CLIM-111/PHYS-111

Intro to the Fundamentals of Atmospheric Science

Lecture Notes #2 - Part 2: The Earth System

The Earth Now:

- The Oceans
- The Atmosphere
- The Surface/Crust
- The Biosphere
- Biogeochemical Cycles

How the Earth Evolved:

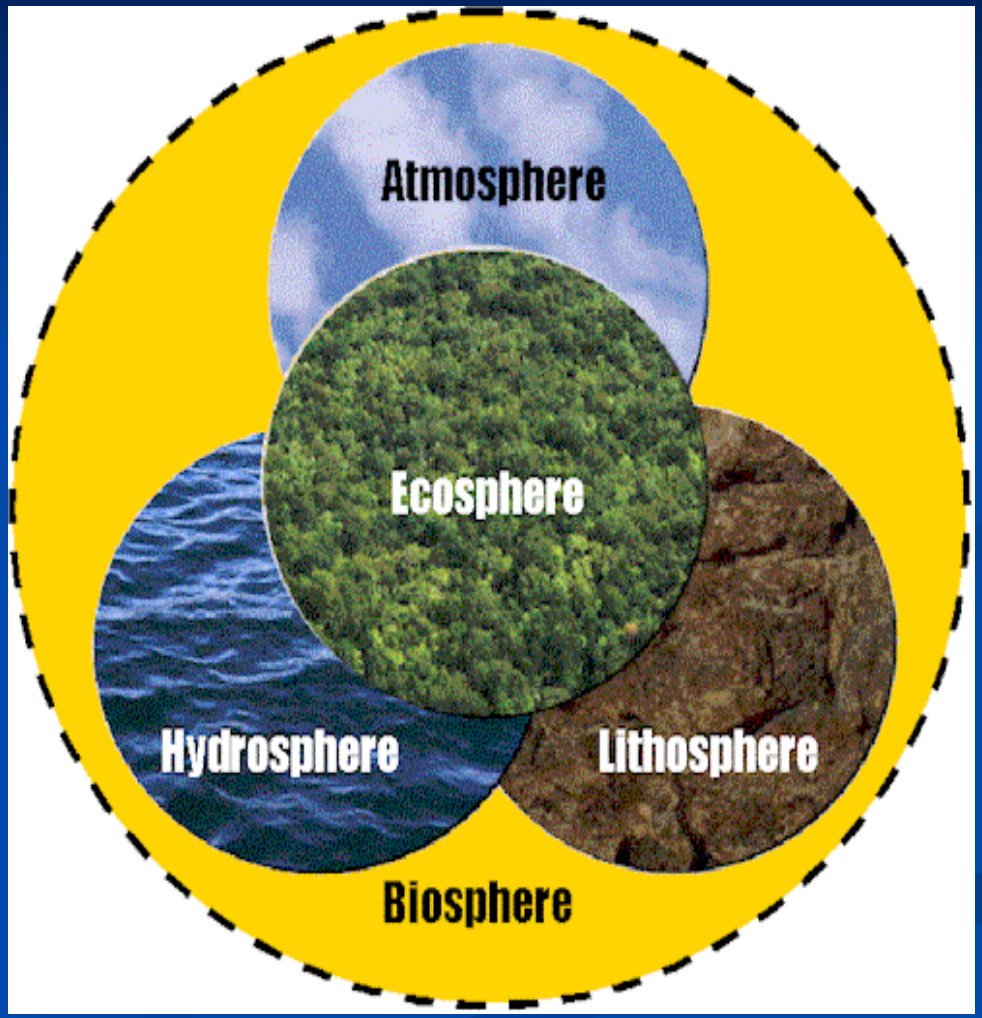
- Temperature
- Oxygen
- Habitability: Life on Earth
- The Goldilocks Problem



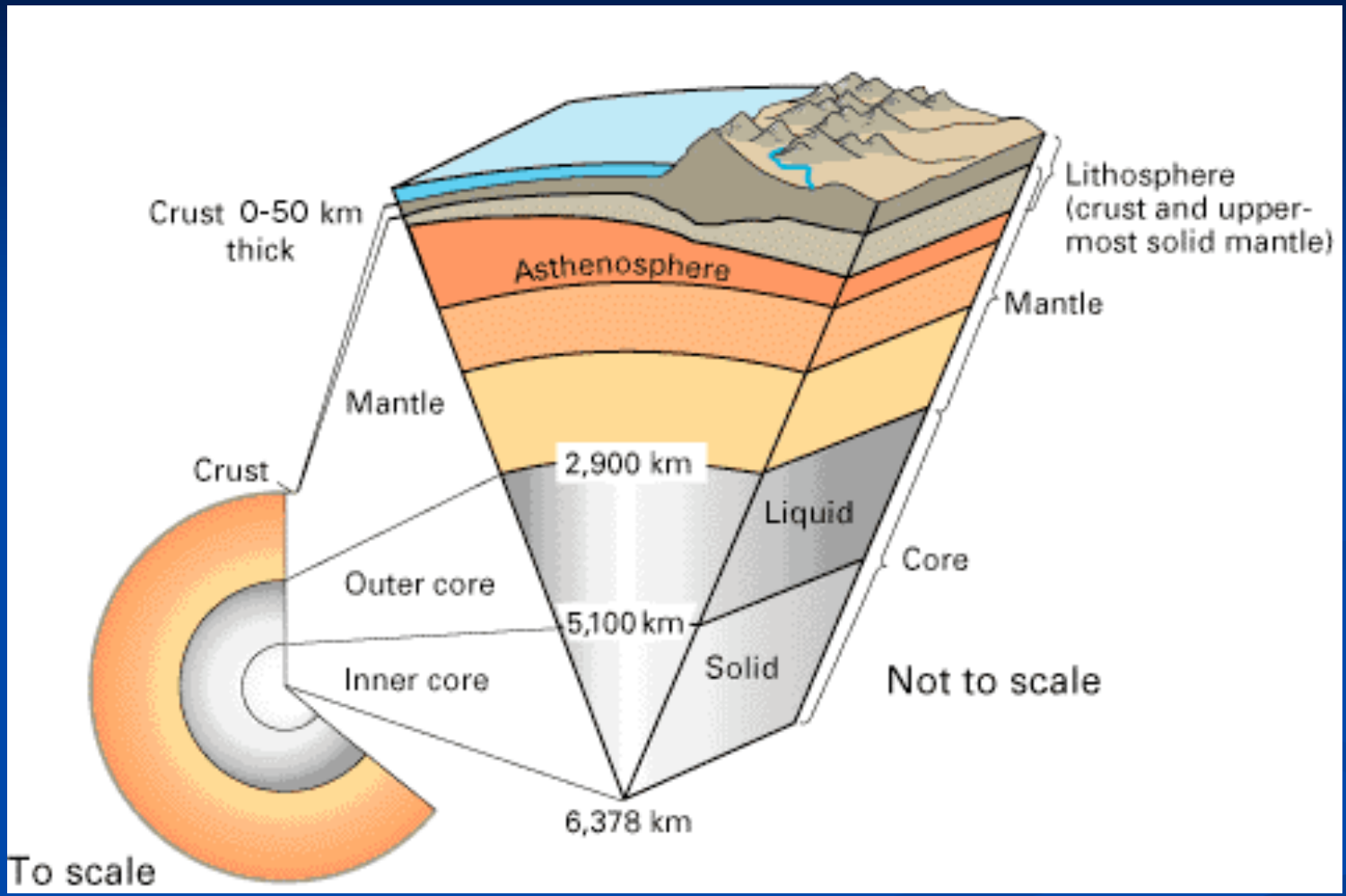
The State of the Terrestrial Biosphere…

is determined, in part, by:

(1) The Hydrological Cycle
(2) Biology
(3) Local Albedo
(4) Surface Interactions

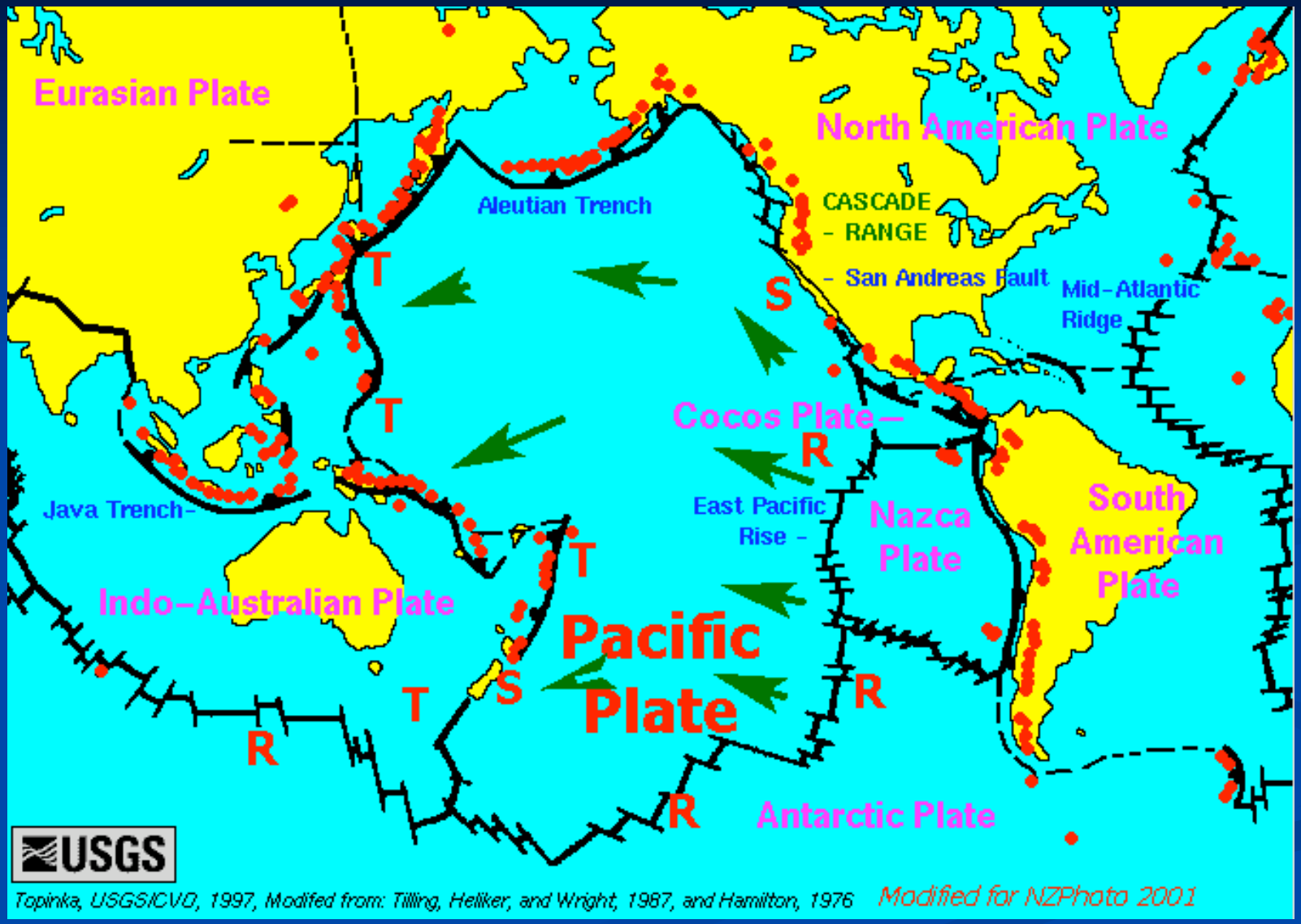


The Earth's Crust, Mantle, and Core



http://oceansjsu.com/images/exp5_interior_earth.gif

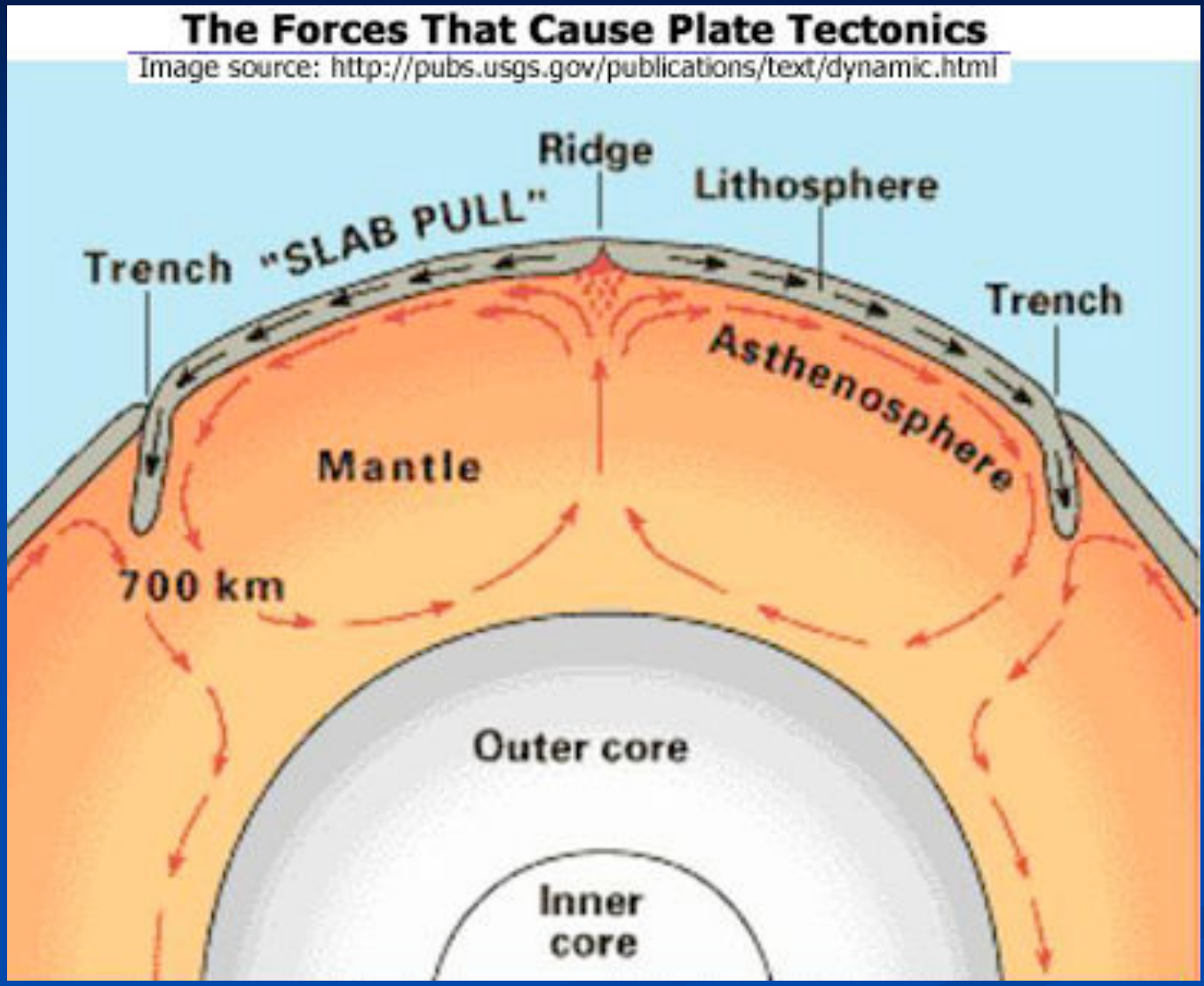
The "Ring of Fire" – Driven by Plate Tectonics



http://nzphoto.tripod.com/volcano/PacificPlate.gif


Redoubt Volcano: 1990

Mantle Convection: Driver of Plate Tectonics



http://www.cas.muohio.edu/limpermuseum/InvestigateConceptsInGeology/_images/Forces%20that%20Cause%20PT.jpg

Plate Subduction at Plate Boundaries

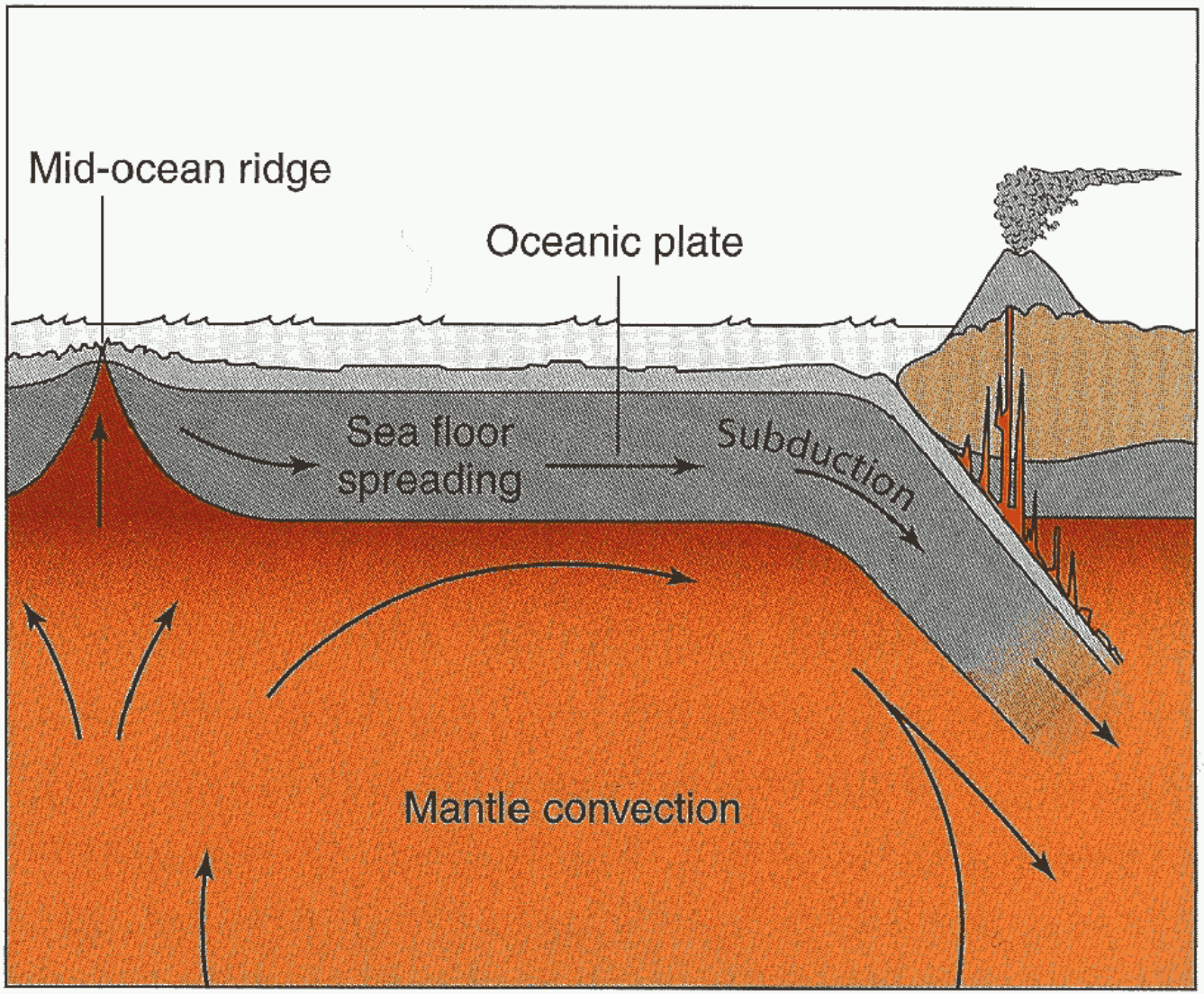


Plate Tectonics and Climate

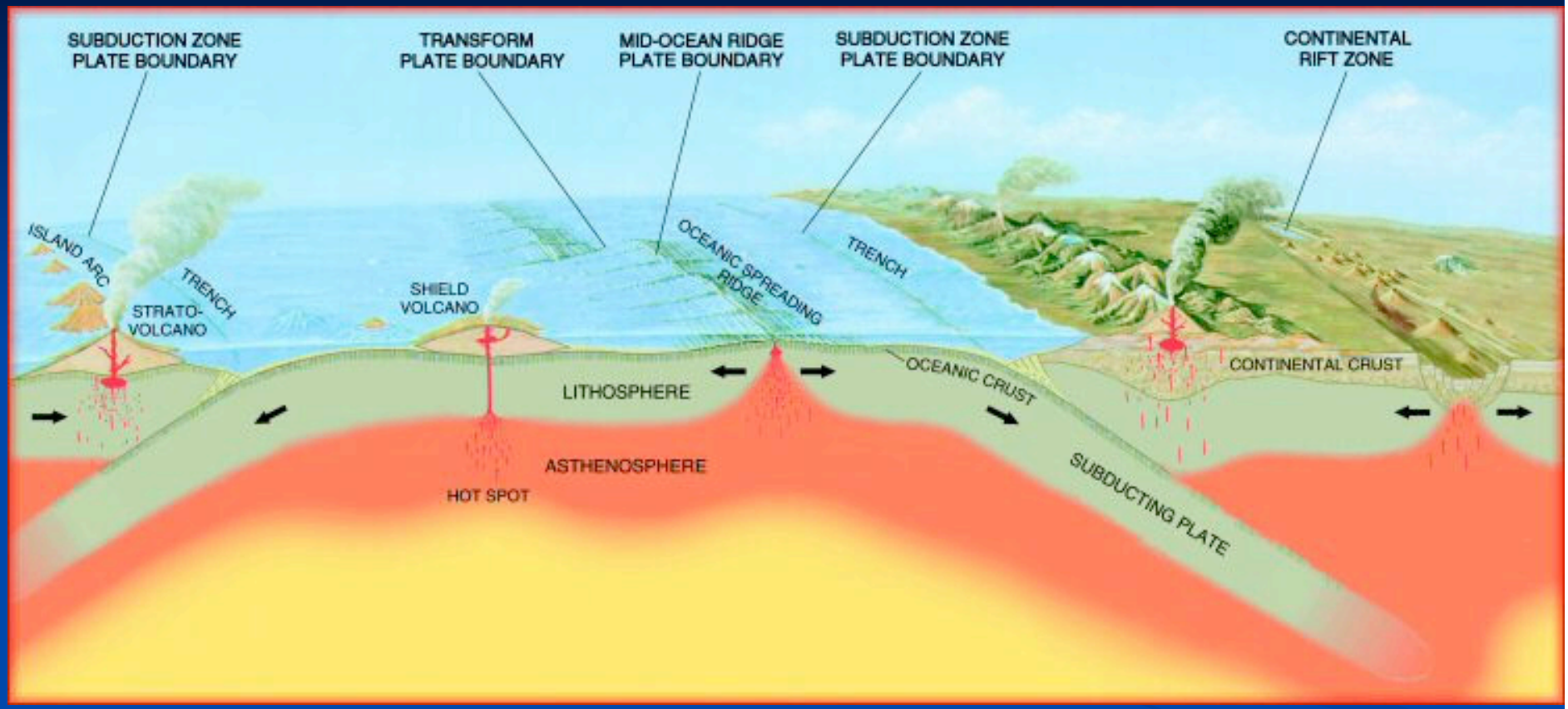


Plate tectonics drives a long term (60-100 MY) cycle of carbon through the biosphere. This regulates climate changes.

http://dilu.bol.ucla.edu/

The Terrestrial Biosphere:

Much of the impact of climate upon animals and humans is through its role in regulating the condition and geographical distribution of forests, grasslands, tundra, and deserts; all elements of the **terrestrial biosphere**.



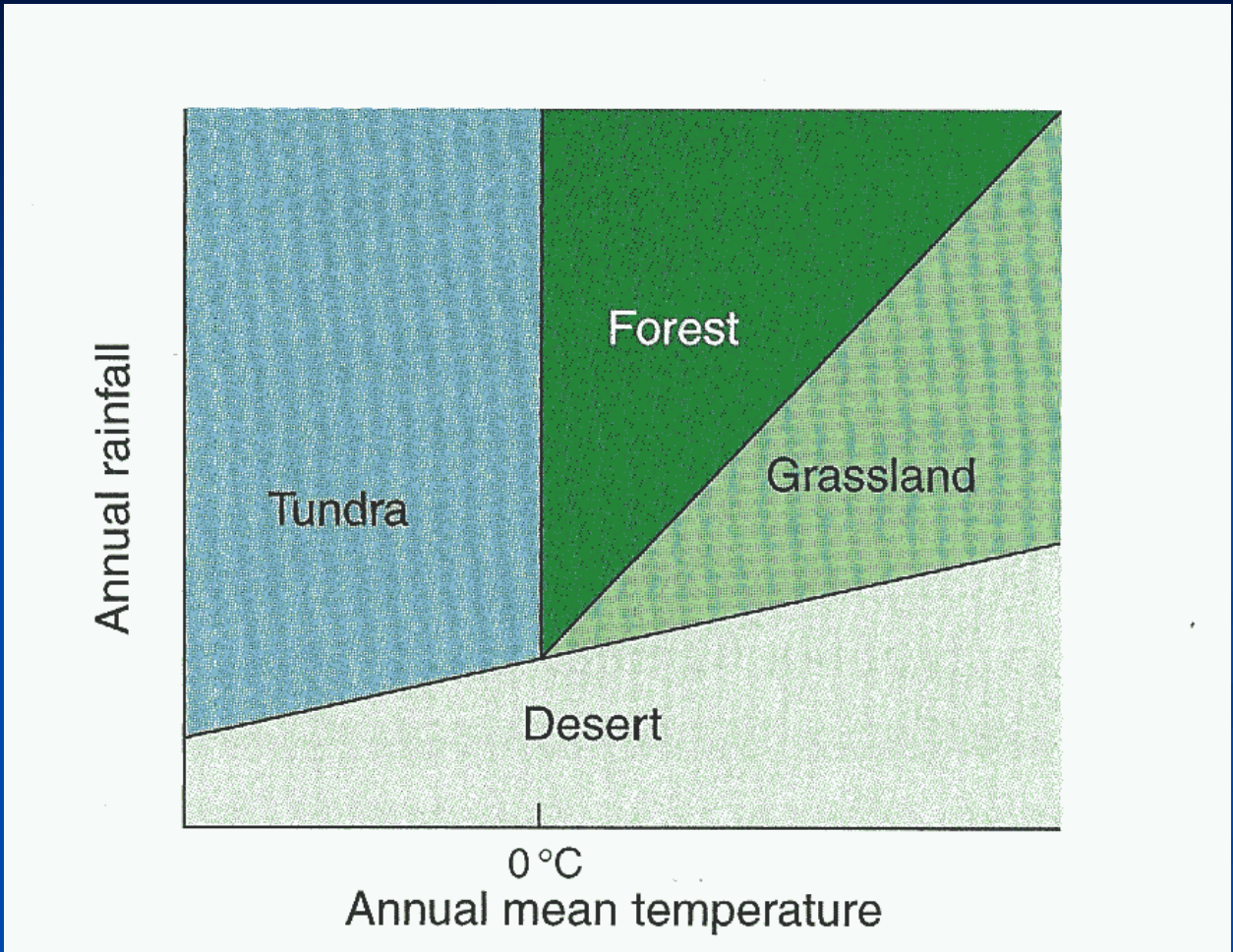
Biomes are geographical regions with climates that favor distinctive combinations of plant and animal species.

For example, **tundra** is the dominant form of vegetation in regions in which the mean temperature of the warmest month < 10^{o}C.



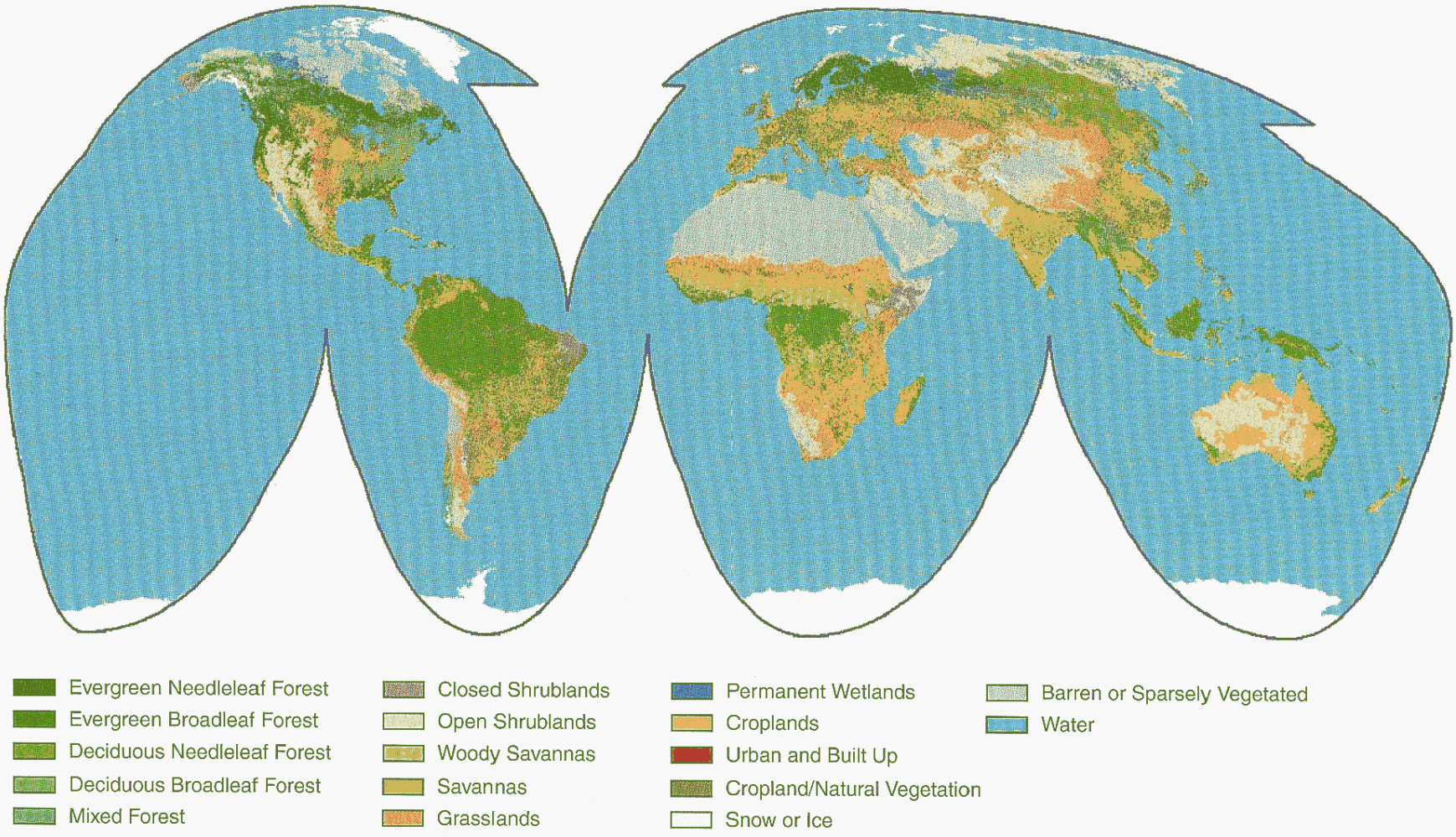
Sparse **desert** vegetation prevails in regions in which potential evaporation (proportional to the quantity of solar radiation reaching the ground) exceeds precipitation.

Preferred Types of Land Vegetation



Conceptual framework for understanding how the preferred types of land vegetation over various parts of the globe depend on the annual-mean temperature and precipitation.

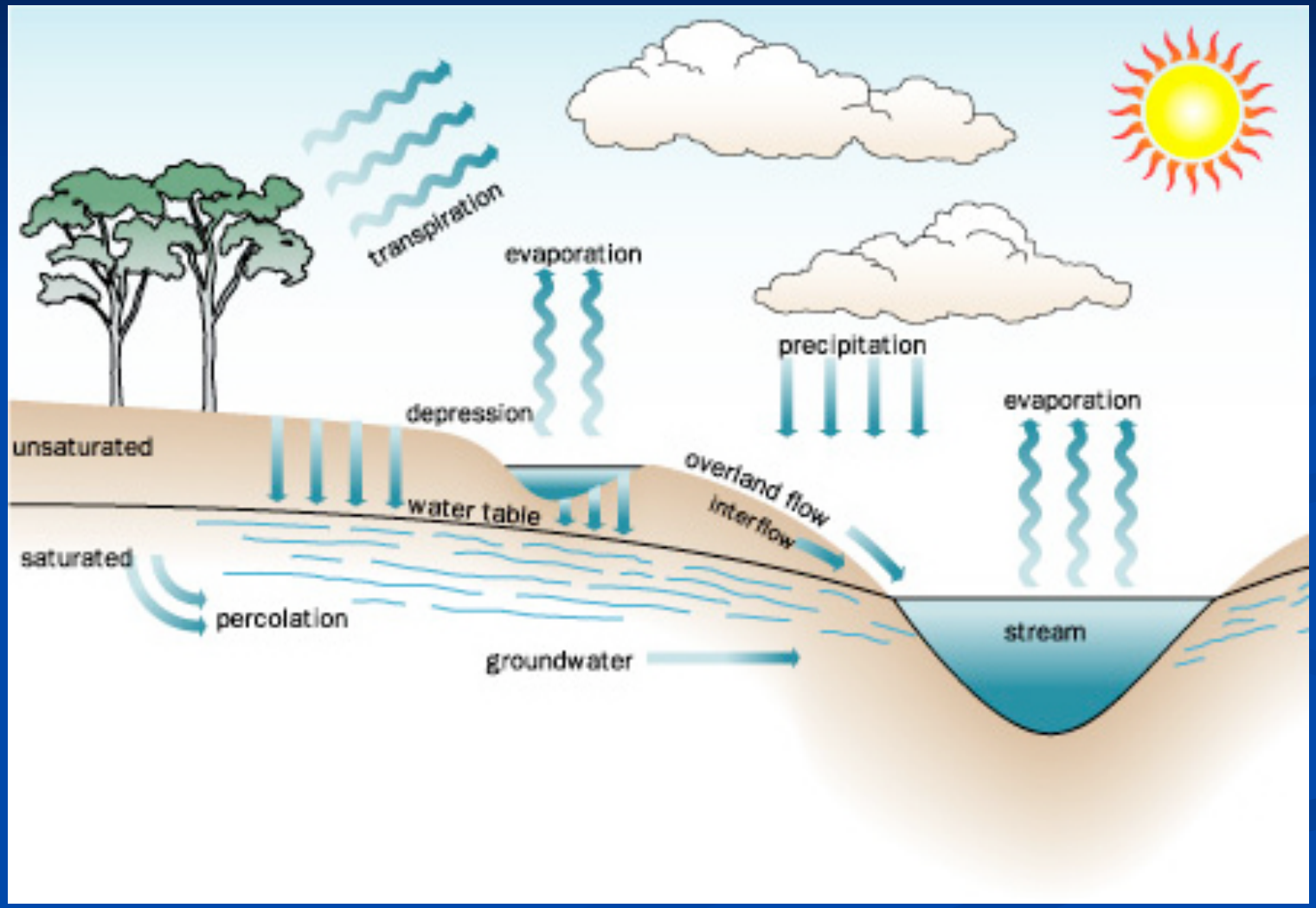
Global Land Cover Characterization



The "ground truth" for assigning and understanding biomes is the observed distribution of land cover.

The Hydrological Cycle

Life on Earth is critically dependent on the cycling of water between the various **Reservoirs,** which are collectively known as the **hydrological cycle.**



http://www.rpdc.tas.gov.au/soer/image/267/water%20quantity/o-ilw_hydrological_cycle-m.jpg

The Hydrologic Cycle and Water Balance

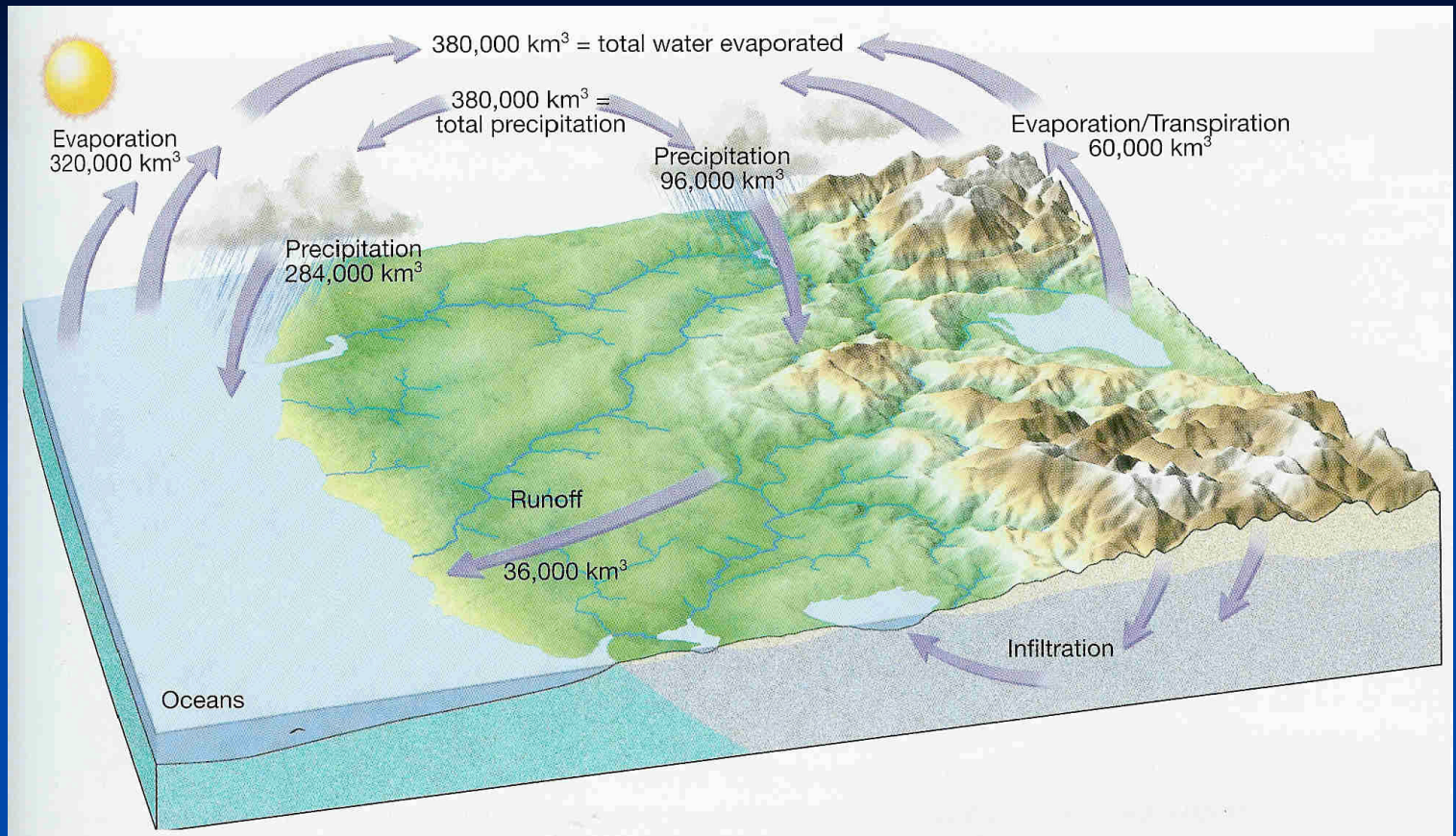
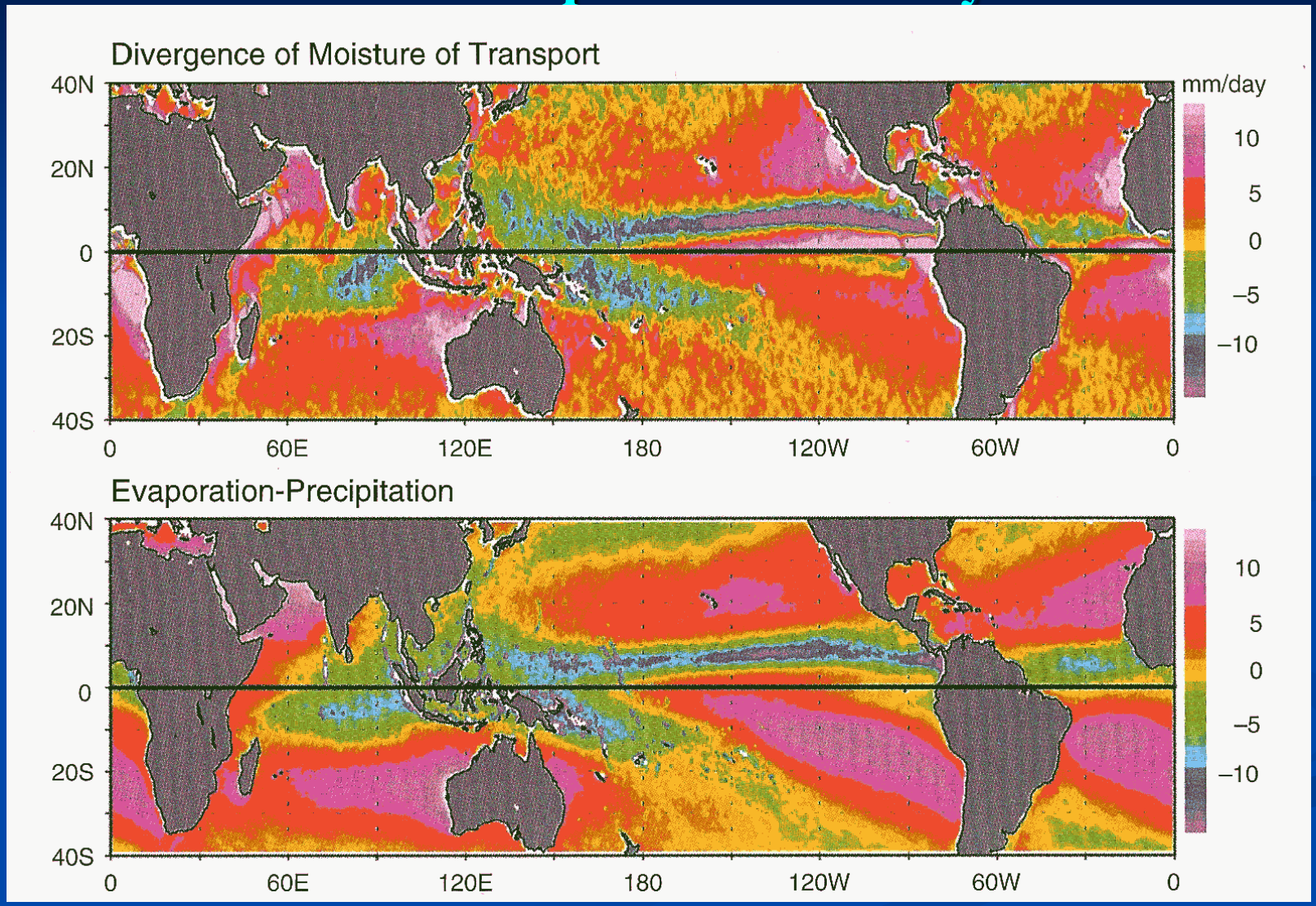


FIGURE 4-2 Earth's water balance. About 320,000 cubic kilometers of water are evaporated annually from the oceans, whereas evaporation from the land (including lakes and streams) contributes 60,000 cubic kilometers of water. Of this total of 380,000 cubic kilometers of water, about 284,000 cubic kilometers fall back to the ocean, and the remaining 96,000 cubic kilometers fall on Earth's land surface. Because 60,000 cubic kilometers of water leave the land through evaporation and transpiration, 36,000 cubic kilometers of water remain to erode the land during the journey back to the oceans.

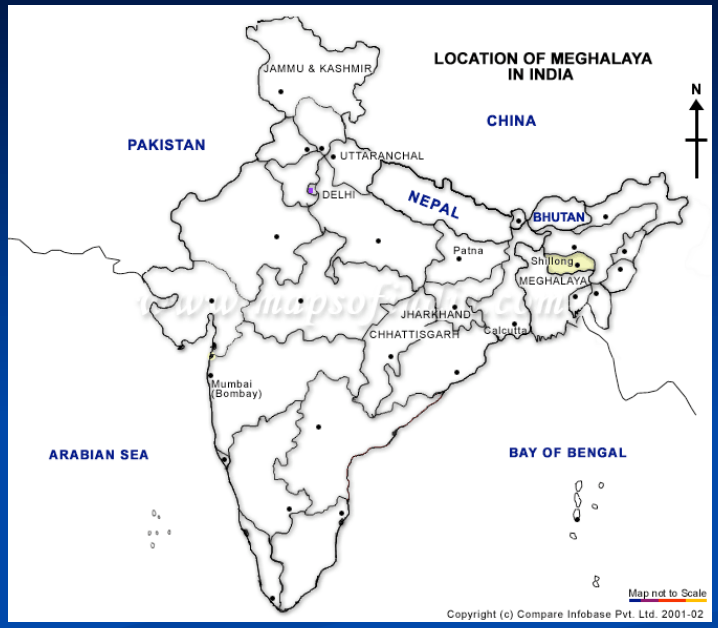
The unending circulation of Earth's water supply is called the hydrologic cycle (or water cycle). The cycle illustrates the continuous movement of water from the oceans to the atmosphere, from the atmosphere to the land, and from the land back to the sea.

Annual Mean Mass Balance of Atmospheric Water Vapor in mm day^{-1}.



The Wettest Place on Earth





Location: In the Indian state of Meghalaya.

Cherrapunji, 1290 meters above sea level, receives an annual rainfall of 1270 cm (~500 inches)
It once rained 2290 cm in one season!

http://www.extremescience.com/wettest.htm

Cause: Monsoons

The Driest Place on Earth



Rainfall: 0.03 inches/year



The Atacama desert is nestled along the coast of Chile, South America - right next to the Pacific Ocean - the biggest body of water in the world.

Much of the desert extends up into the Andes mountains and is very high in elevation.

Unlike more familiar deserts, like the Sahara desert in Africa and the Mojave in California, the Atacama is actually a pretty cold place, with average daily temperatures ranging between 0°C and 25°C.

There has been only 2 inches of rain during the past 59 years.

Cause: Shadow Desert

http://www.extremescience.com/DriestPlace.htm

Reservoirs in the Hydrological Cycle

Reservoirs are characterized by two key parameters:

- Size (or equivalently Mass)
- Residence Time

Generally, the larger the reservoir, the longer it takes for water to cycle through the reservoir.

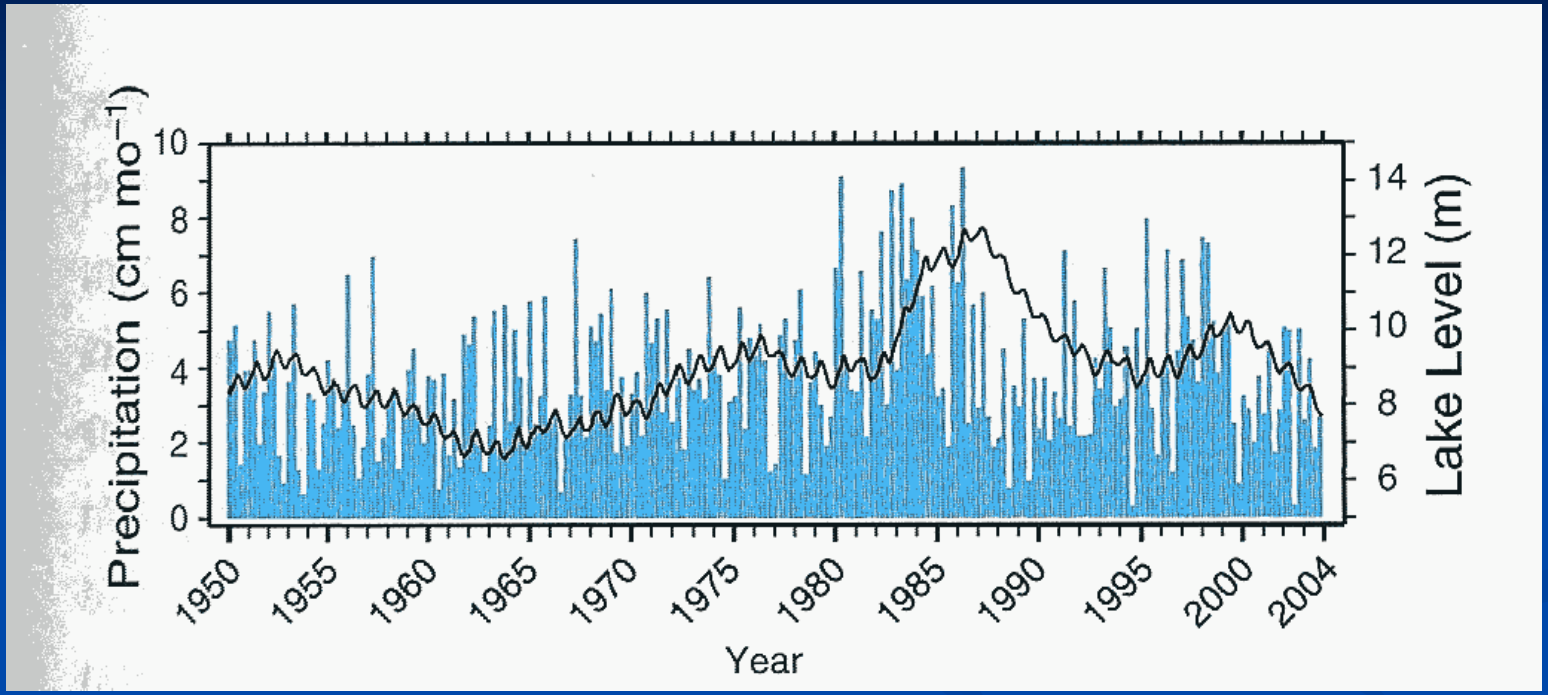
Table 2.2 Masses of the various reservoirs of water in the Earth system (in 10^3 kg m^{-2}) averaged over the surface of the Earth, and corresponding residence times

Reservoirs of water	Mass	Residence time
Atmosphere	0.01	Days
Fresh water (lakes and rivers)	0.6	Days to years
Fresh water (underground)	15	Up to hundreds of years
Alpine glaciers	0.2	Up to hundreds of years[a]
Greenland ice sheet	5	10,000 years[b]
Antarctic ice sheet	53	100,000 years
Oceans	2,700	
Crust and mantle	20,000	10^{11} years

[a] Estimated by dividing typical ice thicknesses of a large alpine glacier (~300 m) by the annual rate of ice accumulation (~1 m).

[b] Estimated by dividing typical ice thicknesses in the interior of the Greenland ice sheet (2000 m) by the annual rate of ice accumulation (~0.2 m).

Consequences of Variation in Precipitation; eg., The Great Salt Lake



1963 historic low

1987 historic high

During this time the lake level rose 6.65m, the area increased by a factor of 3.5, and the volume increased by a factor of 4. Although the precipitation (blue) showed large year to year variations, the level evolved smoothly.

Carbon in the Atmosphere

Carbon Reservoirs and Cycling

Carbon chemical transformations

Methane oxidation:

$CH_4 + 2O_2 \rightarrow CO_2 + H_2O$

Photosynthesis:

$CO_2 + H_2O \rightarrow CH_2O + O_2$

Respiration:

$CH_2O + O_2 \rightarrow CO_2 + H_2O$

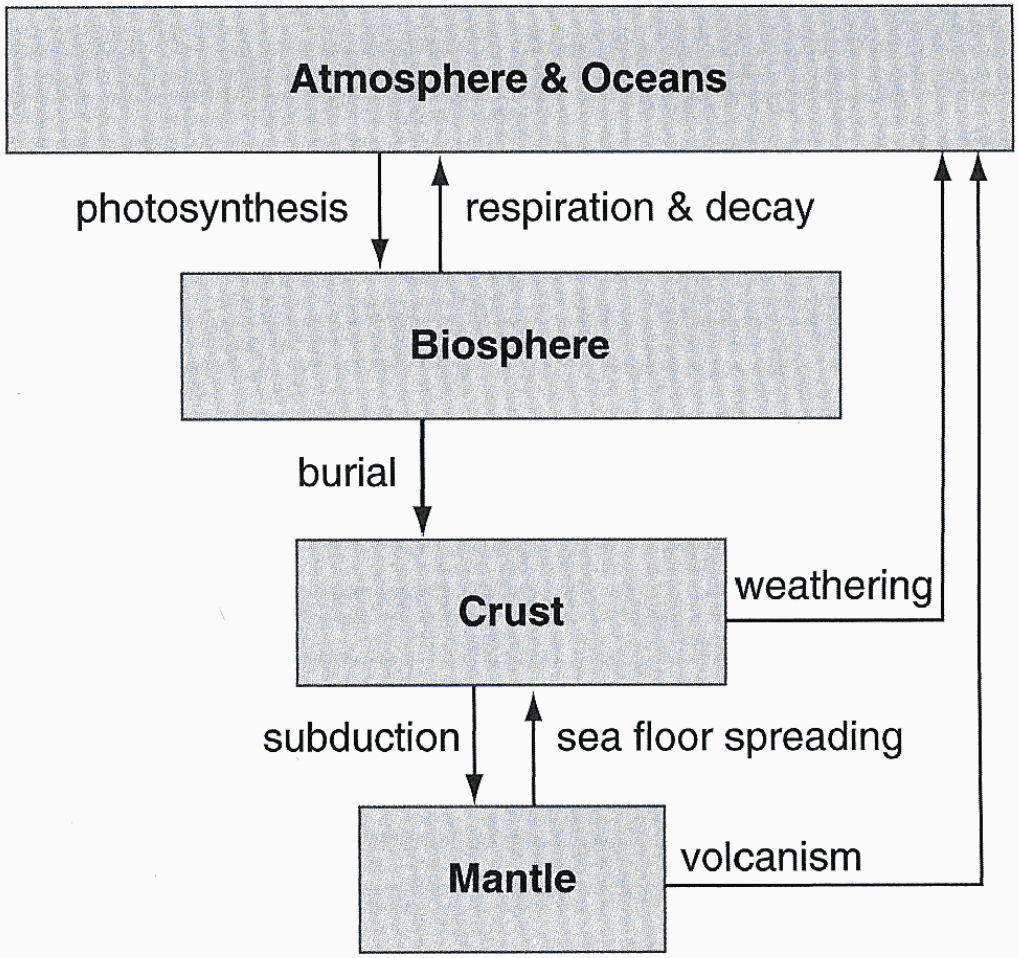


Fig. 2.23 Processes responsible for the cycling of carbon between the various reservoirs in the Earth system.

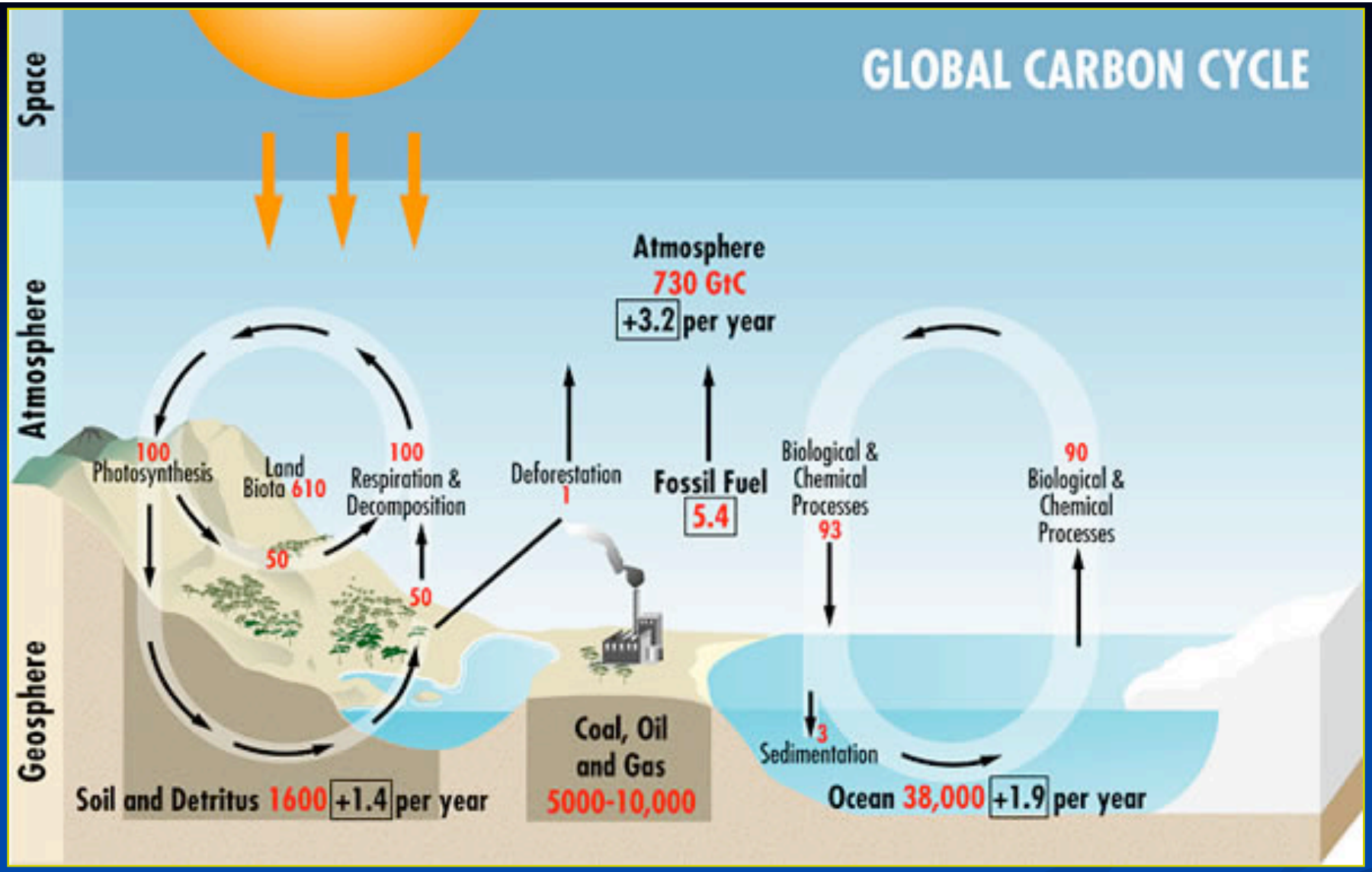
The Carbon Cycle: Important Reservoirs

Table 2.3 Major carbon reservoirs in the Earth system and their present capacities in units of kg m^{-2} averaged over the Earth's surface and their residence times[a]

Reservoir	Capacity	Residence time
Atmospheric CO_2	1.6	10 years
Atmospheric CH_4	0.02	9 years
Green part of the biosphere	0.2	Days to seasons
Tree trunks and roots	1.2	Up to centuries
Soils and sediments	3	Decades to millennia
Fossil fuels	10	—
Organic C in sedimentary rocks	20,000	2×10^8 years
Ocean: dissolved CO_2	1.5	12 years
Ocean CO_3^{2-}	2.5	6,500 years
Ocean HCO^-	70	200,000 years
Inorganic C in sedimentary rocks	80,000	10^8 years

[a] Capacities based on data in Fig. 8.3 (p. 150) of Kump, Lee R.; Kasting, James F.; Crane, Robert G., The Earth System, 2nd Edition, © 2004. Adapted by permission of Pearson Education, Inc., Upper Saddle River, NJ.

Carbon inventories are usually expressed in gigatons (Gt = 10^9 ton).



Most of the exchanges between reservoirs in the hydrological cycle involve phase changes and the transport of a single chemical species, H_2O.

In contrast, the cycling of carbon between reservoirs involves chemical transformations.

http://www.bom.gov.au/info/climate/change/gallery/images/9.jpg

Carbon in the Oceans

Carbon dioxide dissolved in water produces carbonic acid:

$CO_2 + H_2O \Leftrightarrow H_2CO_3$

Weathering of calcium-silicate rocks produces bicarbonate ions:

$CaSiO_3 + H_2CO_3 \rightarrow Ca^{2+} + 2\ HCO_3^- + SiO_2 + H_2O$

Marine organisms incorporate bicarbonate ions into their shells forming calcium carbonate:

$Ca^{2+} + 2\ HCO_3^- \rightarrow CaCO_3 + H_2CO_3$

(c) The Biological Pump

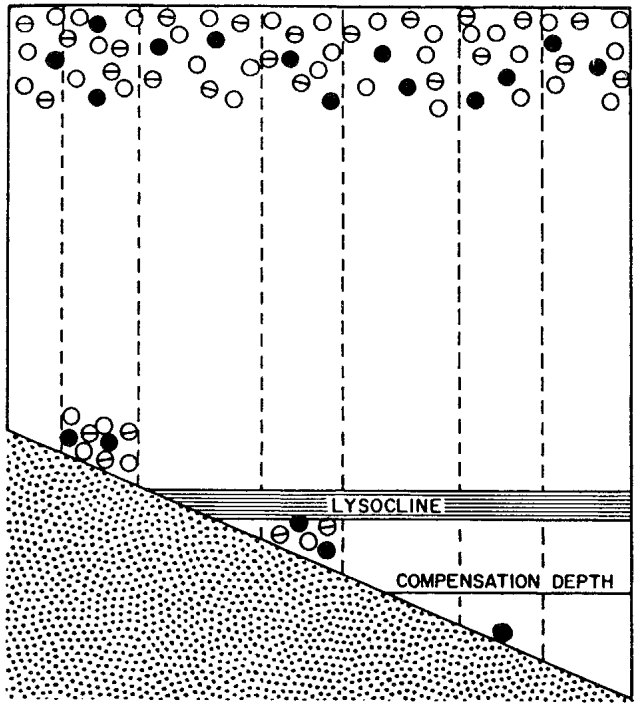


Figure 9.5 (c) Selective dissolution of planktonic foraminifera species at depth. Open circles (*Globigerinoides ruber*) are easily dissolved; circles marked with a bar (*Globigerina bulloides*) are more resistant; dark circles (*Globorotalia tumida*) are most resistant to dissolution. After Be, A. W. H., 1977, ''An Ecological Zoogeographic Taxonomic Review of Recent Planktonic Foraminifera,'' in *Ocean Micropalaeontology* A. T. S. Ramsay, editor (New York: Academic Press).

The reverse of this reaction occurs when the shells fall to the deep ocean and dissolve. That which does not dissolve produces limestone deposits in the ocean sediments.

Sources and Sinks of Carbon

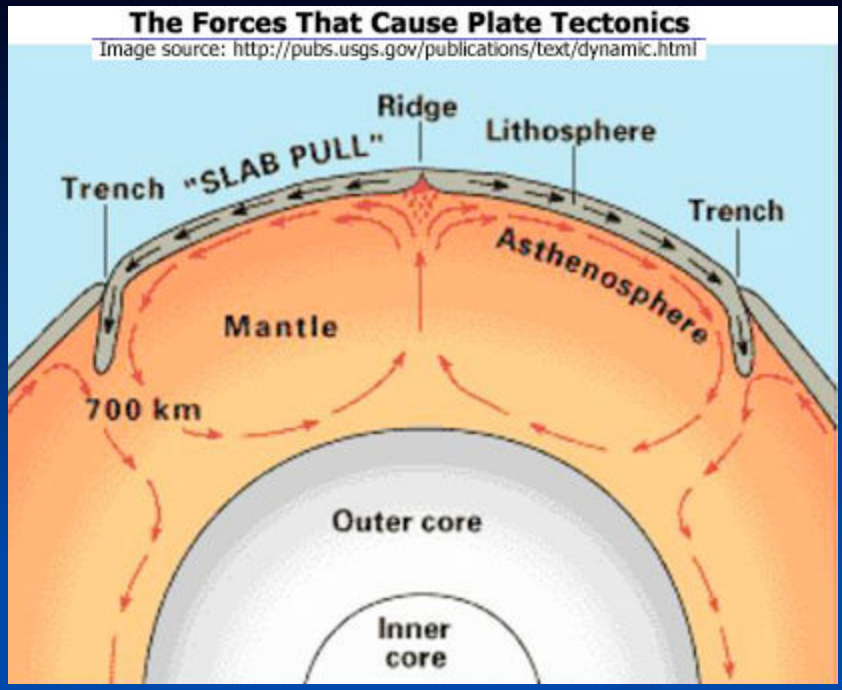
Isotopic Signatures of C

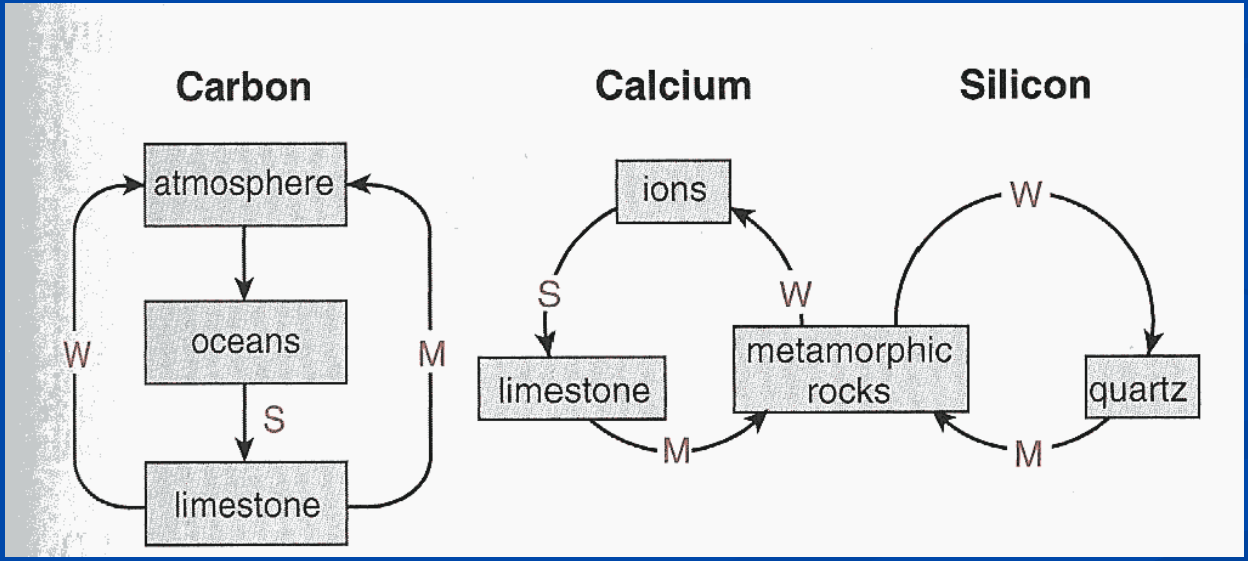
Table 9.6 Inputs and outputs of carbon and their isotopic composition

	Rate (10^{15} g yr^{-1})	$\delta^{13}C$(‰)
Inputs to ocean-atmosphere system		
Oxidation of organic carbon	0.09 ± 0.02	-25 ± 5
Weathering of carbonates	0.16 ± 0.04	0 ± 2
Degassing due to igneous and metamorphic processes	0.09 ± 0.03	-7 ± 3
Total inputs	0.34 ± 0.09	-8 ± 3
Outputs from the ocean-atmosphere system		
Deposition of organic carbon	0.12 ± 0.03	-23 ± 3
Deposition of carbonate carbon	0.22 ± 0.04	0 ± 1
Total outputs	0.34 ± 0.07	-8 ± 2

From Holland, H. D. (1978).

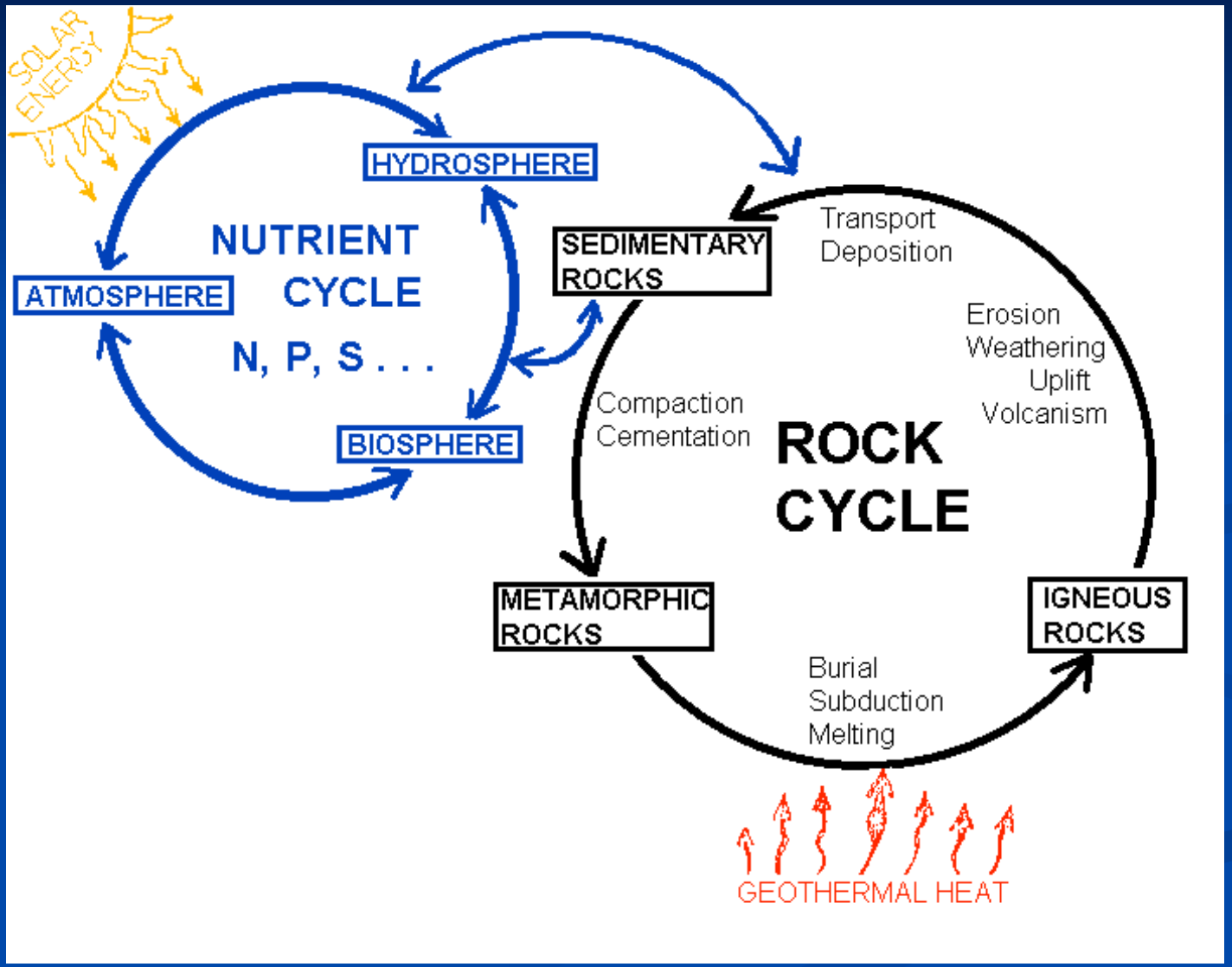
Carbon in the Earth's Crust: The Carbon-Silicate Cycle





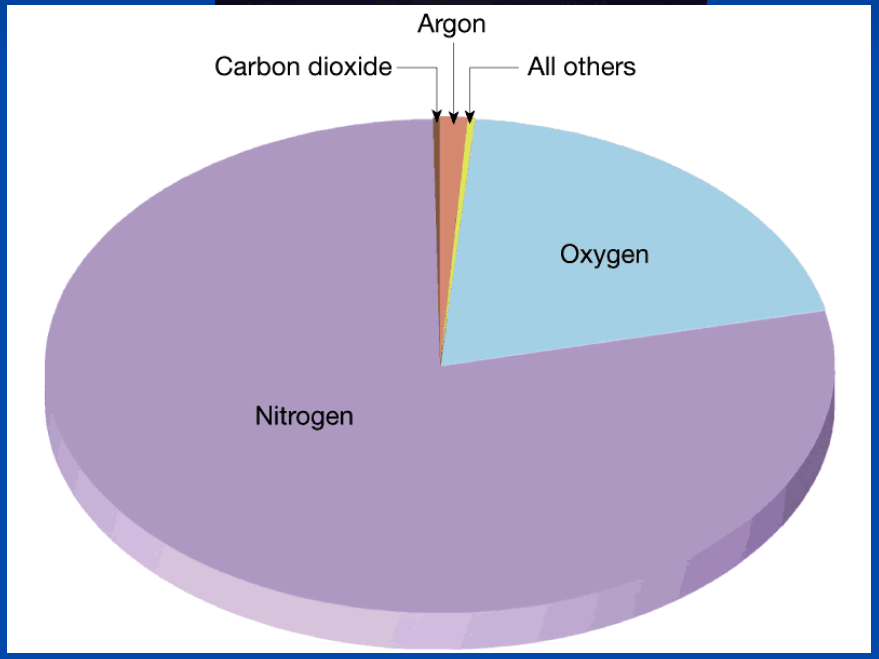
S = sedimentation
M = metamorphism
W = weathering

Biogeochemical Cycles: Driven by Solar Energy and Geothermal Heat



Atmospheric Oxygen





http://tonydude.net/NaturalScience100/chapters/chapter31/images31/ch31_percentage.gif

Table 2.4 Mass of oxygen (in units of 10^3 kg m^{-2}) averaged over the surface of the Earth required to raise the level of oxidation of the various reservoirs in the Earth system to their present state, starting from their state at the time of formation of the Earth[a]

Reservoir	Mass
Atmospheric O_2	2.353
Oceans and sediments	31
Crust Fe^{3+}	>100
Crust CO_3	~100
Crust (other)	>100
Mantle Fe^{3+}	>100

[a] The estimates for the crust and mantle represent conservative lower limits. [Based on data adapted with permission from Catling, D. C., K. J. Zahnle and C. P. McKay, "Biogenic Methane, Hydrogen Escape, and the Irreversible Oxidation of Early Earth," *Science*, **293**, p. 841. Copyright 2001 AAAS.]

crust and upper mantle, it is necessary to invoke the existence of a source of free oxygen that came into play later in the history of the Earth system. Free oxygen is also required to account for the formation of carbonates in the Earth's crust by marine organisms, as illustrated in the following exercise.

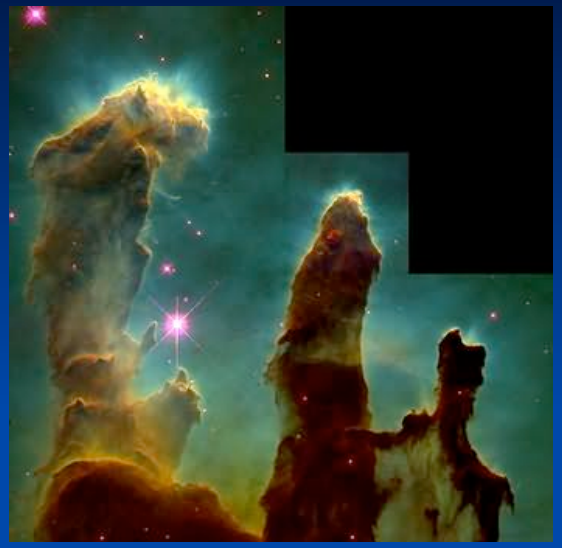
CLIM-111/PHYS-111
Introduction to the Fundamentals of Atmospheric Science
Lecture Notes #2 – Part 3: The Earth System

The Earth Now:
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- The Surface/Crust
- The Biosphere
- Biogeochemical Cycles

How the Earth Evolved:
- Temperature
- Oxygen
- Habitability: Life on Earth
- The Goldilocks Problem



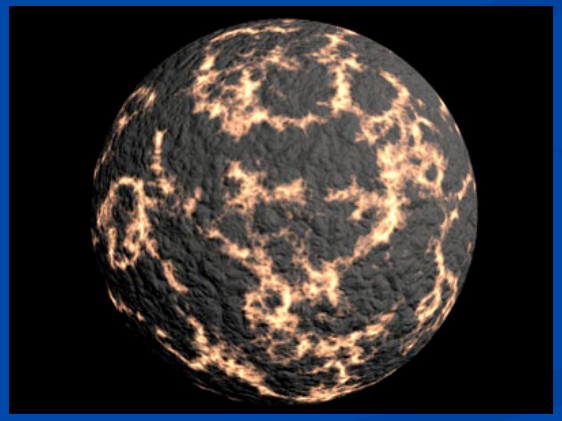
How did the Earth Arrive at its Current State?

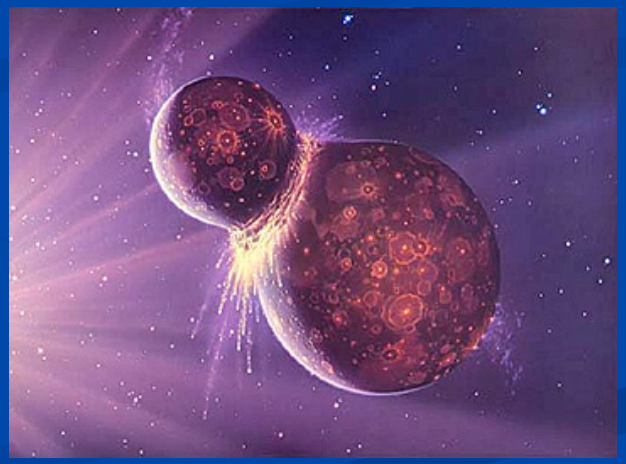


Formation Process
+
Geological Evolution
+
Chemical Evolution
+
Biological Evolution









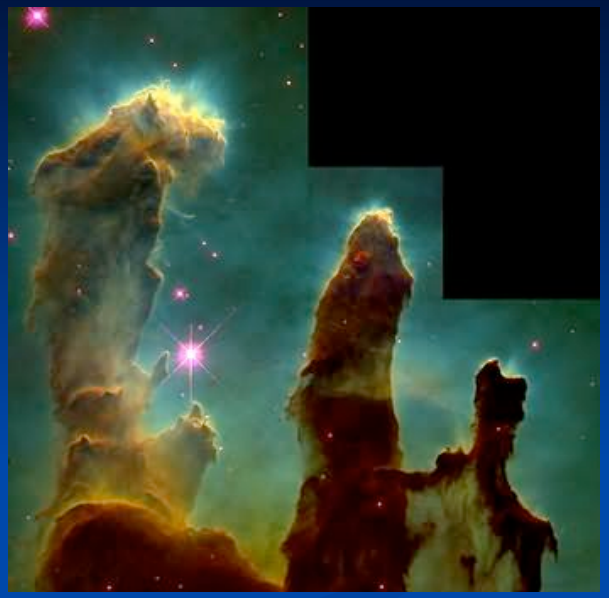
Formation of the Earth-like Planets Begins in Stellar Nurseries

Cone Nebula





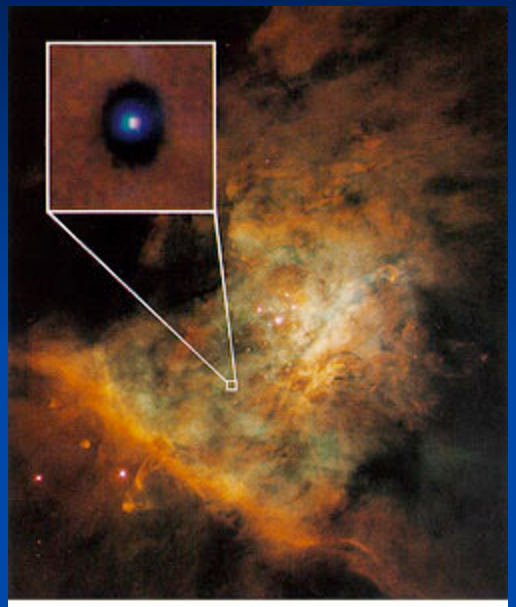
Eagle Nebula





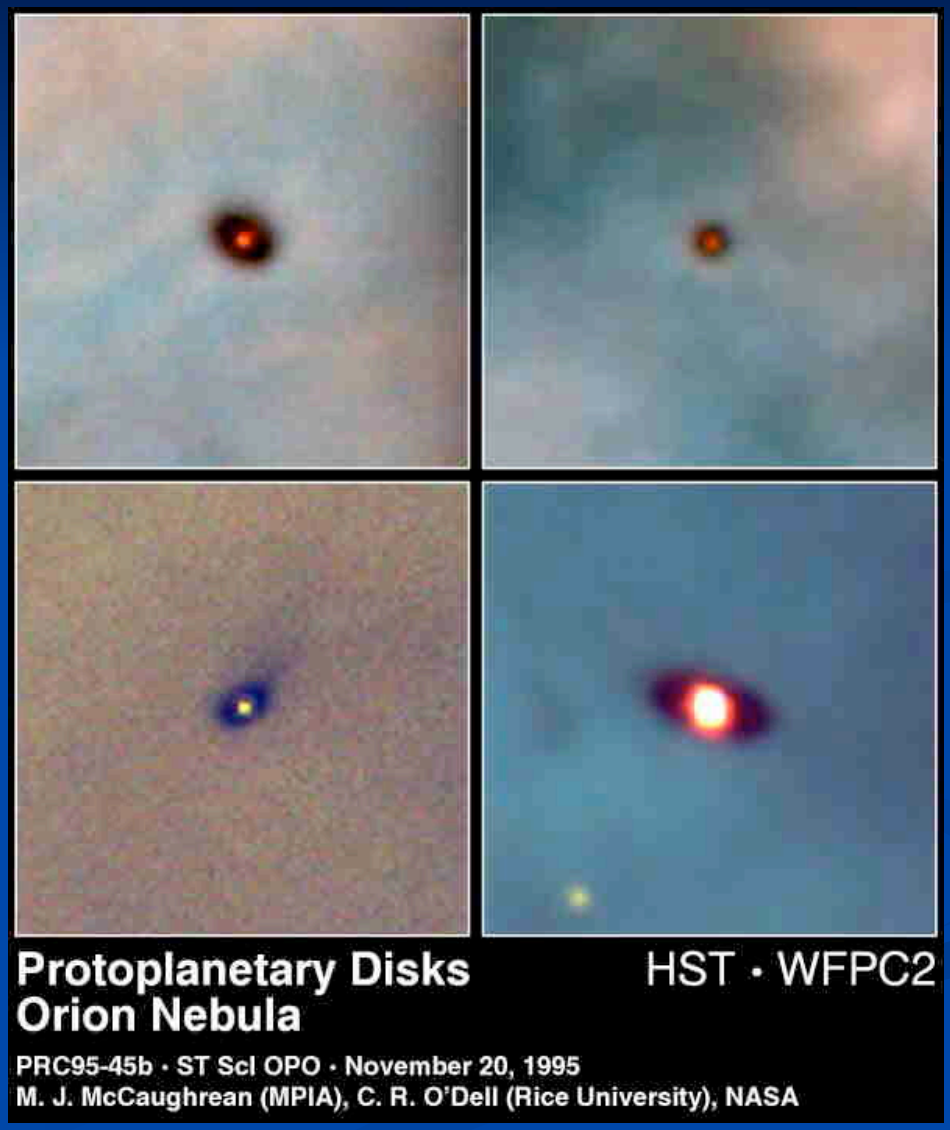
Planets form as a by-product of star formation, thus in the same regions of space.

First Stages of Planet Formation



THE ORION NEBULA CONTAINS YOUNG STARS AROUND WHICH PLANETS MAY BE FORMING.





Planet Formation Sequence

1) Grains form from condensation

2) Grains accrete into planetesimals

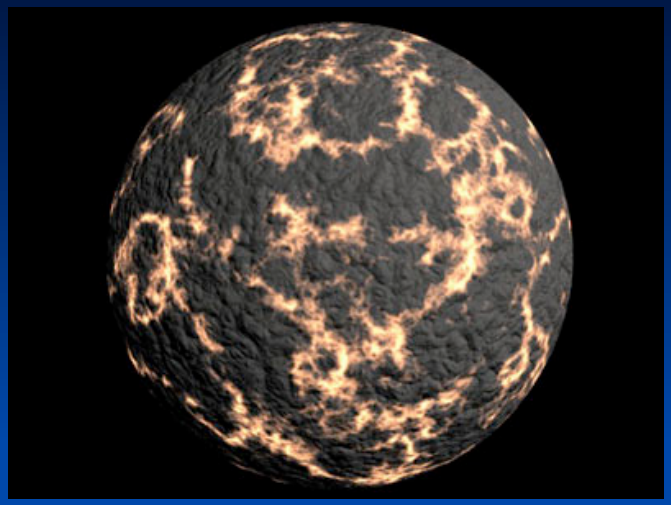
3) Planetesimals grow into planets

4) Giant planets accrete gas

5) Giant planets scatter remaining planetesimals



Atmospheric Evolution and Earth History

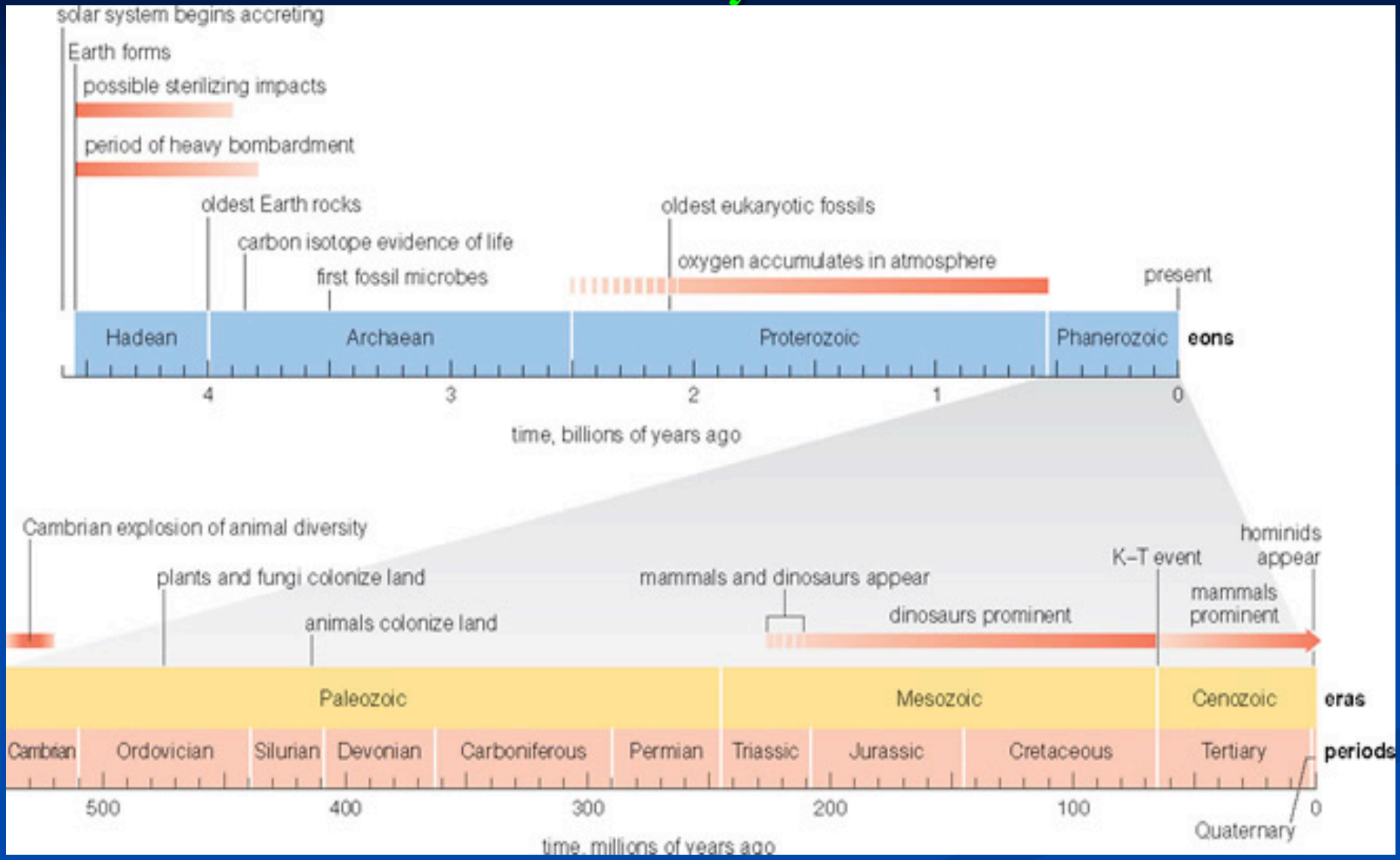








A Brief History of the Earth

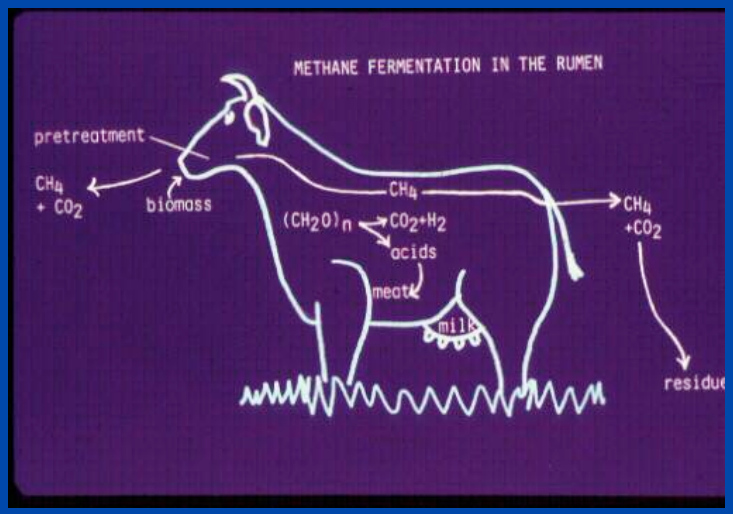


The Early Earth was an Extreme Environment

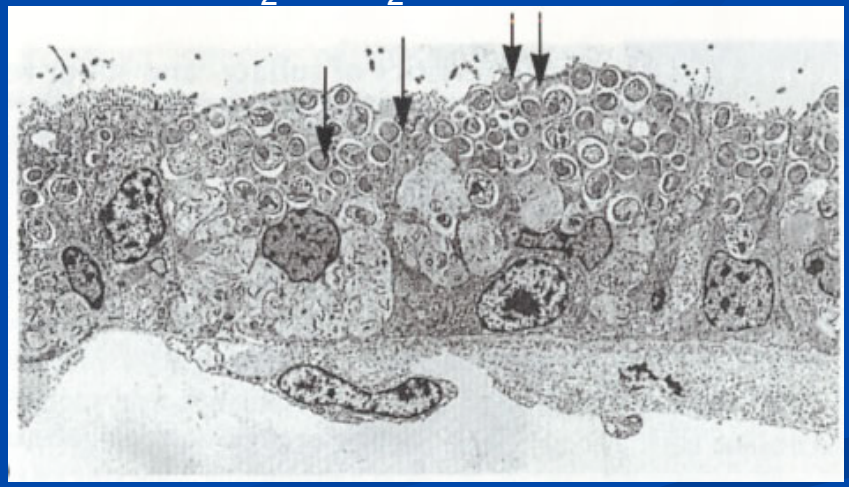
Before oceans,
Before oxygen,
Before photosynthesis,
There was chemosynthesis…..



Methanogenesis:
$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$



Sulfur Reducing Bacteria:
$S + H_2 \rightarrow H_2S$

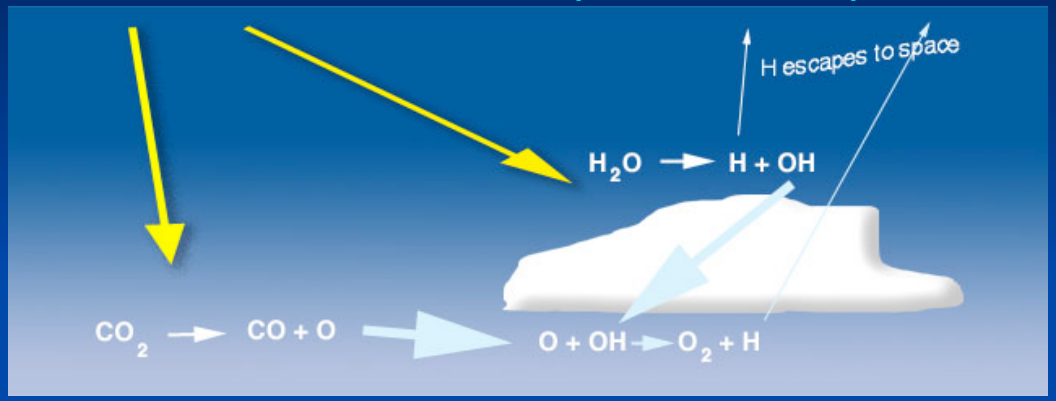


http://www.agen.ufl.edu/~chyn/age4660/lect/lect_08x/lect_08.htm

Sources and Sinks of Atmospheric Oxygen

Sources

(1) Chemical: Photochemical breakup of water vapor



http://www.globalchange.umich.edu/globalchange1/current/lectures/samson/evolution_atm/O2Photolysis.jpg

(2) Biological: Photosynthesis

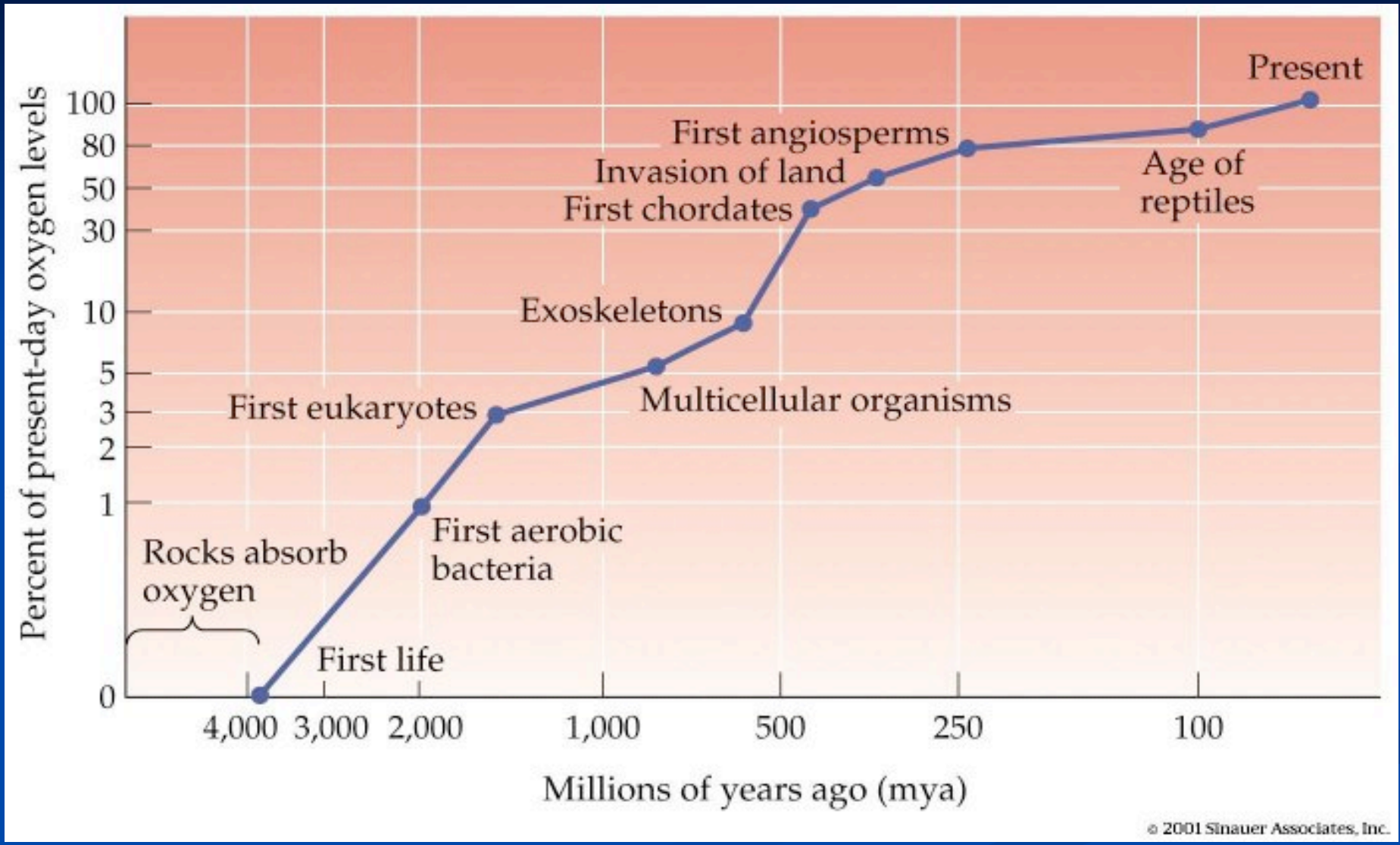
$$6H_2O + 6CO_2 \rightarrow C_6H_{12}O_6 + 6O_2$$



Sinks

(3) Respiration: the reverse of photosynthesis
(4) Oxidation of exposed rocks

Evolution of Oxygen



http://www.prism.gatech.edu/~gh19/b1510/f202a.jpg

Origin of the Earth's Ocean: Clues in the Deuterium to Hydrogen (D/H) ratio

Two Sources:

External (comets & meteorites):
Volatiles such as H_2O, CO_2, CH_4, H_2
Internal (out-gassing): CO_2, H_2O



Deuterium in the ocean is characterized by SMOW (Standard Mean Ocean Water) = 150 ppmv.

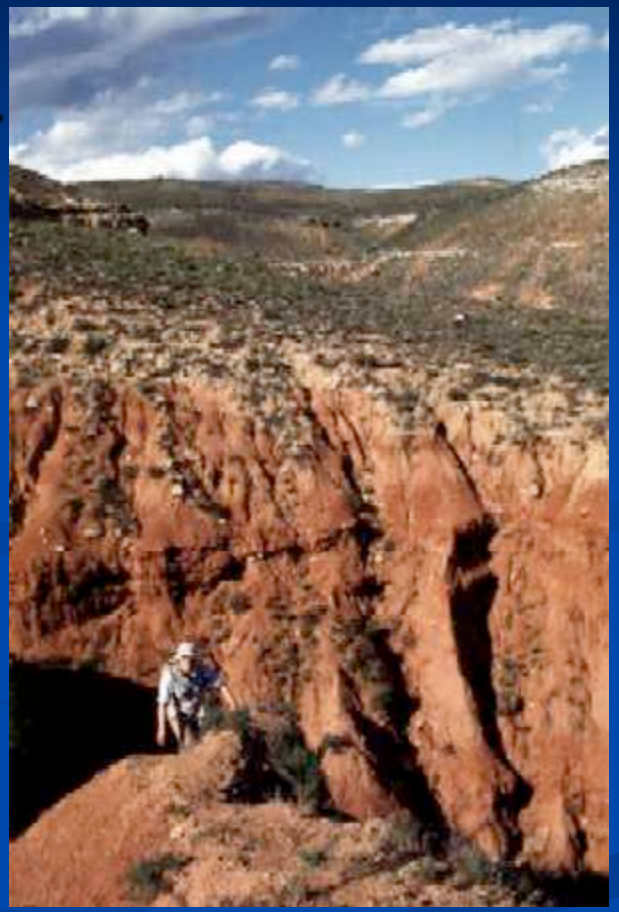
Comets D/N = 2 x SMOW
Carbonaceous Chondrites (CC) ~ 0.8 SMOW
(H & O bound to mineral grains)

CC's are presumably the remnants of the collisions of planetesimals in the asteroid belt, ~2-3 AU from the Sun.

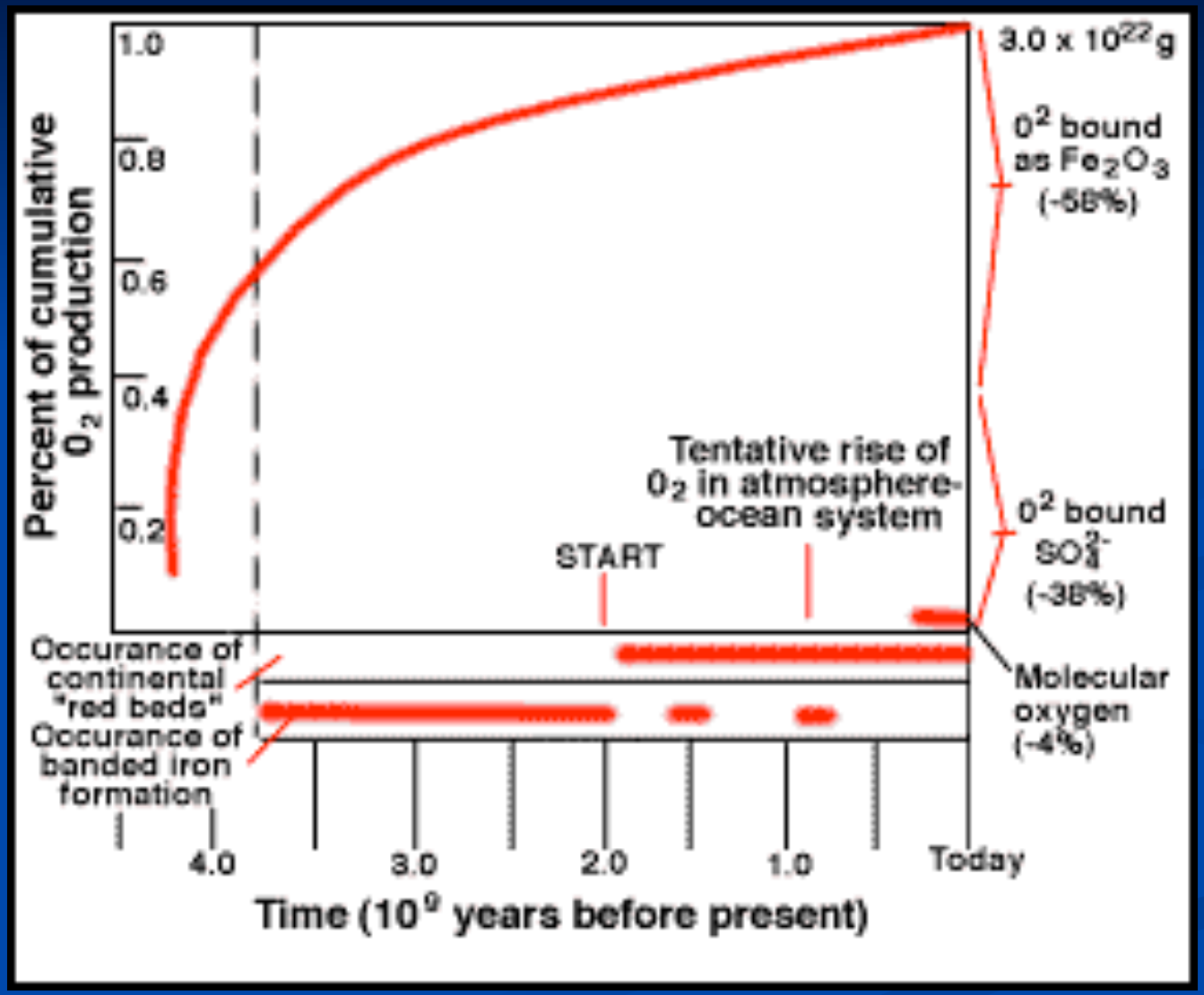
Evidently the oceans formed form the impact of both comets and meteorites from outside the orbit of Mars, i.e., beyond the "iceline."

Redbeds: typically sandstones composed of large amounts of iron oxide (rust) first appear in geological strata about 2 BY ago.





Red Beds and Oxygen



http://www.ux1.eiu.edu/~cfjps/1400/ootwo.gif

Banded Iron Formations

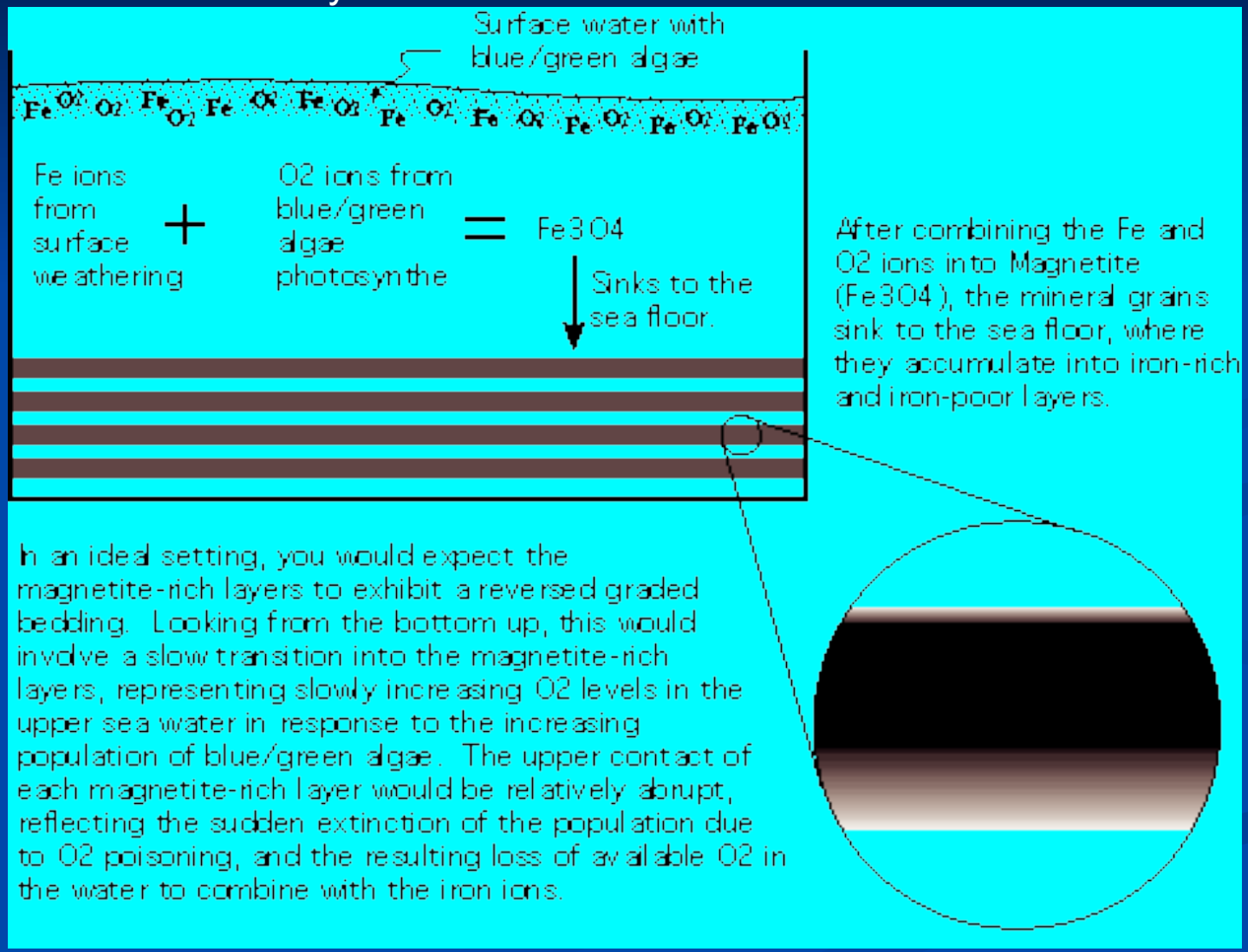
Banded Iron Formations (BIFs) appear at about 3.5 BY ago, and disappear by 2BY ago. They are made of alternating layers of highly oxidized iron and layers of chert. BIFs seem to indicate that the Earth's oceans went through alternating periods of high and low oxygen content, probably as a result of large scale "algae blooms" that were oxygen and nutrient limited.



http://www-eps.harvard.edu/people/faculty/hoffman/Snowball-fig9.jpg

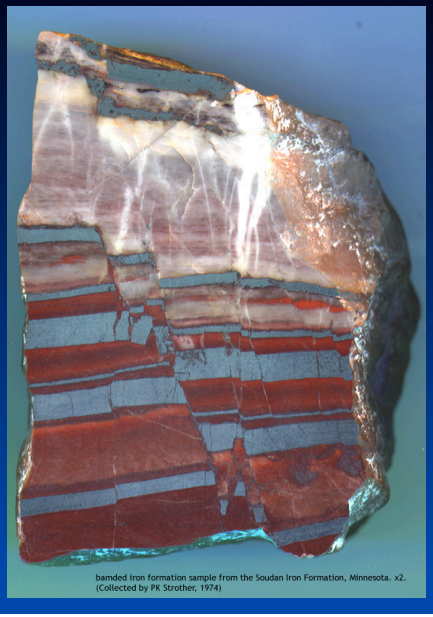
Banded Iron Formations

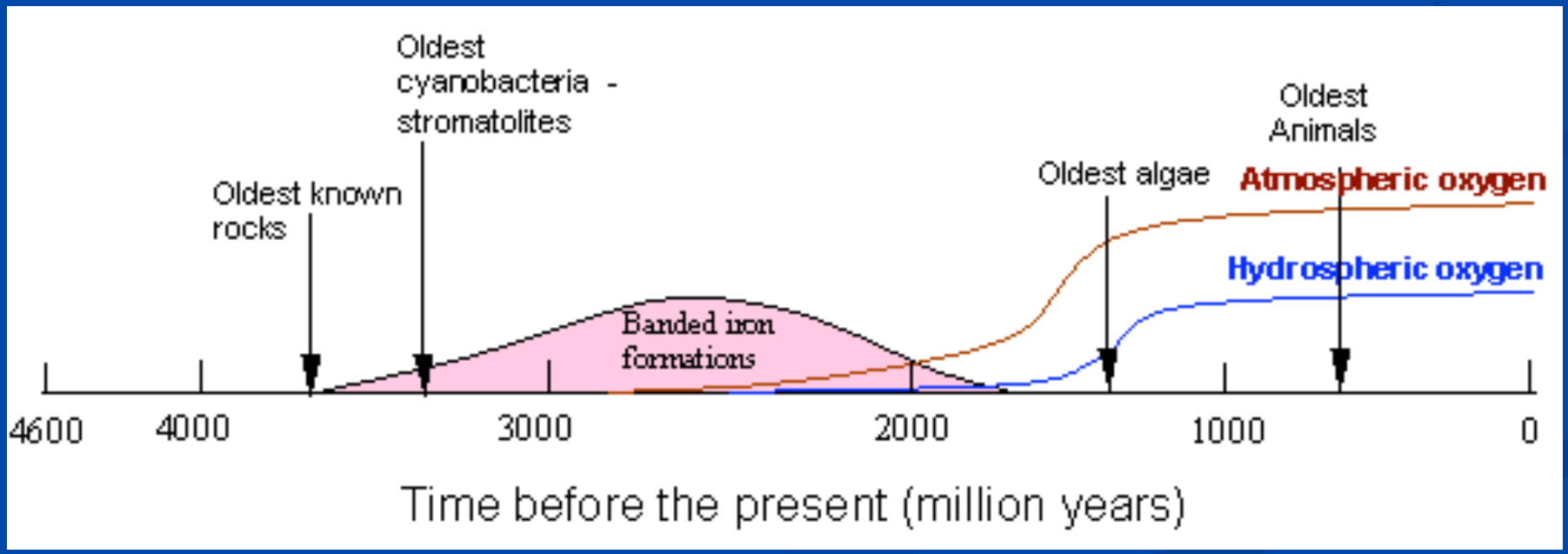
Banded Iron Formations (BIFs) are made of alternating layers of highly oxidized iron and layers of chert.



http://jersey.uoregon.edu/~mstrick/myimages/Banded%20Iron.gif

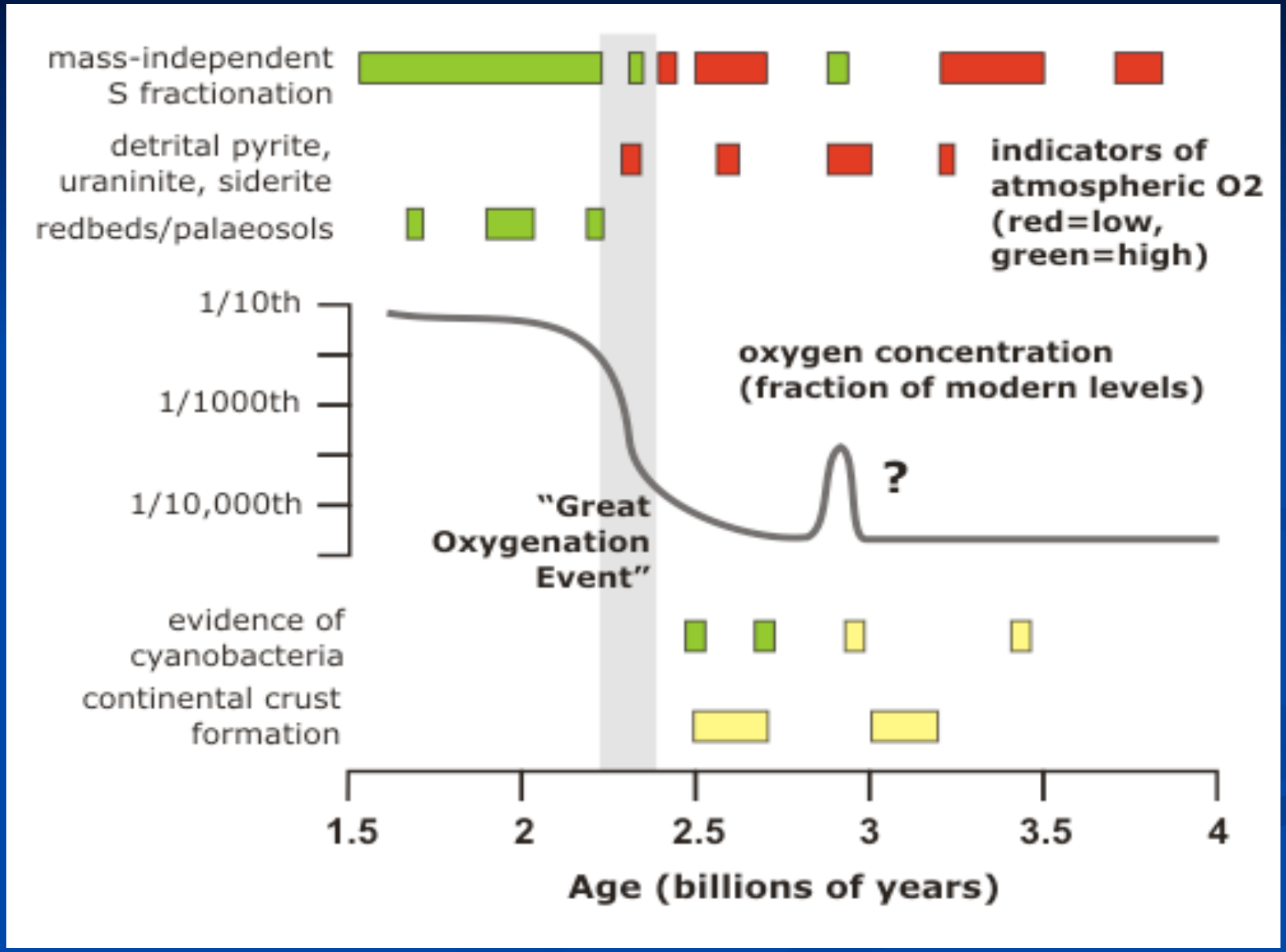
Cyanobacteria and BiFs



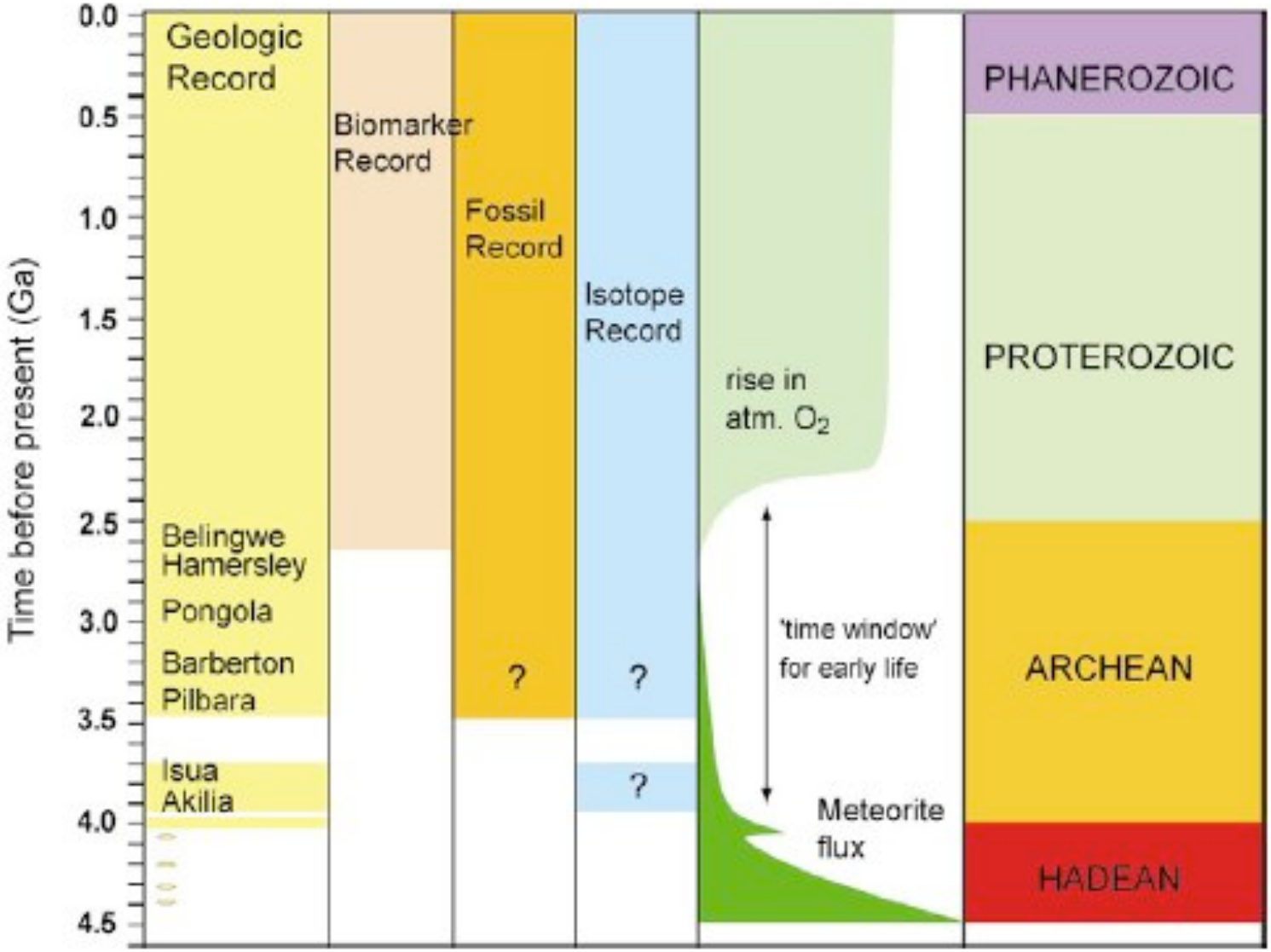


http://hsc.csu.edu.au/earth_environmental/core/time/9_3_1/Image2.gif

Cyanobacteria and Oxygen

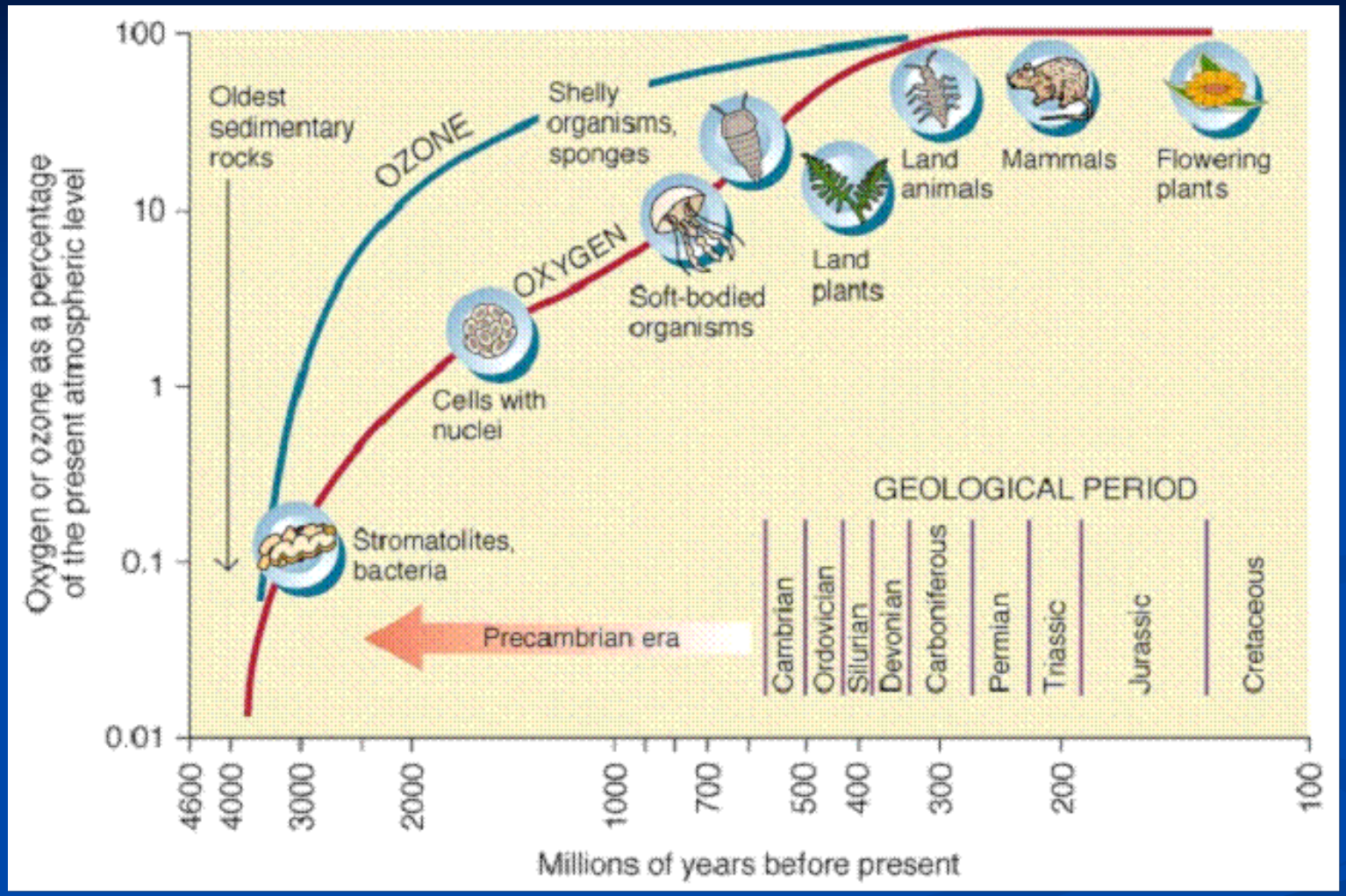


Evidences for Life in Early Earth History



http://www.exobio.cnrs.fr/IMG/jpg/Image1-14.jpg

Free Oxygen and Ozone



http://www.gannon.edu/resource/dept/enviro/EnvGeo/projects2003/atmosphere/page%204_files/image002.gif

Evolution of Atmospheric Carbon Dioxide

High abundances of atmospheric carbon dioxide was needed to provide a strong greenhouse effect for the earth Earth.

Carbon dioxide weathering will influence the chemical composition of soils. Upon lithification, these **paleosols** can provide information on the carbon dioxide abundance of the atmosphere at their time of formation.

Overall, the record of atmospheric carbon dioxide is one of gradual decreasing abundances.

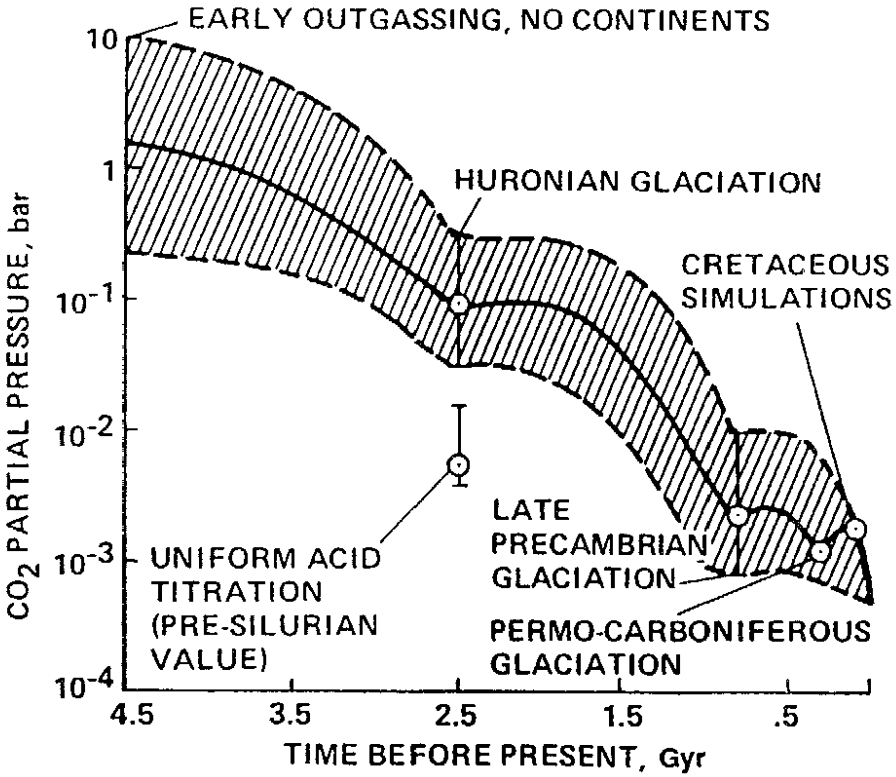
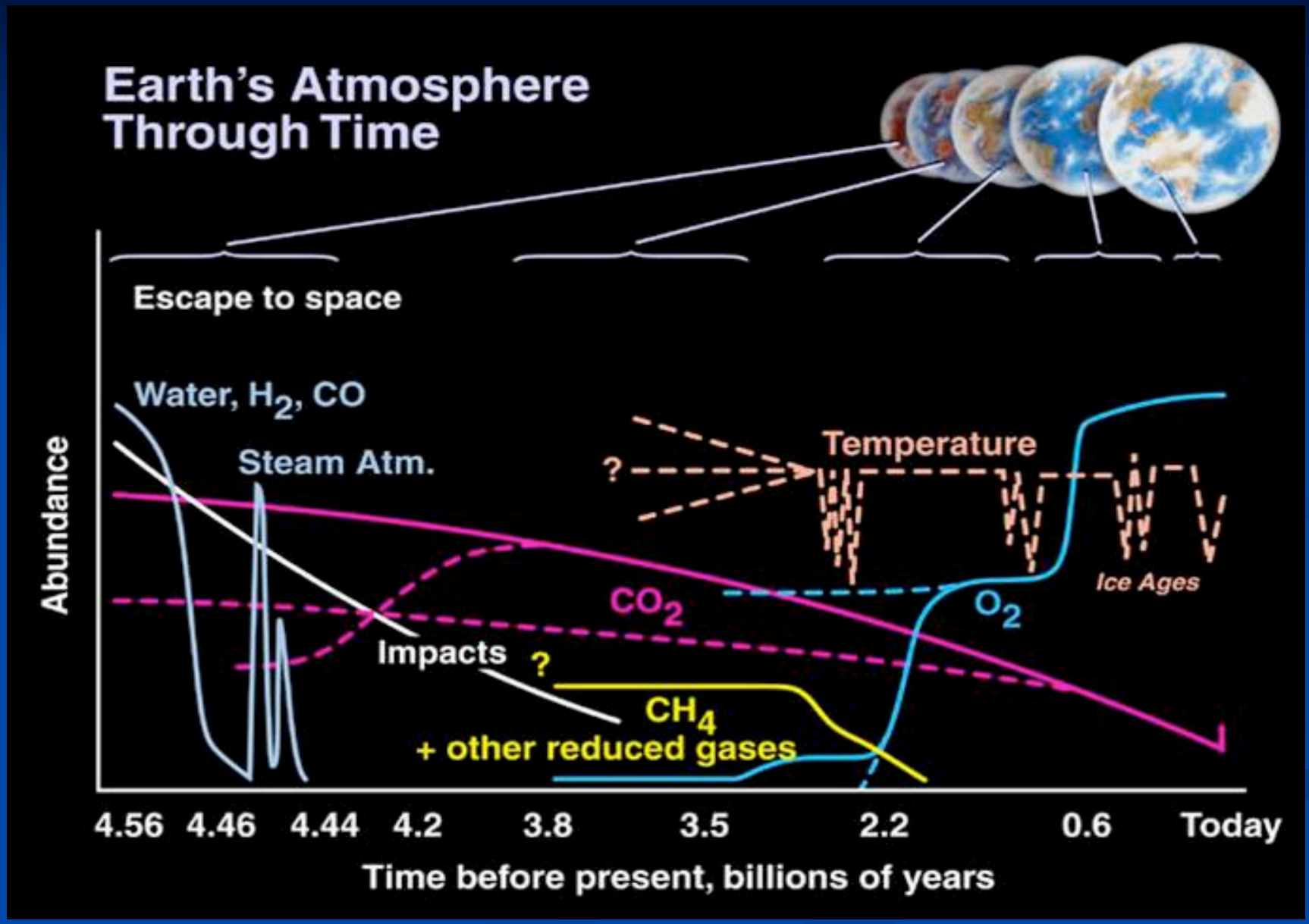


Figure 9.6 Estimated P_{CO_2} over geologic time. The solid line is a best-guess model. The shaded envelope represents the climatologically reasonable range of P_{CO_2}. The point labeled "uniform acid titration" is the pre-Silurian CO_2 pressure estimated by Holland and Zbinden (1986) from paleosol data. After Kasting, J. F., 1987, "Theoretical Constraints on Oxygen and Carbon Dioxide Concentrations in the Precambrian Atmosphere." *Precambrian Res.* **34**, 205.

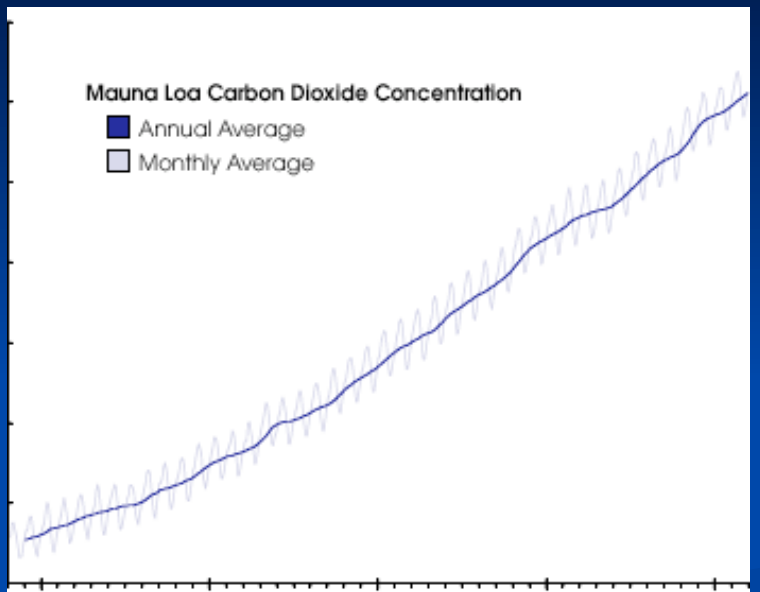
Evolution of the Composition of the Earth's Atmosphere

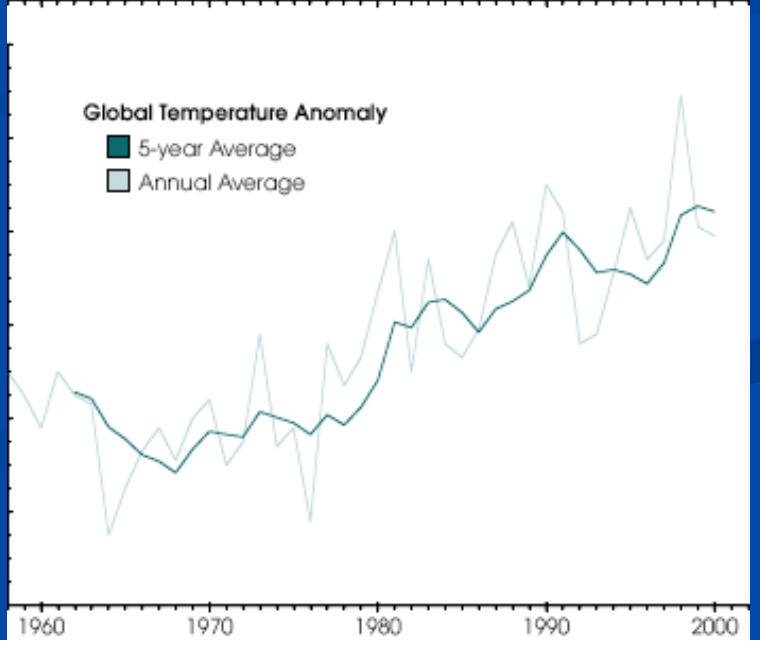


http://shayol.bartol.udel.edu/~rhdt/diploma/lecture_9/earth-atmosphere.jpg

How does the atmosphere respond to environmental change on timescales relevant to life on Earth?

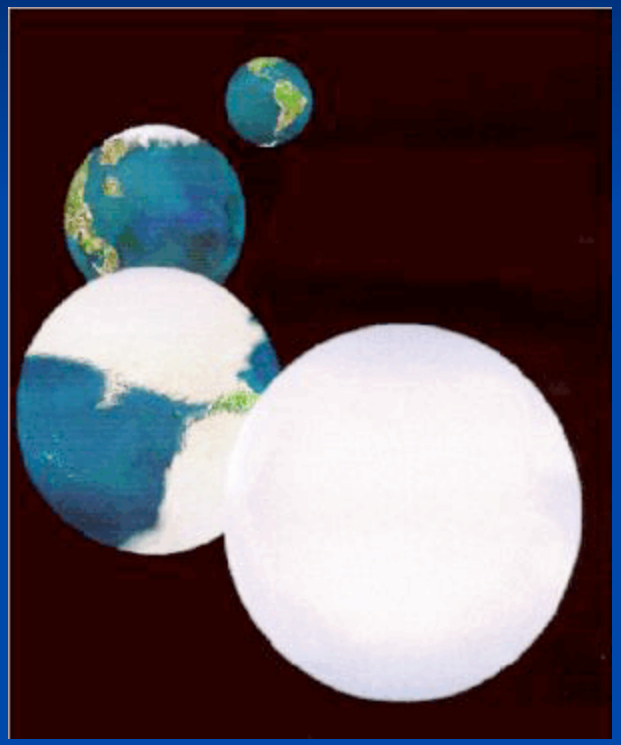




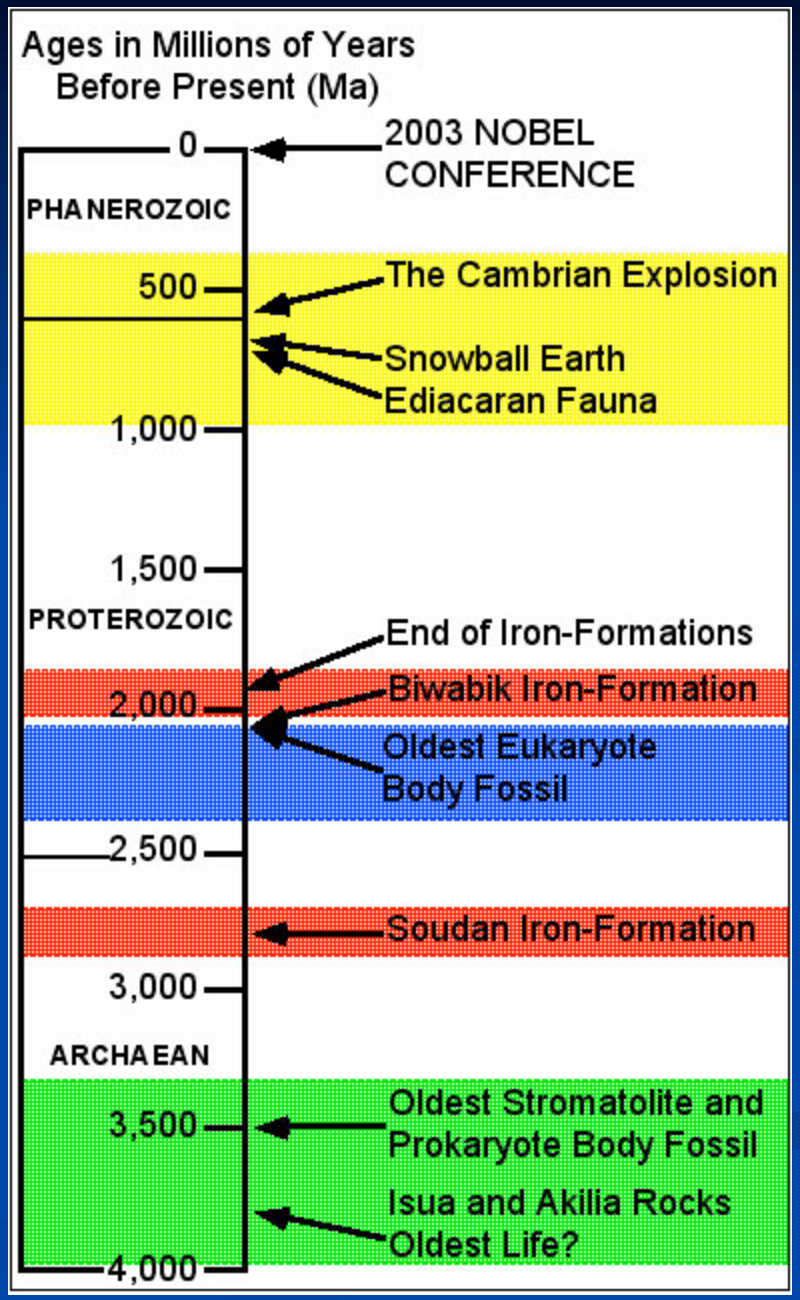


Snowball Earth

Evidence suggest that the Earth has gone through at least one global glaciation.



http://zebu.uoregon.edu/2002/ph123/snowball.gif



http://www.gustavus.edu/oncampus/academics/geology/nobel_display/snowball_time.jpg

The Pleistocene and Pliocene Climate

Paleoclimate records suggest that the Earth's surface temperature over the past few hundred thousand years has undergone numerous and rapid changes.

The mean variation is of order 4-10°C.

Periods of low temperature are generally referred to as Ice Ages.

Periods of warm temperatures are called interglacials. We are currently in an "interglacial."

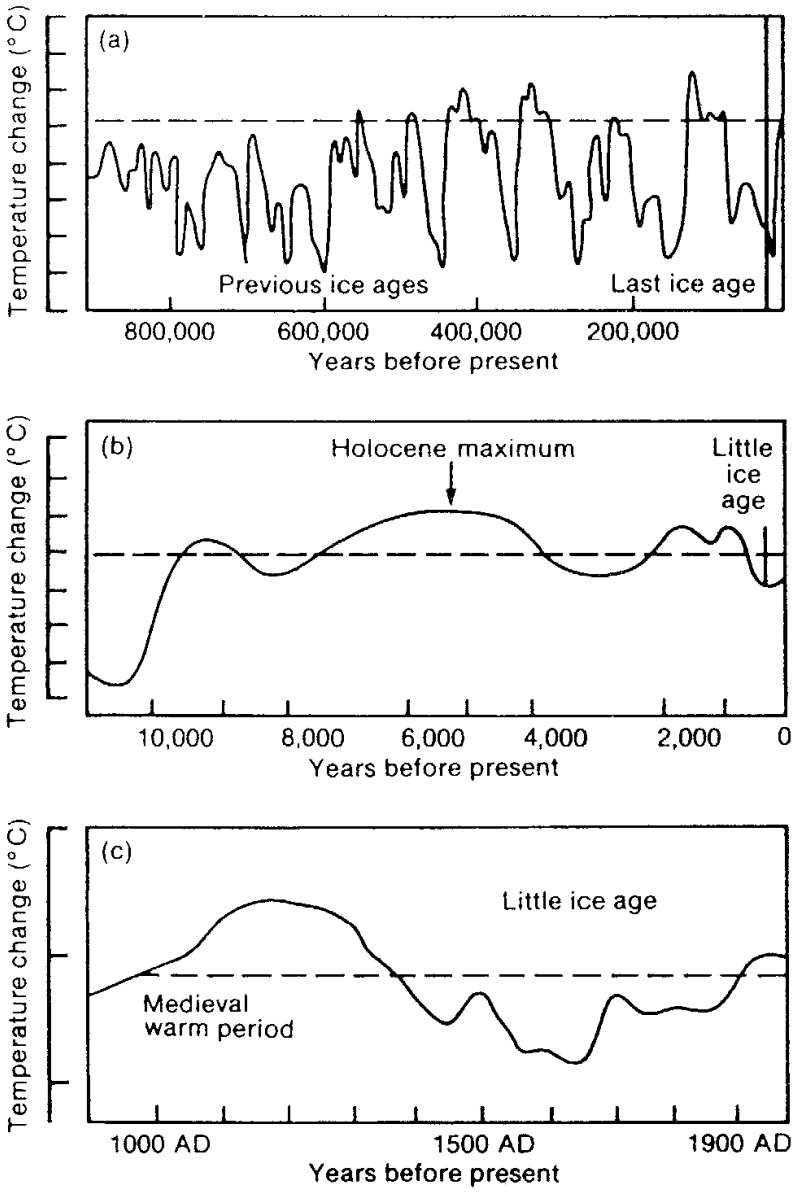
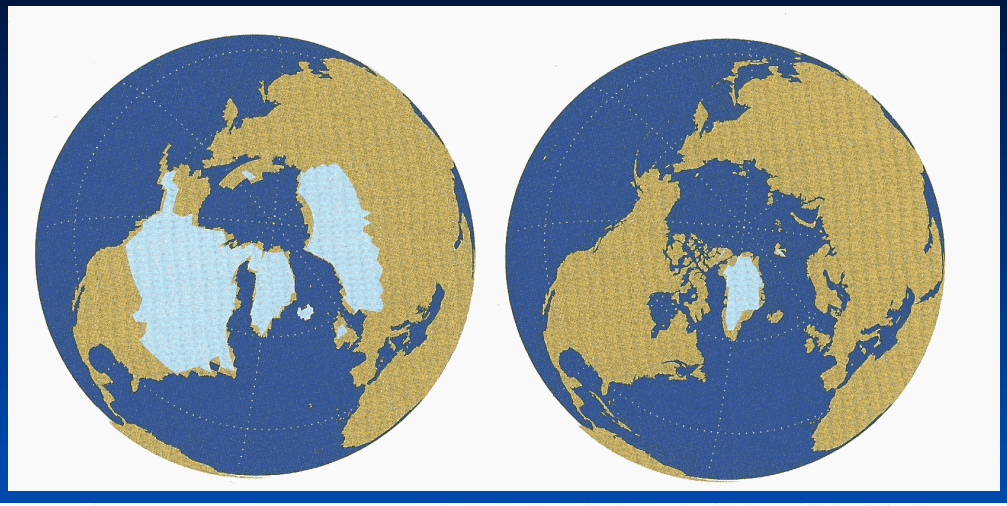
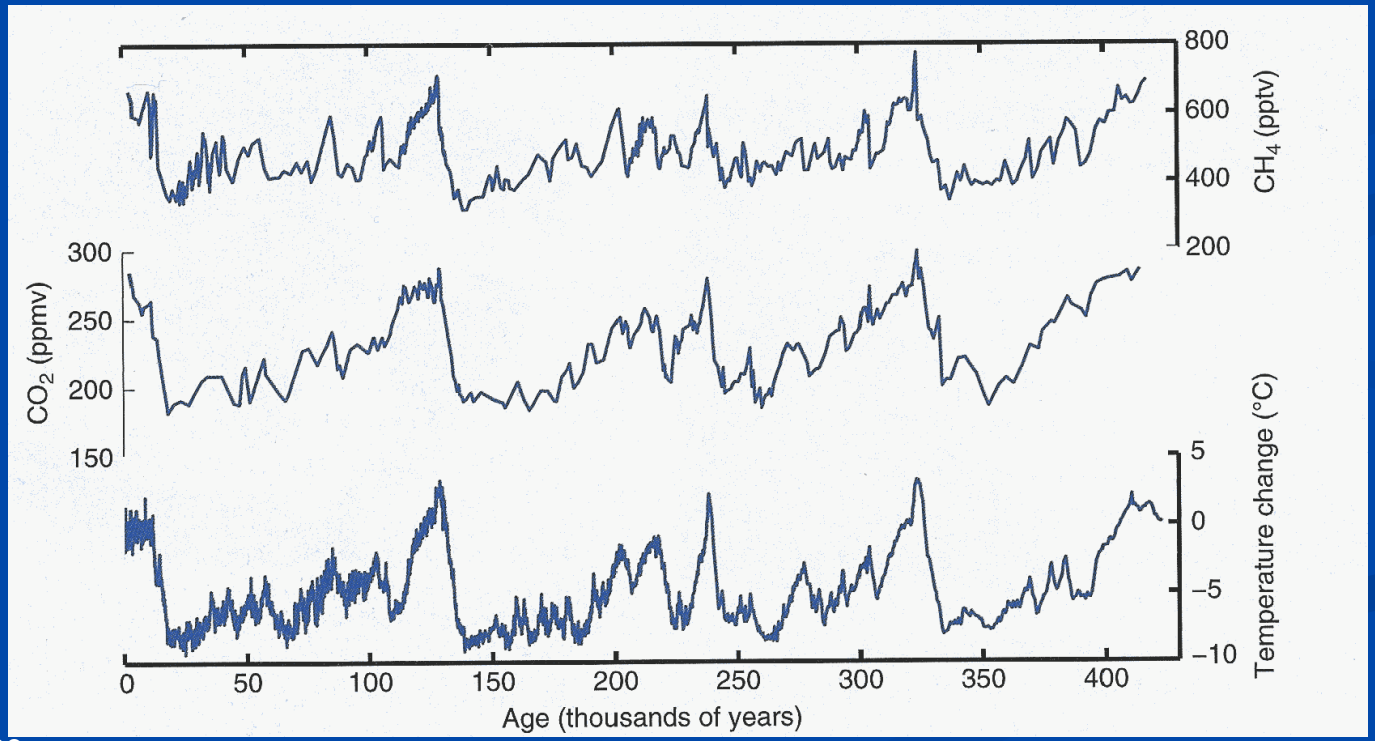


Figure 9.9 Schematic diagrams of global temperature variations for the last million years. Note the different time scales in each panel. The dashed lines represent conditions near the beginning of the twentieth century. After Houghton et al. (1991).

Characteristics of Ice Ages

Ice Ages





CO_2

CH_4

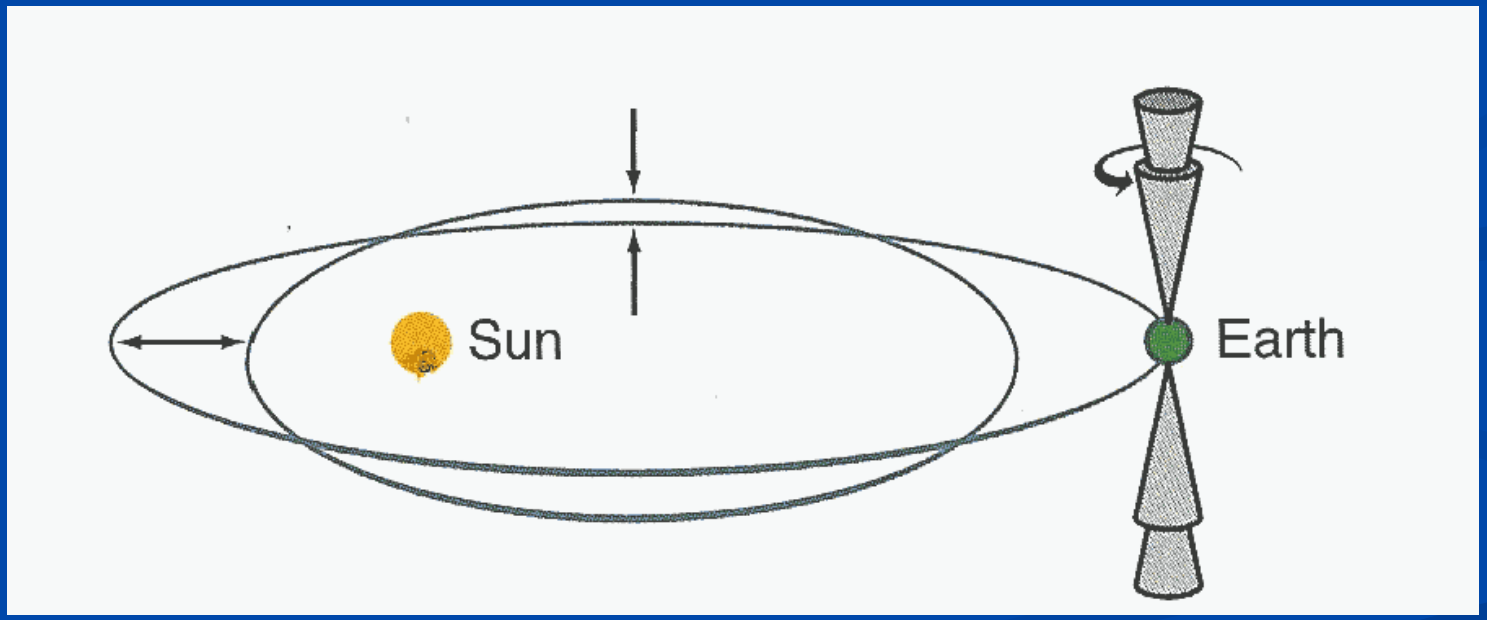
Temperature

Causes of Ice Ages

Variations in Earth's orbital parameters such as obliquity, eccentricity and precession lead to changes in the annual average solar radiation incident upon the Earth.

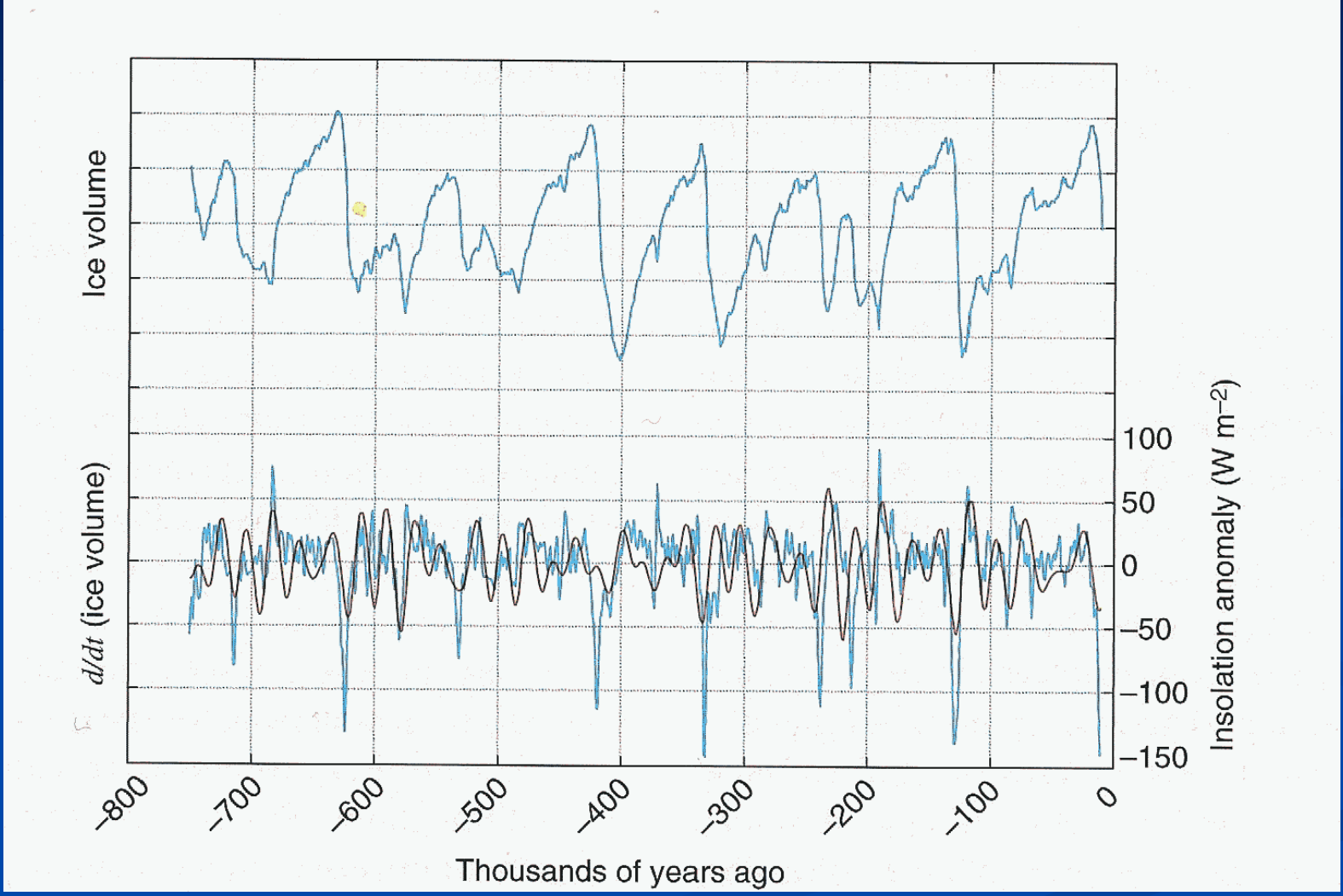
Climate "forcing" from such changes are referred to as Milankovitch cycles.

But this is only one of probably many types of climate forcing.



Causes of Ice Ages

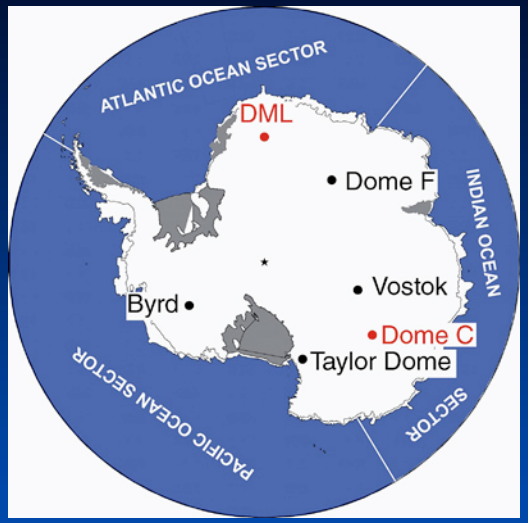
Milankovitch cycles of orbital parameters cause changes in Earth's climate.



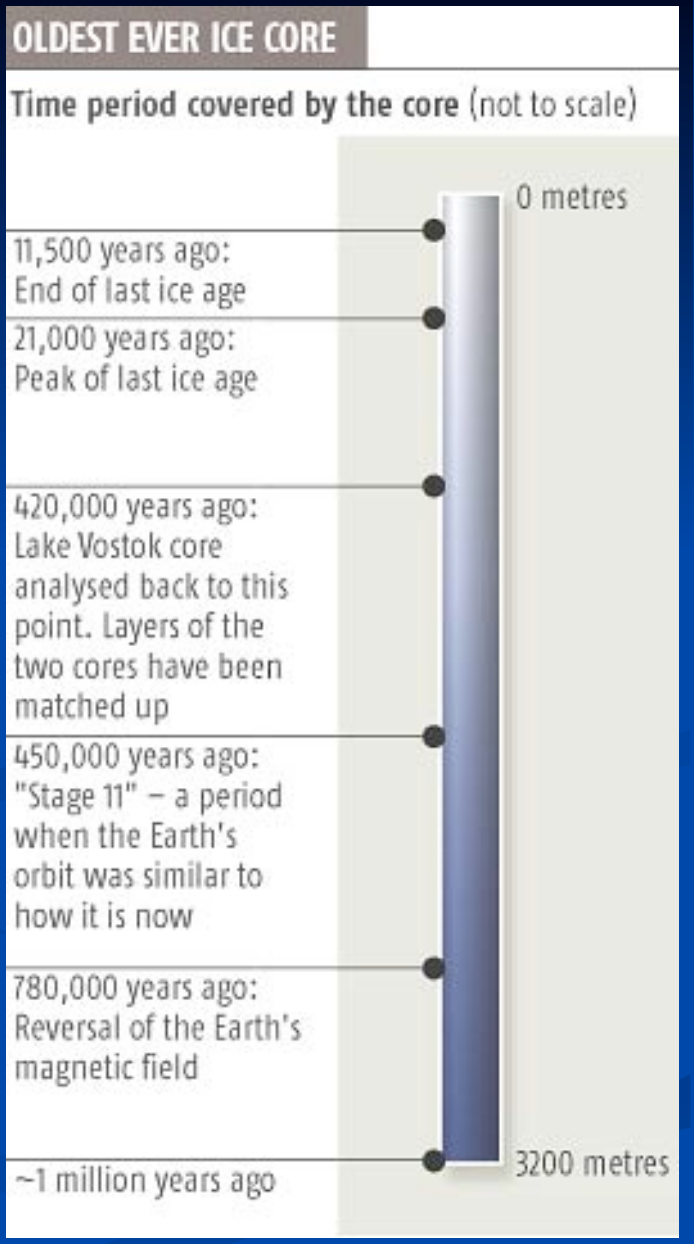
Ice Volume vs. time

Ice Cores




ATLANTIC OCEAN SECTOR
DML
Dome F
INDIAN OCEAN SECTOR
Vostok
Byrd
Dome C
Taylor Dome
PACIFIC OCEAN SECTOR

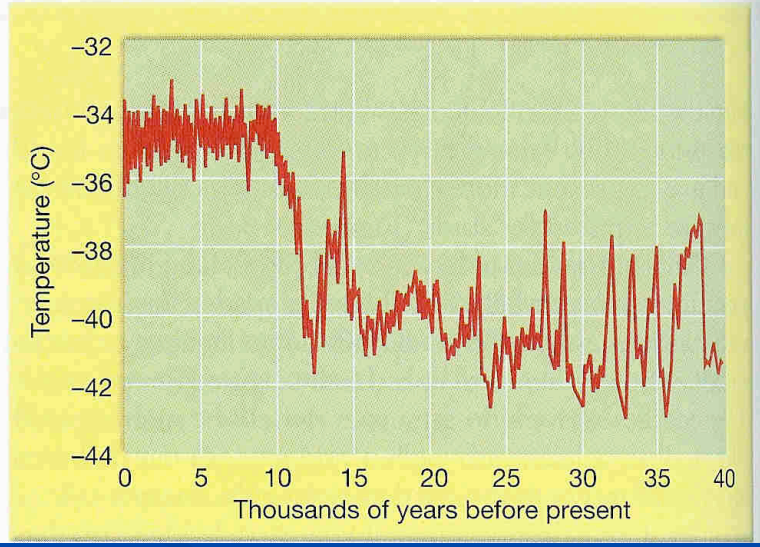



OLDEST EVER ICE CORE
Time period covered by the core (not to scale)
0 metres
11,500 years ago: End of last ice age
21,000 years ago: Peak of last ice age
420,000 years ago: Lake Vostok core analysed back to this point. Layers of the two cores have been matched up
450,000 years ago: "Stage 11" – a period when the Earth's orbit was similar to how it is now
780,000 years ago: Reversal of the Earth's magnetic field
~1 million years ago
3200 metres

Ice Core Analysis

FIGURE 14-3 (a) The National Ice Core Laboratory is a physical plant for storing and studying cores of ice taken from glaciers around the world. These cores represent a long-term record of material deposited from the atmosphere. The lab provides scientists with the capability to conduct examinations of ice cores, and it preserves the integrity of these samples in a repository for the study of global climate change and past environmental conditions. *(Photo by USGS/ National Ice Core Laboratory)* (b) This graph showing temperature variations over the past 40,000 years is derived from oxygen isotope analysis of ice cores recovered from the Greenland ice sheet. *(After U.S. Geological Survey)*

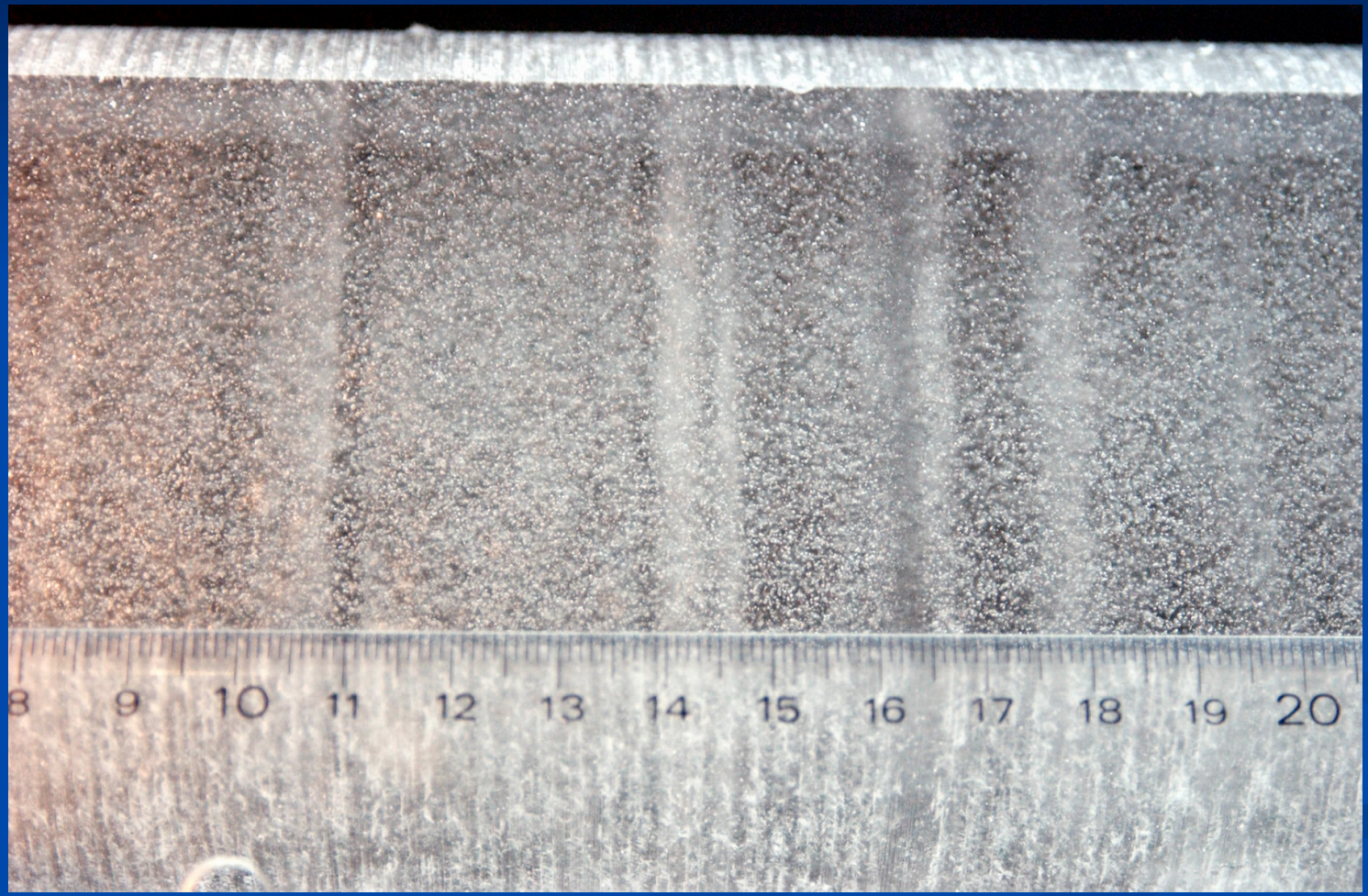




Using oxygen isotope analysis ($^{18}O/^{16}O$ ratios), scientists can use the ratio found in the shells of microorganisms in sediments, and layers of ice and snow, to detect past temperatures.

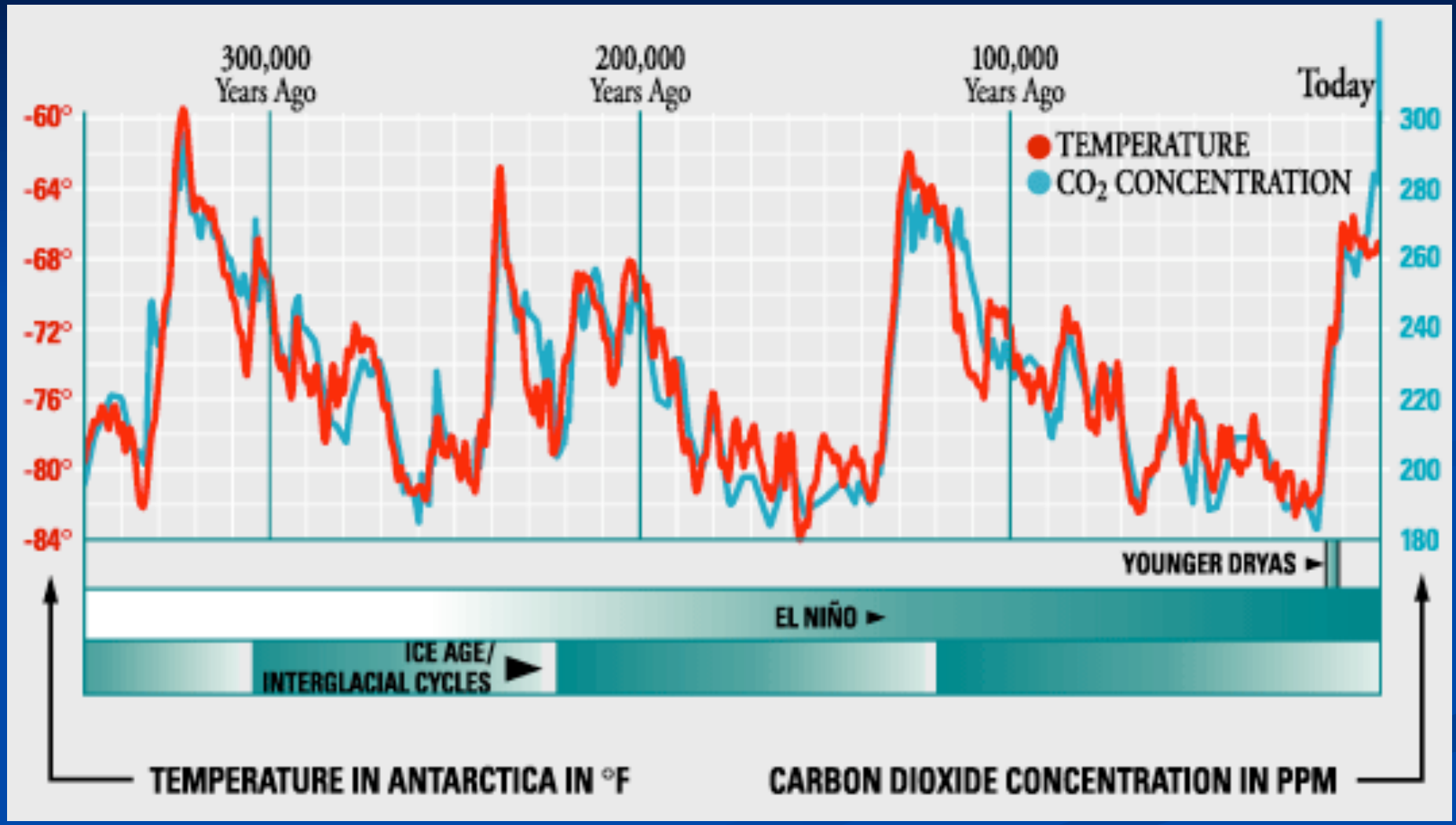
The H/D and $^{18}O/^{16}O$ in water (H_2O) is an indicator of temperature at the time the snow was deposited.

Ice Cores Yield Information on Temperature, CO_2, CH_4, SO_2, dust, pollen, etc.

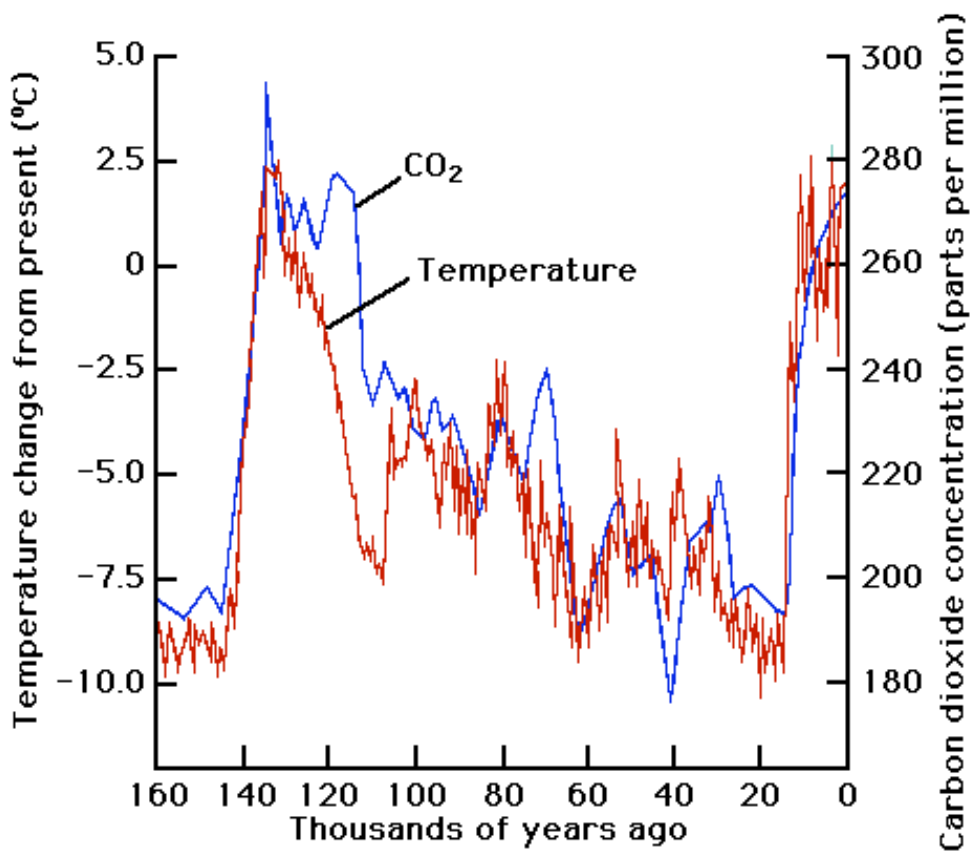


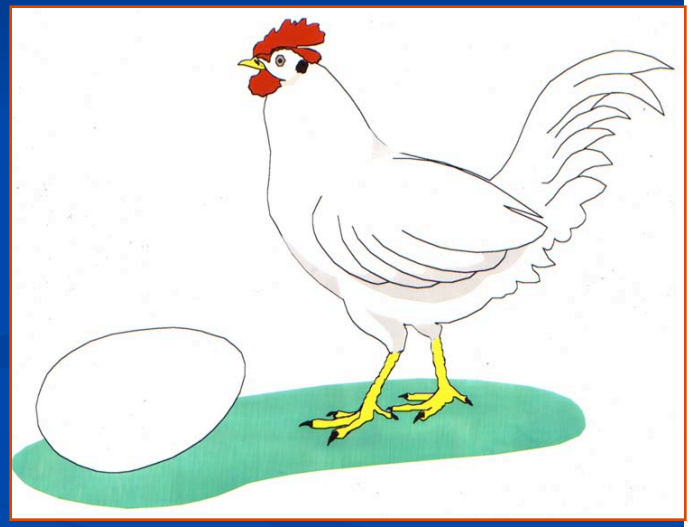
http://www.awi.de/fileadmin/user_upload/News/Press_Releases/2006/1._Quarter/AEROICE-4_p.jpg

Ice Core Temperature and CO_2: Ice Ages



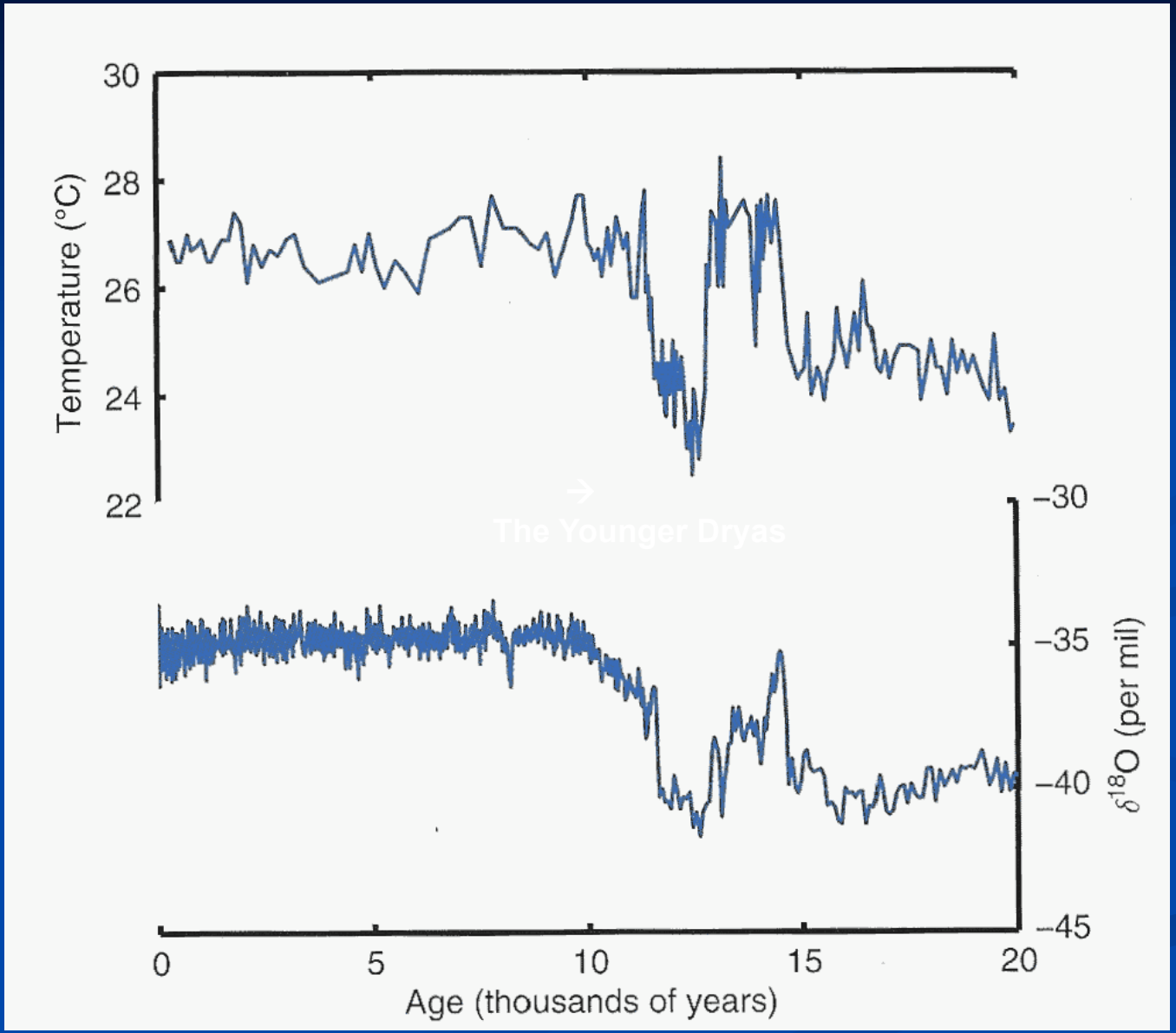
What causes ice ages? CO_2 or temperature?





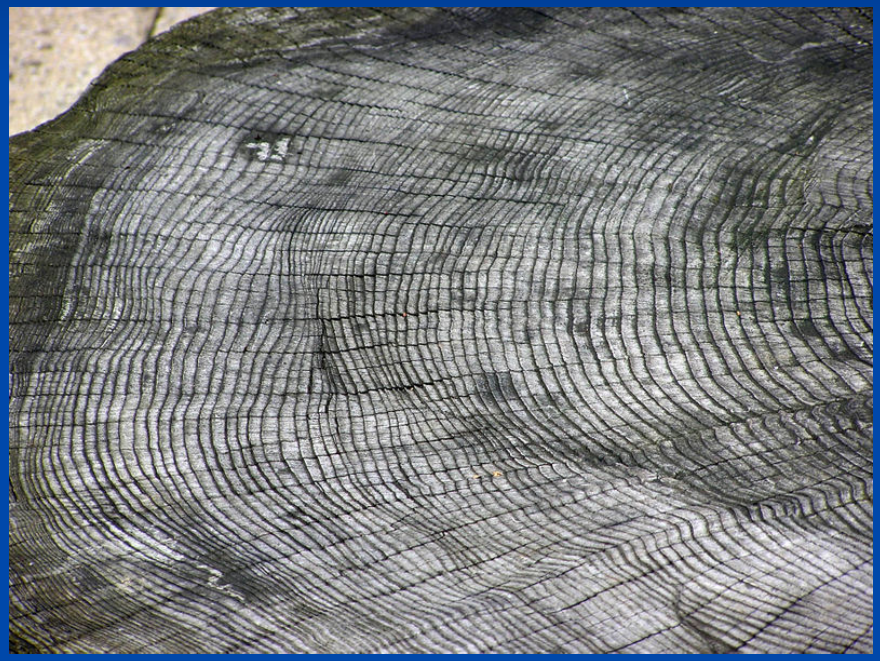
http://www.agen.ufl.edu/~chyn/age2062/lect/lect_29/40_16.GIF

The Last Ice Age and the Younger Dryas



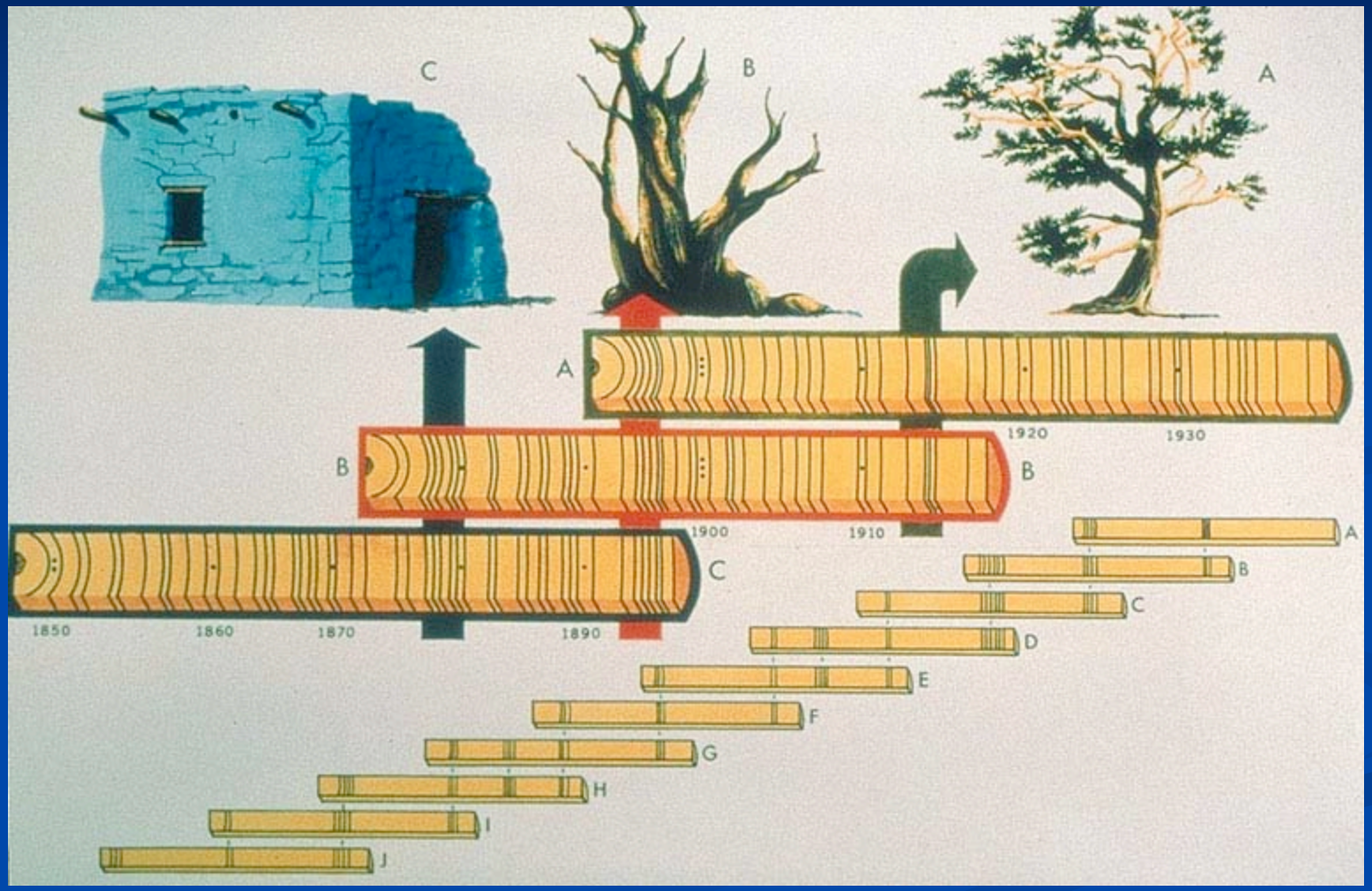
Climate History from Tree Ring Chronologies





Characteristics of each tree ring, such as size and density, reflect the environment (especially climate) that prevailed during the year the ring formed.

Cross-Dating: Samples of trees from overlapping time frames

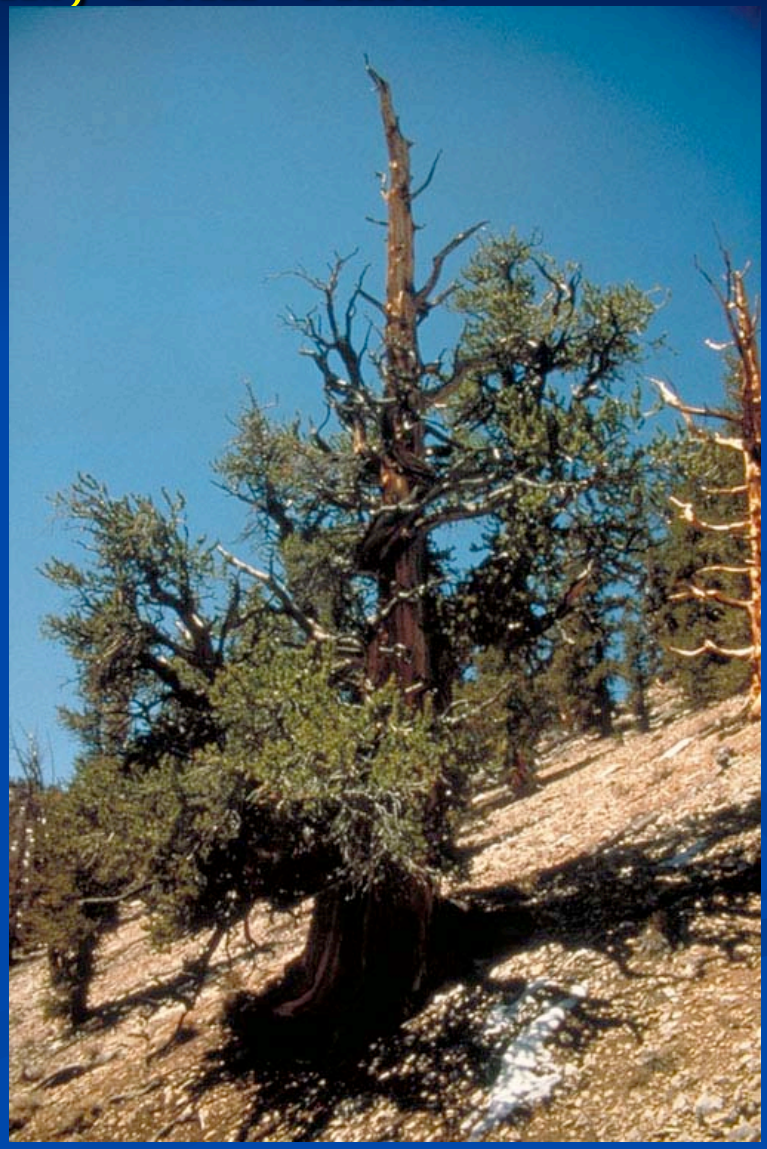


Bristlecone pine (*Pinus longaeva*), White Mountains, California.

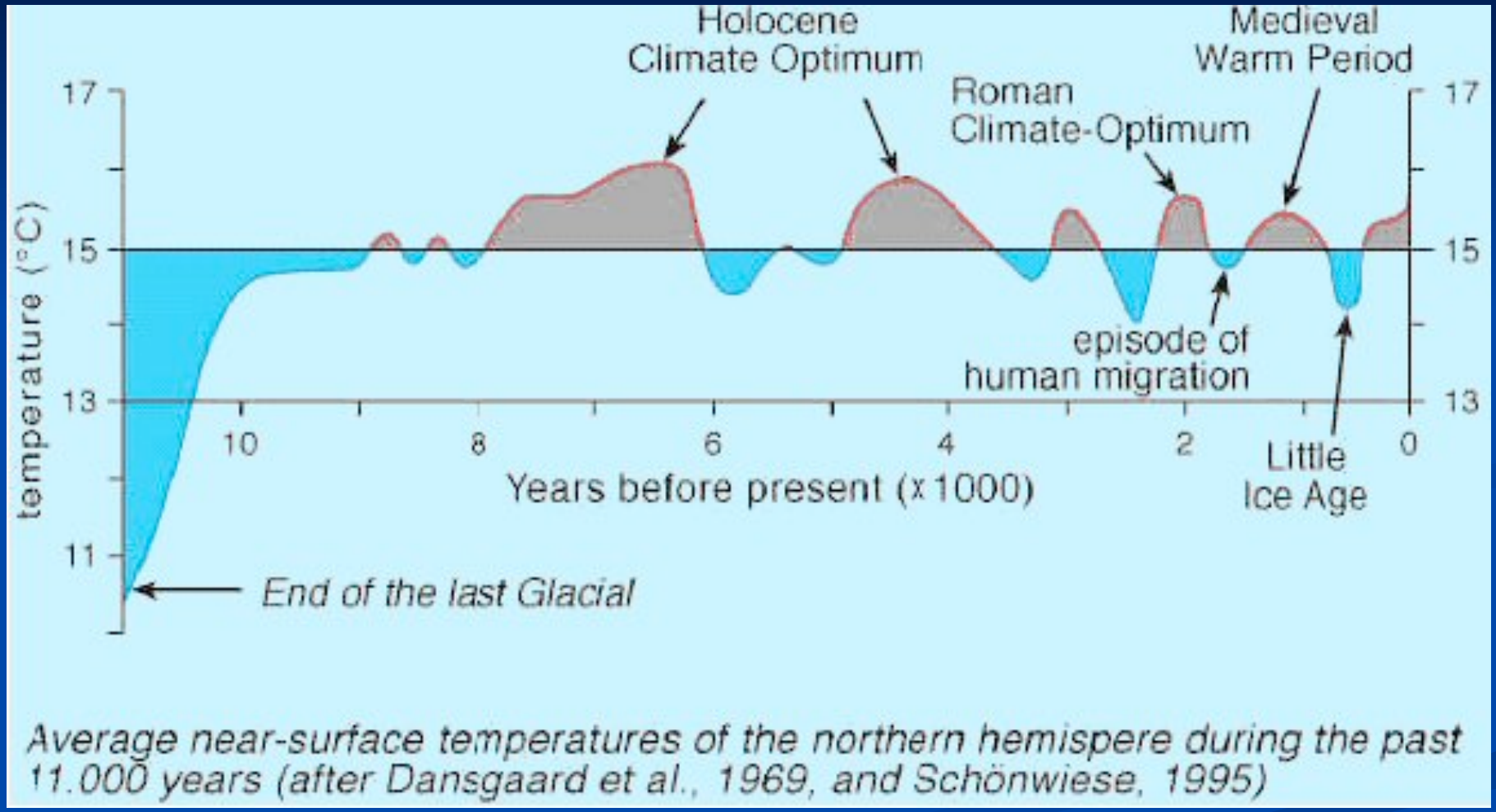
Since one of the goals of dendroclimatology is to reconstruct climate for as long of a period as possible, the oldest trees that can be found are sampled.

Old trees are not always the biggest trees, but are commonly characterized by heavy, gnarled limbs, spiked tops, and in the case of ancient bristlecone pine, "strip bark" stems with only a narrow ribbon of living bark (cambium).

Bristlecone pine of the Great Basin region of western North America are the oldest known living trees, up to 5,000 years old.

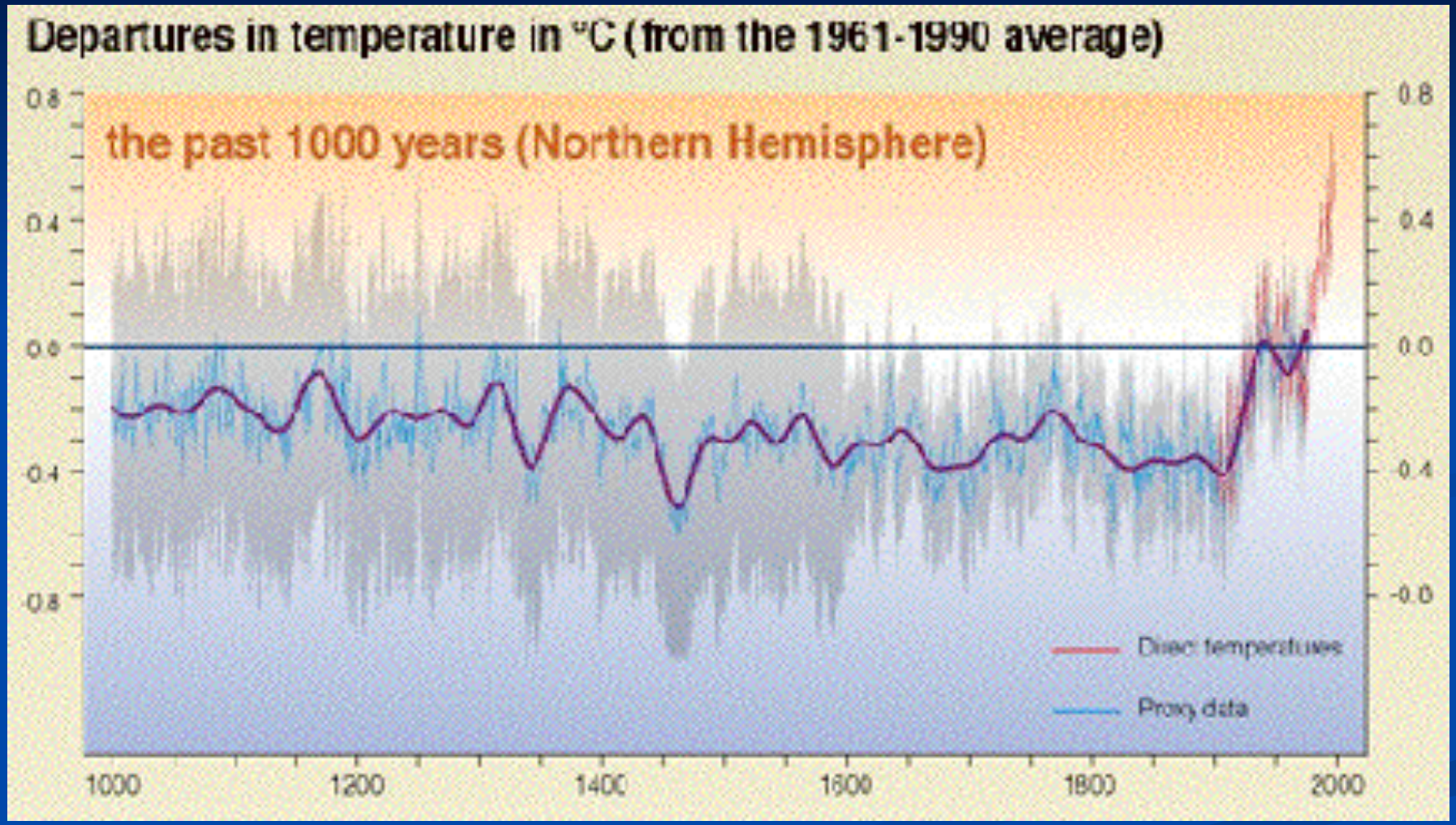


The Last 10,000 years



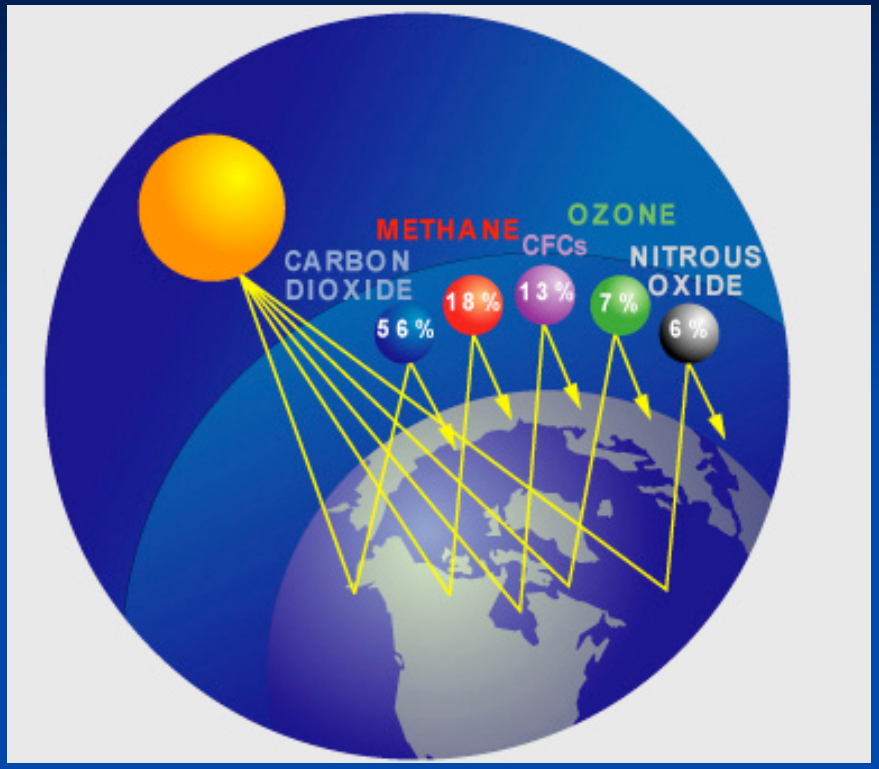
Average near-surface temperatures of the northern hemispere during the past 11.000 years (after Dansgaard et al., 1969, and Schönwiese, 1995)

The Last Millennium

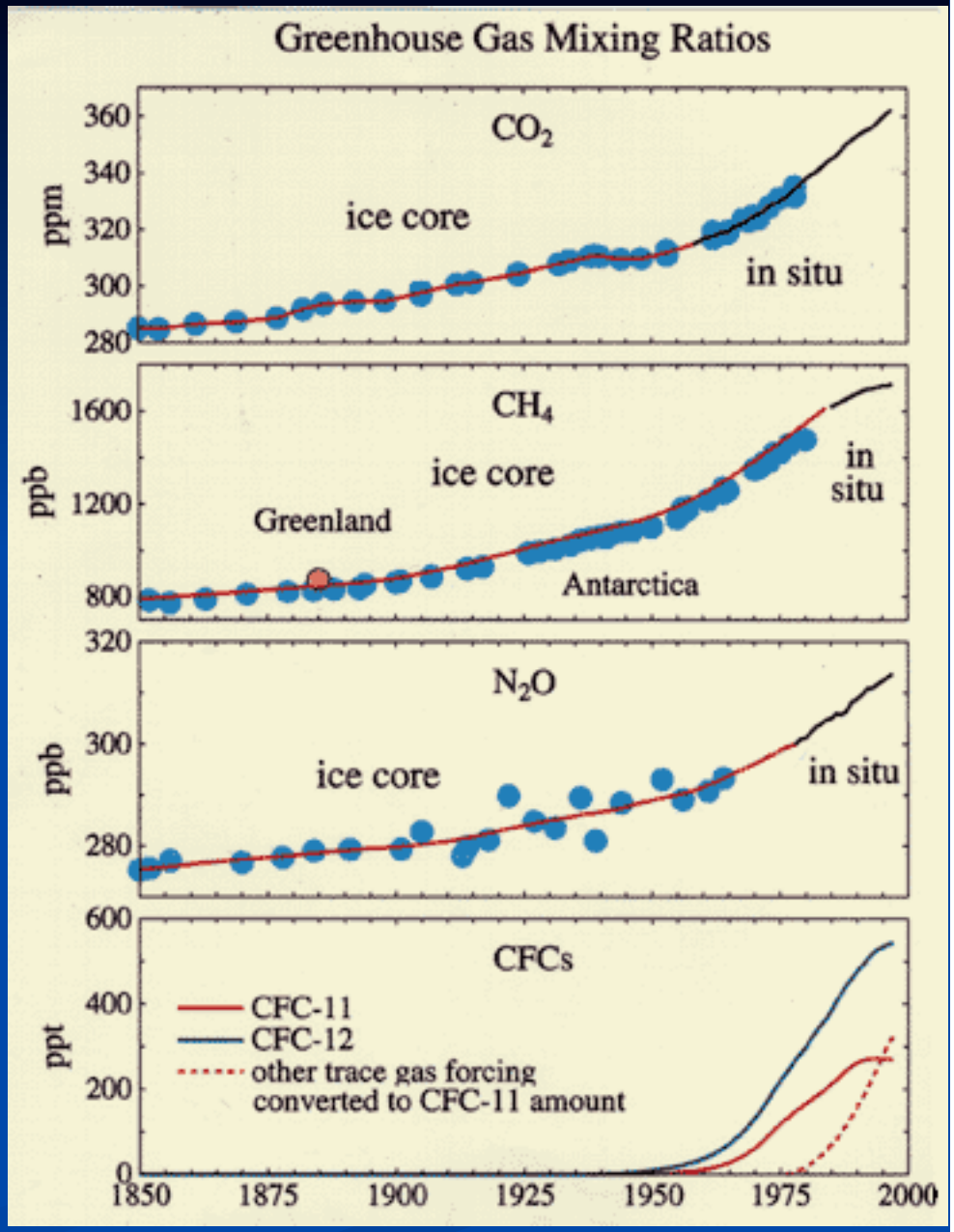


http://muller.lbl.gov/TRessays/MedievalGlobalWarming_files/image003.gif

Greenhouse gases



http://www.koshland-science-museum.org/exhibitgcc/images/causes02.jpg



http://www.agu.org/eos_elec/99148efig1.gif

Sources and Sinks of Sulfur

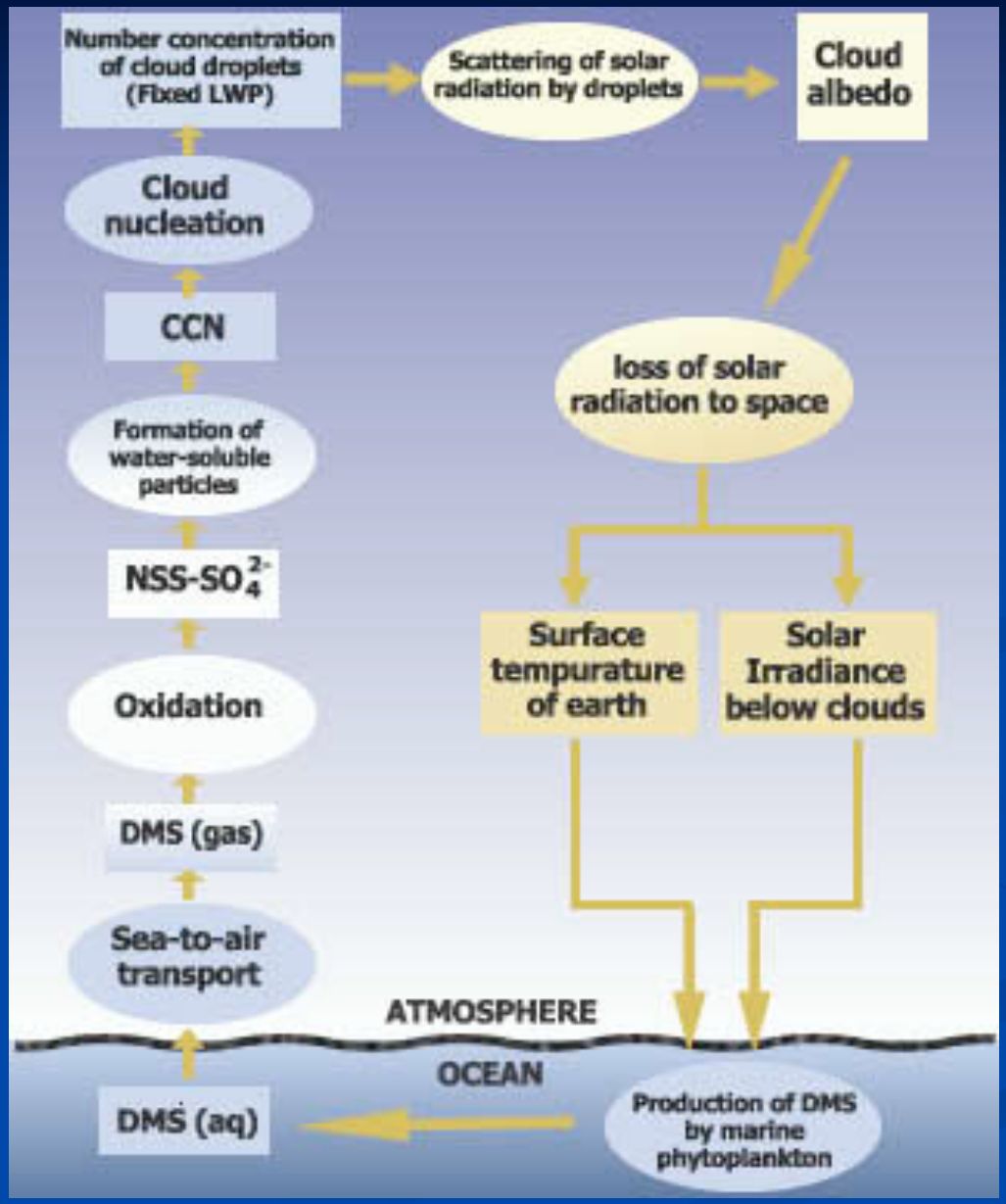
Sources and Sinks

Table 9.7 Estimates of global emission to the atmosphere of gaseous sulfur compounds

Source	Annual flux (Tg)
Anthropogenic (mainly SO_2 from fossil fuel combustion)	80
Biomass burning (SO_2)	7
Oceans (DMS)	40
Soils and plants (H_2S, DMS)	10
Volcanoes (H_2S, SO_2)	10
Total	147 ± 1.4

From Intergovernmental Panel on Climate Change (1990).
The uncertainty ranges are estimated to be about 30% for the anthropogenic flux and a factor of 2 for the natural fluxes.

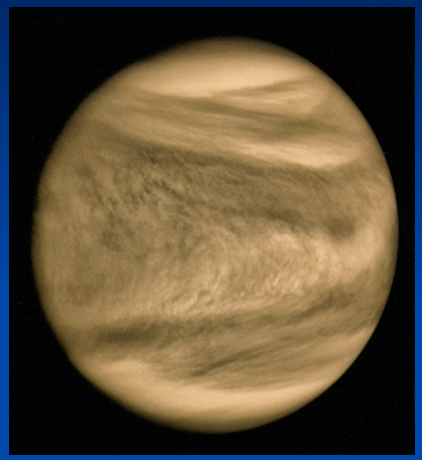
Climate Feedback from DMS



http://www.csa.com/discoveryguides/dimethyl/images/figure1.jpg

What Determines Habitability?

Venus



Too hot

Earth



Just right!

Mars



Too cold

The two primary factors appear to be:
(1) Distance from the Sun
(2) Size & Mass

Comparative Planetary Atmospheres

Table 9.1 Greenhouse effects in planetary atmospheres

	Surface pressure (relative to Earth)	Main greenhouse gases	Surface temperature in absence of greenhouse effect (K)	Observed surface temperature (K)	Warming due to greenhouse effect (K)
Venus	90	> 90% CO_2	227	750	523
Earth	1	~ 0.04%CO_2 ~ 1% H_2O	255	288	33
Mars	0.007	> 90% CO_2	216	226	10

From Intergovernmental Panel on Climate Change (1990).

The Earth clearly stands out in terms of its low relative abundance of carbon dioxide.

So What Factors Contribute to Habitability?

- Distance from sun
- Size
- Surface temperature
- Plate tectonics
- Hydrological cycle
- A Large Moon?
- Others…?

Discussion Questions

(1) What is necessary for a planet to be habitable?

(2) Is the Earth's atmosphere in equilibrium?

(3) Will there be another ice age?

(4) Given the highly complex nature of the Earth's atmosphere, how do you begin to make sense of it all?