The Great Oxidation Event

Ariel D. Anbar
School of Earth and Space Exploration
School of Molecular Sciences
Arizona State University

Photo credit: Tanja Bosak
Earth’s Atmosphere Composition

- N₂
- Ar
- CO₂
- O₂
- rest
Banded Iron Formations (BIFs) of Karijini Gorge are distinctive units of sedimentary rock that are almost always of Precambrian age. Some of the oldest known rock formations.
O$_2$ in Earth’s Atmosphere through Time

- "Great Oxidation Event"
- "Oxygen Overshoot"
- "Neoproterozoic Oxidation Event"
- "The Boring Billion"
- "Whiffs of Oxygen"

Modified after Lyons et al., 2014
Why do we care?
Exoplanets!

3711 confirmed
4496 candidates
927 terrestrial
... and counting!

https://exoplanets.nasa.gov/
Coming Soon: Spectroscopic search for biosignatures
O$_2$ as a Biosignature

Venus

Earth

Mars

Source:
R. Hanel, Goddard Space Flight Center
Welcome to the Anthropocene!
Elon Musk

"You need to live in a dome initially but over time you could terraform Mars to look like Earth and eventually walk around outside without anything on. ... So it's a fixer-upper of a planet."
What caused the Great Oxidation Event?
Photosynthesis?

$\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{O}_2 + \text{CH}_2\text{O}$
Shark Bay
Western Australia
Modern Day
Tumbiana Formation
Western Australia
~ 2.7 billion years old
Dresser Formation
Western Australia
~ 3.5 billion years old
Sulfide Minerals

Major reservoir of Mo

React with $O_2$
When $O_2$ is absent:

- Mo locked in sulfides
- $[Mo]_{\text{ocean}}$ low
When $O_2$ increases:

- Sulfides oxidize
- $[\text{Mo}]_{\text{ocean}}$ rises
Inferring Changes in Seawater Molybdenum vs. Time

Data from Scott et al., 2008
Molybdenum and Other Proxies Indicate a “Whiff” of O₂

Synthesis after Anbar et al., 2007; Kaufman et al., 2007; Duan et al., 2010; Kendall et al., 2013; Garvin et al., 2009; Reinhard et al., 2009
Before the Great Oxidation Event

*Ostrander et al., in review*
O$_2$ in Earth’s Atmosphere through Time

"Great Oxidation Event"

"Oxygen Overshoot"

"Neoproterozoic Oxidation Event"

"The Boring Billion"

"Whiffs of Oxygen"

Modified after Lyons et al., 2014
Summary So Far

• The Great Oxidation Event occurred around 2.3 billion years ago;

• Evidence of microbial mats (“stromatolites”) that might have produced O$_2$ are found as far back as 3.5 billion years ago;

• Molybdenum and other elements in ancient ocean sediments suggest a slightly oxidizing surface environment – and hence O$_2$ production – at least by 2.5 billion years ago and maybe a billion years earlier;

• Photosynthesis was necessary for the Great Oxidation Event but it originated much earlier!
What caused the Great Oxidation Event?
What kept $O_2$ low before the Great Oxidation Event?
O$_2$ in the Atmosphere

$C_{org}$ Burial is Important

Buildup in Atmosphere

Oxygenic Photosynthesis

Aerobic Respiration

Fast

Burial in Sediments

$O_2$
Carbon Isotope Record
Suggests burial of $C_{\text{org}}$ has changed but not enough

\[ f_{\text{org}} = \frac{\delta^{13}C_{\text{in}} - \delta^{13}C_{\text{carb}}}{\delta^{13}C_{\text{org}} - \delta^{13}C_{\text{carb}}} \]

$ f_{\text{org}} $ does increase through time (i.e., increased net $O_2$ production). But it is unlikely to have increased enough to overcome sinks...

Krissansen-Totton et al., 2015
What About Geological Sinks?

Escape of hydrogen to space

Continental weathering

Oxygen, $O_2$

Subaerial volcanic gases

Metamorphic gases

Burial of organic carbon or pyrite

Submarine volcanic gases

Submarine weathering
Earth’s **Interior**
An effectively infinite $O_2$ sink
Earth’s **Interior**

Possible changes

- Change in mantle $f_{O_2}$
- Change in crustal composition
- Change in composition or flux of volcanic gases

There is some support for each of these ideas!
Two-step rise of atmospheric oxygen linked to the growth of continents

Cin-Ty A. Lee1, Laurence Y. Yeung1, N. Ryan McKenzie1,2, Yusuke Yokoyama2, Kazumi Ozaki3 and Adrian Lenardic4

Increased subaerial volcanism and the rise of atmospheric oxygen 2.5 billion years ago

Lee R. Kump1 & Mark E. Barley2

Evidence for a reducing Archean ambient mantle and its effects on the carbon cycle

Sonja Aubech1 and Vincenzo Stagnolli2

Institut für Geowissenschaften, Goethe-Universität, 60323 Frankfurt am Main, Germany

Earth Sciences Department, Sapienza University of Rome, 00185 Rome, Italy

Statistical geochemistry reveals disruption in secular lithospheric evolution about 2.5 Gyr ago

C. Brenhin Keller2 & Blair Schoene1

Redox-induced lower mantle density contrast and effect on mantle structure and primitive oxygen

Tingting Gu1,2, Mingming Li1,2, Catherine McCammon2 and Kanani K. M. Lee1

Atmospheric oxygenation caused by a change in volcanic degassing pressure

Fabrice Galland1, Bruno Scaillet1 & Nicholas T. Andrè2

Atmospheric oxygenation driven by unsteady growth of the continental sedimentary reservoir

Jon M. Husson1 & Shanen E. Peters

Earth’s early O2 cycle suppressed by primitive continents

Matthijs A. Smit1,2 and Klaus Mezger1

ARTICLES

PUBLISHED ONLINE: 18 SEPTEMBER 2017 | DOI: 10.1038/NGEO3030

LETTER

PUBLISHED ONLINE: 16 MAY 2016 | DOI: 10.1038/NGEO2707

LETTERS

PUBLISHED ONLINE: 30 AUGUST 2007 | DOI: 10.1038/nature06058

LETTER

PUBLISHED ONLINE: 19 FEBRUARY 2017, Pages 68–75

LETTER

PUBLISHED ONLINE: 1 JUNE 2017, Pages 300–305
Consequences of Cooling
A Geo-Gedanken Experiment

Hot Earth
Rapid surface-deep exchange
$O_2$ can never rise

Cold Earth
Slow surface-deep exchange
$O_2$ rises easily
To understand the Great Oxidation Event we must develop a theory of Earth system evolution, integrating surface and deep Earth geoscience.