Revolutions that made the Earth

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(with thanks to Jim Lovelock, Richard Boyle, Stuart Daines, Colin Goldblatt, Hywel Williams and especially Andy Watson)
• Driven by rare evolutionary events
• Increasing energy and material flows
• Causing dramatic planetary changes
• Each contingent on the previous one
• *We wouldn’t be here without them*
Evolutionary regime shifts

Population

Nutrients

Recycling

Environment

‘Tree of life’

Williams & Lenton (2010) Oikos 119: 1887-1899
Ages in Ga (10^9 yr BP)

Environment
- Late Impact Cataclysm
- Impact events
- Ocean formation
- Plant accretion
- Planet accretion

Life
- Early impact catastrophes
- First photosynthetic organisms
- First fossil organisms
- First chromosomes
- Genetic code
- Methane-rich atmosphere
- Photosynthetic oxygen

Inception
- Huronian glaciations
- Methane-rich atmosphere
- Life in the oceans

Oxygen Revolution
- Great oxidation
- End of Banded Iron Formations
- Oxygenation of oceans
- Snowball Earths?
- Return of Banded Iron Formations

Complexity Revolution
- Cell differentiation
- Vascular plants
- Eusocial colonies
- Nervous system
- Language

Geological Epoch

<table>
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<th>Hadean</th>
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T. M. Lenton et al. (Working Group 1) 91st Dahlem Workshop on Earth System Analysis for Sustainability (2003)
The Oxygen revolution
Oxygenic photosynthesis (~2.7 Ga)

Image of a colony of the cyanobacteria *Trichodesmium* from Annette Hynes’ website
Why use water?

- General equation for photosynthesis:
  \[ \text{CO}_2 + 2 \text{H}_2\text{A} + hv \rightarrow (\text{CH}_2\text{O})_n + \text{H}_2\text{O} + 2\text{A} \]
  carbon dioxide + electron donor + light energy → carbohydrate + water + oxidized donor

- Many anoxygenic forms:
  - Electron donors: H\(_2\), H\(_2\)S, S\(^0\), SO\(_3^{2-}\), S\(_2\)O\(_3^{2-}\), Fe\(^{2+}\)
  - All easier to extract electrons from than H\(_2\)O

- Need to exhaust these electron donors
  - Requires an unusual environment

- Need to capture sufficient energy to split H\(_2\)O
  - Requires very complex biochemistry
Evolution’s solution

Origin of oxygenic photosynthesis

Evidence becomes compelling
Multiple stages of oxygenation

- **Surface Ocean:** Anoxic
- **Deep Ocean:** Anoxic
- **Atmosphere:** Reducing
  \[ O_2 < 10^{-12} \text{ atm} \]

>2.7 Ga
Multiple stages of oxygenation

Oxygenic photosynthesis

Atmosphere
- Reducing: $O_2 < 10^{-12}$ atm
- Reducing: $O_2 \sim 10^{-6}$ atm

Surface Ocean
- Anoxic
- Oxygenated

Deep Ocean
- Anoxic
- Anoxic

>2.7 Ga

~2.7-2.4 Ga
Multiple stages of oxygenation

Atmosphere
- Reducing
  $O_2 < 10^{-12}$ atm
- Oxidising
  $O_2 > 10^{-3}$ atm

Surface Ocean
- Anoxic
- Oxygenated

Deep Ocean
- Anoxic

Oxygenic photosynthesis
~2.7-2.4 Ga

Great Oxidation
~2.3-1.0 Ga?

>2.7 Ga

Great Oxidation
~2.7-2.4 Ga

>2.7 Ga
History of atmospheric oxygen

PAL = Present Atmospheric Level

Mass Independent Fractionation (MIF) of sulphur isotopes

Long-term oxygen balance

Hydrogen escape

\[ \text{H}_2 \leftrightarrow \text{O}_2 \]

\[ \text{Fe}^{2+} \leftrightarrow \text{O}_2 \]

Reducing volcanic material

\[ \text{CH}_4 \leftrightarrow \text{O}_2 \]

Photochemical reaction

\[ \text{O}_2 \]

Photosynthesis

\[ \text{O}_2 \]

Respiration + Methanotrophy

\[ \text{O}_2 \]

Organic carbon burial

\[ \text{O}_2 \]

Mantle oxidation?

Space

Atmosphere

Crust

Mantle
Photochemical methane oxidation

$$\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$$

Data are published results from Jim Kasting's 1D photochemical model
Why the delayed oxygen rise?

Two stable states for $O_2$ are separated by formation / loss of an ozone layer

Bi-stability of atmospheric oxygen

Oxidised soils <2.2 Ga

MIF of Sulphur
>2.4 Ga

What triggered oxygen rise?

- Present hydrothermal Fe input
- >2.4 Ga global Fe input
- 2.69-2.44 Ga Hamersley BIF Fe deposition
Oxygen and glaciations

PAL = Present Atmospheric Level

Great oxidation
The Complexity Revolution

~1.8 Ga possible eukaryotic alga *Grypania spiralis* ~2cm diameter coils
~0.6 Ga Ediacaran fossils

image from Phil Wilby (BGS)
Origin of eukaryotes (~2 Ga)
Proterozoic evolution

The Proterozoic Ocean

Planavsky et al. (2011) *Nature*

Poulton et al. (2010) *Nature Geoscience*
GENIE model reconstruction
\( \text{O}_2 = 0.1 \text{ PAL, } \text{PO}_4 = 0.5 \times \text{ present day} \)

Mid Pacific

East Atlantic

Results from Stuart Daines
Oxygen and glaciations

PAL = Present Atmospheric Level

Global
Regional

Lesser oxygenation

Lesser oxygenation
Multiple stages of oxygenation

- **Atmosphere**
  - **Reducing**
    - $O_2 < 10^{-12}$ atm
  - **Reducing**
    - $O_2 \approx 10^{-6}$ atm
  - **Oxidising**
    - $O_2 > 10^{-3}$ atm

- **Surface Ocean**
  - Anoxic
  - Oxygenated
  - Oxygenated

- **Deep Ocean**
  - Anoxic
  - Anoxic
  - Anoxic

**Timescales**
- >2.7 Ga
- ~2.7-2.4 Ga
- ~2.3-1.0 Ga?
Multiple stages of oxygenation

Atmosphere
- Reducing: $O_2 < 10^{-12}$ atm
- Oxidising: $O_2 > 10^{-3}$ atm
- Oxidising: $O_2 \sim 10^{-1}$ atm

Surface Ocean
- Anoxic
- Oxygenated
- Oxygenated

Deep Ocean
- Anoxic
- Anoxic
- Anoxic
- Oxygenated

Time periods:
- $>2.7$ Ga
- $\sim2.7-2.4$ Ga
- $\sim2.3-1.0$ Ga?
- $<0.6$ Ga
Proterozoic world

$O_2 \sim 1$-$10\%$ of present atmospheric level (PAL)

Eukaryotic algae (~750 Ma)

Filter-feeding animals (750?-600Ma)

Zooplankton (~550 Ma)

Bioturbation (550-520 Ma)

Onset of bioturbating animals

Less organic carbon burial
Lower C/P burial ratio
Oxygenate sediments

Boyle et al. (2014). *Nature Geoscience* 7: 671-676
Long-term stabilisation of $O_2$

Land plants (~410 Ma)
Land-based oxygen regulator

- Land Vegetation
- Phosphorus Weathering
- P to Ocean and Land
- Organic Carbon Burial
- Fires

O$_2$

Common features of revolutions

- They are caused by (rare) biological innovations
- They involve step increases in information processing, complexity of organisation, energy capture and material flow through the biosphere
- They rely on the Earth system having some instability, such that new waste products can cause catastrophic upheaval in carbon cycling and climate
- They end only when the system finds a new stable state, able to close the biogeochemical cycles again, by recycling all the materials
What about us? (0 Ga)
Increased information processing
New levels of organisation

City of Ur in Iraq (Urim in Sumerian times)
Increased energy and material flows
Earth system instability

Projected Concentration After 50 More Years of Unrestricted Fossil Fuel Burning

CO$_2$ proxy

Temperature proxy

Age (yr BP)
Where next?

- Melt of Greenland Ice Sheet
- Arctic Sea-Ice Loss?
- Boreal Forest Dieback
- Atlantic Deep Water Formation
- Climatic Change-Induced Ozone Hole?
- Boreal Forest Dieback
- Permafrost and Tundra Loss?
- Sahara Greening
- West African Monsoon Shift?
- Indian Monsoon Chaotic Multistability
- Change in ENSO Amplitude or Frequency
- Dieback of Amazon Rainforest
- Instability of West Antarctic Ice Sheet
- Changes in Antarctic Bottom Water Formation?
- Antarctic Ozone Hole

Population density [persons per km²]

Lenton et al. (2008) *PNAS*
Apocalypse?
Retreat?