Earth and Life in the Late Archaean-Early Proterozoic

The major early events:

1. *Oxygenic (aerobic) photosynthesis.*

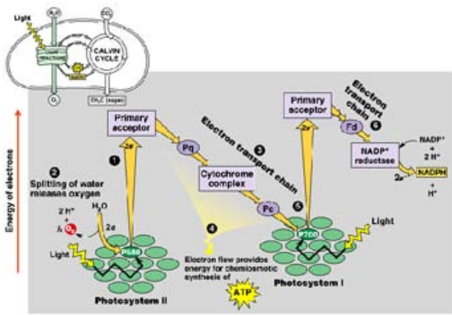
   *Pioneer organism was probably **cyanobacteria***
   (Only anaerobic photosynthesis previously, plus other dominant metabolisms, especially methanogens. Atmosphere probably methane-rich until this point ➔ potent greenhouse gas).
   Why important?…

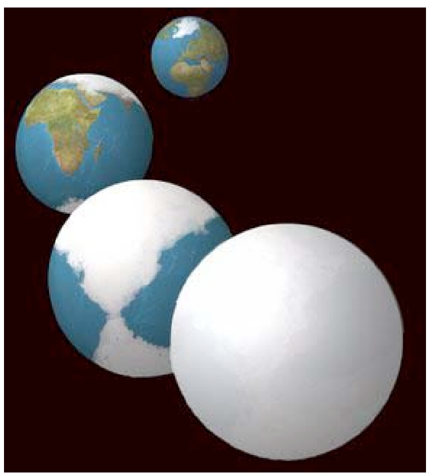
2. *Great Oxidation Event*

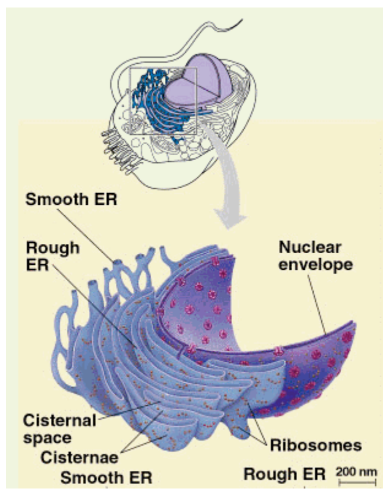
   May have triggered climate disaster (Snowball Earth) and many of the subsequent biological innovations, including multicellular microorganisms, eukaryotic cells, many others.

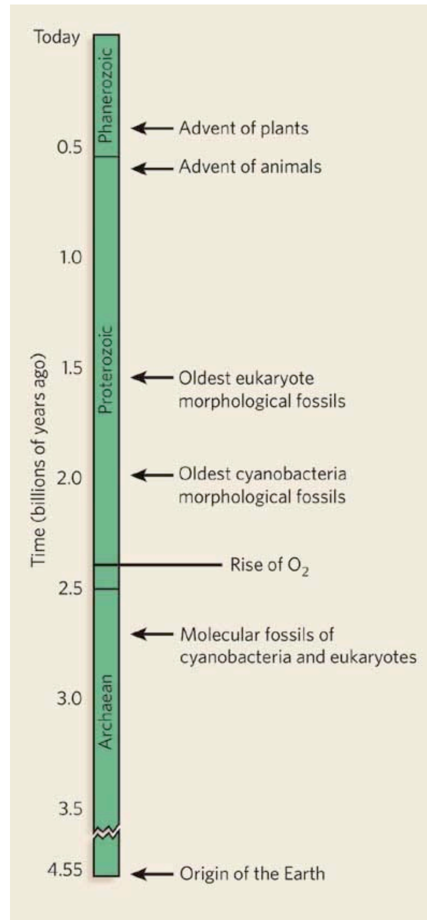
The major questions have to do with the relation between these two.

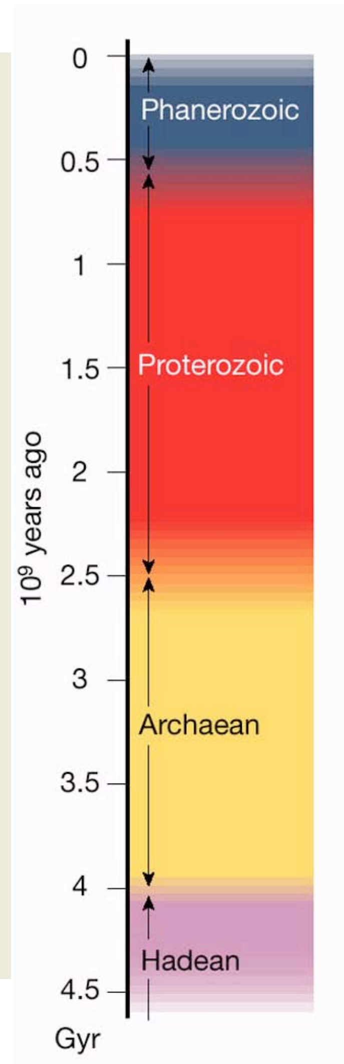
The Late Archean/Early Proterozoic Eon











Atmospheric oxygen: Master of evolution since ~ 2 Gyr ago?

Evidence:

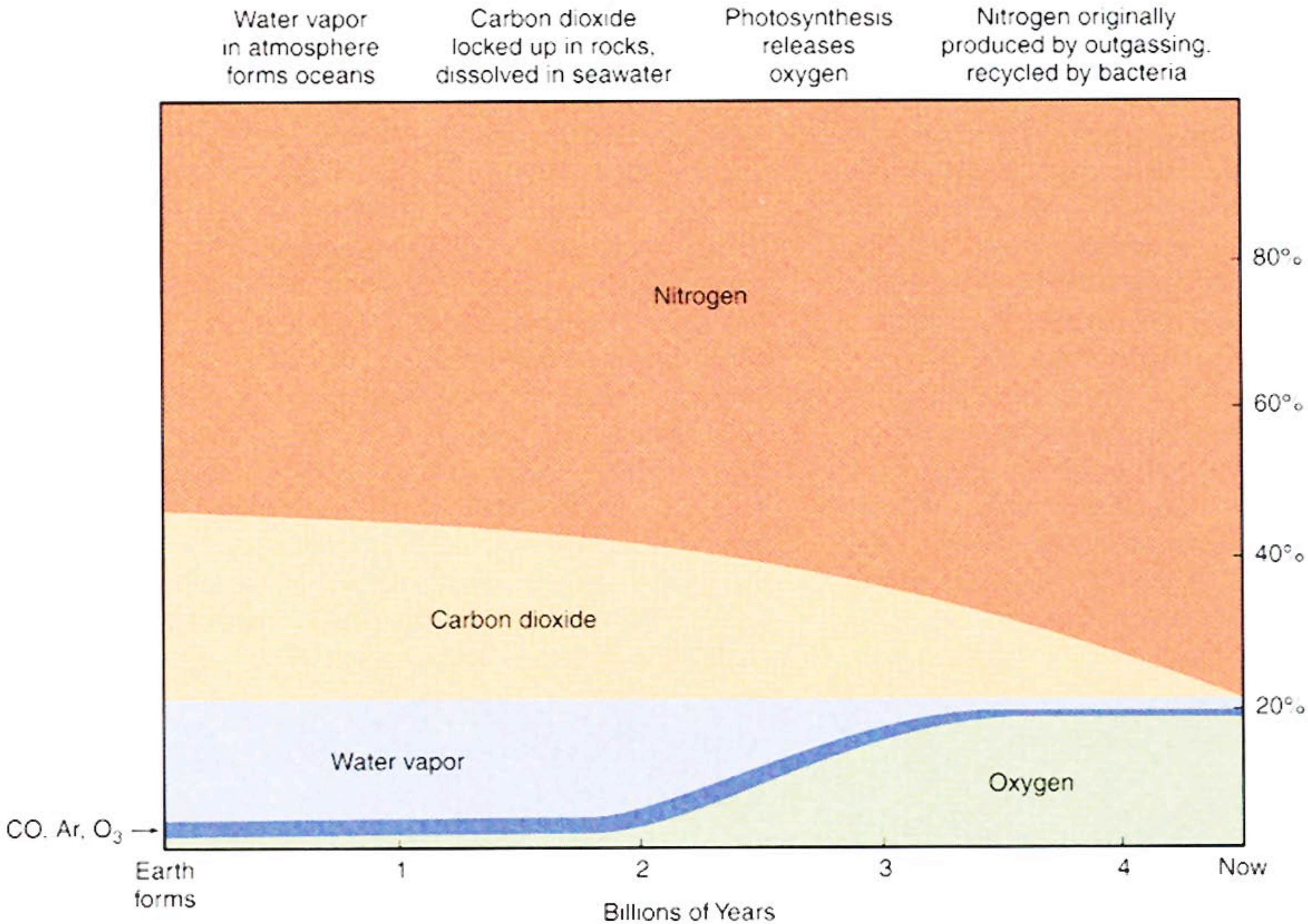
1. Banded iron formations: Form from minerals dissolved in ocean, but this *only* happens in absence of significant oxygen.

So oxygen very low ~ 0.01% back to ~ 2-3 Gyr ago.

2. Sulfur isotope ratios: SO_2, H_2O emitted by volcanoes, but sulfur isotope ratios are altered in presence of oxygen. Shows oxygen very low ~ 0.002% before 2.35 Gyr.

3. "Great oxygen event" at ~ 2.1 Gyr ago. But unsure how much oxygen increased or how long it took (textbook mentions it may have remained *fairly* low, ~ 1%, until Cambrian ~ 0.5 Gyr ago).

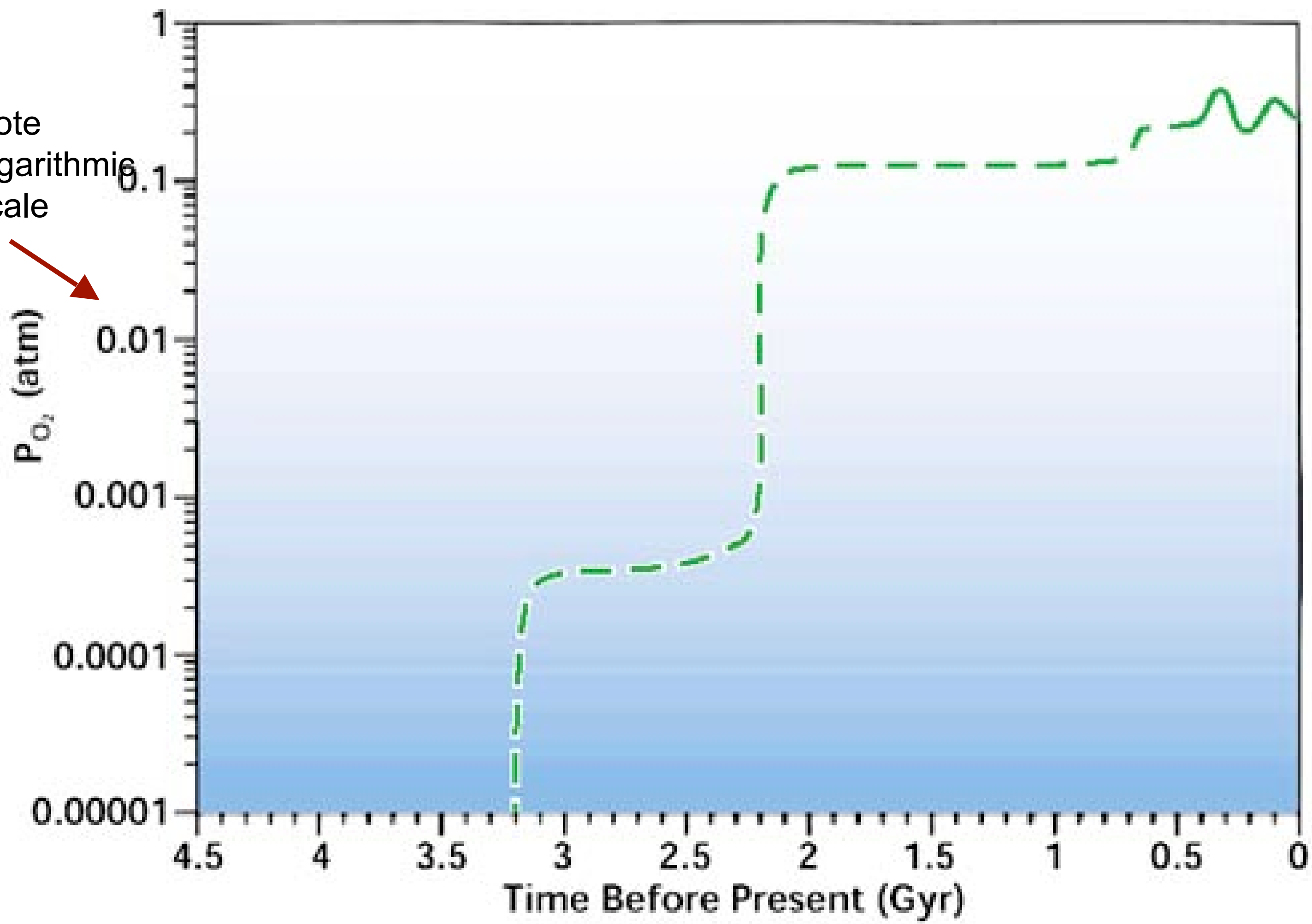
Evolution of the composition of Earth's atmosphere (this is a simplification--see next slide)



Great Oxidation Event(s)

After a minor increase at ~ 3.2 Gyr, a jump by a factor of ~ 100 occurred around 2.2 Gyr ago. Subsequent wiggles may also be important for terrestrial biology.

Note logarithmic scale

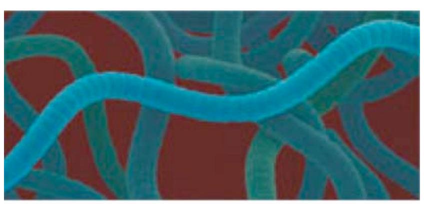


Aerobic photosynthesis and the rise of oxygen

When did oxygenic photosynthesis evolve?

The question is significant because photosynthetic oxygen production by **cyanobacteria** led to **oxygenation** of the atmosphere and oceans, in turn allowing **aerobic respiration** and the evolution of large, complex and ultimately intelligent organisms.

Early life was anaerobic, and developed glycolysis for energy transfer, a pathway still used in all known cells. Glycolysis was sufficient for single-cell life, but no known examples of multicellular complex organisms that are exclusively anaerobic. Further complexity apparently awaited pathways for larger energy transfer: **aerobic photosynthesis**. For example thiamin and B_{12} synthesis are old anoxic pathways rewired to take advantage of oxygen.



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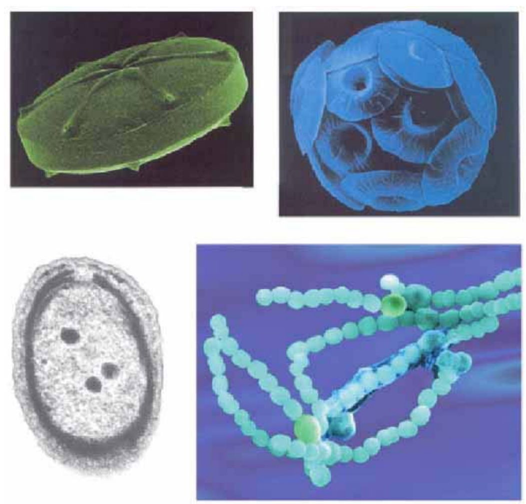

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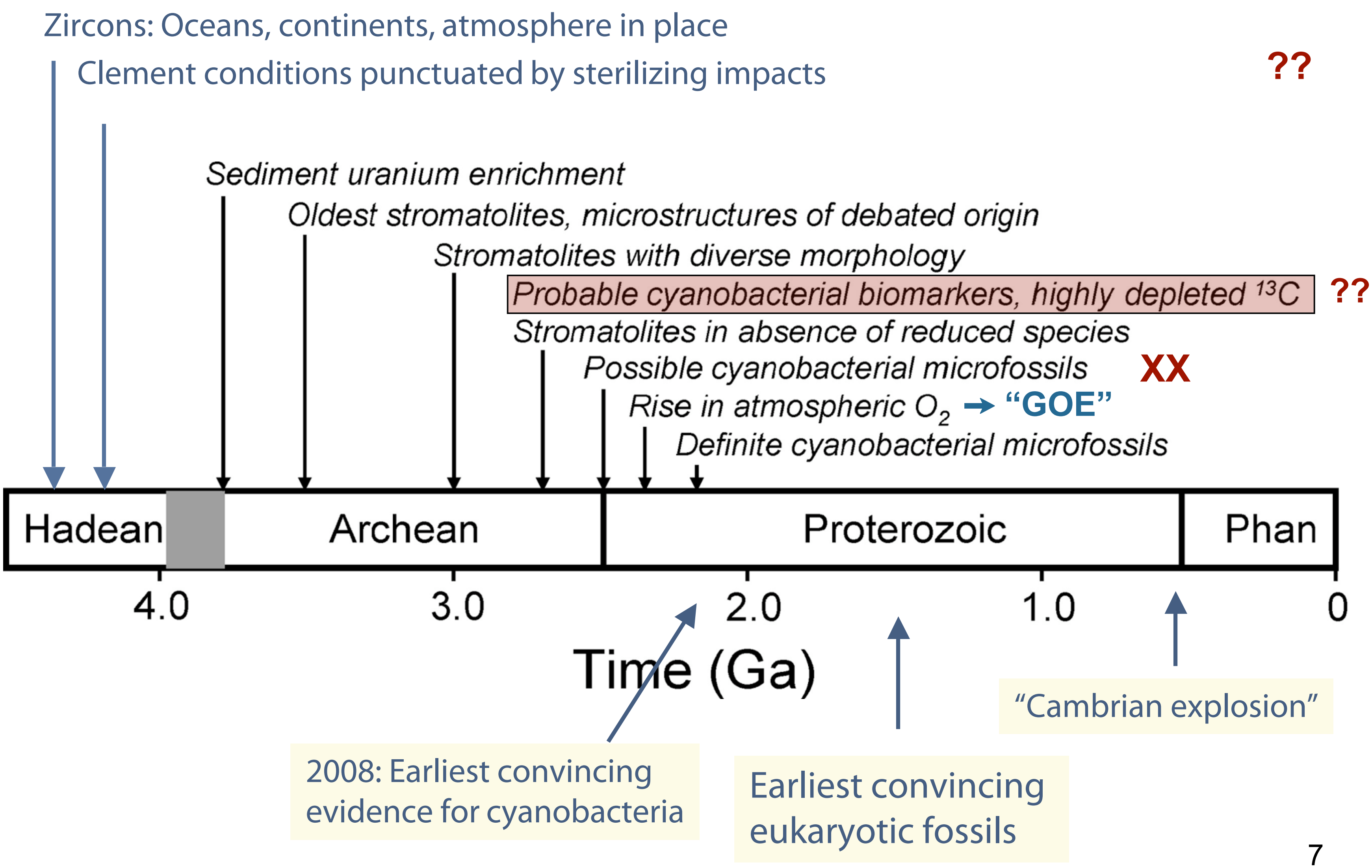
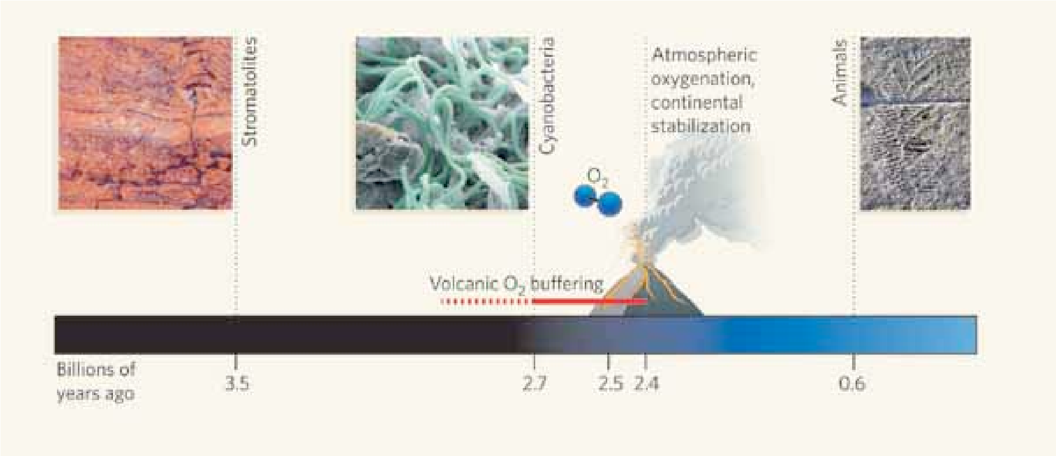
Summary of *possible* evidence related to timing of oxygenic photosynthesis and GOE



A timing problem (now vanished?)

Because cyanobacterial lipid biomarker and other evidence was so much earlier than the Great Oxidation Event, needed to store O_2 in crust until saturated, then released from vents, volcanoes.



Kump et al. (2005): Emergence of volcanoes from the sea

See Buick 2008 abstract below: Argues that there is strong evidence for cyanobacteria at *very* early times

Buick, R. 2008 PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B-BIOLOGICAL SCIENCES **Volume:** 363 **Issue:** 1504 **Pages:** 2731-2743

Abstract: The atmosphere has apparently been oxygenated since the 'Great Oxidation Event' ca 2.4 Ga ago, but when the photosynthetic oxygen production began is debatable. However, geological and geochemical evidence from older sedimentary rocks indicates that oxygenic photosynthesis evolved well before this oxygenation event. Fluid-inclusion oils in ca 2.45 Ga sandstones contain hydrocarbon biomarkers evidently sourced from similarly ancient kerogen, preserved without subsequent contamination, and derived from organisms producing and requiring molecular oxygen. Mo and Re abundances and sulphur isotope systematics of slightly older (2.5 Ga) kerogenous shales record a transient pulse of atmospheric oxygen. As early as ca 2.7 Ga, stromatolites and biomarkers from evaporative lake sediments deficient in exogenous reducing power strongly imply that oxygen producing cyanobacteria had already evolved. Even at ca 3.2 Ga, thick and widespread kerogenous shales are consistent with aerobic photoautrophic marine plankton, and U-Pb data from ca 3.8 Ga metasediments suggest that this metabolism could have arisen by the start of the geological record. Hence, the hypothesis that oxygenic photosynthesis evolved well before the atmosphere became permanently oxygenated seems well supported.

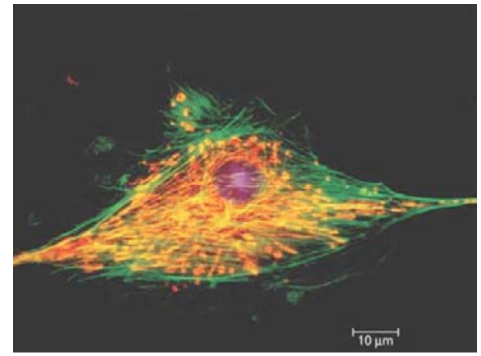
See meeting issue "Photosynthetic and atmospheric evolution"
Philosophical Transactions of the Royal Society B 363, 15 04 Aug 2008,
Can access through UTNetLibrary

Eukaryotes and Endosymbiosis

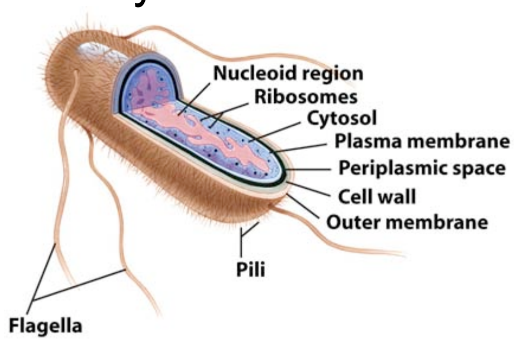
Suggestion: Look up "endosymbiosis"

Eukaryotic microorganisms

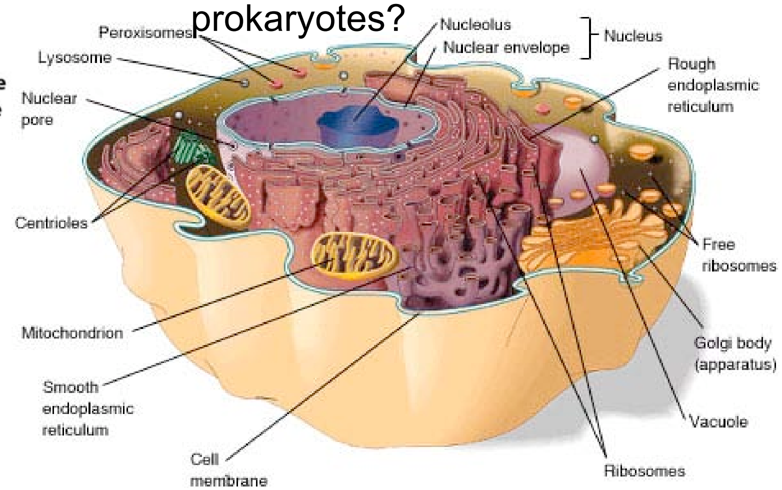
Eukaryotic cell



Prokaryotic cell



Eukaryotic (animal) cell: Huge increase in structural complexity. Organelles former free-living prokaryotes?



Cytoskeleton

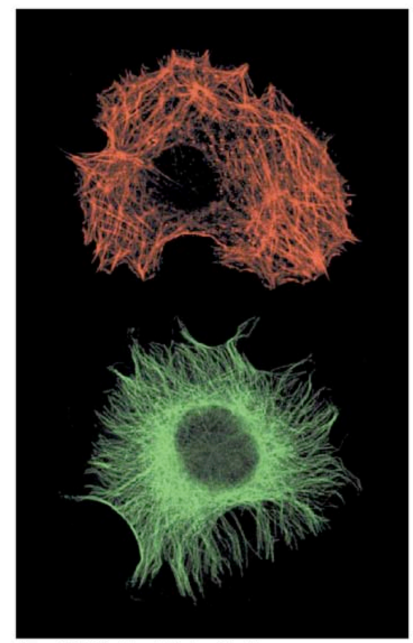


Figure 1-16 Principles of Biochemistry, 4/e

A few suggested results of the Great Oxygenation Event

1. Destroyed the methane greenhouse from methanogenic bacteria, triggering a snowball event on a short timescale.

2. Ultra-high reactivity of oxygen resulted in extinction of most organisms, who were unprepared to adapt. *Some* anaerobes did survive, but the world of larger organisms was to be aerobic from this time on. ***There are no known multicellular organisms that are strictly anaerobic.***

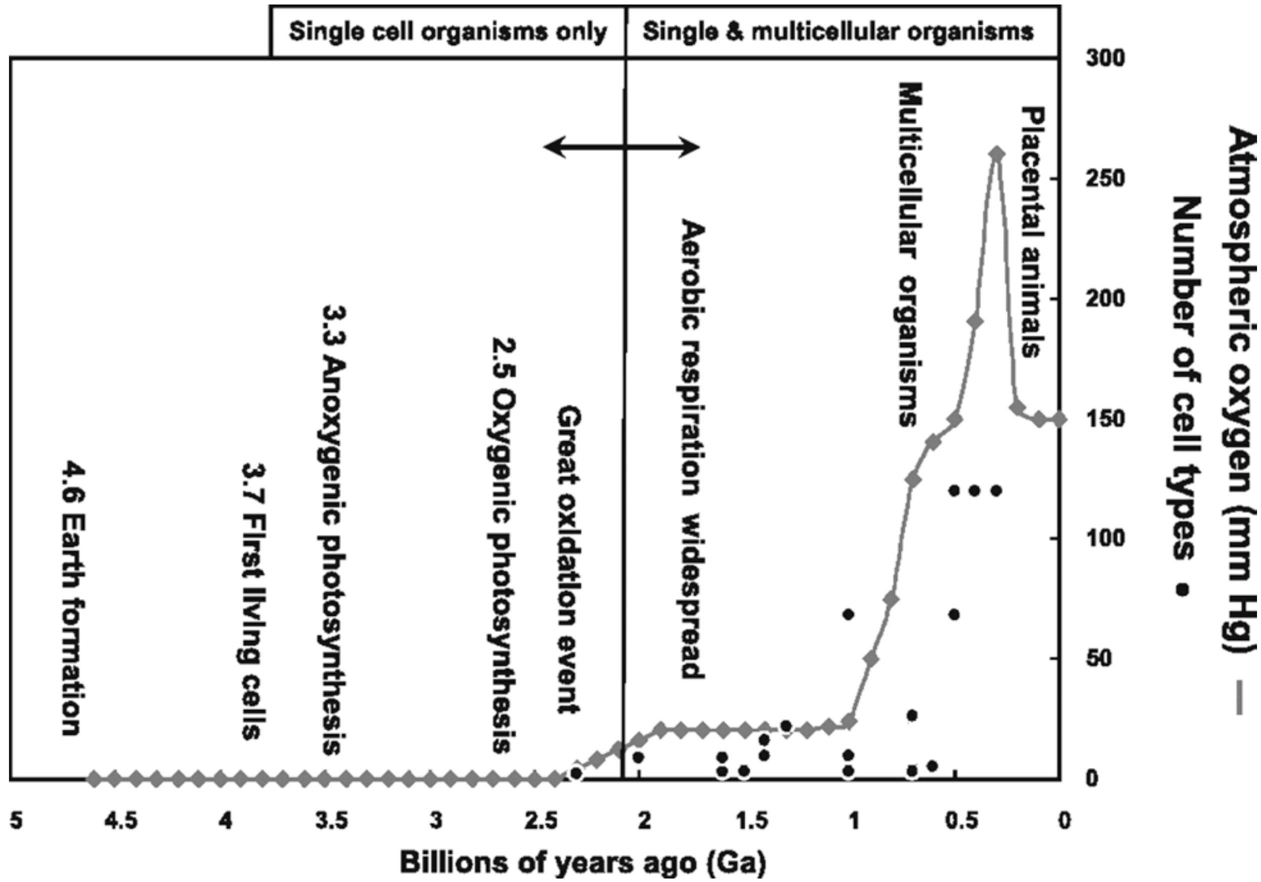
3. Greatly enlarged **range of metabolic networks**. Before oxidation event, only glycolysis. Larger organisms than single cells required more efficient energy producers.

New metabolic networks enlarged pathways for synthesis of metabolites. Thiamin and B_{12} synthesis are two well-known examples.

Many more--ask me if you want references. For example:

Evolution, atmospheric oxygen, and complex disease.
L. G. Koch and S. L. Britton (2007) Physiol Genomics **30**, 205-208

Escalating development of complexity after the Great Oxidation Event



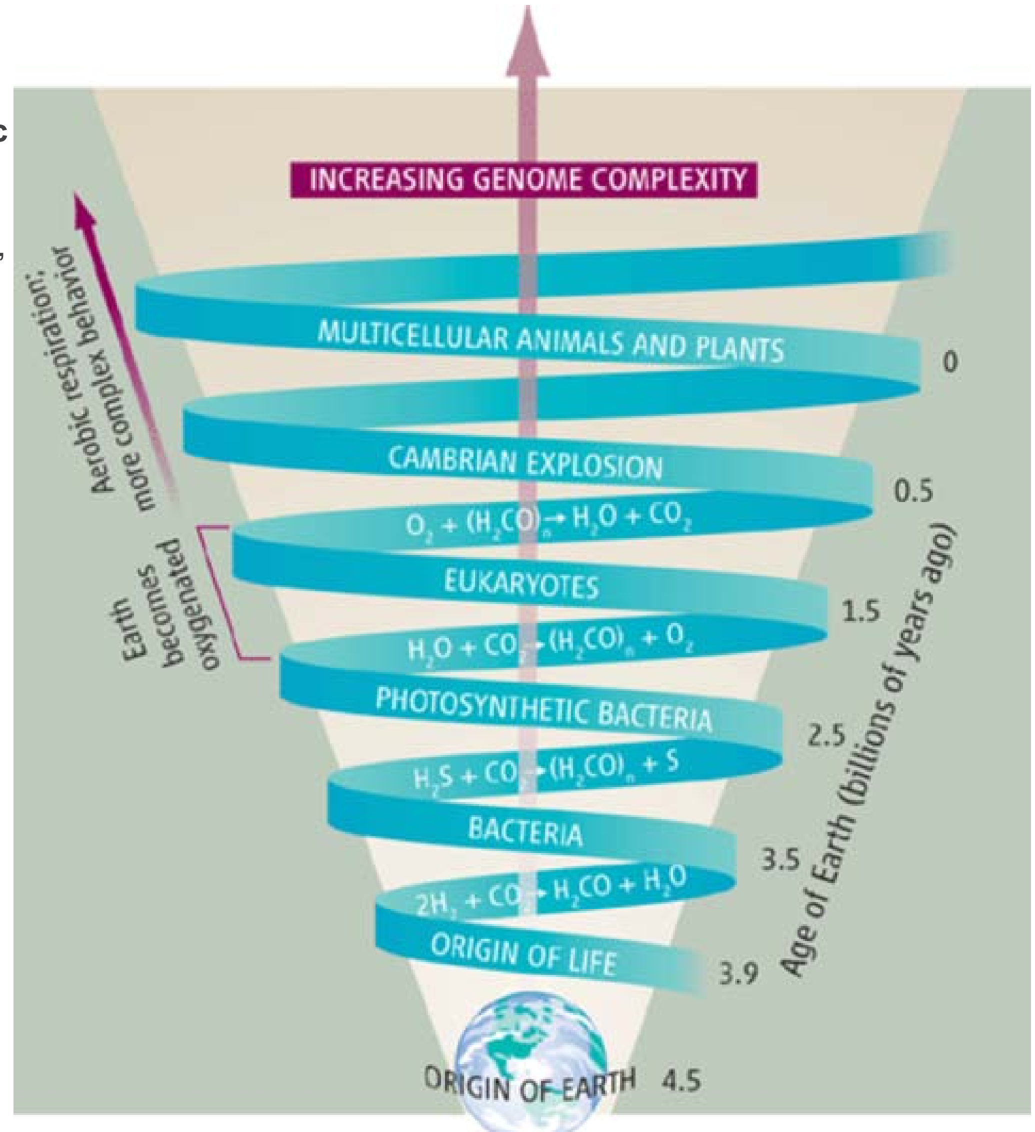
The main uncertainty: Whether oxygenic photosynthesis occurred more than 0.1Gyr before the GOE (as much as 1 Gyr according to some), and if so, how was oxygen stored in crust for so long?

- Not shown is Proterozoic Snowball Earth episode, which may come just after GOE
- Note transition from single to multicellular organisms shortly after GOE.
- Eukaryotes earlier than 1.5 Gyr.
- Next large increase in oxygen at 0.5-1.0 Gyr preceeded Cambrian explosion during which all animal phla appeared.

Oxygen's imprint on genome complexity and metabolic pathways

Speculative overview

The evolution of genomic complexity and metabolic pathways during Earth's history. The earliest origin of life is not known. However, assuming a single last universal common ancestor evolved in mid-Proterozoic, there is evidence of microbial life. When oxygenic photosynthesis evolved is not clear, but geochemical data suggest that between ~2.3 and 2.2.billion years ago, there was sufficient oxygen in the atmosphere to permit an ozone layer to form. That singular event appears to have precipitated a massive increase in genome and metabolic complexity, culminating in the rise of metazoans around 600 million years ago, and the rise of terrestrial plants around 430 million years ago. The feedbacks in the evolutionary trajectory have led to increasing genomic and metabolic complexity.



Great illustration

Tracing Oxygen's Imprint on Earth's Metabolic Evolution. Paul G. Falkowski

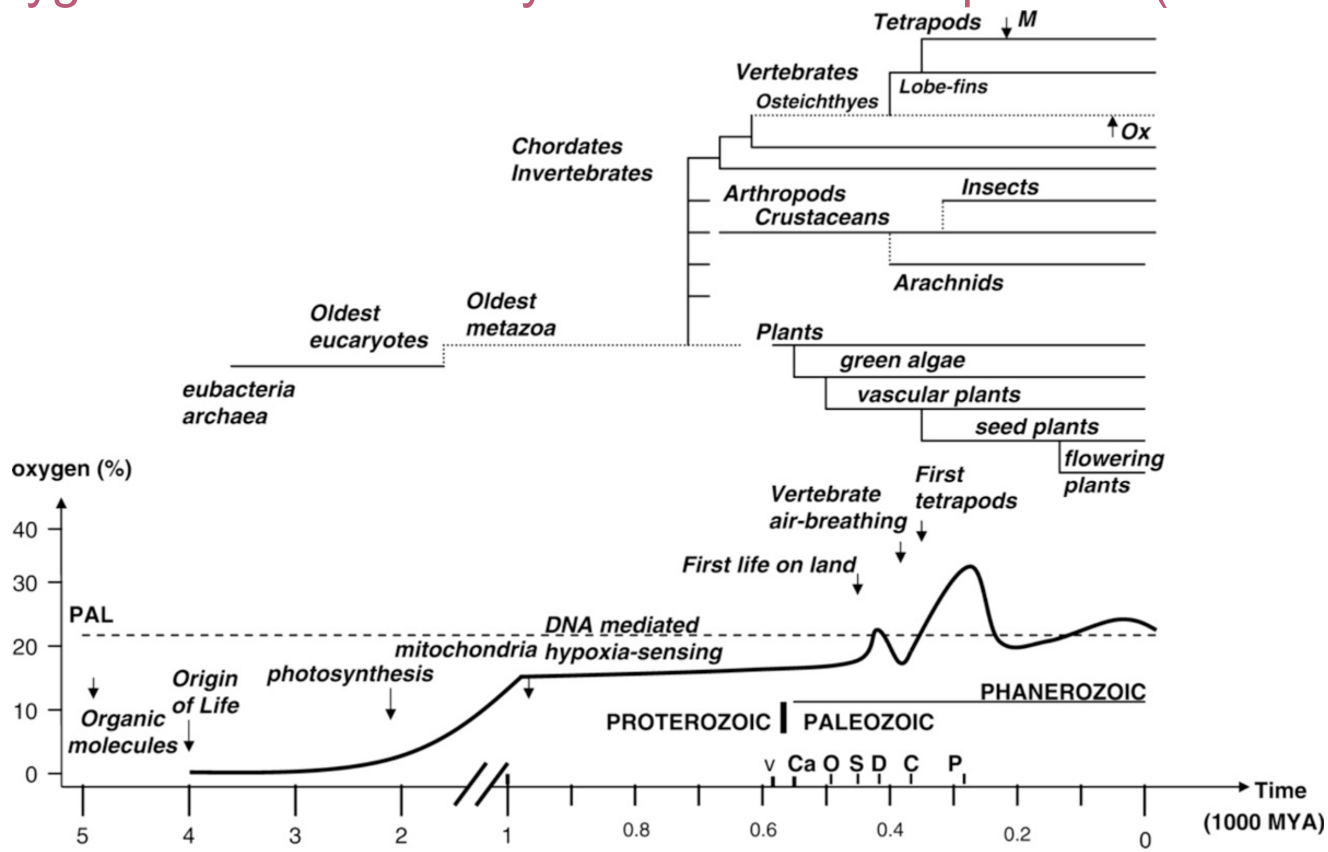
Science 24 March 2006: Vol. 311, pp. 1721

Next three slides list suggested effects of oxygen variations in more recent times, and are here only for your interest:

You are not required to even look at them.

(But I think it is fascinating to see how far scientists, or anyone, will go to use their favorite process, molecule, event, theory, etc., to explain EVERYTHING; and in this case many of them might even be correct: Yes, there were giant insects that were probably a response to oxygen.)

Oxygen and evolutionary milestones in respiration (arrows)



Top: Approximate phylogenetic relationships among taxa. M = Mammals.
Bottom: Qualitative representation of atmospheric oxygen concentration (black tracing) in relation to evolutionary milestones in respiratory processes (arrows). PAL is the present atmospheric level of oxygen (21%). Geologic time abbreviations: V = Vendian Period of the Proterozoic Era; Paleozoic Era periods are Ca = Cambrian; O = Ordivician; S = Silurian; D = Devonian; C = Carboniferous; P = Permian. Note that the fossil record of most animal and plant groups does not begin before the Cambrian and that the geologic time scale is in 1000 million years ago, I.e. in Gyr).

Coping with cyclic oxygen availability: evolutionary aspects, Martin Flück, Keith A. Webster, Jeffrey Graham, Folco Giomi, Frank Gerlach and Anke Schmitz
Integrative and Comparative Biology 2007 47(4):524-531

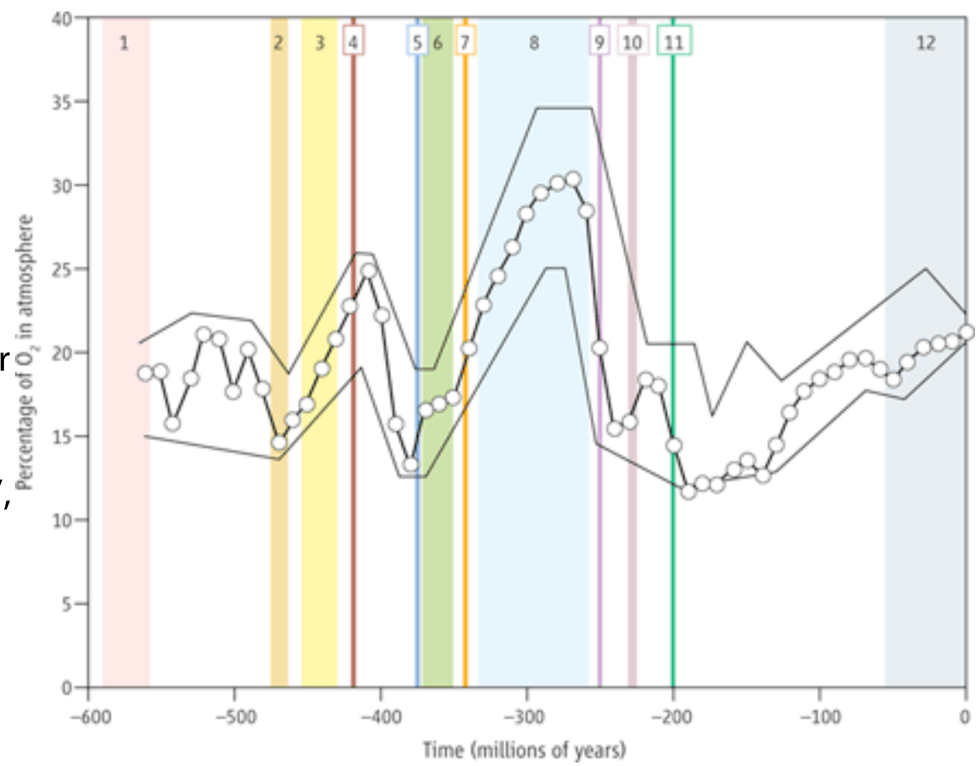
A few much-discussed effects of the *late* "wiggles" in the oxygen abundance vs. time curve

1. Origin of first animal body plans coincides with rapid rise in O_2 (Cambrian explosion, (interval 1 in graph to right)

2. Conquest of land by animals during two independent phases of increasing O_2 concentration: A. (mainly) arthropods ~ 410 Myr ago (interval 4); B. both arthropods and vertebrates, following Devonian mass extinction and period of "stasis" ("Romer's Gap", interval 7)

3. Increasing O_2 through Carboniferous and Permioan (interval 8) coincides with gigantism in arthropod groups, and body size increased across primitive reptile-like animals. **Giant insects (!!)**

4. Increase in body size of mammals in Tertiary linked to rising O_2 (interval 12)

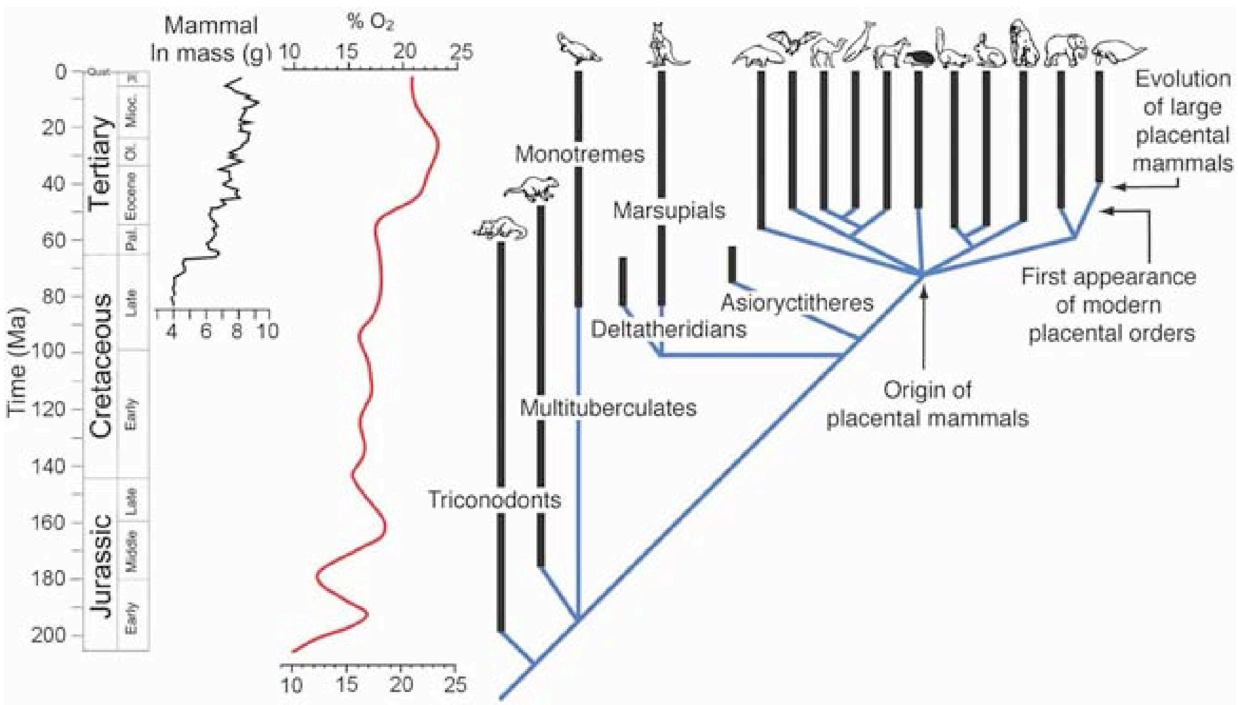


Details of O_2 since Cambrian 0.6 Gyr ago. The numbered intervals denote important evolutionary events that may be linked to changes in O_2 concentration (see text of paper cited below, Berner et al.).

For more, see Berner, R. A. et al. 2007 Science 316, 557, and citations to that paper.

Last example: Oxygen and mammal evolution

Mammal evolutionary events based on fossil morphological (*31*) and molecular (*22*, *32*) evidence, compared with oxygen concentrations in Earth's atmosphere modeled over the past 205 My using carbon and sulfur isotope data sets; O_2 levels approximately doubled over this time from 10% to 21%, punctuated by rapid increases in the Early Jurassic and in the Eocene. Changes in average mammalian body mass is taken from (*27*). Vertical black bars represent known fossil ranges, blue lines represent inferred phylogenetic branching. Only some of the ordinal-level placental mammals are shown.



Falkowski PG, Katz ME, Milligan AJ, Fennel K, Cramer BS, Aubry MP, Berner RA, Novacek MJ, Zapol WM. The rise of oxygen over the past 205 million years and the evolution of large placental mammals. *Science* 309: 2202–2204, 2005