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AST 309L
Timing problems with the evolution of cyanobacteria and eukaryotes, and the rise of atmospheric oxygen

This sheet is meant to clarify the timing and relation between cyanobacteria, the dramatic increase in atmospheric oxygen, and the consequences of this atmospheric change. It was discussed in lecture material from Oct. 30.

Great Oxidation Event : the timing of this event, from varied geochemical evidence, is considered firm: **2.4 Gyr ago**.

→Triggered collapse of a methane greenhouse (from methanogenic bacteria), plunging the planet into a series of extreme glaciations. (Note: methanogens weren't necessarily killed off, just the methane they produce, by oxidation.)

The "GOE" may be associated with a subsequent rise of complexity, possibly eukaryotes and later innovations. Some more recent oxygen variations are certainly correlated with evolutionary developments.

No one has thought of another way to produce so much O_2 besides the earliest **oxygenic (aerobic) photosynthesis**. The question is *not* where the oxygen came from! **The problem has always been the evidence that cyanobacteria arose *much* earlier than the Great Oxidation Event:**

Problem 1 (solved ~ 2003): Oldest cyanobacteria morphological fossils were at 3.5 Gyr (Schopf 1993). That means you have to "hide" the oxygen for 3.5-2.4 = 1.1 Gyr. O_2 does get absorbed by the Earth's crust, but calculations indicate very difficult to hide it for more than a few million years.

2003: Brasier et al. (Nature) announce reanalysis of same fossils → *no evidence for cyanobacteria* or even biomarkers of any sort.

Currently accepted oldest unambiguous cyanobacteria morphological fossils are at 2.0 Gyr: Tidal-flat sedimentary rocks, Canada's Belcher Mountains (1976).
Of course there must be older ones, not discovered yet, if they account for the Great Oxidation Event. And note that there *could* be *much*

Problem 2 (solved 2008?? Rasmussen et al. Oct 23 Nature)
Until Rasmussen et al., the most important results were *lipid biomarker* evidence at 2.7 Gyr:

Hopane (cyanobacteria; Brocks et al. 1999)

Sterane (eukaryotic biomarker; Brocks et al. 2003).

This "lipid biomarker" evidence has always been a problem:
A. Oxygen must be "hidden" in crust for 2.7 – 2.4 = 0.3 Gyr → *still too long*.
B. No cyanobacteria morphological evidence until 2.7-2.0 = 0.7 Gyr later.
C. Oldest convincing eukaryote morphological fossils occur at 1.5 Gyr ago (structurally complex microfossils "acritarchs" in Roper Group of Northern Australia (2004) [Also fairly good evidence for Eukaryotic fossils at 1.7 Gyr ago.]
→ requires about a billion (Gyr) "gap" when there were eukaryotes (from biomarker) but no fossils. Hard to believe, although they could have been so "squishy" that they left no fossils.

Rasmussen et al. (2008 Nature): used new nanometer microprobe NanoSIMS to show that the carbon isotopic ratios suggest the lipid biomarkers of Brocks et al. were contamination introduced some time after these rocks reached their peak metamorphic temperature, about 2.2 Gyr ago.

Therefore the most likely sequence is now:
(1) First cyanobacteria: Morphological evidence > 2.0 Gyr. Probably 2.4-2.5 Gyr ago, assuming they were the source of oxygen for (2).
(2) Great Oxidation Event: 2.4 Gyr ago. Now no puzzle about how the O_2 was "hidden" for so long.
(3) First eukaryotes: > 1.5 Gyr ago (maybe > 1.7; recognize how this has to be considered a lower limit, as do all dates for the "first" anything)

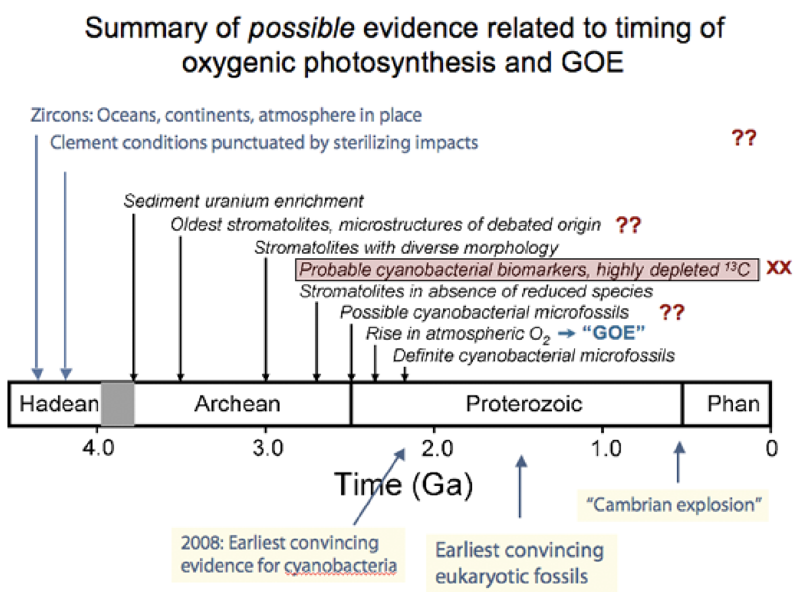
Problem solved? Not quite:

→ After Brocks et al., more findings of lipid biomarkers deposited in other parts of the world, again *before* the rise of oxygen (Dutkiewicz et al. 2006 Geology; Sherman et al. 2007 Organic Geochmistry; Ventura et al. 2007 Proc. Natl. Acad. Sci.) We'll see how this plays out (if it ever does).

Tentative conclusion: Emergence of cyanobacteria linked with *immediate* rise of oxygen in the atmosphere (Great Oxidation Event) and subsequent extreme glaciations.

The more important conclusion: The oxygenation of the atmosphere may be responsible for much of the subsequent development of complexity: eukaryotes, meiosis, multicellularity, …

A timeline to remind you of these developments, and that include the points discussed above is included here.



→ For the questions of interest in this class, the importance of these arguments is that they imply that without oxygenation of the atmosphere, complex life might not have ever developed. And since the oxygenation depends on development of aerobic photosynthesis, we have to conclude that there will be no complex life without the development of aerobic photosynthesis. *However photosynthesis is an extremely complex metabolic process*, which almost certainly developed from early, less complex, metabolic pathways. Which of these was required to get photosynthesis? (If interested, you should take a look at some illustrations of the photosystems I and II. If the diagram looks simple, it is a vast simplification!)

So we end up with what will become a familiar conundrum: The present conclusion can certainly be interpreted as a strong and significant case of *contingency*, since it implies that complex life requires a chain of events that seem so complex that they are unlikely to occur again. From another point of view, too much faith in natural selection will dismiss this argument, and instead point out that photosynthesis is so advantageous a trait for an organism that it seems inevitable that it will develop wherever there is life (and enough sunlight!) → *convergence*.