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# Glacial-interglacial coupling of sedimentary phosphorus and iron over the last 1 Myr: Implications for paleoenvironmental evolution in the Southern Ocean

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The biogeochemical cycles of phosphorus and iron in the Southern Ocean are fundamental drivers of the biological pump and $pCO_2$ regulation. While the coupling of P burial and Fe supply is well-documented in glacial dust-loading models, their long-term interplay in sedimentary environments remains complex, particularly during the climatic reorganization of the Mid-Pleistocene Transition (MPT). In order to decipher the evolving coupling between P and Fe in the critical area, we present a high-resolution, 1-million-year record of sedimentary P speciation and Fe abundance in the sediments recovered at the Del Cano Rise, Southern Ocean.

Our results demonstrate that P burial modes were strictly governed by Fe delivery that depends on the glacial-interglacial redox conditions. Generally, reactive P burial increased during glacial stages in tandem with enhanced dust-derived Fe fluxes, primarily dominated by increased organic P burial under more reducing conditions. Conversely, authigenic apatite formation was notably enhanced during interglacial stages. This suggests that the oxygenated bottom-waters and slower sedimentation rates prevalent during interglacials facilitate early diagenesis, allowing reactive Fe to effectively transfer scavenged P into stable authigenic apatite.

A remarkable departure from this trend was observed at a lower core depth. During this stage, we identified a prominent P enrichment dominated by authigenic apatite, reaching an absolute maximum despite a significant decline in terrigenous Fe flux and evidence of lower primary productivity.

We propose that MPT-related orbital forcing facilitated a highly efficient nutrient sequestration mode. In this scenario, intensified upwelling acted as a primary conduit, delivering a surplus of P to the surface, while stagnant, oxygenated bottom waters served as a critical retention site. The limited reactive Fe effectively scavenged this surplus P, which was then stabilized into a massive authigenic sink due to the prolonged diagenetic window of the interglacial seafloor.

Our study reveals that the P-Fe relationship is a dynamic indicator of shifting oceanographic modes. The potential decoupling at a lower depth demonstrates that internal geochemical feedback can drive exceptional nutrient burial even during low-productivity interglacials, providing critical insights into the non-linear paleoenvironmental evolution and the enhanced nutrient storage capacity of the Southern Ocean since the Early Pleistocene.