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Molecular Insights into Critical Mineral Mobility, Accumulation, and Fractionation in Regolith-Hosted Deposits

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Chemical weathering creates regolith deposits that host rare earth elements (REEs) and platinum group elements (PGEs) associated with secondary minerals. However, the geochemical processes governing the mobility and accumulation of critical elements during weathering are poorly constrained. REEs and PGEs adsorb onto clay and oxide mineral surfaces and incorporate into their structures through unclear pathways. Inaccurate or absent thermodynamic data further hinder prediction of the dominant reactions controlling REE and PGE fate during weathering. Addressing these challenges requires new experimental insights into the mineral-water partitioning behavior and underlying molecular mechanisms that determine the mobility and accumulation of critical minerals in regolith-hosted deposits. This presentation addresses interfacial and mineral substitution reactions controlling REE and PGE behavior, specifically focusing on potential pathways for the chemical fractionation of critical minerals.

Clay and iron oxide minerals host REEs in many regolith deposits. Our studies show that REE fractionations during adsorption to goethite and kaolinite vary with fluid composition. Multiple competing surface and aqueous reactions control uptake but disordered REE coordination shells hindered spectroscopic evaluation. Studies of specific aluminum oxide surfaces provide molecular insight otherwise inaccessible for such disordered REE species, revealing that REEs bind through multiple mechanisms that each display a distinct fractionation. Minerals particles, which are bound by multiple surfaces, may host five or more co-occurring interfacial species for each REE with net fractionation the mass balance sum of differential binding via each contributing adsorption mechanism. Less variable fractionation occurs during incorporation into goethite and montmorillonite, with both minerals favoring heavy REE retention. These integrated findings reveal that an array of competing pathways underlie REE fractionations in weathering environments.

Platinum-palladium fractionation often occurs in iron oxide-rich weathering systems, classically attributed to differences in complexation by chloride. Our studies show that chloride suppresses adsorption of these PGEs to both minerals but causes negligible fractionation. Instead, formation of distinct surface complexes on each iron oxide creates mineral-specific binding affinities for palladium and platinum, generating the observed fractionations. Multi-ligand systems display competitive and cooperative interactions overprinting consistent mineral-specific adsorption affinities. Platinum-palladium fractionation is thus determined by iron oxide mineralogy, which is ultimately controlled by regional climate.