Limited biological productivity in the Archean anoxic ocean

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The activity level of Earth's biosphere is critical for controlling the chemical composition of the atmosphere. The Earth's modern biosphere is powered by oxygenic photosynthesis, which utilizes the ubiquitous water molecule as an electron donor and thus tends to be limited by the availability of light and nutrients. In contrast, before the advent of the oxygenic photosynthesis primary production would have been limited by the geophysical input rate of critical electron donors (e.g., H_2 and Fe^{2+}) from the Earth's interior to the exogenic system.

Here, we revisit previous modelling of the global biogeochemical cycles of H, C, and Fe in order to more precisely reconstruct global net primary production (NPP) during early Archean time prior to the advent of oxygenic photosynthesis. We focus on two idealized scenarios with different configurations of a primitive Archean biosphere: an entirely non-photosynthetic (chemotrophic) biosphere (Case 1) and a biosphere powered solely by anoxygenic photosynthesis (Case 2). The biogeochemical model is designed to track redox (H) balance in the ocean-atmosphere system. We explore the impact of varying key model parameters using a stochastic approach, and search for possible solutions which allow for a warm climate states lacking optically thick organic haze.

Our results suggest that NPP was ~0.1% and ~1% that of the modern Earth for Case 1 and Case 2 biospheres, respectively. In the Case 1 biosphere, H_2-using methanogens contribute ~70% of total NPP, with the remainder contributed by CO-consuming acetogens. The extremely low NPP fluxes produced by our model imply that the geological fluxes of H_2 and Fe^{2+}, rather than light or nutrients, would have been the limiting factor for biological productivity. However, atmospheric CH_4 abundances returned by our model analysis are often high (at least ~10^{-4} – 10^{-3} bar) despite the relatively limited activity of the primitive biosphere.