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Life-Earth coevolution: the role of phosphorus in Archean oxygen accumulation

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Investigating the presence of oxygen on planets within our solar system and beyond is crucial for understanding the potential for life beyond Earth. Oxygen is a key ingredient for life as we know it and serves as a key indicator of habitability and planetary processes [1]. On Earth, the first lasting rise in atmospheric oxygen started ☐2.4 billion years ago and was a crucial process that fundamentally transformed the planet's atmosphere and oceans, leading to the evolution of complex life forms. However, geochemical evidence reveals the existence of intermittent oxic whiffs before that period, although the mechanisms that drove the production of such early oxygen are poorly constrained. Here, we present redox sensitive trace metal and Fe speciation data, as well as phosphorus phase partitioning results, for a 2.94 billion-year-old drill core from the Red Lake area, Canada. Results suggest dynamic oceanic Fe cycling between ferruginous conditions (anoxic Fe-rich), euxinic (anoxic S-rich) and short-lived episodes of oxygenated waters consistent with depleted (<1) Enrichment Factors (EFs) for Vanadium, Molybdenum and Uranium. The sources of oxygen on early Earth are still debated, but the presence of a wide range of stromatolites (sedimentary structures formed by photosynthetic organisms) in the studied area [2-3] points to cyanobacterial photosynthesis as the principal source of oxygen [2], which accumulated in protected shallow areas, unveiling one of the earliest oxic whiffs which predates global atmospheric oxygen accumulation by ☐500 Ma.

The intervals of the drill core described as deposited under oxic water conditions are characterized by pulsed increases in oceanic P concentrations, primarily in the form of authigenic P, and elevated C_{org}/P_{org} ratios relative to the Redfield ratio (the molar ratio of C and P in phytoplankton at C:P = 106:1). These results are indicative of preferential release of P during the remineralization of organic matter [4]. To determine whether this P was recycled to the water column or fixed in the sediment, we compare C_{org}/P_{reac} ratios, where $P_{reac}= P_{auth} + P_{Fe} + P_{org}$. The results also reveal variable C_{org}/P_{reac} ratios which indicate alternating periods of limited recycling, with efficient P fixation in the sediment in association with Fe minerals, and enhanced P recycling to the water column. Interestingly, the intervals of enhanced P recycling are characterized by elevated sulfide content. This condition leads to the dissolution of Fe minerals, releasing sequestered P, and the selective liberation of P from organic matter during bacterial sulfate reduction [4]. Consequently, substantial P fluxes are reintroduced to the water column, potentially promoting photosynthetic primary productivity, a

hypothesis substantiated by the presence of stromatolites. This, in turn, may have intensified organic carbon burial, contributing to incipient ocean episodic oxygenation during the Archean.

Paleoenvironmental reconstructions of early Earth play a key role in unravelling the co-evolution of life and the Earth system. Our understanding of the biogeochemical evolution of the P cycle during the Archean holds the potential to provide insights into environments—on Earth or other terrestrial planets—where sufficient dissolved P could have accumulated. Such systems may have been conducive to the emergence and evolution of life, offering valuable perspectives on the conditions necessary for life's development.

References:

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