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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 Al_2O_3 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 $Al_2O_3 \approx 32\%$) accounts for the compositional variation. For groups 1M and 1F, the anorthositic component is more mafic (estimated $Al_2O_3 \approx 26\%$). 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 returned 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 NEIBER-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 required 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

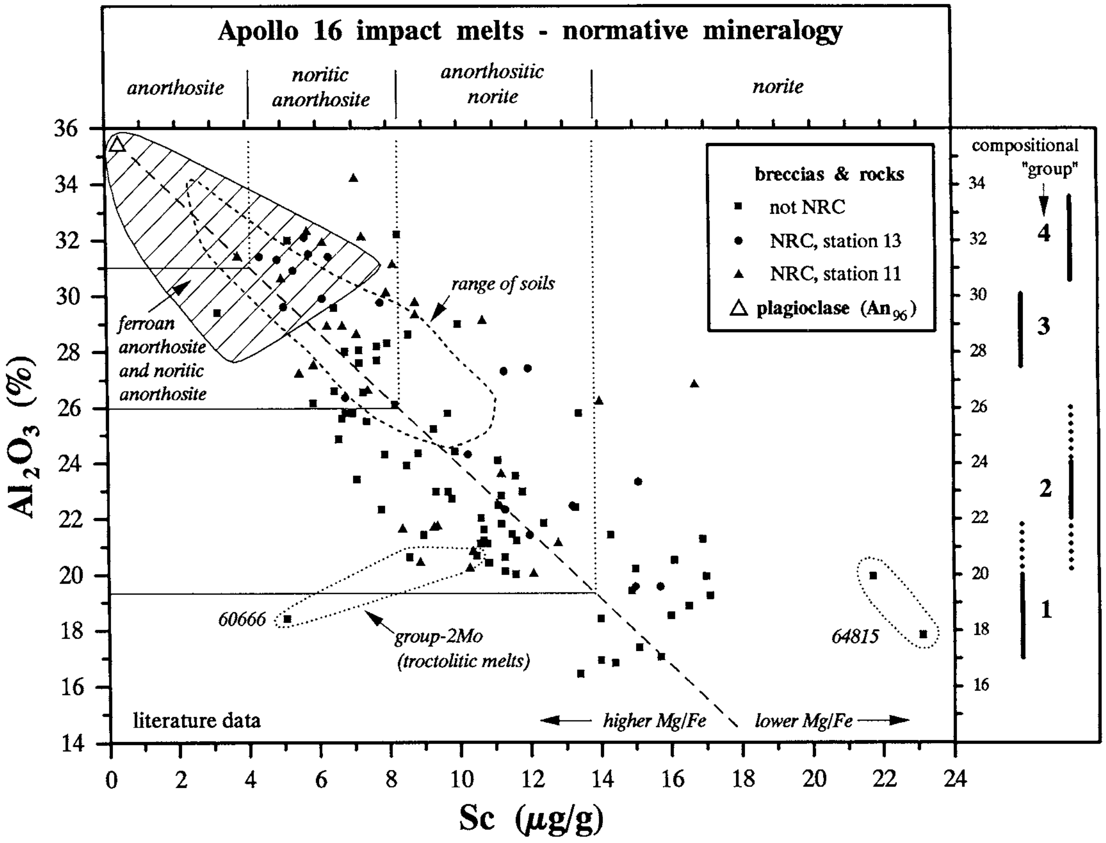

Fig. 1. Anticorrelation of Al_2O_3 and Sc concentrations in Apollo 16 impact-melt rocks. Although the dashed diagonal line is 'eyeballed' and has no special significance, it serves as a rough calibration between the concentrations of Sc, an element determined in this work, and Al_2O_3, which was not. If normative mineral proportions are calculated for the rocks and the mass fractions of minerals converted to volume percent, the compositions can be classified by the scheme at the top of the figure (based on Stöffler et al., 1980). The most mafic melt rocks are noritic, although some contain enough olivine to be considered troctolitic (group 2Mo; see text). The ranges in Al_2O_3 concentration generally associated with the compositional groups, as defined in previous studies, are shown on the right (based largely on Floran et al., 1976, and McKinley et al., 1984, but also other references in Table 2); this scheme is modified somewhat in this work. For a given Al_2O_3 concentration, samples with high Mg/Fe ratios tend to have lower Sc concentrations than those with low Mg/Fe ratios. For example, the five points with group-1 composition that plot on the low-Sc side of the line are for samples 60315 and 60526, which have high Mg/Fe ratios (group 1M), whereas all group-1 samples plotting on the high-Sc side of the line are for low-Mg/Fe samples (group 1F; see Table 4). Sample 60666 has an extremely high Mg/Fe ratio. For comparison, the field for ferroan anorthosites and noritic anorthosites (i.e., samples with >77.5% modal plagioclase) is also shown, as is a point for pure plagioclase such as is found in most Apollo 16 anorthosites (Haskin et al., 1981). NRC = samples from North Ray crater. Sources of melt rock data: Boynton et al. (1975, 1976); Brunfelt et al. (1973); Floran et al. (1976); Fruchter et al. (1974); Haskin et al. (1973); James et al. (1984); Laul et al. (1974), Laul and Schmitt (1973); Lindstrom and Salpas (1981, 1983); Marvin and Lindstrom (1983); Marvin et al. (1987); McKinley et al. (1984); Morrison et al. (1973); Murali et al. (1977); Palme et al. (1978); Ryder and Seymour (1982), Stöffler et al. (1985, combined with Sc data obtained here); Wänke et al. (1973, 1974, 1976); Warren and Wasson (1978); and Wasson et al. (1977). Soil data from Korotev (1981, 1991).

NASA for those splits that were requested specifically for this study (all but a few) included instructions that they be as free as possible of glass coatings and large clasts.

Most of the samples were analyzed as part of one of three experiments. In the "big rock" experiment, two or three splits from different locations on thirty-four large samples (5 g–11.7 kg) were studied. Most of the samples have been well characterized previously, both compositionally and petrographically. Each of the eighty-one splits derives from a different NASA "parent" split number. In each case, the analyzed subsample is the entire quantity of the allocated splits, which ranged in mass from 100 to 170 mg. In the figures, samples from the big-rock experiment are coded by unitalicized upper case letters, including Σ, Θ, Φ, Γ, Ñ, Ω, β, and the symbol & (Table 1). For the "little-rock experiment," thirty-six small rake samples were selected (1.3–12 g). Most of these have not been previously studied and compositional data and petrographic descriptions are unavailable. Samples were received as one split of ~100 mg and each was subdivided into three subsplits of approximately equal mass for analysis. In the figures, samples studied as part of the little-rock experiment are coded by unitalicized numerals (except for 63558[*0*]) and lowercase letters (Table 1). In the "station-13 experiment," thirty melt rocks from station 13 on the ejecta blanket of North Ray crater (Fig. 2) were studied (sample numbers 63xxx). Except for one sample (63558[*0*]), none of the melt rocks included in the other two experiments are from North Ray stations 11 or 13. Two or three subsplits each of one or two splits were studied, i.e., for each of the thirty rocks, 2–6 subsamples ranging in mass from 40 to 80 mg were analyzed. In the figures, samples of the station-13 experiment are coded by *italicized* symbols. In total, I analyzed a total of 315 subsamples of 109 rocks (Table 1).

Data were also obtained for multiple subsamples of melt rocks that do not fit into any of the three main experiments, including

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
							7	63529	222	4	2	3	4	£	65055	173	2	1	X	3
Apollo 16							*Q*	63535	258	4	2	3	2NR?	n	65349	97	3	1	L	2M
%	60018	876	8	4	X	2M/F	*C*	63536	126	2	1	3	2M?	Ω	65357	240	2	2	B	1F
&	60315	451	3	3	B	1M	*Y*	63537	139	2	1	3	3	6	65358	89	3	1	L	1F
¥	60335	165	2	1	X	2M	*/*	63545	252	5	2	3	2M?	o	65365	102	3	1	L	2DB
T	60525	231	2	2	B	1F	*A*	63546	120	2	1	3	4	Z	65757	218	2	2	B	2DB/M
C	60526	233	2	2	B	1M	*L*	63547	156	3	1	3	2NR	p	65758	103	3	1	L	U
ß	60615	242	2	2	B	2M	*S*	63548	151	2	1	3	4	Σ	65777	222	2	2	B	1F
y	60616	107	3	1	L	2M	*J*	63549	246	5	2	3	3	7	65778	92	3	1	L	1F
D	60625	467	3	3	B	2DB	*8*	63555	231	4	2	3	4	Θ	65779	269	2	2	B	2DB
E	60627	238	2	2	B	2Mo	*D*	63556	235	4	2	3	1F	K	65785	260	2	2	B	2NR
U	60635	245	2	2	B	3	*K*	63557	101	2	1	3	4	8	65905	93	3	1	L	1F
Q	60636	346	3	3	B	1F	*0*	63558	101	3	1	L	1M	j	65906	100	3	1	L	2DB
F	60645	228	2	2	B	2F	*9*	63579	221	4	2	3	4	r	65915	97	3	1	L	2M
L	60666	238	2	2	B	2Mo	*G*	63585	355	6	2	3	2NR	W	66095	444	3	3	B	2DB
@	61016	269	2	2	B	2F	*R*	63586	101	2	1	3	4	O	68415	441	3	3	B	3
H	61156	455	3	3	B	2F	*M*	63587	208	4	2	3	2M	X	68416	408	3	3	B	3
v	61225	108	3	1	L	2M	*X*	63596	93	2	1	3	1F	s	68505	102	3	1	L	2DB
9	61247	97	3	1	L	1F	*F*	63597	112	2	1	3	U	t̰	68519	99	4	1	L	2F
Φ	61547	236	2	2	B	2M	*H*	63598	238	4	2	3	1F	Ñ	68525	242	2	2	B	1F
J	61548	239	2	2	B	2F	Y	64476	440	3	3	B	2DB	w	68526	99	3	1	L	4
a	61549	108	3	1	L	2Mo	d	64478	88	3	1	L	2F	l	68825	101	3	1	L	2F
Γ	61568	225	2	2	B	2M	e	64506	98	3	1	L	2M	x	68845	97	3	1	L	4
V	61569	309	2	2	B	U	q	64515	95	3	1	L	2NR	z	68846	93	3	1	L	4
G	62235	465	3	3	B	1F	P	64535	408	3	3	B	2F/M	2	69945	99	3	1	L	1M
b	62245	99	3	1	L	2NR	A	64536	403	3	3	B	2DB							
M	62255	430	3	3	B	2DB	R	64566	241	2	3	B	2DB	**Apollo 17**						
c	62287	96	3	1	L	2F	S	64567	213	2	2	B	2Mo		76135	304	4	2	X	
N	62295	484	3	3	B	2Mo	g	64568	91	3	3	L	2DB		77035	388	3	1	X	
1	63335	218	4	2	3	4	4	64575	95	3	1	L	1F							
U	63355	207	4	2	3	2NR	h	64576	103	3	1	L	2Mo	**Literature**						
W	63505	143	2	1	3	4	m	64578	101	3	1	L	2DB	$	61015	652	1	1	X	2DB
T	63506	121	2	1	3	4	f	64579	103	3	1	L	2F	+	60002c	56	8	1	X	4
N	63508	125	2	1	3	4	k	64585	102	3	1	L	2DB	V	61569	?	1	1	B	U
2	63509	101	2	1	3	4	u	64586	89	3	1	L	2DB	B	64815	?	2	2	B	U
3	63515	112	2	1	3	4	B	64815	237	2	2	B	U	Δ	67513c	252	12	1	X	2NR
4	63525	101	2	1	3	4	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; Wänke *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[ß], 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