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The Earth System

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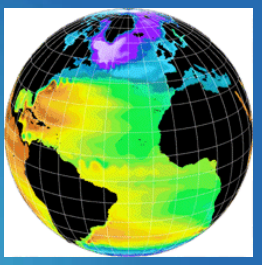
Overview

- The Ocean and Earth System
- The importance of water
  - for a habitable planet
  - the intimate link between water & life
- The Oceans and their effect on the environment
  - the composition of atmosphere
  - climate (from the hot-house to the ice ages)
- Modelling the Earth System

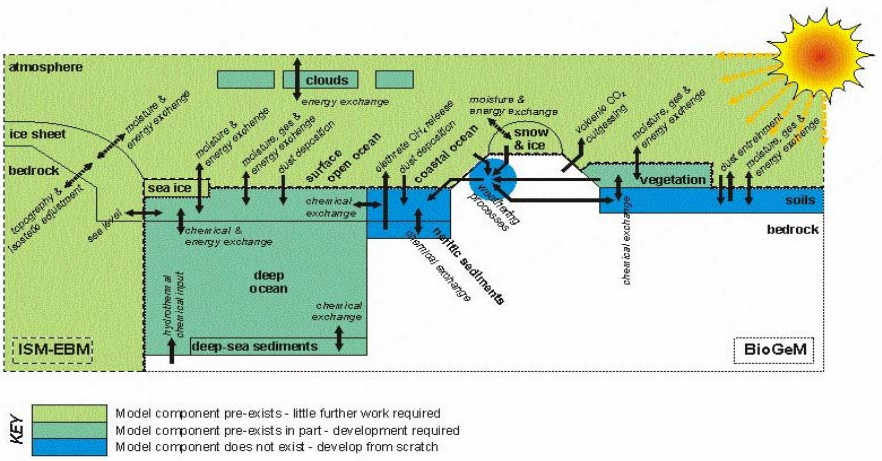
What is the Earth System ?



The Earth System comprises

- ***the solid Earth and the land surface***
- ***the hydrosphere (oceans, rivers & lakes)***
- ***the atmosphere***
- ***the cryosphere (sea-ice, glaciers and the ice caps)***
- ***the biosphere – both terrestrial and marine.***

The Earth System
(according to GENIE)



Slide courtesy of
A. Ridgwell (Genie)

What is Earth System Science?

The components of the Earth system

- ***interact over an enormous range of scales in space and time***
- ***exhibit a range of fascinating phenomena, including***
  - ***the formation and movement of continents***
  - ***the opening and closing of ocean basins***
  - ***the formation and erosion of mountain ranges***
  - ***the waxing and waning of massive ice-sheets***
  - ***the inception and evolution of life***
  - ***climate change on all time scales***

Earth System Science and Modelling seeks to understand and model this system and these processes as a whole.

It is interdisciplinary science - "par excellence"

Essential Earth System Processes

(on land and sea, and in the air)

- Plate tectonics & volcanic activity
- Weathering, erosion, sedimentation
- Biological production, biogeochemistry and the ***carbon cycle***
- Radiation (absorption, reflection, emission...)
- Convection (mantle, atmosphere and ocean)
- Oceanic transport (heat, salt, water, nutrients...)
- Atmospheric transport (heat, water, CO_2, etc)
- Hydrology (evaporation, precipitation, run-off...)
- Ice: accumulation, ablation, transport
- Soils & Sediments (formation & erosion)

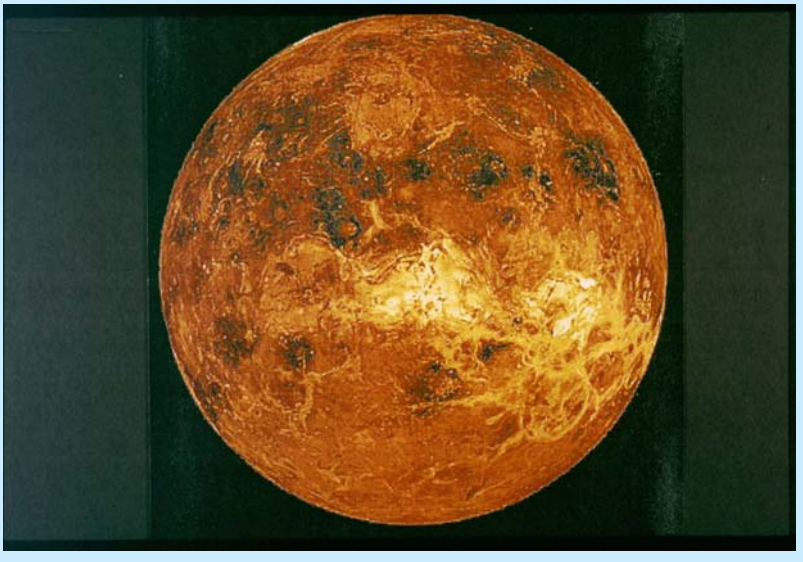
The Oceans

- Are vast (several kilometres deep)
- Contain a vital part of the biosphere
  - the Life Support System of the Planet
- Are little explored, and still not well understood
- Constitute an active biogeochemical reactor
- … the biggest one in the known Universe !!

Earth from Space: the Blue Planet

Venus from Space

Mars from Space



Venus, Earth & Mars : Comparison

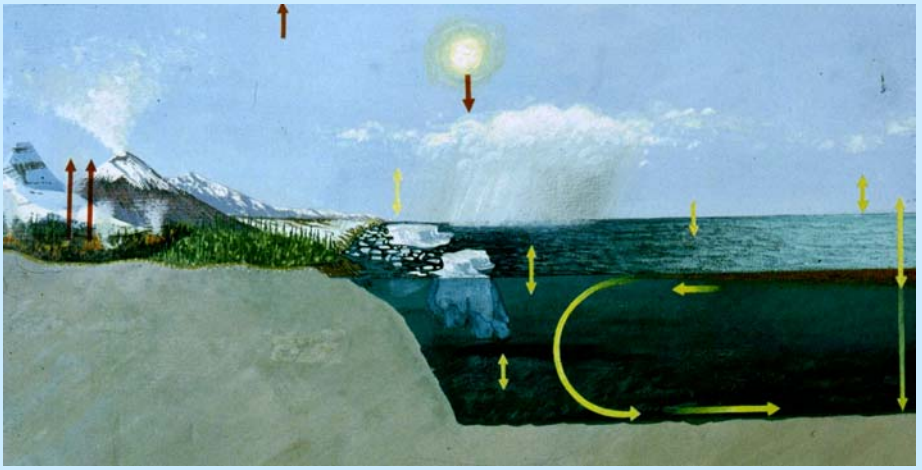
PLANETARY ATMOSPHERES

	Pressure	Atmospheric Composition	Water	Temperature (˚C)
Venus	**90**	**CO_2**	**No**	**460**
Earth	**1**	**$N_2 + O_2$**	**Yes**	**13**
Mars	**0.006**	**CO_2**	**No**	**– 53**

Venus, Earth & Mars : Liquid water and life

- Venus : Too hot (460 C)
  - thick atmosphere (90 bar) : mostly CO_2
  - no liquid water, no oxygen, no life
- Mars : Too cold (-53 C)
  - thin atmosphere (0.006 bar) : mostly CO_2
  - no liquid water (permafrost...), no oxygen, no life
- Earth : Just right !
  - Lots of liquid water
  - Nitrogen & Oxygen in atmosphere
- Planetary engineering, largely by living things…
- The atmosphere: 99.997% of all CO_2 has been removed
- ...some has been replaced by Oxygen
- The processes rely on the presence of water

The Earth & Ocean System
The land surface and the hydrological cycle

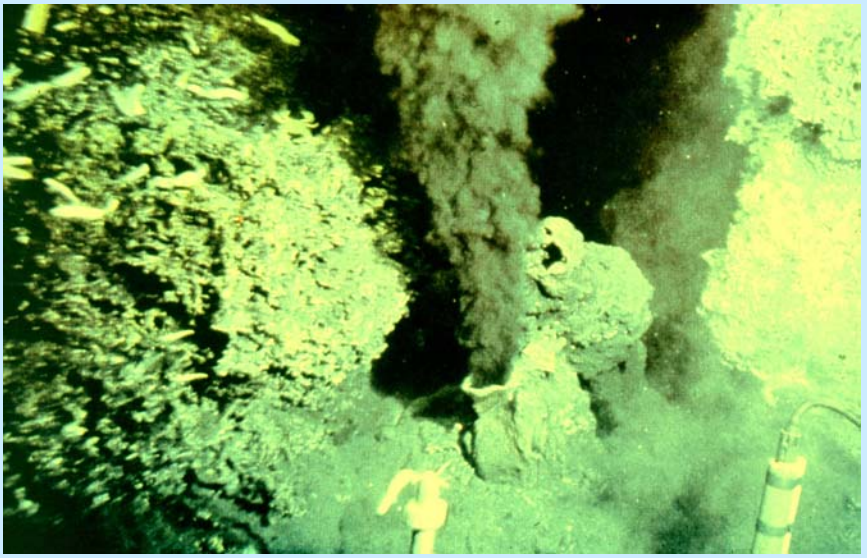


Early evidence of liquid water : Banded iron deposits
(sedimentary rocks) which date from 3.8 Gyr
(cf. age of the Earth ~ 4.5 Gyr)

Early evidence of life (Bacteria)
fossils in the Gun-flint chert from 3.5 Gyr
(and maybe earlier...)

Early biogenic carbonate rocks (Stromatolites)
e.g. at Shark Bay : formed by Bacterial mats

Black Smoker (with animals)
Shrimps, clams, crabs (Atlantic)



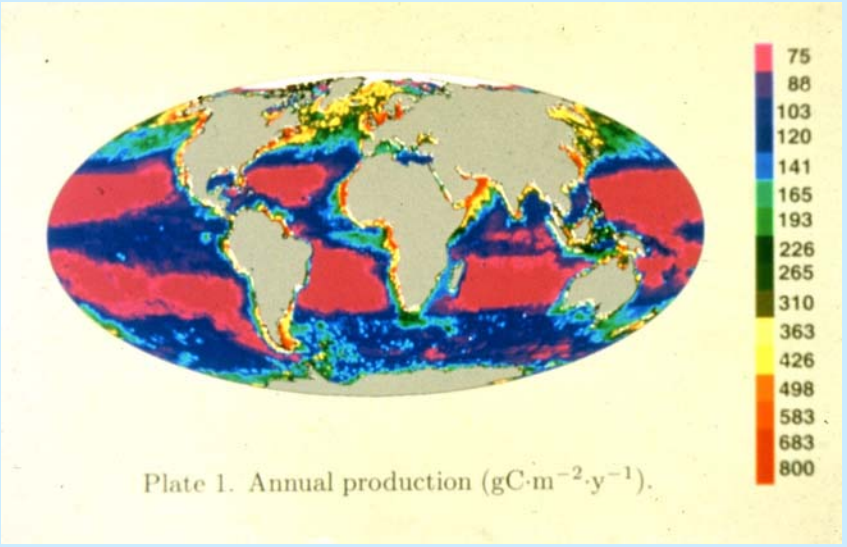
Vent Communities (tube worms in the Pacific)
Use Symbiosis with Chemosynthetic bacteria
Ecosystems which are independent of sunlight...

Conversion of CO_2 to Oxygen, by Photosynthesis

- The evolution of organisms able to **photosynthesise** also occurred early
  - maybe even before 3 Gybp ?
- This is probably **the** crucial event in the history of the Earth
  - because it transformed the composition of the atmosphere
  - by using CO_2 , and producing ***Oxygen***
- which is vital to the ***retention of water***

Cyanobacteria (a.k.a."blue-green algae") were the earliest photosynthesisers

Satellite colour image of Photosynthesis (chlorophyll) produced by marine planktonic plants : roughly the same primary production as on land



Photosynthesis (schematic)

Carbon Dioxide + Water

CO_2 + H_2O + Energy

Photosynthesis ↓ ↑ Respiration / Consumption

H–C–OH + O_2

Carbohydrates + Oxygen

Photosynthesis is important because...

- It utilises solar energy
- and reduces atmospheric Carbon Dioxide
- It produces Oxygen (as a waste product...)
- and this has two important effects...
  - It binds Hydrogen in the upper atmosphere (and so prevents the loss of water...)
  - It produces Organic Matter (high in Carbon, and low in Oxygen) of which some is buried...

Formation of fossil fuels

Coal is formed from land plants

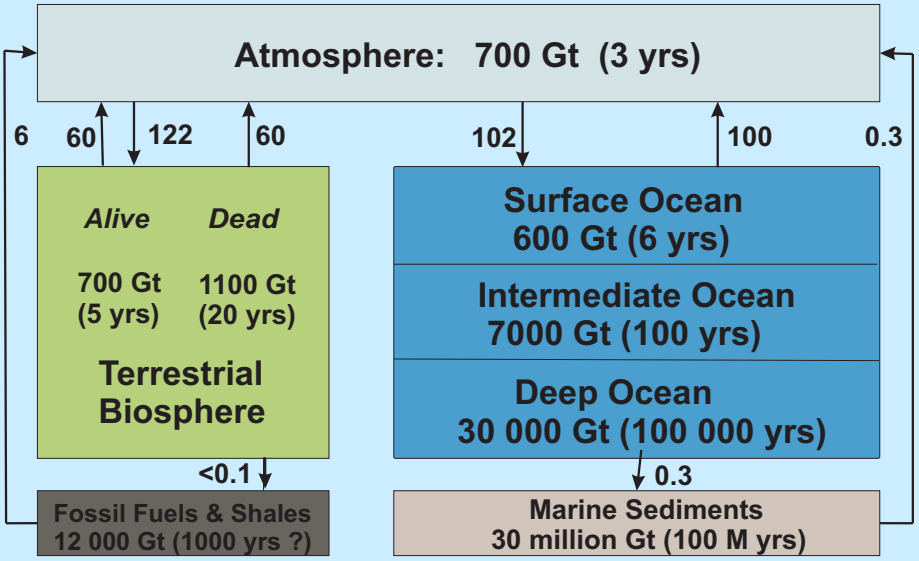
- burial of organic carbon in sediments
- removes Carbon "permanently" (~100 Myr)
- but burning fossil fuels reverses the process
- ... rapidly (~1000 yrs) !

Hydrocarbon Resources are also due to burial of Organic Carbon (kerogen) in sediments.
Oil is formed mainly from marine plant plankton

Total fossil fuel resources amount to about 10,000 Gt(C)... (~0.03% of the total in limestone sediments)

The Global Carbon Cycle

The Carbon Cycle : Inventories, fluxes & residence times



Carbon is also removed as Calcium Carbonate ultimately forming Limestone cliffs

- Limestones are globally the largest reservoir of Carbon
- The formation of calcium carbonate also needs Calcium...

Calcium is produced by ***weathering*** of crustal silicate rocks

Calcium is the other essential ingredient required for Carbon Dioxide removal from the atmosphere

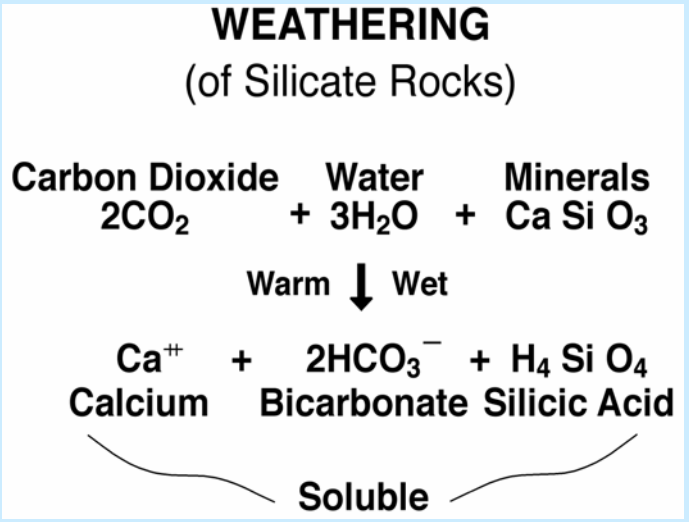
Weathering

- is done by ***water...***
- accelerated by Carbon Dioxide (Carbonic acid)
- produces calcium, bicarbonate and silicic acid

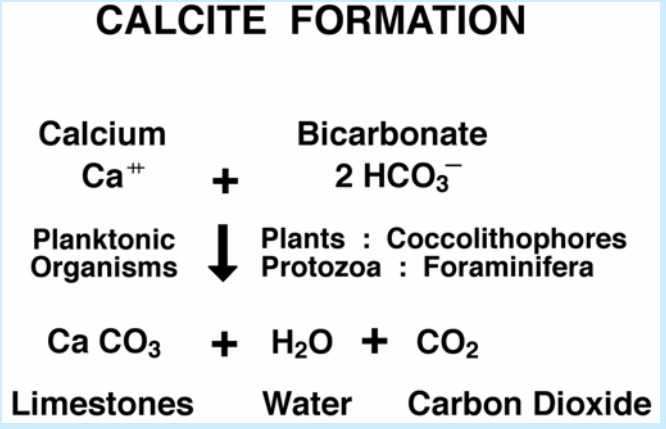
Calcium Carbonate (Calcite, Aragonite, etc)

- can be formed by inorganic precipitation
- but living things do it ***faster*** (even though most surface waters are over-saturated w.r.t. $CaCO_3$)

Weathering (schematic)

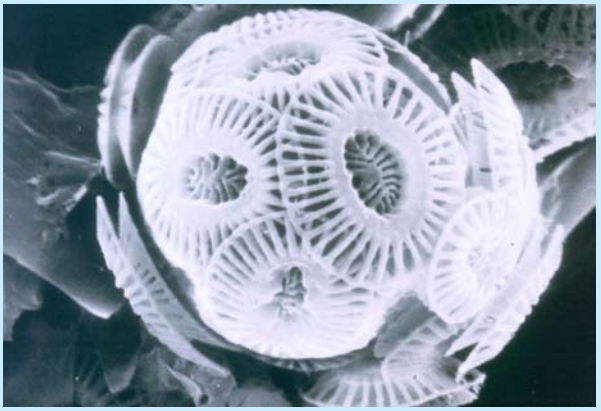


Formation of calcium carbonate (schematic)



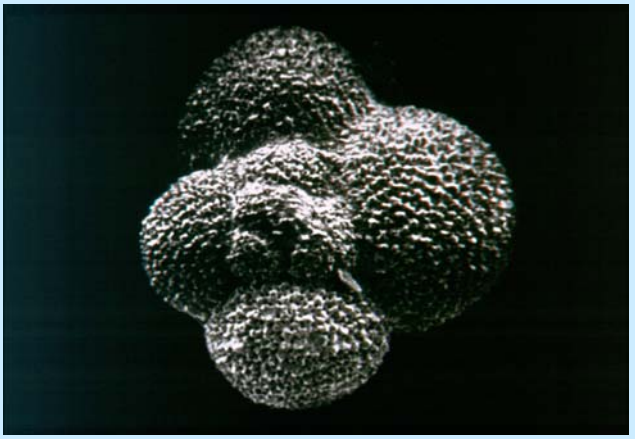
- This process uses calcium and bicarbonate ions
- and ***releases*** CO_2
- It is carried out mainly by planktonic plants (and protozoa)

Coccolithophores
(e.g. Emiliana huxleyi)



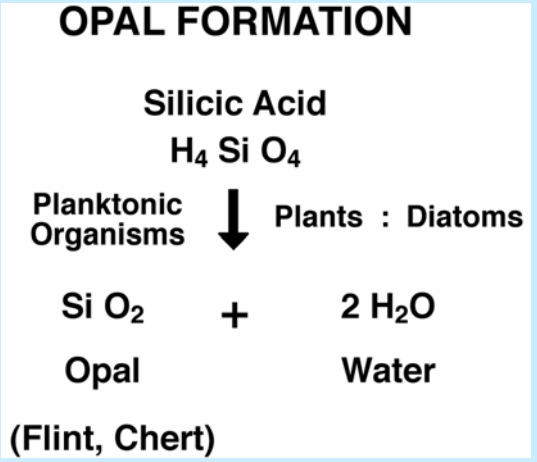
- planktonic plants (algae)
- use photosynthesis
- produce Calcium Carbonate tests (coccoliths)

Foraminifera



- protozoa (a.k.a. protists : “prototype animals”)
- also produce Calcium Carbonate shells
- form calcareous oozes (e.g. Globigerina bulloides)

Opal formation (schematic)



- uses soluble silicic acid to form insoluble silica
- this is also done by planktonic plants (e.g. diatoms)

Diatoms

- planktonic plants
- use photosynthesis
- produce silica (opal)
- => siliceous ooze
- => flint & chert

Weathering

OVERALL

Weathering of Crustal Rocks

$$CO_2 + Ca\,Si\,O_3$$

Water ↓ **Biology**

$$Ca\,CO_3 + Si\,O_2$$

leads to

Deposition of Sedimentary Rocks

and

Removal of Carbon Dioxide

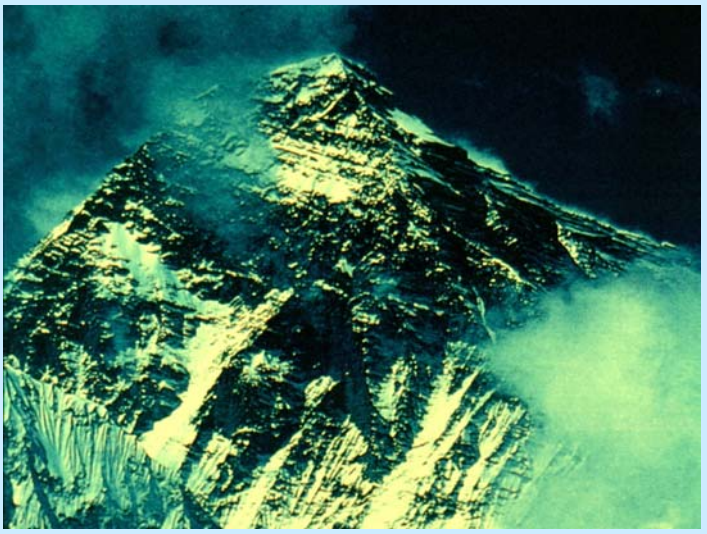
"Les Calanques"

- Eroded granites (Corsica)
- Weathering of these enables...

The formation of Limestones :
e.g. the White Cliffs of Dover

The Dolomite Alps (Italy)

Mount Everest



The summit rocks are also marine limestones

Photosynthesis & Weathering *together* lead to

- Deposition of limestones
- Reduction of atmospheric Carbon Dioxide
  - **99.9%** is now held in sedimentary rocks
  - (and **97%** of the rest is in the oceans)
  - so only **0.003%** remains in the atmosphere
- Both these processes need **Water** and **Life**

The vital processes for planetary engineering (terra-forming)

- ♦ Photosynthesis & Weathering
  - Reduction of Carbon Dioxide
  - Reduced Greenhouse effect
- ♦ Photosynthesis & burial of Organic Carbon
  - Production of atmospheric Oxygen
  - Reduced loss of water (hydrogen) to space
  - ***Multicellular*** plants and animals
  - (bodies, organs, shells, skeletons, motion...)

Closing the loop : Subduction

- ♦ Marine deposition (sedimentary rocks)
  - Especially carbonates
- ♦ terrestrial erosion
  - Silicates and carbonates
- ♦ cycle closed by mountain building and subduction (plate tectonics)
- ♦ timescale >100 Myr

Conclusion

The atmosphere, the climate and the environment of the Earth have been“manufactured”

over geological time

by living things

(especially marine planktonic plants)

and they are still maintained by them

(N.B. “ecosystem services”)