LIFE-ENVIRONMENT COEVOLUTION IN THE ARCHEAN: INSIGHTS FROM PHOSPHORUS CYCLING. F. Cañadas¹, R. Guilbaud², A. G. Fairén¹³ and P. Fralick¹. ¹Centro de Astrobiología (CAB), CSIC-INTA, Madrid, Spain, ²Geoscience Environment Toulouse (GET, CNRS), Toulouse, France, ³Department of Astronomy, Cornell University, Ithaca, NY, USA, ⁴Lakehead University, Thunder Bay, Canada.

One of the central mysteries that astrobiologists face is the origin of life and the source of essential building blocks (carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur; CHNOPS). Phosphorus (P) plays a crucial role in nucleic acids, phospholipids, and adenosine triphosphate (ATP) molecules, constituting vital components in all forms of life. However, on Earth, phosphorus is scarce, locked within low-solubility phosphate minerals, giving rise to a fundamental and enduring question about early Earth's phosphorus supply—the so-called 'phosphate problem' [1].

Phosphorus is a redox-dependent element, meaning its chemical behavior is closely tied to changes in oxidation-reduction reactions. Consequently, environmental conditions play a significant role in determining its speciation and bioavailability, which is a fundamental aspect of the concept of life-environment coevolution in astrobiology. This concept explores the dynamic and reciprocal relationship between living organisms and their surrounding environments, both on Earth and potentially on other celestial bodies. This interplay is crucial in understanding the conditions necessary for the emergence, sustenance, and evolution of life.

Our understanding of the early Earth system depends on accurate reconstructions of Earth’s ancient environments, often based on geochemical measurements of sedimentary archives. In this study, we investigate Fe and P cycling in an iron-rich Archean (~3 Ga) drill core from the Red Lake area (Canada) and, through a sequential extraction, we obtained different Fe pools (Fe_{mag}, Fe_{ox}, Fe_{auth}, Fe_{py}) and P pools (P_{auth}, P_{det}, P_{Fe}, P_{org}).

Results suggest a dynamic Fe cycling between ferruginous conditions (anoxic Fe-rich), euxinic (anoxic S-rich) and short-lived episodes of oxygenated waters that likely developed oxygen-rich oases in protected shallow areas. The sources of oxygen on early Earth are still debated, but the presence 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]. Interestingly, the intervals described as oxic water conditions are preceded by high sulfide content, and characterized by pulsed increases in oceanic P concentrations, primarily in the form of authigenic P.

The Redfield ratio refers to the molar ratio of C and P in phytoplankton and, by extension, in the ocean, and it is remarkably constant at C:P = 106:1. In our study, C_{org}/P_{org} ratios are well above the Redfield value, which is an indication of P-limited conditions and preferential release of P during the remineralization of organic matter. 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, primarily as P_{org}, to the water column.

In our study, 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 increased oxygen concentrations and fostering intermittent oxygenic oases in protected areas.

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.

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References: