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Resolving the Missing Lead Paradox: The Role of a Chemically Heterogeneous Mantle

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The formation of continental crust is crucial for stabilizing the climate and creating unique environments conducive to the development of life. Despite its importance, the evolutionary path of continental crust remains highly debated, particularly concerning the onset of significant crustal extraction. We propose a new theoretical framework for crust-mantle separation, utilizing geochemical constraints from the Th-U-Pb isotope system. The abundance of Pb isotopes in the continental crust is sensitive to the transition of Th and U from the mantle to the crust, providing valuable insights into the history of continental formation.

However, the Th-U-Pb isotope system currently presents an unsettling puzzle known as the "missing Pb paradox," which suggests that the lead isotopic signatures of the continental crust and mantle do not sum to a bulk-Earth composition. We propose that this paradox may be resolved by considering the effect of finite mixing time in the Earth's mantle. The missing Pb paradox assumes that mantle-derived rocks we observe on the Earth's surface accurately represent the mantle composition. However, the more viscous parts of the mantle, influenced by continental extraction, are not detectable until they are remixed with the surrounding mantle—a process that takes time. In other words, the finite mixing in the mantle leads to a mismatch between the actual mantle composition and the composition inferred from mantle-derived rocks, which could be the key to resolving the missing Pb paradox. We will quantify this mixing effect by analyzing the evolving rate of mantle convection, which is influenced by the history of mantle cooling. The innovation in this framework lies in explicitly incorporating the physics of mantle cooling and mixing with the chemical evolution of continental crust, addressing a major challenge in geochemical modeling of continental growth.