Chemical Dispersion Among Apollo 15 Olivine-Normative Mare Basalts

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INTRODUCTION

Most of the crystalline mare basalts at the Apollo 15 landing site are from one of two distinct series, one olivine-normative, the other quartz-normative (e.g., Rhodes and Hubbard, 1973). A large number of chemical analyses for these samples, using varied techniques and varied sample sizes, has been published (compiled in Ryder, 1985). The olivine-normative mare basalts have a much greater range in composition than do the quartz-normative basalts. The two groups have similar trace incompatible element abundance patterns, although the olivine-normative basalts tend to have slightly lower abundances; they also have identical ages and isotopic characteristics (summary in Nyquist, 1977). However, the two groups cannot be related by simple fractionation from some common parental magma or partial melting of a common source (e.g., Rhodes and Hubbard, 1973; Chappell and Green, 1973).

The olivine-normative basalts were sampled predominantly at the edge of Hadley Rille (Station 9a), where they include samples chipped from small boulders. Nonetheless, examples were found to be widely distributed over the mare sites. Small fragments are also present on the Apennine Front, whereas the quartz-normative group appears to be absent from the Front (Ryder, 1986). Furthermore, the regolith chemical data seems to trend toward olivine-normative mare basalts rather than quartz-normative basalts, suggesting that it is the predominant mare type in the upper regolith over the entire landing site (e.g., Rhodes and Hubbard, 1973; Korotev, 1986). However, Korotev (1987, p. 426) suggested that the data for a few critical elements (e.g., Si) was inadequate to substantiate such a claim, except perhaps for Station 9a, at which the interfering highlands component is small.

The olivine-normative mare basalts have textures ranging from fine-grained (<500 microns) with small olivine phenocrysts through medium-grained gabbroic (>500 microns) to coarser-grained gabbroic (>2 mm). The gabbroic-textured samples contain large crystals of pigeonite, but also include plagioclase that poikilitically encloses small rounded olivine and pyroxene grains. No vitrophyric examples are known.

Opinions about the relationships among the olivine-normative mare basalts have varied, even as to whether they represent derivatives of a single magma or of several magmas that differ slightly in composition. The O'Hara group (e.g., Humphries et al., 1972) considered all the samples to be olivine-plus-pigeonite cumulates from a cotectic liquid. However, the hypothesis that quickly gained credence was that the within-group variation was a product of moderate amounts (<15%) of near-surface fractionation of olivine from one singly-saturated (olivine) magma (Rhodes and Hubbard, 1973; Chappell and Green, 1973; Mason et al., 1972; Helmke et al., 1975). On the basis of their own analysis, Rhodes and Hubbard (1973) concluded that the coarse olivine-rich sample 15385 was not comagmatic with the main olivine-normative group.

Binder (1976) and Binder et al. (1980) used a synthesized, hence more comprehensive but less precise, data base. It was less precise because it included microprobe defocussed beam analyses (henceforth referred to as DBAs). These authors
separated the olivine-normative basalts into three distinct flow units on the basis of small, but apparently consistent, compositional differences, particularly evident when the data were cast into normative form. Within each flow unit variation was controlled by olivine fractionation. They also concluded that the 15385/15387 and 15388 samples represented yet two more distinct magmas. One stimulus for the Binder (1976) distinction was the petrographic distinction that had been made by Dowty et al. (1973) between two groups of gabbroic-textured basalts; however, the distinctions made by Binder (1976) do not classify specific samples in the same way as Dowty et al. (1973), nor indeed in quite the same way as Binder et al. (1980).

Haskein et al. (1977) found, for their own suite of analyses of 13 olivine-normative basalts (Heinmke et al., 1973), that the chemical dispersion was no more pronounced than that found in horizontal sections of single terrestrial basaltic flows, and that much of the dispersion could be explained by the sampling of the parent rocks for analysis. Lindstrom and Haskein (1978), who quantitatively modeled the same data set, concluded that the partial separation of major constituent phases on a source explained the observed trace element fractionation in horizontal sections of chemical dispersion by of 13 olivine-normative basalts that compositional separated trends. They a dispersion among analyses; hence the samples could be from distinctions made by more distinct magmas. One stimulus for the single, textured basalts; however, the distinctions made by Haskin et al. (1978) to conclude that neither shallow fractional crystallization nor varied partial melting of a homogeneous source explained the observed trace element fractionation trends. They suggested that short-range unmixing (filter pressing of residual liquid in particular) could be the dominant process, but they did not rule out the possibility of several distinct flows.

In none of the studies described above were the petrographic characteristics given more than fleeting relevant attention. For instance, it was rarely noted whether the sample was fine-grained or coarse-grained, or whether the sample might be a cumulate or liquid composition.

In several cases there have been chemical analyses that are anomalous; the authors have concluded that they represent separate flows (e.g., 15634 and 15643) despite being petrographically similar to the olivine-normative basalts. Most of such analyses are on rather small samples.

In the present study, we made chemical analyses of 12 mare basalts, all but one of them known or believed to be olivine-bearing, using INAA and microprobe fused bead techniques. Our main objective was to provide data adequate to test the Binder (1976) hypothesis that the olivine microgabbro groups represent two magmas distinct from each other and from the finer-grained olivine phenocrystic basalts. We also analyzed one of the basalts with apparently anomalous compositions (15643), two coarse-grained rocks from the Apennine Front (15387 and 15388), and a 4-10-mm particle from the Apennine Front (15274, 3). We used masses large enough to assure a reasonable representivity. Using the compilation of data in Ryder (1985), a few more recently published analyses, and the new analyses reported here, we made mass-weighted averages for all analyzed olivine-normative mare basalts. With these we

### Table 1. New analyses of Apollo 15 mare basalts by microprobe fused bead (MFB) and INAA.

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<th>INAA</th>
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<th>15387</th>
<th>15388</th>
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inspect petrogenetic relationships among the olivine-normative basalts, taking into account some relevant petrographic characteristics.

**SAMPLES ANALYZED**

We analyzed: (1) nine rake samples from Station 9a—15620, 15623, 15633, 15641, 15643, 15651, 15663, 15668, and 15672; (2) two splits of 15387, one of 15388, and a coarse-fine particle 15274,3 from the Apennine Front.

Most of the rake samples are medium- to coarse-grained and gabbroic. They were analyzed to evaluate the suggestion of Binder (1976) and Binder et al. (1980) that olivine microgabbros represent two chemical groups distinct from each other and from olivine-phyric basalts; our samples include representatives of both their groups A and B. Their thesis depended substantially on DBAs, which we can show as being insufficiently accurate for distinctions as fine as they made (see Results section below). Except for 15651 these samples had all been analyzed at least partially. Some analyses, such as that of Ma et al. (1978), are more recent than the Binder (1976) data compilation. However, most splits were of small mass or the analysis lacked critical data such as MgO or useful trace elements. 15668 is distinct in that it is a fine-grained sample with few and tiny phenocrysts. Petrographically it appears to represent a liquid composition. It was reanalyzed because there was little reliable trace element data for it. 15672 was reanalyzed to provide a comparison of our data with that from several other workers. 15643 was selected because Lau and Schmitt (1973) and Ma et al. (1978) considered it to be anomalous (with a positive Eu anomaly) and necessarily from a distinct magma. These authors did not consider the constraints of the sample size of only 49 mg. We attempted to use sample sizes that were more representative; for six of our analyses we homogenized about 500 mg of sample, but for three analyses we only had 200-300 mg.

15387 and 15388 are coarse basalts texturally distinct from most of the olivine-normative basalts, and their relationship to them is obscure. Petrographically, 15387 is indistinguishable from 15385; both are olivine-rich and were called feldspathic peridotites by Dowty et al. (1973) and in most subsequent references. Given the zoning and high Ca abundances of their olivines, hence clearly extrusive origin, picritic basalts—as they were called by Binder (1976)—is a more appropriate name, and will be used here. The age and isotopic characteristics of 15387, for which there is also some chemical data, are indistinguishable from olivine-normative mare basalts, as is the mineral chemistry. There was no previous chemical analysis of 15387. We analyzed a total of about 300 mg as two splits that turned out to be very similar. 15388 is texturally distinctive and lacks olivine; it was called feldspathic microgabbro by Dowty et al. (1973). Existing analyses showed a positive Eu anomaly and low overall incompatible element abundances, but the sample sizes used were very small considering the coarse grain size of the sample. We analyzed a split from 600 mg of homogenized powder. Coarse-fine (2-4 mm) particle 15274,3 (.21) was identified macroscopically as an olivine basalt by Powell (1972); no thin section of it has been made. Because of its tiny size, we used only 80 mg of it.

**ANALYTICAL METHODS**

We inspected the allocated chips in air under a binocular microscope, checking for possible extraneous material (such as adhering regolith), and describing them. Using agate tools, we crushed each sample by hand into a fine powder to homogenize it. A small (<15 mg) portion was fused into a glass bead, in an argon atmosphere (40 psi) and on a Mo strip, at the NASA Johnson Space Center. The equipment and techniques used were described by Brown (1977). The major elements in these glass beads were analyzed on an JEOL
Superprobe 733 at the Dalhousie University, Nova Scotia. The analyses were made at 15 Kv accelerating potential, a beam current of 5 na, and a beam diameter of 10 microns. Data reduction was made using Tracor Northern programs for ZAF corrections. Uncertainties are about 2% for all elements. The glasses were all very homogeneous and analyses of four points per glass were adequate.

Forty to 120 mg of the remaining homogenized powder for each sample was used for the Instrumental Neutron Activation analyses. Samples were irradiated at the University of Missouri Research Reactor; counting and reduction was done at the NASA Johnson Space Center using standard techniques. BCR was used as the standard for all elements except Cr, for which the standard was BHVO.

RESULTS

Our analyses by both microprobe fused bead and INAA are listed in Table 1. Our rare earth data are plotted in Fig. 1. Our analyses by both techniques for FeO and Na2O in any sample are in very good agreement, hence we consider both sets of data to be good analyses of the powders. It is evident that fusing of the powder did not result in significant sodium loss. Table 2 is a comparison of previous analyses for 15672, a so-called olivine microgabbro B (Binder, 1976; Binder et al., 1980), for critical elements. In this sample, pyroxenes reach 2 mm long. There is fairly good agreement for the major elements among all the analyses (including the present one) except the DBA, although the incompatible trace elements vary by over 20%. The DBA differs significantly in Ti, Al, and Mg from the similarity of the major elements of the other analyses. For this reason we consider the faith of Binder (1976) in the data base on which he made his conclusions to be unjustified. [All the group B olivine microgabbros of Binder et al. (1980) had only DBAs. Some other DBAs do not differ from other analyses so much, but many do; the point is that they cannot be considered reliable for the fine distinctions made between possible groups.

Two analyses were made on two of the samples. Sample 15663,16 had a saw-cut surface, and after mild crushing it was separated into two portions: one with sawn surfaces (146 mg; 15663S), the other without sawn surfaces (350 mg, 15663). A fused bead was not made of the sawcut-containing sample, but the FeO and Na2O abundances measured by INAA of the two portions are virtually identical. Both compatible and incompatible trace elements are about 10% higher in 15663S, but there is no evidence for any real contamination from the sawn surfaces; e.g., there is no enrichment in Co, and Ni was not detected. Thus both analyses are used in the mass-weighted averages (below). Two splits of 15387, the coarse-grained picritic basalt sample, had masses of 222 and 81 mg. Despite these small sizes and the coarse grain size of the rock, the two analyses are virtually identical for all elements except Cr. Chromium is concentrated in the small and sparse chromite grains, which can be expected to vary among such small splits. Both analyses are used in the mass-weighted averages (below).

NEW DATA AND COMPARISON WITH EXISTING DATA

The present analyses confirm that all the Station 9a samples are typical olivine-normative mare basalts (Table 1, Fig. 1). Most have very similar compositions with MgO ranging from 10.3 to 11.7%, except for the very fine-grained sample 15668, which has only 8.9% MgO (in agreement with earlier analyses). However, 15651 appears to have anomalously low FeO, which in the absence of other chemical data apart from the DBA is enigmatic, but might suggest a plagiodase excess in the sample. The incompatible trace elements vary among the samples by only 15%, except for 15641, which is almost 15% lower than any of the others. Chromium is the most varied compatible trace element, consistent with the uneven distribution of chromite. The only major element analysis that is significantly different from those previously published is that of 15651, for which the FeO abundance is lower than the others, about 20% instead of about 22%; both INAA and fused bead give lower FeO, hence it is a characteristic of the split, not an analytical peculiarity. The (Al2O3+CaO) is correspondingly higher, and it may be a plagiodase-enriched sample. Sample 15643, proposed by Lau and Schmitt (1973) to be anomalous, does not in fact have a positive Eu anomaly and is instead quite ordinary, as suggested by an earlier major element analysis by Christian et al. (1972). These data emphasize the limitations of making inferences based on partial analyses of small samples; the sample used by Lau and Schmitt (1973) was only 49 mg.

The coarse-fine sample 15274,3 (our analysis 21), for which no thin section yet exists, was described macroscopically by Powell (1972) as an olivine basalt with about 20% olivine. The analysis of 81 mg shows it to be very similar to the picritic basalt 15385 for all elements, including the pattern and abundance of incompatible trace elements. Its Al2O3 is slightly higher and its MgO slightly lower, but it surely represents the same parent rock type. The data also agree reasonably well with the major element analysis for 15385 by Ma et al. (1976), but not with that by Rhodes and Hubbard (1973); the incompatible trace elements of 15385 by Ma et al. (1976) are 20-25% higher than in our 15387 analysis, and those of Rhodes and Hubbard (1973) are twice as high. A clast from breccia 15299 (.201) analyzed by Warren et al. (1987) has

<table>
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<tr>
<th>TABLE 2. Comparative analyses of 15672.</th>
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References: (1) DBA—Dowty et al. (1973); (2) Christian et al. (1972); (3) Lau and Schmitt (1973); (4) Ma et al. (1976)—Analysis a; (5) Ma et al. (1976)—Analysis b; and (6) present study.
a composition very similar (remarkably so given the fact that its mass was only 49 mg). We suggest that all these samples represent essentially the same cumulate rock, but the coarse grain size has resulted in some unrepresentative analyses. Unlike the other two samples (15385 and 15387), coarse-fine particle 15274.3 (21) and breccia 15299 were collected at Station 6, not Station 7. Thus these samples expand the known geographical range of this rock type and make it more likely that it is of local rather than exotic genesis.

15388 is petrographically unique among the Apollo 15 samples (Doutty et al., 1973). Our new analysis confirms the positive Eu anomaly and low incompatible element abundances found in the two previous analyses (Laut and Schmitt, 1973; Ma et al. 1976). Our larger mass confirms that the sample is also high in TiO$_2$ (about 5%) and that the sample is aluminous. Its petrogenesis will be discussed below.

**Mass-Weighted Averages**

Numerous chemical analyses of Apollo 15 olivine-normative mare basalts have been made, including many on the same rock sample. They include neutron activation, XRF, and wet chemical analyses, and sample sizes ranging from a few milligrams to a few grams. Each technique covers a different spectrum of elements with varied precision and accuracy. There are few analyses for both major and trace elements on reasonably representative sample sizes. In most of the discussions of the petrogenesis of the basalts (summarized in the introduction), each analytical group has tended to use only its own data, thus restricting both the number of samples and elements used. The synthesis of Binder (1976) and Binder et al. (1980) is an exception.

In an attempt to overcome the analytical deficiencies, we have made mass-weighted averages of all of the Apollo 15 olivine-normative samples as a basis for assessing the relationships among and the petrogenesis of these basalts. In principal this method is similar to that used by Binder (1976) and Binder et al. (1980). Our data base, which comprises more than 50 separate rock samples, differs in that it includes more results from many samples, including our own, which are on reasonably representative-sized samples for the grain sizes, and does not include DBAs, for the reasons outlined above. For our own data we use the FeO and Na$_2$O derived by INAA rather than by fused bead, although the difference is not significant. Apart from unreliable data, which is totally excluded, we have assumed that all analyses are equally valid estimates of the particular split analyzed, although this certainly may not be true; for instance, most major element analyses by INAA will not be as precise as those derived from XRF. However, making a totally objective calculation of how to weight analyses according to technique is difficult and would probably not create any major differences in our results, except as noted in the discussions. The unreliable data includes the DBAs, the rare earth data of Christian et al. (1972) (which is consistently much higher than that from other laboratories), some of the magnesia values derived from INAA, and a few other odd analyses. For the mass used, an attempt was made to find out how much sample the analyzed split represented, e.g., if 500 mg of sample was ground up and 60 mg was analyzed by INAA, then the sample mass used for this analysis was the weighted average was 500 mg. In most cases use of the published information and the Curatorial data packs allowed retrieval of this information, but in a few cases this was not possible and a conservative estimate of the probable mass used was made.

Our mass-weighted averages do suffer for petrogenetic purposes in that variation within a sample is suppressed (such that the scale of variation of this suite remains unknown) and different elements rely on different splits and different sample sizes, e.g., the rare earth data are rarely based on as much mass as the major elements. The averages also suffer from the interlaboratory biases. The present data set would not compare in value with a set of analyses for many major and trace elements on splits of homogenized samples of many basalts, using several grams from each. Nonetheless, we consider our averages to be the best available estimates of the bulk composition of each of the Apollo 15 olivine-normative mare basalts.

**Chemical Dispersion and Relationships Among Olivine-Normative Mare Basalts**

Samples classified as microgabbro groups A and B by Binder et al. (1980) for which analyzes other than DBAs exist are plotted in Fig. 2, which summarizes most of the major element data for them. A similar plot was used by Binder et al. (1980, Fig. 8e) to show the distinction of Group A from Group B. Our data base shows no discrimination of the groups, either when our own data (small diamonds) or average data (large diamonds) are inspected. This overlapping of the two "groups" is seen in other plots (not shown) as well. There is also no distinction of these microgabbros from the finer-grained,
Fig. 3. Major element plots for the mass-weighted averages of the Apollo 15 olivine-normative mare basalts and 15388. Open circles are fine-grained basalts; solid squares are medium- and coarse-grained basalts. Largest symbols are for analyses comprising over 500 mg, intermediate symbols are 250-500 mg, and smallest symbols are less than 250 mg. Solid triangles are picritic basalts (numbered; the prefix 15 is understood). Star is the impact melted sample 15256. Fractionation lines are drawn from 15555 as an arbitrary starting point; for olivine, ten percent subtraction is indicated by the shaded square. The olivine assumed is about Fo 65; the clinopyroxene assumed is a calcic pigeonite with Mg/(Mg+Fe) about 55; the composition of the assumed plagioclase is irrelevant.

The data in Fig. 2 appear to be dispersed along an olivine control line, but such a line on this plot is similar to either a plagioclase control line or simply a closure-sum line. (By closure-sum line we mean that analyses, summing near to 100%, will plot along a line in element plots whose data dominates the analysis, even if they are multiple analyses of the same object. As "FeO + MgO" goes up by an absolute x%, then "Al₂O₃ + CaO," which compose the bulk of the remainder except SiO₂, will go down by about x%. It so happens that olivine-control and plagioclase-control lines on Figs. 2 and 3a have slopes similar to closure-sum lines, i.e., about 1.) The spread of data is probably too wide for simple closure, and indeed the nonnative plots show that the effect is that of olivine, not plagioclase. However, there are complications shown by the data, as discussed below.

At present we have chosen to further assess the synthesis, mass-weighted data mainly from element-element plots; we are not certain of the validity of using more quantitative, multivariate methods (including least-squares techniques) on such a synthesized data base. On our plots (Figs. 3, 4) we use different symbols to make some assessment of sample size (hence representivity). Where different sample sizes were available for different elements on a plot, the symbol represents the size for the smaller mass. We also use different symbols to distinguish samples with fine grain sizes with small olivine...
phenocrysts from those with coarser grain sizes, on the assumption that the fine-grained samples probably have compositions similar to that of their parent magmas, whereas the coarser ones may or may not.

The major elements, despite the dispersion (which is less when only larger sample sizes are considered), suggest that the samples form a single compositional group that is related mainly by olivine fractionation (Fig. 3a). This sequence trends in the olivine-richer direction to the coarse picritic basalt samples, and in the opposite direction to the 15388 sample (Fig. 3a). However, some of the data is apparently not precise enough to confirm simple olivine fractionation; there is a large degree of scatter introduced by either petrogenetic processes other than fractionation, or sampling problems induced by small or merely different subsamples, or both. For instance, on Fig. 3b (MgO versus FeO) the picritic basalts (especially the larger mass-analyzed ones 15385 and 15387) are consistent with being olivine cumulates from the main series. (Further discussion of these coarser samples will be deferred to the following section.) However, within the main series there is no consistent olivine trend. Furthermore, the coarser samples form a group that is distinct from the finer ones, in the direction of pyroxene (+ olivine?) addition, on Fig. 3b. The finer ones themselves form a line roughly consistent with plagioclase variation (Fig. 3b). The petrographic characteristics of these basalts and the experimental data (e.g. Humphries et al., 1972) for these compositions (which show plagioclase far removed from the liquidus of even the most evolved of these compositions) preclude the separation of plagioclase crystals.

Olive fractionation should not result in variation of either Ca/Al or Sm/Eu ratios. Figure 4c shows that there is a variation of the Ca/Al ratio; however, this variation is not correlated with Sm/Eu variation (Fig. 4a) as it would be from plagioclase variation. Pyroxene has a small effect on the Ca/Al ratio, but not enough to cause anywhere near the amount required. We conclude that the data for Ca and Al are simply not good enough to assess the petrogenetic relations among these basalts, or that some process we do not understand is the cause of the variation. Figure 4b also shows the dispersion in the Sm/Eu ratio, and the trend appears to be a plagioclase trend. But it is also the trend expected of random variation of Sm around

Fig. 4. Variation of some rare earth element parameters for mass-weighted averages of Apollo 15 olivine-normative mare basalts and 15388. Symbols as in Fig. 3.
a constant Eu abundance. Indeed all the analyses do have Eu just under 1 ppm. The total variation in Sm is much greater than can be expected from olivine fractionation, and suggests some other cause—analytical, sampling, or alternate petrogenetic processes.

Simple olivine fractionation should result in an anticorrelation of precisely measured incompatible elements with MgO. Figure 4c (Sm v. MgO), like Fig. 4b, shows the much wider dispersion of Sm than can be explained by reasonable olivine fractionation, although there is a rough increase of Sm with decreasing MgO. The coarser-grained samples are on average richer in MgO than are the finer-grained samples. The scatter in the main (nonpicritic) group is more aligned with pyroxene than olivine, although olivine could have contributed to this effect.

The major elements thus seem to be paradoxical; in sum they are compatible with olivine fractionation (e.g., Fig. 3a), but in detail olivine fractionation cannot explain the data (e.g., Fig. 3b,c). The incompatible trace elements, represented by the precisely-measured Sm, show a much greater variation than can be accommodated by reasonable amounts of olivine fractionation. The element correlations we have considered cannot readily distinguish the causes of this variation. Assuming analytical problems are minimal, then the possibilities are sample size problems, the hodge-podge nature of the data base (synthesising data from different splits of a rock), or more complex petrogenetic processes.

One of the potential processes that may influence the chemistry of a sample is short-range unmixing. Lindstrom and Haskin (1978) invoked this process to explain their own data as being consistent with samples from a single undifferentiated flow. In their model each analysis is a mixture of crystal phases and a common residual liquid; least-squares modeling showed that the analyses were consistent with varying mixes of olivine, spinel, pyroxene, plagioclase, and residual liquid. They found olivine to be the most variable phase, with samples up to 30 relative % more or less than the average abundance (actually, 5.5 ± 3.5 absolute % minimum, 9.5 ± 3.0 absolute % maximum), and that spinel and residual liquid also had large relative variations (spinel being a minor phase and residual liquid able to move relatively easily; e.g., by filter pressing). The amount of variation they found appears to be at the upper limit of that expected from a single flow, and the data set used comprises only part of the known range of these basalts. For instance, the large, well analyzed, and finer-grained sample 15556 was not included in their analyses, yet is the most evolved of the well-characterized samples, e.g., Mg’ about 0.40 (see Ryder, 1985). Its inclusion, as well as inclusion of other more evolved samples such as 15668, would probably cause the model to exceed the criteria for a single flow.

There is a difficulty in distinguishing the effects of short-range unmixing and sampling problems; indeed they are conceptually the same thing except that short-range unmixing includes relative movement of phases (especially early-crystallized ones and residual liquids). Both cases are a question of scale: the sample size relative to the unmixing package size. The present data base, especially where multiple analyses are combined or only one analysis on a small sample is available, does not allow the estimation of the scale of short-range unmixing, hence whether the dispersion is merely sampling error or real within-sample-size unmixing. However, the reasonable within-sample consistency of at least some comparative analyses of single rocks, such as 15672 and 15556, shows that there are differences between samples (unless all splits were taken from a very restricted portion), which means either different flow compositions, traditional fractionation processes (e.g., crystal settling), or unmixing at scales larger than the samples (i.e., tens of centimeters). However, we suggest that a much better, unified data base for these basalts is required before their relationships can be understood adequately in terms of the petrogenetic causes of chemical variation. This improved data base would comprise major and trace element analyses on large splits, including duplicate or even replicate analyses, of many of these samples.

Picritic basalts

On all of the elemental plots (Figs. 3 and 4), 15385 and 15387 fall in a position consistent with their origin by addition of about 30% olivine to almost any member of the olivine-normative basalt suite. The smaller samples 15274,3 and 15299c show more dispersion but in most plots are similarly roughly consistent with only olivine accumulation. Considering the small sample sizes (80 and 49 mg, respectively), their analyses are likely to be grossly unrepresentative and subject to modal phase variation. The major element data, the similarity of the rare earth patterns, the mineral chemistry, and the similarity of the radiogenic age of 15385 (Ar-Ar 3.39 Ga; Husain, 1974) to the olivine-normative basalts suggest that these basalts are in fact olivine cumulates from an olivine-normative basalt magma. The whole-rock Rb-Sr isotopic data also plot within analytical error on the same isochron as the olivine-normative basalts. It is apparent that the subsample of 15385 from which Rhodes and Hubbard (1973) concluded that this basalt was unrelated to the olivine-normative basalts was unrepresentative.

15388

15388 is an unusual basalt in that it has a positive Eu anomaly. The only reasonable hypothesis for a positive Eu anomaly in lunar samples is that of plagioclase accumulation, and on all of the element plots (Figs. 3 and 4) 15388 falls in the direction of plagioclase addition from the olivine-normative mare basalts. However, simple plagioclase accumulation is not the explanation; the sample is also higher in TiO2 and it lacks olivine completely. The lower trace element contents and lower Sm/Eu ratio suggest about 50% plagioclase accumulation, but in most plots are similarly roughly consistent with only olivine accumulation. Considering the small sample sizes (80 and 49 mg, respectively), their analyses are likely to be grossly unrepresentative and subject to modal phase variation. The major element data, the similarity of the rare earth patterns, the mineral chemistry, and the similarity of the radiogenic age of 15385 (Ar-Ar 3.39 Ga; Husain, 1974) to the olivine-normative basalts suggest that these basalts are in fact olivine cumulates from an olivine-normative basalt magma. The whole-rock Rb-Sr isotopic data also plot within analytical error on the same isochron as the olivine-normative basalts. It is apparent that the subsample of 15385 from which Rhodes and Hubbard (1973) concluded that this basalt was unrelated to the olivine-normative basalts was unrepresentative.
be consistent with the apparent flow alignment of mineral phases in 15388, and the mineral chemistry; testing this hypothesis awaits more quantitative modeling and the acquisition of isotopic data. Such an origin would be unusual; it requires that a liquid more fractionated than any known sample produced the most obviously cumulate sample in the suite. Such an origin would directly influence our concepts about the physical volcanology of the Apollo 15 olivine-normative basalts.

OLIVINE FRACTIONATION AND SURFACE FLOWS

The data analysis above appears to be generally consistent with the concept that the compositions of the olivine-normative mare basalts are related to each other largely by olivine fractionation, as proposed by Rhodes and Hubbard (1973), Chappell and Green (1973), and others. This hypothesis is also consistent with the experimental phase equilibria data (Humphries et al., 1972), which show that even for evolved compositions olivine (+ spinel) is at the liquidus at temperatures much higher than that of pyroxene. Thus pyroxene separation (although not pyroxene effects in sampling problems or short-range unmixing) cannot be expected to have influenced element abundances in the analyses. However, the petrography of the samples brings into question the nature and location of such a fractionation process. Fine-grained basalts, which are likely to reasonably represent actual liquid compositions, occur from almost the most magnesian samples to the least magnesian samples, so that the most magnesian samples do not consist solely of cumulate rocks. Furthermore, vesicular samples (of which this suite contains some spectacular examples) are also represented by a wide compositional range, and it is less likely that a very vesicular rock is a cumulate. Thus it appears that compositions among the most magnesian were extruded as liquids, not that the magnesian samples all represent cumulates from some average composition.

The range of compositions of the main olivine-normative mare basalts corresponds with about 15% olivine fractionation. However, few rocks contain anywhere near that much olivine. In phenocryst form the amount of olivine is nearly always only a few percent; much of the olivine occurs as small anhedral crystals grown with pyroxenes and poikilitically enclosed in plagioclases. This texture in itself is quite unusual. The more fractionated basalts do not seem to have a consistent pattern of less modal olivine, although the data at present is poor for quantitative comparison. These characteristics suggest to us that most of the olivine fractionation deduced to have taken place did so prior to the lavas reaching the Apollo 15 landing area, perhaps prior to extrusion. Thus the basalts represent a range of lava compositions flooding as multiple thin flows into the area, perhaps from a common parent that was fractionating in a subsurface magma chamber. Nonetheless, the picritic basalts provide evidence that substantial (30%) olivine accumulation did occur at the surface in some lavas. The total picture is thus quite complicated; the Apollo 15 olivine-normative mare basalts cannot be imagined easily as a single erupted flow that crystallized olivine after extrusion and changed its composition uniformly as it cooled.

This complicated picture is enhanced by a consideration of the distribution of the basalts around the landing site. In particular, as detailed by Ryder (1986), olivine-normative basalts are found on the Apennine Front, whereas the quartz-normative basalts have not so far been identified among Front samples (Stations 6, 6a, and 7). These Front samples include the clearly cumulate samples. Olivine-basalts might be present at 100 m up the Front because they originally flowed there, or ponded up to that height. Alternatively they may have been thrown there by impact, in which case they would need to be the locally dominant flow(s) at the very surface, or quartz-normative basalts should be equally abundant on the Front. The understanding of this distribution promises evaluation of the surface flow history of the basalts filling Palus Putredinis.

CONCLUSIONS

New analyses and a synthesis of previous ones for olivine-normative mare basalts from the Apollo 15 landing site provide no evidence that they comprise more than one chemical group, such as the four (olivine-phyric, microgabbro A, microgabbro B, and picritic basalts) suggested by Binder (1976) and Binder et al. (1980). The single group includes vesicular and both coarse-grained and fine-grained basalts. The general trend is that of olivine separation. For the entire suite, rather than the more limited sets investigated by many workers, the dispersion of compositions along the olivine trend is probably too great to be explained by short-range unmixing of an unfractonated flow. Thus the olivine separation is a genuine effect, presumably by crystal settling. The petrographic characteristics of the basalts suggests that much of the olivine that caused the dispersion is not present in the samples, and therefore much of it may be in subsurface magma chambers. Multiple thin flows, each of which may have had its own surface fractionation, are consistent with many of the petrographic features of the samples.

There is considerable dispersion among analyses in our synthesised data base over and above that produced by olivine separation. The reasons could be analytical, from sampling problems, from the combining of analyses from different splits subject to different sampling problems, or from petrogenetic processes other than simple fractionation. One such process is short-range unmixing. The present data base, which includes few analyses for both major and trace elements on large subsamples of any of the basalts, is inadequate (despite covering more than 50 samples) to distinguish among these possibilities or to assess the scale at which short-range unmixing took place, if it did at all. The understanding of the nature and causes of dispersion among this suite of basalts requires a thorough reanalysis of the basalts for both major and trace elements on representative subsamples of many members of the Apollo 15 olivine-normative mare basalt suite.

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REFERENCES


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