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Exploring oceanographic and redox influences on the spread of Archean photosynthesis

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An oxygenated atmosphere and ocean in chemical disequilibrium with carbon biomass provides the largest potential energy reservoir for complex life on Earth. However, the transition to an oxygenated atmosphere and ocean on Earth was a long-term, spatially uneven process affected by both local and global-scale changes. Furthermore, the lag of at least 500 Myr between the evolution of photosynthesis and the Great Oxygenation Event (GOE) at 2.4 Ga implies that a rise in surface O_2 might not be a direct consequence of oxygenic photosynthesis (OP). Marine cyanobacteria were responsible for OP, but local O_2 production would have depended on nutrient supply by ocean circulation. The marine biogeochemical environment was different in anoxic oceans: the cycling of macronutrients like P was limited by a weak biological pump, the deep ocean was predominantly Fe^{2+} rich, and transient local euxinia (sulfidic conditions) might have occurred in the open ocean. In addition to net nutrient supply, OP could have been limited by competition with organisms conducting iron and sulfide-based anoxygenic photosynthesis (AP) in the presence of the alternative electron donors Fe^{2+} and H_2S. Thus, circulation-influenced spatial heterogeneity in nutrients and electron donors could have controlled the extent of open ocean habitat favorable for cyanobacteria, limiting globally integrated O_2 production and net accumulation near the GOE. Whether OP required such favorable environmental conditions to dominate over AP globally and begin producing sufficient O_2 for atmospheric oxygenation is unknown.

We simulate Archean conditions using a 3D Earth system model (cGEnIE) and a newly modified biogeochemical model that includes AP. We find that ocean circulation dynamically impacts the spatial distribution of nutrients, Fe^{2+}, and H_2S with consequences for the extent of oxygen ‘oases’. Additionally, total macronutrient, Fe^{2+}, and H_2S inventories and their (re)cycling within the ocean may also influence the success of OP in these oases relative to AP. We suggest that spatial heterogeneity in marine redox could control the ability of OP to persist in the open ocean and potentially, the likelihood of planetary oxygenation.