

Press Release

For Immediate Release

HKU Study Uncovers Mineral “Sink” that Reduced Phosphorus in Early Oceans Potentially Delaying Earth’s Oxygen Rise

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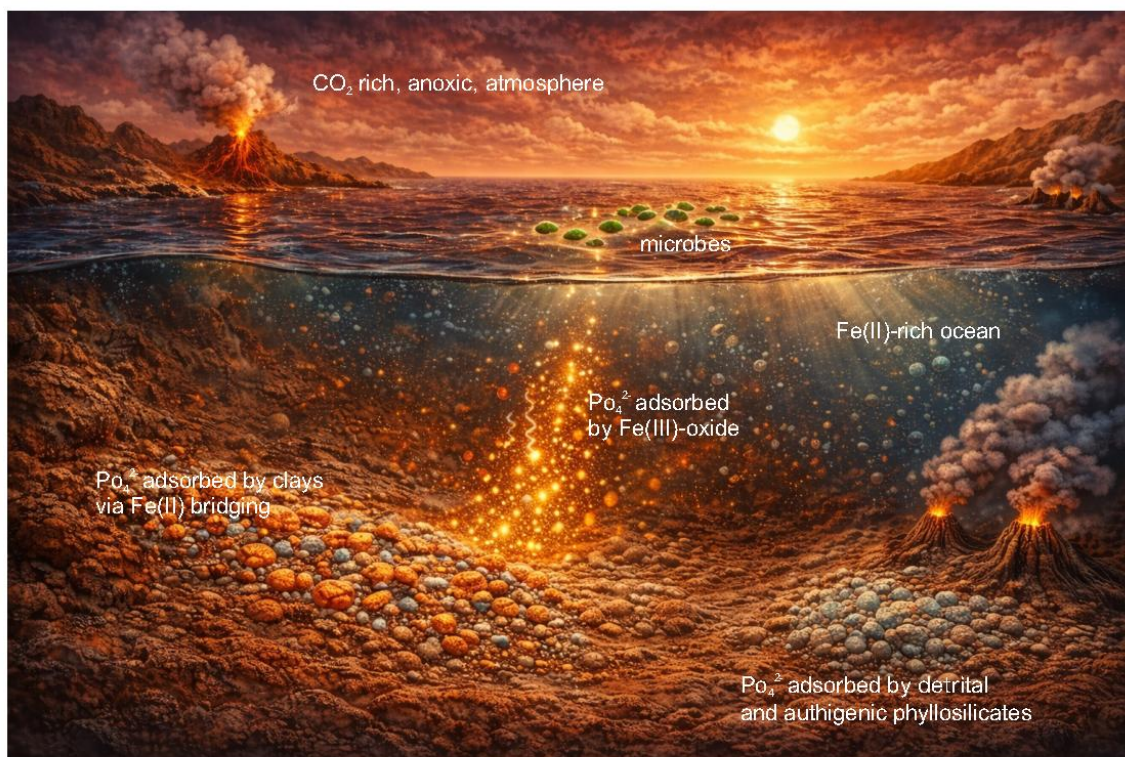


Image 1. Illustration of Fe(II)-enhanced phosphate adsorption onto phyllosilicates in Archean iron-rich oceans, a process that may have limited marine productivity and delayed atmospheric oxygenation.

Scientists have long sought to explain a key mismatch in Earth’s early history: oxygen-producing photosynthesis evolved hundreds of millions of years before atmospheric oxygen began to rise during the Great Oxidation Event. This delay has been linked to limited phosphorus—a nutrient essential to life—but the specific processes controlling phosphorus availability in the iron-rich oceans of Archean Earth (approximately 3.2–2.5 billion years ago) remained unclear. A study led by the Department of Earth and Planetary Sciences at The University of Hong Kong (HKU) has identified a previously overlooked process that may explain this prolonged delay. The research was conducted in collaboration with the University of Science and Technology of China (USTC).

The work was led by HKU’s Professor Guochun ZHAO (Mok Sau-King Professor) as corresponding author, alongside Emeritus Professor Min SUN and Dr Xing CUI, Postdoctoral Fellow and first author of the paper. Professor Jihua HAO of USTC served as co-corresponding author. By combining laboratory experiments with simulations, the team systematically revealed, for the first time, that in the ferruginous (Fe²⁺-rich) oceans of early Earth, common phyllosilicate minerals—including kaolinite, montmorillonite, nontronite, and lizardite—could effectively trap dissolved phosphate on their surfaces. This process was driven by an “Fe(II) bridging effect,” where Fe²⁺ ions formed chemical links between mineral surfaces and phosphate. As these mineral particles settled and were buried in sediments, this mechanism removed essential phosphorus from seawater, limiting its availability to support marine life. The findings have been published in *Nature Communications*.

Phosphorus and the Early Earth Puzzle

Phosphorus is an essential element for life and a key component of cellular membranes and nucleic acids. In many marine environments, its limited availability constrains primary productivity, making its cycling and bioavailability critical to understanding the co-evolution of the biosphere and geosphere. While interactions between minerals and dissolved phosphate play a vital role in the modern phosphorus cycle, how these interactions operated under the very different atmospheric and oceanic chemistry of the early Earth, particularly during the Archean, has remained unclear.

Under anoxic and acidic weathering conditions of early Earth, the formation of Fe(III)-oxides was minimal, limiting their role as “phosphorus carrier”. Yet increasing attention has focused on clay minerals (a group of phyllosilicates), which possess strong phosphorus adsorption capacity and may have acted as a primary alternative for phosphorus sequestration.

“Surface environments on the early Earth were vastly different from today, with oceans containing higher concentrations of dissolved Fe(II) and silica, and almost no sulfate,” explained the paper’s first author, Dr Xing Cui. High silica levels could have competed with phosphate for mineral surface sites, while the scarcity of oxygen and low sulfate helped maintain iron in its Fe(II) form. “How these unique water chemistry conditions influenced the adsorption and transport of phosphorus by clay minerals is a key piece of the puzzle in understanding the environmental constraints on early life evolution,” said Dr Cui.

The research team simulated the water chemistry of Archean rivers and oceans and systematically investigated the adsorption behaviour of phosphate onto common phyllosilicate minerals. The results showed that even at low to moderate concentrations of Fe^{2+} (20 μM to 0.1 mM), phosphate adsorption onto phyllosilicate surfaces was significantly enhanced, with a much stronger effect than that of other divalent cations such as Ca^{2+} and Mg^{2+} . Although high concentrations of dissolved silica in the early oceans partly inhibited phosphate adsorption, the enhancing effect of Fe(II) remained dominant. “Through molecular simulations, we further uncovered the underlying mechanism,” said Dr Cui. “Fe(II) can form stable bridging complexes between the mineral surface and phosphate ions, substantially boosting adsorption efficiency. This ‘Fe(II) bridging effect’ was likely widespread in early iron-rich water bodies.”

Phosphorus and Life–Environment Co-evolution

By integrating experiment results with modelling, the team reconstructed a new picture of the early Earth’s phosphorus cycle. During the mid to late Archean (ca. 3.2–2.5 billion years ago), as continents emerged and weathering intensified, rivers delivered large amounts of terrigenous detrital clay minerals to the oceans. In iron-rich rivers, these clays could adsorb phosphorus via the Fe(II) bridging effect, and following rapid burial in coastal sediments, act as an efficient sink that removed phosphorus from seawater.

At the same time, ongoing seafloor weathering may have supplied nutrients, but newly formed phyllosilicates such as lizardite and nontronite, produced during seafloor weathering of mafic/ultramafic crust, could likewise efficiently adsorb dissolved phosphate with the aid of Fe(II), leading to its rapid burial and maintaining low levels of bioavailable phosphorus in the early oceans.

“Our Monte Carlo simulations estimate that during the late Archean, the phosphorus burial flux facilitated solely by phyllosilicate adsorption could have been comparable to the total reactive phosphorus input by rivers at that time,” noted co-corresponding author Professor Jihua HAO. “This implies that phyllosilicate adsorption was a major sink in the early Earth’s phosphorus cycle, effectively removing phosphorus from the ocean water

column.”

This persistent phosphorus limitation may have delayed a significant rise in marine primary productivity, partially explaining why the Great Oxidation Event (GOE) occurred hundreds of millions of years after the emergence of oxygenic photosynthesis.

This work intimately links mineral surface chemistry, aquatic geochemistry and biogeochemical cycles. “It not only deepens our understanding of the environmental and biological co-evolution of the early Earth, but also provides an analogue framework for investigating nutrient cycling and potential habitability of other planetary bodies, such as early Mars,” said Professor Guochun ZHAO, the corresponding author of the paper. In reducing, iron-rich aquatic environments, clay minerals may commonly play a key role as nutrient “regulators”.

For more details, please refer to the journal paper “*Phyllosilicate adsorption limited phosphorus bioavailability in early ferruginous oceans*” published in *Nature Communications*: <https://doi.org/10.1038/s41467-026-69293-4>

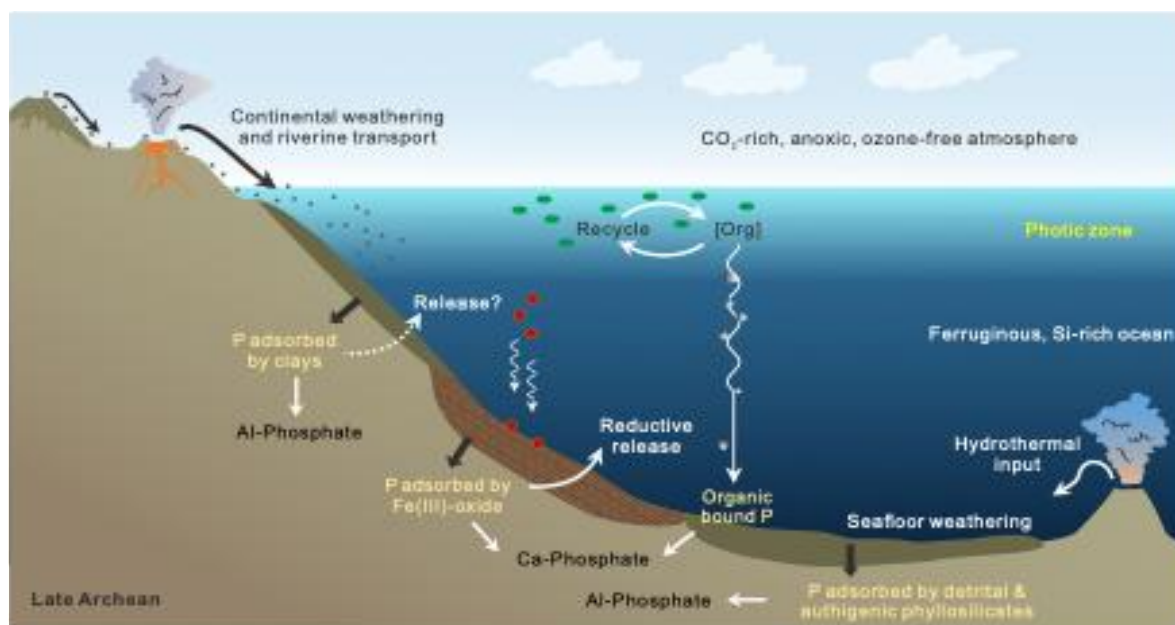


Image 2: A schematic diagram of the phosphorus cycle model for the early Earth (late Archean), illustrating continental weathering and riverine transport, and the burial process in ferruginous oceans, emphasising the previously underestimated crucial role of phyllosilicate minerals. Image credit: X. Cui et al. (2026). *Nature Communications*.

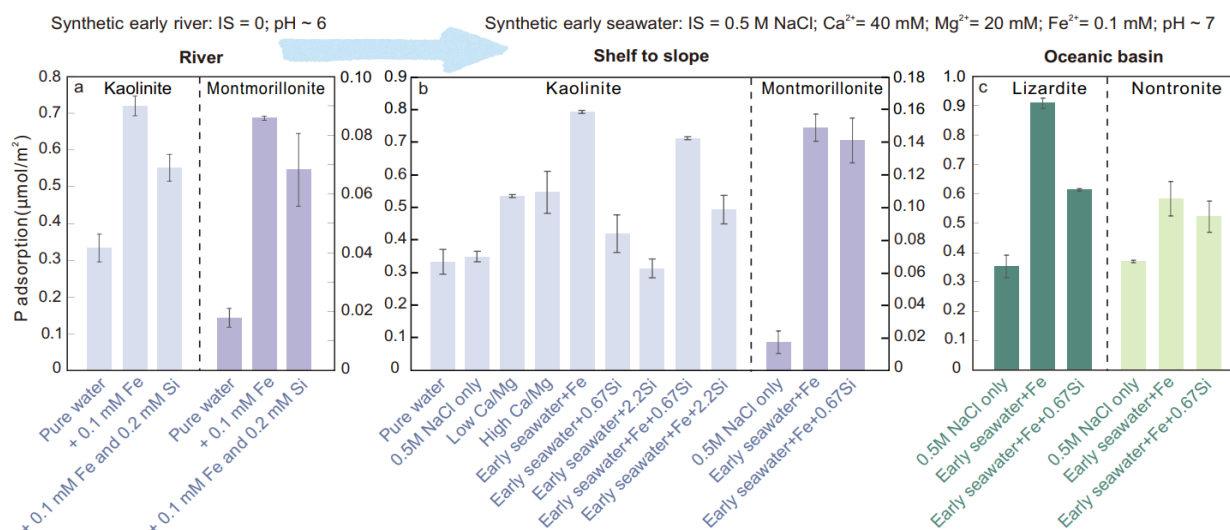


Image 3: Experimental results showing adsorption of dissolved orthophosphate onto common detrital and authigenic phyllosilicate minerals in simulated early aquatic environments. Image credit: X. Cui et al. (2026). Nature Communications.

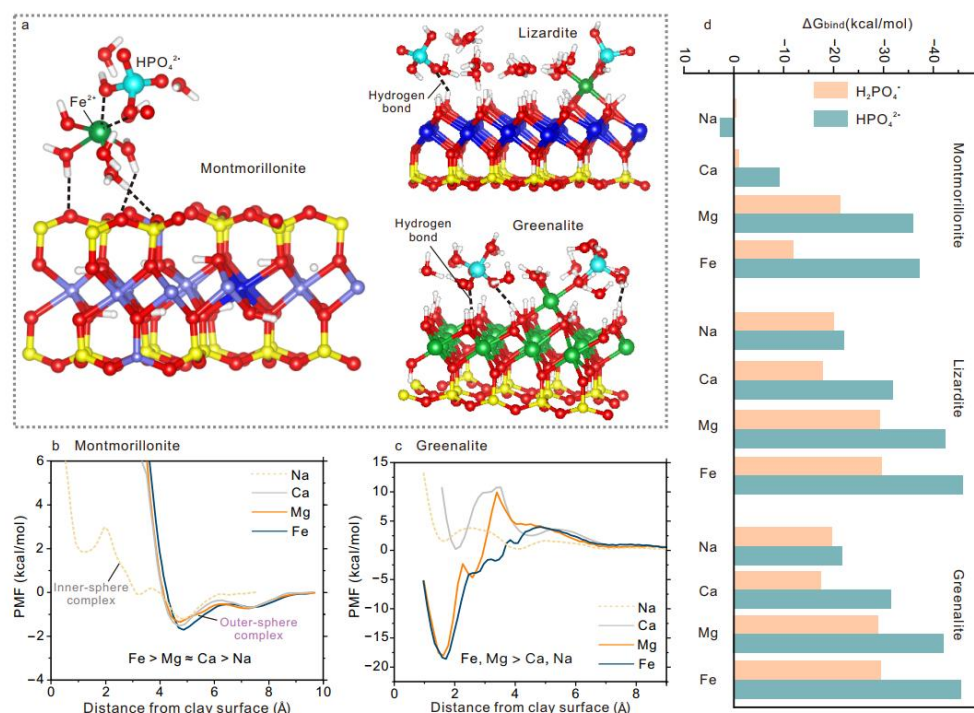


Image 4: Molecular simulation results showing phosphate adsorption onto montmorillonite, lizardite, and greenalite surfaces, highlighting the superior performance of Fe(II) in the cation bridging effect. Image credit: X. Cui et al. (2026). Nature Communications.



Image 5: A group photo of the HKU research team. From left: Professor Guochun ZHAO, Dr Xing CUI, and Professor Jihua HAO.

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