CLAST PROVENANCE IN IMBRIUM IMPACT-MELT BRECCIAS. L. A. Haskin, R. L. Korotev, and B. L. Jolliff, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Campus Box 1169, Washington University, One Brookings Drive, St. Louis, MO 63130 (lah@levee.wustl.edu)

Introduction: We have suggested that the Th-rich, mafic impact-melt breccias (MMBs) found at the Apollo sites consist mainly of Imbrium ejecta [1,2]. Arguments against this hypothesis are most plausibly made for the Apollo 17 poikilitic melt breccias [e.g., 3,4]. Nonetheless, we consider the hypothesis and its implications in light of the concentration of Th (and, by inference, KREEP) that occurs in the Procellarum KREEP Terrane [5,6].

A principal characteristic of the Apollo MMBs is the commonality of their KREEPy melt component, which has noritic bulk composition of intermediate *Mg*' (~61) and abundances of incompatible trace elements that closely resemble those of Apollo 15 KREEP basalt. All MMBs also contain a chemical component of feldspathic upper crust [7] and many contain clasts of feldspathic materials such as lithologies occurring in the feldspathic highlands [e.g., 8–10]. Here, we explore the proposition that the provenance of most of the feldspathic materials may have been the substrates onto which molten Imbrium ejecta fell.

Ejecta modeling estimates indicate that, on average, Imbrium ejecta deposits should be hundreds of meters or more thick at all Apollo sites and should contain roughly 20% to 40% Imbrium ejecta (more at the Apollo 15 site) [11]. If so, the MMBs would constitute the bulk of the Imbrium ejecta, because the MMBs make up roughly 20 to 40% of the regoliths sampled at the Apollos 14, 16, and 17 sites [2]. If the MMBs are indeed the bulk of the Imbrium ejecta, then most or all of the Imbrium ejecta were molten [1,2,12, 13]. The remaining portion of the regoliths then would constitute the local substrates onto which the Imbrium ejecta fell.

On the basis of the Lunar Prospector γ-ray data [5], the only plausible provenance for the Apollo MMBs, which are the most Th-rich lithologies common at the Apollo sites, appears to be the Moon's unique, KREEPy, geochemical province that we have called the "High-Th Oval Region" [1] or "Procellarum KREEP Terrane" [6,7]. The Apollo 17 MMBs might be Serenitatis-produced melt rather than Imbrium-produced melt [e.g., 4], as the Procellarum KREEP Terrane appears to extend part of the way into the Serenitatis basin.

It has traditionally been considered that the feldspathic component of the MMBs was picked up by the melt as it was impelled through shattered but solid upper crust on its route out of the expanding transient crater or that it otherwise mixed with upper crustal material during the ejection process [e.g., 14,15]. The melt would have been quenched by heat exchange with this clastic material and by partial dissolution of it. If (1) most of the Imbrium ejecta were molten at the time of their release from the impact crater, as we suggest [1], (2) they stayed molten during their transport because they were too massive to radiate away heat, and (3) they descended as melt at high velocity onto the sites of secondary cratering or even if they descended as hot material that melted on kinetic energy release at the time they struck the ground [1], then part and perhaps most of the clastic feldspathic component of the resulting MMBs would have been incorporated at the site of secondary impact. Regardless of the mechanism, there is some evidence that clast incorporation might occur outside the crater even in small terrestrial impacts [16]. We thus consider below the nature of the Apollo MMBs and their host regoliths from the hypothetical point of view that the Imbrium ejecta arrived largely as melt.

Site Differences: For the most part, clasts found within MMBs are different in type and relative abundance from one Apollo sampling site to another and these differences are matched by the regolith in which the MMBs occur. Anorthositic lithic clasts and plagioclase mineral clasts are rare in both the Apollo 14 MMBs [<4% in 14321; 17] and in the Apollo 14 regolith [<2%; 18]. Similarly, ferroan anorthosite is rare in those Apollo 15 MMBs generally believed to be products of the Imbrium impact [19] as well as the regolith [20,21]. The absence of typical feldspathic crustal material in these Apollo 14 and 15 materials implies that, prior to the Imbrium impact, the Procellarum KREEP Terrane lacked typical feldspathic crust [7,19]. In contrast, MMBs from Apollo 16 contain abundant feldspathic clasts and have the highest proportion of plagioclase clasts that derive from ferroan anorthosite [9,22]. The same can be said of the Apollo 16 soils, and the clastic components of the MMBs appear to be the same as those of the soils [23]. It is likely that the feldspathic components of the Apollo 16 regolith are largely Nectaris ejecta (i.e., pre-Imbrium) [23,24]. At Apollo 17, ferroan anorthosite is again rare in the MMBs as well as the regolith [25,26]. However, the principal type of feldspathic lithic clast in the Apollo 17 MMBs is feldspathic granulitic breccia [27,28] and this lithology (including its unique siderophile-element signature [1]) is also a common component of the regolith [25]. The Apollo 17 feldspathic granulitic breccias are probably not Imbrium ejecta but occurred in the Taurus-Littrow area prior to the Imbrium impact because those Apollo 17 regolith breccias that are devoid of both mare material and MMBs are generally similar in composition to the feldspathic granulitic breccias [25].

It has been pointed out that different near-surface materials might have been picked up by different batches of melt issuing from different locations within an expanding transient crater [e.g., 16]. A single large impact could thus deliver both MMBs and unconsolidated feldspathic materials such that the feldspathic clasts and regoliths would match for a given site but differ from site to site. To derive both the MMBs and the feldspathic regolith mainly from ejecta from the Imbrium basin would be inconsistent, however, with the results of ejecta deposit modeling the bulk of the material of the regolith should be of local origin.

Textures: The textures of at least some MMBs, are consistent with a mechanism by which the bulk of the clasts were derived from the substrate rather than from within the transient crater. For example, the Apollo 16 dimict breccias consist of ferroan anorthosite and mafic impact melt in a mutually intrusive relationship [9,29,30]. They are believed to have formed by injection of impact melt into anorthositic bedrock at the bottom of a large, expanding crater cavity [9,31]. A problem with this scenario, however, is how, in a large impact into the Central Highlands, such a mafic (≤22% Al_2O_3), KREEP-rich melt zone could overlie highly feldspathic ferroan anorthosite (~33% Al_2O_3 [9]). Perhaps instead, the Apollo 16 dimict breccias were produced by impact into the feldspathic Central Highlands of a large body of mafic melt ejected from the Imbrium basin cavity. Droplets of semiviscous melt of similar composition were injected into fragmented feldspathic material to form the feldspathic fragmental breccias of North Ray crater [10].

The poikilitic and aphanitic MMBs of Apollo 17 resemble each other chemically but not texturally. Their clast types are somewhat different [8]. The proportion of melt component ("KREEP norite") is higher in the poikilitic breccias [7]. The aphanitic breccias, which have accretionary textures suggestive of melt that flowed across a fragmented surface [27], apparently cooled more quickly than the poikilitic breccias because they acquired a higher clast load. The poikilitic breccias, which did not acquire enough clasts to chill them to fine-grained texture, cooled more slowly within the ejecta deposit. This scenario requires a thick deposit for this slow-cooling process to occur.

We might imagine the textures that would result from the following scenario for arrival of molten primary ejecta in large quantities at a secondary impact site. Imagine massive in-flight bodies of melt in amounts corresponding to local thicknesses of hundreds of meters arriving at high velocity over a short time interval onto broad areas of preexisting megaregolith. At all distance scales, features would depend on the surface density, size distribution, arrival rates, and arrival angles of the incoming melt. Substantial impact excavation would occur, as well as substantial lateral motion of impacted melt and excavated substrate, resulting in mixing and burial. Large batches of incoming melt might produce broad, coherent layers of mixed material ranging in lateral extent to kilometers or greater. Large blobs of melt whose impact sites were separated by distances of the same order as their diameters or greater might lead to lenses or pseudolayers of uneven thickness with melt rock interspersed with other breccia types. The apparent layering on the upward tilted Silver Spur near Hadley Rille may have resulted from such a mechanism. So might the layering observed on the massifs flanking the Taurus-Littrow valley.

It is difficult to conjecture what textural properties of MMBs could diagnostically indicate such an origin. Specific surface materials such as agglutinates and glass spherules would be uncommon in the MMBs because they would have dissolved or become too diluted by excavation and mixing of material of the megaregolith to be found readily as clasts in the MMBs. If the upper part of the Apollo 17 North Massif consisted of deposits that derived from molten basin ejecta mixed with local regolith, then the properties of the station-6 boulder samples would be those of the rocks formed by impacting melt. It could be an informative exercise to interpret their features from that viewpoint.

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