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A double-edged sword: The role of sulfate in anoxic marine phosphorus cycling through Earth history

MICHAEL A. KIPP

Duke University

Presenting Author: michael.kipp@duke.edu

Phosphorus (P) is the limiting nutrient for marine oxygenic photosynthesis. Phosphorus availability in the ocean is thus thought to have controlled biological productivity and oxygen production throughout Earth history. Assessments of P levels in ancient seawater typically draw on the P content of marine sediments. Low P in Precambrian siliciclastic and Fe-rich sediments has led many to infer that the marine P reservoir was smaller-than-modern at that time - implying lower-than-modern biological productivity [1]. However, an alternative interpretation exists: that the low P content of those sediments reflects inefficient P burial in a P-rich, anoxic ocean [2]. Here I consider these disparate schools of thought, with a focus on the role of sulfate in the P cycle. Using a biogeochemical model [3], I will show that P burial is efficient in anoxic, low-sulfate settings - conditions that characterized the Archean, and perhaps Proterozoic deep ocean. In contrast, in anoxic environments within a sulfate-rich ocean, P burial is inhibited (as observed today). This model reconciles conflicting views of the Precambrian P cycle, suggesting that the size of the marine sulfate reservoir may have played an important role in setting marine P bioavailability through time. The model also implies both positive and negative sulfate-mediated feedbacks that impact P cycling and oxygen production/consumption at different timescales, with implications for the habitability of the ancient Earth or other ocean-bearing planetary bodies.

[1] Reinhard, et al. (2017), *Nature* 541, 386-389.

[2] Poulton (2017), *Nature Geoscience* 10, 75-76.

[3] Kipp (2022), *Geophysical Research Letters* 49(20), e2022GL099817.