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Positive Ce anomalies in lunar rocks record volatile-rich vapor condensates from the Moon-forming disk

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The Moon's bulk composition provides a fundamental test of models for the origin of the Earth–Moon system, yet it is difficult to reconstruct because lunar samples are differentiated products of core formation, magma-ocean crystallization and later magmatism. Two first-order observations are nevertheless robust: Earth and Moon are indistinguishable in multiple isotope systems (e.g., O, Ti, Ca, Cr, Zr and W), whereas the Moon is depleted in moderately volatile elements and commonly exhibits heavier stable isotope compositions than Earth. These constraints, however, are non-unique: a range of impact scenarios (Earth-like impactor, Earth-dominated disk, efficient post-impact equilibration) and volatile-loss pathways (incomplete condensation and/or evaporation during disk cooling and magma-ocean evolution) can reproduce them.

Here we introduce an independent constraint from rare earth element (REE) systematics. Because Ce should track neighboring REEs during lunar differentiation, systematic Ce anomalies are not expected. Instead, lunar samples exhibit a subtle but pervasive positive Ce anomaly relative to terrestrial rocks and planetary meteorites (Ce/Ce* = 1.06 ± 0.003, 2SE) (Fig. 1). We interpret this signature as accretionary, reflecting incorporation of volatile-rich vapor condensates in the Moon-forming disk. Under melt–vapor equilibrium in a disk with bulk silicate Earth (BSE) composition, Ce partitioning is strongly controlled by oxygen fugacity (f_{O2}) under relatively oxidizing conditions, allowing Ce to decouple from adjacent REEs during disk cooling. We show that this redox-sensitive fractionation constrains the contribution of vapor condensates to the Moon and yields new insights into Earth–Moon formation.

