Chemical Composition and Origin of Apollo 15 Impact Melts

GRAHAM RYDER
Lunar and Planetary Institute, Houston, Texas

PAUL SPUDIS
U. S. Geological Survey, Flagstaff, Arizona

To better understand the Apennine Front, we have analyzed 14 Apollo 15 impact melt rocks, including hand samples, rake samples, and coarse fines, for major (fused bead microprobe) and trace element (INAA) abundances. The melt rocks show a remarkable diversity of chemical composition, although all but one have typical KREEP incompatible-element patterns. They appear to form five chemical groups, all but the most KREEP-rich of which may represent single impacts. Three groups are of low-K Fra Mauro composition; none correspond to very high alumina (VHA) compositions. The compositions are unlike nearly all other impact melts and regoliths from highland sites, indicating a distinct provenance for the Apollo 15 samples. Serenitatis basin impact melt compositions (Apollo 17 poikilitic boulders) are not duplicated, although one Apollo 17 aphanitic melt sample (73215) is similar to one of the Apollo 15 groups. The Apollo 15 group consisting only of 15445 and 15455 remains the best candidate for Imbrium basin impact melt, while the most KREEP-rich group probably consists of melts produced in varied post-Imbrian impacts into the Apennine Bench Formation (Apollo 15 KREEP basalt flows). The most populated group was previously unrecognized and could be either pre- or post-Imbrian basin; it is possible that it, not 15445/15455, represents Imbrium melt. One unique sample has a non-KREEP incompatible element pattern with low abundances and a positive Eu anomaly. Its target was rather primitive and would not appear to be of regional extent or present in the area in post-Imbrian times; it is either a pre-Imbrian melt or exotic. The Apennine Front does not consist of a monolithic LKFM composition but shows a much wider diversity of compositions than was previously recognized.

INTRODUCTION

A primary objective of the Apollo 15 mission was to sample the material constituting the Apennine Front [Swann et al., 1972; Spudis and Ryder, 1985]. The Front is part of the Montes Apenninus chain, which marks the southeastern topographic rim of the Imbrium basin. Its materials were expected to be a combination of uplifted materials older than Imbrium (especially Serenitatis basin ejecta) and Imbrium basin ejecta. The site is on the main topographic ring of Imbrium and between the intermediate and main topographic rings of Serenitatis (Figure 1); therefore it has a roughly similar radial relationship to each basin. The Imbrium basin is superposed on the Serenitatis basin. Potential differences between Serenitatis and Imbrium ejecta would be significant in understanding the regional variation of materials on the moon at ~3.9 b.y. ago, in turn placing constraints on the earliest evolution of the lunar crust.

Impact melts, including impact melt breccias, are a very important type of sample. Their compositions provide average compositions of part of the target volume, as recognized in terrestrial craters, even when the target is distinctly heterogeneous [Grieve et al., 1977]. Whether complete chemical homogenization is true for lunar basin-produced melts is not known, but is a reasonable assumption. Impact melts are coherent and hence survive subsequent comminution better than friable lithologies. They are comparatively straightforward to analyze because of their homogeneity, and meaningful, representative analyses can be obtained from small chips. Their siderophile signatures provide information about the degree of target contamination or the impactor itself. Their melting resets isotopic systems, hence the events that produced them are potentially datable, although in fine-grained varieties the mineral separations necessary for producing isochrons may not be possible and the vagaries of degassing of clasts may hinder the production of plateaux in 40Ar-39Ar studies.

Because of a general paucity of nonmare materials collected from the Apennine Front, little systematic analysis or synthesis of Apollo 15 impact melt samples has previously been done. To constrain the sources of materials in the Apennine Front, we have made chemical analyses of 14 impact melts for major and trace element abundances to provide information on the variety of compositions present, and to compare these compositions with samples from other landing sites. Because the Front is roughly low-K Fra Mauro basalt (LKFM) in composition, and some melt rocks are LKFM, some melts may actually represent the Front in being impact melt of the same composition. These melts could have been produced by pre-Imbrian impacts, in the Imbrium event, or by impact into the Front. Our study also aims to assess whether melts that are identical to Serenitatis basin impact melts occur among our samples of the Front; such recognition would not only provide evidence for the influence of Serenitatis on the pre-Imbrian terrain sampled at Apollo 15, but would also establish the homogeneity of melts produced in basin-scale impacts.

Our samples comprise individually collected rocks, rake samples, and coarse fines particles, all collected from the Apennine Front (Stations 6A and 7). They include some rocks already analyzed, both to provide a complete and consistent data set and to check on the reproducibility, hence reliability, of the analyses. In Table 1 and the text, the samples are generally referred to by the actual split analyzed; the descriptions, and genealogy for coarse fines, are given in the Appendices. The chemical composition of each sample is that of melt plus clasts, not melt alone; most clasts are too small and intimately mixed with melt for the clean melt to be separated. The samples are all fine-grained with low (<20%) abundances of clasts. The melt rocks are extremely diverse in texture.
Fig. 1. Ring systems of the Imbrium and Serenitatis basins and location of the Apollo 15 landing site (A15). Apollo 15 lies on the Imbrium basin main topographic rim (IBR), whereas it lies inside the Serenitatis basin main topographic rim (SBR), between the Serenitatis basin rim and an inner ring defined by the Haemus Mountains. Apollo 15 is at the same relative radial range to the Serenitatis basin center as the Apollo 17 landing site (A17). Base is the National Geographic Society Lambert equal-area projection of the lunar nearside; north at top.

CRITERIA FOR THE RECOGNITION OF IMPACT MELTS

Clast-free impact melts have igneous textures, but can be distinguished from endogenic melts by their meteoritic siderophile elements, uneven textures produced from heterogeneous nucleation with inhomogeneous distribution of nuclei, or phase relationships incompatible with igneous processes. However, most impact melts contain clastic material (impact melt breccias; Stöffler et al., [1980]). Many have textures once interpreted and named recrystallized, and hence were believed to be of metamorphic origin [e.g., Albee et al., 1973]. Genuinely metamorphic rocks, e.g., granulitic breccias [Stöffler et al., 1980], do occur on the moon, and their distinction from impact melt breccias is petrogenetically significant. We use several criteria to identify samples as clast-bearing impact melts rather than metamorphic breccias:

Euhedral/Skeletal Olivines

Such olivines are similar to those in rapidly cooled igneous rocks, but do not survive even mild recrystallization. Their presence even in minor amounts and as tiny grains (as in 15445 [Ryder and Bower, 1977a]) implies an origin from a melt.

Bladed Ilmenites and Ilmenite Chains

Ilmenite crystallizes from silicate melts in euhedral, bladed forms that are less well developed at slower cooling rates [e.g., Usselman et al., 1975]. In fairly obvious impact melts, such as the clast-poor Apollo 17 poikilitic boulders [Simonds et al., 1975], the bladed ilmenites occur as interoikocryst chains. In clearly metamorphic rocks such as granulites, ilmenite is most commonly anhedral, dominantly as small equant isolated grains. In such rocks, chains are rare. Bladed or tabular ilmenites are taken as an indicator of impact melt, especially when they occur in chains.

Interstitial Glass

Rapid melt crystallization can produce residual glass, whereas metamorphic devitrification will destroy glass. If reheating of a rock were sufficient to cause minor partial melting, and then
TABLE 1. Chemical Analyses of Apollo 15 Impact Melts

<table>
<thead>
<tr>
<th>FB</th>
<th>INAA</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
<th>(7)</th>
<th>(8)</th>
<th>(9)</th>
<th>(10)</th>
<th>(11A)</th>
<th>(11B)</th>
<th>(11C)</th>
<th>(12)</th>
<th>(12A)</th>
<th>(13)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>15405</td>
<td>15414</td>
<td>15436</td>
<td>15304</td>
<td>15314</td>
<td>15434</td>
<td>15357</td>
<td>15514</td>
<td>15359</td>
<td>15356</td>
<td>15308</td>
<td>15308</td>
<td>15445</td>
<td>15445</td>
<td>15414</td>
<td></td>
</tr>
<tr>
<td>%SiO2</td>
<td>50.7</td>
<td>49.6</td>
<td>49.2</td>
<td>48.0</td>
<td>48.5</td>
<td>49.0</td>
<td>48.5</td>
<td>47.1</td>
<td>47.5</td>
<td>45.7</td>
<td>46.3</td>
<td>46.0</td>
<td>43.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiO2</td>
<td>1.79</td>
<td>1.47</td>
<td>1.44</td>
<td>1.37</td>
<td>1.24</td>
<td>1.19</td>
<td>1.31</td>
<td>1.08</td>
<td>1.03</td>
<td>0.96</td>
<td>1.80</td>
<td>1.56</td>
<td>2.38</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al2O3</td>
<td>16.1</td>
<td>18.3</td>
<td>16.7</td>
<td>17.3</td>
<td>15.7</td>
<td>15.2</td>
<td>16.1</td>
<td>17.9</td>
<td>18.0</td>
<td>20.5</td>
<td>19.0</td>
<td>17.3</td>
<td>22.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FeO</td>
<td>11.1</td>
<td>8.9</td>
<td>9.3</td>
<td>8.6</td>
<td>7.6</td>
<td>9.9</td>
<td>8.6</td>
<td>8.6</td>
<td>8.1</td>
<td>7.3</td>
<td>8.5</td>
<td>9.2</td>
<td>8.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>11.5</td>
<td>9.7</td>
<td>8.3</td>
<td>11.5</td>
<td>11.0</td>
<td>8.3</td>
<td>11.3</td>
<td>9.7</td>
<td>8.0</td>
<td>7.5</td>
<td>7.5</td>
<td>10.4</td>
<td>10.3</td>
<td>7.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>10.4</td>
<td>11.5</td>
<td>10.7</td>
<td>10.5</td>
<td>10.1</td>
<td>9.7</td>
<td>10.2</td>
<td>11.1</td>
<td>10.8</td>
<td>12.0</td>
<td>11.3</td>
<td>10.2</td>
<td>13.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na2O</td>
<td>0.836</td>
<td>0.820</td>
<td>0.775</td>
<td>0.521</td>
<td>0.421</td>
<td>-</td>
<td>0.583</td>
<td>0.500</td>
<td>0.594</td>
<td>0.561</td>
<td>0.651</td>
<td>-</td>
<td>0.484</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K2O</td>
<td>0.877</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>MnO</td>
<td>0.183</td>
<td>0.141</td>
<td>0.149</td>
<td>0.143</td>
<td>0.129</td>
<td>-</td>
<td>0.153</td>
<td>0.133</td>
<td>0.134</td>
<td>0.093</td>
<td>0.129</td>
<td>-</td>
<td>0.101</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P2O5</td>
<td>0.654</td>
<td>0.576</td>
<td>0.890</td>
<td>0.367</td>
<td>-</td>
<td>-</td>
<td>0.340</td>
<td>0.441</td>
<td>0.185</td>
<td>0.475</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mg' = atomic Mg/(Mg + Fe); FB = microprobe fused bead analysis; INAA = instrumental neutron activation analysis.

*INAA analysis normalized to Sc = 18.2, because of mass loss (see text).

†Mass of sample used in INAA in milligrams.

subsequent cooling were rapid enough, an interstitial glass might be produced. However, other igneous textures, such as skeletal olivines, would be destroyed in such a process, and such a glass would differ chemically from a residual glass: A residual glass being a fractional crystallization product would have very low magnesium, whereas a partial-melt glass being more of an equilibrium product would have moderate magnesium. To eliminate this unlikely possibility of a partial melt origin of a glass requires microprobe analysis, as was done on Apollo 14 melts by Ryder and Bower [1976a]. In general, interstitial glass can be accepted as an indicator of an impact melt origin.

Rounded Clasts

During their assimilation into a superheated melt, clasts commonly acquire smoothly curved outlines. For instance, such rounded fragments are produced in the process of making fused beads from powders using the method of Brown et al. [1977] when melting is not properly completed. (Many clasts, either refractory or added late in the cratering process when the melt has lost much of its superheat, retain angular shapes). In contrast, recrystallization produces clast shapes tending toward polygonal.

Mineral Composition Variation

Recrystallization tends to eliminate zoning within mineral grains and compositional differences among grains. This is fastest for olivines; in the lunar case, it may be barely effective for plagioclases. Many granulitic breccias have very narrow ranges of mineral compositions, particularly for mafic grains. In impact melts, cooling tends to be too fast to eliminate all zoning of clasts, even within olivines, hence a range of compositions exists. Crystallization also produces zoned crystals. In recrystallized rocks, any compositional range tends to diverge in both directions away from the smaller (more easily equilibrated) matrix grains, whereas in impact melt breccias nearly all of the clasts are more refractory than the smaller groundmass crystals; most of the less refractory clasts are totally assimilated into the melt or show partially melted textures. Microprobe data are essential for the use of this criterion.
Vesicles

Crystallizing melts, including mare basalts, commonly retain vesicles ranging from spherical to slit-like. It is unlikely that vesicles could actually form during metamorphism of (volatile-poor) breccias, indeed they are more likely to be destroyed during recrystallization. Thus the presence of vesicles in a sample is an indicator of an impact melt which has been metamorphosed little, if at all.

Plagioclase Laths

Plagioclase most commonly crystallizes from nonplutonic melts as lath-shaped crystals. Plagioclase clasts in breccias, however, are derived from a variety of sources and have been subjected to comminution, and most are therefore blocky or equant. Metamorphism will tend to make them more anhedral. A rock in which groundmass plagioclase is dominantly lath-shaped (although clasts are not) is probably of impact melt origin. However, moderate metamorphism of a (dry) lunar impact melt without comminution may not change the texture appreciably, but could have some effect on the chemistry, especially devolatilization.

The criteria outlined in the above sections cannot always distinguish impact melt breccias from recrystallized rocks; some recrystallized rocks may indeed have originally been impact melts. Some criteria may be in conflict, e.g., residual glass with equant ilmenites. Nonetheless, their combined use can generally represent the Front composition, then their similarity to the Apollo 17 poikilitic melts (interpreted to be Serenitatis basin melt) but different from the melt of 15445 and 15455 that had previously been concluded to be Imbrium impact basalt 

Previous work on the Apennine Front and Apollo 15 impact melts

Several early studies led to the inference that the Apennine Front consists of materials of low-K Fra Mauro basalt (LKFM) composition, i.e., essentially basaltic, with 17-18% Al_2O_3 and 0.2-0.4% K_2O. Regolith glass compositions include a compositionally diffuse LKFM cluster that increases in modal abundance toward the Front [Reid et al., 1972; Carr and Meyer, 1974]; and chemical mixing models are also consistent with increasing LKFM abundance toward the Front [e.g., Duncan et al., 1975; Walker and Papike, 1981]. Orbital geochemical data indicate that LKFM compositions are widespread in at least the northern Apennines [Clark and Hawke, 1981; Spudis, 1986]. Finally, a few impact melt breccia samples are of LKFM composition, for instance, the melt of the "black and white" rocks 15445 and 15455 [Reid et al., 1977].

Spudis [1980] postulated that the LKFM glass composition was derived from exposure of Serenitatis ejecta within Hadley Delta, as these glasses appear from Fe and Mg data to be similar in chemistry to the Apollo 17 poikilitic melts (interpreted to be Serenitatis basin melt) but different from the melt of 15445 and 15455 that had previously been concluded to be Imbrium basin melt [Ryder and Bower, 1977a]. If the LKFM glasses represent the Front composition, then their similarity to the Apollo 17 poikilitic melts indicates either that the Front is dominated by Serenitatis ejecta or that Imbrium ejecta and Serenitatis melt have very similar compositions. The Front regoliths are complicated and contain mare basalts, KREEP basalts, and pyroclastic green glasses. Spudis [1980] constructed a possible cross section (Figure 2) in which Imbrium melt and ejecta constitute a minor fraction of Front deposits. Inspection of impact melt samples offers one avenue for furthering our understanding of the Apennine Front.

In early regolith population studies [e.g., Cameron et al., 1973; Powell et al., 1973; Phinney et al., 1972], impact melts were not identified and were apparently subsumed in varied "recrystallized microbreccia" categories. Even the larger samples such as 15455 were interpreted as recrystallized [Christie et al., 1973]. Thus any work done on Apollo 15 impact melts prior to the greater appreciation of the impact melting process from the Apollo 16 [Simonds et al., 1973] and Apollo 17 [Simonds et al., 1974] poikilitic melt rocks was done without recognition of their melt origins. Simonds et al. [1975], in a reinspection of Apollo 15 highlands rocks, identified impact melt breccias as the most abundant category; their list roughly corresponds with the 14 samples analyzed in the present study. For individually numbered rock samples, all available data is summarized in the Catalog of Apollo 15 Rocks [Ryder, 1985].

15405, chipped from the boulder at Station 6A, was identified as a fine-grained impact melt by Simonds et al. [1975] and Ryder [1976]. It has a limited clast population of Apollo 15 KREEP basalts and "quartzmonzodiorites," and a melt composition rather like Apollo 15 KREEP basalts [Christian et al., 1976; Lindstrom, 1986; Blanchard, unpublished data, 1977]. The analysis of supposed 15405 sawdust by Laul and Schmitz [1973] is so different and incompatible with petrography that it would appear to be unreliable. 40Ar-39Ar data indicate a melt age of a little over 1 b.y. [Bernatowicz et al., 1978]. Peculiarly, a U-Pb age (ion microprobe) for a zircon in a quartzmonzodiorite clast is 4.365 ± 0.030 b.y. [Compston et al., 1984], substantially predating both the Imbrium basin and Apollo 15 KREEP basalts. Coarse-fine particle 15404,18, analyzed by Helmke et al. [1973], is petrographically similar to 15405 but a little glassier; it is a little more enriched in rare-earths. Only 25 mg were analyzed, so the difference might not be significant. 15404,18 might be a fragment of the 15405 boulder, as it was collected at its base from fines that composed the boulder "fillet" [Swann et al., 1972].

15445 and 15455, the "black-and-white" rocks from Spur Crater, were recognized as impact melts by Simonds et al. [1975] and Ryder and Bower [1977a]. The latter believed them to be samples of the same melt unit according to their petrographic and chemical similarities, including siderophile trace element ratios [Ganapathy et al., 1973; Gros et al., 1976], Lindstrom [1986] analyzed three splits of each sample and found them to be very similar to each other. Ryder and Bower [1977a] interpreted the parent melt unit to be the melt produced by the Imbrium impact itself because of the deep-seated, pristine igneous nature of the clasts within the melt and the lack of any surficial debris (e.g., regolith breccias) among clasts. The bulk composition is a magnesian LKFM composition, unlike 15405. 40Ar-39Ar ages of ~3.9 b.y. were obtained for 15445 by Alexander and Kahl [1974] and Bogard (unpublished data, 1980), although good plateaux were not obtained. Bernstein [1983] reported 40Ar-39Ar laser stepwise-release results, again finding no plateaux, giving "ages" of 3.76 ± 0.09 b.y. for 15445 and an imprecise 3.90 ± 0.25 b.y. for 15455. All of these ages are consistent with an Imbrium origin but do not prove it.

15308 was unrepresentatively chipped and was described in earlier work [Dowty et al., 1973; Simonds et al., 1975] as an anorthositic norite. Most of the sample is melt and the anorthositic norite is a clast. Murali et al. [1977] analyzed bulk rock, finding an LKFM composition for 15308 less magnesian and richer in rare-earths than 15445/15455. 15357 was analyzed...
GEOLOGIC CROSS SECTION OF THE APOLLO 15 LANDING SITE

Fig. 2. Schematic cross-section of the geology of the Apollo 15 landing site [after Spudis, 1980]. North to left, south to right.

by Helme and Haskin [1972], who did not publish the data but stated that rare-earths were about 80X chondritic abundances (i.e., roughly LKFM composition). 15359 was analyzed by Murari et al. [1977], demonstrating an LKFM composition not unlike 15308, except for a lower TiO₂ abundance and higher rare-earths. Among the coarse-fines particles of impact melt (other than 15404,18) only 15314,30 has any chemical data; its trace elements are reported by Hubbard and Wiesmann [1975]. They also report a bulk ²⁷Sr/⁸⁶Sr of 0.71024. Rock samples 15356 and 15436 have not been analyzed previously.

The available chemical data is inadequate to really assess the nature of impact melts in or on the Apennine Front, or the events that produced them. It is obvious that 15405 is from an event later than and totally separate from Imbrium or the Apennine Front, and it seems likely that 15445/15455 are a little different from the few other poikilitic melts and hence might be a product of the Serenitatis basin event.

METHODS OF CHEMICAL ANALYSIS

Following petrographic identification of samples as fine-grained impact melt breccias, small chips (51 to 114 mg, most about 100 mg) were obtained. They were chosen to avoid any obvious clasts as much as possible. The chips were ground to a fine powder using an agate mortar and pestle on a flow bench in a clean room. In one case (15308), an effort was made to separate apparent clast material. Five to 10 mg of powder was taken from most samples for making a fused bead; the remaining powder was used for instrumental neutron activation analysis (INAA).

INAA was conducted using the standard procedures, detectors, and data storage and reduction system of the Johnson Space Center [Jacobs et al., 1977]. Samples and standards were sealed in silica tubes and irradiated at the University of Missouri Research Reactor. The flux was 8 × 10¹³ cm⁻² sec⁻¹ for 8 hours. The irradiated materials were counted in the normal 3 sets. The main standard was basalt BCR, with BHVO run as a check, and some Cr and Ni data were obtained with SARM as the standard. The results are listed in Table 1. The general consistency with previous trace element analyses for the melts demonstrates both that the analyses are good and that the sample sizes of 50 to 100 mg are large enough to be representative for rocks of this fine-grain size.

For sample 15455,257, there was about 50% sample loss during irradiation. Assuming no contamination, the raw results provide ratios among but not absolute amounts of elements. In Table 1, the data for 15455,257 have been normalized to the precisely measured element Sc, assumed to be the same as in 15445,243. Thus these are not real measurements but are adequate for the purposes of this paper. Lindstrom [1986] analyzed three samples of each of 15445 and 15455 melt and found them to be identical, hence our INAA "data" for 15455 are not essential.

Fused beads were made using the methods of Brown [1977], heating the powder on a Mo strip in an argon atmosphere. Not all fusing produced completely molten products, but all beads were used. The beads were made into polished grain mounts and analyzed on the JSC Cameca microprobe, using an accelerating voltage of 15 KV and a beam current of 30 nA. The standard for most elements was kaersutite. Ten to 20 spots were taken on glass in each bead. A few glasses were not entirely homogeneous, but most were, including those containing 20% to 25% unmelted relics. The results are listed with the INAA data in Table 1.

A fused bead was made of standard rock BCR and analysed...
with the impact melt breccias. The analysis, slightly adjusted for the Na$_2$O loss during fusion, is listed in Table 2 with that of the BCR recommended abundances of Flanagan [1973]. The comparison shows that the fused bead method generally gives very good results. SiO$_2$, however, appears to be substantially too low and Al$_2$O$_3$ slightly too high in the fused bead analysis. However, for the lunar samples the totals are all close to 100% and comparison with previous analyses of some of the same rocks does not indicate any inconsistency of their SiO$_2$ abundances. Although Na$_2$O was lost during fusion of BCR (analysis 1.13% cf. 3.27% in Flanagan [1973]) the fusion of the lunar samples did not result in sodium loss, as can be seen from Table 1. This is probably a result of both the low initial sodium and the low time or temperature of melting that resulted in incomplete fusion.

Even for those samples that did not completely fuse, the glass appears to be a whole-rock melt, not a partial melt. For example, glass from 15405,112 appears to have 20–25% relics but its analysis (Table 1) matches very well a previous analysis by Christian et al. [1976] for all elements. There are some discrepancies between the INAA data and the fused bead for FeO that may be a sampling effect of taking small samples for fused beads. For instance, 15445 has higher FeO in the INAA and has low MgO compared with previous analyses and its “twin” 15455 [Ryder and Bower, 1977a]. The indication is that fused bead analyses are subject to small errors in the plagioclase/mafic ratio; the INAA sample is the more representative.

Sample 15308 was subdivided in an attempt to separate apparent clast material, providing three splits: A—apparent clast; B—clast plus melt not easily separable; C—melt only. The INAA results (Table 1) suggest that the apparent clast material was not significantly different from the melt, perhaps merely a more fractured area. Only the fraction C had enough mass for a portion to be taken for a fused bead. For small sample 15304,66 no portion was taken for a fused bead.

### Chemical Composition and Origins of Apollo 15 Impact Melts

The results for both INAA and fused bead analyses are shown in Table 1, roughly in order of decreasing abundances of incompatible elements. Figure 3 is a plot of rare earths and other incompatible elements normalized to chondritic abundances, and Figure 4 plots relationships among the three refractory and petrogenetically significant elements Ti, Sm, and Sc.

### Diversity of Composition

All the samples but one have 15% to 20% Al$_2$O$_3$ (most 16% to 18%) and the rare-earth and other incompatible element ratios of KREEP; they fall into the general categories of low-K and medium-K Fra Mauro basalt (LKFM and MKFM). Materials similar in both major and trace element composition to the Apollo 16 VHA melts or even higher alumina materials are absent. The samples are consistent with a general LKFM composition for the Front, but it is clear that no monolithic LKFM composition is represented by the samples; instead there is a remarkable diversity of compositions. Lindstrom [1986], in analyses of Apennine Front materials, has also found a diversity of compositions; however, apart from 15405, 15445, and 15455, it is not clear at present which of her samples might be impact melts.

The diversity observed has considerable implications for mixing models of Apollo 15 regoliths in which LKFM is an important component, and a choice has to be made on what is the average or dominant composition for the Apennines. Models can be inverted, and with exact knowledge of all other components, mixing models could indicate which of the analyzed samples, if any, is dominant in the Apennines. The impact melt compositions are unlike the regoliths from the lower slopes of the Apennines (Stations 2 and 6 soils) that have green glass and mare basalts mixed in with the Apennine Front materials.

#### Grouping of Compositions

The compositions of Apollo 15 impact melts appear to fall into five distinct groups, which we have labelled A to E (Table 1; Figure 4). The range of compositions does not consist of one melt composition diluted by a single clast phase, as is demonstrated by the nonlinearity of the compositions on Figure 4, on which mixing lines are straight lines. Impacts produce rather homogeneous melt compositions, and for comparison Figure 4 includes the fields for analyses of melt from the terrestrial Manicouagan crater [Floran et al., 1978], all produced in a single event, and the Apollo 17 poikilitic melt rocks, also commonly interpreted as from a single event, the Serenitatis basin impact [e.g., Spudis and Ryder, 1981].

The clusterings of the Apollo 15 impact melt compositions are tight enough to suggest that groups B and C might represent separate, single events; Group D (15445 and 15455) a third event; and the single Group E sample a fourth event (Figure 4). Group A, despite the similarity of incompatible elements, shows too much variation in TiO$_2$, Sc, K$_2$O, and FeO to be considered the product of a single impact. If 15404,18 is considered as well, the range of compositions is even greater. One sample of Group B (15434,13) has distinctly lower K$_2$O, Rb, and Cs abundances than the others; the ratios of these elements to the refractories (Figure 3) suggest that a volatile loss, perhaps during impact melting itself, has affected the chemical composition of the sample. In addition to our five samples of Group B melt, four Apollo 15 2–4 mm regolith particles analyzed by Drake et al. [1973] have descriptions and a corresponding photograph for one of them that suggests that they too are fine-grained impact melts, despite their description merely as "KREEP-rich noritic breccias." The INAA analyses for these samples show them to be very similar to the Group B samples analyzed in the present study. Thus Group B consists of nine samples. The chemical groups do not correspond with texture in any way; it is possible that more microprobe data on clasts might show some correspondences with groups.

### TABLE 2. Comparison of BCR Major Element Analyses

<table>
<thead>
<tr>
<th>Element</th>
<th>Fused Bead</th>
<th>Flanagan [1973]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>52.3</td>
<td>54.5</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>2.19</td>
<td>2.20</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>14.0</td>
<td>13.6</td>
</tr>
<tr>
<td>FeO*</td>
<td>12.0</td>
<td>12.1</td>
</tr>
<tr>
<td>MgO</td>
<td>3.6</td>
<td>3.5</td>
</tr>
<tr>
<td>CaO</td>
<td>7.1</td>
<td>6.9</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>3.27$^\dagger$</td>
<td>3.27</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>1.73</td>
<td>1.70</td>
</tr>
<tr>
<td>Cr$_2$O$_3$</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>MnO</td>
<td>0.17</td>
<td>0.18</td>
</tr>
<tr>
<td>Sum</td>
<td>96.4</td>
<td>98.0</td>
</tr>
</tbody>
</table>

$^*$Total Fe as FeO.

$^\dagger$Normalized to Flanagan [1973] value.
Fig. 3. Incompatible elements plus Sc and Ti in Apollo 15 impact melt samples (data from Table 1), normalized to CI-meteorites × 1.5 [Taylor, 1982; Taylor and McLennan, 1985]. Apollo 14 KREEP from Warren and Wasson [1979] shown for comparison and multiplied by 2 for clarity. Samples (1) 15405,112, (2) 15414,34, (3) 15436,6, (4) 15404,66 (5) 15414,144, (6) 15434,13, (7) 15357,14, (8) 15314,146 (9) 15359,10 (10) 15359,10 (10) 15356,7 (11) 15308,8-C, (12) 15445,243, (12A) 15455,257 (normalized to Sc = 18.2, see text), (13) 15414,35. Numbers correspond with Table I column heads.

Figure 4 also plots LKFM materials from elsewhere on the moon for comparison. The Apollo 15 samples are distinct from LKFM from other landing sites (see below also), including most Apollo 16 poikilitic rocks and Apollo 14 soil and KREEP, indicating that Apollo 15 samples have a separate provenance. If typical Imbrium impact melts are represented among these Apollo 15 samples, as is likely, then the Apollo 14 and 16 samples are not similar to Imbrium melts at this range from the basin center; they may be more compatible with local provenances.

Origins of Groups of Impact Melts

Imbrium was the last major basin affecting the Apollo 15 landing site, and created the Apennine Front. Samples can be considered in reference to this event: The Front may consist of pre-Imbrian materials deposited as Imbrium ejecta or exposed within the Front due to structural uplift. Some of the ejecta may consist of Imbrium melt itself, deposited virtually simultaneously with the formation of the Front (actually just slightly preceding it if the rings are formed, as generally believed, by immediate postimpact modification). Some of the melts may be post-Imbrium, formed in smaller, local events, making them a superficial, rather than integral, component of the Front (Figure 2).

With but one exception (15414,35), all of our analyzed impact melts are KREEP-rich, the majority being of LKFM composition. Although the ultimate origin of LKFM is still unresolved, it appears that the most well-studied LKFM melt rocks are of basin origin (e.g., the Apollo 17 poikilitic melts; Simonds et al. [1974]). Spudis [1984] proposed that LKFM is produced mostly by basin-forming impacts; part of the reason for this postulation was the observation from orbital geochemical data that, in general, the lunar highlands surface is both too aluminous and too KREEP-poor to produce LKFM melts during the formation of small (10–100 km diameter) impact craters. We do not exclude the possibility that some LKFM melts are produced by craters rather than basins [Spudis and Ryder, 1981], but at places around the moon where the origin of LKFM melt rocks is perceived as being well understood, a basin origin for these rocks is usually invoked. For this reason, in the following discussion we place emphasis on identifying possible basin sources for the Apollo 15 impact melts.

Group D, 15445 and 15455, remains the best candidate for representatives of the Imbrium basin impact melt sheet [Ryder and Bower, 1977a], despite the fact that only these 2 out of the 14 samples analyzed in this study belong to it. Group D samples contain deep-seated, plutonic clasts that might be
expected from a melt of basin-scale origin; they are at least close to Imbrium in age and have Mg-rich, LKFM matrix compositions, which are also expected from a large, basin-sized impact origin. Moreover, 15445 was sampled under the impression that it was a chip from the meter-sized boulder nearby [Swann et al., 1972; D. R. Scott, personal communication, 1985], and if that is its source then it represents a substantial sample. Groups E and A are not like LKFM compositions, the composition that might be expected of Imbrium melt if the Apennine Front soils represent average Imbrium ejecta. The proportion of actual Imbrium melt in the Apennine Front is expected to be low, as most material is excavated as fragmental,
not molten, debris, and most of the melt is expected to stay within the transient cavity rather than form a part of the basin rim [Grieve et al., 1981; Spudis, 1986]. Thus the low abundance of Group D materials at the Apennine Front is not incompatible with an Imbrium basin melt origin.

Groups B and C are LKFM and cannot be discarded as Imbrium melt candidates, although at present we have no evidence that they are of an appropriate age or contain a suitable clast population. Their Ti-Sc-Sm relationships (Figure 4) suggest little contamination by Apollo 15 KREEP basalt or mare basalt, hence they are of highlands derivation and may be pre-Imbrian and part of the Imbrium ejecta deposit or exposed within the Front as uplifted, pre-Imbrian deposits (Figure 2). One objective of the present study was to see if Serenitatis melt could be identified among Apollo 15 samples; 15359, a Group C member, was postulated to be such by Spudis [1980]. However, it appears that Group C is consistently lower in TiO₂ than the Apollo 17 poikilitic melts, though similar in all other elements. Thus either Group C is not from the same melt event or basin-scale impacts produce a less uniform composition than do Manicouagan-sized impacts. The nonpoikilitic Apollo 17 aphanitic melts (including boulder 1, Station 2; 73215 and 73255) form a very disperse field (Figure 4) and were suggested by Spudis and Ryder [1981] to be of local origin or from some basin other than Serenitatis. They are unlike Groups B or C, with the exception that the chemistry of one sample (73215; Blanchard et al. [1976]) is very similar to Group C samples. It is possible that an alternative of Spudis and Ryder [1981], that basin-scale impacts produce more varied compositions among aphanitic melt blobs than is generally recognized at terrestrial melt sheets, is the case. Such varied compositional characteristics would include siderophile element ratios. However, with only one Apollo 17 sample having a chemical identity with samples at the Apollo 15 site, any interpretation vis-a-vis Serenitatis is conjectural. Further data, particularly siderophile elements (especially Ir/Au) ratios and crystallization ages, could make relationships among these Group C samples and 73215 much clearer. Group B, which is well-populated and may well represent a single event, is more KREEP-rich than the other LKFM groups, and is rather like Apollo 16 poikilitic LKFM samples except for its consistently higher Sc/Sm. It could well represent a pre-Imbrian basin event melt (e.g., Insularum basin, see Spudis and Ryder [1985]); it is unlike any known Serenitatis basin material. The Group B melt could have formed from post-Imbrian impacts into the Apennine Front and Apennine Bench, mixing in Apollo 15 KREEP basalt with Imbrian basin LKFM material. This might best explain their occurrence at the LM site (some Drake et al. [1973] samples). In this case, their ages should be less than 3.9 b.y. and the Apennine Front average composition would be less magesian than the Group D melts. However, no simple mixing relationships among known samples appear capable of producing the Group B melt, even if a mare basalt component were included to produce the low Ti/Sc ratio. Ages for these Group B melts would greatly constrain their petrogenesis.

Group A melts do not form a coherent group and have a high KREEP content. At least 15405 is much younger than the Imbrian basin (~1.3 b.y.; Bernatowicz et al. [1978]). Group A samples are most readily interpreted as produced from small, local impacts into the Apennine Bench Formation, which probably consists of Apollo 15 KREEP basalt flows [see Spudis and Hawke, 1986]. Some portions of the Apennine Bench region have even higher Th than the extant KREEP basalt samples (e.g., rim of Archimedes; Th = 18 ppm; Metzger et al. [1979]), compatible with a Group A compositions and the presence of "quartz-monzodiorite" fragments in 15405.

The single sample 15414.35 forming Group E is completely anomalous and unrelated to KREEP, as shown not only by the rare-earth pattern but the near chondritic Ti/Si and Sc/Si ratios (Figures 3, 4). The target included cumulus plagioclase, as shown by the positive Eu anomaly, even though the Al₂O₃ content is only 22%. Furthermore, the Th/U ratio, despite the errors associated with these measurements, appears to be much lower than the ~3.8 commonly found in lunar and meteoritic samples, including KREEP. Silver [1976] showed that plagioclase and pyroxene have lower Th/U ratios than the liquids from which they crystallized. This suggests that the target contained little trapped liquid with KREEP, Mg-suite, or mare characteristics. The characteristics, including the low Mg', are consistent with a target of cumulate plagioclase and pyroxene that was produced during the ferroan-anorthosite-producing, magma-ocean epoch. Because targets of this composition do not currently exist in the Apollo 15 region [Davis and Spudis, 1985], we suggest that this sample is either of pre-Imbrian age or was thrown to the Apollo 15 site as an exotic rock. An age for 15414.35 would be helpful in evaluating how long such pristine targets were in existence on the moon.

SUMMARY AND CONCLUSIONS

Fourteen identified impact melts, including hand samples, rake samples, and coarse fines, from the Apennine Front, Apollo 15 landing site, show a wide range in trace element abundances; all but one have a typical KREEP incompatible-element pattern. All but the same exception have low-K Fra Mauro basaltic (LKFM) or medium-K Fra Mauro basaltic (MKFM) compositions. The melt chemistries appear to form five groups (labelled A to E, in order of decreasing incompatible elements); all except Group A may represent single impact events. The most KREEP-rich Group A, which is diverse enough to suggest multiple impacts, includes 15405, a sample dated as about 1.3 b.y. old; the group probably represents small post-Imbrian impacts into the local Apennine Bench Formation. Group D, consisting of only the two larger hand samples 15445 and 15455 (~3.9 b.y.), is still the best candidate for Imbrium basin impact melt [Ryder and Bower, 1977a]. The other three undated groups may well all be pre-Imbrian materials forming an integral part of the Apennine Front, but none are similar to the Apollo 17 poikilitic melt samples, commonly believed to represent the Serenitatis basin impact melt sheet [e.g., Simonds et al., 1974]. One of the diverse aphanitic melts of the Apollo 17 site, 73215, is similar to Group C, but conclusions as to the presence of Serenitatis melt at the Apollo 15 landing site or the variation of composition of impact melt produced in a basin event remain conjectural with the present data. Group B, the most populous group, with five samples in the present study and probably four from previous work [Drake et al., 1973], is probably pre-Imbrian but could postdate the Imbrium basin. Group E has a non-KREEP incompatible element pattern and is most compatible with impact melting of a primitive, cumulate target of a type that no longer exists in this region of the moon, at least in large (100 km²) areas. It is probably pre-Imbrian or completely exotic to the Apollo 15 site.

The Apollo 15 impact melts have diverse composition, but also are distinct from most other lunar melt samples. Apollo 16-type VHA impact melts are not represented, nor are any
other Apollo 14, 16, or 17 LKFM compositions (rocks or soils) represented, with one aphanitic Apollo 17 melt being a possible exception. Thus the Apennine Front seems to have a provenance distinct from other highland areas on the moon.

The regolith of the Apennine Front collected on the Apollo 15 mission is unlike any of the studied melt compositions, because the regoliths are contaminated with postbasin KREEP basalts, mare basalts, and green glasses. It is clear that there is no single monolithic LKFM melt composition in the Apennine Front, and mixing models for Apollo 15 regolith compositions must make a choice on what Apennine Front composition to use; the present study has not clarified this choice but has indeed shown more diversity among Front lithologies than was previously recognized. We intend to use the compositions derived in this study in our work currently in progress using mixing models on regolith compositions in an attempt to better define the lithologies making up the Apennine Front.

The interpretation of the major and trace element data presented in this paper would be greatly facilitated with additional siderophile data, particularly Ir/Au ratios, which are perhaps diagnostic of specific events or at least targets [Hertogen et al., 1978; Spudis and Ryder, 1981] and good crystallization ages. For such fine-grained rocks, only $^{40}$Ar-$^{39}$Ar ages are at present likely to be possible. Unfortunately, in many fine-grained, perhaps diagnostic of specific events or at least targets [Hertogen et al., 1978; Spudis and Ryder, 1981] and good crystallization ages. For such fine-grained rocks, only $^{40}$Ar-$^{39}$Ar ages are at present likely to be possible. Unfortunately, in many fine-grained, clast-bearing melt breccias $^{40}$Ar-$^{39}$Ar determinations have not been produced. Nevertheless, such ages are an essential part of the proper interpretation of the relationships among and origins of Apollo 15 impact melts.

### APPENDIX A

**TABLE A1. Genealogy of Coarse Fines (4-10 mm) Particles**

<table>
<thead>
<tr>
<th>Parent Regolith</th>
<th>Individual Particle</th>
<th>Chemical Split (this paper)</th>
<th>Potted Butt or Chips for TS</th>
<th>Thin Sections</th>
<th>Other Splits</th>
</tr>
</thead>
<tbody>
<tr>
<td>15304 (g)</td>
<td>.7</td>
<td>.66</td>
<td>.16</td>
<td>.47,.48</td>
<td>.29</td>
</tr>
<tr>
<td>15314 (a)</td>
<td>.26</td>
<td>.144</td>
<td>.38</td>
<td>.97</td>
<td></td>
</tr>
<tr>
<td>15314 (e)</td>
<td>.30</td>
<td>.146</td>
<td>.40</td>
<td>.100,.101</td>
<td>.77</td>
</tr>
<tr>
<td>15414 (d)</td>
<td>.10</td>
<td>.34</td>
<td>.10</td>
<td>.30,.31</td>
<td>.17</td>
</tr>
<tr>
<td>15314 (c)</td>
<td>.3</td>
<td>.35</td>
<td>.11</td>
<td>.32,.33</td>
<td></td>
</tr>
<tr>
<td>15344 (f)</td>
<td>.5</td>
<td>.13</td>
<td>.53</td>
<td>.140,.141</td>
<td></td>
</tr>
</tbody>
</table>

### APPENDIX B

**Petrographic Descriptions of the Analyzed Impact Melts**

Letters below refer to the corresponding photomicrograph (Figure A1). The split in parentheses is that of the chemical analysis.

(a) 15304,.7 (.66) has a fine-grained ophitic texture with groundmass plagioclases up to 60 $\mu$m and the enclosing pyroxenes generally less than 100 microns. The plagioclases are lathy to stubby and the pyroxenes granular to irregular. Ilmenite/ulvospinel occurs in chains up to 400 $\mu$m long; most individual crystals are not euhedral blades but some are. Angular interstitial silicic glass particles less than 30 $\mu$m across are scattered through the sample. Round vesicles are present but not common. Clasts are obvious and compose perhaps 10% of the sample, but are smaller than 1 mm. All are single minerals, mainly plagioclase but some mafic grains. Their shapes range from angular to rounded.

(b) 15308 (.8) has a fine-grained feathery or variolitic melt with skeletal mafic grains and lathy plagioclases. The mafic grains are all less than 20 $\mu$m; the plagioclases rarely reach 50 $\mu$m long. Opaque phases are poorly developed and presumably much of the groundmass is glass. Numerous small holes may be vesicles. The melt phase contains few clasts in general; those present are generally small, angular plagioclases. However, 15308 does contain coarser lithic clasts with polygonal texture that are plagioclase-rich but contain orthopyroxenes as well.

(c) 15314,.26 (.144) has a well-developed micropoikilitic texture in which small clasts are not obvious. The pyroxene oikocrysts are generally less than 150 $\mu$m across and contain small (less than 20 $\mu$m), irregularly shaped plagioclases. Plagioclases also occur as large blocky or tabular grains up to 100 $\mu$m. Oikocrysts tend to touch, without abundant interoikocryst regions, and some contain olivine cores. Ilmenite/ulvospinel grains do not form chains, and most are not blades. Interstitial silicic glass is clearly visible, though not common. Most of the dark-rimmed circles in the photograph are sectioning artifacts; their presence makes the identification of genuine vesicles tenuous. Clasts are small and all are monomineralic; they are mainly plagioclase but a few of the larger ones (still less than 500 $\mu$m) are mafic grains. The clasts commonly have distinct overgrowth rims.

(d) 15314,.30 (.146) has a fine-grained intersertal texture with well-developed plagioclase laths 50-100 $\mu$m long. Skeletal olivines up to 100 $\mu$m long are present but most of the groundmass mafic grains appear to be pigeonite. The interstitial material (30% to 40%) is a fine-grained mass including pyroxene, metal, and oxide phases; any glass is not particularly silicic. The opaque phases give the interstitial material a pearly appearance. The melt appears to have been rapidly quenched from a near-liquid state. Clasts are moderately angular and are mainly plagioclases less than 500 $\mu$m long; mafic grains are rarer and no lithic clasts are present.

(e) 15356 (.7) has a well-developed micropoikilitic texture with pigeonite oikocrysts about 200 X 100 $\mu$m. The oikocrysts contain about 40 vol% plagioclases as small, lathy to blocky grains, most less than 25 $\mu$m long. Interoikocryst patches contain more and larger plagioclases, commonly stubby, and contain conspicuous angular interstices of silicic glass and cryptocrystalline material (including plagioclase, pyroxene, ilmenite, and phosphate). More rarely the melt texture is subophitic to intersertal. Ilmenite crystals are tabular but do not tend to form chains. Clasts compose 5-10% of the sample, and are less than 150 $\mu$m across. Most are angular plagioclases; some are olivines. Dowty et al. [1973] provided microprobe analyses of minerals in 15356.

(f) 15357 (.14) has a micropoikilitic texture with pigeonite oikocrysts about 100 $\mu$m across containing abundant small stubby plagioclases. Some coarser (50 $\mu$m) plagioclases are interoikocryst or penetrate oikocrysts. Ilmenites are elongated but not blades; most are anhedral and "swiss cheese"-textured. Intersertal silicic glass with apatite is common. Clasts are larger, more varied, and more abundant (10-20%) than in 15356, although most are monomineralic (plagioclase; some olivine). One distinctly outlined ophitic/subophitic-textured area is probably a clast but might be a groundmass variant. One lithic clast is a poikilitic granule. Steele et al. [1972] reported microprobe analyses of minerals in 15357.

(g) 15359 (.10) has a fine-grained ophitic texture, with pigeonite oikocrysts about 100 $\mu$m across. The enclosed plagioclase grains are stubby and euhedral, with a fairly even grain size of 30-50 $\mu$m. Interolikocryst grains are not much larger than
Fig. A1. Photomicrographs of Apollo 15 impact melts analyzed in this study, in numerical order. Split number to right of parent number is thin section illustrated; split number underneath is that of chip for chemical analysis; for coarse fines the split number for the individual particle is placed above the thin section number. All transmitted light; all same scale, 1 mm X 1 mm field. v = vesicle.

chadacrysts. Ilmenites tend to be anhedral, dispersed, and very small (less than 20 μm). Interstitial glass appears to be rare, although silica and apatite grains are present. In one area the groundmass grades into a different texture with strongly bladed ilmenite and plagioclase grains. Most clasts, which are less than 1 mm across, are monomineralic, angular to subrounded plagioclase grains, but olivine and pyroxene are present. Many mineral clasts have overgrowth rims. Several lithic clasts types occur, including polygonalized olivine, and one fragment consisting of glassy melt with mafic phenocrysts surrounded by a mafic corona. Plagioclase fragments include flame-textured and other recrystallized textures. Dowty et al., [1973] reported microprobe analyses of minerals in 15359.

(b) 15405 (112) has a very dense, fine-grained variolitic texture
with elongate crystals of plagioclase, pyroxene, and ilmenite with some interstitial glass. Rare small skeletal pigeonite phenocrysts are present. Lenticular fissures (slit vesicles) are common. The clasts in 15405 are angular to subrounded and have a very restricted provenance of KREEP basalt and "quartzmonodiorite" debris, as both lithic and mineral fragments. Most clasts are fractured and otherwise severely shock-affected. Microprobe analyses of materials in 15405 were reported by Ryder [1976] and Ryder and Bower [1976b, 1977b].

(i) 15414,2 (.34) is a very vesicular micropoikilitic melt. The oikocrysts vary in grain size from only a few tens of microns (the majority) to perhaps 150 μm. Most plagioclase are stubby and less than 20 μm long. Ilmenites are euhedral blades and occur as chains. Interstitial glass is common and contains tiny phosphate needles. Clasts, which are mainly plagioclase, are very angular. Lithic clasts appear to be absent.
(j) 15414.3 (.35) is a micropoikilitic melt with a mottled texture. The oikocrysts are 400–500 μm across and contrast sharply with their enclosed plagioclase chondracrys, which are laths 20 to 50 μm long. Pigeonite oikocrysts contain about 60% plagioclase and the sample is more plagioclase-rich than the others investigated in this study. The ilmenites are bladed and form chains. Small olivines are present. There are very few clasts; those present are small (100 μm), angular to subrounded.

(k) 15434.5 (.13) has a microphotic or micropoikilitic groundmass, with small (50 μm?) pigeonite oikocrysts enclosing tiny (less than 20 μm) lathy to stubby plagioclases. Ilmenites are small (less than 20 μm) and anhedral, rarely blades. Clasts (5–10%) are mainly less than 20 μm and are mainly untwinned, blocky plagioclases. One 1-mm clast is a flame-textured plagioclase and one clast (100 μm) is silica.

(l) 15436 (.6) is a very vesicular, fine-grained melt. The groundmass has a fairly granular texture but with many lathy plagioclases and ubiquitous tiny ilmenite blades. Interstitial glass, most within and among areas of plagioclase grains, is common, and phosphate needles are common. Clasts include plagioclases and lithic fragments, and most are angular. The lithic fragments include coarser poikilitic impact melt fragments (most common) and finer grained melts. The lithic fragments are up to 600 μm across.

(m) 15445 (.243) is a fine-grained, ophitic/granular melt. Mafic grains are blocky, about 10–30 μm across; plagioclases occur as stubby tiny grains within the mafic grains and as 10–30 μm blocky grains between the mafic grains. Ilmenite is needle-like, most about 10 μm long. Small olivine and plagioclase clasts are difficult to distinguish from melt-crystallized products. The melt is banded and foliated around larger clasts. Clasts include banded and foliated around larger clasts. Clasts include lithic and plagioclase clasts and ubiquitous tiny ilmenite blades. Interstitial glass, most within and among areas of plagioclase grains, is common, and phosphate needles are common. Clasts include plagioclases and lithic fragments, and most are angular. The lithic fragments include coarser poikilitic impact melt fragments (most common) and finer grained melts. The lithic fragments are up to 600 μm across.

(n) 15445 (.257) has a texture, grain size, and mineralogy very similar to 15445, except where the melt cuts through a large norite clast where it is even finer grained. As with 15445, the clast population consists of plutonic varieties (norites and troctolites) and lacks surficial debris. The largest clast is an anorthositic norite almost 10 cm across. Petrographic and mineral chemical data were reported by Ryder and Bower [1977a] and Reid et al. [1977].

Acknowledgments. The manuscript benefitted from reviews by O. B. James, G. J. Taylor, F. Hörz. This work was supported by NASA grants No. W15 and 814. This paper is Lunar and Planetary Institute Contribution No. 615. The Lunar and Planetary Institute is operated by the Universities Space Research Association under Contract No. NASW-4066 with the National Aeronautics and Space Administration.

REFERENCES

Fig. A1. (continued)


Dowty, E., G. H. Conrad, J. A. Green, P. F. Hlava, K. Keil, R. G. Moore, C. E. Nehru, and M. Prinz, Catalog of Apollo 15 rake samples from stations 2 (St. George), 7 (Spur Crater) and 9a (Hadleys Rille), *Univ. of New Mexico, Inst. of Meteoritics, Spec. Publ.* No. 8, 75 pp., 1973.


G. Ryder, Lunar and Planetary Institute, 3303 NASA Road One, Houston, Texas 77058.

(Received May 8, 1986; revised October 13, 1986; accepted November 12, 1986.)