Goldschmidt 2026 Abstract
https://doi.org/10.46427/gold2026.34811

Deep phosphorus recycling requires exceptionally cold subduction

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Phosphorus is a key bio-essential element, yet the efficiency of its recycling into Earth's deep mantle remains poorly constrained. High-pressure phosphate inclusions in sublithospheric diamonds provide a rare opportunity to track deep phosphorus transport. Here we report tuite (γ-$Ca_3(PO_4)_2$) inclusions from two lower mantle-derived diamonds. A diamond from Juína, Brazil hosts a tuite inclusion co-occurring with low-Mg# (~65) ferropericlase and calcite. Trace-element and Sr–O isotope compositions of the tuite support its derivation from subducted altered oceanic crust. In contrast, a diamond from the DO-27 kimberlite, Canada, contains three tuite inclusions coexisting within a meta-peridotitic assemblage comprising high-Mg# ferropericlase (~90), retrogressed bridgmanite, CaSi-perovskite, and stishovite[1]. These observations provide mineralogical confirmation that phosphorus is transported into Earth' s lower mantle as tuite. However, thermodynamic calculations reveal that the formation of these diamonds and their inclusions requires the subducting slab to follow the coldest endmembers of slab geotherms observed in modern subduction systems. Such stringent conditions would have been rarely met and consequently minimized deep phosphorus recycling over geological time. Thus, phosphorus is dominantly retained in the crust through shallow mantle recycling, maintaining an accessible surface phosphorus reservoir critical for nutrient availability and the origin of life. The exceptionally cold subduction conditions not only enable deep phosphorus transport but also generate distinctive mineral assemblages of the slab mantle. Thermodynamic modeling of cold (<1080°C) harzburgitic slab mantle shows that it comprises ~44 wt.% stishovite + 55 wt.% ferropericlase + 1wt.% CaSi-perovskite. This newly recognized mineral assemblage drastically increases previous estimates of cold slab density and seismic velocity. Thus, temperature is a first-order control on slab mineralogy and rheology, determining slab stagnation or penetration at the transition zone–lower mantle boundary.

[1] Goldschmidt, Zhang et al. (2026), Geology, https://doi.org/10.1130/G54011.1