WHAT GOT MELTED TO FORM LUNAR MAFIC IMPACT-MELT BRECCIAS?

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Prominent among rock types at each of the last four Apollo sites are impact melt breccias (IMBs) that are substantially more mafic (18–24% FeO+MgO) than typical feldspathic lunar crust (6–10% [1,2]). Mafic IMBs (MIMBs) are the most mafic, common component of the regoliths at Apollos 14 and 16 and account for ~70% of the regolith of the South Massif at Apollo 17 [3–5]. In addition to being mafic (for the lunar highlands), MIMBs are characterized by high concentrations of incompatible trace elements and are the principal carriers of the geochemical signature associated with KREEP in the regolith of the Apollo landing sites. With few exceptions all rocks with compositions corresponding to "Fra Mauro basalts" (LKFM, HKFM, etc.) are actually MIMBs. An important feature of MIMBs is that compositions differ from landing site to landing site, and several different compositional groupings of MIMBs have been identified at the Apollos 15, 16, and 17 sites (Table 1).

One long-standing question of lunar science is "what got melted?" to form the MIMBs. There is no consensus answer. In this study I address the question again, with the specific goal of accounting for the compositional variation among MIMB groups in terms of impact mixing of a small set of common components.

Data. Complete sets of compositional data are available for only a limited number of samples, so I calculated average concentrations for the various compositional groups that have been advocated in order to work with a high-quality data set (Table 1). A significant fraction of the Fe in some MIMBs, particularly those from Apollo 16, is in reduced form and is extralunar. Thus, I have resolved total Fe into Fe^{2+} (i.e., FeO) and Fe^0, based on the Ni concentrations and the observation that the Fe^0 is carried by $Fe_{94}Ni_6$ metal [4]. This consideration is important when accounting for the Mg' (bulk mole % MgO/[MgO+FeO]) of the mafic silicates. In all cases, SiO_2 was calculated by difference (after inclusion of MnO, P_2O_5, and ZrO_2; Table 1).

Normative mineralogy. Normatively, MIMBs range from norites (A14, A15-A,B,&C, A17-high) and olivine norites (A15-D, A16-1M, A17-poik) to anorthositic norites (Fig. 1). Some (at least) of the most feldspathic MIMBs (A16-2DB) tend to contain feldspar clasts derived from ferroan anorthosite whereas such clasts are rare in some of the mafic varieties [6–8], suggesting that the variation in plagioclase to pyroxene ratio may be largely due to variable proportions of clastic anorthosite. One puzzling feature of MIMBs is the wide variation in Mg'. Fig. 2 shows that Mg' correlates roughly with normative olivine abundance. Among MIMB samples at Apollo 16 with high normative olivine (group 2Mo, represented here by a single sample, 62295), a troctolite component appears to be the carrier of the olivine [4].

Normative unmixing. The two observations above suggest that if the proper amounts of anorthosite and troctolite were "removed," in the normative (mathematical) sense, from each of the different groups of MIMB, perhaps a common

residual composition might be revealed. To explore this hypothesis, I first removed normative troctolite, represented by sample 76535 (Table 2), from each of the compositions of Table 1 in proportions sufficient to lower the Mg' of each residual composition to the value in the MIMB with the lowest Mg' (64, in A15-A). I assumed that the most likely anorthositic material in the MIMBs was typical upper crustal material, not "pure" (>90% plagioclase) anorthosite. Thus next, I removed a "feldspathic upper crust" component (Table 2; based on [1] and the feldspathic lunar meteorites) until the residual compositions derived from each melt group all had the Al_2O_3 concentration of the MIMB residue with the lowest Al_2O_3 after subtraction of troctolite. This procedure altered the Mg' values, so I adjusted the proportions of the troctolite and feldspathic components iteratively until all residues had the same Mg' and Al_2O_3.

Result. The "residues" range from 21% (A16-2Mo) to 89% (A15-A) of the mass. On average, concentrations of lithophile elements in the residues (residue 1, Table 2) strongly resemble those of KREEP basalts from Apollos 15 and 17. The resemblance can be improved slightly if a greater proportion of troctolite is removed (residue 2).

To approach the problem additively, I have modeled the compatible lithophile elements of Table 1 as a mixture of four components: A15 and A17 KREEP basalts, feldspathic upper crust, and troctolite (76535). This simple model accounts remarkably well for the observed major element compositions of most of the MIMB groups (Fig. 3). TiO_2 is substantially underestimated in some melt groups (A15-E, A16-2DB), possibly because there is ilmenite-rich lithology in their source regions. In all cases except for A15-E, the best-fit mixtures even comes within a factor of two of accounting for the incompatible elements.

Discussion. This exercise demonstrates that the compositions of mafic impact-melt breccias, in general, as well as the first-order differences in composition among the groups, can be explained by three supercomponents: KREEP basalt, Mg-suite troctolite, and generic feldspathic upper crustal material. Each of these supercomponents actually represents several lithologies and a range of compositions that probably differ from group to group and site to site. For example, the KREEP component probably represents extrusive KREEP basalt and its intrusive equivalent spanning a range of compositions that represent different degrees of differentiation (varying SiO_2 and absolute concentrations of incompatible elements). The troctolite component may also includes plutonic norite, spinel troctolite, etc. The general features of this model are similar to some advocated previously [9,10].

Taking the model results at face value, the high abundance of KREEP basalt component in most of the MIMBs (Fig. 3) is consistent with a scenario in which the MIMBs derive from an anomalous region, presumably where the Imbrium basin now exists (i.e., "High-Th Oval Region" of [11]), in which KREEP basalt or its precursor was a domi-

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nant surface or near surface material and where troctolitic plutons also occurred. Some MIMBs incorporated anorthositic material typical of the highlands. Such a model accounts better for the low abundance of feldspathic components in MIMBs (compared to the KREEP basalt plus troctolite components; Fig. 3) than one in which MIMBs form during large impacts that penetrate feldspathic upper crust and melt (mainly) mafic and KREEP-like material of the lower crust [e.g., 12,13].
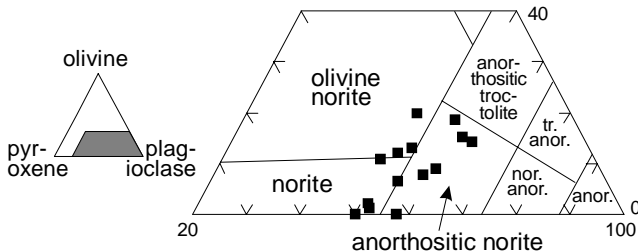
References: [1] Korotev et al. (1996) M&PS **31** 909–924. [2] Korotev (1996) M&PS **31**, 403–412. [3] Jolliff et al. (1991) GCA **55**, 3051–3071. [4] Korotev (1994) GCA **58**, 3931–3969. [5] Jolliff et al. (1996) M&PS **31**, 116–145. [6] James et al. (1984) PLPSC **15**, C63–C86. [7] Spudis et al. (1991) PLSC **21**, 151–165. [8] Ryder et al. (in press) GCA. [9] Ryder (1979) PLSC **10**, 561–581. [10] Garrison & L.A. Taylor (1980) Proc. Conf. Lunar Highlands Crust, 395–417. [11] Haskin, this volume. [12] Ryder & Wood (1977) PLSC **8,** 655–668. [13] Spudis & Davis (1986) PLSC **17**, E84–E90. [14] Stöffler et al. (1980) Proc. Conf. Lunar Highlands Crust, 51–70.

**Table 1.** Concentrations of some key elements in different compositional groups of mafic impact-melt breccias (MIMBs).

		A14	A15 A	A15 B	A15 C	A15 D	A15 E	A16 1F	A16 1M	A16 2DB	A16 2NR	A16 2Mo	A17 poik	A17 aph	A17 high
SiO_2	%	48.0	48.7	47.1	47.6	45.3	46.7	47.6	46.4	44.7	45.1	45.4	46.3	46.4	48.1
TiO_2	%	1.65	1.85	1.16	0.94	1.53	1.58	1.20	1.37	0.93	1.00	0.70	1.51	0.78	1.63
Al_2O_3	%	16.7	16.2	16.6	18.6	17.4	19.9	19.3	17.1	22.0	21.2	20.4	18.1	20.9	17.2
Cr_2O_3	%	0.19	0.20	0.26	0.20	0.23	0.16	0.18	0.22	0.16	0.17	0.17	0.20	0.22	0.20
Fe^0	%	0.56	0.14	0.34	0.28	0.36	0.05	0.86	1.66	1.63	0.96	0.87	0.39	0.27	0.30
FeO	%	9.95	10.1	9.65	7.73	9.0	7.6	7.59	7.55	5.90	6.46	5.15	9.14	7.91	9.14
MgO	%	10.3	10.0	13.2	11.9	14.7	10.8	9.9	13.4	10.9	11.1	11.1	12.7	10.2	11.0
Mg´	%	64.9	63.9	70.9	73.4	74.5	71.8	69.9	75.9	76.7	75.4	83.6	72.5	69.6	68.2
CaO	%	10.4	10.4	10.2	11.5	10.3	12.3	11.8	10.7	12.8	12.9	11.7	11.1	12.4	10.9
Na_2O	%	0.79	0.73	0.58	0.57	0.54	0.64	0.54	0.62	0.49	0.50	0.45	0.65	0.52	0.67
K_2O	%	0.64	0.85	0.32	0.24	0.17	0.12	0.35	0.43	0.19	0.30	0.09	0.22	0.18	0.32
Sc	µg/g	21.7	20.5	19.6	14.2	17.2	16.2	14.8	14.6	10.8	12.2	9.7	17.0	17.3	19.3
Co	µg/g	40	24	39	30	33	20	41	64	66	44	45	31	30	28
Ni	µg/g	400	140	260	225	300	85	590	1090	1070	650	590	295	215	240
Sm	µg/g	40	36	22	15	10.4	4.5	25	22	13	13	8.4	15	14	23
Eu	µg/g	2.69	2.38	1.95	1.80	1.73	1.60	1.94	1.97	1.49	1.51	1.15	1.88	1.42	1.97
Th	µg/g	17.6	14.5	7.4	5.7	3.4	1.7	8.8	8.1	4.3	4.4	3.1	5.0	5.2	8.5

Fig. 1. Normative mineralogy of compositions of Table 1 plotted on the classification diagram of [14], after converting volume % values of [14] to mass %.
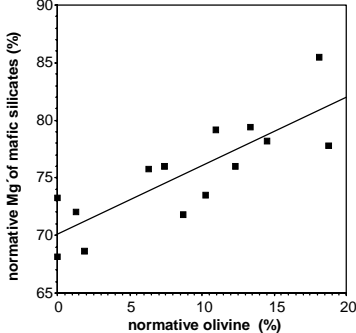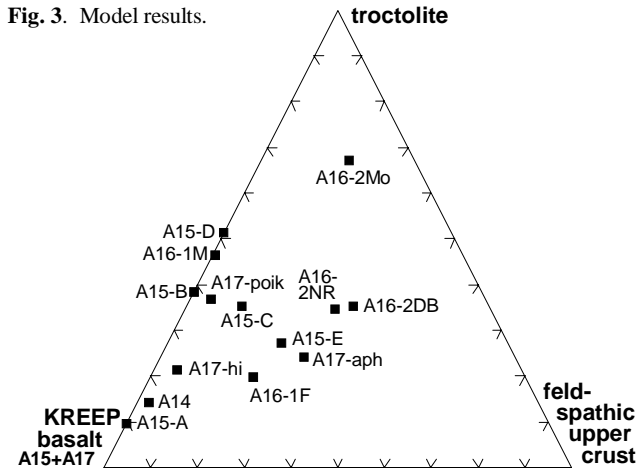
Fig. 2. The normative Mg´ of mafic silicates in MIMBs correlates with the proportion of normative olivine ($R^2 = 0.67$).

Fig. 3. Model results.

Table 2. Mean composition of residues after removal of troctolite and feldspathic upper from compositions of Table 1, and comparison to KREEP basalts.

	troc- tolite	feldsp. crust	mean residue 1	mean residue 2	s.d.	KREEP basalt A15	KREEP basalt A17
SiO_2	42.9	45.0	49.0	49.6	2.0	51.0	48.3
TiO_2	0.05	0.27	2.2	2.5	0.6	2.0	1.3
Al_2O_3	20.7	29.1	14.5	13.9	(0.0)	16.0	13.6
Cr_2O_3	0.11	0.08	0.29	0.31	0.1	0.28	0.50
Fe^0	0	~0	10.5	11.1	1.6	~0	~0
FeO	5.0	3.7	1.4	1.6	1.8	9.7	15.0
MgO	19.1	4.6	10.3	9.3	1.3	8.8	9.5
Mg´	87.	69.	63.6	60.0	(0.0)	61.8	53.0
CaO	11.4	16.6	9.8	9.7	0.5	9.9	10.2
Na_2O	023	0.41	0.84	0.90	0.13	0.80	0.44
K_2O	0.03	0.024	0.5	0.6	0.2	0.60	0.25
Sc	3	7	26	28	4	20	48
Co	27	13	61	64	48	20	36
Ni	25	130	1000	1100	1100	20	60
Sm	0.6	1.0	32	35	12	26	23
Eu	0.73	0.92	2.6	2.8	0.3	2.1	1.6
Th	0.1	0.34	12	13	5	10	6