide clues of the oxygen level in the atmosphere.[26] When the environment is anoxic, the ratio of ferruginous and euxinic out of the total iron mass is lower than the ratio in an anoxic environment such as the deep ocean.[27] One of the hypotheses suggests that microbes in the ocean already oxygenated the shallow waters before the GOE event around 2.6–2.5 Ga.[13][27] The high concentration ferruginous and euxinic states of sediments in the deep ocean showed consistency with the evidence from banded iron formations.[13]

Isotopes

There are two types of isotope fractionation considered: mass-dependent fractionation (MDF) and mass-independent fractionation (MIF). Isotopes in marine sediments of the accumulation of oxygen such as carbon, sulfur, nitrogen, transitional metals (chromium, molybdenum and iron) and other non-metal elements (selenium) are considered as MDF evidence.[13]

For example, a spike in chromium contained in ancient rock deposits formed underwater shows accumulated chromium washed off from the continental shelves.[28] Since chromium is not easily dissolved, its release from rocks requires the presence of a powerful acid such as sulfuric acid (H_2SO_4) which may have formed through bacterial reactions with pyrite.[29]

The critical evidence of GOE was the MIF of sulfur isotopes that only existed in anoxic atmosphere disappeared from sediment rocks after 2.4–2.3 Ga.[30] MIF only existed in an anoxic atmosphere since oxygen (and its photochemical product, an ozone layer) would have prevented the photolysis of sulfur dioxide. The process of MIF sedimentation is currently uncertain.[13]

Fossils and biomarkers

Stromatolites provide some of the fossil evidence of oxygen, and suggest that the oxygen came from photosynthesis. Biomarkers such as 2α-methylhopanes from cyanobacteria were also found in Pilbara, Western Australia. However, the biomarker data has since been shown to have been contaminated and so results are no longer accepted.[31]

Other indicators

Some elements in marine sediments are sensitive to different levels of oxygen in the environment such as transition metals molybdenum and rhenium.[32] Non-metal elements such as selenium and iodine are also indicators of oxygen levels.[33]

Hypotheses

There may have been a gap of up to 900 million years between the start of photosynthetic oxygen production and the geologically rapid increase in atmospheric oxygen about 2.5–2.4 billion years ago. Several hypotheses propose to explain this time lag.

Increasing flux

Some people suggest that GOE is caused by the increase of the source of oxygen. One hypothesis argues that GOE was the immediate result of photosynthesis, although the majority of scientists suggest that a long-term increase of oxygen is more likely the case.[34] Several model results show possibilities of long-term increase of carbon burial,[35] but the conclusions are indecisive.[36]

Decreasing sink

In contrast to the increasing flux hypothesis, there are also several hypotheses that attempt to use decrease of sinks to explain GOE. One theory suggests that composition of the volatiles from volcanic gases were more oxidized.[12] Another theory suggests that the decrease of metamorphic gases and serpentinization is the main key of GOE. Hydrogen and methane released from metamorphic processes are also lost from Earth's atmosphere over time and leave the crust oxidized.[37] Scientists realized that hydrogen would escape into space through a process called methane photolysis, in which methane decomposes under the action of ultraviolet light in the upper atmosphere and releases its hydrogen. The escape of hydrogen from the Earth into space must have oxidized the Earth because the process of hydrogen loss is chemical oxidation.[37]

Tectonic trigger


2.1-billion-year-old rock showing banded iron formation

One hypothesis suggest that the oxygen increase had to await tectonically driven changes in the Earth, including the appearance of shelf seas, where reduced organic carbon could reach the sediments and be buried.[38][39] The newly produced oxygen was first consumed in various chemical reactions in the oceans, primarily with iron. Evidence is found in older rocks that contain massive banded iron formations apparently laid down as this iron and oxygen first combined; most present-day iron ore lies in these deposits. It was assumed oxygen released from cyanobacteria resulted in the chemical reactions that created rust, but it appears the iron formations were caused by anoxygenic phototrophic iron-oxidizing bacteria, which does not require oxygen.[40] Evidence suggests oxygen levels spiked each time smaller land masses collided to form a super-continent. Tectonic pressure thrust up mountain chains, which eroded to release nutrients into the ocean to feed photosynthetic cyanobacteria.[41]

Nickel famine

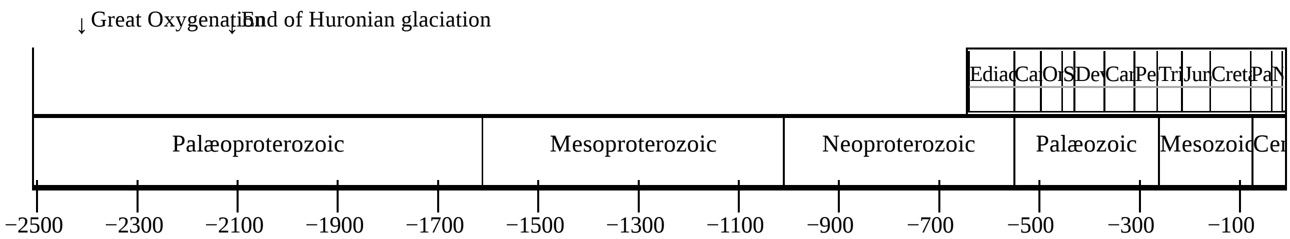
Early chemosynthetic organisms likely produced methane, an important trap for molecular oxygen, since methane readily oxidizes to carbon dioxide (CO_2) and water in the presence of UV radiation. Modern methanogens require nickel as an enzyme cofactor. As the Earth's crust cooled and the supply of volcanic nickel dwindled, oxygen-producing algae began to out-perform methane producers, and the oxygen percentage of the atmosphere steadily increased.[42] From 2.7 to 2.4 billion years ago, the rate of deposition of nickel declined steadily from a level 400 times today's.[43]

Bistability

Another hypothesis posits a model of the atmosphere that exhibits bistability: two steady states of oxygen concentration. The state of stable low oxygen concentration (0.02%) experiences a high rate of methane oxidation. If some event raises oxygen levels beyond a moderate threshold, the formation of an ozone layer shields UV rays and decreases methane oxidation, raising oxygen further to a stable state of 21% or more. The Great Oxygenation Event can then be understood as a transition from the lower to the upper steady states.[44][45]

Role in mineral diversification

The Great Oxygenation Event triggered an explosive growth in the diversity of minerals, with many elements occurring in one or more oxidized forms near the Earth's surface.[46] It is estimated that the GOE was directly responsible for more than 2,500 of the total of about 4,500 minerals found on Earth today. Most of these new minerals were formed as hydrated and oxidized forms due to dynamic mantle and crust processes.[47]



Million years ago. Age of Earth = 4,560

Role in cyanobacteria evolution

In a field research done in Lake Fryxell, Antarctica, researchers found out that mats of oxygen-producing cyanobacteria can produce a thin layer, one or two millimeters thick, of oxygenated water in an otherwise anoxic environment even under thick ice. Thus, before oxygen started accumulating in the atmosphere, these organisms could have possibly adapted to oxygen.[48][49] Eventually, the evolution of aerobic organisms that consumed oxygen established an equilibrium in the availability of oxygen. Free oxygen has been an important constituent of the atmosphere ever since.

Origin of eukaryotes

It has been proposed that a local rise in oxygen levels due to cyanobacterial photosynthesis in ancient microenvironments was highly toxic to the surrounding biota, and that this selective pressure drove the evolutionary transformation of an archaeal lineage into the first eukaryotes.[50] Oxidative stress involving production of reactive oxygen species (ROS) might have acted in synergy with other environmental stresses (such as ultraviolet radiation and/or desiccation) to drive selection in an early archaeal lineage towards eukaryosis. This archaeal ancestor may already have had DNA repair mechanisms based on DNA pairing and recombination and possibly some kind of cell fusion mechanism.[51][52] The detrimental effects of internal ROS (produced by endosymbiont proto-mitochondria) on the archaeal genome could have promoted the evolution of meiotic sex from these humble beginnings.[51] Selective pressure for efficient DNA repair of oxidative DNA damages may have driven the evolution of eukaryotic sex involving such features as cell-cell fusions, cytoskeleton-mediated chromosome movements and emergence of the nuclear membrane.[50] Thus the evolution of eukaryotic sex and eukaryogenesis were likely inseparable processes that evolved in large part to facilitate DNA repair.[50][53]

See also

- Geological history of oxygen – Timeline of the development of free oxygen in the Earth's oceans and atmosphere
- Medea hypothesis
- Pasteur point
- Rare Earth hypothesis – Hypothesis that complex extraterrestrial life is an extremely rare phenomenon
- Stromatolite

References

1. Holland, Heinrich D. (2006). "The oxygenation of the atmosphere and oceans" (http://rstb.royalsocietypublishing.org/content/361/1470/903.full.pdf) (PDF). *Philosophical Transactions of the Royal Society: Biological Sciences*. **361**: 903–915. doi:10.1098/rstb.2006.1838 (https://doi.org/10.1098%2Frstb.2006.1838).
2. Margulis, Lynn; Sagan, Dorion (1986). "Chapter 6, "The Oxygen Holocaust" " (https://books.google.com/books?id=eo_sMMRxgAUC&lpg=PA99&ots=oWKooBsh1G&dq=oxygen%20holocaust&pg=PA99#v=onepage&q=oxygen%20holocaust&f=false). *Microcosmos: Four Billion Years of Microbial Evolution*. California: University of California Press. p. 99. ISBN 9780520210646.
3. Lyons, Timothy W.; Reinhard, Christopher T.; Planavsky, Noah J. (February 2014). "The rise of oxygen in Earth's early ocean and atmosphere". *Nature*. **506** (7488): 307–315. Bibcode:2014Natur.506..307L (https://ui.adsabs.harvard.edu/abs/2014Natur.506..307L). doi:10.1038/nature13068 (https://doi.org/10.1038%2Fnature13068). ISSN 0028-0836 (https://www.worldcat.org/issn/0028-0836). PMID 24553238 (https://pubmed.ncbi.nlm.nih.gov/24553238).
4. Sosa Torres, Martha E.; Saucedo-Vázquez, Juan P.; Kroneck, Peter M.H. (2015). "Chapter 1, Section 2: The rise of dioxygen in the atmosphere". In Kroneck, Peter M.H.; Sosa Torres, Martha E. (eds.). *Sustaining Life on Planet Earth: Metalloenzymes Mastering Dioxygen and Other Chewy Gases*. Metal Ions in Life Sciences. **15**. Springer. pp. 1–12. doi:10.1007/978-3-319-12415-5_1 (https://doi.org/10.1007%2F978-3-319-12415-5_1). ISBN 978-3-319-12414-8. PMID 25707464 (https://pubmed.ncbi.nlm.nih.gov/25707464).
5. Hodgskiss, Malcolm S.W.; Crockford, Peter W.; Peng, Yongbo; Wing, Boswell A.; Horner, Tristan J. (27 August 2019). "A productivity collapse to end Earth's Great Oxidation" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6717284). *PNAS*. **116** (35): 17207–17212. doi:10.1073/pnas.1900325116 (https://doi.org/10.1073%2Fpnas.1900325116). PMC 6717284 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6717284). PMID 31405980 (https://pubmed.ncbi.nlm.nih.gov/31405980).
6. University of Zurich (17 January 2013). "Great Oxidation Event: More oxygen through multicellularity" (https://www.sciencedaily.com/releases/2013/01/130117084856.htm). *ScienceDaily*. Retrieved 27 August 2019.
7. "The Rise of Oxygen" (http://www.astrobio.net/news-exclusive/the-rise-of-oxygen/). *Astrobiology Magazine*. Retrieved 6 April 2016.
8. "Researchers discover when and where oxygen began its rise" (https://uwaterloo.ca/science/news/researchers-discover-when-and-where-oxygen-began-its-rise). Science News. University of Waterloo.
9. Dutkiewicz, A.; Volk, H.; George, S.C.; Ridley, J.; Buick, R. (2006). "Biomarkers from Huronian oil-bearing fluid inclusions: An uncontaminated record of life before the Great Oxidation Event". *Geology*. **34** (6): 437. Bibcode:2006Geo....34..437D (https://ui.adsabs.harvard.edu/abs/2006Geo....34..437D). doi:10.1130/G22360.1 (https://doi.org/10.1130%2FG22360.1).
10. Caredona, Tanai (6 March 2018). "Early Archean origin of heterodimeric Photosystem I" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5857716). *Elsevier*. **4** (3): e00548. doi:10.1016/j.heliyon.2018.e00548 (https://doi.org/10.1016%2Fj.heliyon.2018.e00548). PMC 5857716 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5857716). PMID 29560463 (https://pubmed.ncbi.nlm.nih.gov/29560463).
11. Howard, Victoria (7 March 2018). "Photosynthesis originated a billion years earlier than we thought, study shows" (https://www.astrobio.net/also-in-news/photosynthesis-originated-billion-years-earlier-thought-study-shows/). *Astrobiology Magazine*. Retrieved 23 March 2018.

12. Holland, Heinrich D. (November 2002). "Volcanic gases, black smokers, and the great oxidation event". *Geochimica et Cosmochimica Acta*. **66** (21): 3811–3826. Bibcode:2002GeCoA..66.3811H (https://ui.adsabs.harvard.edu/abs/2002GeCoA..66.3811H). doi:10.1016/s0016-7037(02)00950-x (https://doi.org/10.1016%2Fs0016-7037%2802%2900950-x). ISSN 0016-7037 (https://www.worldcat.org/issn/0016-7037).
13. Catling, David C.; Kasting, James F. (2017). *Atmospheric Evolution on Inhabited and Lifeless Worlds*. Cambridge: Cambridge University Press. doi:10.1017/9781139020558 (https://doi.org/10.1017%2F9781139020558). ISBN 9781139020558.
14. University of Zurich (17 January 2013). "Great Oxidation Event: More oxygen through multicellularity" (https://www.sciencedaily.com/releases/2013/01/130117084856.htm). *ScienceDaily*.
15. Anbar, A.; Duan, Y.; Lyons, T.; Arnold, G.; Kendall, B.; Creaser, R.; Kaufman, A.; Gordon, G.; Scott, C.; Garvin, J.; Buick, R. (2007). "A whiff of oxygen before the great oxidation event?". *Science*. **317** (5846): 1903–1906. Bibcode:2007Sci...317.1903A (https://ui.adsabs.harvard.edu/abs/2007Sci...317.1903A). doi:10.1126/science.1140325 (https://doi.org/10.1126%2Fscience.1140325). PMID 17901330 (https://pubmed.ncbi.nlm.nih.gov/17901330).
16. Dahl, T.W.; Hammarlund, E.U.; Anbar, A.D.; Bond, D.P.G.; Gill, B.C.; Gordon, G.W.; Knoll, A.H.; Nielsen, A.T.; Schovsbo, N.H. (30 September 2010). "Devonian rise in atmospheric oxygen correlated to the radiations of terrestrial plants and large predatory fish" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2964239). *Proceedings of the National Academy of Sciences*. **107** (42): 17911–17915. Bibcode:2010PNAS..10717911D (https://ui.adsabs.harvard.edu/abs/2010PNAS..10717911D). doi:10.1073/pnas.1011287107 (https://doi.org/10.1073%2Fpnas.1011287107). ISSN 0027-8424 (https://www.worldcat.org/issn/0027-8424). PMC 2964239 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2964239). PMID 20884852 (https://pubmed.ncbi.nlm.nih.gov/20884852).
17. Catling, David C.; Claire, Mark W. (August 2005). "How Earth's atmosphere evolved to an oxic state: A status report". *Earth and Planetary Science Letters*. **237** (1–2): 1–20. Bibcode:2005E&PSL.237....1C (https://ui.adsabs.harvard.edu/abs/2005E&PSL.237....1C). doi:10.1016/j.epsl.2005.06.013 (https://doi.org/10.1016%2Fj.epsl.2005.06.013). ISSN 0012-821X (https://www.worldcat.org/issn/0012-821X).
18. Bekker, Andrey (2014). "Huronian Glaciation". In Amils, Ricardo; Gargaud, Muriel; Cernicharo Quintanilla, José; Cleaves, Henderson James (eds.). *Encyclopedia of Astrobiology*. Springer Berlin Heidelberg. pp. 1–8. doi:10.1007/978-3-642-27833-4_742-4 (https://doi.org/10.1007%2F978-3-642-27833-4_742-4). ISBN 9783642278334.
19. Kopp, Robert E.; Kirschvink, Joseph L.; Hilburn, Isaac A.; Nash, Cody Z. (2005). "The Paleoproterozoic snowball Earth: A climate disaster triggered by the evolution of oxygenic photosynthesis" (http://www.pnas.org/cgi/reprint/0504878102v1). *Proceedings of the National Academy of Sciences of the United States of America*. **102** (32): 11131–11136. Bibcode:2005PNAS..10211131K (https://ui.adsabs.harvard.edu/abs/2005PNAS..10211131K). doi:10.1073/pnas.0504878102 (https://doi.org/10.1073%2Fpnas.0504878102). PMC 1183582 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1183582). PMID 16061801 (https://pubmed.ncbi.nlm.nih.gov/16061801).
20. Lane, Nick (5 February 2010). "First breath: Earth's billion-year struggle for oxygen" (https://www.newscientist.com/article/mg20527461.100-first-breath-earths-billionyear-struggle-for-oxygen.html). *New Scientist*. No. 2746.
21. Evans, D.A.; Beukes, N.J.; Kirschvink, J.L. (March 1997). "Low-latitude glaciation in the Palaeoproterozoic era". *Nature*. **386** (6622): 262–266. Bibcode:1997Natur.386..262E (https://ui.adsabs.harvard.edu/abs/1997Natur.386..262E). doi:10.1038/386262a0 (https://doi.org/10.1038%2F386262a0). ISSN 0028-0836 (https://www.worldcat.org/issn/0028-0836).
22. Sperling, Erik; Frieder, Christina; Raman, Akkur; Girguis, Peter; Levin, Lisa; Knoll, Andrew (August 2013). "Oxygen, ecology, and the Cambrian radiation of animals" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3746845). *Proceedings of the National Academy of Sciences of the United States of America*. **110** (33): 13446–13451. Bibcode:2013PNAS..11013446S (https://ui.adsabs.harvard.edu/abs/2013PNAS..11013446S). doi:10.1073/pnas.1312778110 (https://doi.org/10.1073%2Fpnas.1312778110). PMC 3746845 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3746845). PMID 23898193 (https://pubmed.ncbi.nlm.nih.gov/23898193).
23. Utsunomiya, Satoshi; Murakami, Takashi; Nakada, Masami; Kasama, Takeshi (January 2003). "Iron oxidation state of a 2.45 Byr-old paleosol developed on mafic volcanics". *Geochimica et Cosmochimica Acta*. **67** (2): 213–221. Bibcode:2003GeCoA..67..213U (https://ui.adsabs.harvard.edu/abs/2003GeCoA..67..213U). doi:10.1016/s0016-7037(02)01083-9 (https://doi.org/10.1016%2Fs0016-7037%2802%2901083-9). ISSN 0016-7037 (https://www.worldcat.org/issn/0016-7037).

24. Hofmann, Axel; Bekker, Andrey; Rouxel, Olivier; Rumble, Doug; Master, Sharad (September 2009). "Multiple sulphur and iron isotope composition of detrital pyrite in Archaean sedimentary rocks: A new tool for provenance analysis" (https://darchive.mblwhoilibrary.org/bitstream/1912/3068/1/manuscript_revised_with_figs.pdf) (PDF). *Earth and Planetary Science Letters*. **286** (3–4): 436–445. Bibcode:2009E&PSL.286..436H (https://ui.adsabs.harvard.edu/abs/2009E&PSL.286..436H). doi:10.1016/j.epsl.2009.07.008 (https://doi.org/10.1016%2Fj.epsl.2009.07.008). hdl:1912/3068 (https://hdl.handle.net/1912%2F3068). ISSN 0012-821X (https://www.worldcat.org/issn/0012-821X).
25. Eriksson, Patrick G.; Cheney, Eric S. (January 1992). "Evidence for the transition to an oxygen-rich atmosphere during the evolution of red beds in the lower proterozoic sequences of southern Africa". *Precambrian Research*. **54** (2–4): 257–269. Bibcode:1992PreR...54..257E (https://ui.adsabs.harvard.edu/abs/1992PreR...54..257E). doi:10.1016/0301-9268(92)90073-w (https://doi.org/10.1016%2F0301-9268%2892%2990073-w). ISSN 0301-9268 (https://www.worldcat.org/issn/0301-9268).
26. Lyons, Timothy W.; Anbar, Ariel D.; Severmann, Silke; Scott, Clint; Gill, Benjamin C. (May 2009). "Tracking Euxinia in the Ancient Ocean: A Multiproxy Perspective and Proterozoic Case Study". *Annual Review of Earth and Planetary Sciences*. **37** (1): 507–534. Bibcode:2009AREPS..37..507L (https://ui.adsabs.harvard.edu/abs/2009AREPS..37..507L). doi:10.1146/annurev.earth.36.031207.124233 (https://doi.org/10.1146%2Fannurev.earth.36.031207.124233). ISSN 0084-6597 (https://www.worldcat.org/issn/0084-6597).
27. Canfield, Donald E.; Poulton, Simon W. (1 April 2011). "Ferruginous Conditions: A Dominant Feature of the Ocean through Earth's History". *Elements*. **7** (2): 107–112. doi:10.2113/gselements.7.2.107 (https://doi.org/10.2113%2Fgselements.7.2.107). ISSN 1811-5209 (https://www.worldcat.org/issn/1811-5209).
28. Frei, R.; Gaucher, C.; Poulton, S.W.; Canfield, D.E. (2009). "Fluctuations in Precambrian atmospheric oxygenation recorded by chromium isotopes". *Nature*. **461** (7261): 250–253. Bibcode:2009Natur.461..250F (https://ui.adsabs.harvard.edu/abs/2009Natur.461..250F). doi:10.1038/nature08266 (https://doi.org/10.1038%2Fnature08266). PMID 19741707 (https://pubmed.ncbi.nlm.nih.gov/19741707). Lay summary (https://dx.doi.org/10.1038/461179a).
29. "Evidence of Earliest Oxygen-Breathing Life on Land Discovered" (http://www.livescience.com/16714-oxygen-breathing-life-chromium.html). *LiveScience.com*. Retrieved 6 April 2016.
30. Farquhar, J. (4 August 2000). "Atmospheric Influence of Earth's Earliest Sulfur Cycle" (https://semanticscholar.org/paper/c1f374a7b0b4f7526fc901fa641081e586505bbc). *Science*. **289** (5480): 756–758. Bibcode:2000Sci...289..756F (https://ui.adsabs.harvard.edu/abs/2000Sci...289..756F). doi:10.1126/science.289.5480.756 (https://doi.org/10.1126%2Fscience.289.5480.756). ISSN 0036-8075 (https://www.worldcat.org/issn/0036-8075). PMID 10926533 (https://pubmed.ncbi.nlm.nih.gov/10926533).
31. French, Katherine L.; Hallmann, Christian; Hope, Janet M.; Schoon, Petra L.; Zumberge, J. Alex; Hoshino, Yosuke; Peters, Carl A.; George, Simon C.; Love, Gordon D. (27 April 2015). "Reappraisal of hydrocarbon biomarkers in Archean rocks" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4434754). *Proceedings of the National Academy of Sciences*. **112** (19): 5915–5920. Bibcode:2015PNAS..112.5915F (https://ui.adsabs.harvard.edu/abs/2015PNAS..112.5915F). doi:10.1073/pnas.1419563112 (https://doi.org/10.1073%2Fpnas.1419563112). ISSN 0027-8424 (https://www.worldcat.org/issn/0027-8424). PMC 4434754 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4434754). PMID 25918387 (https://pubmed.ncbi.nlm.nih.gov/25918387).
32. Anbar, Ariel D.; Rouxel, Olivier (May 2007). "Metal Stable Isotopes in Paleoceanography" (https://semanticscholar.org/paper/d0f689dab2e508cb27195bea95a61f8abdfac06f). *Annual Review of Earth and Planetary Sciences*. **35** (1): 717–746. Bibcode:2007AREPS..35..717A (https://ui.adsabs.harvard.edu/abs/2007AREPS..35..717A). doi:10.1146/annurev.earth.34.031405.125029 (https://doi.org/10.1146%2Fannurev.earth.34.031405.125029). ISSN 0084-6597 (https://www.worldcat.org/issn/0084-6597).
33. Stüeken, E.E.; Buick, R.; Bekker, A.; Catling, D.; Foriel, J.; Guy, B.M.; Kah, L.C.; Machel, H.G.; Montañez, I.P. (1 August 2015). "The evolution of the global selenium cycle: Secular trends in Se isotopes and abundances". *Geochimica et Cosmochimica Acta*. **162**: 109–125. Bibcode:2015GeCoA.162..109S (https://ui.adsabs.harvard.edu/abs/2015GeCoA.162..109S). doi:10.1016/j.gca.2015.04.033 (https://doi.org/10.1016%2Fj.gca.2015.04.033). ISSN 0016-7037 (https://www.worldcat.org/issn/0016-7037).
34. Kirschvink, Joseph L.; Kopp, Robert E. (27 August 2008). "Palaeoproterozoic ice houses and the evolution of oxygen-mediating enzymes: the case for a late origin of photosystem II" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2606766). *Philosophical Transactions of the Royal Society B: Biological Sciences*. **363** (1504): 2755–2765. doi:10.1098/rstb.2008.0024 (https://doi.org/10.1098%2Frstb.2008.0024). ISSN 0962-8436 (https://www.worldcat.org/issn/0962-8436). PMC 2606766 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2606766). PMID 18487128 (https://pubmed.ncbi.nlm.nih.gov/18487128).

35. des Marais, David J.; Strauss, Harald; Summons, Roger E.; Hayes, J.M. (October 1992). "Carbon isotope evidence for the stepwise oxidation of the Proterozoic environment". *Nature*. **359** (6396): 605–609. Bibcode:1992Natur.359..605M (https://ui.adsabs.harvard.edu/abs/1992Natur.359..605M). doi:10.1038/359605a0 (https://doi.org/10.1038%2F359605a0). ISSN 0028-0836 (https://www.worldcat.org/issn/0028-0836). PMID 11536507 (https://pubmed.ncbi.nlm.nih.gov/11536507).
36. Krissansen-Totton, J.; Buick, R.; Catling, D.C. (1 April 2015). "A statistical analysis of the carbon isotope record from the Archean to Phanerozoic and implications for the rise of oxygen". *American Journal of Science*. **315** (4): 275–316. Bibcode:2015AmJS..315..275K (https://ui.adsabs.harvard.edu/abs/2015AmJS..315..275K). doi:10.2475/04.2015.01 (https://doi.org/10.2475%2F04.2015.01). ISSN 0002-9599 (https://www.worldcat.org/issn/0002-9599).
37. Catling, D.C. (3 August 2001). "Biogenic Methane, Hydrogen Escape, and the Irreversible Oxidation of Early Earth". *Science*. **293** (5531): 839–843. Bibcode:2001Sci...293..839C (https://ui.adsabs.harvard.edu/abs/2001Sci...293..839C). doi:10.1126/science.1061976 (https://doi.org/10.1126%2Fscience.1061976).
38. Lenton, T.M.; Schellnhuber, H.J.; Szathmáry, E. (2004). "Climbing the co-evolution ladder". *Nature*. **431** (7011): 913. Bibcode:2004Natur.431..913L (https://ui.adsabs.harvard.edu/abs/2004Natur.431..913L). doi:10.1038/431913a (https://doi.org/10.1038%2F431913a). PMID 15496901 (https://pubmed.ncbi.nlm.nih.gov/15496901).
39. Eguchi, James; Seales, Johnny; Dasgupta, Rajdeep (2019). "Great Oxidation and Lomagundi events linked by deep cycling and enhanced degassing of carbon" (https://www.nature.com/articles/s41561-019-0492-6.epdf). *Nature Geoscience*. **13**: 71–76. doi:10.1038/s41561-019-0492-6 (https://doi.org/10.1038%2Fs41561-019-0492-6). Retrieved 13 December 2019.
40. "Iron in primeval seas rusted by bacteria" (https://phys.org/news/2013-04-iron-primeval-seas-rusted-bacteria.html). *Phys.org*. April 2013.
41. American, Scientific. "Abundant Oxygen Indirectly Due to Tectonics" (http://www.scientificamerican.com/podcast/episode/5C271294-EE45-D925-BEBBEF03016A7CF4/). *Scientific American*. Retrieved 6 April 2016.
42. "Breathing Easy Thanks to the Great Oxidation Event" (http://www.scientificamerican.com/podcast/episode/breathing-easy-thanks-to-great-oxid-09-04-13/). Scientific American. Retrieved 6 April 2016.
43. Konhauser, Kurt O.; et al. (2009). "Oceanic nickel depletion and a methanogen famine before the Great Oxidation Event". *Nature*. **458** (7239): 750–753. Bibcode:2009Natur.458..750K (https://ui.adsabs.harvard.edu/abs/2009Natur.458..750K). doi:10.1038/nature07858 (https://doi.org/10.1038%2Fnature07858). PMID 19360085 (https://pubmed.ncbi.nlm.nih.gov/19360085).
44. Goldblatt, C.; Lenton, T.M.; Watson, A.J. (2006). "The Great Oxidation at 2.4 Ga as a bistability in atmospheric oxygen due to UV shielding by ozone" (http://www.cosis.net/abstracts/EGU06/00770/EGU06-J-00770.pdf) (PDF). *Geophysical Research Abstracts*. **8**: 00770.
45. Claire, M.W.; Catling, D.C.; Zahnle, K.J. (December 2006). "Biogeochemical modelling of the rise in atmospheric oxygen". *Geobiology*. **4** (4): 239–269. doi:10.1111/j.1472-4669.2006.00084.x (https://doi.org/10.1111%2Fj.1472-4669.2006.00084.x). ISSN 1472-4677 (https://www.worldcat.org/issn/1472-4677).
46. Sverjensky, Dimitri A.; Lee, Namhey (1 February 2010). "The Great Oxidation Event and Mineral Diversification". *Elements*. **6** (1): 31–36. doi:10.2113/gselements.6.1.31 (https://doi.org/10.2113%2Fgselements.6.1.31). ISSN 1811-5209 (https://www.worldcat.org/issn/1811-5209).
47. "Evolution of Minerals" (http://www.scientificamerican.com/article.cfm?id=evolution-of-minerals). *Scientific American*. March 2010.
48. "Oxygen oasis in Antarctic lake reflects Earth in distant past" (https://www.sciencedaily.com/releases/2015/09/150901140759.htm). *ScienceDaily.com*. September 2015.
49. Doran, Peter T.; Jungblut, Anne D.; Mackey, Tyler J.; Hawes, Ian; Sumner, Dawn Y. (1 October 2015). "Antarctic microbial mats: A modern analog for Archean lacustrine oxygen oases" (https://escholarship.org/uc/item/9gr788vv). *Geology*. **43** (10): 887–890. Bibcode:2015Geo....43..887S (https://ui.adsabs.harvard.edu/abs/2015Geo....43..887S). doi:10.1130/G36966.1 (https://doi.org/10.1130%2FG36966.1). ISSN 0091-7613 (https://www.worldcat.org/issn/0091-7613).
50. Gross, J.; Bhattacharya, D. (August 2010). "Uniting sex and eukaryote origins in an emerging oxygenic world" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2933680). *Biol. Direct*. **5**: 53. doi:10.1186/1745-6150-5-53 (https://doi.org/10.1186%2F1745-6150-5-53). PMC 2933680 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2933680). PMID 20731852 (https://pubmed.ncbi.nlm.nih.gov/20731852).
51. Hörandl E, Speijer D (February 2018). "How oxygen gave rise to eukaryotic sex" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5829205). *Proc. Biol. Sci*. **285** (1872): 20172706. doi:10.1098/rspb.2017.2706 (https://doi.org/10.1098%2Frspb.2017.2706). PMC 5829205 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5829205). PMID 29436502 (https://pubmed.ncbi.nlm.nih.gov/29436502).

52. Bernstein, H.; Bernstein, C. (2017). "Sexual communication in archaea, the precursor to meiosis". In Witzany, Guenther (ed.). *Biocommunication of Archaea*. Springer International Publishing. pp. 103–117. doi:10.1007/978-3-319-65536-9 (https://doi.org/10.1007%2F978-3-319-65536-9). ISBN 978-3-319-65535-2.
53. Bernstein, Harris; Bernstein, Carol (2013). "Chapter 3 – Evolutionary origin and adaptive function of meiosis". In Bernstein, Carol; Bernstein, Harris (eds.). *Meiosis*. Intech Publ. pp. 41–75.

External links

- Lane, Nick (5 February 2010). "First breath: Earth's billion-year struggle for oxygen" (https://www.newscientist.com/article/mg20527461.100-first-breath-earths-billionyear-struggle-for-oxygen/). *New Scientist*. No. 2746. Archived (https://web.archive.org/web/20110106141826/http://ptc-cam.blogspot.com/2010/02/first-breath-earths-billion-year.html) 2011-01-06 at the Wayback Machine