EARTH SCIENCES

Breathing Life into Oxygen

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If one could boil all of Earth's behavior down to a single number—a statistic that captured the rich intersection of geological, chemical, and biological processes operating on our planet's surface—a strong argument could be made for the atmosphere's O_2 content. That is presently 21% by volume, but a wide range of data extracted from the geologic record demonstrates that O_2 levels have varied considerably. To first order, Earth's history is written in O_2, and tangled in the story are plate tectonics, the rock cycle, the evolution of photosynthesis, and the appearance of animals. In *Oxygen*, Don Canfield lucidly unpacks this story through a careful mix of overview and detail, with a focus on the relevant biogeochemical mechanics.

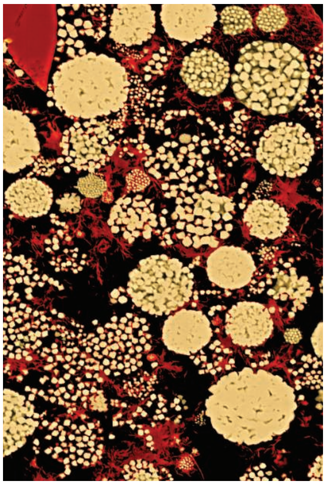
Oxygen
A Four Billion Year History
by Donald E. Canfield
Princeton University Press, Princeton, NJ, 2014. 222 pp. $27.95, £19.95. ISBN 9780691145020.

Although it's widely appreciated that molecular oxygen derives from photosynthesis, understanding the dynamics and history of O_2 encompasses a rich and complex multiscale problem. Canfield (a biogeochemist at the University of Southern Denmark) walks readers through a logical foundation of the processes connecting solid Earth with the chemistry and biology of oceans and atmosphere. Not a recondite history of O_2, the book explores how we reconstruct redox processes that operated in ancient environments and how to think about the behavior of biogeochemical cycles across geological time.

Much of the book proceeds chronologically, with the cadence set by critical redox and evolutionary phenomena such as anaerobic metabolisms before oxygen and the evolution of photosynthesis. Canfield takes full advantage of the process-history duality that underpins all good Earth science, presenting different geobiological processes that affect O_2 in the context of critical historical events.

The chapter on cyanobacteria, one of the highlights of the book, is presented with a spectacular blend of scientific discovery and evolutionary wonderment. By inventing oxygen-producing photosynthesis, this group changed the world in a fashion unmatched by any other evolutionary innovation (save perhaps the human brain). Canfield also does a wonderful job emphasizing the potential feedbacks between O_2 in the atmosphere and oceans and the rock cycle (which both buries and exposes organic matter and pyrite). Although these connections among tectonics, sedimentary geology, and biogeochemical cycles appear critically important, they remain understudied.

Given the book's scientific breadth, I found remarkably few points that I would dispute. In his discussion of the evolution of oxygenic photosynthesis, Canfield places too much emphasis on the pigments and not enough on the photochemistry. And he attributes the rise of oxygen circa 2.35 billion years ago to a change in the composition of volcanoes, an idea championed by Dick Holland. But there is little geological support for such a change, and at times during the past 100 million years volcanic outgassing changed manyfold while oxygen levels seem to have shifted little.



Locked away. Pyrite burial (here pyrite framboids in a thin section of a shale) "represents an oxygen source to the atmosphere."

Canfield's research has played a major role in shaping current knowledge of geobiological interactions among the iron, sulfur, carbon, and oxygen cycles. He is particularly adept at leveraging understanding of modern processes to study the past. In the book, he effectively uses autobiographical anecdotes to drive the narrative and connect related concepts. He also reveals how much impact geochemists from the previous generation (such as Bob Garrels, Bob Berner, and Dick Holland) have had on his thinking. Like his talks, Canfield's prose presents stories and concepts with a youthful enthusiasm that masks substantial wisdom.

Breakthroughs in analytical chemistry are improving our ability to read paleoenvironmental history from sedimentary rocks, and breakthroughs in molecular biology and genomics are providing stronger frameworks for interpreting the evolution of biota and metabolisms. Consequently, our understanding of Earth's O_2 history is remarkably dynamic. Canfield does a great job of acknowledging what we don't know and identifying areas that are in radical flux. He recognizes that the subject will likely require a very different book in 30 years. I suspect that might be closer to 10.

Compared with two other recent works on O_2 and early Earth history (*1*, *2*), Canfield's book is more focused on understanding the key biogeochemical processes. Not satisfied to simply present the history, he strives to make readers familiar with the relevant mechanics. He demands that we wrestle simultaneously with geochemical observations used to assess ancient O_2 levels, the processes that provide the sources and sinks for oxygen (including how these processes have changed with time), and the poorly understood phenomena that introduce uncertainty into our knowledge.

Concise and easily read, *Oxygen* provides an ideal starting block for those interested in learning about Earth's O_2 history and, more broadly, the function and history of biogeochemical cycles. It requires no substantial prior knowledge of Earth science, although readers with some exposure to that field (or prepared with Wikipedia at the ready) will gain a much deeper understanding of O_2 on Earth. The endnotes provide valuable entries for readers who wish to explore particular points in greater depth and, in other cases, enable brief digressions for interesting personal notes without disrupting the logical thread of a given concept. And the detailed bibliography captures a vast swath of the relevant primary literature. I highly recommend Canfield's book for anyone with even a remote interest in Earth history, as O_2 singularly encompasses much of what makes our planet special.

References

1. N. Lane, *Oxygen: The Molecule That Made the World* (Oxford Univ. Press, Oxford, 2002).
2. A. H. Knoll, *Life on a Young Planet: The First Three Billion Years of Evolution on Earth* (Princeton Univ. Press, Princeton, NJ, 2003); reviewed in (*3*).
3. G. M. Narbonne, *Science* **301**, 919 (2003).

10.1126/science.1248669

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