enormous net oxygen production of cyanobacteria should have completely overwhelmed the inorganic hydrothermal "sinks" and Earth should have experienced a rapid oxygen build-up.

A parsimonious way to avoid these dilemmas is to consider an early Earth with an ambient oxygen content sufficient to support aerobic recycling of the net organic carbon productivity in surface waters (*3*) and sufficient to stimulate the early evolution of photosystem II in the cyanobacteria (*5*). It is difficult to assign a value of oxygen that would make this possible, but a level near 1 to 2% of the present atmospheric level is minimal. This is also enough to provide some minimal ozone protection against the ultraviolet flux from the young sun, which would have been higher than today.

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References and Notes
1. J. Xiong *et al.*, *Science* **289**, 1724 (2000).
2. H. D. Holland, *The Chemical Evolution of the Atmosphere and Oceans* (Princeton Univ. Press, Princeton, NJ, 1984); M. Schidlowski, *Nature* **333**, 313 (1988).
3. K. M. Towe, *Nature* **348**, 54 (1990); *Adv. Space Res.* **18** (no. 12), 7 (1996).
4. J. Veizer and S. L. Jansen, *J. Geol.* **93**, 625 (1985).
5. K. M. Towe, *Nature* **274**, 657 (1978); M. O. Dayhoff, *Precambrian Res.* **20**, 299 (1983).

The major groups of photosynthetic bacteria, such as cyanobacteria (blue green filaments, ~5-micrometer diameter) and purple sulfur bacteria (spheres), have formed stable ecological associations for billions of years.

Response

OUR KNOWLEDGE OF THE ARCHEAN ENVIronment and its biota is exceedingly fragmentary, but the few available clues are helpful. Atmospheric oxygen levels must have been very low before oxygenic photosynthesis developed. During the Archean Eon, high-temperature hydrothermal emanations contributed reduced species such as H_2S, H_2, Fe^{2+}, and CH_4 at a rate that probably exceeded the modern rate of $(0.12$ to $1.2) \times 10^{12}$ moles per year (*1*) and therefore easily overwhelmed the major nonbiological source of free oxygen, namely the photodissociation of H_2O vapor estimated at $\sim 10^{10}$ moles of O_2 per year (*2*). Even in the absence of an ozone ultraviolet shield, benthic photosynthetic microorganisms could have survived during the day-night cycle by migrating vertically within ultraviolet-shielding minerals (*3*) and by using organic pigments (*4*), to optimize the beneficial versus deleterious effects of solar radiation. As Towe points out, ferrous iron is indeed a sink for aqueous sulfides. However, nonoxygenic photosynthetic bacteria can also use alternative substrates such as hydrogen from hydrothermal sources, and even ferrous iron itself (*5*).

Towe proposes a constraint on ancient oxygen levels from an estimation of Archean global rates of organic carbon cycling, including its sedimentation. However, uncertainties in our knowledge make estimating such constraints extremely difficult. For example, despite their generally much greater productivity, the presence of ancient oxygenic photosynthetic ecosystems cannot be clearly discerned from nonoxygenic photosynthetic ecosystems by using estimates of sedimentary organic carbon contents, as the following illustrates. For a pre-3.0-billion-year-old Earth lacking oxygenic photosynthesis but with a geothermal heat flow that was two to three times the modern value (*6*), global primary productivity might have been in the range of 10^{14} grams of carbon per year (*7*). Assuming an Archean global sedimentation rate equal to the modern value [1.3×10^{16} grams per year (*8*)], and assuming that half of the organic carbon from global primary productivity was ultimately buried in aqueous sediments, the mean organic carbon concentrations of sediments would have been about 0.4 weight %. This value would be indistinguishable from carbon concentrations of modern marine sediments, which scatter widely but have a mean value near 0.6 weight % (*9*).

Once oxygenic photosynthesis arose, respiration probably developed simultaneously, perhaps even earlier, given the enormous benefit of respiration both as an effective energy-harvesting strategy and as a sink to mitigate potentially toxic oxidants. About 99.9% of today's primary productivity is soon recycled by the biosphere (*8, 10*). Therefore, over the long term, biological oxygen production has probably always been nearly balanced by biological and abiotic oxygen sinks.

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References and Notes
1. H. Elderfield and A. Schultz, *Annu. Rev. Earth Planet. Sci.* **24**, 191 (1996).
2. J. F. Kasting and J. C. G. Walker, *J. Geophys. Res.* **86** 1147 (1981).
3. B. K. Pierson, in *Early Life on Earth*, Nobel Symp. No. 84, S. Bengston, Ed. (Columbia Univ. Press, New York, 1994), pp. 161–180.
4. J. G. Dillon and R. W. Castenholz, *J. Phycol.* **35**, 673 (1999); F. Garcia-Pichel, *Origins Life Evol. Biosphere* **28**, 321 (1998).
5. A. Ehrenreich and F. Widdell, *Appl. Environ. Microbiol.* **60**, 4517 (1994).
6. D. L. Turcotte, *Earth Planet. Sci. Lett.* **48**, 53 (1980).
7. D. J. Des Marais, in *Geomicrobiology*, J. Banfield and K. Nealson, Eds. (Mineralogical Society of America, Washington, DC, 1997), vol. 35, pp. 429–445.
8. R. A. Berner and D. E. Canfield, *Am. J. Sci.* **289**, 333 (1989).
9. H. D. Holland, *The Chemistry of the Atmosphere and Oceans* (Wiley, New York, 1978).
10. C. B. Field *et al.*, *Science* **281**, 237 (1998).

CORRECTIONS AND CLARIFICATIONS

REVIEW: "Subduction and slab detachment in the Mediterranean-Carpathian region" by M. J. R. Wortel and W. Spakman (8 Dec., p. 1910). In Fig. 1, intended to illustrate the evolution of plate boundaries in the Mediterranean-Carpathian region, the text and graphics on the map did not correspond with the appropriate geographic features. The correct figure is shown below.

CREDITS: (TOP) L. PRUFERT-BEBOUT; (BOTTOM) J. R. WORTEL AND W. SPAKMAN