Revolution that made the Earth

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(with thanks to Richard Boyle, James Clark, Stuart Daines, Colin Goldblatt, Hywel Williams and especially Andy Watson)
What do I mean by revolutions?

- Driven by rare evolutionary events
- Causing dramatic planetary changes
- Each contingent on the previous one
- *We wouldn’t be here without them*
Origin of the Earth (4.6 Ga)
Earth history

• There have been a series of habitable states:

- **Hadean**
- **Archean**
- **Proterozoic**
- **Phan.**

Life timeline:
- **4 Gyr ago**
  - Origin of life
- **3 Gyr ago**
  - Oxygenic photosynthesis
- **2 Gyr ago**
  - Eukaryotes
- **1 Gyr ago**
  - Animals
- **0 Gyr ago**
  - Us

Environmental timeline:
- **No O₂**
- **Low O₂**
- **Mid O₂**
- **High O₂**
Earth history

- There have been a series of habitable states
- Separated by extreme environmental changes
Earth history

- There have been a series of habitable states
- Separated by extreme environmental changes
- Driven by co-evolution of life and the planet
The Hadean (4.6-3.8 Ga)
The Archean (3.8-2.5 Ga)
Origin of life (3.8-3.3 Ga)

3.5 Ga stromatolite from S. Africa
Dividing cells (3.26 Ga)

Thanks to Andy Knoll (Harvard) for this photograph
Emergence of nutrient recycling

The ‘Flask’ model

Emergence of nutrient recycling

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Emergence of nutrient recycling

The ‘Flask’ model

Nutrient input  Abiotic variables

Nutrient output

Emergence of nutrient recycling

The ‘Flask’ model

Nutrient input  Abiotic variables

Seeded with clonal population of microbes

Nutrient output

Emergence of nutrient recycling

The ‘Flask’ model

Nutrient input, Abiotic variables, Population diversifies, Nutrient output

Recycling Ratio

Emergence of nutrient recycling

The ‘Flask’ model

Nutrient input  Abiotic variables

Recycling population expands

Nutrient output

Recycling Ratio

Time

Population

Environmental regulation?
Environmental regulation?

Organisms contribute to self-regulating feedback mechanisms that have kept the surface of the Earth habitable for life. “Symbiosis as seen from space”.
Organisms contribute to self-regulating feedback mechanisms that have kept the surface of the Earth habitable for life. “Symbiosis as seen from space”.

The Earth is not a unit of selection! Why should the organisms that leave the most descendants be ones that contribute to regulating their planetary environment?
Emergence of environmental regulation

Spatial system of ‘flasks’ connected in a ring

Measure the ‘Error’ = Mismatch between the state of the abiotic environment and the organisms’ preference

Williams & Lenton (2008) PNAS 105(30), 10432-10437
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Mechanism of regulation

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Mechanism of regulation

Environment-improving ecosystem

Environment-degrading ecosystem

Net transfer of organisms

Large population

Small population

Williams & Lenton (2008) *PNAS* 105(30), 10432-10437
Evolutionary regime shifts

Population
Nutrients
Recycling
Environment

Williams & Lenton (2010) Oikos
Carbon cycle stability (past 4 Gyr)

Shields and Veizer (2002)
Oxygenic photosynthesis (~2.7 Ga)

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

• General equation for photosynthesis:

\[
\text{CO}_2 + 2 \text{H}_2\text{A} + \text{hv} \rightarrow (\text{CH}_2\text{O})_n + \text{H}_2\text{O} + 2\text{A}
\]

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

Potential sources of evidence for OP:

- Oxygen:
  - Fossils:
    - micro-fossils (Australia)
    - dividing cells (S. Africa)
  - Carbon isotopes:
    - Isua graphite (Greenland)
  - Biomarkers:
    - Barite sulfur isotopes (Australia)
    - Buck reef chert (S. Africa)
  - Counter-evidence for AP:
    - Barites (S. Africa)

- Loss of iron from paleosols
  - MIF of S weakens (Pongola glaciation)
  - Molybdenum, rhenium mobilised
  - Red beds

- Oxidised paleosols
  - Oxidised soils, Mn deposits

- Evidence becomes compelling
The smoking gun (2.5 Ga)

- Anbar et al. (2007) Science
The Great Oxidation (~2.4 Ga)

- Paleosols (ancient soils)
  - >2.44 Ga loss of iron during weathering
  - 2.44-2.2 Ga ambiguous
  - <2.2 Ga oxidised iron retained

- Red beds (hematite) from 2.32 Ga

- Banded Iron Formations (BIFs)
  - Largely disappear by 1.8 Ga
History of atmospheric oxygen

PAL = Present Atmospheric Level

Mass Independent Fractionation (MIF) of sulphur indicates $O_2 < 10^{-5}$ PAL

Long-term oxygen balance

Hydrogen escape

O_2

Space

Atmosphere

Hydrogen escape

O_2

Photosynthesis

O_2

Respiration + Methanotrophy

O_2

Oxidative weathering

O_2

Organic carbon burial

O_2

Reducing volcanic material

Fe^{2+}

Mantle oxidation?

Mantle

Crust

Photochemical reaction

CH_4 + O_2

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.
Bi-stability of atmospheric oxygen

Two stable states for atmospheric $O_2$ 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

Bi-stability of atmospheric oxygen

Snowball Earth? (2.2 Ga)
Oxygen and glaciations

PAL = Present Atmospheric Level

Great oxidation
The ‘boring billion’ (or so)
Eukaryotes from prokaryotes
Origin of Eukaryotes (~2 Ga?)

~1.8 Ga possible eukaryotic alga *Grypania spiralis* ~2cm diameter coils
Proterozoic evolution

The Proterozoic Ocean

Planavsky et al. (2011) *Nature*

Poulton et al. (2010) *Nature Geoscience*
GENIE model reconstruction

$O_2 = 0.1$ PAL, $PO_4 = 0.5 \times$ present day

Mid Pacific

East Atlantic

Results from Stuart Daines
Oxygen and glaciations

PAL = Present Atmospheric Level
‘Snowball Earths’?
(0.71 Ga & 0.64 Ga)
Hypothesised trigger: Land colonisation

Fungi ~1430 Ma  
Cyanobacteria ~850 Ma  
Algae ~750 Ma  
Proto-lichens ~600 Ma

Yuan et al. (2005) *Science* 308: 1017-1020

- Microfossils
- Molecular clocks
- Carbon isotope signature of photosynthetic microbial communities

Hypothesis for $O_2$ Rise

- $O_2$
- Organic Carbon Burial
- P to Land and Ocean
- Phosphorus Weathering
- Land Colonization

Hypothesis for global cooling

CO$_2$ → CaCO$_3$ Burial → Ca and Mg to Ocean → Silicate Weathering → Land Colonization → Global Temp. → CO$_2$

Support for increased weathering

- Increasing strontium isotope ratio $^{87}\text{Sr}/^{86}\text{Sr}$
- Sulphate accumulation in the ocean
- Clay mineral production
- Appearance of phosphorite deposits around 600 Ma
- Suggests $\text{O}_2$ rise around Gaskiers glaciation

Complex communities (~0.6 Ga)

Image from Phil Wilby
The Ediacarans

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 upheavals in climate, etc.
- 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
Earth system instability

Projected Concentration After 50 More Years of Unrestricted Fossil Fuel Burning

CO₂ Concentration [ppmv]

Temperature proxy

Age (yr BP)
Today’s CO₂ Concentration
After 45 More Years of current energy use patterns

Today’s CO₂ Concentration

Today’s CO₂ Concentration
Tipping Points in the Earth system

Lenton et al. (2008) PNAS
Geoengineering responses

Reflect more sunlight back to space

Remove CO$_2$ from atmosphere and store it

Where next?

- **Apocalypse**
  - Global tipping into a state unable to support current societies

- **Retreat**
  - Lower energy, lower material consumption, lower population

- **Revolution**
  - High energy, high recycling world supporting billions of people
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