THE "GREAT LUNAR HOT SPOT" AND THE COMPOSITION AND ORIGIN OF "LKFM" IMPACT-MELT BRECCIAS.

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An Observation: In an extension and refinement of previous work [1], it can be shown that the composition of virtually any type of mafic impact-melt breccia from the Apollo missions that has been identified with the composition known as LKFM can be modeled well as a mixture of four components: (1) a norite with composition similar to that of Apollo 15 KREEP basalt (mean abundance: 54%), (2) Fo_{90} dunite (mean: 13%), (3) typical feldspathic upper crust (FUpCr, mean: 33%), and FeNi metal (0.11–1.68%). Relative proportions of the components vary among different breccia types (Fig. 1) this variability accounts for the compositional differences among the breccias. The KREEP norite component of the model, derived iteratively from best-fit model residuals (Table 1), is slightly richer in normative pyroxene (43% vs. 39%) and poorer in normative quartz (3% vs. 8%) than Apollo 15 KREEP basalt. The dunite component was assumed to be like sample 72415, but with Fo_{90} and no normative pyroxene or plagioclase. The FUpCr component of the model is that derived from the feldspathic lunar meteorites [2]. The FeNi component is $Fe_{94}Ni_6Co_{0.4}$ metal such as found in Apollo 16 melt breccias [3].

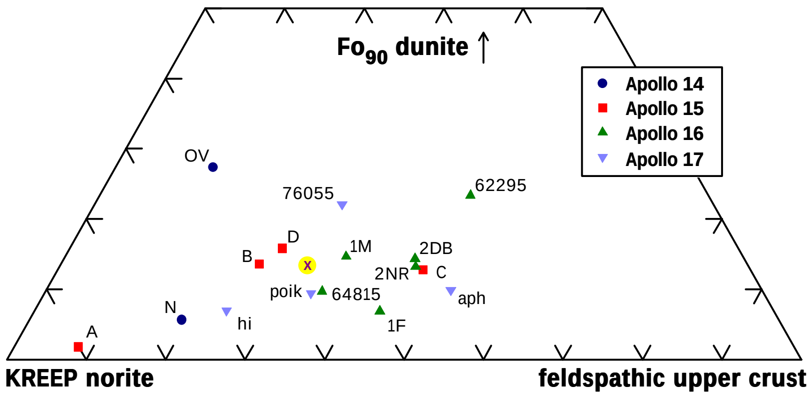

Figure 1. Model results, excluding the minor FeNi component. Each point represents a compositional group of mafic, Th-rich impact-melt breccia. Apollo 14: normal (N) and olivine vitrophyres [OV; 5]. Apollo 15: groups A, B, C, & D [19]. Apollo 16: groups of [3] plus anomalous samples 62295 (1Mo) and 64815. Apollo 17: aphanitic, poikilitic [20], "hi-Sm" [21], and anomalously magnesian sample 76055 [20]. The "x" is the site-weighted mean.

On average, the large variation in *Mg´* (mole % Mg/[Mg+Fe]) among the breccias (61–81) can be explained only by ~0–30% high-*Mg´* dunite, not by Mg-suite norite or troctolite, as previously suggested [1]. The mass-balance requirement for a feldspathic component is satisfied better by typical feldspathic upper crust (~28% Al_2O_3) than by ferroan anorthosite (~35% Al_2O_3) for all mafic melt breccias except the group-2 breccias of Apollo 16 ("VHA," i.e., 2DB, 2NR, and 62295 of Fig. 1). For Apollo 17 mafic melt breccias only, the model fit is improved by inclusion of a component of CI chondrite in addition to the FeNi component in order to account for the high Ir/Au ratio of Apollo 17 breccias. This component probably represents meteoritic material that is carried by the FUpCr component at Apollo 17 (i.e., granulitic breccias [4]).

Caveats: Quantitatively, the mass-balance model does not succeed unless the composition of the KREEP norite component is allowed to vary among the different melt breccia types; a single composition (Table 1) is inadequate. The variation takes two forms. First, ratios of concentrations of incompatible to compatible elements (e.g., Sm/Fe) must vary in the range 0.5 to 1.6 times that of the mean. For example, the normal impact-melt breccias of Apollo 14 (N, Fig. 1) require a KREEP component with ~50 µg/g Sm whereas the group-D melt breccias of Apollo 15 require a KREEP component with only ~16 µg/g Sm. Second, there must be minor variation in the abundance of subcomponents of the KREEP component representing alkali anorthosite, granite, ilmenite, and chrome spinel. For example, compared to the KREEP norite composition of Table 1, the KREEP component of the Apollo 15 group-A melt breccias is depleted in Na, Sr, and Eu relative to highly incompatible elements (e.g., Sm). In terms of the model, these breccias require +94% KREEP norite and –12% alkali anorthosite components. Similarly, the olivine vitrophyres of Apollo 14 (an impact-melt lithology [5]) contain more K, Rb, and Cs than can be supplied by the proportion of KREEP norite component required to supply the Sm. In terms of the model, this melt lithology requires +53% KREEP norite and +3% granite components.

Table 1. Average composition of the KREEP norite model component.

	%		µg/g
SiO_2	49.4	Sc	25
TiO_2	2.2	Co	15
Al_2O_3	15.6	Rb	17
FeO_T	10.9	Sr	210
MgO	9.2	Cs	0.71
MnO	0.165	La	71
CaO	10.0	Ce	186
Na_2O	0.89	Sm	32
K_2O	0.56	Eu	2.9
BaO	0.082	Tb	6.7
Cr_2O_3	0.26	Yb	23
ZrO_2	0.13	Lu	3.2
P_2O_5	0.5	Hf	25
Σ	99.9	Ta	2.9
		Th	11.9
Mg'	60.1	U	3.2

Interpretation, Speculation, and Pontification of the Kind That Can Only Be Done in Conference Abstracts. The Apollo mafic (LKFM) melt breccias are not the products of impacts into typical feldspathic crust. Instead, they all derive from basin-sized impacts into what we might call the "Great Lunar Hot Spot" which, after solidification, became the "high-Th oval region" [6] or the "Procellarum KREEP Terrane" [7], i.e., the unique, mafic, Th-rich province identified by the Apollo and Lunar Prospector gamma-ray spectrometers [8]. Most were probably produced by impact of an iron meteorite (the FeNi component) that formed the Imbrium basin [3,4]. The LKFM composition is a special product of the Procellarum KREEP Terrane; it is not the average composition of the lower crust [9,10] in the "Feldspathic Highlands Terrane" [7] or the composition to be expected for material exposed by the South-Pole–Aitken impact [11]. Consequently, the observation that LKFM melt breccias are more mafic than the feldspathic highlands and are much richer in Th provides little evidence that the crust in the Feldspathic Highlands Terrane becomes substantially more mafic with depth or that urKREEP [12,13] or its derivatives occurs at the base of the crust globally. [Note also that the correlation between 'maficness' of basin ejecta and basin diameter of [10] vanishes (R^2 = 0.27) if the data for Imbrium (in the Procellarum KREEP Terrane) and Serenitatis (partly in the Procellarum Th Terrane or Imbrium ejecta [4]) are eliminated.]

Given reasonable whole-Moon compositions, most of the Moon's Th must have occurred in the Great Lunar Hot Spot prior to the Imbrium impact. In the vicinity of the Imbrium impact, the hot spot, to several tens of kilometers depth, consisted predominantly (>50%) of material with an average composition approximating that of the KREEP model component. The material was partially differentiated laterally and vertically such that different volumes of ejected impact melt (i.e., the Apollo mafic melt breccias) varied somewhat in relative abundances of differentiation products.

The dunite component of the model represents material of the upper mantle heterogeneously distributed in the ejected impact melt. This mantle component may have been assimilated in part by the KREEP magma prior to the Imbrium impact. The early geometry of the Hot Spot, presumably a large, thick body of magma, is more likely to lead to convection or gravitational instability leading to turbulent mixing of these components than the "sandwich" model envisioned by [12]. Almost certainly, however, the upper mantle was within the melt zone of the Imbrium impact [14]. It is likely that the KREEP paradox [12], i.e., the combination of evolved incompatible elements and moderately primitive *Mg´* in Apollo 15 KREEP basalt and KREEP-bearing melt breccias, is a special feature of the Procellarum KREEP Terrane that is ultimately related to mixing of an urKREEP magma and olivine-rich mantle material. The KREEP norite model component probably itself represents a mixture of urKREEP and mantle olivine.

Many, if not most, of the highly differentiated lithologies found in the Apollo collection (e.g., alkali anorthosite, granite, felsite, quartz monzodiorite) were probably not formed by processes in the Feldspathic Highlands Terrane, but are probably special products of the Great Lunar Hot Spot. The east-west differences of [15,16] are probably manifestations of the location of the Procellarum KREEP Terrane. Because the norites, troctolites, and gabbronorites of the Mg suite of lunar plutonic rocks are thought to be derived from KREEP-basalt-like magma [17], they are also likely products of differentiation in the Great Lunar Hot Spot. Thus there is no reason to expect, based on our limited sampling, that at points distant from the Procellarum KREEP Terrane, KREEP-contaminated, Mg-rich magmas intruded the feldspathic crust [e.g., 10,12].

Some or most of the feldspathic crust component of the breccias may have been incorporated into the breccias outside the basin cavity at the point of impact of the ejected melt [4,18]. If so, then the proportion of feldspathic crust in the target area may have been considerably less than the 33% mean implied by the mass-balance model, i.e., prior to the Imbrium impact, the Great Lunar Hot Spot may have had little or no feldspathic crust [22].

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