The Case for an Imbrium Origin of the Apollo Th-Rich Impact-Melt Breccias

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Abstract—Mafic, Th-rich impact-melt breccias, most of which are identified with the composition known as "LKFM," are the most common rock type in the nonmare regoliths of the Apollo lunar landing sites. The origin of mafic impact-melt breccias bears on many lunar problems: the nature of the late meteoroid bombardment (cataclysm); the spatial distribution of KREEP, both near the surface and at depth; the ages of the major basins; and the composition of the early crust of the nearside lunar highlands. It is thus crucial that the origin of mafic impact-melt breccias be accurately understood. Because of both intra- and intersite differences in composition of mafic impact-melt breccias samples, apparent differences in crystallization age, and differences in siderophile-element ratios, previous studies have argued that either (1) most mafic impact-melt breccias are the products of several large craters local to the site at which they were found but that some are of basin origin or that (2) they are all from the Imbrium (Apollos 14 and 15), Nectaris (Apollo 16), and Serenitatis (Apollo 17) basins. Here, we reconsider the hypothesis that virtually all of the Th-rich, mafic impact-melt breccias from the Apollo missions are products of the Imbrium impact.

Ejecta deposit modeling based on modern crater scaling indicates that the Imbrium event produced ejecta deposits that average hundreds of meters thick or more at all Apollo highland sites, thicker than some previous estimates. Substantial amounts of Imbrium ejecta should have been sampled at every Apollo highland site. We suggest that the mafic impact-melt breccias may be the principal form of those ejecta. The Imbrium projectile impacted into Th-rich material that we regard as part of a unique, mafic, lunar geochemical province we call the High-Th Oval Region. Based on the surface distribution of Th, only basins within the High-Th Oval Region excavated Th-rich material; the Th concentrations of the highlands as observed by the Apollo orbiting γ-ray experiments are consistent with the estimates from ejecta modeling. Of the younger basin-forming impacts, only Imbrium was large enough to produce the copious amount of melt required by the ubiquitous presence of mafic impact-melt breccias in the Apollo-sampled regolith. The High-Th Oval Region may have been still molten or hot at shallow depths ~4 Ga ago when the Imbrium projectile struck. We reason that compositional heterogeneity of ejected melt breccia is to be expected under these circumstances. We argue that siderophile-element "fingerprints" of mafic impact-melt breccias are not inconsistent with production of all common types by a single projectile. We suggest the narrow range of ages of 3.7–4.0 Ga for all successfully dated mafic impact-melt breccias may reflect a single event whose age is difficult to measure precisely, rather than a number of discrete impact events closely spaced in time, such that reported age variations among mafic impact-melt breccias reflect the ability to measure $^{40}Ar/^{39}Ar$ ages with greater precision than the accuracy with which measured portions of mafic impact-melt breccias have recorded the time of their formation.