11. Co-evolution of atmosphere and life

I. Intro
   A. Earth is the only planet in the solar system that has life
   B. Earth has a variety of other unique features
      1. active plate tectonics
      2. O_2 in atmosphere/oxidizing sfc.
      3. rel. low atmos. CO_2
      4. liquid water/moderate temperatures
      5. “organizational” surface structures
   C. what role (if any) does life play here?
   D. begin by looking at the atmosphere
   E. evolution of life and the atmosphere are strongly linked
   F. provides strong evidence for how life processes may have affected the global environment

II. Early earth history **mod. Fig. 10-1**
   A. Hadean - early part of earth’s history
      1. crust initially too unstable for life
      2. more stable crustal features begin to form (eg, oceans)
      3. zircon data suggest the timing of this stabilization was shorter than once thought
   B. Archean
      1. life evolves, atmosphere begins to change
      2. major metabolic patterns/processes evolved
         a. evolution of biogeochemical cycles

III. Initial atmosphere
   A. scientists once thought that the early atmosphere was highly reducing
      1. dominated by methane and ammonia
      2. not likely
         a. photochemical destruction would keep their conc. low
      3. early origin of life studies used such an atmosphere
         a. causes some problems in interpreting these results
         b. reducing gasses may have been more prevalent in localized environments
   B. dominant gasses in Hadean atmos were most likely N_2, CO_2, and CO **Table 1.1**
      1. CO_2 may not have been as high into the Archaen
   C. only trace quantities of methane and ammonia
      1. likely produced by rxns. between seawater and volcanic rocks
      2. photochemical destruction would keep their conc. low
      3. some H_2 production from rxns. between basalts and water
   D. contained no appreciable free oxygen

IV. Origin of life
   A. life as we know it requires 2 things
      1. liquid water
      2. organic polymers (nucleic acids, proteins, etc.)

3. these requirements constrain the origin of life **Fig. 10.1**
    a. early Earth's too unstable during accretionary period of the Hadean
    b. onset of weathering and evolution of oceans implies running water

B. several possible sources of precursors to early biological polymers
1. likely required non-biological synthesis of carbon compounds
    a. simple amino acids, sugars, etc.
2. origin of life expts.
    a. lab expts. to simulate conditions on the early earth
        (i) water, gasses in ancient atmosphere, energy source
3. Miller-Urey expts. (1953) **show photo**
4. these expts. show that this type of pre-biotic synthesis is possible
5. other mechanisms/sources
    a. cabonaceous chondrities
        (i) meteorites - contain OM which apparently formed abiotically in space
6. ultimately require some energy source to fix carbon

C. next require the ability to polymerize these simple compounds **Fig. From Bada**
1. unclear
2. structure of clay minerals may have served as templates (catalysis) for the polymerization of OM into organisms
3. increasing evidence for the role of hydrothermal vents
    a. source of reduced materials needed to make reduced carbon compounds
    b. iron sulfide surfaces may have been important catalytic sites for polymerization

D. the next step involves polymers becoming more stable
1. evolution of molecules capable of catalyzing simple self-replication
2. origin of "life"

E. evolution then continues through the RNA-world and eventually the "modern" DNA world
1. see Bada article for a nice review

V. Life originates sometime around ~3.5 – 3.8 bybp **mod Fig. 10-1**

C. definite evidence back to 3.5, less definitive evidence back to 3.8 **show pictures**

D. several types of evidence
1. microfossils - spherical carbon-containing structures indicative of prokaryotic cells
2. stable carbon isotopes (somewhat controversial)
3. stromatolites **show my stromatolite picture**
    a. layered sed. mats of calc. carbonate and org. matter
        (i) bulbous mats form cm's to meters across
    b. ppts. grow into mounds and sometimes into large reef-like structure
    c. presently formed when mats of cyanobacteria ppt. calcite as a by-product of photosynthesis
    d. common today in hypersaline environs. where high salt excludes cyano predators
    e. in ancient times stromatolites formed in shallow seas

E. first organisms were likely Archaea **show Fig. 10.8**
1. original organisms were anaerobes
2. obtain energy by oxidizing OM
3. hyperthermophiles also likely important

a. blue line at the root of the tree

F. methanogens also likely to be early organisms
1. $CO_2 + H_2$ -> $CH_4 + H_2O$
2. this process is quite “ancient”
3. methane production may have been important in controlling Earth’s early climate as CO_2 levels decreased
    a. methane is a greenhouse gas
    b. more later

VI. Evolution of photosynthesis

C. next major evolutionary event affecting Earth
1. thought to have occurred 3 - 3.5 bybp perhaps earlier **Fig. 6.7**
2. associated with photosynthetic organisms that formed ancient stromatolites

D. anoxygenic photosynthesis **show equations with picture**
1. $2H_2S + CO_2$ -> $(CH_2O) + 2S° + H_2O$
2. $2S° + 3CO_2 + 5H_2O$ -> $3(CH_2O) + 2SO_4^{2-} + 4H^+$
3. use solar energy to oxidize sulfide/sulfur and make OM
4. process still occurs today
    a. purple and green sulfur bacteria
    b. obligate anaerobes

E. evolution of oxygenic photosynthesis
1. likely occurred by the substitution of water for H_2S
2. water more plentiful than H_2S
3. process is also more energetically efficient
4. $CO_2 + H_2O$ -> $CH_2O + O_2$
5. at least 2.7 bybp **back to Fig. 6.7**

VII. With the evolution of photosynthesis you have the origin of a complete biological C cycle

C. biological prdn and cons. of C **my figure**
1. use C to transfer solar energy into a simple food chain
2. effectively allows transfer of solar energy into a food chain/biogeochemical cycle
3. no net build-up of reduced or oxidized forms of these elements

D. evolution of sulfate reduction also important
1. complete cycle that recycles this inorganic constituent
2. sulfate reduction also appears to be quite ancient
3. prob not important until later – 2.7 bybp (?)
4. sulfate levels were low in the Archaen
    a. required time for sulfate to reach sufficient levels in seawater
    b. anoxygenic photosynthesis
    c. sulfide oxidation by O_2 production

E. similar factors likely important in the evolution of the N cycle
1. require complete cycle to ensure that all N doesn’t end up in one pool
2. N fixation w/o denitrification would deplete atmospheric N_2 in several million years

VIII. Oxygen in the early atmosphere (Hadean and early Archean)

A. small amounts of oxygen produced by photolysis and perhaps early oxic photosynthesis
B. photodissociation of water vapor to produce O_2 (H_2O + hv -> H_2 + O_2)
   1. much of the H_2 lost to space
C. under some circumstances photolysis could eventually lead to the loss of all water
   1. dead oxidized planet
   2. e.g., Venus – more later
D. retention of water on Earth is related to sequestering of atmos. CO_2 early in the Earth's history
   1. important for the evolution of a habitable planet.

IX. biological O_2 production began at least ~2.7 bybp **Fig. 5-12**

A. oxygen does not accumulate in the atmosphere until ~2.3 bybp
B. reason for this ~400 my delay in O_2 accumulation not well understood
C. requires a change in the relat. between sources and sinks
   1. if sinks > sources then O_2 does not accumulate
      a. sinks consume all O_2 that is produced
   2. once sources > sinks, leads to accumulation
      a. sinks decreased with time (sources constant)
      b. sources increased with time
D. most O_2 initially produced early in the Archean consumed by oxidation of reduced substances on the Earth's surface
   1. reduced iron and sulfur, reduced mantle components and gasses
      a. not well-constrained
   2. large O_2 sinks early on
   3. swamp out oxygen sources
   4. leads to no net accumulation at first
E. likely that O_2 production by photosyn also increased over time during this period

X. Evolution of oxygen in rock record **next mod Fig. 10-1**

A. rock record suggests that free O_2 did not accumulate until ~2.3 bybp
   1. need sources > sinks to get net accumulation
B. what is the geologic evidence for when the rise in atmos O_2 began
C. banded iron formations (BIFs)
   1. alternating layers of silica and iron-rich minerals (Fe(II) and Fe(III) oxides)
      a. almost all found prior to 1.9 bybp
   2. source of oxygen not well-understood
      a. photosynthesis is one possibility
      b. photoxidation of iron is also a possibility
   3. can't be used to directly infer the O_2 content of the atmosphere
   4. can be taken as evidence of a changing atmosphere
D. detrital uraninite and pyrite
   1. reduced minerals that are generally oxidized during weathering
   2. disappear around 2.2 bybp
   3. consistent with the rise of atmos. O_2

4. only set a lower limit for atmos. O_2 at the time of their disappearance
    a. need 10^{-3} bars or 0.005 PAL to oxidize these minerals
5. atmos. O_2 must have crossed this threshold around the time of their disappearance

E. paleosols and redbeds
    1. paleosols (ancient soils)
        a. iron content of palesols suggest that before 2.2 bybp atmos. O_2 was < 0.01 PAL and after 1.9 bybp was > 0.15 PAL
    2. redbeds
        a. sandy sediments primarily containing hematite (Fe_2O_3) other iron oxide deposits
        b. iron more oxidized than in BIFs
        c. requires higher oxygen levels than that for BIFs
        d. earliest redbeds found ~2.2 bybp
        e. formation of redbeds consistent with the appearance of O_2 in the atmos. at this time

F. Sulfur isotope ratios
    1. pattern of of sulfur isotope fractionation changes at ~2.3-2.45 bybp **Fig. 11-13**
    2. Phanerozoic (> 540 mybp) samples show mass dependent fractionation
        a. fall on the $\Delta^{33}S = 0$ line in this figure
        b. fractionation follows well-defined and predicted mass-dependent fractionation
        c. this fractionation extends back to ~2 bybp
    3. samples older than ~2.45 bybp show mass-independent fractionation
        a. fall off the line
    4. change from mass independent to mass dependent fractionation related to presence of atmos O_2
    5. mass independent fractionation can only occur in atmosphere
        a. rxns. in aqueous or solid phases are mass dependent
    6. when O_2 is present all atmos S is oxidized to sulfate before it is lost by deposition (rainfall) **first Fig. 11-14**
        a. sulfur cycling in the atmosphere leads to no isotopic fractionation
        b. fractionation that is ultimately preserved in the sediments has to be mass dependent
    7. when O_2 is absent or low, sulfur cycling is more complex (can go in both directions)
        a. S can leave the atmos in a number of different forms **2nd Fig. 11-14**
        b. any mass independent fractionation that occurs in the atmos therefore has the potential to be preserved in the sediment record.
        c. modeling suggests that O_2 needs to be at least 10^{-5} PAL for this to occur.

XI. All observations suggest rapid rise in atmos O_2 did not occur until ~2.3-2.4 bybp
    A. GOE – great oxidation event **Figs. 5-12**
    B. Later increase in O_2 was more gradual
    C. likely well below PAL until Cambrian
    D. also likely varied since then

XII. Evolution of ozone
    A. the accumulation of free O_2 in the atmos also led to the accumulation of ozone

1. ozone in the atmos is important in filtering out UV irradiation **show O_3 slide**
2. catalytic cycles produce and consume ozone in the atmos.
3. attenuates solar energy flux between ~180-320 nm

B. even a small amt of atmos oxygen leads to enough ozone to provide some protection
1. partial screen likely to have formed ~1.9 bybp **Fig. 11-16**
2. presence of this UV filter allowed life to move out of the oceans and onto land
3. consistent with the timing of the evolution of eukaryotes and other higher plants

XIII. Changes in CO_2 with time and paradox of the faint young sun paradox

A. initial sun was likely ~75% as bright as it is today **Fig. 12-2**
1. this solar luminosity and the present atmos would have led to a frozen earth until ~1.9 bybp
2. ancient metamorphosed sediments back to 3.8 bybp imply running water
   a. zircon data pushes it back farther

B. suggests that there had to have been a "super-greenhouse" to keep temperatures warm
1. CO_2 and methane likely candidates

C. CO_2 likely initially important but methane may have become increasingly important in the Archean after life forms
1. methane production likely increased once life formed
   a. production by methanogens larger than abiotic production (serpentization)
   b. could have been 1000 ppm or more
   c. oxidation by O_2 not significant
2. siderite content of late Archean paleosols
   a. sets an upper limit for atmos CO_2 **Fig. 12-4**
   b. combined with the freezing point of water, this constrains the atmospheric gas content to the upper left portion of this figure - **click**
   c. suggests that CO_2 levels could have dropped significantly by the late Archean
   (i) for comparison present day CO_2 is 0.0002 - 0.0004 bar
   d. methane and CO_2 possibly of equal importance as atmospheric components that led to the needed super-greenhouse

D. Why would CO_2 have dropped
1. weathering, calcium carbonate precipitation and origin of life would all have removed CO_2 from the Archean atmosphere **Fig. 10-1**
   a. amount of carbon in sed rocks as OM and calcium carbonate may have been fairly close to its present day value by the late Archean
2. active plate tectonics as we know it does not start until early Proterozoic
   a. don't have a "complete" carbonate-silicate cycle **mod C-S cycle figure**
   b. effective CO_2 removal from the atmosphere without as efficient replacement

E. Archean methane production has the potential to develop a positive feedback loop affecting global temperatures **Fig. 12-5 then 12-6**
1. high methane also leads to an anti-greenhouse effect
   a. avoids runaway temperatures

F. all of this then leads to some interesting feedback mechanisms involving atmos CO_2 and methane and Archean climate control
1. because methane prdn. is largely biologically-driven, climate control could have been quite "Gaian" in nature

G. a variety of factors in the late Archean likely led to a breakdown in this type of climate control **next Fig. 10.1**
   1. evolution of oxygenic photosynthesis enhances oxidation of methane by O_2
   2. other factors may have contributed to a decrease in methane prdn. at this time
   3. low methane and CO_2 then lead to a decrease in the greenhouse effect
   4. this then coincides the first documented glaciation on Earth
      a. Huronian glaciation **Fig. 12-11**
   5. development of plate tectonics then "completes" the carbonate-silicate cycle
      a. allows for long-term climate regulation by CO_2 **show C-S fig**
      b. rebound from this global glaciation event

H. With low methane levels the ability to control CO_2 has played the key role in maintaining habitable conditions in spite of increasing solar luminosity
   1. interest in understanding the rel. role of geochemical vs. biological processes in maintaining this level of atmos. CO_2
   2. how these different feedback mechanisms work

I. Long-term climate regulation **2nd Fig. 12-11**
   1. climate stabilization broke down at beginning and end of Proterozoic
      a. Huronian glaciation
      b. Neoproterozoic Snowball Earth
         (i) entire oceans may have been frozen
   2. Phanerozoic oscillated between hot houses and cold houses
      a. long-term carbonate-silicate cycle modulated by other factors
         (i) biological processes and organic C burial
         (ii) changes in tectonic activity
         (iii) periods of rapid seafloor spreading – high CO_2
         (iv) spreading rates slows down - low CO_2 and deeper ocean basins
      b. cooling in the mid-Cenozoic may be related to changes in weathering rates
         (i) more later

XIV. Later evolution

A. O_2 in atmosphere allowed evolution of more complex organisms
   1. eukaryotes, plants, animals

B. mass extinction events also important in the evolutionary process
   1. several major mass extinction events
   2. end of Permian
   3. end of Cretaceous
   4. caused by a variety of factors
   5. biological, geological, extra-terrestrial
   6. Cretaceous-Tertiary
      a. extinction of dinosaours
      b. allowed for the evolution of mammals
      c. may have been caused by a meteor impact

XV. The role of life processes in modern day global cycles/processes

A. present day controls on O_2 in atmosphere
   1. evolution of life has led to an oxidizing environ. on the Earth's sfc

2. present day oxygen level controlled by a balance between photosynthesis and carbon burial
    a. $CO_2 + H_2O \iff CH_2O + O_2$
3. bury OM in sediments leave O_2 in atmos.
    a. Carboniferous period **Fig. 11-20 and 12-11**
4. clearly more complex – discussions in book
5. other feedback mechanisms help maintain O_2 and CO_2 within certain limits and control large-scale excursions
    a. more later

B. can think of the earth as having a reducing core and an oxidizing crust
1. without the external forcing of continued photosynthesis this could not exist
2. life harvests solar energy and uses it to maintain this disequilibrium
3. ability of life to sequester this input of solar energy very important

XVI. liquid water/moderate temp.

A. provides the medium for geochemical cycles
1. cycles elements that are needed for life
2. also implies a reasonable ambient temp. on the planet
    a. not a runaway greenhouse like Venus

B. may be related to the ability of the Earth system to initially sequester atmos. CO_2 in crustal rocks
1. development of feedback loops that control CO_2
2. other greenhouse gases of some importance
    a. methane and N_2O
    b. these are also produced by anoxic microbial processes
        (i) methanogenesis and denitrification

C. as the earth evolved from an anoxic to oxic environ. the cycles of these gasses also prob. played a role in fine-tuning climate regulation

XVII. Run-away greenhouse on Venus

A. similar size, density & K/U ratio (defines internal heat flow)
1. probably started out with similar amounts of water and similar amounts of CO_2
2. however on Earth most CO_2 is locked up as limestone and sed. org. matter
    a. on Venus it has remained in the atmosphere
    b. as a result sfc. temps of Venus much hotter
        (i) >400°C

B. on Earth the IR flux/temp feedback is an important negative feedback that controls climate **Fig. 3-22**

C. early in the history of Venus the breakdown in the IR flux/temp feedback was critical
1. feedback can break down if atmos contains too much water **Fig. 5-3**
2. if you never hit the water vapor line it never rains
    a. atmosphere continues to gain water
    b. greenhouse effect continually increases
    c. increasing sfc. temp does not lead to an enhanced IR flux at the top of the atmos
    d. traps heat more effectively – **show Fig. 19-2**
3. this may have happened on Venus during early history **show Archer figure**
    a. closer to Sun

   b. solar flux greater than that to present-day Earth – even when sun was dimmer 4.6 bybp

D. atmos becomes warm and full of water vapor
   1. negative feedback breaks down
      a. get out of control "runaway greenhouse" **show 2nd Archer figure (w/anim)**

E. photolysis in upper atmos. led to loss of water
   1. H_2 lost to space, O_2 reacts with reduced iron in crustal material or with reduced gasses in atmos.
   2. atmos. on Venus now only has traces of water

F. lack of water then inhibits silicate weathering and volcanic CO_2 accumulates
   1. volcanic sulfur gasses also accumulate as sulfuric acid
   2. hot dry planet with a thick CO_2 rich atmosphere

XVIII. Mars follows a different path

A. smaller solar flux means it starts colder
   1. CO_2 condenses out

B. small size means a smaller radioactive heat source
   1. shuts down carbonate-silicate cycle

XIX. On Earth the retention of water and trapping of CO_2 in the crust avoided a "runaway greenhouse"

A. leads to a rapid decrease in atmos. CO_2 during the Archaen
   1. ppt. of $CaCO_3$
   2. org. matter formation

B. what role does life play in all of this