
**Using the South Pole-Aitken (SPA) Impact Melt Composition to Infer Upper Mantle Mineralogy and Timing of Potential Mantle Overturn.**

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**Introduction:** From a few particles of anorthosite in Apollo 11 soil samples, John Wood and others [1-3] quickly deduced the Moon had been surrounded by a lunar magma ocean (LMO) that differentiated, producing an anorthositic crust that forms the ancient cratered highlands of the Moon seen today. The base of the differentiated sequence is expected to have been composed of Mg-rich olivine and olivine with increasing amounts orthopyroxene. The shallowest mantle would then be composed mostly of clinopyroxene and other materials enriched in elements that were incompatible during LMO crystallization. That sequence has an inverted density profile that may have prompted an overturn of the cumulate pile to stabilize the density structure of the lunar interior (e.g., [4-7]). Ilmenite-rich material, carried downward by the overturn, became an important source region for pyroclastic basalts like those at Apollo 17.

**A Probe of the Mantle:** Impact bombardment altered the crust, in some cases melting the anorthosite, any intrusions within it, and, in the largest impacts, the upper mantle. A simple calculation [8] indicates ~10^8 km^3 of impact melt was produced. Approximately half (if not more) of the impact melt volume was produced by the SPA basin-forming event. The largest fraction of the melt stayed within the central melt pool. That melt may have differentiated, producing a new series of layered lithologies. In the case of SPA, liquid lines of descent suggest olivine may have crystallized and settled downward. Progressive crystal fractionation would have driven the remaining liquid towards noritic compositions [9-11], which is observed today.

A more sophisticated examination of SPA impact melt differentiation [12], based, in part, on a hydrocode assessment of the SPA impact event and depth of melting [13], also produced noritic material, but only if the mantle had not yet overturned. Alternatively, the results suggest any mantle overturn was not a global event.

**Implications for Timing:** The duration of the LMO ranges from 10 Myr based on heat loss rates through a simple conducting lid [7], to ~100 Myr based on tungsten ratios measured in low- and high-Ti mare basalts and KREEP [14], and ~200 Myr based on heat loss rates through a tidally deforming lid [15,7]. Cumulate overturn is hypothesized to have occurred toward the final stages of LMO solidification, after the cumulate density inversion developed [4,5,7,16]. That implies the SPA-forming impact occurred significantly earlier than currently thought if, for example, the LMO had a simple conducting lid, at ~4.5 Ga [7], or the LMO solidification and cumulate overturn were delayed to ~4.3 Ga, a delay accommodated by tidal heating of the conducting lid [15,7]. The latter is consistent with a recent model of the impact flux to the Moon, which was used to estimate an age of 4.35 Ga for the formation of SPA [17] and consistent with a crater-counting surface age of ~4.26 Ga [18]. If SPA did indeed form prior to the hypothesized LMO cumulate overturn, it is possible that the impact event triggered the overturn process, affecting a broad portion, if not all, of the lunar interior structure, though further analyses are required to verify this hypothesis.

**Conclusions:** The upper mantle of the Moon at the time of the SPA impact featured clinopyroxene rather than olivine. If mantle overturn occurred, it may have been triggered by the SPA impact event on the lunar farside. That impact event has also been implicated in the origin of a magmatic epoch on the nearside [19].