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The Moon in the Skye: insights into the formation and evolution of the lunar magma ocean

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On the Moon, mare basalts were the results of explosive volcanic eruptions which sampled mantel material during the ascent. Apollo 15 and Apollo 17 missions have landed on the edge of Mare Imbrium and Mare Tranquillitatis respectively and collected numerous volcanic material, including basaltic lavas, mantle and crustal xenoliths, and magnesium rich green glasses. Studies of the green glass indicate that the melt from which it formed originated about 400 kilometres below the Moon's surface.

Due to the absence of tectonic reworking, a protracted mantle convection history and the lack of weathering, and notwithstanding meteorite impacts, the pristine nature of the lunar samples can be used to both better constrain magma-storage depth during plume-like volcanic activity and provide better understanding on the crystallization of magma oceans. Unlike most erupted volcanic material on Earth, whole rock lava and xenolith samples present at the Moon’s surface likely preserve pressure and temperature at which they have formed or have reequilibrated. In this study, we used thermodynamic modelling to constrain the minimum depth of magma storage and the equilibrium depth of mantle and crustal xenoliths (i.e. picrite, dunite, troctolite).

Our results indicate that there were two levels of magma storage beneath the Mare Imbrium at the time of the eruption, at 140 ± 11 km depth and at ~ 82 km depth below the KREEP layer (~ 60 km). Picrite and dunite are equilibrated at 130-150 km depth, troctolite at 80 km depth and anorthosite between 0 and ~ 35 km depth. The maximum equilibrium depth for forsterite-rich olivine in picrite xenoliths and green glass beads is estimated at 490 ± 10 km. Estimated lunar mantel potential temperature (Tp) is 1490 °C, which is similar to the Icelandic Tp (~ 1490 °C) and close to the North Atlantic Province Tp (1350 °C).

There are strong petrological similarities in the internal architecture of the first 150 km of the Moon presents Shiant Isles Main Sill (135 m) (SIMS) in Scotland), suggesting similar formation processes. The SIMS formed with a significant crystal cargo (~ 15 vol%), which then differentiates through settling of crystals from a vigorously convective magma and the concomitant rising of buoyant melt giving rise to a sandwich horizon significantly above the mid-point (~ 75 %) of the sill total thickness. On the Moon, the predominant current theory of lunar formation suggests the

formation of a flotation anorthosite crust on the top of a rapidly convecting magma ocean. However, in such environment (Ra ~ 10^{30}), anorthosite crystals are likely to be re-entrained, suggesting the crust might have only formed once the magma ocean had an aggregate crystal cargo of roughly 50%.

Hence, the petrological information contained in picritic sills on Earth might give direct insights into the formation and evolution of the magma ocean on the Moon. Based on our observations, we argue that lunar differentiation would have then been driven by the formation of a stagnant lid, compaction through buoyant flow of anorthite-rich melt and then further refinement through magmatism on the moon.