Climate Dynamics (5)
Biogeochemistry and Climate

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Biogeochemistry & Climate : Overview

- The importance (for climate & habitability) of
  - biological processes (life, death, photosynthesis...)
  - geological processes (vulcanism, sedimentation...)
  - chemical processes (nutrients, CO_2, carbonates...)
  - the intimate link between water & life
- The role of the oceans
  - as an active biogeochemical reactor
  - the biggest one on the planet !
  - part of the system controlling atmospheric CO_2
  - the location for about 50% of photosynthetic production
  - the site of the major sinks for carbon (organic & inorganic)

A Brief History of Earth Climate

- The Archaean (up to < 2.5 Gyr BP) seems to have been mostly warm or hot (???) despite the faint young sun (30% less insolation at 4.5 Gyr BP)
- There is evidence for low-latitude (global ???) glaciation at ~2.5 Gyr BP (the Huronian glaciation), and also in the late Precambrian (at ~ 800 Myr BP)
- Since then (i.e. during the Phanerozoic), warm periods (e.g. the Devonian, Cretaceous) have been punctuated by major glaciations (e.g. Permo-Carboniferous, at ca 290 Myr BP)
- The warm periods may be initiated by increased CO_2 due to major episodes of vulcanism (e.g. at end of Permian)...
- ...and are (somewhat) associated with major deposition of carbonate rocks, and thus (perhaps) with high but reducing atmospheric CO_2 levels ...
- ...until low CO_2 causes (triggers ?) another glaciation (???)

Venus, Earth & Mars

- Venus is too hot (460 C)
  - thick atmosphere (90 atmos) : mostly CO_2
- Mars is too cold (-53 C)
  - thin atmosphere (0.006 atmos) : also mostly CO_2
- Earth is just right (15C) [for liquid water, & life]
  - its atmosphere is mostly Nitrogen & **Oxygen**
  - Extraordinary : far from thermodynamic equilibrium
  - the result of planetary engineering (geophysiology)
  - by **plants**, which remove CO_2 & replace by Oxygen

Liquid water on Earth

- Banded Iron deposits
  - are **sedimentary** rocks
- provide evidence for existence of liquid water at the surface from very earliest times (3.8 GyrBP)
  - (c.f. age of Earth ~ 4.5 GyrBP)
  - [NB : much iron implies oxygen was absent]
- Water on Mars ?
  - Subsurface, frozen
- Water on the Moon ???

Evidence for Life on Earth

- Fossil Bacteria in (e.g.) **Gun-flint chert**
  - from 3.5 GyrBP (maybe earlier)
- Nothing but bacteria for ~ 3 Gyr
  - [NB : bacteria are single-celled prokaryotes]
- About 3 GyrBP, **Cyanobacteria** evolved
  - [cyanobacteria = “blue-green algae”]
- the earliest photosynthesisers ??
  - [proper (eukaryotic) plants arose much later]
- [NB : Possibility of ancient life on Mars???
  - Disputed evidence for very peculiar small bacteria]

Reducing & replacing atmospheric CO_2

- The advent of Photosynthesis is **the** crucial event in planetary engineering ...
- Evolved very early (3 Gybp ?)
- Affects atmospheric composition
  - and thus climate (through radiative effects)
  - because water vapour & CO_2 are the major GH gases
- Removes CO_2 , and produces Oxygen
  - which may be vital to the **retention of water**
    - (preventing radiolysis, and escape of hydrogen)
  - and is necessary for multi-cellular life...

Photosynthesis

- uses solar energy
- uses (and reduces) atmospheric Carbon Dioxide
- produces Oxygen (a waste product)
- produces Organic Matter ...
  - e.g. carbohydrates $(CH_2O)_n$ (approx)
- But the whole cycle is reversed by respiration...
- Leads to seasonal cycles of CO_2, O_2, etc
- Has no net effect on atmospheric CO_2, without...

Removal of Carbon

- buried organic material (kerogen)
- may form fossil fuels (coal and oil)
- removes carbon by burial in sediments
  - (for times ~100Myr, characteristic of plate tectonics)
- leaves oxygen in atmosphere “permanently”
- CO_2 also removed as Calcium Carbonate
  - limestones, chalk etc
- this is actually the biggest reservoir of carbon
- but its formation needs Calcium too...

Weathering of crustal (basic silicate) rocks

- Produces calcium : the other essential ingredient for calcium carbonate formation
- done by heat, frost, wind, rain (water)
- accelerated by Carbon Dioxide (carbonic acid)
- produces calcium, bicarbonate and silicic acid
- need to form Calcium Carbonate (Calcite etc)
  - this can be formed by inorganic precipitation
  - but living things do it faster

Calcium Carbonate formation

- $Ca^{++} + 2\ HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$
- and $Ca^{++} + CO_3^{2-} \rightarrow CaCO_3$
- done by
  - planktonic plants (algae, especially coccolithophores)
    - produce Calcium Carbonate tests (coccoliths)
    - form e.g. chalks (especially in Cretaceous)
  - and protozoa (e.g. foraminifera)
    - primitive ("proto") animals
    - form calcareous oozes, e.g. globigerina ooze (G. bulloides)

The Silica Cycle

- silicic acid (H_4SiO_4) is produced by weathering
- and is removed by Opal formation
- this is also done by planktonic plants (diatoms)
  - especially under regions of high biological production (e.g. upwelling areas)
  - accumulation of siliceous oozes
  - producing flints and cherts

Weathering (overall)

- Erosion of basic silicate rocks
- removes Carbon Dioxide from atmosphere
  - without affecting the oxygen level
- produces siliceous deposits, and sedimentary carbonate rocks, including e.g.
  - the White Cliffs of Dover, the Dolomites, and the summit of Mount Everest
  - All of which are marine limestones
- which are subsequently sub-ducted, metamorphosed and melted to produce basic silicate rocks....

Photosynthesis & Weathering

- together have lead to...
- Deposition and burial of organic and inorganic carbon (fossil fuels, limestones etc)
- Reduction of atmospheric Carbon Dioxide
  - 99.7 % of which is now sequestered in rocks
  - 97% of the remainder is in the ocean
- Both these processes need **Water**
- and are carried out (or accelerated by) **Life**

Conclusions (1)

- Earth's atmosphere has been "manufactured", and is maintained by, living things...
  - ... especially by marine planktonic plants
- major variations of CO_2 concentrations have been driven by the interaction of biogeochemical sinks and geological source processes (vulcanism)
- these have had major effects (±20C ?) on climate
- major (Huronian, late Precambrian) glaciations were probably associated with, and possibly partly caused by, low atmospheric CO_2 levels
- So biogeochemistry is important to climate
  - on long (Myr) time-scales, at least

The evolution of the Earth (Geological Eras)

- Archaean (3.6 to ~2.5 Gyr BP)
  - Carbon Dioxide & Methane atmosphere
  - bacteria (including photosynthetic cyanobacteria) only
- Proterozoic (2.5 to 0.7 Gyr BP)
  - elimination of methane (by oxidation)
  - Carbon Dioxide and Oxygen (1%) atmosphere
  - evolution of eukaryotes
    - (by symbiosis of chloroplasts & mitochondria ?)
  - Cells with nuclei → Sex (!) → Accelerated evolution
- Phanerozoic (since 0.7 Gybp : the last 15% of Earth history)
  - The "Cambrian Explosion"
  - Multicellular plants & animals (which need Oxygen)
  - Nitrogen & Oxygen atmosphere (elimination of CO2)
  - reduced Greenhouse Effect : temperature regulation (?)

Primary Production and Nutrients

- Living things need and make proteins, etc, too
- Requires Nitrogen (N) and Phosphorous (P)
- Obtained from nutrients
  - especially nitrate (NO_3^{2-}) and phosphate (PO_4^{3-})
- nutrients are strongly depleted in surface waters
  - by primary production (by algae & cyanobacteria)
- and regenerated (re-mineralised) in deep waters by respiration
  - especially that due to bacterial processes

The Redfield Ratios

- The proportions of bio-chemically active elements in organic material (soft tissue) of marine plankton are rather constant (but not completely so)
- These mean proportions are approximately
  - P:N:C:O:= 1:16:103:172 (Takahashi et al 1985)
- These are known as the **Redfield Ratios**
- Variations occur, due to differing proportions of carbohydrates [$\sim(CH_2O)_n$], lipids [$\sim(CH_2)_n$], proteins, amino acids, etc
- "inorganic" components including calcite [$CaCO_3$] and silica [SiO_2] are also present, in variable proportions, in planktonic "shells" (tests)