

The great lunar hot spot and the composition and origin of the Apollo mafic (“LKFM”) impact-melt breccias

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Abstract. Thorium-rich, mafic impact-melt breccias from the Apollo 14–17 missions, that is, those breccias identified with the composition known as “LKFM,” are regarded largely as products of basin-forming impacts that penetrated the feldspathic crust and sampled underlying mafic material and magma-ocean residuum carrying the compositional signature of KREEP (potassium, rare earth elements, phosphorous). Despite considerable compositional variation among such breccias, compositions of all of them correspond to mixtures of only four components: (1) a norite with composition generally similar to that of Apollo 15 basalt (mean abundance: 58%; range: ~30–95%), (2) Fo₉₀ dunite (mean: 13%, range: 1–27%), (3) feldspathic upper crust (mean: 29%, range: 4–50%), and FeNi metal (0.1–1.7%). Petrographic evidence has shown that much of the feldspathic component, but none of the KREEP component, is clastic. This observation and the high proportion of KREEP norite component in the breccias suggest that the melt zone of the impact or impacts forming the breccias contained little feldspathic material but consisted predominantly of material with the average composition of KREEP norite. The dunite component probably derives ultimately from the upper mantle. These conclusions support the hypothesis that the breccias were not formed in typical feldspathic crust but instead by one or more impacts into what is designated here “the great lunar hot spot,” that is, the anomalous Th-rich terrane in the Imbrium-Procellarum area identified by the Apollo and Lunar Prospector gamma-ray spectrometers. The LKFM composition is a special product of the great lunar hot spot and is not the average composition of the lower crust in typical feldspathic highlands. Similarly, Mg-suite and alkali-suite plutonic rocks of the Apollo collection are likely all differentiation products of the hot spot, not of plutons that might occur in typical feldspathic crust.

1. Introduction

The subject of this paper is one of the most common rock types collected on the Apollo lunar missions. These rocks have gone by many names over the years. Descriptively, they could be called the “Apollo, ancient, moderately mafic, incompatible-element-rich, crystalline, impact-melt breccias.” For about 20 years, however, they have been popularly known as low-K Fra Mauro basalts, LKFM basalts, or, even more cryptically, just plain LKFM [e.g., Reid *et al.*, 1977; McCormick *et al.*, 1989]. As detailed below, the term LKFM is fraught with ambiguity. Thus I will refer to such breccias as “Apollo mafic melt breccias” or just “mafic melt breccias” [Haskin *et al.*, 1998], although out of context these terms are also inappropriate because, in the literal sense, they could include breccia types specifically excluded from consideration here. Excluded lithologies include glassy breccias produced by brecciation of the ancient (~3.9 Ga) crystalline breccias by subsequent impacts, mafic breccias that are poor in incompatible elements that may not be related to the incompatible-element-rich breccias, and mafic melt breccias that may have formed distant from the Apollo sites (e.g., those that might be inferred to be present in or around the South Pole Aitken basin) that are not related to the Apollo breccias in provenance.

The Apollo mafic melt breccias are among the most enigmatic rocks collected on the Moon. The enigmas take many forms:

1. We can infer from results of the Clementine mission [Lucey *et al.*, 1998] and the lunar meteorites [e.g., Korotev *et al.*, 1996a; Korotev, 1999a] that typical lunar highlands are feldspathic ($\text{Al}_2\text{O}_3 \approx 28\%$, $\text{FeO} + \text{MgO} \approx 9\%$), yet the mafic melt breccias, which are among the most common nonmare rock types of the Apollo 14, 15, 16, and 17 sites, are considerably more mafic ($\text{FeO} + \text{MgO} = 19\text{--}29\%$).

2. Ratios of Mg to Fe in mafic melt breccias are highly variable but appear to be uncorrelated with any other geochemical parameter.

3. By terrestrial standards the Apollo mafic melt breccias have the somewhat unusual combination of being both mafic and rich in incompatible minor and trace elements like P, K, rare earth elements (REEs), and Th. Absolute concentrations of incompatible elements vary by more than a factor of 5 among the breccias, yet ratios of any two incompatible elements are very similar in all samples and are essentially the same as those in samples of feldspathic basalt found at the Apollo 15 site that is known as KREEP basalt for its high concentrations of K, REE, P, and other incompatible elements. This observation has long been taken as evidence that these polymict breccias all contain a component of KREEP basalt, or some related precursor, and that the KREEP component is the only significant source of incompatible elements in the breccias. However, some types of mafic melt breccia contain higher concentrations of incompatible elements than do typical samples of igneous KREEP basalt, indicating that the

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KREEP component of those breccias is richer in incompatible elements than is Apollo 15 KREEP basalt itself.

4. The composition of the breccias, that is, the "LKFM composition," cannot be explained as a mixture of known lunar igneous rock types or as a combination of the mineral and lithic clasts observed in the breccias; some cryptic component seems to be present [McCormick *et al.*, 1989; Spudis *et al.*, 1991; Ryder *et al.*, 1997].

5. The LKFM composition is consistent with that of an equilibrium liquid, yet no LKFM samples of igneous origin are known; all are polymict breccias [e.g., Reid *et al.*, 1977].

6. In part because mafic melt breccias from different sites have different compositions and reported crystallization ages, and because the Apollo sites were strongly influenced by at least three major basins, the melt breccias are usually believed to be the products of basin-forming impacts. However, nearly all crystalline samples of mafic melt breccias that have been dated give crystallization ages in the narrow range of about 3.8–4.0 Ga [Haskin *et al.*, 1998].

7. At least a dozen compositional groupings occur, suggesting that the breccias were formed by numerous impacts, too many for them all to have been produced in a few nearside basins. However, the presence of a KREEP component in all the breccias, despite the relatively restricted distribution of KREEP on the surface of the Moon around the Imbrium-Procellarum region [Lawrence *et al.*, 1998], suggests that they were all produced in a small region of the crust, perhaps by a single basin-forming impact [Haskin *et al.*, 1998].

8. Finally, breccias of several, if not most, of the compositional groups contain FeNi metal of a distinctive composition, suggesting they were all formed by, or contain the remnants of, a single iron meteorite [Korotev, 1987a, 1994, 1997; Haskin *et al.*, 1998].

The purpose of this paper is to provide an explanation for these various observations and examine the constraints the Apollo mafic melt breccias provide on models of lunar crust formation. The study focuses on three key aspects of the breccias: (1) they are mechanical mixtures of older materials, (2) they vary significantly in composition, and (3) they are probably all related by process and proximity in that all or most were formed by one or more large impacts 3.9 Gyr ago in the relatively small region of the crust of the Apollo landing sites (the Imbrium, Serenitatis, Nectaris region). In this context I address the questions: Can the average composition of Apollo mafic melt breccias, as well as the compositional differences among them, be explained by mixing different proportions of a small number of reasonable components? If so, what do these components and their relative abundances tell us about the process that formed the breccias and the nature of the target region? More specifically, I test the hypothesis from the mass-balance perspective that all the Apollo mafic melt breccias are mixtures dominated by four types of materials: (1) a KREEP norite resembling Apollo 15 KREEP basalt, (2) forsteritic olivine, (3) feldspathic material of the upper crust, and (4) an iron meteorite. The rationale and justifications for this hypothesis are also presented. I emphasize that an important key to understanding the Apollo mafic melt breccias are those occasional samples (14068, 62295, 76055) that are generally like other samples at their respective sites but which contain an excess of high-Mg/Fe olivine.

Many previous works have addressed the composition, components, and origin of Apollo mafic melt breccias. This work differs from previous works in two important ways. With respect to components, previous works have concentrated on specific types

of breccia or a small subset of chemical elements [e.g., Dowty *et al.*, 1974b; Ryder and Bower, 1977; James *et al.*, 1984; Shervais *et al.*, 1988; Ryder and Stockstill, 1997]. In this work I consider essentially the full range of melt breccias that have been associated with the LKFM composition as well as a more extensive suite of chemical elements. With respect to origin, most previous works have assumed, usually implicitly, that some, if not most, of the Apollo mafic melt breccias were formed in regions of typical crust, that is, that a basin-sized impact anywhere on the Moon would likely produce impact-melt breccias of LKFM composition [e.g., Spudis and Davis, 1986; Lucey *et al.*, 1995]. In fact, the mafic nature of the breccias compared to typical feldspathic crust has long been taken as evidence that the crust becomes more mafic and KREEP-rich with depth [Ryder and Wood, 1977]. In this work I consider the breccias in light of the new view advocated by Haskin *et al.* [1998], namely, that the Apollo mafic melt breccias were not formed in typical feldspathic crust but that all were formed in a region of anomalously mafic and Th-rich crust.

The paper begins with a review of the evolution of the LKFM concept. I then discuss the various types or compositional groupings of mafic (LKFM) melt breccias and present a compilation of average compositions. Next follows a description of the first mass-balance model that reasonably accounts for the composition of the Apollo mafic melt breccias, on average, as well as the compositional differences among them. Finally, I discuss the implications of the model results in light of the global view of the Moon provided by Clementine and Lunar Prospector.

2. Etymology and Evolution of LKFM

Fra Mauro is the name of a geologic formation surrounding the Imbrium basin and is also the name of the region of the Apollo 14 lunar landing site [Wilhelms, 1987, p. 204]. The formation was named for a 16th century Italian geographer and cartographer [e.g., Cowan, 1997].

In its original invocation in 1971 by the Apollo Soil Survey, Fra Mauro basalt was not a crystalline basalt, but the designation of a "compositional group" of impact glasses found in the Apollo 14 soil that was basaltic in composition [Apollo Soil Survey, 1971]. The Apollo Soil Survey noted the similarity between the compositions of Fra Mauro basalt glass and sample 14310 from Apollo 14, which is now believed to be a nearly clast-free impact-melt rock. In 1972 the term Fra Mauro basalt was first applied to an actual rock (14310) [Ridley *et al.*, 1972], although in related papers, Fra Mauro basaltic glass was also equated with KREEP [Reid *et al.*, 1972a, b].

In 1973 the Apollo Soil Survey noted that a wide range of K concentrations occurred among glasses of Fra Mauro basaltic composition in the Apollo 15 regolith [Reid *et al.*, 1972a]. The terms high-K, moderate-K, and low-K Fra Mauro first occurred in that context, but always as an adjective. Low-K Fra Mauro glasses were those with $0.12 \pm 0.07\%$ K_2O , compared with $0.47 \pm 0.17\%$ and $1.1 \pm 0.4\%$ for moderate-K and high-K Fra Mauro glasses and 0.6% for Apollo 15 KREEP basalt. An important evolutionary step in the concept of low-K Fra Mauro basalt occurred in the early 1970s when the composition was first used as a component in a mass-balance (mixing) model for Apollo 16 soils [Taylor *et al.*, 1973; Schonfeld, 1974] and average highlands crust [Taylor and Jakeš, 1974] even though the term had not yet been applied to an Apollo 16 rock sample.

The first use of the acronym LKFM occurred in a 1973 paper describing glass compositions in Apollo 16 soil [Ridley *et al.*, 1973]. That paper made a distinction between the LKFM compo-

sition and medium- (MKFM; alternately, moderate-K [Reid *et al.*, 1972b] and intermediate-K [Vaniman and Papike, 1980]) and high-K Fra Mauro compositions, which were still equated with KREEP. Again, LKFM was used as an adjective. The practice of using LKFM as a noun was well established by 1977, however [e.g., Hess *et al.*, 1977; Reid *et al.*, 1977; Ryder and Wood, 1977; McKay and Weill, 1977; Taylor and Jakeš, 1977]. About that same time the first reports of detection of Fra Mauro basalt from orbit by remote-sensing techniques occurred, on the basis of data for Fe [Charette *et al.*, 1977] and Th [Haines *et al.*, 1978].

It appeared that Fra Mauro basalts must ultimately have an igneous origin because of the similarity of major-element concentrations in LKFM and MKFM rocks (including Apollo 15 KREEP basalt) to those of liquids on the orthopyroxene-plagioclase cotectic of the silica-olivine-anorthite pseudoternary phase diagram [Walker *et al.*, 1972; Taylor and Bence, 1975; McKay and Weill, 1977; Hess *et al.*, 1977]. By 1977, however, it was largely recognized that crystalline LKFM samples were all impact-melt rocks and breccias [e.g., Hess *et al.*, 1977; Reid *et al.*, 1977; Warren and Wasson, 1977]. In their classic paper "In search of LKFM," Reid *et al.* [1977] reviewed the significance of the LKFM composition. They recognized that there was no igneous LKFM among Apollo samples, only impact melt breccias, glasses, and soils, which were all clearly mixtures, but that the compositions nonetheless corresponded closely to those of liquids in equilibrium with plagioclase and olivine (and, for MKFM, pyroxene). All of the rock samples listed and identified with LKFM by Reid *et al.* [1977] were impact-melt breccias from Apollo 15, 16, and 17. Curiously, the average K₂O concentration of the listed rocks is 0.24%, approximately twice that of the original LKFM glasses, and for some of the rocks (60315, 62235, 77135), K₂O concentrations fall instead in the range of the medium-K Fra Mauro glasses ($\geq 0.3\%$). By 1980, LKFM had become synonymous with mafic impact-melt rocks and breccias, although the K₂O concentration of rock samples used to represent LKFM had continued to "kreeep" up to values as high as 0.49% [Vaniman and Papike, 1980; Basaltic Volcanism Study Project, 1981].

Dence *et al.* [1976] argued that the matrix of an Apollo 17 melt breccia they studied (a sample of A17-A of Table 1), which had the LKFM composition and which was believed to have been formed in the Serenitatis impact, was essentially a melt of "the upper 60 km of highland crust." Ryder and Wood [1977] reasoned instead that melt breccias believed to be from basin-forming impacts (Imbrium and Serenitatis) were so much more mafic (~18% Al₂O₃) than the upper crust (they assumed 25% Al₂O₃) that the breccias could contain melt only from the "deeper portion" of the crust. They concluded that the crust must be layered, becoming more mafic with depth, and that the LKFM composition was the average composition of the middle region of the crust. The hypothesis that the average composition of some lower portion of the crust is that of LKFM was refined by Spudis and Davis [1986] and is now generally accepted [e.g., McCormick *et al.*, 1989]. Recently, the LKFM concept has been extended on the basis of results of the Clementine mission: "...the Fe abundance of the interior of [the] South Pole Aitken [basin] lies within the LKFM field.... Thus, the lower crust in this part of the Moon is also LKFM in composition" [Lucey *et al.*, 1995, p. 1153]. This supposition implies that LKFM is moonwide in occurrence at depth, not a special product or component of the Fra Mauro formation, and that LKFM can now be identified without knowledge of the concentration of K or other incompatible elements. The reasoning that leads to the hypothesis that, globally, the lower crust of the Moon has the LKFM composition implic-

ally assumes that the Apollo LKFM melt breccias were formed in regions of typical crust. This assumption was rejected by Haskin *et al.* [1998] for reasons discussed below (section 5.1).

The term LKFM has outlived its usefulness. Either as an adjective or as a noun, the term is essentially undefined and consequently ambiguous. It has been used interchangeably to refer to a composition, a chemical component, a rock type, and the lower crust. The composition associated with LKFM has evolved to cover such a wide range (Al/[Fe+Mg], Fe/Mg, K₂O, etc.) that most mafic polymict rocks from the highlands are included. The term is nondescriptive and misleading in the literal sense. Rocks identified as LKFM are usually better designated impact-melt breccias [Stöffler *et al.*, 1980].

3. Compositional Variation and Groupings

Compositions of samples of Apollo mafic melt breccias vary, both intrasite and intersite. As shown in detail below, at the Apollo 15, 16, and 17 sites, compositional groupings or clusters have been recognized, that is, there are subsets of samples that are compositionally more similar to each other than they are to samples from other groups [see also Jolliff, 1998]. In several cases, samples assigned to a group based on composition are also texturally distinct from samples of other groups, for example, the melt phase of the Apollo 16 dimict breccias [James *et al.*, 1984] and the Apollo 17 poikilitic breccias [Spudis and Ryder, 1981]. One interpretation of these observations is that each group represents melt formed in a separate impact [e.g., Ryder and Seymour, 1982; Reimold and Nieber-Reimold, 1984; Ryder and Spudis, 1987; Korotev, 1991]. Here I do not make that assumption, but I do assume that melt-breccia samples from a given site that are similar to each other in composition all derive from the same unit of impact melt, that is, a contiguous sheet, lens, or body. This assumption is the basis for using data from many samples to calculate an average composition for the unit or compositional group (Table 1). In some cases I cannot strongly defend the assignment of a particular sample to one group instead of another. This is unimportant, however, because I use the groupings to define the compositional range of mafic melt breccias and take averages as a way of minimizing the effects of sampling error and interlaboratory bias. The sixteen groups of Table 1 cover nearly the entire range of compositions observed among representative samples of Apollo melt breccias that have been associated with the LKFM composition.

3.1. Calculation of Average Compositions

Modeling of the type described below requires precise and representative compositional data for a complete suite of elements. Unfortunately, lunar breccias are heterogeneous, analyzed subsamples are small, and data for a complete set of chemical elements are seldom available for any given analyzed subsample. Consequently, reported concentrations, particularly for incompatible and siderophile elements, are sometimes variable among analyzed subsamples of a given sample or set of samples that might reasonably be assigned to a specific compositional group.

An extreme but not unrealistic example would be to have Ni and K₂O data from one laboratory for three samples that have concentrations of these elements at the high end of their respective ranges and to have Ir and Cs data from another laboratory for three different samples that have concentrations of these elements at the low end of the range. A simple calculation of the mean of all available data would lead to unrepresentative Ni/Ir or K₂O/Cs

Table 1. Average Compositions of Mafic Impact-Melt Breccia Groups From Apollo 14, 15, 16, and 17

	A14		A15				A16					A17			Apollo		
	N	OV	A	B	C	D	1M	1F	1S	2DB	2NR	2Mo	P	A	H	O	Mean
SiO ₂	48.3	46.5	50.3	47.8	46.8	46.3	46.7	47.0	45.3	45.7	45.3	45.1	46.5	46.3	47.1	45.2	46.8
TiO ₂	1.68	1.30	1.79	1.16	0.93	1.53	1.37	1.20	1.60	0.93	1.00	0.70	1.51	0.79	1.63	1.30	1.32
Al ₂ O ₃	16.76	12.40	15.32	16.51	19.18	17.58	17.10	19.30	19.00	22.00	21.20	20.40	18.31	20.44	17.24	16.10	17.4
FeO _T	10.32	9.86	10.64	9.89	8.08	9.41	9.69	8.82	9.20	8.00	7.70	6.41	8.96	8.12	9.77	9.21	9.22
MgO	10.22	19.20	9.25	13.27	12.14	14.92	13.35	9.90	12.05	10.90	11.10	14.78	11.74	10.87	10.98	16.95	12.97
MnO	0.131	0.130	0.169	0.140	0.107	0.131	0.100	0.115	0.117	0.090	0.090	0.092	0.119	0.116	0.136	0.116	0.123
CaO	10.13	7.90	10.28	10.19	11.41	10.33	10.70	11.85	11.90	12.75	12.65	11.70	11.25	12.00	11.07	9.59	10.64
Na ₂ O	0.810	0.800	0.771	0.585	0.569	0.543	0.622	0.536	0.526	0.494	0.500	0.457	0.665	0.498	0.690	0.533	0.635
K ₂ O	0.68	0.51	0.89	0.351	0.273	0.157	0.43	0.35	0.27	0.19	0.27	0.089	0.269	0.214	0.322	0.205	0.382
BaO	0.101	0.086	0.091	0.051	0.037	0.028	0.055	0.057	0.041	0.030	0.031	0.019	0.038	0.034	0.055	0.031	0.056
Cr ₂ O ₃	0.182	0.229	0.221	0.259	0.192	0.241	0.222	0.178	0.243	0.162	0.174	0.183	0.190	0.234	0.200	0.191	0.208
ZrO ₂	0.162	0.135	0.128	0.068	0.056	0.038	0.100	0.107	0.066	0.051	0.054	0.034	0.065	0.052	0.096	0.049	0.088
P ₂ O ₅	0.55	0.57	0.69	0.35	0.31	0.21	0.45	0.40	0.31	0.24	0.19	0.14	0.28	0.22	0.33	0.21	0.38
S	0.09	0.07	n.d.	n.d.	n.d.	n.d.	0.11	0.11	0.11	0.10	0.11	0.07	0.08	0.04	n.d.	0.07	0.08
Σ	100.2	99.7	100.6	100.7	100.2	101.5	101.0	99.9	100.7	101.6	100.4	100.2	100.0	99.9	99.6	99.8	100.3
Mg'	63.8	77.6	60.8	70.5	72.8	73.9	71.1	66.7	70.0	70.8	72.0	80.4	70.0	70.5	66.7	76.6	71.5
Mg'(c)	66.1	78.9	61.8	71.7	73.8	74.5	75.6	70.0	72.6	76.6	75.4	82.1	70.1	70.3	67.6	76.9	73.3
Sc	21.1	17.8	21.1	19.6	14.3	17.2	14.6	14.8	22.0	10.8	12.2	9.8	16.8	17.2	19.3	14.0	17.1
Co	33	36	24	39	29	35	64	41	47	66	44	34	28	26.5	28	43	36.5
Ni	332	297	127	263	214	303	1090	590	629	1070	650	403	241	181	239	490	387
Rb	16.2	22.0	23.0	14.0	10.0	3.9	11.4	9.8	6.5	5.6	6.0	6.0	6.1	6.0	14.5	5.2	11.9
Sr	156	156	179	156	168	169	187	178	150	185	166	129	173	156	165	156	164
Cs	0.77	0.69	0.89	0.40	0.27	0.20	0.52	0.42	0.34	0.22	0.22	0.53	0.22	0.22	0.65	0.09*	0.47
La	88.8	58.2	79.4	46.0	33.7	22.6	49.6	54.6	34.2	27.5	27.6	18.8	33.4	28.4	51.5	24.5	47.2
Ce	216	158	205	121	89	59	129	142	91	72	72	50	87	74	133	62	122
Sm	37.0	25.3	36.3	21.7	15.0	10.4	22.5	24.8	15.8	12.7	12.7	8.26	15.0	12.7	23.1	10.9	20.9
Eu	2.73	2.01	2.38	1.95	1.78	1.73	1.97	1.94	1.71	1.49	1.51	1.17	1.92	1.38	1.97	1.75	1.92
Tb	7.7	6.1	7.7	4.4	3.1	2.1	4.5	5.0	3.49	2.54	2.52	1.71	3.11	2.63	4.62	2.42	4.43
Yb	26.7	19.8	24.9	14.6	10.3	7.0	15.4	16.8	11.9	8.6	8.9	6.2	10.9	9.5	16.1	8.4	15
Lu	3.76	2.64	3.52	2.13	1.50	1.03	2.07	2.26	1.67	1.16	1.20	0.86	1.47	1.31	2.18	1.23	2.09
Hf	29.7	22	28.3	14.9	11.2	7.7	17.3	18.8	11.8	9.3	9.6	6.4	12.2	9.5	17.4	8.8	16.4
Ta	3.62	2.56	3.25	1.91	1.33	1.01	1.93	2.00	1.30	1.02	1.11	0.77	1.57	1.26	2.06	1.24	1.96
Ir	8.7	6.6	2.3	4.9	4.5	3.3	21.0	12.8	12.4	26.3	15.9	7.9	6.9	5.7	5.5	13.0	8.8
Au	7.5	n.a.	1.9	4.8	3.7	2.6	24.7	12.0	11.0	22.9	13.4	8.0	3.6	2.7	3.8	7.2	7.5
Th	16.1	11.5	14.9	7.4	5.7	3.47	8.1	8.8	5.40	4.3	4.4	2.90	5.40	4.5	8.5	3.5	8.2
U	4.5	2.94	4.0	2.15	1.72	0.92	2.13	2.24	1.44	1.14	1.26	0.78	1.56	1.26	2.29	0.88	2.24
(Ir/Au) _{CI}	0.34	-	0.37	0.30	0.35	0.37	0.25	0.31	0.33	0.33	0.35	0.29	0.56	0.61	0.42	0.53	0.34

Oxides, Fe⁰, and S concentrations in weight percent, Ir and Au in ng/g, and others in μg/g. FeO_T, total Fe as FeO; Mg', mole percent MgO/(MgO+FeO_T); Mg'(c), Mg' of the non-meteoritic components, based on fraction of FeNi and CI from Model 2; (Ir/Au)_{CI}, CI normalized Ir/Au ratio; n.d., no data. The "Apollo Mean" column was obtained by averaging by landing site first (e.g., all A16), then averaging the means for the four sites. See section 3.2 for sources of data.

* This Cs value [from *Palme et al.*, 1978] is suspiciously low compared to other alkalis and was ignored in the modeling.

ratios in the group average. I have attempted to overcome these problems by combining data from as many analyses as possible and by estimating missing data in some analyses prior to computing an average. For example, given data for Sm or Th, it is straightforward to make an accurate estimate of the concentration of Tb or U because of the strong correlations among incompatible elements (e.g., Figure 1). Most variation in major element concentrations among samples of a given group of mafic melt breccias involves Al₂O₃ and FeO+MgO, which anticorrelate. Data for MgO are not obtained in many analyses. Thus I have estimated MgO concentrations from FeO concentrations and the mean MgO/FeO ratio of samples in the group for which both elements were determined. For siderophile elements it is particularly important to estimate concentrations for those samples with low concentrations prior to computing group averages. Data for these samples are usually lacking because concentrations lie below detection limits of most analytical methods. Averaging only the available data for Au and Ir will invariably lead to mean values that are unrepresentatively high. The correlation between Ni and Au and, to a lesser extent, Ni and Ir is very strong in mafic melt

breccias, so I have estimated Au and Ir data, which are lacking for many analyses, from the more abundant Ni data.

3.2. Compositional Groupings, by Landing Site

3.2.1. Apollo 14. Although previous work has not described any compositional groupings among the Apollo 14 melt breccias, there appear to be two compositional extremes. On many two-element plots the majority of samples fall along a mixing line (dashed lines in Figure 2) defined by the average composition of the samples and plagioclase. Similar trends, which are probably clast-matrix mixing trends, are seen in some of the Apollo 16 groups [Korotev, 1994]. The typical or normal Apollo 14 samples are those that populate the group designated here as A14-N (Table 1). Some samples, however, plot off the main trend and appear to fall along a trend toward dunite or olivine (solid line). These samples include 14068 [Hubbard *et al.*, 1972] and 14066 [Rose *et al.*, 1972], which have long been recognized as different because they are richer in Mg, as well as two samples moderately enriched in Mg described by Warren and Wasson [1980]. The

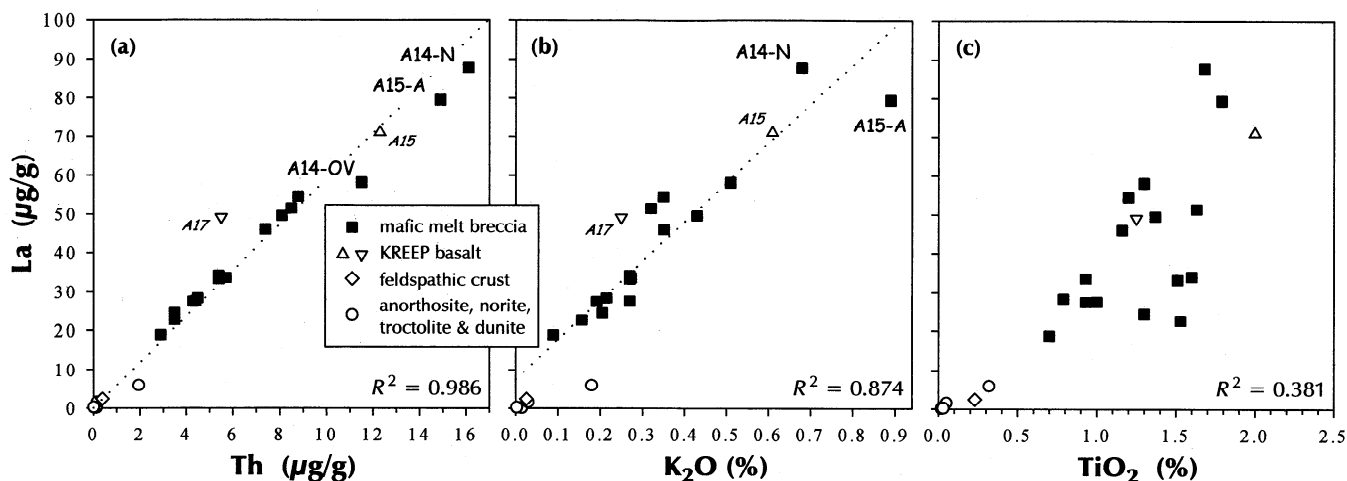


Figure 1. Concentrations of some elements in mafic melt breccia groups (solid squares, from Table 1) and comparison to pristine rocks (open triangles and circles) and typical feldspathic upper crust (FUpCr, Table 2). The R^2 values refer to the mafic melt breccias only. The triangles represent Apollo 15 (Table 3) and Apollo 17 [Blanchard *et al.*, 1975; Salpas *et al.*, 1987] KREEP basalt. The circles represent anorthosite (FAn; Table 2), norite [Ryder, 1979], troctolite (sample 76535 [Rhodes *et al.*, 1974; Haskin *et al.*, 1974]), and dunite (sample 72415/7 [Laul and Schmitt, 1975; Dymek *et al.*, 1975]). In Figures 1a and 1b the dotted lines are regression lines. The KREEP sub-components of Model 3 are in large part necessitated by the lack of perfect correlation in plots like these.

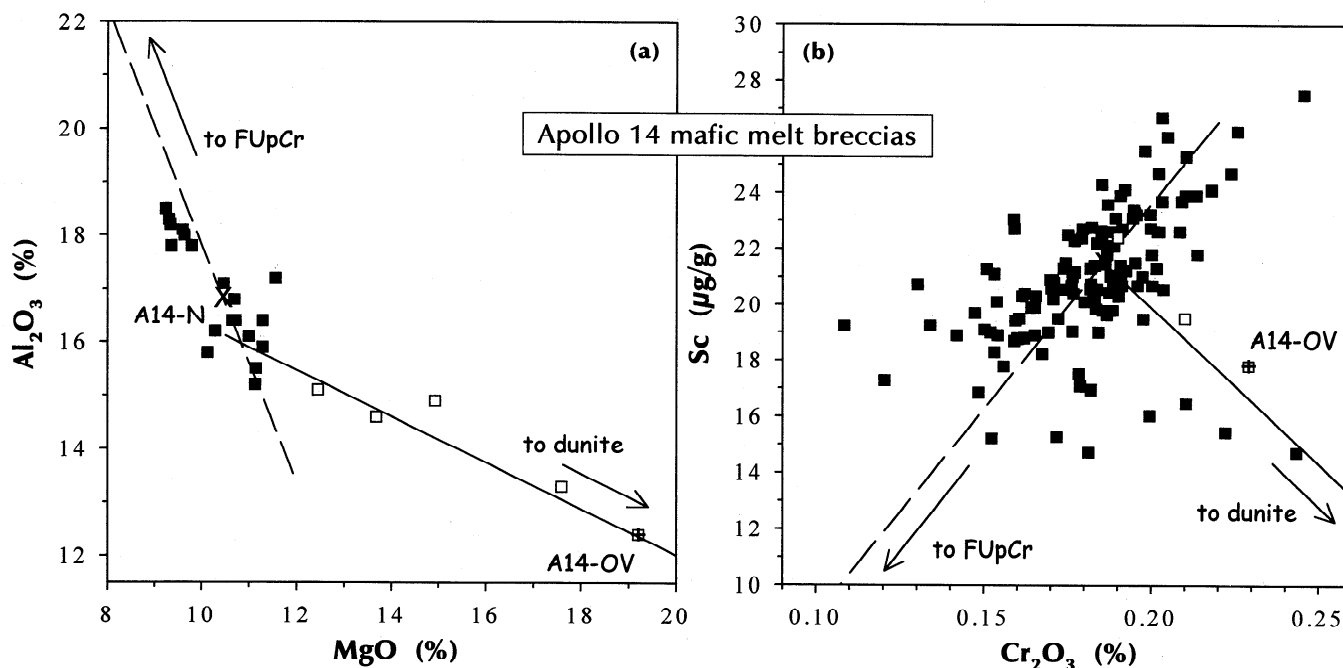


Figure 2. (a) The squares represent samples of mafic melt breccias from the Apollo 14 mission. The solid squares are normal samples, and the X represents their mean, the A14-N composition of Table 1. These samples tend to plot along a mixing line (dashed) defined by the A14-N mean composition (X) and the feldspathic upper crust (FUpCr) component of the model described here, which probably occurs largely as clasts in the breccias. Some samples (open squares) deviate from the trend in the direction of dunite (e.g., sample 72415) or highly magnesian olivine. The most extreme of these (open squares with plus sign inside) are the olivine vitrophyres from sample 14321 [Shervais *et al.*, 1988]. The solid line is defined by (1) the average composition of the vitrophyres, the A14-OV composition of Table 1 (the AOV composition of Shervais *et al.* [1988]), and (2) the dunite component of the model described here (off scale). (b) The solid squares are all 2- to 4-mm fragments of impact-melt breccias from regolith sample 14161 [Jolliff *et al.*, 1991]. The open squares are the MgO-rich samples of Figure 2a and the two lines are the same as those of Figure 2a. A few of the 14161 samples also plot off the trend in the direction of dunite. The following sources provide the data for this figure and the A14 averages of Table 1: Christian *et al.* [1976], Hubbard *et al.* [1972], Jolliff *et al.* [1991], Morgan *et al.* [1972], Philpotts *et al.* [1972], Rose *et al.* [1972], Scoon [1972], Shervais *et al.* [1988], Wänke *et al.* [1972], and Willis *et al.* [1972].

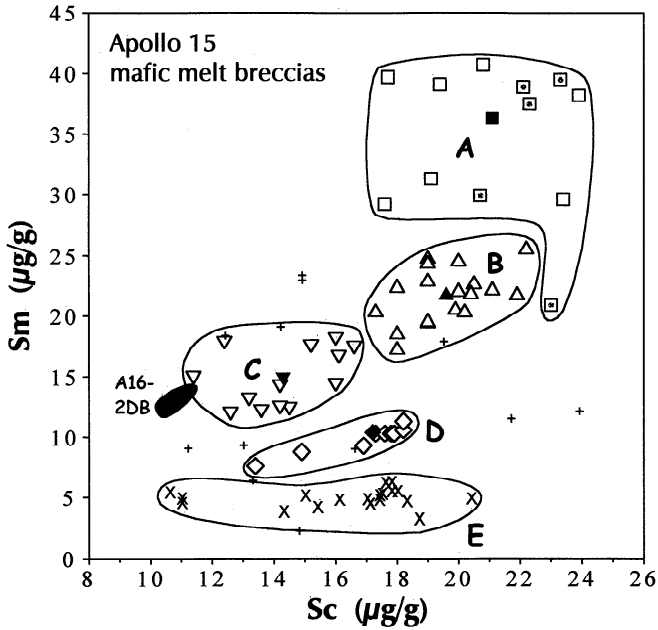


Figure 3. Sc and Sm concentrations in Apollo 15 mafic melt breccias; this element pair is useful for distinguishing among melt breccia groups [Korotev, 1994; Jolliff *et al.*, 1996]. The letters A–E represent the compositional groups of Ryder and Spudis [1987], although that classification was based on only 16 of the analyses plotted here. For the purpose of computing the averages of Table 1 (solid squares), analyses plotting in the fields depicted here (or which could be inferred to be similar when data for Sc or Sm were unavailable) were averaged. If for a given analysis data for other elements were clearly inconsistent with those of other analyses included in a group, the analysis was not included. The plus signs represent analyses excluded or otherwise unclassified by the process and not included in any averages. For some samples, multiple analyses are plotted. For example, all the squares (group A) enclosing a small circle represent subsamples of 15405. Group A consists mostly of subsamples of 15405 and 15459. Group D consists entirely of subsamples of 15445 and 15455. Clearly, groups B and C may represent a continuum. For comparison, the range in the average compositions of 16 samples of Apollo 16 group 2DB is shown (Figure 4). The following sources provide the data for this figure and the A15 averages of Table 1: Blanchard *et al.* [1977b], Christian *et al.* [1976], Drake *et al.* [1973], Ganapathy *et al.* [1973], Gros *et al.* [1976], Laul and Schmitt [1973], Laul *et al.* [1988], Lindstrom *et al.* [1988], Murali *et al.* [1977], Ryder and Spudis [1987], Ryder *et al.* [1988], and some otherwise unpublished data cited by Ryder [1985].

most extremely magnesian melt-breccia lithology from Apollo 14, however, are the olivine vitrophyres from sample 14321 [Allen *et al.*, 1979; Shervais *et al.*, 1988]. Because they are the most extreme, I have included the average composition of the olivine vitrophyres (the “AOV” composition of Shervais *et al.* [1988]) as “group” A14-OV in Table 1.

3.2.2. Apollo 15. Few large samples of impact-melt breccia were obtained from the Apollo 15 site. Most Apollo 15 mafic melt breccias are small rocks from the regolith or clasts in breccias. The data set for the Apollo 15 mafic melt breccias is the poorest of the missions in that most available analyses are based on small subsamples, there are few analyses for major elements by high-precision techniques, and there is considerable scatter among data for some elements, particularly TiO₂ and MgO.

Ryder and Spudis [1987] proposed five compositionally distinct groupings of melt breccias from Apollo 15, which they designated A, B, C, D, and E. However, Ryder *et al.* [1988] used a more complete data set and concluded that either there were more than five groups or there were no groupings at all, only a continuum of compositions. Whether or not compositional groupings actually occur, the groups of Ryder and Spudis [1987] represent the compositional extremes of the Apollo 15 mafic melt breccias (Figure 3). Although the selection of samples to include in each group is somewhat arbitrary, particularly for groups B and C, I have calculated averages for groups A, B, C, and D as discussed in the caption of Figure 3. I have not included group E in Table 1 because, for a variety of reasons detailed by Haskin *et al.* [1998], group E does not appear to be closely related to other Apollo mafic melt breccias.

Of the mafic melt breccias discussed here, Apollo 15 group A is extreme in that it is richest in Fe, has the lowest Mg' and lowest concentrations of siderophile elements, and is most similar in major-element composition to Apollo 15 KREEP basalt. It is also

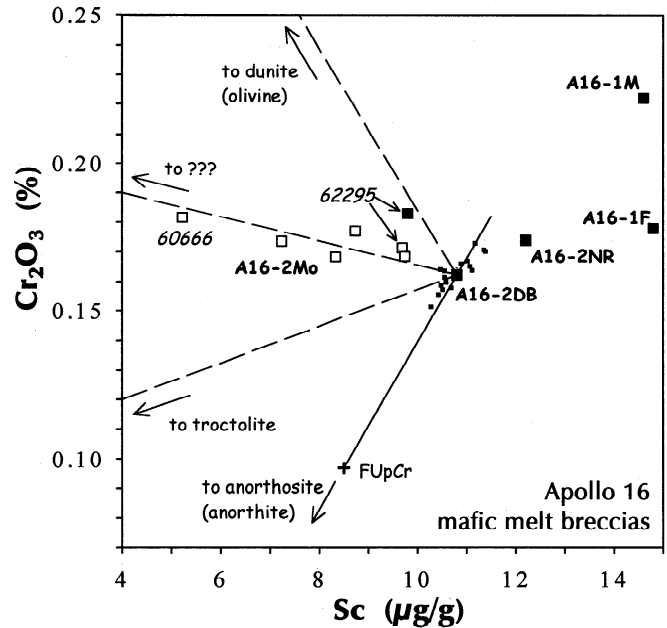


Figure 4. Sc and Cr₂O₃ concentrations in Apollo 16 mafic melt breccias. The large solid squares represent the averages of Table 1 for the compositional groups; group A16-1S plots off the figure at 22 µg/g Sc. The lines are mixing lines connecting the composition of group A16-2DB (Table 1) and the dunite (72415), troctolite (76535), and the FUpCr model component. The small squares represent the 16 samples of group 2DB from which the A16-2DB average was computed [Korotev, 1994]. The large open squares represent the six samples of group 2Mo [Korotev, 1994]. These samples appear related in that, compositionally, they correspond to mixtures of group 2DB and varying amounts of some Cr-rich component intermediate in Cr concentration to dunite and troctolite (spinel troctolite?). Unfortunately, major element data exist for only one of the group 2Mo samples, 62295. Thus sample 62295 represents group 2Mo in Table 1. The offset in Cr concentration between the two 62295 points occurs because the unfilled point is based only on the data of Korotev [1994], whereas the solid square (Table 1, A16-2Mo) is an average based on data of Hubbard *et al.* [1973], Rose *et al.* [1973], Wänke *et al.* [1976], and Korotev [1994]. All other Apollo 16 data in the figure and the A16 averages of Table 1 are from Korotev [1994].

the only group that almost certainly was not formed in a basin-forming impact. The best studied sample, 15405, shows no evidence of an event at ~3.9 Ga and appears to have a crystallization age of ~1 Ga [Ryder, 1985].

3.2.3. Apollo 16. At Apollo 16 several compositional groups of melt breccias have long been recognized [Floran *et al.*, 1976]. Table 1 includes four groups of mafic melt breccias advocated by Korotev [1994] (1M, 1F, 2DB, and 2NR) for which there are many samples of each. Groups A16-2DB and A16-2NR are very similar and would be indistinguishable from each other if the intersample compositional scatter were as great as it is for other melt breccia groups. The samples of group 2DB, in particular, form a tight cluster on plots of lithophile elements (Figure 4). Korotev [1994] also showed that a fifth group, designated 2Mo, is generally similar to group 2DB but is variably enriched in an olivine-bearing component. Figure 4 makes the essential arguments. Unfortunately, complete compositional data are available for only one of the samples, 62295, and this sample is among the least extreme of the group 2Mo samples. Nevertheless, because it is the only one for which a complete data set is available, sample 62295 represents group A16-2Mo in Table 1. From Figure 4 we can infer that the most extreme (i.e., most Sc poor) of the A16-2Mo samples, 60666 ("basaltic impact melt" portion [Ryder and Norman, 1980]), is very rich in Mg. The electron microprobe results of Dowty *et al.* [1974a] confirm that with 18.6% MgO the sample is richer in MgO than any of the compositions of Table 1. I have also included a group designated here as A16-1S. The composition in Table 1 is based entirely on sample 64815, which is compositionally distinct from other Apollo 16 mafic melt breccias [Korotev, 1994]. There is some evidence that other small rocks in the regolith are compositionally similar [Korotev *et al.*, 1997], in which case sample 64815 may represent an actual compositional "group."

I have not included group 2M of Korotev [1994] because this group consists of a hodgepodge of samples with compositions somewhat similar to groups 2DB and 2NR but not similar enough to be included in these compositionally tight groups. Together, the various group 2 melt breccias of Apollo 16 are samples that have been designated VHA (very high alumina) basalts in older literature and have been regarded by some as distinct from breccias associated with the LKFM composition [Spudis, 1984; McKinley *et al.*, 1984]. Some samples that have been identified as VHA basalts are considerably more aluminous (up to 26% Al₂O₃) than the compositions discussed here. I suspect, largely on the basis of results from this work (section 5.4) but also on the basis of the distribution of data points on plots such as Figure 4 of Korotev [1994], that most of the samples of melt group 2 that are compositionally more feldspathic than groups 2DB and 2NR (e.g., group 2F of Korotev [1994]) are breccias consisting of mafic impact melt such as that of group 2DB with a high load of partially assimilated, mostly anorthositic clasts.

3.2.4. Apollo 17. Two textural variants, poikilitic and aphanitic, of Apollo 17 mafic melt breccias have long been recognized, as have compositional distinctions between them [Spudis and Ryder, 1981]. I have included mean compositions of these two groups as A17-P and A17-A of Table 1. I also include the group recognized and designated the "high-Sm" group by Jolliff *et al.* [1996] as group A17-H. Finally, sample 76055 is compositionally anomalous [Spudis and Ryder, 1981; Ryder and Gillis, 1999]. Again, this unique sample differs from other Apollo 17 mafic melt breccias in being richer in Mg. I have included a "group" designated A17-O in Table 1 which is represented only by sample 76055. The following sources provide the data for the

A17 averages of Table 1: Blanchard *et al.* [1975], Higuchi and Morgan [1975], Hubbard *et al.* [1974], James *et al.* [1975], Jolliff *et al.* [1996], Lunar Sample Preliminary Examination Team [1973], Morgan *et al.* [1974], Nava [1974], Palme *et al.* [1978], Philpotts *et al.* [1974], Rhodes *et al.* [1974], Simonds [1975], Wänke *et al.* [1974, 1975], Warren and Wasson [1978], Warren *et al.* [1991], and some otherwise unpublished data cited by Meyer [1994].

3.2.5. Apollo Mean. The composition in Table 1 listed as "Apollo Mean" was obtained by first calculating the mean of the groups for each site, then by averaging the four site means. This mean has no special significance in that it does not reflect the distribution of mafic melt breccias at the Apollo sites (e.g., among samples, A17-P is much more common than A17-H). Because I have made a special point of including the Mg-rich but atypical samples as "groups" (A14-O, A16-2Mo, A17-O), the Apollo Mean composition is probably richer in Mg than the typical Apollo mafic melt breccia.

4. Mass-Balance Model

Compositions of terrestrial impact-melt breccias can be successfully modeled as mixtures of rocks known to occur in the target area of the impact [e.g., Dence, 1971; Grieve, 1975; Grieve and Floran, 1978; Korotev *et al.*, 1996b]. Attempts to model the Apollo mafic melt breccias have not been as successful, in part because there is less independent knowledge of the lithologies at the target site than in the typical terrestrial case. Instead, on the basis of their terrestrial analogs, the Apollo mafic melt breccias have been used as tools to infer the structure and lithologies of the lunar crust [Ryder and Wood, 1977].

The problems and history of modeling the composition of the Apollo mafic melt breccias have been described well by Ryder [1979] and also Garrison and Taylor [1980] and Reid *et al.* [1977]; the following discussion assumes that the reader is generally familiar with those works. Petrographic studies have shown that the breccias contain a wide variety of lithic and mineral clasts [James *et al.*, 1978; Spudis *et al.*, 1991; Ryder *et al.*, 1997], and the compositions of Table 1 are consequently those of mixtures of melt and clasts. The melt itself is undoubtedly a mixture of several rock types which may not be well represented by the distribution of clasts [Ryder *et al.*, 1997]. Thus, in reality, the breccias are complex mixtures. However, as noted by Ryder [1979, p. 561], "In simplified form, the broadly accepted components are 1) anorthosite 2) KREEP 3) high-Mg and 4) meteoritic." The meteoritic component is volumetrically insignificant but essential to account for siderophile elements, including iron. The compositional necessity for the other three components is evident in Figure 5. At least one anorthositic component is required to supply the Al (Figure 5b). Some type of KREEP component is required to account for the high concentrations of incompatible elements (Figure 5d) and the fact that incompatible-element ratios in the melt breccias are the same as those of KREEP basalt. The weak correlation between TiO₂ and incompatible elements among melt-breccia groups (Figure 1c) suggests that the KREEP component also supplies much of the Ti, although some models have included mare basalt to help account for Ti [Ryder, 1979]. Some type of mafic component(s) as rich in Mg as troctolite or dunite is required to account for the high concentrations of Fe and Mg in the breccias compared to typical feldspathic upper crust (Figures 5c and 5d).

In this section I present a new model. I begin with the four "broadly accepted" but generalized components of Ryder [1979].

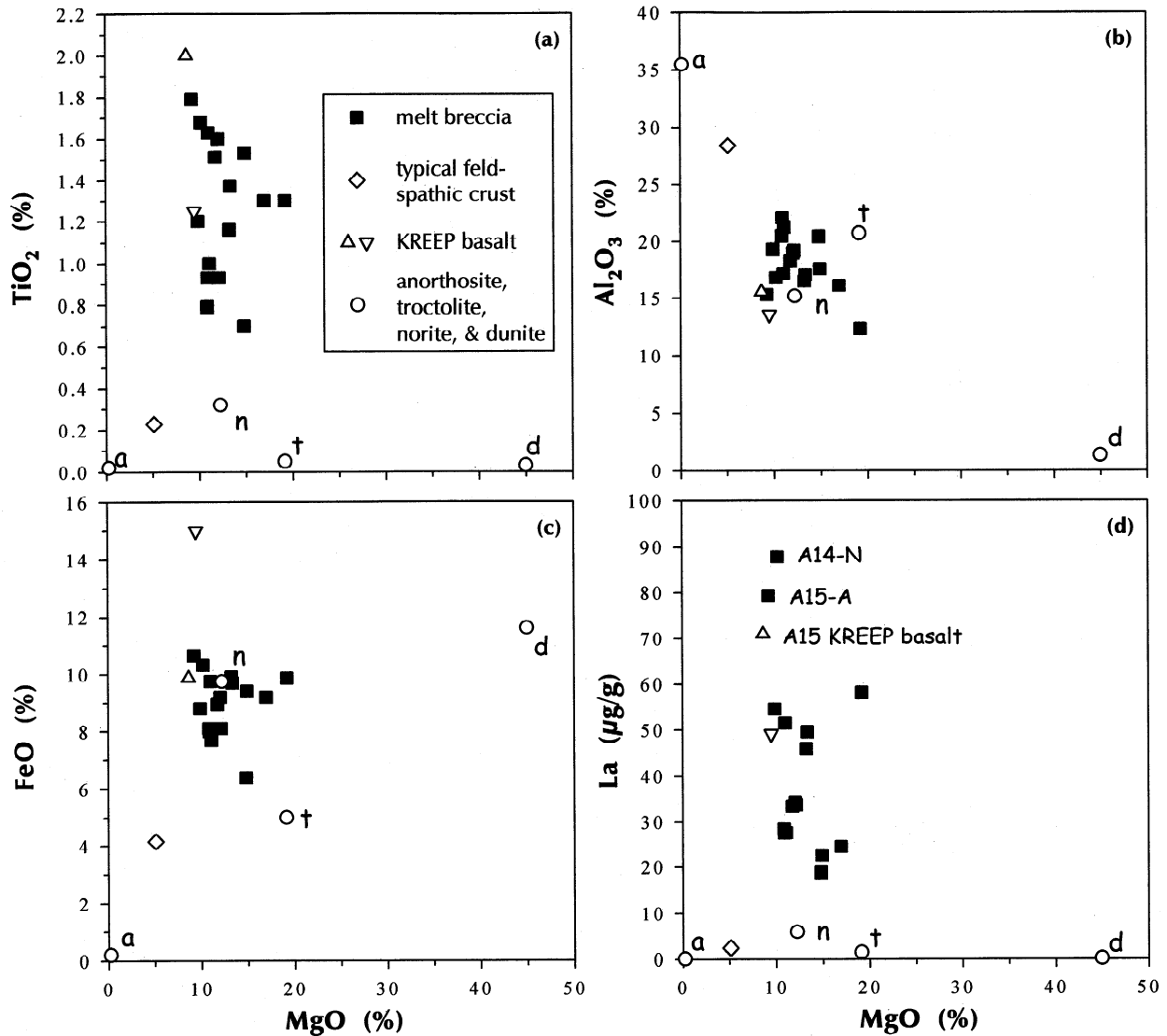


Figure 5. Concentrations of some elements in mafic melt breccia groups (solid squares, from Table 1) as a function of MgO concentration and comparison to pristine rocks and typical feldspathic upper crust (FUpCr, Table 2). See Figure 1 for key and sources of data.

In each case, however, the lithology or composition I have chosen to represent the component is not that which has been the most popular in previous models, and in each case I present the rationale for why I have made the specific choice. The model presented is the most successful end product of much experimenting with many more components and compositions than are discussed and presented here. I show that the model (Model 1) accounts reasonably well for first-order compositional features of the melt breccias but that it consistently does not account well for some elements. By changing the composition of the KREEP component of the model (Model 2), a better fit can be obtained for all breccias. However, in some breccia groups the model still does not account well for certain elements or suites of geochemically related elements unless additional minor subcomponents are included (Model 3).

4.1. Components

In brief, the choice of specific model components was forced largely by parsimony and trial and error; that is, within the re-

striction of keeping the number of components to a minimum, the chosen components "work" and others "do not work" as well. In the subsequent discussion I use capitalized designations like "FUpCr" and "Dun90" to refer to model components and use "feldspathic upper crust" and "dunite" to refer more generically to materials or lithologies.

4.1.1. Feldspathic components. Most previous models have used highly feldspathic ferroan anorthosite as the feldspathic component [Boynton *et al.*, 1976; Wasson *et al.*, 1977; Wänke *et al.*, 1977; Ryder, 1979; Stöffler *et al.*, 1985]. Such an approach is satisfying in that ferroan anorthosite is represented by numerous samples that appear to be relict igneous rocks of the early lunar crust. However, it is unlikely that highly feldspathic ferroan anorthosite is the principal feldspathic component of the Apollo mafic melt breccias. Ferroan anorthosite is uncommon to rare in the regoliths of Apollo 14, 15, and 17. Lithic clasts of ferroan anorthosite are rare to absent in at least some samples of Apollo mafic melt breccias [Spudis *et al.*, 1991] and are only common in the Apollo 16 breccias. The numerous feldspathic lunar meteor-

Table 2. Relative Weighting Factors r_i and Compositions of Components Used in Mass-Balance Modeling

	r_i	Dun90	FLM	FUpCr	FAn	FeNi	KREEP Subcomponents of Model 3						
							CI	AlkAn	Ilmenite	Granite	Spinel	Zircon	Whitl.
SiO ₂	2	40.5	44.8	45.0	44.5	0	31.	47.4	0.35	65.3	0.4	32.4	0.35
TiO ₂	10	0.007	0.23	0.23	0.02	0	0.1	0.2	56.5	0.90	0.12	0.015	
Al ₂ O ₃	2	0.11	28.0	28.4	35.5	0	2.23	31.2	0.2	12.0	62	0.02	
FeO _T	2	9.72	4.56	4.15	0.2	120.4	33.3	2.0	34.0	7.2	7.4	0.1	0.80
MgO	2	49.1	5.38	5.13	0.2	0	22.3	1.0	7.70	2.20	22.6		3.2
MnO	5	0.126	0.065	0.060	0.005	0	0.35	0.03	0.57	0.10	0.05		0.027
CaO	2	0.13	16.3	16.5	19.2	0	1.77	16.2	0.40	5.20	0.2	0.009	40.4
Na ₂ O	10	0.003	0.35	0.34	0.38	0	0.92	1.7	0.0	0.9	0		0.44
K ₂ O	20	0.0007	0.026	0.026	0.015	0	0.091	0.3	0.0	5.0	0		
BaO	5	0.0001	0.004	0.004	0.001	0	0.000	0.066	0	0.335	0		
Cr ₂ O ₃	10	0.34	0.100	0.094	0.002	0	0.53	0.0	0.84	0.06	6.4		
ZrO ₂	10	0.0002	0.005	0.005	0.000	0	0.0007	0.04	0	0.17	0.00	65.9	
Σ		100.0	99.8	99.9	100.0	(100)	92.6	100.1	100.5	99.3	99.2	98.4	45.2
Mg		90	67	69	64	—	54	47	29	35	84		29
Sc	5	3.6	8.3	8.3	0.4	0	7.9	5	200	15	0	61	
Co	10	40	19.2	9.6	0.2	3600	683	5	20	12	50		
Ni	10	150	219	5	5	60000	14960	25	50	15	200		
Rb	20	0.0	0.83	0.79	0.2	0	3.1	6	0	110	0		
Sr	10	1	154	156	182	0	10.6	550	0	170	0		
Cs	20	0.0	0.038	0.035	0	0	0.25	0.24	0	3.3	0		
La	5	0.019	2.36	2.4	0.13	0	0.32	43	0	69	0	0.70	7860
Ce	5	0.055	6.25	6.3	0.32	0	0.82	103	0	173	0	2.4	20700
Sm	5	0.008	1.10	1.11	0.055	0	0.2	16.7	0	30	0	6.9	3410
Eu	10	0.01	0.79	0.80	0.81	0	0.076	6.5	0	2.6	0	0.05	39.5
Tb	5	0.024	0.23	0.24	0.085	0	0.049	3.1	0	6.2	0	10.2	597
Yb	5	0.027	0.92	0.93	0.028	0	0.22	9.3	0	33	0	392	1760
Lu	5	0.0055	0.133	0.134	0.0036	0	0.033	1.3	0	4.9	0	29	214
Hf	5	0.04	0.81	0.82	0.014	0	0.14	6.1	0	29	0	10006	
Ta	10	0.005	0.11	0.11	0	0	0.019	0.66	0	6.3	0	500	
Ir	10	0	9.35	0	0	1500	654	0	0	0	0		
Au	10	0	3.29	0	0	1300	190	0	0	0	0		
Th	10	0.01	0.39	0.39	0.14	0	0.040	4.7	0	37	0	20	424
U	10	0.003	0.12	0.13	0.05	0	0.011	1.1	0	11.5	0	40	52

Oxide concentrations in wt %, others in $\mu\text{g/g}$, except Ir and Au in ng/g . FeO_T, total Fe as FeO; r_i , relative weighting factor, in percent; see text. Dun90 = Dunitite component, based largely on regression of data for sample 72415 of *Laul and Schmitt* [1975] to ~0% normative plagioclase and conversion of the normative olivine from Fo₈₇ to Fo₉₀; also data of *Dymek et al.* [1975], *Higuchi and Morgan* [1975], *Lunar Sample Preliminary Examination Team* [1973], and *Rhodes et al.* [1974], with some values (e.g., Sc) estimated from troctolite samples 76335 and 76535. FLM = mean composition of feldspathic lunar meteorites ALHA81005, MAC88105, Yamato-86032, QUE93069, and Dar al Gani 262 (from numerous literature sources). FUpCr = Feldspathic upper crust component, calculated from FLM component; see text. FAn = Ferroan anorthosite component, based largely on sample 15415 data of *Ryder* [1985]. FeNi = FeNi metal component, mean for metal in Apollo 16 melt breccias, from *Korotev* [1994, Table 5]. CI = Volatile-free CI chondrite component, that is, 1.36C, where C values are the "Mean CI Chondr." values of *Anders and Grevesse* [1989]. AlkAn = Alkali anorthosite component, mean from data of *Jolliff et al.* [1991], *Laul* [1986], *Marvin et al.* [1991], *Shervais et al.* [1984], *Warren and Wasson* [1980], and *Warren et al.* [1981, 1983a, b, 1987, 1990]. Ilmenite = Ilmenite component, based on analysis of an ilmenite in A16-1M sample 60315 by *Hodges and Kushiro* [1973]; Sc, Co, and Ni values estimated. Granite = "Granite" (felsite) component, mean based on data of *Blanchard and Budahn* [1979], *Blanchard et al.* [1977a], *Jolliff et al.* [1991], *Morris et al.* [1990], *Ryder and Martinez* [1991], *Shih et al.* [1993], and *Warren et al.* [1983a, 1987]. Spinel = Spinel component, mean of analyses of two grains from A16-2Mo sample 62295 by *Hodges and Kushiro* [1973]; Co and Ni concentrations estimated. Zircon = Zircon component, mean from *Wopenka et al.* [1996]; Ta assumed. Whitl. = Whitlockite component, mean based on data of *Lindstrom et al.* [1985] and *Jolliff et al.* [1993], with Th and U normalized from data of *Korotev and Kremser* [1992].

ites [e.g., *Korotev et al.*, 1996a] and results of the Clementine mission [*Lucey et al.*, 1995; *Tompkins and Pieters*, 1999] show that typical upper crust does not consist of highly feldspathic anorthosite (e.g., >34% Al₂O₃) but is more mafic in composition (~28% Al₂O₃). The use of highly feldspathic ferroan anorthosite (i.e., <0.5% FeO and MgO) as the feldspathic model component makes the implicit assumption that all of the Fe and Mg of the feldspathic upper crust derives from the same source as the Mg-rich and KREEP components of the mafic melt breccias. This is not necessarily the case [*Korotev and Haskin*, 1988].

The most conservative approach is to make no assumptions about the source of the Fe and Mg in typical feldspathic crust.

Thus, initially, I included a single feldspathic component, one representing typical feldspathic upper crust itself (FUpCr), that is, polymict material. However, as shown below, for the group 2 breccias of Apollo 16 (only), results of Model 2 are improved by using a component representing highly feldspathic ferroan anorthosite (FAn); thus two feldspathic components, FUpCr and FAn, were included in the model. The FUpCr component is similar to the anorthositic gabbro components of *Reid et al.* [1977] and *Schonfeld* [1974]. Clastic material such as feldspathic granulitic breccia is represented by the FUpCr component.

The FAn component is based on sample 15415 [*Ryder*, 1985] and the FUpCr component is based on feldspathic lunar meteor-

ites. I obtained the composition of the FUpCr component by first calculating mean concentrations of each element (C_{FLM}) in the five most feldspathic lunar meteorites (Table 2), that is, those probably not contaminated significantly by mare-derived material or any form of KREEP [Korotev *et al.*, 1996a, Korotev, 1999a]. This composition is similar to that of the calculated residual composition of the Apollo 16 regolith after the mare components and the mafic melt-breccia components are subtracted [Korotev, 1996, 1997]. Because the feldspathic lunar meteorites are composed of regolith and probably derive from the upper few tens of meters of the crust, they are contaminated with meteoritic material to an extent greater than is probably typical, say, of the upper 10 km of farside highlands. Thus I calculated meteorite-free concentrations for the FUpCr component (C_{FUpCr} ; Table 2) from the mass-balance equation $C_{FLM} = C_{FUpCr}f + C_{CI}(1-f)$, where C_{CI} is the concentration "Mean C1 Chondr." from Table 1 of *Anders and Grevesse* [1989] and $f = 0.0194$. The value of f was chosen to reduce C_{FUpCr} to essentially zero for Ir and Au, which leaves 5 $\mu\text{g/g}$ Ni (from $C_{FLM} = 219$) and 9.6 $\mu\text{g/g}$ Co (from $C_{FLM} = 19.2$).

4.1.2. KREEP norite component. A significant question is whether the KREEP component of the mafic melt breccias is, at one extreme, a material generally similar to the igneous KREEP basalts of Apollo 15, which are moderately enriched in incompatible elements, or, at the other, some unsampled material like the hypothesized urKREEP of *Warren and Wasson* [1979] or ultra-KREEP of *Jolliff* [1998] that may have much greater concentrations of incompatible elements than known samples of KREEP basalt. If the KREEP component of the breccias is like KREEP basalt, then the KREEP component supplies most of the Mg and Fe in the breccias. If, instead, the KREEP component of the breccias is severalfold enriched in incompatible elements compared to KREEP basalt (e.g., 4–5 \times [Jolliff, 1998]), then a smaller abundance of that component is required to account for the concentrations of incompatible elements in the breccias and the Mg-rich component or other unidentified mafic components must be the carriers of much or most of the Mg and Fe in the breccias [e.g., *Wänke et al.*, 1975].

As with ferroan anorthosite, Apollo 15 KREEP basalt is a satisfying model component in that it occurs as an igneous rock. Also, the time of KREEP volcanism appears to have coincided with the Imbrium impact [Ryder, 1994]. One problem, however, is that Apollo 15 KREEP basalt cannot account for the high concentrations of incompatible elements in the A14-N and A15-A melt breccia groups because these breccias have greater concentrations of incompatible elements, on average, than does Apollo 15 KREEP basalt (Figure 5d). To surmount this problem, previous models have used, as the KREEP component, compositions based on samples from Apollo 12 and 14 with very high concentrations of incompatible elements. All such samples are polymict breccias or glasses which are, or contain a large component of, mafic melt breccia. This circular approach is unsatisfactory for the purpose of modeling the composition of the melt breccias.

In the model presented here I make the following compromise. I assume initially that the KREEP component of the mafic melt breccias is generally similar in composition to Apollo 15 KREEP basalt (e.g., sample 15386). This assumption is based largely on the observation that the major-element composition of the mafic melt breccias with the highest concentrations of incompatible elements, A15-A (Table 1), is very similar to that of Apollo 15 KREEP basalt (KREEP-1 of Table 3). Any other assumption would be more ad hoc and model dependent. We do not know the composition of the hypothesized urKREEP [Warren and Was-

son, 1979], KREEP norite [Ryder and Wood, 1977], KREEP substratum [Spudis and Davis, 1986], or any other hypothetical deep KREEP material, although we might reasonably infer its composition [Jolliff, 1998].

The principal modification I make from previous models is the "sliding KREEP" assumption, that is, a decoupling of the compatible and incompatible elements in the KREEP component. I assume the major-element composition of the KREEP component is similar to Apollo 15 KREEP basalt but that in a given melt breccia group, concentrations of incompatible elements (e.g., Sm) may be systematically higher or lower. The major impetus for this assumption is that without it, the model fails, but with it, the model succeeds remarkably well. The assumption is reasonable in that, as mentioned above, the KREEP component of the A14-N and A15-A breccias clearly has greater concentrations of incompatible elements than does the average Apollo 15 KREEP basalt (Figure 5d). Also, because KREEP is a highly differentiated material, it is likely that local conditions will lead to KREEP that is not everywhere identical in incompatible-element concentrations; a factor of 2 or 3 variation is reasonable if not expected. The sliding KREEP assumption does not necessarily require that the cause of the variation in incompatible-element abundances be different degrees of differentiation, which would lead to a variation in major-element abundances as well. On a small scale, factor-of-2 variation in concentrations of incompatible elements among analyzed samples is observed within some groups of mafic melt breccias, and that variation is unaccompanied by systematic variation in abundances of major elements (e.g., A16-1F [Korotev, 1994]). The sliding KREEP treatment assumes that on the size scale of a basin, each melt breccia group represents a finite volume of target material and among these large volumes the same type of variation occurs as among small samples of breccia.

To accommodate variable incompatible to compatible element ratios, I have used two KREEP components in the model, representing the low and high extremes of a range of incompatible-element concentrations. I derived the compositions in the following manner. First, I tabulated data for many samples of Apollo 15 KREEP basalt and calculated average concentrations. The mean composition obtained is listed as KREEP-1 in Table 3. Second, for the KREEP-1L and -1H components, concentrations of compatible lithophile elements (SiO_2 , TiO_2 , Al_2O_3 , FeO, MgO, MnO, CaO, Cr_2O_3 , and Sc) and siderophile elements (Ni, Co, Ir, and Au) were initially assigned to be the same concentrations as those of the KREEP-1 component. Third, concentrations of highly incompatible elements (Zr, Ba, REE, Hf, Th, and U), plagiophile elements (Na_2O , Sr, and Eu), and the alkali elements (K_2O , Rb, and Cs) were calculated from regressions against Sm, such as those of Figure 6, in the manner of *Warren and Wasson* [1979] and *Jolliff* [1998]. The mean concentration of Sm in the samples of the data set was 32 $\mu\text{g/g}$. The KREEP-1L and KREEP-1H concentrations were defined arbitrarily as those corresponding to a factor of 2 lower (16 $\mu\text{g/g}$) and factor of 2 higher (64 $\mu\text{g/g}$) Sm concentration. Thus all highly incompatible elements are also a factor of 2 higher (KREEP-1H) and lower (KREEP-1L) in the two KREEP-1x components because the intercept of the regression lines is the origin on plots such as those of Figure 6b, within uncertainty. For the other elements, which are moderately compatible with feldspar, intercepts were nonzero (e.g., Figure 6a), and there is a smaller relative difference between the concentrations in the KREEP-1L and KREEP-1H compositions. Finally, because incompatible minor elements such as Na_2O , K_2O , and ZrO_2 differed between the two compositions, concentrations of

Table 3. Evolution of Composition of KREEP Components Used in Modeling

	KREEP (Model)						2/1
	1	1L (1)	1H (1)	2 (3)	2L (2)	2H (2)	
SiO ₂	52.0	52.5	51.1	49.3	49.7	48.6	0.95
TiO ₂	2.0	2.02	1.96	2.18	2.20	2.15	1.09
Al ₂ O ₃	15.56	15.7	15.29	15.78	15.90	15.55	1.01
FeO _T	9.87	9.96	9.70	10.68	10.76	10.52	1.08
MgO	8.67	8.74	8.51	9.16	9.23	9.03	1.06
MnO	0.147	0.149	0.145	0.156	0.157	0.153	1.06
CaO	9.33	9.41	9.16	10.2	10.28	10.05	1.09
Na ₂ O	0.80	0.60	1.20	0.87	0.79	1.04	1.09
K ₂ O	0.61	0.30	1.22	0.56	0.28	1.12	0.92
BaO	0.082	0.042	0.163	0.082	0.041	0.161	1.00
Cr ₂ O ₃	0.313	0.316	0.307	0.255	0.257	0.251	0.81
ZrO ₂	0.124	0.063	0.245	0.134	0.067	0.267	1.08
P ₂ O ₅ *	0.55	0.27	1.03	0.55	0.28	1.10	1.00
S*	0.09	0.09	0.09	0.09	0.09	0.09	1.00
Σ	100.1	100.2	100.1	100.0	100.0	100.1	-
Mg*	61.0	61.0	61.0	60.5	60.5	60.5	0.99
Sc	21	21	21	24.9	25.1	24.6	1.18
Co	20	20	20	15.3	15.4	15.1	0.78
Ni	10	10	10	9.2	9.3	9.1	9.2
Rb	16.8	8.4	33.5	17.2	8.6	34.4	1.02
Sr	189	167	234	207	195	231	1.10
Cs	0.59	0.31	1.15	0.74	0.37	1.47	1.25
La	71	36	141	71.3	35.6	143	1.00
Ce	183	92	363	185	92.7	371	1.01
Sm	32	16	64	32	16	64	1.00
Eu	2.56	2.08	3.52	2.83	2.44	3.59	1.11
Tb	6.3	3.1	12.6	6.7	3.33	13.32	1.07
Yb	21.3	10.8	42.4	22.7	11.3	45.4	1.07
Lu	2.9	1.48	5.73	3.14	1.57	6.29	1.08
Hf	26	13.4	52.2	24.7	12.3	49.4	0.94
Ta	2.9	1.48	5.87	2.93	1.47	5.86	1.01
Ir	0	0	0	0	0	0	
Au	0	0	0	0	0	0	
Th	12.3	6.3	24.2	11.9	5.96	23.8	0.97
U	3.4	1.74	6.7	3.22	1.61	6.45	0.95

Oxide concentrations in wt %, others in µg/g; FeO_T, total Fe as FeO. KREEP-1 is the average composition of Apollo 15 igneous KREEP basalt, based on data of Hubbard *et al.* [1973, 1974]; Rhodes and Hubbard [1973]; Murali *et al.* [1977]; Warren and Wasson [1978], Korotev [1987b] and unpublished data, this laboratory, for samples from 15273; Simon *et al.* [1988]; and Ryder and Sherman [1989]. Other compositions are derived; see text. The column headed 2/1 contains the ratio of KREEP-2 to KREEP-1.

* Not used in modeling.

the compatible major-element oxides in each composition were normalized by a common factor (≈1) to yield a sum of oxides of 100% for the two extreme KREEP-1x components (Table 3).

Operationally, the effect of including the two KREEP components in the models (Models 1–3) is that some combination of the two will ideally account for the breccias. Thus, initially, both KREEP components were used to model each composition. The two KREEP components were then combined in the proportions indicated by the least squares solution, and the model calculations were repeated with a single KREEP component (see footnote to Table 4). This process leads to the same results (i.e., same values of *f*) but smaller model uncertainties (± of Table 4). In Table 4, which summarizes results for all models, I report the fraction of that recombined component ("KREEP") as well as the concentration of Sm in the recombined component ("Sm in KREEP").

I do not include a component representing Apollo 17 KREEP basalt [Salpas *et al.*, 1987] in the modeling because, unlike

Apollo 15 KREEP basalt, relative concentrations of some incompatible elements in Apollo 17 KREEP basalt are significantly different from those of the mafic melt breccias (e.g., Figures 1a and 1b), indicating that such a component cannot be the KREEP component of the breccias in general. Also, from the mass-balance viewpoint the composition of Apollo 17 KREEP basalt corresponds reasonably to a ~50:50 mixture of Apollo 15 KREEP basalt and some hypothetical low-Ti basalt, suggesting that Apollo 17 KREEP basalts derive from some type of hybrid magma that is not widespread or abundant.

4.1.3. Mg-rich component. As Ryder [1979] notes, it is the nature of the high-Mg component that has been most controversial. In previous models this component has been represented by

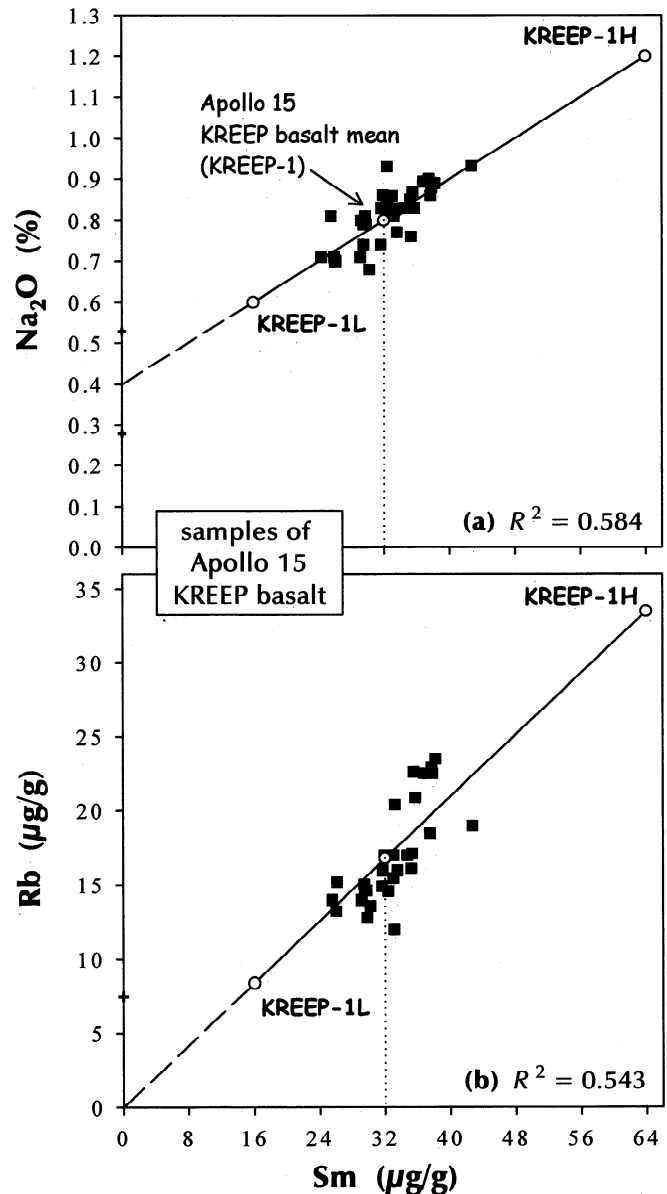


Figure 6. Correlation of Na₂O and Rb with Sm in samples of Apollo 15 KREEP basalt (data from sources listed in Table 3). The diagonal lines are simple least squares fits to the data. The compositions of the KREEP-1L and KREEP-1H components (Table 3) are represented by the open circles at the ends of the solid line segments. The uncertainties in the intercepts are 95% confidence limits.

plutonic and extrusive rocks like troctolite [Dence *et al.*, 1976], norite [Ryder, 1979], troctolite and dunite [Shervais *et al.*, 1988], troctolite, norite, and dunite [Ryder and Stockstill, 1997], dunite and mare basalt [Boynton *et al.*, 1976], other collections of mafic rocks, including gabbronorites and spinel troctolites [Dence *et al.*, 1976; Stöffler *et al.*, 1985], and hypothetical components [Wasson *et al.*, 1977; Wänke *et al.*, 1977, 1978, and earlier papers cited therein; Shervais *et al.*, 1988].

I have chosen to use a dunite component with Fo₉₀ olivine, designated Dun90, as the high-Mg component for several reasons. First, mafic melt breccias have a considerable range of Mg' (bulk mole percent Mg/[Mg+Fe]) (Table 1, Figure 7). The high Mg' (77–80) of some melt breccia groups (A14-O, A16-2Mo, A17-O) requires that the high-Mg component have high Mg'. No known lunar norite has Mg' values sufficiently high to account for the high values in these breccia groups (Figure 5c). Second, a simple calculation of the normative mineralogy of the compositions of Table 1 shows that MgO/FeO ratio of the nonmetal portion of the breccias correlates well ($R^2 = 0.71$) with the normative abundance of olivine (Figure 7). This correlation implies that the wide range in Mg' among the breccias is caused by variable olivine abundance and that high-Mg' melt breccias contain a significant proportion (20–25%) of high-Mg' olivine (Fo₉₁, by extrapolation of Figure 7). Third, all of the melt breccia groups with high abundances of normative olivine in Figure 7 are actually observed to have high modal abundances of high-Mg' (Fo₇₅₋₉₅) olivine (A14-O: Shervais *et al.* [1988]; A15-D: Ryder and Bower [1977], for 15445/55; A16-2Mo: Ryder and Norman, [1980], for 62295; A17-O: Chao [1973], for 76055). Fourth, the mixing trends for the olivine-rich samples (Figures 2, 3, and 4) are consistent with variable amounts of dunite, although group 2Mo of Apollo 16 may be more consistent with troctolite or spinel trocto-

lite (Figure 4). Finally, in the models to be described below, I have substituted a norite component [e.g., Ryder, 1979] for the Dun90 component. Such a component provides poorer fits than does the Dun90 component to those melt breccias with high normative abundances of olivine (Figure 7).

The composition of the Dun90 component (Table 2) is based on Apollo 17 sample 72415-7 but with olivine converted from Fo₈₇ to Fo₉₀ and the proportion of normative plagioclase reduced to ~0%, as in the least aluminous 72417 samples of Laul and Schmitt [1975]. Normatively, like 72415/7, the Dun90 component contains 0.5% chromite.

4.1.4. Meteoritic components. Mafic melt breccias are rich in siderophile elements. Previous models that have included a meteoritic or "extralunar" component to account for siderophile elements have used components based on chondritic compositions [Boynton *et al.*, 1976; Ryder, 1979; Stöffler *et al.*, 1985]. However, relative abundances of siderophile elements in the breccias are not chondritic. Also, there is considerable evidence that the siderophile elements in Apollo 16 mafic melt breccias derive from an iron meteorite [Korotev, 1994] and that Fe₉₄Ni₆Co_{0.4} metal from the same bolide occurs in the melt breccias of Apollo 14, 15, and 17 as well [Haskin *et al.*, 1998]. Thus I have included two meteoritic components in the modeling, one, designated FeNi, representing the average composition of the FeNi metal in the Apollo 16 mafic melt breccias and the other, CI, representing volatile free CI chondrite (Table 2). The principal difference between these two components is the Ir/Au ratio; thus their relative proportions in the model solutions are determined almost entirely by the Ir/Au ratios of the melt breccias.

4.2. Least Squares Modeling

The least squares modeling used here is similar to that described previously [Korotev and Kremser, 1992; Korotev *et al.*, 1995]. In essence, for a mixture (melt breccia) with concentration C_i of element i ($i = 1, n$) and a set of m assumed components j ($j = 1, m$) with concentrations C_{ij} , a mass-balance equation $Y_i = \sum C_{ij} f_j$ can be written for each element, where f_j is the mass fraction of each component in the mixture and Y_i is an estimate of C_i . If the number of elements, n , exceeds the number of components, m , the system is overdetermined and Y_i will not, in general, equal C_i . In this case a least squares solution can be obtained by minimizing $\chi^2 = \sum [(C_i - Y_i)/\omega_i]^2$. The values $(1/\omega_i)^2$, where ω_i has the same units (e.g., weight %, $\mu\text{g/g}$, etc.) as C_i and Y_i , are factors that allow giving more weight to some elements than others, if desired, and which account for differences in magnitude and units of the concentration values. The least squares solutions are the set of values f_j (mass fractions of components) and Y_i (model concentrations in the mixture). In general, χ^2 decreases as m increases, so mathematically excellent, but potentially unrealistic, fits can be obtained by including a large number of components. In order to compare the goodness of fit among models (i.e., a set of assumed components) in which different numbers of components are tested, χ^2/ν is minimized, where $\nu = n - m$.

Thirty-one elements are used to constrain the models (Table 2). These include all major elements, most minor elements (P and S are excluded for lack of sufficient data), a number of key incompatible trace elements, and some siderophile elements. The choice of elements was determined largely by available data.

I have selected weighting factors empirically to achieve balance between obtaining results that are reasonable (most elements should be fit well) and realistic (some elements cannot be fit well). For convenience, the weighting factors are tabulated as

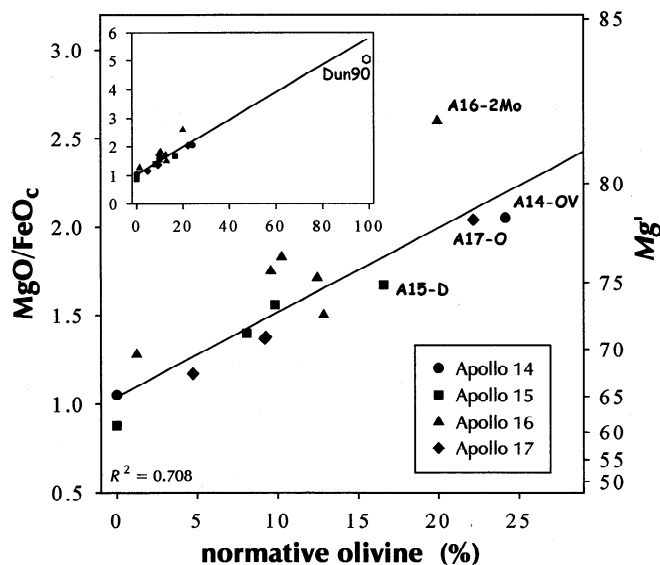


Figure 7. Ratio of MgO to FeO and normative Mg' (mole % Mg/[Mg+Fe]) of mafic silicates as a function of fraction of normative olivine for the mafic melt breccia groups of Table 1 (based on FeO carried by nonmeteoritic components). All of the groups (labeled) that have high abundances of normative olivine also have high modal abundances of Fo₇₅₋₉₅ olivine. The line is a simple least squares regression. Extrapolation of the line to 100% olivine yields Mg' = 91 ± 23% (95% confidence); thus Mg' of the dunite (Dun90) component was set to 90.

relative (%) values, r_i , in Table 2, where $\omega_i = r_i C_i / 100$. For example, if $r_i = 5$, then a relative residual $[(C_i - Y_i) / C_i]$ of 5% leads to an error-weighted residual $[(C_i - Y_i) / \omega_i]$ of 1. Subjectively, for a "good fit," relative residuals for the major rock-forming elements should be low, <2%, but higher relative residuals can be tolerated for minor or trace elements, particularly those which are determined with poorer analytical precision (e.g., Zr, Rb, Ta, and U by instrumental neutron activation analysis). Thus, in order to force relative residuals to be low for SiO_2 , Al_2O_3 , FeO , MgO , and CaO (i.e., 97% of the mass of a typical melt breccia), I have set $r_i = 2$ (i.e., 2%). One might expect that if the major elements agree within 2%, then TiO_2 , MnO , Cr_2O_3 , Na_2O , and Sc would also agree within a few percent, but on the basis of preliminary results, the standard deviation in relative residuals for these elements ranged from 7% (MnO) to 16% (TiO_2). Thus I set r_i higher (5 or 10) for these elements. Preliminary results also showed that standard deviations in relative residuals for the alkali elements (K_2O , Rb , and Cs) were in the 20–30% range, so for these elements I set r_i to 20. For the REE, I set r_i to a low value (5) as a means of forcing relative REE abundances (the "REE pattern") to be matched well. Similarly, standard deviations in the relative residuals for elements associated with plagioclase (Na , Sr , Eu) were typically ~10%, so r_i is 10 for these elements, as it is for most other trace elements. Note that for a given model, if all relative residuals are exactly equal to r_i , then $\chi^2 = n = 31$, and that for a five-component model, $\chi^2/\nu = 31/(31-5) \approx 1.2$. Thus models with values of χ^2/ν approximately equal to unity or less can be regarded as "good fits."

I regard the subsequent discussion as that of a single mass-balance model but use the designations Model 1, Model 2, etc., to refer to refinements or variations of the model.

4.3. Results

4.3.1. Model 1. In Model 1 the composition of each melt breccia group of Table 1 was modeled as a mixture of the KREEP-1L, KREEP-1H, FUpCr, FAn, Dun90, FeNi, and CI components. For most melt breccia groups the least squares solutions led to negative values of f_{FAn} and, in some cases, f_{CI} . When this occurred, the FAn or CI component was excluded and a new solution was obtained. In some other cases the model uncertainty in f_{FAn} or f_{CI} exceeded the values of f_{FAn} or f_{CI} (e.g., $f_{\text{FAn}} = 0.12 \pm 0.23$). In all such cases, exclusion of the component led to a lower χ^2/ν ; thus the component was excluded.

For most of the breccia groups, Model 1 provides a fit that is inadequate but not poor. Values of χ^2/ν range from 0.9 to 4.1, with a mean of 2.2. Estimated concentrations Y_i are systematically and significantly in error (different from C_i) for about half the elements. For example, Y_{Cr} averages $20 \pm 9\%$ high and Y_{Sc} averages $9 \pm 4\%$ low ($\pm = 95\%$ confidence limit). Poor fits ($\chi^2/\nu = 2.7$) were obtained for A14-N and A15-A, which are dominated (>80%) by the KREEP component; thus it is unlikely that the poor fits involve, for example, erroneous concentrations of these elements in the FUpCr or Dun90 components. The results of Model 1 indicate that the KREEP component of the mafic melt breccias is, on average, compositionally similar in general but different in detail from Apollo 15 KREEP basalt (KREEP-1).

4.3.2. Model 2. Model 2 is identical to Model 1, except that it uses a different pair of KREEP components, designated KREEP-2L and KREEP-2H. The compositions were derived as follows. I assigned the residuals of Model 1 to the KREEP component, that is, I calculated the composition of a hypothetical KREEP component for each melt breccia group that would give a perfect

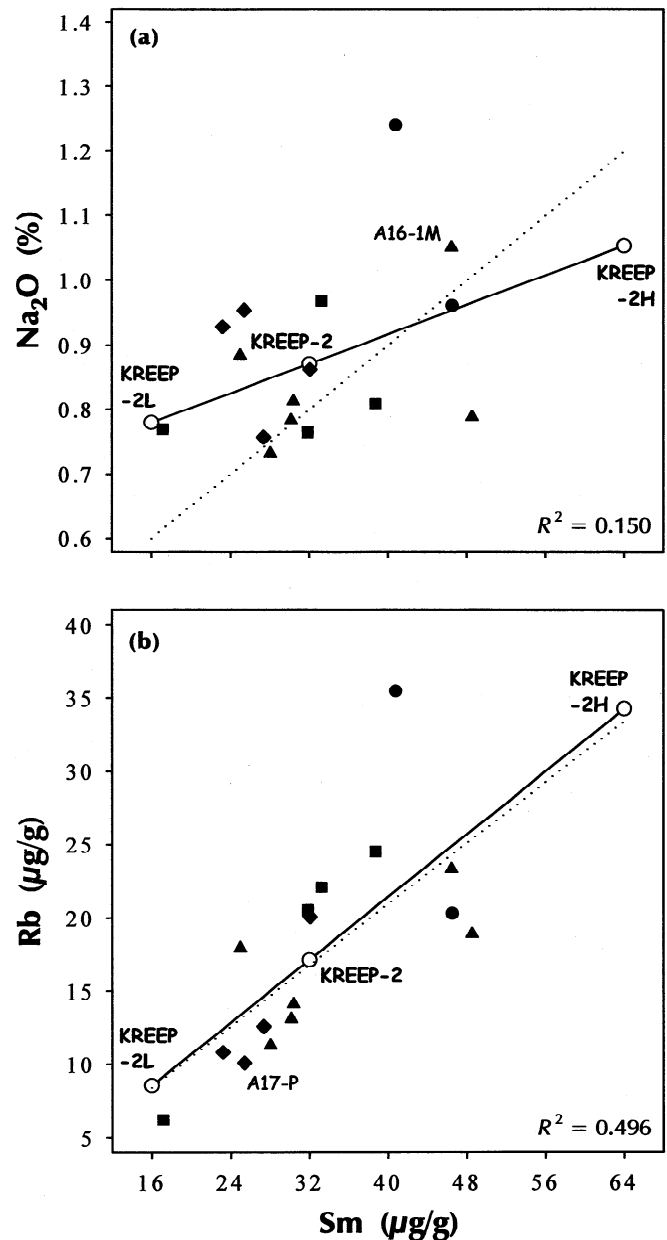


Figure 8. Correlation of Na_2O and Rb with Sm in the residual KREEP compositions derived from the results of Model 1 (see text). Each solid symbol represents a KREEP composition calculated from one of the melt breccia groups of Table 1 (key: Figure 7). (a) For Na_2O the solid line is a simple least squares fit to the filled points; (b) for Rb the line passes through the origin and the mean of the solid points. The concentrations of Na_2O and Rb in the KREEP-2L and -2H components were taken as values of the lines at 16 and 64 $\mu\text{g/g}$ Sm (open circles). For reference, the dotted lines are the solid lines of Figure 6, that is, the correlations for samples of Apollo 15 KREEP basalt. The scatter of the points about the solid lines in part leads to the need for the (a) alkali anorthosite and (b) granite components of Model 3. For example, Figure 8a shows that the KREEP component of A16-1M contains more Na_2O (also, Sr and Eu) than the mixture of KREEP-2L and -2H necessary to supply the Sm ; thus in Model 3 a positive amount AlkAn component (Table 8) is required to supply the excess Na_2O (also, Sr and Eu). Similarly (Figure 8b), the KREEP component of A17-P contains less Rb (also, K_2O and Cs) than the mixture of KREEP-2L and -2H necessary to supply the Sm ; thus a negative amount of the granite component is required to achieve mass balance (Table 8).

fit using the value of f_j obtained from Model 1. For Ni, Co, and the compatible elements, initial concentrations in the KREEP-2L and KREEP-2H components were simply the averages obtained by this procedure (i.e., KREEP-2 of Table 3). Concentrations of incompatible elements varied significantly among the residual KREEP compositions; for example, Sm concentrations ranged from 16.5 $\mu\text{g/g}$ for the KREEP component of A15-D to 46 $\mu\text{g/g}$ for A14-N and A16-1F. This range provided correlations among incompatible elements such as those of Figure 8. Thus, as in Model 1, the KREEP-2L component was assigned 16 $\mu\text{g/g}$ Sm (KREEP-2 of Table 3) and all other incompatible elements were assigned values corresponding to 16 $\mu\text{g/g}$ Sm based on the regressions for each element against Sm. Similarly, the KREEP-2H composition is based on 64 $\mu\text{g/g}$ Sm. Finally, the compatible elements were normalized to provide a sum of oxides of 100.0%. The KREEP-2L and -2H compositions derived in this manner were then used to calculate a new set of f_j and Y_i for each melt breccia group, and new residuals were calculated. After three iterations, no improvement in the mean χ^2/ν was obtained. The resulting compositions for the KREEP-2, KREEP-2L, and KREEP-2H components are listed in Table 3.

The KREEP-2 composition is sufficiently similar to the KREEP-1 composition (i.e., Apollo 15 KREEP basalt) to be regarded as "KREEP," but it differs systematically in several important ways. First, the major element composition corresponds to a greater proportion of normative clinopyroxene (8 versus 5%) and correspondingly less normative quartz (3 versus 8%). Second, concentrations of Na_2O , Sr, and Eu are all $\sim 10\%$ greater in KREEP-2, consistent with a slightly greater proportion of normative albite (7.4 versus 6.8%). Third, as discussed above, concentrations of Cr_2O_3 and Sc are significantly different (-19 and $+18\%$; Table 3). Finally, relative concentrations of incompatible elements are somewhat different; for example, heavy REE are relatively enriched by $\sim 7\%$ compared to light REE, qualitatively consistent with the greater proportion of normative clinopyroxene. Concentrations of Co and Ni are also substantially different, but values obtained for these elements by this method are highly uncertain.

Predictably, the goodness of fit for Model 2 is improved over Model 1. Values of χ^2/ν range from 0.3 to 2.0, with an average of 1.2, compared to 2.2 for Model 1 (Table 4). Because the KREEP-2 composition was calculated from the f values and residuals of Model 1, the f values are nearly the same for the two models (Table 4), and, for the Apollo Mean composition, the model fit is nearly perfect ($\chi^2/\nu = 0.07$). In order to provide calibration for the somewhat nonintuitive χ^2/ν concept, a comparison between the observed concentrations and the model concentrations is provided in Table 5 for two representative melt breccia groups.

A significant result of Model 2 is that only for the group 2 melt breccias of Apollo 16 is the fit improved by including the FAn component. For A16-2DB and A16-2Mo a better fit is obtained by substituting the FAn component for FUpCr; for A16-2NR a mixture (18% FUpCr + 27% FAn) provides the best fit. Similarly, although all breccia groups require some FeNi component, only for the Apollo 17 breccias is the fit improved by also including the CI component.

As in Model 1, I have calculated, for each melt breccia group, the composition of the KREEP component that provides a perfect fit, using the values of f_j derived from Model 2. The average of these compositions, which for lithophile elements differs insignificantly from the KREEP-2 composition of Table 3, is given in Table 6. In essence, this composition is the average composition

Table 5. Results of Model 2: Comparison of Observed (C_i) and Model-Estimated (Y_i) Compositions of Two Selected Melt Breccia Groups

	A16-1F		A17-P	
	C_i	Y_i	C_i	Y_i
SiO_2	47.0	45.7	46.5	47.0
TiO_2	1.20	1.18	1.51	1.34
Al_2O_3	19.30	19.52	18.30	18.27
FeO_T	8.80	8.72	8.95	8.85
MgO	9.90	9.96	11.75	11.72
MnO	0.115	0.111	0.119	0.123
CaO	11.85	11.86	11.25	11.22
Na_2O	0.54	0.61	0.67	0.60
K_2O	0.35	0.42	0.27	0.27
BaO	0.058	0.061	0.038	0.039
Cr_2O_3	0.178	0.188	0.190	0.213
ZrO_2	0.107	0.098	0.065	0.063
Σ	99.4	98.4	99.6	99.7
Sc	14.8	16.1	16.8	17.5
Co	41.0	45.5	28.0	26.4
Ni	590	579	240	268
Rb	9.8	12.7	6.1	8.1
Sr	178	173	173	167
Cs	0.42	0.55	0.22	0.35
La	54.6	52.6	33.4	33.4
Ce	142	137	87.0	86.9
Sm	24.8	23.6	15.0	15.0
Eu	1.94	1.91	1.92	1.79
Tb	5.00	4.91	3.11	3.13
Yb	16.8	16.8	10.9	10.7
Lu	2.26	2.33	1.47	1.48
Hf	18.8	18.2	12.2	11.6
Ta	2.00	2.16	1.57	1.38
Ir	12.8	13.0	6.9	6.6
Au	12.0	11.3	3.6	3.5
Th	8.80	8.75	5.40	5.58
U	2.24	2.38	1.56	1.52
χ^2/ν		0.827		0.910

Oxide concentrations in wt %, Ir and Au in $\mu\text{g/g}$, others in $\mu\text{g/g}$; FeO_T , total Fe as FeO .

of the KREEP component of the Apollo mafic melt breccias, assuming that the other components are only feldspathic upper crust (plus ferroan anorthosite, for Apollo 16 group 2 breccias), dunite, and meteoritic material. For comparison, the "average high-K KREEP" composition of Warren [1989] is also given in Table 6. The compositions are similar. Because the composition of Warren [1989] was deliberately derived from samples (many of which were mafic melt breccias) with the highest concentrations of incompatible elements, concentrations of these elements in "average high-K KREEP" are ~ 1.6 times greater than the average KREEP component of the mafic melt breccias. Other significant differences are that the KREEP composition derived here is richer in MgO (9.2 versus 8.3%) and Cr_2O_3 (0.26 versus 0.18%).

Results of Model 2 imply again that the modified-KREEP/FUpCr/Dun90/FeNi model accounts well for the "average" mafic melt breccia but not as well for some specific breccia types. For example, Model 2 underestimates the concentration of TiO_2 by 11% of the value in A17-P (e.g., Table 5) but overestimates it by 37% in A17-A. Model 2 concentrations of Cr_2O_3 range from -19% (A17-A) to $+26\%$ (A14-N) of the observed values, considerably outside the range of analytical error. All alkali elements (K_2O , Rb, and Cs) are underestimated by 7–30% in A15-A but are overestimated by 19–30% in A16-1F. Elements associated

Table 6. Average Composition of the KREEP Norite Component of the Apollo Mafic Impact-Melt Breccias (2), and Comparison to High-K KREEP (1) of Warren [1989]

	Warren	This Work	
	1	2	±
SiO ₂	50.3	49.5	1.0
TiO ₂	2.0	2.21	0.19
Al ₂ O ₃	15.1	15.77	0.25
FeO _T	10.3	10.76	0.14
MgO	8.3	9.16	0.09
MnO	0.136	0.157	0.007
CaO	9.8	10.21	0.17
Na ₂ O	0.94	0.88	0.07
K ₂ O	0.96	0.57	0.11
BaO	0.15	0.084	0.013
Cr ₂ O ₃	0.18	0.26	0.03
ZrO ₂	0.19	0.137	0.024
Σ	98.4	99.6	—
Mg'	59	60.3	0.8
Sc	23	25.1	1.5
Cr	1200	1760	180
Co	25	16	5
Ni	—	97	43
Rb	22	18	4
Sr	200	208	17
Y	400	*255	40
Zr	1400	1010	180
Cs	1.0	0.76	0.18
Ba	1300	748	120
La	110	73	11
Ce	280	190	30
Pr	37	*25	4
Nd	178	*118	17
Sm	48	33	5
Eu	3.3	2.86	0.20
Gd	58	*39	6
Tb	10.0	6.8	1.0
Dy	65	*43	6
Ho	14	*9.3	1.3
Er	40	*25	4
Tm	5.7	*3.6	0.5
Yb	36	23	3
Lu	5.0	3.2	0.4
Hf	38	25	4
Ta	5.0	3.0	0.4
Th	22	12	2
U	6.1	3.3	0.6

Values in column 2 were calculated from results of Model 2. Oxide values in wt %, others in μg/g. ± = 95% confidence limit based on $N=16$.

* Estimated values based on other REE, for reference.

mainly with plagioclase (Na₂O, Sr, and Eu) are underestimated by 12–18% in A15-A but are overestimated by 8–18% in A17-O. Although not highly incompatible elements, all of these "problem" elements are those which are carried mainly by the KREEP elements are those which are carried mainly by the KREEP component of the model (Table 7). The sliding KREEP treatment accounts well for the variation in the abundance of highly incompatible elements among the KREEP components of the various breccia groups. Results of Model 2 suggest that the KREEP component of the breccias also varies in the concentrations of other elements and these variations are not strongly correlated with the relative abundance of highly incompatible elements.

4.3.3. Model 3. Model 3 was designed to explore, in a normative sense, the nature and relative abundance of components required to account for the remaining residuals as well as the variation in concentrations of highly incompatible trace elements in the KREEP component. In Model 3 a single average KREEP component was used, KREEP-2 of Table 3, and six additional components, regarded here as KREEP subcomponents, were added to account for the deviations from average KREEP. Two of these are mineral components needed to account for the variation in the highly incompatible elements: (1) whitlockite for REE, Th, and U and (2) zircon for Zr, Hf, and Ta. In effect, these two components substitute for most of the variation accommodated by the sliding KREEP treatment of Model 2. Although I am aware of no analytical data directly indicating high concentrations of Th and U in lunar whitlockite, data of Korotev and Kremser [1992, Table 3] suggest high concentrations of Th and U in lunar whitlockite or a whitlockite-rich lithology. I am also not aware of any data for Ta in lunar zircon and have assumed that the Ta required to account for mass balance is carried mainly by zircon or a phase for which the abundance correlates with the abundance of zircon.

Four additional components are needed to account for the problem elements leading to the poor residuals of Model 2. In essence, these subcomponents of the KREEP component reflect the deviations about the regression lines of Figure 8. Because the magnitude of the residuals for TiO₂ and Cr₂O₃ do not correlate

Table 7. Percent of Mass Contributed by Each Component for the Typical Apollo Mafic Impact-Melt Breccia, Based on Results of Model 2 for the Apollo Mean Composition of Table 1

	KREEP 57%	Dun90 13%	FUpCr 29%	FeNi 0.6%	Σ 100%
Si	60	11	28	0	99
Ti	95	0	5	0	100
Al	52	0	48	0	100
Ca	55	0	45	0	101
Na	81	0	16	0	97
Sr	74	0	28	0	102
Eu	87	0	12	0	99
Fe	66	13	13	7	100
Mg	41	48	12	0	100
Mn	73	13	14	0	100
Sc	83	3	14	0	100
Cr	70	21	13	0	104
K	96	0	2	0	98
Rb	95	0	2	0	97
Cs	102	0	2	0	105
Zr	98	0	2	0	100
Ba	96	0	2	0	98
La	99	0	1	0	101
Ce	99	0	2	0	101
Sm	100	0	2	0	102
Tb	98	0	2	0	100
Yb	99	0	2	0	101
Lu	99	0	2	0	101
Hf	98	0	1	0	100
Ta	98	0	2	0	99
Th	95	0	1	0	96
U	94	0	2	0	96
Co	24	14	8	56	101
Ni	14	5	0	87	106
Ir	0	0	0	97	97
Au	0	0	0	97	97

with those of any other element, Model 3 includes components representing the minerals (3) ilmenite and (4) chromian spinel. Ilmenite occurs in all mafic melt breccias and high-Cr spinel has been reported in at least some [Hodges and Kushiro, 1973]. As noted above, residuals for Na₂O, Sr, and Eu mutually correlate. Among lunar rocks these elements are at their highest concentrations in alkali anorthosites; thus Model 3 includes a component of (5) alkali anorthosite (AlkAn). Finally, the K₂O, Rb, and Cs occur in high abundance in lunar granites and felsites [e.g., Jolliff, 1998]; thus the Model 3 also includes a component representing (6) lunar granite.

Initially, all six extra components were included for each melt breccia group. If in the model solution the uncertainty σ_j in the fraction of component j exceeded the absolute value of f_j , that is, if f_j was zero within model uncertainty, then the minor component j was removed from the final model. In all cases this procedure causes χ^2/ν to decrease. Each solution reported in Table 8 is that for the set of minor components leading to the minimum χ^2/ν . For the six extra components of Model 3, negative values of f_j were allowed because, as discussed below (section 5.2.2), negative values have physical significance. Compositions and sources of data for the additional components of Model 3 are given in Table 2. Raw results of Model 3 are reported in Table 8 and the results are summarized in Table 4. Values of f_j and uncertainties σ_j differ between the tables because in Table 4 the values reflect results using combined components for easier comparison with Models 1 and 2. For example, in Table 4 the values listed as KREEP (Model 3) are the sums of f values for KREEP-2 and the six KREEP subcomponents. Similarly, the sum $f_{\text{FUpCr}} + f_{\text{FAn}}$ is reported for FUpCr. These summed values were used to prepare Figure 9.

Compared to Model 2, Model 3 provides a better fit for all the breccia groups except A14-N and A15-D (Table 4); the average value of χ^2/ν is 0.9, compared to 1.2 in Model 2. With Model 3 the TiO₂ residuals of Model 2 are explained by an Ilmenite component ranging in abundance from -0.83% (A15-B) to +1.16% (A16-S) but averaging ~0% (a necessary consequence of the averages and normalizations leading to the KREEP-2 composition). This result can be interpreted in the following way. The KREEP-

2 component (an average composition) contains 4.1% normative ilmenite, but the normative abundance of ilmenite in the KREEP components of the mafic melt breccias ranges from 3.0% (= 4.1–0.83/0.756, where 0.756 is the fraction of KREEP-2 component in A15-B; Table 8) to 6.4% (= 4.1+1.16/0.494, where 0.494 is the fraction of KREEP-2 component in A16-S). Similarly, the Cr residuals require -0.44% (A17-H) to +0.68% (A17A) Spinel component.

Volumetrically, the AlkAn and Granite components are the most important of the KREEP subcomponents. AlkAn ranges from -9% (A15-A) to +7% (A16-1M) and Granite ranges from -5% (A15-D) to +10% (A14-N). In other words, the deficiency of A15-A in Na, Sr, and Eu compared to Sm and other highly incompatible elements can be explained by a normative deficiency of the KREEP component in alkali anorthosite, albite, or some related material rich in Na, Sr, and Eu. Similarly, the high K₂O/Sm and Th/Sm ratios of A14-N and A15-A compared to the Apollo Mean composition can be explained by an enrichment in Granite component [Jolliff, 1998].

As expected, the abundance of the two components that carry the highly incompatible elements, Whitlockite and Zircon, are highly correlated ($R^2 = 0.936$), and both are well correlated with the Granite component ($R^2 = 0.906$ and 0.864). These correlations provide the basis of the sliding KREEP treatment of Model 2 in that if a given melt breccia has a concentration of Sm that is high (or low) by a certain factor with respect to the average, then concentrations of Zr and K₂O are also high (or low) by about the same factor. However, there is no correlation ($R^2 \leq 0.010$) between the abundance of Whitlockite or Zircon with AlkAn.

5. Discussion

The modeling presented here demonstrates that there is no compositional impediment to the hypothesis that all of the Apollo mafic melt breccias are principally mixtures of a KREEP norite similar in composition to Apollo 15 KREEP basalt, dunite, typical feldspathic upper crustal material, and FeNi metal from an iron meteorite. Quantitatively, there are two significant results of the modeling exercise:

Table 8. Results of Model 3: Percent of Component

	KREEP		KREEP Norite					Dunite			Feldspathic		Meteoritic		Σ	χ^2/ν
	AlkAn	Gran.	Ilm.	Spin.	Zirc.	Whitl.	Total	Sm	Dun90	FUpCr	FAn	Total	FeNi	CI		
A14-N	71.8	0.0	9.9	0.0	0.0	0.089	0.36	82.2	46.5	5.4	13.4	13.4	0.53		101.5	1.77
A14-OV	56.5	4.6	8.2	0.0	0.0	0.057	0.16	69.6	38.7	26.9	4.0	4.0	0.39		100.8	1.43
A15-A	92.1	-9.2	6.8	-0.7	-0.4	0.024	0.17	88.8	40.4	0.7	11.3	11.3	0.14		100.9	1.38
A15-B	75.6	-6.2	-1.9	-0.8	0.4	-0.035	-0.05	66.9	31.0	10.8	22.5	22.5	0.34		100.6	0.71
A15-C	45.5	0.0	0.0	-0.3	0.0	-0.006	0.00	45.2	32.2	12.0	41.9	41.9	0.29		99.5	0.49
A15-D	52.0	0.0	-4.6	0.9	0.0	-0.041	-0.17	48.0	19.6	18.0	34.4	34.4	0.23		100.6	2.46
A16-1M	40.6	7.3	4.6	0.5	0.0	0.053	0.19	53.2	41.4	16.1	29.1	29.1	1.56		100.0	0.90
A16-1F	48.1	0.0	3.6	0.0	0.0	0.055	0.23	52.0	46.6	6.8	39.9	39.9	0.86		99.7	0.66
A16-1S	49.4	0.0	-0.9	1.2	0.0	0.000	0.00	49.6	31.3	10.8	40.2	40.2	0.85		101.5	1.21
A16-2DB	42.7	0.0	-1.7	0.0	0.0	-0.008	-0.03	40.9	29.9	14.3		44.1	44.1	1.70	100.9	0.38
A16-2NR	34.6	1.7	0.0	0.3	0.0	0.007	0.02	36.7	32.9	12.6	32.6	17.2	49.8	1.00	100.1	0.32
A16-2Mo	34.6	-2.4	-2.2	0.0	0.0	-0.013	-0.05	30.0	27.9	23.8		45.3	45.3	0.55	99.6	1.41
A17-P	57.1	2.3	-3.3	0.3	-0.4	-0.013	-0.09	56.0	26.0	10.0	32.3	32.3	0.19	0.59	99.2	0.90
A17-A	51.7	-5.1	-2.4	-0.6	0.7	-0.025	-0.08	44.2	27.5	7.3	47.8	47.8	0.12	0.54	99.9	1.09
A17-H	72.5	-3.6	-0.8	0.0	-0.4	0.000	0.00	67.7	33.0	6.4	25.4	25.4	0.25	0.25	100.1	0.31
A17-O	42.8	5.4	-2.7	0.5	-0.4	-0.014	-0.09	45.5	23.7	23.7	28.3	28.3	0.43	1.03	98.9	1.28
Apollo Mean	56.0	1.0	2.2	0.0	0.0	0.016	0.06	59.3	35.1	12.8	27.7	27.7	0.57		100.4	0.11
Mean \pm	2.5	2.1	0.9	0.3	0.3	0.008	0.03	0.8		0.7	2.4	2.1	0.04	0.20	4.0	

"Sm" is the concentration ($\mu\text{g/g}$) of Sm in the KREEP component of the mafic melt breccia, obtained by combining preceding components in proportions indicated. "Mean \pm " is the mean 1- σ model uncertainty. "KREEP" is the KREEP-2 model component.

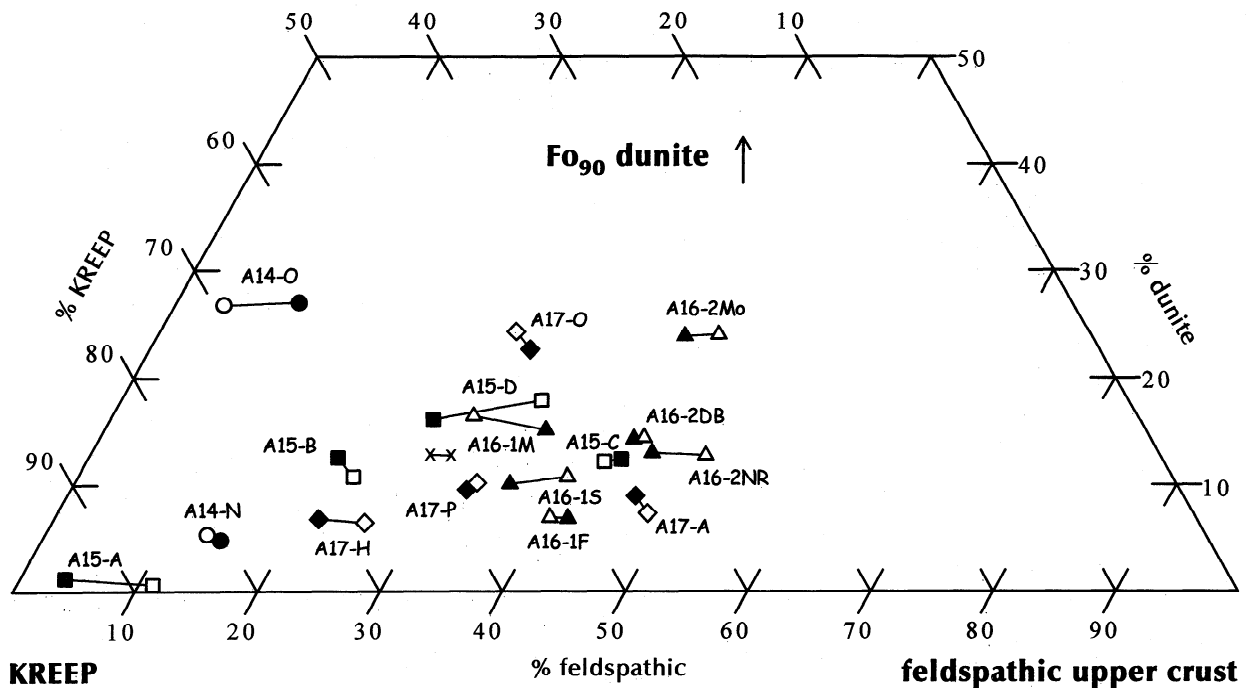


Figure 9. Principal (>98%) components of the Apollo mafic melt breccias, based on results of Model 2 (open symbols) and Model 3 (solid symbols). The X's represent model results for the Apollo Mean composition of Table 1. The "feldspathic upper crust" apex represents the FUPCr + FAn components of Table 2 (only the A16-2xx groups contain the FAn component). The KREEP apex represents the KREEP-2L + KREEP-2H components for Model 2 or KREEP-2 plus the six KREEP subcomponents of Table 2 for Model 3.

1. There is no need to invoke a component of urKREEP or some other ultra-KREEPY component; the KREEP component of the Apollo mafic melt breccias need not be substantially different in composition from samples of presumably extrusive KREEP basalt. The abundance of this KREEP component in the breccias is high, ranging from ~30 to 90+% and averaging ~58% (Table 4; Figure 9). A single component closely representing an observed lithology can supply both the incompatible elements and most of the "maficness" of the breccias (Table 7); no mare-basalt-like component is required.

2. The large variation in MgO abundance and Mg' among mafic melt breccias (Figures 5 and 7) can be explained as a mixing effect between the KREEP norite component ($MgO = 9\%$, $Mg' = 60.5$) and a dunite component ($MgO = 45\%$, $Mg' \approx 90$) that ranges in abundance from 1 to 27% among the breccias. Fractionation of a magma is not required and is probably not the cause of the variation in Mg' [Dowty, 1974b].

Mathematical success of a mass-balance model such as that described here supports but does not and cannot prove the hypothesis that the breccias are actual mixtures of the lithologies represented by the components of the model. Models involving other components may provide equivalently good or better fits to the wide range of mafic melt breccia compositions. However, the KREEP-dunite-crust-metal model is simple, it is a logical extension of previous models, and no better model that accounts for the wide range of melt breccia compositions considered here using actual lunar rock types has been described and quantitatively defended. Thus, in the following discussion I accept the hypothesis and the quantitative model results and assert a set of corollaries. The implications of the corollaries are extensive. Petrogenetic, isotopic, and geophysical constraints may provide insurmountable

obstacles to all or part of the scenario described. The scenario, nevertheless, does account for numerous observations that are difficult to explain by conventional models for the formation of the breccias and some of the components they contain.

5.1. Layered-Target Model

The generally accepted model for formation of the Apollo mafic impact-melt breccias, which I will call the layered-target model, is that the composition of the breccias (i.e., the LKFM composition) represents the average composition of the lower crust of the Moon on a global scale. This model derives from the observation that the breccias are more mafic and richer in incompatible elements than typical feldspathic surface crust [Ryder and Wood, 1977] coupled with geophysical data and general acceptance of the magmasphere model of lunar crust formation [Warren, 1985]. With respect to basin-forming impacts, the relevant features of the magmasphere model are (1) the crust is feldspathic at the surface and becomes more mafic with depth, (2) the early lunar crust was laterally uniform in structure and composition such that, for example, the Imbrium, Serenitatis, Nectaris, and South Pole Aitken impacts generally encountered the same stratigraphy, (3) urKREEP, the residual liquid from crust formation [Warren and Wasson, 1979], was largely concentrated between the upper mantle and lower crust, (4) the crust was intruded by plutons of Mg-rich magma from the mantle, and (5) these magmas interacted with both urKREEP and the crust to form Mg-suite and alkali-suite rocks [Ryder and Wood, 1977; Warren, 1985; Spudis and Davis, 1986; Lucey et al., 1995; Shervais and McGee, 1998; McCallum, 1998; Papike et al., 1998].

Although not usually stated explicitly, an essential feature of

the layered-target model is that the incompatible elements must derive from some type of ultra-KREEP, for example, urKREEP or some derivative of urKREEP with very high concentrations of incompatible elements, while the bulk of the Fe and Mg derive from noritic or gabbroic material of the lower crust [e.g., *McCallum*, 1998]. However, no petrogenetic model that quantitatively accounts for composition of the Apollo mafic melt breccias in terms of a stratified crust has been offered. In the models of *Ryder and Wood* [1977] and *Spudis and Davis* [1986], the nature of the LKFM norite is not clear. Is it a mafic material related to ferroan anorthosite, a Mg-suite norite, some mixture of both, or neither?

5.2. Great Lunar Hot Spot

The most serious problem for any model in which the mafic melt breccias are formed in a region of typical crust such as that thought to derive from a global magmasphere (e.g., *Spudis and Davis* [1986, Figure 4] or *Vaniman et al.* [1991, Figure 2.5d]) is that it cannot account for the overall high abundances of incompatible elements in the breccias. On average, the breccias contain 8.2 $\mu\text{g/g}$ Th (Table 1). If this is taken as the global average composition of the zone of melting for basin-forming impacts, for example, 30- to 70-km depth [*Spudis and Davis*, 1986], then the bulk Moon concentration of Th would have to be at least 480 ng/g, some 11 times greater than in H chondrites [*Wasson and Kallemeyn*, 1988]. Thus there is simply not enough Th in the whole Moon to provide a global layer such that an Imbrium-sized impact anywhere on the lunar surface would produce impact-melt breccia with 8 $\mu\text{g/g}$ Th. Consequently, the Apollo mafic melt breccias cannot have been produced by impacts into regions of typical feldspathic crust. They must instead all derive from impact(s) into a region of crust that was both mafic and rich in incompatible elements, namely, the region identified as the "high-Th oval region" of *Haskin* [1998] or "Procellarum KREEP Terrane" [*Jolliff et al.*, 1999], which has been shown to be a unique geochemical terrane by the Lunar Prospector mission [*Lawrence et al.*, 1998]. This means that the Apollo mafic melt breccias can provide little information about the composition, structure, and nature of typical feldspathic crust. However, as detailed below, they can provide a great deal of information about the nature of the early (pre-Imbrium) Procellarum KREEP Terrane, what we might call "the great lunar hot spot."

5.2.1. KREEP norite target. The compositions of the Apollo mafic melt breccias indicate that the melt zone of the impacts that formed them consisted of a large proportion of noritic, Th-rich material [*Haskin et al.*, 1998], a material designated here as KREEP norite. For the Imbrium impact, which formed some or most of the breccias, the melt zone would encompass the entire crust and perhaps a portion of the upper mantle (section 5.2.3). Thus the compositions of the breccias virtually require that before the Imbrium impact the great lunar hot spot consisted largely of KREEP norite to a considerable depth and lateral extent. This conclusion is largely observational and not model dependent. It is supported, however, by the large volume of Th-rich Imbrium ejecta that appears to be distributed over the lunar surface [*Haskin*, 1998].

At face value, the mass-balance model presented here suggests specifically that prior to the Imbrium impact, the principal component of the hot spot was a KREEP norite or a suite of lithologies with the average composition of KREEP norite (15.8% Al_2O_3 ; $Mg^*=60$) with moderately high concentrations of incompatible elements (e.g., $33 \pm 5 \mu\text{g/g}$ Sm, $12 \pm 2 \mu\text{g/g}$ Th, and 3.3

$\pm 0.6 \mu\text{g/g}$ U; Table 6). If we assume that the average Th concentration of the hot spot was 12 $\mu\text{g/g}$, that the bulk Moon contains 110 ng/g Th (based on 30 ng/g of U [*Drake*, 1986]), and that the hot spot was a cylinder 600 km in diameter and 40 km in depth, then the hot spot contained ~40% of the Moon's Th. If the bulk Moon has as little as 56 ng/g Th [*Warren and Wasson*, 1979], then the hot spot contained most of the Moon's incompatible elements.

The origin of the hot spot will undoubtedly be the focus of much interest in the next few years. Its existence suggests gross asymmetry in the differentiation of the lunar crust [*Warren and Wasson*, 1979], possibly as a result of some type of gravitational interaction with Earth or a large, early impact [*Cadogan*, 1974; *Warren and Kallemeyn*, 1998]. Clearly, its existence had a profound influence on the thermal history of the Moon [*Wieczorek and Phillips*, 1999b]. Because of the large volume of K-, Th-, and U-rich material, the hot spot must have been, literally, hot and possibly partially molten at the time of basin formation [*Spudis*, 1984; *Spudis et al.*, 1984; *Ryder*, 1994; *Haskin*, 1998]. A hot target is supported by the observation that "clasts of LKFM" are not observed in the mafic melt breccias [*Spudis et al.*, 1991; *Ryder et al.*, 1997].

5.2.2. Heterogeneity of the hot spot. The modeling presented here does not succeed unless it is assumed that the KREEP norite component of the breccias was not everywhere identical in composition. Considering the size of the hot spot and the size of the Imbrium impact, this is not an unreasonable assumption because for most of the affected elements the magnitudes of the variations in abundances of the responsible component or phase are small in the absolute sense. For example, Model 3 suggests, at one extreme, that the KREEP component of the volume of material leading to the Apollo 17 aphanitic melt breccias (A17-B) had 3% normative ilmenite, whereas, at the other extreme, that leading to the group 1S at Apollo 16 (actually, a single unusual sample, 64815) contained 6%, a factor-of-2 variation. For the highly incompatible elements the concentrations similarly range over a factor of 2.2, on average (e.g., 20–47 $\mu\text{g/g}$ for Sm; Table 4), but only a fraction of a percent change in the absolute abundance of whitlockite and zircon are required to effect this range.

Clearly, most of the variation reflects that the hot spot was differentiated, that there was some physical separation of the differentiation products [*Jolliff*, 1998], and that the impact(s) that formed the breccias was not 100% efficient in remixing the separated components. Clasts of evolved lithologies occur in many of the breccias [e.g., *Blanchard et al.*, 1977a, b; *Ryder and Bower*, 1977; *Shervais et al.*, 1984; *Lindstrom*, 1984; *Marvin et al.*, 1991], and some melt breccia samples have exceedingly high concentrations of incompatible elements [*Lindstrom*, 1984; *Jolliff*, 1998]. Both alkali anorthosite and granite or felsite are likely differentiation products of a KREEP norite magma [*Shervais et al.*, 1984; *Marvin et al.*, 1991; *Snyder et al.*, 1995; *Jolliff*, 1998]. Variation in the abundance of alkali anorthosite component, for example, among different laterally and vertically separated volumes of the target region is to be expected if local conditions led to crystallization of alkali anorthosite followed by separation of the residual magma.

5.2.3. Mantle dunite. To review, a model-independent set of observations is that some Apollo mafic melt breccias have high abundances of normative olivine (up to 25%; Figure 7), those same breccias have high abundances of modal olivine, and the olivine is highly forsteritic (section 4.1.3). The modeling presented here shows that, on average, a dunite component (Dun90) with Fo₉₀ olivine (as inferred from Figure 7) accounts for the

olivine enrichments better than does norite, troctolite, or a dunite of substantially different composition and that most of the melt breccia groups contain at least some of the dunite component.

The most likely ultimate source of the dunite component is the upper mantle. This conclusion follows from several lines of reason. First, the lack of correlation between abundances of the Dun90 and FeNi components ($R^2 = 0.016$) argues to some extent that the olivine-rich component of the melt breccias does not derive from the impactor that formed the breccias. Second, mantle overturn of the type envisioned by *Hess and Parmentier* [1995] would lead to a mantle capped by highly magnesian olivine. Third, the early hot spot would have consisted largely of ur-KREEP liquid, perhaps superheated from radioactive decay, that was sufficiently large and hot to have reacted with the mantle and assimilated material of the mantle prior to the Imbrium impact [*Korotev*, 1999b; *Wieczorek and Phillips*, 1999b]. Fourth, even without such a process, the Imbrium impact itself almost certainly melted and excavated material of the upper mantle. This conclusion follows from several observations. (1) The diameter of the Imbrium excavation cavity is 744 km [*Wieczorek and Phillips*, 1999a]. (2) Because they were collected outside of basins, most of the Apollo mafic melt breccias must be samples of ejected melt, not samples of melt pooled in a basin [*Haskin et al.*, 1998]. (3) The ratio of depth of excavation to diameter of the excavation cavity is ~ 0.1 [*Croft*, 1980; *Wieczorek and Phillips*, 1999a]. (4) For an excavation cavity of 744 km the depth of melting is about equal to the depth of excavation, that is, 70–80 km [*Cintala and Grieve*, 1998 (although their equations are not strictly applicable if the target were hot or molten)]. (5) The average thickness of the nearside crust is only 55 km [*Neumann et al.*, 1996]. Thus it is reasonable that Imbrium ejecta contained material of the mantle.

Although the ultimate source of most of the Mg in the Apollo mafic melt breccias is likely to have been the mantle, as reasoned above, the Dun90 component does not necessarily represent early mantle cumulates. As a reviewer of this paper noted, a mantle cumulate would have high a concentration of Ni, for example, $\sim 2000 \mu\text{g/g}$, whereas the Dun90 component of the model contains only $150 \mu\text{g/g}$ (Table 2). A value of $150 \mu\text{g/g}$ "works" while a value of $2000 \mu\text{g/g}$ does not in that it substantially overestimates the concentration of Ni in the most Mg-rich breccia groups. Thus the actual dunite component of the breccias is probably mantle olivine reprocessed in such a way as to lose Ni; for example, it was assimilated by the urKREEP melt and recrystallized as a Mg-suite cumulate. Clearly, our best-preserved dunite sample, 72415, is not a mantle cumulate [*Ryder*, 1984]. For reasons presented by *Korotev* [1990], I reject the notion of *Ringwood et al.* [1987] that the Apollo mafic melt breccias contain a komatiite component with high concentrations of Ni. Nickel formerly in a dunite or komatiite component cannot now be in the FeNi metal component, as required by the treatment of *Ringwood et al.* [1987], because the metal in the breccias has a Ni concentration (6%; Table 2) that is already at the low end of the range observed in meteoritic metal.

The variable abundance of the dunite component in the Apollo mafic melt breccias (Figure 9), which in turn accounts for the large variation in the Mg/Fe ratio among the breccias (Figure 7), must reflect heterogeneity in the distribution olivine in the target area. A possible explanation is that the Dun90 component represents clastic material incorporated into the protobreccias during the impact, although some of this component may have subsequently melted and recrystallized. The high abundance of high-Mg' olivine grains observed by *Spudis et al.* [1991] and *Ryder et al.* [1997] in A15-D and A17-P breccias is the physical manifestation of the Dun90 model component. However, the KREEP norite component of the breccias is itself almost certainly a mixture of urKREEP magma and olivine assimilated from the mantle prior to the Imbrium impact. Such a process would account for "the KREEP paradox" [*Warren*, 1988], that is, the combination of evolved incompatible element abundances and moderately primitive Mg' in Apollo 15 KREEP basalt and KREEP-bearing melt breccias. The geometry of the early hot spot, presumably a large, thick body of magma, is more likely to lead to convection or gravitational instability followed by turbulent mixing than the "sandwich" model envisioned by *Warren* [1988] and *Warren et al.* [1981].

The proportion of Dun90 component in the Apollo Mean composition is 13% (Table 4), a value that implies a significant proportion of mantle-derived material in the breccias, on average. Strictly in terms of the model, 13% is an upper limit estimate of the average proportion of mantle material in the breccias because Mg-rich breccia compositions are overrepresented in Table 1 compared to the actual abundance of Mg-rich breccias among samples (e.g., A17-O). If the KREEP norite component itself contains a component of mantle dunite, then the proportion of mantle material in the breccias is greater, but does not exceed 21%, on average (i.e., all the Mg in the KREEP norite model component derives from a subcomponent of dunite; section 5.6).

5.2.4. Evolved and Mg-suite lithologies. A significant corollary to the arguments made here, one that is supported by, but not dependent upon, the mass-balance model, is that many, if not most, of the highly differentiated lithologies found in the Apollo collection, for example, the alkali anorthosites, granites, felsites, and quartz monzodiorites, are probably unique products of the great lunar hot spot. The east-west differences of *Warren and Wasson* [1980] and *Warren et al.* [1981] are probably manifestations of the location of the hot spot. Also, because (1) the norites, troctolites, and gabbro-norites of the Mg suite of lunar plutonic rocks are thought to derive from KREEP-basalt-like magma [*Taylor et al.*, 1993; *Snyder et al.*, 1995], (2) KREEP is largely restricted to the hot spot, and (3) the KREEP-magma probably contained Mg derived from the mantle, the Mg-suite rocks are also likely to have been differentiation products unique to the hot spot. Thus there is no reason to expect, on the basis of our limited sampling, that at points distant from the hot spot, KREEP-contaminated, Mg-rich magmas intruded the feldspathic crust, as is generally believed [*Spudis and Davis*, 1986; *Warren*, 1988; *Papike et al.*, 1998]. If there are mafic plutons in the feldspathic crust [*Tompkins and Pieters*, 1999], petrogenetically these are probably unrelated to Apollo samples we have come to identify with the Mg suite of lunar plutonic rocks.

Note that all Mg-suite and evolved plutonic rocks of the Apollo collection are rocks ejected from a basin, which accounts for the lack of ages < 3.9 Ga among such rocks. If the hot spot was partially molten at the time of the Imbrium impact [e.g., *Haskin et al.*, 1998], then we might expect that similar, but younger, rocks may exist.

5.2.5. Feldspathic clasts. The $\sim 29\%$ (mean; range: 4–50%; Table 4) feldspathic component of the breccias overestimates the proportion of feldspathic material in the melt zone of impact(s) because the feldspathic component of the breccias is largely clastic material. This corollary follows from three observations: (1) clast assemblages, on average, are more feldspathic than matrix [*Spudis et al.*, 1991], (2) the main cause of compositional variation among samples of a given compositional group is a variable ratio of mafic melt to feldspathic components (Figure 2) [*Koro-*

tev, 1994; Jolliff *et al.*, 1996], that is, clast-melt mixing, and (3) clasts probably derive from points distant from the melt zone within the basin cavity [McCormick *et al.*, 1989] or perhaps outside the cavity (section 5.4). There may have been little or no anorthositic crust in the region of the hot spot prior to the Imbrium or Serenitatis impacts. Thus the 8 $\mu\text{g/g}$ mean Th concentration of the breccias (Table 1) is a lower limit to the mean Th concentration of the melt zone of the impact(s) forming the breccias; the 12 $\mu\text{g Th}$ of the KREEP norite component is the upper limit (section 5.2.1).

5.3. Single Impact?

We have suggested elsewhere [Haskin *et al.*, 1998] that it is reasonable that all or most of the Apollo mafic melt breccias were formed during the impact of the Imbrium bolide. (Haskin *et al.* [1998] unintentionally overlooked the summary of Ryder [1985] for 15405 which would indicate that group A15-A was probably not formed during the time of basin formation, 3.9 Gyr ago.) We believe the Imbrium bolide to have been an iron meteorite with a composition like that of the FeNi component of the model (Table 2). Such a component accounts reasonably well for the concentrations of Ni, Ir, and Au in most of the melt breccia groups, whereas a chondritic component does not account for the siderophile elements because the chondritic Ir/Au ratio is much greater than that of the breccias (Table 1).

The Apollo 17 mafic melt breccias all have higher Ir/Au ratios than the FeNi component of the model and mafic melt breccias from other sites (Table 1). This observation has been taken as evidence of a separate impact, one by an impactor with higher Ir/Au ratio [Morgan *et al.*, 1974]. If this hypothesis is assumed, then a different meteoritic (FeNi) component should be used in the model for the Apollo 17 breccias than, say, for the Apollo 16 breccias. As argued by Haskin *et al.* [1998], however, the high Ir/Au ratios of Apollo 17 melt breccias probably result instead from the presence of a second meteoritic component, one with a greater Ir/Au ratio than the metal and which is carried by clasts of

feldspathic granulitic breccia. Such clasts, which at Apollo 17 are both rich in siderophile elements and have nearly chondritic Ir/Au ratios, are prevalent in the Apollo 17 mafic melt breccias and are a major lithologic carrier of the FUpCr model component of the melt breccias. In terms of this hypothesis, the CI component of the mass-balance models represents the meteoritic component of the granulitic breccias and, as such, is actually a subcomponent of the local FUpCr component. Only the Apollo 17 mafic melt breccias require a CI component in addition to the FeNi component to account for the Ir/Au ratios (Tables 4 and 8).

There are several arguments that the A17-P (poikilitic) breccias, at least, do not derive from the Imbrium impact but from the Serenitatis impact (summarized in Haskin *et al.* [1998]). The relatively high Ir/Au ratios of all Apollo 17 mafic melt breccias (Table 1) suggest that if the A17-P melt breccias were formed by the Serenitatis impact, then all Apollo 17 melt breccia must have been. On the basis of lithophile-element abundances, however, there is no reason to expect that the Apollo 17 mafic melt breccias, in general, or the A17-P melt breccias, in particular, were formed in a target area substantially different from that of the Apollo 15 and 16 breccias (Figure 10). If the Apollo 17 melt breccias were, in fact, formed by the Serenitatis impact, then the Serenitatis bolide also impacted the great lunar hot spot [Haskin *et al.*, 1998].

5.4. Origin of Feldspathic Clasts

It is noteworthy that for all but three of the 16 melt breccia groups of Table 1, the mass-balance requirement for some type of feldspathic component (Figure 5b) is satisfied entirely by the FUpCr component (feldspathic upper crust, a noritic anorthosite composition); the FAn component (ferroan anorthosite) is not needed and does not improve the fit for most melt breccia groups. This result supports the arguments made earlier that common, not extreme, feldspathic materials of the crust are the most likely feldspathic components of the melt breccias. Only for the group 2 melt breccias of Apollo 16 (i.e., the "VHA basalts" [Korotev,

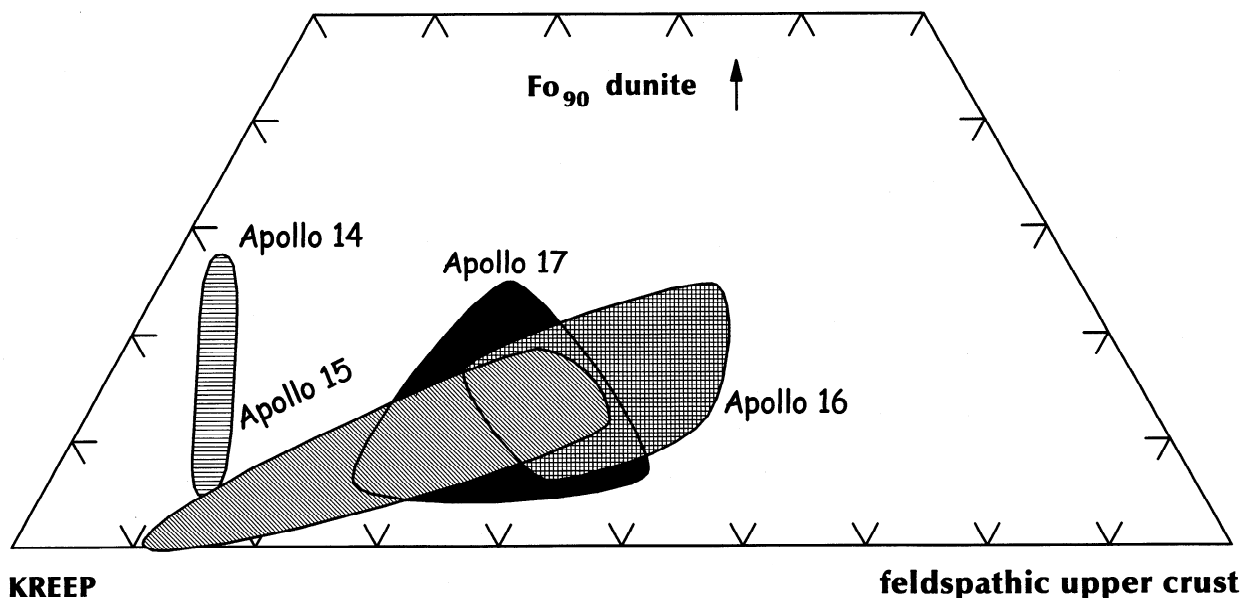


Figure 10. Like Figure 9 (Model 3), but with the range of breccias from each landing site depicted. There is little compositional evidence that the Apollo 17 melt breccias, for example, derive from a substantially different target area than those of Apollo 15 or 16.

1994]) is the model fit improved by using the FAn component instead of (A16-2DB and A16-2Mo) or in addition to (A16-2NR) the FUpCr component (section 4.3.2). The model results suggest that the Apollo 16 group 2 breccias differ from the others discussed here in that they contain the largest proportion of feldspathic material (45–50%) and the feldspathic material is more aluminous than that in the breccias from other sites.

A curious observation is that for Apollo 14 and 15, feldspathic lithologies are rare both in the regolith and as clasts in the mafic melt breccias, yet for Apollo 16 and 17, specific feldspathic lithologies that are uniquely distinct to (or, at least, characteristic of) the respective sites are both a common component of the regolith and a common clast type in more than one compositional group of mafic melt breccia that occurs at the site. For example, at the Apollo 17 site feldspathic granulitic breccia is a common component of the nonmare regolith [Jolliff *et al.*, 1996] as well as a prominent clast type in at least two of the groups of mafic melt breccias, A17-P and A17-A [Spudis and Ryder, 1981]. Although feldspathic granulitic breccias occur at other sites, the Apollo 17 feldspathic granulitic breccias are compositionally distinct in having high concentrations of siderophile elements, with an Ir/Au ratio different from that of the mafic melt breccias. As discussed in section 5.3, this is the probable reason that only the Apollo 17 melt breccias require a model component of CI chondrite. If the Apollo 17 mafic melt breccias were all formed by the Serenitatis impact, then these observations simply imply that feldspathic granulitic breccia was a common lithology of the Serenitatis target area. If they derive instead from Imbrium, then conventional models of melt-breccia formation [Simonds, 1975; Grieve *et al.*, 1977] suggest that different units of melt (i.e., the four Apollo 17 compositional groups) that were ejected toward the Apollo 17 site [Haskin *et al.*, 1998] incorporated clasts of this type within the Imbrium basin, but perhaps just before or as the melt left the basin cavity [McCormick *et al.*, 1989]. Haskin *et al.* [1998], however, suggest instead that the clasts do not derive mainly from near the basin cavity but from the point of secondary impact of the molten ejecta, that is, the melt is from Imbrium and the clasts are from the Serenitatis area.

The hypothesis that some or even a major portion of the clast load derives from outside the basin cavity may also explain why ferroan anorthosite is both a common lithology in the Apollo 16 regolith and a common clast type in the Apollo 16 mafic melt breccias, whereas it is rare at the other sites, either as a regolith constituent or as a clast type in mafic melt breccias. In particular, such a mechanism explains the enigma of the dimict breccias. The Apollo 16 dimict breccias consist of ferroan anorthosite and A16-2DB impact melt in a mutually intrusive relationship [Stöffler *et al.*, 1981; James *et al.*, 1984; McKinley *et al.*, 1984]. The dimict breccias are believed to have formed by injection of impact melt into anorthositic bedrock at the bottom of a large, expanding crater cavity [Stöffler *et al.*, 1979; James *et al.*, 1984; Taylor *et al.*, 1991, Figure 6.40]. A problem with this scenario, however, is how, in a large impact into the Central Highlands, such a mafic ($\leq 22\%$ Al_2O_3 , Table 1), KREEP-rich melt zone could overlie [McKinley *et al.*, 1984] highly feldspathic ferroan anorthosite ($\sim 33\%$ Al_2O_3 [James *et al.*, 1984]); there is no independent evidence that such a mafic layer ever occurred in the Apollo 16 area. Perhaps, instead, the Apollo 16 dimict breccias were produced by impact into the feldspathic Central Highlands of a large blob of mafic, Th-rich melt ejected from the Imbrium basin cavity. This melt bomb carried sufficient energy to melt and assimilate anorthosite in the secondary crater so as to account for the high proportion of feldspathic material (44%; Table 4) in

the melt-breccia phase of the Apollo 16 dimict breccias (A16-2DB). Semiviscous melt of similar composition (group A16-2NR) was injected as spray [Marvin *et al.*, 1987] into fragmented feldspathic material to form the feldspathic fragmental breccias of North Ray crater. Other more feldspathic Apollo 16 impact-melt breccias (e.g., compositional group 2F of Korotev [1994]) are then variable mixtures of feldspathic crustal material and mafic impact melt such as that of group 1F, 1M, or 2DB that was not injected into massive, fractured anorthosite.

5.5. Historical Mg-Rich Components

Lunar highlands breccias have long been recognized to be mixtures of four types of components: feldspathic, KREEPy, Mg-rich, and meteoritic [Taylor and Bence, 1975; Ryder, 1979]. Here I specifically advocate that the Apollo mafic melt breccias are mainly mixtures of typical feldspathic crust (itself a mixture of lithologies with the average composition of a noritic anorthosite), KREEP norite generally similar to Apollo 15 KREEP basalt, dunite derived from the mantle, and FeNi metal from an iron bolide. From a historical perspective it is worthwhile to reconcile previous models in terms of the one I present here.

Although not stated in such terms, the models of Wasson *et al.* [1977] and Wänke *et al.* [1975, 1976, 1978] were also largely efforts to account for the composition of the Apollo mafic melt breccias as mixtures of the same nominal components used here. Results differ among the models because of different assumptions about the specific nature of the components. Wasson *et al.* [1977] and Wänke *et al.* [1975, 1976, 1978], in effect, assumed compositions for the feldspathic and KREEP components and calculated the composition of the Mg-rich component by subtracting off the contributions of other components. Normatively, the compositions obtained for the Mg-rich component by both Wasson *et al.* and Wänke *et al.* are olivine-rich compositions, but not as olivine-rich as the dunite component used here.

The samples upon which the SCCRV (Sc, Cr, V, and Mg-rich) component of Wasson *et al.* [1977] is based are largely mafic melt breccias (A16-2DB, A16-1F, A16-1S, and A17-P). Wasson *et al.* assumed that the feldspathic component was highly feldspathic ferroan anorthosite, the KREEP component was essentially similar to A14-N melt breccias, and the meteoritic component was chondritic. The SCCRV composition they calculated is that of a peridotite. Compositionally, it differs from the dunite component assumed here mainly in being poorer in Mg ($Mg' = 76$, compared to 90) and richer in Fe, Ti, and Cr. These differences arise because (1) the 12–13% of Fe, Mg, and Cr in the melt breccias (on average; Table 7) that is carried by the FUpCr component ($Mg' = 69$) of the model presented here is instead assigned to the SCCRV component because the anorthosite component of Wasson *et al.* is essentially devoid of these elements, (2) the KREEP component used here (KREEP-2 of Table 3) is richer in Ti and Cr than the KREEP component of Wasson *et al.*, and (3) some of the samples upon which the SCCRV composition is based (64815 = A16-S, 77545 = A17-P) are rich in Ti, that is, they have a component of normative ilmenite in excess of that contributed by the KREEP norite component (Table 8).

The Mg-rich component of Wänke *et al.* [1975, 1976, 1978] was thought to be dominated by "primary matter," unfractionated material that accreted after the anorthositic crust had formed. Like Wasson *et al.* [1977], Wänke *et al.* [1976, 1977] assume a KREEP component equivalent to the A14-N melt breccias (sample 14321). The KREEP component was mathematically subtracted in proportion sufficient to reduce the La concentration of

the residuum to ~0. The residuum was assumed to be a binary mixture of the feldspathic component and the Mg-rich component. In effect, the composition of the Mg-rich component was calculated by extrapolation of mixing lines, based on samples with a range of Al/(Fe+Mg) ratios. Note that in this treatment the Mg-rich component also includes the meteoritic component. Wänke et al. specifically excluded from their analysis samples with >25 µg/g La, effectively excluding the mafic melt breccias. However, the most mafic of the samples they did include, that is, those with the greatest proportion of Mg-rich component, are all polymict breccias containing feldspathic material and mafic impact melt such as that in mafic melt breccias. Thus their Mg-rich component is essentially the Mg-rich component of the mafic melt breccias, which is why the excluded samples (e.g., 60315 and 77035 in Figure 1 of Wänke et al. [1976]) nevertheless plot along the mixing lines.

The procedure of Wänke et al. [1975, 1976, 1978] does not yield a unique solution; the Mg-rich component could have any composition ranging from that of the most mafic sample (~17% Al₂O₃) to that corresponding to an Al₂O₃ concentration of zero. Wänke et al. chose to extrapolate to the point where the Al/Sc ratio was chondritic. This operation leads to an olivine norite composition (6% Al₂O₃), one richer in normative plagioclase (~16%) than the dunite component used here (0%). A "longer" extrapolation would have instead led to a peridotitic ultramafic composition similar to that of SCCRV. As with SCCRV, the Mg-rich component of Wänke et al. has lower *Mg'* (78) than the dunite component used here (90). In principal, the process used by Wänke et al. could have led to a composition richer in normative olivine and one with greater *Mg'*. It did not for several reasons: (1) at least one olivine-rich sample, 62295 (A16-2Mo [Wänke et al., 1976, Figure 1]), was excluded from the analysis despite having <25 µg/g La, (2) the KREEP component of Wänke et al. has a higher value of *Mg'* (68) than the KREEP component used here (60.5), thus lowering the Mg concentration of the Mg-rich component, and (3) the Mg-rich component of Wänke et al. includes the meteoritic components (largely FeNi metal), which also lowers the bulk *Mg'*.

Mafic melt breccias are the principal carriers of Fe, Mg, Sc, and Cr in the nonmare Apollo regoliths; they are also the principal carriers of incompatible elements and siderophile elements [Korotev, 1997]. Most interelement correlations observed among samples of nonmare polymict breccias and regolith are mixing lines between Th-rich, FeNi-rich, mafic melt breccias and feldspathic materials of the upper crust. Put another way, correlations such as those of Wänke et al. [1976, Figures 4, 5, 6, and 8] and Wänke et al. [1977, Figure 1] are mixing lines between (1) a mixture (breccia) consisting of, first, material from the Procellarum KREEP Terrane [Jolliff et al., 1999], that is, the anomalous terrane represented by the yellow and orange regions of the Lunar Prospector gamma-ray maps [Lawrence et al., 1998], and, second, the basin-forming bolide and (2) the Feldspathic Highlands Terrane [Jolliff et al., 1999] represented in blue on the Prospector maps. In the model presented here, the dunite component and the KREEP component represent lithologies that coexist in the melt zone of the Imbrium impact. Such a model predicts that among all nonmare polymict samples in the Apollo highlands, the Mg-rich component must increase in relative abundance with the KREEP component. In other words, polymict samples with a high proportion of Mg-rich component must generally also have a high proportion of KREEP component because the only source of the two components is mafic melt breccia. On the other hand, Wänke et al. [1976, 1977] argue that the Mg-rich component is

dominated by late accreting material, in which case there should be no correlation between the abundance of the Mg-rich component and the KREEP component in lunar highlands samples. However, such a correlation exists. All of the Apollo samples with high abundances of the Mg-rich component on the mixing diagrams of Wänke et al. [e.g., Wänke et al., 1976, Figure 1] are KREEP-rich, mafic melt breccias, whereas those with low abundances of the Mg-rich component are not.

The principal argument of Wänke et al. [1976, 1977] that the Mg-rich component is not a lunar plutonic rock like dunite (72415) or troctolite (76535), as suggested here, is that the Fe/Sc ratio of "lunar highlands rocks" (polymict breccias) is relatively constant and different from that of dunite and troctolite. As noted above, most nonmare polymict materials from the Apollo sites are mixtures of feldspathic material of the upper crust and mafic impact melt. The melt phase is the major carrier of Fe, Mg, Sc, and Cr in the polymict samples; thus the Fe/Sc ratio of all polymict samples (all Th-rich ones, at least) is essentially that of the mafic melt breccias. In the mafic melt breccias, Fe, Sc, and Cr are carried mainly by the KREEP component (Table 7), which has a low Fe/Sc ratio (pyroxene), but a small portion is also carried by the Mg-rich (dunite) component, which has a high Fe/Sc ratio (olivine). Thus the mean Fe/Sc ratio of polymict samples lies intermediate to KREEP basalt and dunite, but much closer to that of the KREEP component. Wänke et al. [1976] are correct in concluding that dunite is not a volumetrically important component of lunar highlands rocks, but because the Fe-Sc correlation [Wänke et al., 1976, Figure 4] is dominated by mixing between KREEP norite and feldspathic crust, they are incorrect in concluding that the Fe-Sc correlations eliminates low-Fe/Sc materials such as dunite and troctolite as "the Mg-rich component." For the same reasons Wänke et al. were obliged to subtract the KREEP component prior to calculating the composition of the Mg-rich component, they must subtract the KREEP component before plotting Sc against Fe for the purpose of that argument.

5.6. What Is LKFM?

The LKFM composition is ubiquitous at the Apollo sites because (1) the composition of the great lunar hot spot is, on average, that of LKFM or MKFM (depending upon definitions; section 2), (2) the Imbrium bolide struck the hot spot, and (3) Imbrium ejecta are common in nonmare Apollo regoliths [Haskin, 1998]. Almost certainly, the original LKFM glasses of the Apollo Soil Survey were impact glasses formed, probably by small impacts, in the anomalous regolith in and around the great lunar hot spot, a regolith dominated by a chemical component of KREEP norite. The glass compositions vary from site to site for the same reasons that regolith compositions vary, namely, variation in the abundances of other components. In terms of the hypotheses considered by Reid et al. [1977], "LKFM is a common mixture" in that it is common in the vicinity of the Apollo landing sites and all such mixtures contain a large component of KREEP norite, but also "LKFM is a unique mixture" in that there is only one great lunar hot spot. In the terms of older literature, the KREEP norite component of the model presented here is equivalent to igneous MKFM (or IKFM). Most LKFM samples represent dilution of MKFM by impact mixing with low-K lithologies. High-K Fra Mauro materials are differentiates of MKFM.

One confusing aspect of the LKFM enigma has been the interpretation, based on early work of Walker et al. [1972], Hess et al. [1977], and McKay and Weill [1977], that the LKFM composition was that of a liquid in the silica-olivine-anorthite system and

therefore that the Fra Mauro "basalts" were products of partial melting [e.g., *Taylor and Bence, 1975*]. The KREEP component of the LKFM melt breccias (effectively, the "essence of LKFM") may, in fact, be the composition of an equilibrium liquid [e.g., *Spudis et al., 1991*]. Because the KREEP component dominates in the melt breccias and the other two volumetrically important components (mantle dunite and feldspathic upper crust; Figure 9) consist mainly of either olivine or anorthite, all Apollo mafic melt breccias plot in the vicinity of the olivine-plagioclase cotectic on the silica-olivine-anorthite phase diagram (Figure 11). Impact melt breccias exist that are more feldspathic and which consequently plot closer to the anorthite apex occur [*Warren and Wasson, 1977; Korotev, 1994*], but these are not identified with the LKFM composition.

The model and discussion presented here beg the questions of how and why the hot spot should consist of such a large volume of material with the average composition of KREEP norite and just what KREEP basalt is. I offer the KREEP-dunite-crust model with some geochemical support but with little petrogenetic or geophysical constraint; thus I shift many of the problems associated with the petrogenesis of extrusive KREEP basalt to the petrogenesis of a huge volume of KREEP norite probably several tens of kilometers thick and hundreds of kilometers in lateral extent. For those inclined to seek a petrogenetic harmony, I offer the following caveats and considerations. As acknowledged in the beginning of this section, it is a model assumption that the KREEP component of the melt breccias resembles Apollo 15

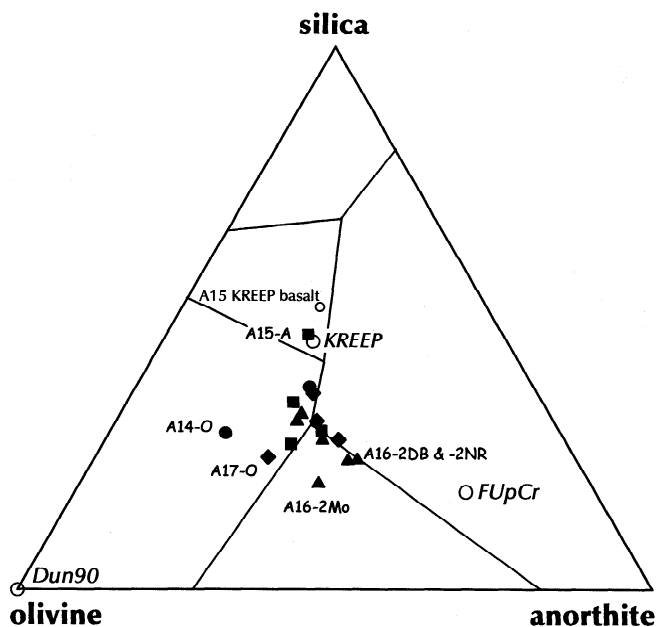


Figure 11. Normative olivine, silica, and anorthite abundances of mafic melt breccia groups (solid symbols) of Table 1 plotted on the pseudoternary phase diagram of *Walker et al. [1972]*. The large open circles represent the three major components of the mass-balance model. The one labeled KREEP is the average composition of the KREEP norite component of the Apollo mafic impact-melt breccias (Table 6); the small open circle is Apollo 15 KREEP basalt (Table 3). That "LKFM" melt breccias plot about olivine-plagioclase cotectic is probably a fortuity in that the breccias (obvious mixtures) are dominated (Figure 9) by a peritectic melt component (i.e., KREEP norite) but also contain significant and variable amounts of olivine from the mantle and feldspathic material from the crust.

KREEP basalt in composition, an assumption supported, but not proven, by mass-balance arguments. Other mass-balance models (sets of components) might be invoked that are mathematically equivalent or superior but which have significantly different petrogenetic implications. Except for the one discussed below, however, I have not succeed in finding such a model.

One interpretation of the model results is that the KREEP-norite component of the model (Table 6) is or approximates the composition of a liquid that existed in the hot spot >4 Gyr ago. That liquid was at least partially differentiated at the time of basin formation, as argued in section 5.2, and the breccias consist of recombined early and late differentiates, as well as feldspathic crust and reprocessed mantle olivine. Clearly, KREEP-like or KREEP-derived lithologies much more evolved than the KREEP component of the model exist (e.g., the ultra-KREEP of *Jolliff [1998]*), and it becomes a semantic question whether the most evolved differentiates or the KREEP-norite whole are regarded as "the KREEP component" of the melt breccias.

A related interpretation is that the KREEP norite component of the model (and, consequently, KREEP basalt) represents a liquid that contains components of mantle olivine and feldspathic crust derived by mixing and assimilation. Mathematically, one can resolve the KREEP-norite component of the model into urKREEP or ultra-KREEP (low Mg' , high Si, high REE), plagioclase-rich, and olivine-rich subcomponents. If, as an extreme but simple example, the KREEP norite component of the model (KREEP-2) is assumed to be itself a 45:41:14 mixture of ultra-KREEP ($MgO < 1\%$, $Mg' < 0.1$, $Sm = 80 \mu g/g$), FUpCr, and Dun90 components, then the proportion of KREEP component required for mass balance for the Apollo Mean composition (Model 2) decreases from 57% KREEP norite to 26% ultra-KREEP, the proportion of Dun90 component increases from 13 to 21%, and the proportion of FUpCr component increases from 29 to 53%. All other proportions and χ^2/v remain the same. Mass balance arguments cannot be used to choose among this model, the one presented in section 4, or some intermediate model because they are all mathematically equivalent.

An interpretation that is unlikely, both in terms of the model results as well as simple consideration of the breccia compositions, is that crustal differentiation led to an urKREEP liquid considerably more enriched in incompatible elements than Apollo 15 KREEP basalt, the liquid migrated to the hot spot, and the impact(s) that formed the breccias mixed that KREEP component with largely unrelated mafic lithologies to fortuitously yield impact-melt breccias with compositions similar to Apollo 15 KREEP basalt.

5.7. What LKFM Is Not

LKFM is not the composition of the lower crust of the Moon. The Apollo mafic melt breccias are not melts of lower crustal norites contaminated with some type of ultra-KREEP. As noted in section 5.2, the high concentrations of incompatible elements in the Apollo mafic melt breccias prohibit the melt breccia composition from being the composition of lower crust globally. Because LKFM is a special product of the Procellarum KREEP Terrane [*Jolliff et al., 1999*], the Apollo mafic melt breccias do not and cannot offer evidence that in the Feldspathic Highlands Terrane the crust becomes more mafic with depth.

At points distant from the hot spot the feldspathic crust may, in fact, be more mafic at depth than at the surface. Overall, however, evidence is weak that it is as mafic as norite or gabbro at depth. Only a small fraction of the central peaks studied by

Tompkins and Pieters [1999] are as mafic as the Procellarum KREEP Terrane. *Spudis and Davis* [1986] argue that the crust becomes more mafic with depth on the basis of a correlation ($R^2 = 0.58$) between basin diameter and the fraction of mafic model components (norite, LKFM, and KREEP), as estimated from mixing models for the compositions of basin ejecta. If the Imbrium and Serenitatis impacts occurred in the great lunar hot spot and not in regions of typical feldspathic crust, then the points representing these basins should be eliminated from the analysis, which lowers R^2 to 0.27 (0.24 if the proportion of mafic material is stated on a mare-free basis). The correlation would be even poorer if a point for the South Pole Aitken basin were included because the ejecta of the South Pole Aitken basin [*Lucey et al.*, 1995] is much more feldspathic than the correlation of *Spudis and Davis* [1986] would imply.

Because in the Imbrium-Procellarum region the principal carrier of the Fe and the carrier of the incompatible elements in the crust are one and the same, KREEP norite (Table 7), it is unlikely that any low-to-moderate-Th ($<3 \mu\text{g/g}$) mafic material that might have been excavated and exposed, for example, in the South Pole Aitken basin [*Lucey et al.*, 1995; *Lawrence et al.*, 1998] is closely related to materials that we have called LKFM, and there is no particular advantage to identifying such material as LKFM.

6. Conclusions

Melt breccias from basin-forming impacts integrate huge volumes of crust to depths comparable to the thickness of the crust [*Cintala and Grieve*, 1998]. The Apollo, KREEP-bearing, mafic ("LKFM") impact-melt breccias, all or most of which were probably created during formation of the Imbrium and possibly Serenitatis basins, provide one of our best estimates of the composition of the upper ~60 km of the Moon in the vicinity of the impact(s) that created them. In this context, the model presented here to explain the composition of the Apollo mafic melt breccias, in conjunction with results obtained by Lunar Prospector [*Lawrence et al.*, 1998] and arguments presented elsewhere [*Haskin*, 1998; *Haskin et al.*, 1998; *Jolliff et al.*, 1999; *Wieczorek and Phillips*, 1999b], suggest the following scenario. This scenario is not offered as a petrologic model but as one possible statement of the events that seem to be required by the composition of the melt breccias.

By some yet unidentified mechanism, urKREEP, the late-stage liquid from crystallization of the lunar mantle and crust, pooled in the Procellarum region of the lunar nearside. Because the liquid was rich in K, Th, and U, it was slow to cool. The geometry of this magma body is not clear, but it must have extended hundreds of kilometers laterally and a few tens of kilometers in depth, hence the designation "the great lunar hot spot." There may have been little or no feldspathic crust in the area. The liquid, which was mafic and ferroan (high Fe/Mg), reacted with and assimilated magnesian (low Fe/Mg) olivine. This olivine was derived from the upper mantle, perhaps following overturn of the mantle as envisioned by *Hess and Parmentier* [1995]. Mixing, assimilation, and crystallization produced a liquid of noritic composition and intermediate Fe/Mg, similar in composition to the KREEP basalts of Apollo 15.

By the time of the Imbrium impact 3.9 Gyr ago, the hot spot was at least partially differentiated and the source of all or most of those plutonic rocks of the Apollo collection that are not related to ferroan anorthosites, namely, granite-like rocks and rocks of the Mg-rich suite and alkali suite. The Imbrium impactor, which was probably an iron bolide [*Korotev*, 1987a, 1994, 1997],

struck the hot spot and encountered a target largely of KREEP norite bulk composition. The impact distributed Th-rich, metal-bearing ejecta over the lunar surface [*Haskin*, 1998; *Haskin et al.*, 1998]. Because of the proximity of the Apollo sites to the Imbrium basin and because Imbrium was the last basin to form in the vicinity, most of the mafic, Th-rich impact-melt breccias collected on the Apollo missions are largely Imbrium ejecta [*Haskin et al.*, 1998], although some of those breccias may have been produced by other impacts into the hot spot. The Imbrium impact was sufficiently large that olivine of the upper mantle and/or olivine-rich cumulates of hot-spot differentiation were heterogeneously incorporated into the impact melt. Feldspathic components of the breccias were largely incorporated into the ejected impact melt from the perimeter or outside of the basin cavity. The Apollo mafic melt breccias vary in composition because (1) differentiation products of the KREEP norite magma were heterogeneously distributed in the target area and (2) the Imbrium impact led to protobreccias (ejected bodies of clast bearing melt) with differing proportions of the main breccia components (KREEP norite, dunite, feldspathic crust, FeNi metal). The Procellarum KREEP Terrane [*Jolliff et al.*, 1999; *Wieczorek and Phillips*, 1999b] is the present expression of the great lunar hot spot, following the Imbrium impact and flooding of basins by mare basalt magmas.

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