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INVITED REVIEW

Magmatic evolution of the Moon

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ABSTRACT

Although incomplete because of the imperfect and somewhat random sampling of rock types by the Apollo and Luna missions (1969–1976), the history of lunar magmatism has been reconstructed by numerous researchers over the past three decades. These reconstructions have illustrated the continuous nature of lunar magmatism (from 4.6 to ~2.0 Ga) and the large influence of early differentiation and catastrophic bombardment on lunar mantle dynamics, magmatism, and eruptive style. In this review, we group magmatism into multiple stages of activity based on sampled rock types and evaluate the models for each stage.

Stage 1 is early lunar differentiation and associated magmatism. Partial melting of the Moon soon after accretion was responsible for producing an anorthositic crust and a differentiated lunar interior. The extent of lunar melting and mantle processing depends strongly on the mechanisms that induced melting. Estimates for the time over which melting and crystallization occurred range from tens to hundreds of millions of years. Stage 2 is the disruption of lunar magma ocean cumulates. Soon after the crystallization of most of the lunar magma ocean, the cumulate pile experienced gravitational overturn. This resulted in transport of late-forming cumulates into the deep lunar mantle and mixing of magma ocean cumulates on a variety of scales. Stage 3 is the post-magma ocean highland magmatism. Whereas the ferroan anorthositic crust was probably produced during the crystallization of a magma ocean, the slightly younger Mg suite and alkali suite plutonic rocks may have been generated by decompressional melting of early magma ocean cumulates during cumulate pile overturn. A KREEP and crustal signature was incorporated into these primitive basaltic magmas through assimilation near the base of the lunar crust or through melting of a hybridized mantle. The alkali suite could represent either the differentiation products of Mg suite parental magmas or a separate, but contemporaneous episode of basaltic magmatism. Stage 4 is pre-basin volcanism. Sample analysis and remote sensing data indicate that early lunar volcanism (KREEP basalts and high-alumina basalts) was contemporaneous with periods of highlands plutonism and catastrophic bombardment of the lunar surface. The relationship between early stages of lunar volcanism and the contemporaneous plutonism is not clear. The KREEP basalts may be volcanic equivalents to both the Mg suite and alkali suite. Stage 5 is the late remelting of magma ocean cumulates and eruption of mare basalts. Basin-associated eruption of mare basalts occurred during and following the late stages of catastrophic bombardment. This volcanic activity was possibly an extension of the thermal event that initiated pre-basin volcanism. Mare basalts exhibit a wide range of composition resulting from near-surface fractionation of chemically distinct primary basaltic magmas. Most likely, mare basalts were produced by small to moderate degrees of partial melting of hybrid cumulate sources in the deep lunar mantle. Alternatively, the mixed chemical signatures observed in many mare basalts may be interpreted as indicating assimilation of late-stage, evolved cumulates by melts produced deep in the cumulate pile. The wide range of compositions exhibited by the mare basalts compared with earlier episodes of basaltic magmatism may reflect the thermal regime in the lunar mantle that limited the extent of partial melting and melt-source homogenization.