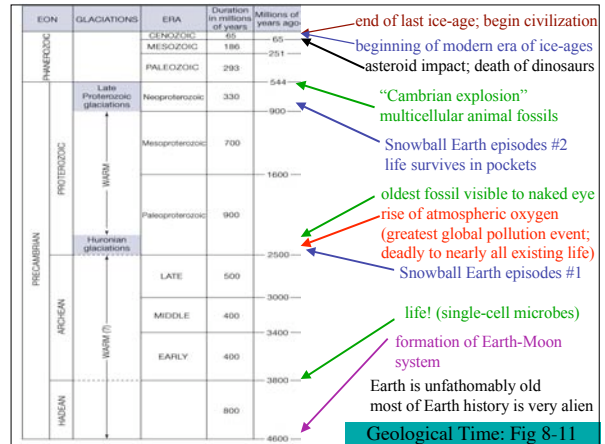


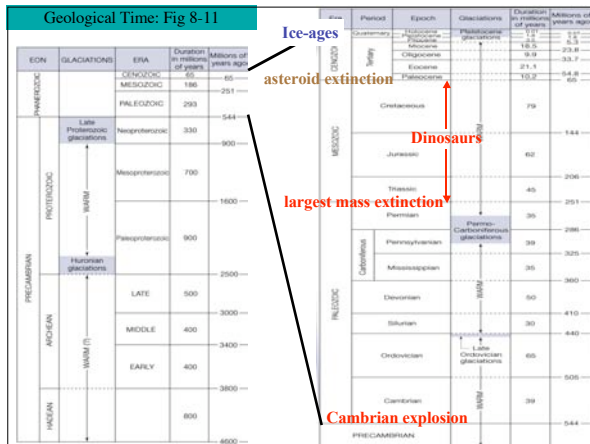
Lecture 20

Origin of the atmosphere (Chap. 10)

The carbon cycle and long-term climate (Chap. 8 of the textbook: p.158-170)



Geological Time: Fig 8-11



Origin of Earth's atmosphere & ocean

The early atmosphere came from **outgassing** (release of gases from the solid Earth) and **impact degassing** (release of gases when ice-rich asteroids hit)

Volcanoes give out mostly water and CO₂, with relatively small quantities of H₂, CO, and CH₄, and no O₂.

Before the Earth's iron core formed, during 4.5-4.4 Ga, Earth's atmosphere may have contained a considerable proportion of H₂ and other **reducing** gases (those that would tend to react with oxygen, were it present).

(a)

H₂, CH₄, NH₃

FeO, silicates and Fe

(b)

H₂O, CO₂, H₂, minor H₂, CO

Fe₂O₃, FeO and silicate minerals

Fe core

The reduced to oxidized gas ratio (H₂/H₂O, CH₄/CO₂, etc.) in volcanic gases, in particular, depends on the degree of oxidation in the upper mantle, the source region for such gases.

(a) before (b) after core formation

The Hadean climate: Poorly known

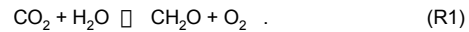
The atmosphere in the Hadean (4.5-3.8 Ga) can only be guessed at using theory -- we have hardly any rock data from this time

Nitrogen would be delivered to Earth in nitrogen-containing organic compounds that we find in some meteorites or as ammonia (NH₃) ice. In either case, impact degassing converts it to N₂. We expect about 0.8 bar N₂ in the Hadean atmosphere, as today.

Carbon would be delivered in organic compounds too. But it tends to get oxidized to CO₂. How much CO₂ there was is not known. It seems likely that CO₂ would react rapidly with the seafloor. This presents the conundrum that Earth may have had so little CO₂ in the atmosphere at this time (when the Sun was fainter) that Hadean Earth could have been frozen.

Carbonate-silicate cycle

Over geologic time, CO₂ is controlled by the carbon cycle, which has several different parts. The familiar part is the **organic carbon cycle**, in which plants (and many microbes) convert CO₂ and H₂O into organic matter and O₂ by photosynthesis. Organic matter has average stoichiometry "CH₂O", so the reaction for (oxygenic) photosynthesis can be written as



Respiration and decay reverse R1 (photosynthesis)

Organic cycle - not a long-term control

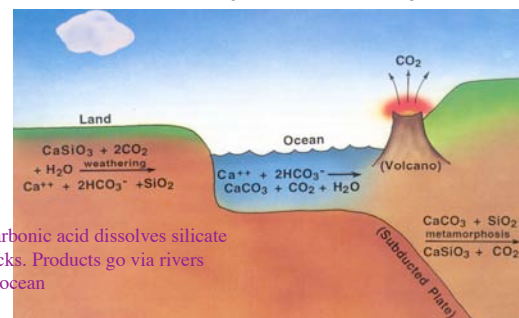
The organic carbon cycle cannot be the primary control on CO₂ levels over long time scales.

CO₂ is continually input from volcanoes. To draw down CO₂ over geological time via the biosphere would require that much organic carbon leak out at somehow.

An imbalance that does occur when organic carbon is buried in sediments cannot be maintained at large levels for long because it is controlled by a negative feedback loop involving atmospheric O₂. Basically an increase in organic carbon burial causes an increase in O₂, which in turn causes a decrease in organic carbon burial. This cycle is controlled by oxygen rather than by climate,

Inorganic cycle - a viable long-term control

The part of the carbon cycle most important to long-term climate is the **inorganic carbon cycle**, sometimes called the **carbonate-silicate cycle**. (below - like Fig 8-17)



Inorganic cycle - a long-term negative feedback

- 1) CO₂ gets removed into calcium carbonate on the seafloor
- 2) CaCO₃ gets subducted
- 3) CO₂ gets released back into the atmosphere by thermal decomposition of CaCO₃

Timescale = 0.5 million years to replenish & recycle the CO₂

Thought experiment: What would happen if the Earth froze over?

- 1) Hydrological cycle shuts down. No weathering of surface rocks.
- 2) Volcanic activity continues unabated
- 3) Eventually the CO₂ greenhouse effect would melt the ice. (Estimated to take 0.3 bars CO₂, which builds up in 10 m.y.)

Negative feedback

Weathering rate depends on temperature directly (chemical kinetics) and indirectly through the amount of rainfall.

[Qu.] Why should rainfall depend on temperature?

The rate of silicate weathering slows down as Earth's surface becomes colder. Because CO₂ is being extracted at a lower rate, this allows CO₂ to accumulate and Earth to warm up again.

This maintains an equable climate over timescales of ~10⁶ years.

Qu.) Why is this feedback irrelevant for anthropogenic global warming?

Failure of climate stabilization on Venus & Mars

Venus has a mean surface temperature of about 460°C, while Mars' mean temperature is about -55°C.

Venus was close enough to the Sun that it lost its water by the process of photodissociation followed by escape of hydrogen to space. Once water was lost, silicate weathering could not occur, so volcanic CO₂ accumulated.

Mars formed farther from the Sun, so that a stronger atmospheric greenhouse effect would have been needed to warm its surface. It can be shown that CO₂ and H₂O by themselves could not have kept Mars warm early in its history when the Sun was less bright. However, Mars had another serious problem: Mars is only ~1/9th of Earth's mass. Thus, its interior cooled more rapidly than Earth's, and widespread volcanism ceased a long time ago. Without volcanism, there was no mechanism for recycling CO₂, so CO₂ should have accumulated in the crust as carbonate or on the surface as CO₂ ice. However, the early Martian atmosphere (because of low Martian gravity) was cumulatively blasted away to space by comet or asteroid impacts.

Mars shows that size matters: A small, geologically inactive planet can neither develop a stable climate nor hold on to its atmosphere.

What makes a good planet go bad?

Venus
(runaway
greenhouse)

Earth
("just right")

Mars
(virtually no
greenhouse)



- Oceans boiled away
- No more weathering
- Carbon partitions to atmosphere
- CO₂ is ~245,000 times that on Earth
T_s = 460 C

- has oceans
- hydrological cycle
- weathering returns CO₂ to lithosphere
- plate tectonics (volcanoes) return carbon to atmos.
- negative feedback

- farther from Sun; too cold for liquid water
- no water vapor greenhouse
- too small for plate tectonics
- no carbon cycle
- CO₂ is ~16 times Earth
T_s = -55C