Evolution of Earth's phosphorus cycle

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The macronutrient phosphorus (P) is essential for terrestrial life, and is conventionally considered to be the element that ultimately limits primary productivity in the oceans on geologic timescales. Given its centrality in biochemistry and importance in fueling marine biogeochemical cycles, there has been a sustained effort to reconstruct the dynamics of Earth's P cycle through time. However, many aspects of P cycle evolution remain obscure, in large part due to a lack of empirical constraints. Here, we present a new compilation of P abundances in fine-grained, marine siliciclastic rocks from nearly 8,000 individual samples. Our database provides evidence for inhibition of authigenic P burial in shallow marine environments through most of the last 3.5 billion years. We suggest that this inhibition was linked to extreme nutrient P limitation that resulted in an unusual, non-Redfieldian elemental stoichiometry in marine primary producers. We then place our record into a quantitative biogeochemical framework and find that a combination of enhanced P scavenging in an anoxic, iron-rich ocean and a nutrient-based bistability in atmospheric O_2 levels would have created an exceptionally stable low-oxygen world for much of Earth's history. However, a fundamental shift in the P cycle occurred in the late Precambrian (between 800-635 Ma), roughly coincident with a previously inferred shift in marine redox state and the initial emergence of complex multicellular life.