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Compositional variation in Apollo 16 impact-melt breccias and inferences for the geology and bombardment history of the Central Highlands of the Moon

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Abstract—High-precision data for the concentrations of a number of lithophile and siderophile elements were obtained on multiple subsamples from 109 impact-melt rocks and breccias (mostly crystalline) from the Apollo 16 site. Compositions of nearly all Apollo 16 melt rocks fall on one of two trends of increasing Sm concentration with increasing Sc concentration. The Eastern trend (lower Sm/Sc, Mg/Fe, and Sm/Yb ratios) consists of compositional groups 3 and 4 of previous classification schemes. These melt rocks are feldspathic, poor in incompatible and siderophile elements, and appear to have provenance in the Descartes formation to the east of the site. The Western trend (higher Sm/Sc, Mg/Fe, and Sm/Yb ratios) consists of compositional groups 1 and 2. These relatively mafic, KREEP-bearing breccias are a major component (~35%) of the Cayley plains west of the site and are unusual, compared to otherwise similar melt breccias from other sites, in having high concentrations of Fe-Ni metal (1–2%). The metal is the carrier of the low-Ir/Au (~0.3 × chondritic) siderophile-element signature that is characteristic of the Apollo 16 site.

Four compositionally distinct groups (1M, 1F, 2DB, and 2NR) of Western-trend melt breccias occur that are each represented by at least six samples. Compositional group 1 of previous classification schemes (the “poikilitic” or “LKFM” melt breccias) can be subdivided into two groups. Group 1M (represented by six samples, including 60315) is characterized by lower Al₂O₃ concentrations, higher MgO and alkali concentrations, and higher Mg/Fe and Cr/Sc ratios than group 1F (represented by fifteen samples, including 65015). Group 1M also has siderophile-element concentrations averaging about twice those of group 1F and Ir/Au and Ir/Ni ratios that are even lower than those of other Western-trend melt rocks (Ir/Au = 0.24 ± 0.03, CI-normalized). At the mafic extreme of group 2 (“VHA” melt breccias), the melt lithology occurring as clasts in feldspathic fragmental breccias from North Ray crater (group 2NR) is compositionally distinct from the melt lithology of dimict breccias from the Cayley plains (group 2DB) in having higher concentrations of Sc, Cr, and heavy rare earth elements and lower concentrations of siderophile elements. The distinct siderophile-element signature (high absolute abundances, low Ir/Au ratio) suggest that the four groups of mafic melt breccia are all somehow related. Ratios of some lithophile elements also suggest that they are more closely related to each other than they are to melt breccias from other Apollo sites. However, none of the breccia compositions can be related to any of the others by any simple process of igneous fractionation or mixing involving common lunar materials. Thus, the origin of the four groups of mafic melt breccia is enigmatic. If they were produced in only one or two impacts, then a mechanism exists for generating regimes of impact-melt breccia in a single impact that are substantially different from each other in composition. For various reasons, including the problem of delivering large volumes of four different types of melt to the Apollo 16 site, it is unlikely that any of these breccias were produced in basin-forming impacts. If they were produced in as many as four crater-forming impacts, then the unusual siderophile-element signature is difficult to explain. Possible explanations are (1) the four groups of melt breccia all contain metal from a single, earlier impact, (2) they were each formed by related metal-rich meteoroids, or (3) some common postimpact process has resulted in metal of similar composition in each of four melt pools.

Within a compositional group, most intrasample and intersample variation in lithophile element concentrations is caused by differences among samples in the proportion of a component of normative anorthosite or noritic anorthosite. In most cases, this compositional variation probably reflects variation in clast abundance. For group 2DB (and probably 2NR), differences in abundance of a component of ferroan anorthosite (estimated Al₂O₃ ≈ 32%) accounts for the compositional variation. For groups 1M and 1F, the anorthositic component is more mafic (estimated Al₂O₃ ≈ 26%). Some group-2 samples may be related by a troctolitic component of varying abundance.

INTRODUCTION

IMPACT-MELT BRECCIAS and rocks are the most common lithologies occurring at the Apollo 16 site in the lunar Central Highlands. Of the 543 samples described in the *Catalog of Apollo 16 Rocks* (RYDER and NORMAN, 1980), which includes all “rocks” greater than 1 g in mass, 30% are described

as some type of crystalline melt breccia or clast-poor melt rock. Another 17% are glassy breccias, glass bombs, or glassy fragments, all of which are a type of impact product. About 3% are dimict (dilithologic) breccias in which one of the two predominant lithologies is crystalline impact melt and the other is anorthosite (STÖFFLER et al., 1980; JAMES, 1981). Together, these melt lithologies account for 50% of the re-

turned rocks. Most of the rest are polymict breccias (e.g., fragmental breccias, regolith breccias) that contain lithified impact melt as clasts. The high abundance of impact-melt breccias among returned rocks is not simply the result of sampling bias (e.g., SPUDIS, 1984). In order to account for the high concentrations of ITEs (incompatible trace elements) in mature Apollo 16 regolith (<1 mm fines), mass balance models require an average of 35% components of crystalline melt breccia rich in ITEs (KEMPA et al., 1980; MORRIS et al., 1986), and the soils undoubtedly also contain ITE-poor melt breccias.

Although impact-melt lithologies from Apollo 16 are compositionally diverse, some compositions are more prevalent than others. This has led to speculation that different compositional "groups" each represent different impact events and that some melt compositions can be attributed to specific craters or basins (FLORAN et al., 1976; HERTOGEN et al., 1977; JAMES et al., 1984; LINDSTROM, 1984; MCKINLEY et al., 1984; SPUDIS, 1984; REIMOLD and NIEBER-REIMOLD, 1984). Previous studies have not achieved consensus on the number of compositional groups represented by the Apollo 16 melt rocks or the number of impacts required to produce the observed compositional diversity. At one extreme, the melt rocks are considered to be dominated by a few basin-forming events (HERTOGEN et al., 1977; SPUDIS, 1984), while at the other, numerous smaller impacts are favored (RYDER, 1981; REIMOLD and NIEBER-REIMOLD, 1984). It is not the purpose of this paper to determine the specific number of impact events required to account for the Apollo 16 impact-melt rocks, however. Any significant advancement in this area will require an extensive, self-consistent set of geochronological data, which does not presently exist. Instead, the main purpose is to present and review the constraints imposed by sample compositions on models for the impact history of the Central Highlands. Data obtained here show that the samples impose a more rigid set of constraints than previously realized. The paper will focus on the most enigmatic samples, the mafic (noritic) melt breccias with high concentrations of incompatible and siderophile elements (the "LKFM" and "VHA basalts"). A secondary goal is to explore causes of compositional variation among melt-breccia samples that were likely produced in a single impact.

There have been several previous studies of compositional groupings within the suite of Apollo 16 melt rocks (FLORAN et al., 1976; RYDER and SEYMOUR, 1982; MCKINLEY et al., 1984; SPUDIS, 1984; REIMOLD and NIEBER-REIMOLD, 1984). However, all have been impeded by the small number of analyzed samples, the consequent necessity to compare results obtained by a variety of different analytical techniques from a number of different laboratories, and the almost total lack of information on intrasample compositional variation. Thus, I have analyzed multiple subsamples of a large number of rocks by a common technique. Because glassy impact melts have been well studied in previous works, samples studied here are mainly crystalline melt rocks, which are believed to be produced in larger impacts than those yielding glassy melt rocks (MORRIS et al., 1986; BORCHARDT et al., 1986). However, I discuss possible relationships between the crystalline and glassy melts.

Compositional data reported in this work were obtained by INAA (instrumental neutron activation analysis) using

isotopes with half-lives >12 hours. This provides data of high precision (<3% relative standard deviations) for some elements (e.g., Na, Sc, Cr, Fe, Co, La, Sm, and Eu), data of intermediate precision (typically 5–15%) for other elements (e.g., Ca, Ni, Sr, Cs, Au, Ir, Th, and U), but no data for certain elements that have been favored in other studies, namely Mg, Al, K, and Ti (HUBBARD et al., 1973b; FLORAN et al., 1976; NANEY et al., 1977; RYDER, 1981; RYDER and SEYMOUR, 1982; LINDSTROM, 1984; MCKINLEY et al., 1984; SPUDIS, 1984; REIMOLD and NIEBER-REIMOLD, 1984; STÖFFLER et al., 1985). This is not a serious shortcoming. Factors that cause variation in abundances of these four major and minor elements are adequately reflected by variation in concentrations of trace elements determined well by INAA. Because of their relatively simple mineralogy (primarily plagioclase, pyroxenes, and olivine), major-element concentrations vary predictably in Apollo 16 melt rocks (and polymict samples from the lunar highlands, in general). The first-order effect is that concentrations of elements such as Fe, Mg, Mn, Sc, and Cr that are associated with mafic minerals vary inversely with the concentrations of Al and, to a lesser extent, Ca as the ratio of plagioclase to mafic minerals varies (Fig. 1). Second-order effects, such as variation in Fe/Mg ratio of mafic minerals or the relative abundances of olivine, ilmenite, and spinel have a stronger relative influence on the concentrations of elements such as Sc and Cr than on Mg and Al. As a result, differences among samples or groups of related samples are more evident on plots involving Sc and Cr than on plots using Mg and Al. Thus, presentation of lithophile-element data in this paper relies largely on plots of Sc, Cr, and Sm concentrations. Samarium is used to represent the ITEs; plots involving other precisely determined ITEs yield similar conclusions because concentrations of all ITEs are highly correlated in the samples.

SOME CONVENTIONS

Throughout the paper, the term "sample" refers to a specific rock with a five-digit NASA identification number (e.g., rock sample 65015) whereas "subsample" refers to that portion of a rock sample actually analyzed in these experiments. The term "split" refers to the subsample allocated for study by NASA (e.g., NASA split number 65105.60) and "subsplit" refers to subsamples of a split made in this laboratory.

Each of the Apollo 16 samples studied here is coded by a single unique 'keyboard' character in the figures. The key to this scheme is described in the "Sampling and Analysis" section and presented in Table 1. For convenience, discussion of a specific sample often includes the plot symbol in square brackets following the five-digit NASA sample number (e.g., 65015[#]). *Italicized* alphanumeric plot symbols are used exclusively for samples from station 13.

Most of the rocks studied here are breccias in that they contain mineral and lithic clasts. In the classification of STÖFFLER et al. (1985), the designation "impact-melt rock" is reserved specifically for clast-free melt rocks. Because no petrographic information is available for some of the samples studied here, I sometimes refer to samples (or groups of samples) as melt "rocks" for convenience, with no implication about clast content (e.g., IRVING, 1975).

SAMPLING AND ANALYSIS

Sampling

Selection of samples was based on descriptions in RYDER and NORMAN (1980) and STÖFFLER et al. (1985) and was biased in favor of crystalline rocks; most are described as "basaltic" or "poikilitic impact melt" (RYDER and NORMAN, 1980). The sample request to

Table 1. List of samples studied, with plot symbols (S), total mass analyzed (mg), number of subsplits (N) and number of splits (M) analyzed, experiment designation (E: L = little-rock experiment, B = big-rock experiment, 3 = station-13 experiment, and X = miscellaneous sample not part of any particular experiment), and compositional group (G: U = ungrouped; for others, see text).

S sample	mg	N	M	E	G	S sample	mg	N	M	E	G	S sample	mg	N	M	E	G			
Apollo 14						5	63526	135	2	1	3	4	i	64817	103	3	1	L	U	
14078	170	1	1	X		E	63527	253	4	2	3	1M	#	65015	323	2	1	X	1F	
14310	476	4	1	X		6	63528	139	2	1	3	4	#	65015	74	3	1	L	1F	
Apollo 16						7	63529	222	4	2	3	4	£	65055	173	2	1	X	3	
%	60018	876	8	4	X	2M/F	Q	63535	258	4	2	3	2NR?	n	65349	97	3	1	L	2M
&	60315	451	3	3	B	1M	C	63536	126	2	1	3	2M?	Ω	65357	240	2	2	B	1F
¥	60335	165	2	1	X	2M	Y	63537	139	2	1	3	3	6	65358	89	3	1	L	1F
T	60525	231	2	2	B	1F	I	63545	252	5	2	3	2M?	o	65365	102	3	1	L	2DB
C	60526	233	2	2	B	1M	A	63546	120	2	1	3	4	Z	65757	218	2	2	B	2DB/M
β	60615	242	2	2	B	2M	L	63547	156	3	1	3	2NR	p	65758	103	3	1	L	U
y	60616	107	3	1	L	2M	S	63548	151	2	1	3	4	Σ	65777	222	2	2	B	1F
D	60625	467	3	3	B	2DB	J	63549	246	5	2	3	3	7	65778	92	3	1	L	1F
E	60627	238	2	2	B	2Mo	8	63555	231	4	2	3	4	⊙	65779	269	2	2	B	2DB
U	60635	245	2	2	B	3	D	63556	235	4	2	3	1F	K	65785	260	2	2	B	2NR
Q	60636	346	3	3	B	1F	K	63557	101	2	1	3	4	8	65905	93	3	1	L	1F
F	60645	228	2	2	B	2F	O	63558	101	3	1	L	1M	j	65906	100	3	1	L	2DB
L	60666	238	2	2	B	2Mo	9	63579	221	4	2	3	4	r	65915	97	3	1	L	2M
@	61016	269	2	2	B	2F	G	63585	355	6	2	3	2NR	W	66095	444	3	3	B	2DB
H	61156	455	3	3	B	2F	R	63586	101	2	1	3	4	O	68415	441	3	3	B	3
v	61225	108	3	1	L	2M	M	63587	208	4	2	3	2M	X	68416	408	3	3	B	3
9	61247	97	3	1	L	1F	X	63596	93	2	1	3	1F	s	68505	102	3	1	L	2DB
Φ	61547	236	2	2	B	2M	F	63597	112	2	1	3	U	t	68519	99	4	1	L	2F
J	61548	239	2	2	B	2F	H	63598	238	4	2	3	1F	N	68525	242	2	2	B	1F
a	61549	108	3	1	L	2Mo	Y	64476	440	3	3	B	2DB	w	68526	99	3	1	L	4
Γ	61568	225	2	2	B	2M	d	64478	88	3	1	L	2F	l	68825	101	3	1	L	2F
V	61569	309	2	2	B	U	e	64506	98	3	1	L	2M	x	68845	97	3	1	L	4
G	62235	465	3	3	B	1F	q	64515	95	3	1	L	2NR	z	68846	93	3	1	L	4
b	62245	99	3	1	L	2NR	P	64535	408	3	3	B	2F/M	2	69945	99	3	1	L	1M
M	62255	430	3	3	B	2DB	A	64536	403	3	3	B	2DB	Apollo 17						
c	62287	96	3	1	L	2F	R	64566	241	2	3	B	2DB	76135	304	4	2	X		
N	62295	484	3	3	B	2Mo	S	64567	213	2	2	B	2Mo	77035	388	3	1	X		
1	63335	218	4	2	3	4	g	64568	91	3	3	L	2DB	Literature						
U	63355	207	4	2	3	2NR	4	64575	95	3	1	L	1F	\$	61015	652	1	1	X	2DB
W	63505	143	2	1	3	4	h	64576	103	3	1	L	2Mo	+	60002c	56	8	1	X	4
T	63506	121	2	1	3	4	m	64578	101	3	1	L	2DB	V	61569	?	1	1	B	U
N	63508	125	2	1	3	4	f	64579	103	3	1	L	2F	B	64815	?	2	2	B	U
2	63509	101	2	1	3	4	k	64585	102	3	1	L	2DB	Δ	67513c	252	12	1	X	2NR
3	63515	112	2	1	3	4	u	64586	89	3	1	L	2DB							
4	63525	101	2	1	3	4	B	64815	237	2	2	B	U							
							5	64816	107	3	1	L	1M							

Literature data: JAMES *et al.* (1984) for 61015 (mean of 6); KOROTEV (1991) for particle 2.19 from 60002,139; WASSON *et al.* (1977) for 61569 and 64815; WANKE *et al.* (1976) for 64815; JOLLIFF (1991, 1992) for particles from 67513.

samples from Apollos 14 (14310 and 14078) and 17 (76135 and 77035). Also reported are analytical results for a single, large (400–700 mg) subsplit each of 61015[β], 61016[@], and 65015[#]. These results represent mass-weighted mean concentrations of magnetic and nonmagnetic fractions from an experiment described by KOROTEV (1990), where results from siderophile elements only were reported. In the figures, the miscellaneous samples are coded with various nonalphanumeric symbols (Table 1).

New INAA data obtained as part of other studies of this laboratory are also reported here. These include data for clasts extracted from six regolith breccias, and particles from the 2–4-mm grain-size fractions of soil 67513 (JOLLIFF, 1991, 1992). These experiments will be described in more detail elsewhere, but the data provide useful comparison to data obtained in this study.

Analysis

Subsamples were analyzed by INAA using procedures similar to those described in KOROTEV (1991), except that (1) subsamples in the little-rock experiment were irradiated for 48 h, those in the station-13 experiment were irradiated for 36 h, and all others were irradiated for 24 h, and (2) all samples received an additional radioassay during the time period 5–6 days following neutron irradiation for a total of three radioassays.

LITHOPHILE ELEMENTS AND COMPOSITIONAL GROUPINGS

Discussion of compositional grouping within the suite of Apollo 16 melt rocks is hampered by the wide variety of

names that have been used to refer to rocks of a particular composition or petrographic character, some of which are misleading if taken literally (e.g., “very high alumina [VHA] basalts”; Table 2). For convenience of discussion, I refer to a particular composition or group of rocks with similar composition as a “compositional group” (Fig. 3). As a working model, but with some modifications, I adopt the four compositional groups of MCKINLEY *et al.* (1984), which are based on three groups of FLORAN *et al.* (1976). These four groups have numeric designations that, although not as colorfully descriptive as some of the wordier names (Table 2), avoid textural connotations in what is essentially a compositional classification system. In the schemes of FLORAN *et al.* (1976) and MCKINLEY *et al.* (1984), group numbers correlate with alumina concentration (Fig. 1); thus, the most mafic (noritic) samples are included in group 1 and the most feldspathic samples are in group 4. In this section, I argue that there are compositionally distinct subgroups of some of the four previously recognized groups and that not all samples fall into one of the four groups. Note that the lumping of different samples into a particular group or subgroup based on composition is not intended to imply that the samples are all products of a single impact or that one group or subgroup is genetically distinct from another; it is merely a convenience

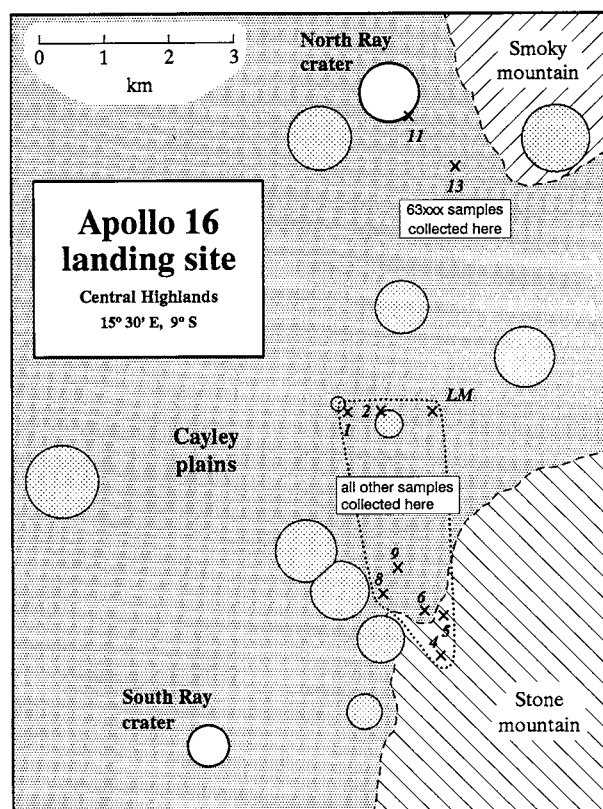


FIG. 2. Schematic map of the Apollo 16 landing site. Numbered sample collection stations are marked by an X. Station 13 is within the continuous ejecta blanket of North Ray crater, a relatively recent crater (~50 Ga); South Ray crater is even younger (~2 Ga) (ARVIDSON et al., 1975). Nearly all melt rocks (>1 g) collected at station 13 were analyzed in this study. All other samples analyzed in this work were collected from the central and southern stations, although literature data for some samples from station 11 (67xxx) are presented.

for discussion of samples of similar composition that may or may not be genetically related. Thus, I make no statistical justifications for the groupings. However, below I discuss compositional features (e.g., element ratios) that distinguish samples of one group or subgroup from another.

To simplify presentation of data in some figures, I have computed sample mean compositions based on the multiple subsamples (Fig. 4). Simple means of the sample means are presented in Table 3 for samples belonging to the same compositional group, along with *intragroup* RSDs (relative standard deviations). I have also computed *intrasample* RSDs by group; these data are not presented, but some conclusions based on the results are discussed below.

Systematic Compositional Variation—Anorthosite Mixing

A theme that will be developed numerous times throughout this section is that much of the compositional variation in Apollo 16 melt rocks, both *intrasample* and *intragroup*, derives from variation in the proportions of two components, an anorthosite component poor in most lithophile elements and a melt component that is more mafic and richer in ITEs.

The anorthosite-melt mixing effect is a common cause of *intrasample* compositional variation. Typically, on two-element variation diagrams involving lithophile elements, replicate subsamples of a given rock define or suggest linear trends. These trends usually lead to positive correlations between Sc and Sm concentrations (Fig. 5a,b); if Sc concentrations are highly variable, negative correlations between Sc and CaO concentrations are also observed (Fig. 5c). Some samples where the anorthosite-mixing effect is most apparent are 60018[β], 60015[β], 60625[D], 61016[@], 63335[1], 63529[7], and 64578[m]. The effect is particularly common in group 2, occurs in groups 3 and 4, but is not seen in group 1. For many samples, the compositional variation most likely results from variability in abundance of anorthosite clasts, either discrete clasts or clasts dissolved in the melt. For others, (e.g., 64535[P]), the most feldspathic subsamples are, or contain a component of, glass. Such glass occurs as coatings on and veins in dimict breccias and is compositionally more feldspathic than the crystalline melt (JAMES et al., 1984). Extreme cases of the anorthosite-mixing effect are seen among subsamples of 60018[β] and 61016[@], which are shocked rocks containing group-2 melt rock, anorthosite, and glass lithologies. For such rocks it is nearly impossible to obtain uncontaminated subsamples of the melt rock. On two-element variation diagrams, subsamples from these two rocks plot along mixing lines between anorthosite and mafic melt rock similar to that in the dimict breccias (Fig. 5b,c).

Group 1: ITE-Rich, Poikilitic Melt Breccias

Group 1 is restricted here to samples with average concentrations of Sm exceeding 15 $\mu\text{g/g}$, consistent with the usage of FLORAN et al. (1976) and MCKINLEY et al. (1984). Including the three type specimens (60315, 62235, and 65015; FLORAN et al., 1976), twenty-one of the samples studied here are group-1 melt rocks. All of the samples for which petrographic data are available are described as poikilitic (RYDER and NORMAN, 1980), although some are texturally heterogeneous (63527[E]). Group-1 samples are characterized by having low concentrations of CaO and Al_2O_3 and the highest concentrations of ITEs and elements associated with mafic phases among common Apollo 16 lithologies. Usually, ITE concentrations alone are sufficient to separate samples of group 1 from those of group 2 (Fig. 4). Only two samples analyzed here, 63596[X] and 68525[N], are at all ambiguous in having lower ITE concentrations than the others and also being more feldspathic (higher CaO, lower Sc and Cr; Fig. 6). However, based on their Cr/Sc ratios, the samples are clearly related to group 1 (group 1F; Fig. 7a), not group 2; texturally, they are poikilitic melt rocks of group 1 with unusually high clast contents, not anomalous group-2 samples ("Correlation of clast content . . ." section).

Subdivision of group 1

On plots involving Cr, six of the samples (1M) are separated from the other fifteen (1F) by a gap (Fig. 6a). The most Cr-rich samples are poorest in Ca (Fig. 6b). I designate these two subgroups "group 1M" (mafic) and "group 1F" (feldspathic) and advocate that these two sets of samples represent different populations of melt rock.

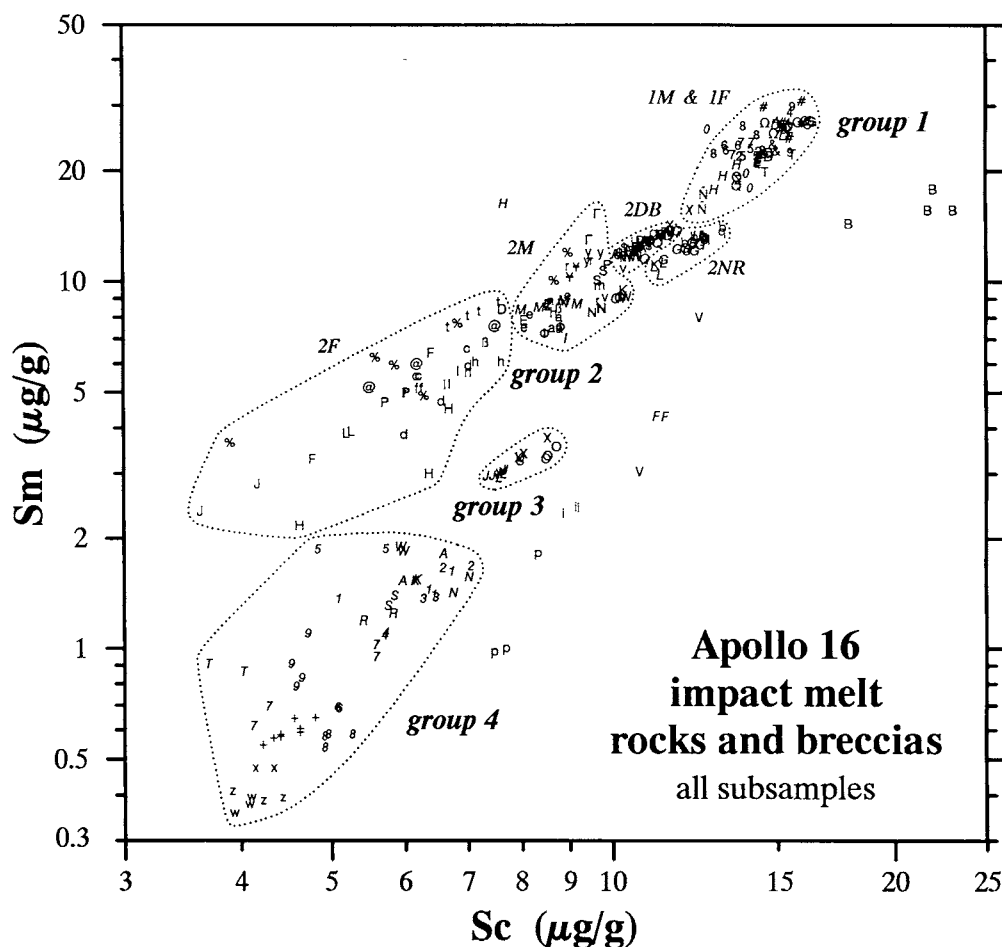


FIG. 3. Sm and Sc concentrations in all subsamples of Apollo 16 melt rocks and breccias studied here, plotted on logarithmic scales to show relative differences. The four numbered compositional groups of MCKINLEY et al. (1984) (based on FLORAN et al., 1976) are indicated, along with major subdivisions of group 2 as defined in this work (for clarity, subgroup group 2Mo is not distinguished, but see Figs. 18a and 24). In this and subsequent figures, each of the different 'keyboard' characters represents a different sample; two to eight subsamples are plotted for each sample (see Table 1 for symbol key). All *italicized* characters represent samples from station 13 near North Ray crater. Among the group-4 samples, numeric characters represent samples that are microporphyrritic in texture and upper-case alphabetic characters represent intergranular samples, except that 63505[W] is micropoikilitic and 63506[T] is subophitic-interstitial (STÖFFLER et al., 1985). All group-4 sample are from station 13, except that 68526[w], 68845[x], and 68846[z] are from station 8 and 6002c[+] is from the bottom of the deep drill core at the LM station (KOROTEV, 1991).

Although the gap in Cr concentrations is small and it is possible that data for additional samples would fill the gaps, other data suggest that two populations occur. The strongest compositional argument is that on a plot of Sc and Cr concentrations (Figs. 6b, 7a), samples of group 1F define a trend consistent with anorthosite mixing and the samples of group 1M do not plot on this trend, i.e., two separate batches of mafic melt appear to be involved. Curiously, on the Sc-Sm plot (Fig. 8), which is usually one of the most useful in separating different compositional groups, samples of groups 1M and 1F overlap and are indistinguishable from each other. However, if the dichotomy in the group-1 samples is accepted, then other compositional differences between the two subgroups are evident in averages (although there is considerable overlap among individual splits). Group 1M has concentration of Na, K, Rb, and Cs that average 15–20% greater than those of group 1F, even though concentrations of tri-

valent REEs, Hf, Ta, Th, and Ba are nearly identical for the two groups (Tables 4, 5). Also, concentrations of Sr and Eu average 4% greater in group 1M, despite that CaO concentrations are 10–15% lower (Fig. 7b), leading to a slightly shallower Eu anomaly in group 1M than group 1F (Fig. 9). These observations are all consistent with a greater abundance of alkali feldspar in group 1M.

Literature data for other major elements are consistent with the differences observed in the INAA data, but are not sufficient to prove the dichotomy because so few analyses are available. Precise major-element data are available for only one group-1M sample, 60315[&], and less precise analyses are available for 60526[C] (Table 4). Both analyses confirm that these two rocks are unusual compared to typical group-1F melt breccias (e.g., 65015[#]) in being poorer in Al_2O_3 and considerably richer in MgO (MgO: 13.4% for group 1M and ~10% for group 1F). (Note in Table 4 and Fig. 6 that

Table 2. Designations used here for compositional groups of Apollo 16 impact-melt breccias and rocks, with alternate designations and type specimens.

group	sub-group	other designations or descriptors	type specimens [fig. symbols]	reference
1		group 1	60315[&], 62235[G], 65015[#]	F, Mc, Sp
		poikilitic [-textured] [melt] [rock/breccia], PMB pyroxene poikiloblastic [breccia] POIK [Apollo 16] LKFM (low-K Fra Mauro) [basalt] low-Al ₂ O ₃ LKFM; mafic LKFM intermediate-K Fra Mauro [Apollo 16] KREEP[y] [rich] [basalt] [rocks] type-1		F, I, J, Mc, RN, RS, Ry, VP D D, I, L J, K, RS, Sp+ BV, Sp, VP N, Ry H, Mo, R+, RN, Ry, St K
	1M 1F	none none	60315[&], 60526[C], 63527[E] 65015[#], 62235[G], 63556[D]	this work this work
2	(all)	group 2	60335[¶], 61016[@], 61156[H], 63545[l], 63585[G], 64567[S]	F, Mc, Sp
		VHA (very high alumina) [basalt]	61016[@], 61156[H], 62295[N], 63545[l], 64567[S]	F, H, I, J, J+, L, LS, M, MJ, ML, R+, RN, Ry, Sp, St
		(mafic: > 8 µg/g Sc, ~< 26% Al ₂ O ₃) [high Al ₂ O ₃] [aluminous] LKFM low-Al ₂ O ₃ basaltic high-Sc VHA type-2	62295[N], 64455 62295[N], 63545[l], 66095[W] 61015[\$], 63355[U], 67435 61015[\$]	BV, N, Sp, VP Ry Mo K
	2DB	dimict (dilithologic) breccia [melt]	61015[\$], 62255[M], 64476[Y], 64567[S]	J, J+, K, Mc, MJ, RS, Sp
	2NR	[North Ray crater] VHA from feldspathic fragmental breccias	from 67016, 67xxx 63355[U], 63547[L], 63585[G]	J, K., LS, M+, Mc, ML, Sp this work
	2Mo	troctolitic [basalt] olivine rich	62295[N] 62295[N], 64567[S], 60666[L]	I, VP this work
	2M	low-Sc VHA feldspathic intersertal igneous rock (FIIR) [low-An] [An-poor] anorthositic gabbro subophitic-intersertal (>8 µg/g Sc, but ≠ 2DB, 2NR, or 2Mo)	60335[¶], 66095[W] 63536[C], 63545[l] 60335[¶], 63536[C]	Mo D, J, RN N, RS, VP St this work
		(feldspathic: < 8 µg/g Sc, ~> 26% Al ₂ O ₃)		
	2F	[glassy] impact-melt splashes (IMS) [glassy] melt bombs (crystalline)	coatings on others 67687 60645[F], 64579[f], 64478[d]	Mo Bo this work
	3		group 3	68415[O], 68416[X], 63549[J]
		anorthositic basalt	68415[O], 68416[X]	I
		high-Al ₂ O ₃ [basaltic]	68415[O], 63549[J], 65055[E]	RS, Ry
		high-An (An-rich) anorthositic gabbro	68415[O], 68416[O], 67559	RS, VP
		anorthositic norite melt rock (ANMR)	60635[U], 67559, 68415/6[O/X]	R+, RN, DS
		suboph-ophitic-intersertal (impact) melt rock	63537[Y], 63549[J], 67559	St
		noritic-anorthosite melt rock	68415[O]	J, MJ
		olivine-free, An-rich anorthositic gabbro	63549[J]	VP
		gabbroic anorthosite		L
		68415 group	68415[O]	RN
	684xx 635xx	68415[O], 68416[X] 63537[Y], 63549[J], 65055[E]?	this work this work	
4		group 4	60017, 67475, 64538, 64435	Mc, Sp
		feldspathic [fragment laden] [melt breccia]	from 67xx3 and 67016	J, L, LS,
		feldspathic microporphyratic (FM) [melt breccia] intergranular [melt breccia/rock]	63335[1], 63509[2], 63515[3] 63508[N], 63546[A], 63557[K]	DS, RN, R+, St, J, R+, RN, St
U	ungrouped			
	olivine-free, An-rich anorthositic gabbro	65758[p]	VP	
	none, but similar to group 3	64817[i], 65758[p]	this work	
	none, but possibly anomalous group 1	68415[B], 63597[F], 61569[V]	this work	

Bo	BORCHARDT et al. (1986)	K	KOROTEV (1987a)	Ry	RYDER (1981)
BV	BVSP (1981)	L	LINDSTROM (1984)	RS	RYDER and SEYMOUR (1982)
D	DELANO et al. (1973)	LS	LINDSTROM and SALPAS (1983)	R+	REIMOLD et al. (1985)
DS	DEUTSCH and STÖFFLER (1987)	M+	MARVIN et al. (1987)	RN	REIMOLD and
F	FLORAN et al. (1976)	MJ	MORGAN and JAMES (1981)		NIEBER-REIMOLD (1984)
H	HUBBARD et al. (1973a,b)	ML	MARVIN and LINDSTROM (1983)	Sp	SPUDIS (1984)
I	IRVING (1975)	Mc	MCKINLEY et al. (1984)	Sp+	SPUDIS et al. (1989)
J	JAMES (1981, 1986)	Mo	MORRIS et al. (1986)	St	STÖFFLER et al. (1985)
J+	JAMES et al. (1984)	N	NANEY et al. (1977)	VP	VANIMAN and PAPIKE (1980)

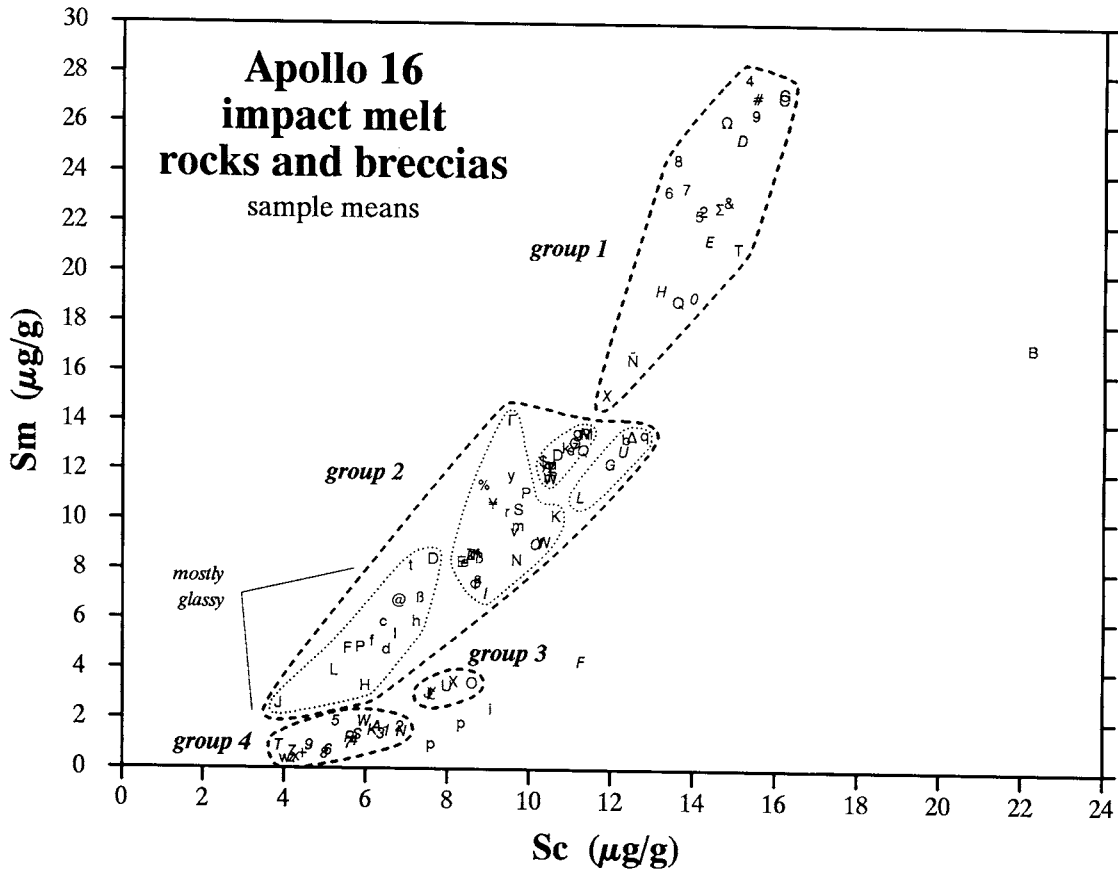


FIG. 4. Comparison of Sc and Sm concentrations in all Apollo 16 melt groups using sample mean compositions plotted on linear scales (compare with Fig. 3). For most samples, sample means were calculated as mass-weighted means of element concentrations in all subsamples. For five samples, one each highly anomalous subsample has been ignored (60636[Q], 63335[I], 63558[O], 63598[H], and 64815[B]). For a few samples, two mean compositions are calculated and plotted if one or more subsamples differ considerably in composition from the others but none are unusual with respect to other samples (e.g., 64535[P]). Compositionally nonuniform samples and samples with compositionally anomalous subsamples are noted in Table A1. Highly heterogeneous sample 61569[V] is excluded (Fig. 3).

sample 62235[G] is one of the most mafic of the group-1F samples, yet there is still a significant difference in MgO and Al₂O₃ concentrations between 62235 and the two groups-1M samples.) To a first approximation, addition of olivine to the composition of group 1F accounts for the composition of group 1M. In detail, however, the mass balance requires an unlikely assemblage: group 1M corresponds normatively to a mixture of 88.4% group 1F, 9.0% olivine (Fo₈₈), 1.9% alkali feldspar (Ab₆₅Or₃₅), 0.1% chromite, and 0.6% ilmenite. This constraint provides a hurdle to models attempting to relate the two compositions ("Siderophile Elements" section).

Some of the compositional differences between groups 1M and 1F are reflected in petrographic differences reported among poikilitic rocks. Of the poikilitic melt rocks studied by SIMONDS et al. (1973), three are assigned here to group 1M (60315, 63558, and 64816) and three to group 1F (63556, 64575, and 65015). Average compositions of the orthopyroxene oikocrysts are in the range En₆₅₋₇₃ for group 1F and En₇₉₋₈₂ for group 1M. Olivine is about twice as abundant in group 1M (2-6%) as in group 1F (1-3%). The differences in mineral compositions and MgO concentration led to a significantly different bulk Mg' ($Mg' = \text{mole percent Mg/}$

$[\text{Mg} + \text{Fe}]$) for the two groups, although bulk Mg' is not straightforward to evaluate because of the large and varied concentrations of Fe-Ni metal in the samples ("Siderophile Elements" section). Mg' based on total Fe is 71 ± 1 for group 1M and 67 ± 1 for group 1F, but these are increased to ~ 76 and 70, respectively, in the nonmetal portion of the samples (Table 4).

That the group-1 might be divisible was previously suggested by REIMOLD and NIEBER-REIMOLD (1984), who noted that 65015[#] and 63556[D] contained less normative olivine than 60315[&] and 64815[B]. In subsequent discussion, I assume that groups 1F and 1M represent two discrete batches of melt (possibly from the same impact). However, even if they represent a poorly sampled continuum within a single batch of melt, the observations summarized here provide information on processes that cause melt heterogeneity and most of the conclusions reached below remain valid.

Anorthosite mixing in group 1

At the scale of sample masses used in these experiments, both intrasample and intragroup compositional variation is

Table 3. Average concentrations in Apollo 16 melt-rock groups for elements determined by INAA, and intragroup relative standard deviations (RSDs).

Concentrations	N	M	Na ₂ O %	CaO %	Sc μg/g	Cr μg/g	Fe %	Co μg/g	Ni μg/g	Rb μg/g	Sr μg/g	Zr μg/g	Cs μg/g	Ba μg/g	
1M	6	17	0.622	10.8	14.6	1520	7.53	63.9	1090	11.4	187	740	0.52	489	
1F most*	11	33	0.536	12.3	14.8	1220	6.49	40.8	590	9.8	178	790	0.42	514	
1F all	15	42	0.530	12.7	14.3	1160	6.24	40.1	570	9.7	179	730	0.43	474	
64815	1	4	0.525	11.9	22.3	1690	7.35	45.9	610	6.4	146	500	0.33	367	
2DB	16	39	0.494	13.0	10.8	1110	6.22	65.8	1070	5.6	185	380	0.22	265	
2NR	6	24	0.486	12.4	12.2	1190	5.98	44.1	650	6.0	166	400	0.22	277	
3, all	6	17	0.488	16.1	7.9	650	3.33	16.9	190	2.2	178	100	0.09	79	
3, 6841x	2	6	0.489	16.2	8.38	659	4.32	13.5	137	2.1	184	113	0.09	86	
3, 635xx	2	6	0.488	16.1	7.57	648	4.25	17.4	195	2.6	175	100	0.08	75	
4 all	20	56	0.533	17.2	5.4	360	2.26	6.9	43	0.9	192	35	0.04	42	
4 i'gran.	5	10	0.581	17.1	6.2	345	2.48	6.2	32	1.0	201	46	0.02	51	
4 μporph.	9	25	0.537	17.0	5.6	385	2.30	8.1	60	1.0	189	36	0.05	42	
		La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	Hf	Ta	Ir	Au	Th	U
		μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	μg/g	ng/g	ng/g	μg/g	μg/g
1M		49.6	129	78	22.5	1.97	4.51	15.4	2.07	17.3	1.93	21.0	24.7	8.1	2.13
1F most*		54.6	142	84	24.8	1.94	4.99	16.8	2.26	18.8	2.00	12.8	12.0	8.8	2.24
1F all		50.3	131	78	22.9	1.86	4.59	15.5	2.09	17.3	1.86	12.7	11.5	8.2	2.09
64815		35.6	92.5	58	17.1	1.69	3.53	12.1	1.64	12.0	1.32	12.3	10.8	5.5	1.42
2DB		27.5	72	43	12.7	1.49	2.54	8.56	1.16	9.3	1.02	26.3	22.9	4.3	1.14
2NR		27.6	72	43	12.7	1.51	2.52	8.86	1.20	9.6	1.11	15.9	13.4	4.4	1.26
3, all		6.99	18.2	11	3.19	1.06	0.65	2.35	0.325	2.42	0.28	8.7	3.1	1.16	0.31
3, 6841x		7.54	19.6	12	3.45	1.13	0.70	2.50	0.343	2.61	0.30	5.4	3.6	1.23	0.34
3, 635xx		6.60	17.1	10	3.06	1.03	0.61	2.26	0.311	2.31	0.28	9.1	2.4	1.12	0.31
4 all		2.37	6.1	3.9	1.12	1.14	0.23	0.91	0.127	0.85	0.12	~2	<1	0.37	0.11
4 i'gran.		3.07	7.9	5.0	1.45	1.24	0.30	1.16	0.162	1.11	0.15	~2	<1	0.47	0.14
4 μporph.		2.47	6.4	3.9	1.17	1.12	0.24	0.95	0.133	0.89	0.13	~2	<1	0.40	0.11
RSDs (%)	N	M	Na ₂ O	CaO	Sc	Cr	Fe	Co	Ni	Rb	Sr	Zr	Cs	Ba	
1M	6	17	6.0	2.8	5.5	4.6	7.1	22	22	9	4.6	12	11	9.2	
1F most*	11	33	8.9	4.6	6.0	6.1	7.6	38	43	17	8.6	8	15	10.5	
1F all	15	42	8.2	6.4	8.7	10.5	9.7	33	38	18	7.3	18	15	17.9	
2DB	16	39	4.1	1.9	3.2	3.5	7.3	25	26	22	4.7	12	17	4.8	
2NR	6	24	2.5	1.8	4.4	3.7	7.7	46	50	10	2.9	6	20	7.3	
3	6	17	1.6	0.3	5.2	4.2	3.7	38	59	27	4.0	9	11	6.7	
4	20	56	15.3	2.9	17.7	21.3	15.1	48	96	55	8.4	47	105	39	
		La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	Hf	Ta	Ir	Au	Th	U
1M		12.0	11.6	12.6	11.6	4.2	11.8	10.8	11.0	11.0	11.4	29	23	11.6	12.0
1F most*		9.2	8.9	7.9	8.8	4.8	8.2	8.6	8.1	9.3	9.8	42	55	10.0	7.7
1F all		17.4	17.3	16.6	17.2	9.3	17.2	16.4	16.1	17.5	16.1	36	49	16.6	14.8
2DB		4.7	4.6	6.3	4.7	1.7	5.2	4.8	4.6	4.8	5.3	26	26	5.5	8.0
2NR		7.3	8.0	7.6	7.8	2.5	7.9	7.1	7.6	7.3	6.4	64	50	9.4	8.6
3		7.1	7.3	7.0	7.2	4.8	7.5	5.4	5.2	6.7	6.7	61	57	5.1	8.2
4		47	47	43	45	14.4	43	43	42	47	52	—	—	63	61

N = Number of samples averaged; M = Total number of subsamples. Mass-weighted mean concentrations were calculated first from all subsamples of each sample (excluding a few highly anomalous subsamples), then simple averages (\bar{x}) and sample standard deviations (s) of all samples in each group were calculated; $RSD = 100s/\bar{x}$. * Excludes feldspathic, vesicular samples 60636 [Q], 63596 [X], 63598 [H], and 68525 [N].

greater in melt rocks of group 1 than in compositionally similar rocks of group 2 (e.g., group-2DB, below; Figs. 3, 4). Most likely, these differences reflect differences in grain size and texture between the two types of melt. Although samples of group 2 are petrographically diverse, they are usually fine grained and seldom poikilitic. In contrast, oikocryst sizes in the group-1 samples (up to 5 mm; MCKINLEY et al., 1984) approach the size of the analyzed subsamples. Nonuniform distribution of mesostasis phases (whitlockite and K-rich glass; e.g., SIMONDS et al., 1973) on the scale of the subsample size causes variation in REE and Ba concentrations (RSDs; Table 3). However, there is practically no difference in intrasample precision between samples of the big-rock and little-rock experiments for ITEs in group 1 despite the factor-of-four difference in subsample mass.

Unlike for the other melt groups, intrasample compositional variation in group 1 is not obviously related to the anorthosite-mixing effect (e.g., 65015 [#]; Fig. 5a). However, intragroup variation exceeds intrasample variation, particularly in group-1F, leading to linear trends on many two-element variation diagrams (Figs. 6–8). Quantitative modal data are scarce, but samples reported as “clast laden” (60636 [Q]) or having “numerous clasts most of which are plagioclase” (63596 [X]) are more typical among the Sc- and

Sm-poor samples (RYDER and NORMAN, 1980). Thus, the trends represent mixing between mafic, ITE-rich melt and more feldspathic, ITE-poor clasts.

Although plagioclase grains are one of the most common clast types in these melt rocks, the mixing relationship implied by the linear trends of Figs. 7 and 8 require a feldspathic component considerably more mafic than pure plagioclase. On Fig. 8 the trends for both groups 1M and 1F lead to Sc concentrations of about 7–8 μg/g when extrapolated to ITE concentrations typical of Apollo 16 anorthosites and noritic anorthosites (e.g., ≤ 3 μg/g Sm). Similarly, among group-1F samples, CaO anticorrelates with Sc (Fig. 7), and extrapolation of the trend to 7–9 μg/g Sc leads to a component with $17 \pm 2\%$ CaO. This composition corresponds to noritic anorthosite (~85% plagioclase, by volume), similar in composition to some lunar meteorites (e.g., Fig. 6 of JOLLIFF et al., 1991b) and only slightly more feldspathic than estimates of the average or typical upper crust of the Moon (TAYLOR, 1975, 1982; KOROTEV et al., 1980). It also corresponds to the composition of the group-3 melt rocks (Tables 4, 5). In fact, for all lithophile elements determined here, the compositions of the four most Sm-poor samples of group-1F can be modeled well as mixtures of noritic anorthosite, represented by the average composition of group-3 melt, and nor-

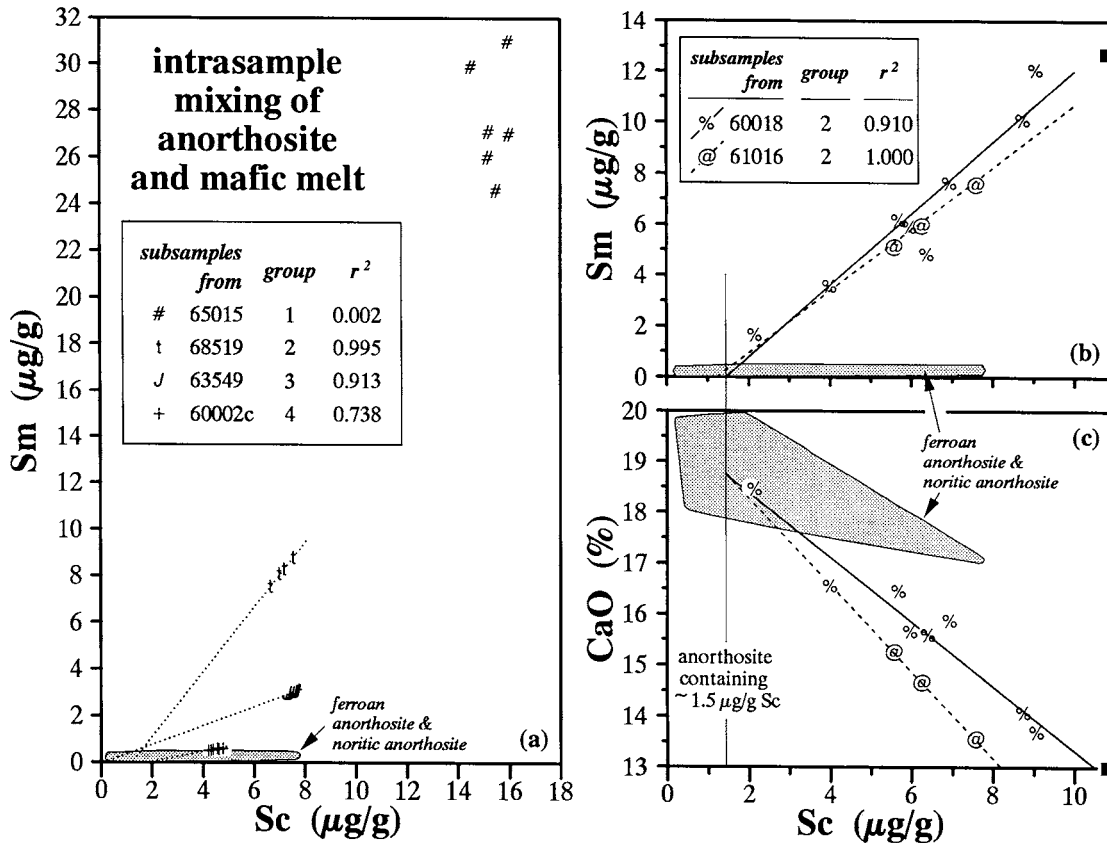


FIG. 5. The major cause of *systematic* intrasample compositional variation in many Apollo 16 melt rocks and breccias of groups 2, 3, and 4 is the mixing effect associated with varying abundance of anorthositic clasts in a melt matrix that is both more mafic (greater Sc) and richer in ITEs (Sm) than the anorthosite. (a) This effect leads to correlation of Sc and Sm concentrations among subsamples. The samples plotted here are not necessarily representative, but are some for which four or more subsamples were analyzed (one sample from each of the main compositional groups). For samples of groups 2, 3, and 4, lines fit to the data usually extrapolate into the field for anorthosite ($<4 \mu\text{g/g Sc}$, Fig. 1); the dotted lines represent simple linear regressions of Sc against Sm. In contrast, the coarse-grained, poikilitic texture of group-1 rocks is the main cause of compositional variation among subsamples, not variation in clast abundance, so no correlation is observed (e.g., 65015[#]). (b) Subsamples of group-2 samples 60018[%] and 61016[@] are particularly variable in composition and plot along mixing lines between group-2 melt similar to that found in dimict breccias (solid square) and anorthosite. Ferroan anorthosite has virtually no Sm, so extrapolation of the mixing lines to $\sim 0 \mu\text{g/g Sm}$ yields the Sc concentration of the anorthosite. For both 60018 and 61016, the anorthosite component has about $1.5 \mu\text{g/g Sc}$, corresponding to about 34% Al_2O_3 (Fig. 1). (c) Calcium is the only element determined here that anticorrelates with Sc as a result of the anorthosite mixing effect because Ca and Al (not determined) are the only elements that have greater concentrations in anorthosite than in the melt rocks. However, relative variation in Ca concentrations is not as great as those of Sc and Sm, and Ca is not determined as precisely, thus the anticorrelation is not evident in most samples. This plot demonstrates that for 60018 and 61016 the correlations on the Sc-Sm plot (b) are not caused, for example, by olivine, which (like anorthosite) has low concentrations of Sc and Sm. For simplicity, in most subsequent plots only the two most Sc-rich of the 60018 subsamples are plotted because only these contain a high proportion of mafic melt.

itic melt having the average composition of the five most Sm-rich group-1F samples. In this model, the anorthositic norite component of the group-1 melt rocks ranges in abundance from 0% (by definition) up to 50% in the most feldspathic sample (63596[X]), suggesting a high clast content in some samples. If the clastic material observed petrographically in group-1 melt rocks is, in fact, predominantly plagioclase mineral grains and not lithic clasts of noritic anorthosite, then some of the mafic-mineral components of the original clasts have been preferentially assimilated by the melt (SIMONDS, 1975).

In addition to nonuniform distribution of clastic anorthosite and ITE-bearing phases, other phases cause compositional heterogeneity in group-1 melt rocks. Three subsamples are anomalous in containing high concentrations of Sr, Eu, and alkali elements (60636[Q], 63558[O], and 63598[H]). The anomalous subsamples apparently contain an unrepresentatively high abundance of sodic plagioclase or alkali feldspar. For 60636 and 63558, the anomalous subsample also has the greatest concentrations of ITEs (Ba, REEs, Th) among the subsamples, suggesting a physical association between the alkali-bearing phase(s) and ITE-rich phases.

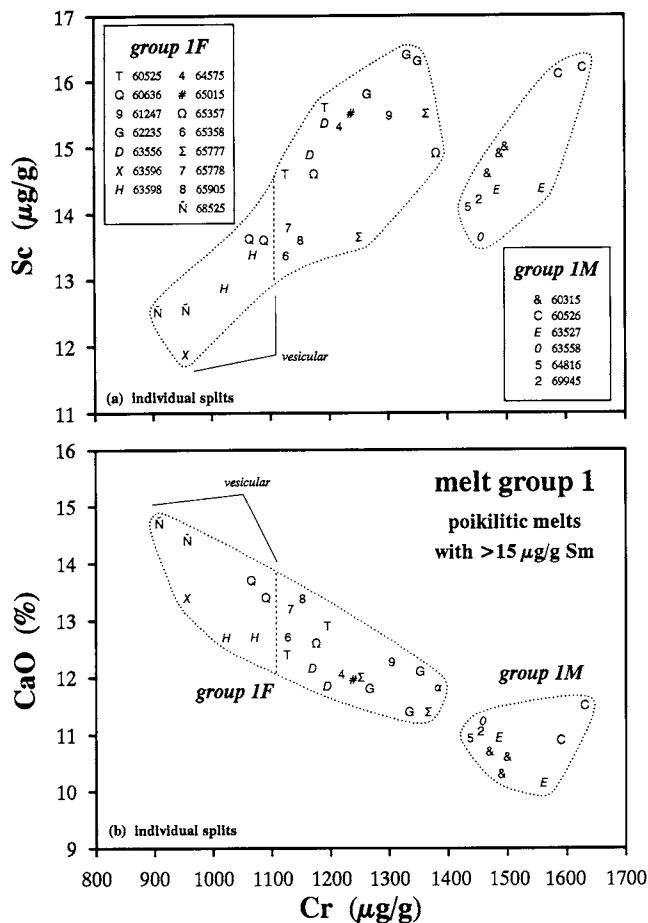


FIG. 6. (a) The group-1 melt rocks can be divided into two subgroups, 1M and 1F, based mainly on Cr (among elements analyzed here) and Mg concentrations. (b) Group-1M also tends to be less feldspathic (lower CaO and Al₂O₃) than group-1F, but on average has higher concentrations of elements associated with alkali feldspars (Na, K, Rb, Cs, Sr, and Eu; Tables 3 and 4). Samples that are highly vesicular or vuggy occur in group 1F and tend to be less mafic (higher CaO, lower Sc and Cr; see also Fig. 8).

Correlation of clast content with vesicularity in group-1 melt rocks

Of the twenty-one group-1 samples studied here, the four most feldspathic samples (60636 [Q], 63596 [X], 63598 [H], and 68525 [N]; Fig. 6) are each described as being vesicular or, in the case of 60636, having “many crystal-lined vugs;” the most feldspathic of these, 63596 [X], is described as being “extremely vesicular” (RYDER and NORMAN, 1980). As inferred in the preceding section, these four samples are also those richest in clasts, suggesting a correlation between vesicularity and clast abundance. Clast-rich melt rocks are believed to cool more quickly during the first seconds of cooling (SIMONDS, 1975), which may lead to trapping of gas that might otherwise escape under conditions of slower cooling.

Samples not included in group 1, but possibly related

Some melt rocks are compositionally distinct from those designated here as group 1, but bear some similarities that

suggest that may be related. These rocks are worthy of consideration because if the group-1 rocks are products of a single impact, then compositionally anomalous samples of that melt may provide information about conditions of melt formation and cooling history.

Samples 61569 [V] and 63597 [F], although poikilitic and having Sc and Cr concentrations at the low end of the range for group 1, are excluded here from group 1, primarily because of their low concentrations of ITEs (Fig. 8). Sample 63597 [F] is the most mafic of the low-ITE samples. Subsamples of 61569 [V] vary considerably in ITE and alkali concentrations (Fig. 8; Table A1) and represent an extreme case of non-

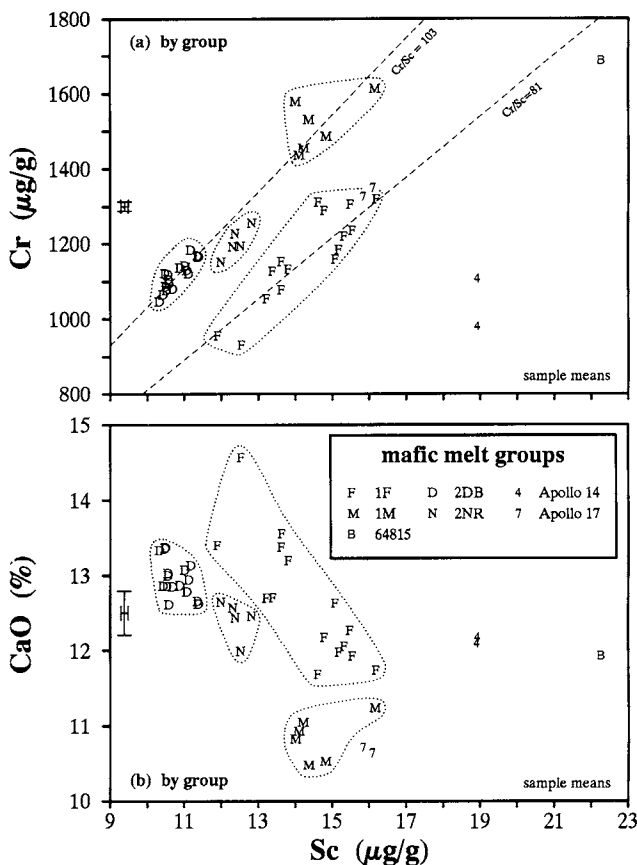


FIG. 7. Concentrations of elements associated with major mineral phases in mafic melt breccias. (a) For any given Apollo 16 mafic melt group (1M, 1F, 2DB, or 2NR), intragroup compositional variation is caused mainly by variation in the proportion of an anorthositic component, which causes correlated variation of Cr and Sc along trends (dashed lines) that pass through the origin. Melt groups 1M and 2DB have similar Cr/Sc ratios (~103), different from that of group 1F (~81). The Cr/Sc ratios reflects mafic mineralogy and increase roughly with Mg/Fe ratio (Fig. 11). The two group-1F points with the lowest Sc concentrations are samples 63596 [X] and 68525 [N]; this figure supports the inclusion of these samples in group 1F, not 2DB, as may be implied from Fig. 4. (b) Concentrations of CaO anticorrelate roughly with Sc in group 1F because of variation in the anorthosite component, but this correlation is not apparent in the other groups because the relative variation for CaO is small and CaO is determined less precisely than Sc and Cr ($\pm 1\sigma$ uncertainty bars shown). For comparison, data for Apollo 14 melt rocks 14078 and 14310 and Apollo 17 melt breccias 76135 and 77035 are also shown.