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Earth's Magma Ocean Solidification Dynamics and Geochemical Consequences

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Short-lived isotope systems indicate that the Earth's mantle became compositionally heterogeneous within the first tens of millions of years after formation. While Hf–W signatures can be explained by core formation, Sm–Nd and Lu–Hf anomalies require silicate differentiation. Despite these geochemical constraints, no comprehensive geodynamic framework has yet fully explained how such early differentiation processes operated during magma ocean crystallization and subsequent mantle evolution.

We conducted mantle-scale fluid dynamics simulations that account for trace element partitioning between solids and silicate melt, solid-liquid segregation, phase change, and mantle convection [1]. Our study explores the solidification dynamics and geochemical evolution of the early Earth's mantle, tracking Sm/Nd, Hf/W, and Lu/Hf in both solids and liquids.

Our results show that repeated solidification and remelting generate a vertically extensive, marble-cake–like geochemical mantle structure. Both superchondritic and subchondritic ratios are observed throughout the mantle at the end of magma ocean solidification.

We also find that low-pressure fractionation plays a major role in shaping Lu/Hf systematics. This challenges constraints on the extent of silicate-silicate differentiation derived from Primitive Upper Mantle (PUM) compositions: if bridgmanite, i.e., high pressure, dominated fractionation, large-scale differentiation would be inconsistent with refractory lithophile element systematics. However, substantial low-pressure solid–liquid fractionation, as predicted by our simulations, relaxes this constraint.

[1] Boukaré, CÉ., Badro, J. & Samuel, H. (2025), Nature 640, 114–119.