Papers Presented to the

WORKSHOP ON THE GEOLOGY AND PETROLOGY OF THE APOLLO 15 LANDING SITE

NOVEMBER 13-15, 1985

Sponsored by:
Lunar and Planetary Institute
National Aeronautics and Space Administration
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Regolith samples from the Apollo 15 landing site provide an opportunity to trace soil mixing on a horizontal scale of about 1-5 km. Pure mare basalt occurs on one side of the landing site and highland materials are piled up on the Apennine Front on another. If the local regoliths were to be composed of comminuted products of exclusively local crystalline rocks, the question of mixing would not arise. If these were to be mixed by processes of simple gravitational mass wasting and/or by micrometeoritic bombardment, the mixing process would have been relatively easy to understand. However, other complicating processes and/or events make the overall process of regolith mixing at this site much more challenging to understand. Fire fountaining event(s) deposited green glass spherules that are distinct from all mare basalts. There are craters of impacts that have excavated substantial proportions of one and more kinds of substrate—e.g. Dune excavating mostly mare basalts, St. George excavating crystalline highland material, and Spur excavating green glasses. There is a possibility of the existence of a ray from an exotic source emplacing non-local material (KREEP basalts?) at this site. Regolith mixing at this site, therefore, must be understood in terms of the surface features and other photogeologic interpretations of this site [6].

Mixing model calculations [8] have been performed on the chemical compositions of many soils from different stations. The results provide a good guide for models that are dependent on intelligently chosen end members. We are testing an approach using only the modal abundance data on crystalline fragments and green glass spherules. We have constructed a pseudo-fence diagram of the Apollo 15 site showing the distribution of major lithic fragments actually present at the various sampling stations (Fig. 1).

The diagram shows that:

(a) KREEP basalt is uniformly distributed on the Front and through the high grounds near the ALSEP/LM location,

(b) Occurrence of green glass is dominantly a Spur crater phenomenon; green glass has been redistributed by post-mare cratering events from this point source,

(c) Highland rock fragments are uniformly distributed on the Front; St. George crater has not affected the present day distribution of highland rock fragments in the Apollo 15 soils,

(d) Abundance of mare basalt fragments is controlled not only by the distance from mare-highland boundary [cf. 8] but also by the downslope movement of regolith near the rille [cf. 7] and by the depth of penetration by local cratering events (e.g. Dune).

KREEP basalt enrichment in Apollo 15 soils in a linear fashion extending from ALSEP/LM location through Station 6 on the Front may give the appearance of the presence of a ray rich in KREEP basalt fragments. However, we prefer a different scenario on the basis of the modal data and the pseudo-fence diagram. Assume that KREEP basalt is local and that the pre-mare regolith (or, at least the one before the last major lava flooding of the Apollo 15 embayment) was uniformly rich in KREEP basalt fragments. Into this embayment flowed one (or more) low viscosity mare basalt lava that not only carved out the Hadley Rille, but also eroded part of the then regolith in the embayment. The eroded bench was irregular in shape and is now represented by Stations 9A, 9, 1 and 4. The bench had a veneer of mare basalt that thins in the direction
Figure 1. Pseudo-fence diagram showing the major modal abundances of major lithic particles in Apollo 15 soils. Station numbers are at the bottom of the modal modal bar graph for each station.
of all high grounds (Fig. 2). Post-mare cratering comminutes the thin veneer of the mare basalt, mixes KREEP basalt fragments from below and produces a regolith to which is added material from the Front including the green glass ejected from Spur crater.


Post-mare basalt soil
Pre-mare basalt soil
Pre-mare basalt bedrock

Mare basalt

Fig. 2. Simplified and schematic cross section from Hadley Rille through Stn. 3 and ALSEP/LM. Pre-mare soil and mare basalt in reality are likely to be intercalated with many flows and thin syn-mare soils. Post-mare regolith is thinner on the slopes than it is on relatively flat ground.
Samples from 12 different mare units have been identified (in some cases tentatively) among the Apollo 15 samples. Of these, 5 are VLT pyroclastic (green) glass units (units A through E of Delano and Li (1)), one is an impact (yellow) glass unit derived from a LT mare basalt flow (2), and the remaining 6 are all regular LT mare basalt units. The latter 6 units were initially defined by Dowty et al. (3) on the basis of textural characteristics of rake samples and broad beam microprobe analyses. The majority of the Apollo 15 mare basalts belong to 4 of these units, i.e., the pyroxene phric unit, the olivine phric unit, and two olivine microgabbro units (A and B). In addition, Dowty et al. identified two rake samples (15385 and 15387, these are the most olivine-rich mare materials thus far found) from a feldspathic peridotite (in reality a picrite basalt) unit and one rake sample (15388), which has an apparent positive Eu anomaly and 42% plagioclase (4), from a feldspathic microgabbro unit.

As shown in Fig. 1, as an example, the Apollo 15 mare units lie along a series of compositional trends defined by the entire suite of pyroclastic and mare basalt magmas. These, and similar plots, quite clearly show that all mare materials were produced by a common petrogenetic sequence from a common set of source materials, as depicted in Fig. 2 (5,6). The fact that all mare materials lie along common compositional trends categorically rules out all proposed petrogenetic models in which each unit, or some subset of the entire suite of mare units, is considered to have both an individually tailored source region and a genesis needed to explain some subset of the total array of petrological, chemical, and/or isotopic data. Given the general model of the mare basalt source regions and of mare basalt genesis derived from a synthesis of the major oxide/major mineral [Pl(Or,Ab,An), Py(Wo,En,Fs), Ol, 1lm, and Chr], compatible siderophile (Co, Ni) and incompatible (K, Rb, Sr, Ba, and REE) trace element data and the isotopic ratios of the Rb/Sr and Sm/Nd systems (5,6), the genesis of the Apollo 15 VLT and LT mare units is briefly as follows:

The primary magmas of all 12 units were derived by about 30% partial melting of their source regions which are located at depth of less than 200 km, Fig. 2. The normative compositions of source region of each of the 5 VLT pyroclastic green glass units is within about 1 Wt% of 6.1% Pl (Or0.6,Ab4,An95), 14% Py (Wo18,En62,Fs20), 78.5% Fo76, 0.2% 1lm, and 1.1% Chr. The average normative composition of the source regions of the 7 LT mare basalt units is 5.7% Pl (Or1,Ab11,An88), 11.8% Py (Wo20,En58,Fs22), 79.9% Fo73, 1.2% 1lm, and 1.2% Chr. The source regions of the olivine phric unit and the olivine microgabbro unit A have compositions close to this average, while that of the pyroxene phric unit can be characterized as having about 1% less Pl than the average, those of the olivine microgabbro unit B and the feldspathic microgabbro unit as having 1% more Pl than the average, and that of the picrite basalt unit as having about 2% more Pl than the average LT source region.

These 30% primary melts rose to the crust-mantle boundary where they pooled in one or more magma storage chambers, Fig. 2. However, the primary magmas of the pyroclastic green glasses remained in their magma chamber(s) only a short time and therefore lost no olivine (as reflected by their high normative Ol, Co, and Ni contents) or volatiles (as reflected by the volatile
coatings on the glass beads and their low \( \frac{^{238}U}{^{204}Pb} \) ratios) and assimilated little or no urKREEP residual from the storage chamber(s) wall rocks. The trace element patterns shown in Fig. 3 are accounted for if the 30% primary melts assimilated no urKREEP residuals if the data on the REE contents of the green glasses of Ma et al. (7) are correct, or if the primary magmas assimilated a minute amount (0.07%) of fractional melt from the urKREEP wall rocks if the Taylor et al. (8) data are correct. In either case, the low incompatible trace element contents of the green glass magmas is due to their have assimilated little or no urKREEP residual wall rocks during their short stay in the magma chamber(s).

In contrast to the green glass magmas, the primary magmas of the other Apollo 15 units remained long enough in the storage chamber(s) so that they cooled and lost olivine via fractional crystallization as reflected by their relative positions in the quaternary phase diagram and their decreasing Co (Fig. 1) and Ni contents. Specifically the amount of Ol lost by each of the primary magmas in the storage chambers is: olivine microgabbro unit A, 21%; olivine microgabbro unit B, 25%; olivine phryic unit, 28%, and the pyroxene phryic unit and the yellow impact glass unit each 31% (the amount of olivine lost from the picrite basalt and feldspathic microgabbro units can not be determine since the magma compositions of these units are not accurately defined on the basis on only 1 to 2 samples). As these primary magmas cooled and lost olivine, they also assimilated urKREEP redsiduals from the wall rocks. The amounts of incompatible trace elements in the basalts, their trace element patterns (Fig. 3), and isotopic ratios (Fig. 4) are accounted for if the magmas of the olivine phryic and olivine microgabbro units A and B each assimilated about 0.4% of urKREEP residual, that of the pyroxene phryic unit assimilated about 0.5% of the residual, and that of the yellow impact glass unit assimilated 10.5% urKREEP residual (again, until their magmas are accurately defined, the amount of urKREEP residual assimilated by the primary magmas of the two remaining units can not be accurately defined). In all cases, the urKREEP residuals assimilated by the Apollo 15 mare basalt magmas was formed by 7-8% fractional remelting of the parental urKREEP materials. Since all the magmas obtained the bulk of their incompatible trace element from the same type of urKREEP residual, this indicates that either the magmas all used (successively) the same magma chamber or the individual storage chambers were close enough together that the spatial variation in the composition of the residuals was of no significance in the case of the Apollo 15 basalts.

Fig. 1. Observed (open and filled circles for low and high Ti magmas, respectively; the Apollo 15 magmas are also indicated by an x) and calculated (curved lines) variations of the Co contents of the mare basalt magmas as a function of their degree of olivine fractionation (1-f) in the shallow magma chambers shown in Fig. 2.

Fig. 2. Schematic representation of the density-graded bands of the mare basalt source region, the magma storage chambers, and the major steps in the genesis of the mare basalt magmas.

Fig. 3. Observed (lines) and calculated (X's and filled circles) incompatible trace element contents of the Apollo 15 units. The units are: YG - yellow glass unit, PP - pyroxene phric unit, O1 - the very similar olivine phric and microgabbro units, and GG - the green glass units (the continuous line are the data from (8) and the broken line are those from (7)). The calculated values given along the O1 curves is an average fit to all the O1 and PP data together.

Fig. 4. Observed (rectangles) and calculated (filled circles) initial $^{87} \text{Sr}/^{86} \text{Sr}$ values of various mare units as a function of age.
COMPARISON OF PETROLOGY, GRAIN SIZES, AND SURFACE MATURITY PARAMETERS FOR APOLLO 15 REGOLITH BRECCIAS AND SOILS. D.D. Bogard, D.S. McKay, R.V. Morris, P. Johnson, and S.J. Wentworth, Code SN4, NASA Johnson Space Center, Houston, TX 77058 (1 also Northrup Services Inc.; 2 also Lockheed/LEMSCO)

Introduction: We have analyzed 28 Apollo 15 regolith breccias for their petrographic and textural properties and for the surface exposure indices solar noble gases and Is/FeO. These data, along with compositional data determined for the same breccias by R. Korotev, permit detailed comparisons to be made between Apollo 15 soils and Apollo 15 regolith breccias which were formed by lithification of soil components. Two breccias, 15265 and 15086, were disaggregated by either freeze-thaw or ultrasonic techniques and sieved into several grain size fractions in order to examine the soil material that pre-dated breccia formation. The purpose of these experiments is to examine similarities and differences in compositional components and irradiation history between regolith breccias and local, present day soils. A similar study of Apollo 16 regolith breccias is reported by (1), and earlier reports on Apollo 15 breccias were given by (2,3).

Surface Maturity: Various indicators of the duration of exposure of fine-grained material at the lunar surface (surface maturity) show considerable similarity between these regolith breccias and soils and cores returned from the Apollo 15 site. The parameter Is/FeO, a normalized measure of the quantity of fine-grained metal produced by micrometeorite bombardment at the lunar surface, shows a range in these breccias that is typical of Apollo 15 immature and submature soils, although Is/FeO for the breccias do not completely overlap the range for soils at the most mature end of the scale. Mean Is/FeO for 28 regolith breccias is 25.0 whereas for 25 surface soils the mean is 59.8, more than twice as high. Core soils are intermediate; the mean Is/FeO is 39.2 for 46 evenly space samples from the deep drill core (4). Of the 28 regolith breccias analyzed, all but one (15688) contain noble gases implanted by the solar wind in concentrations that are typical for Apollo 15 soils (Fig.1). Agglutinate concentrations for these breccias correlate roughly with Is/FeO, although some breccias (e.g. 15295 and 15505) have few identifiable agglutinates, yet contain appreciable Is/FeO and solar gases. These observations indicate that most Apollo 15 regolith breccias contain a sizeable component that resembles lunar soil, and that most breccias are somewhat less mature than typical soil. No significant compositional difference seems to exist between the solar gases trapped in these breccias and in typical soils. Averaged elemental ratios (and one sigma uncertainty of the mean) of trapped noble gases in 27 of these breccias are: $^4\text{He}/^3\text{He}=161\pm75$, $^{22}\text{Ne}/^{36}\text{Ar}=0.35\pm0.18$, $^{84}\text{Kr}/^{36}\text{Ar}=4.6\pm1.2 \times10^{-4}$, and $^{132}\text{Xe}/^{36}\text{Ar}=0.86\pm0.35 \times10^{-4}$. The last three of these ratios are similar to trapped ratios shown by a large number of bulk soils of different surface maturities from the Apollo 15 drill core (5). The He/Ar ratios for the breccias are considerably lower than the range of values shown by drill core soils, and suggest that greater He loss has occurred from the breccias, probably during mild heating that accompanied breccia formation.

Comparison of Disaggregated Breccias with Soils: Breccia 15086 disaggregated by freeze-thaw has a grain size distribution indistinguishable from a typical Apollo 15 submature soil such as 15071. Other disaggregated breccias including 15265, 15298, and 15565 also resemble soils in their grain size parameters, although some differences exist between the freeze-thaw and ultrasonic versions. A comparison of disaggregated breccia with typical soils from Apollo 15 show very similar properties. For example, disaggregated breccia 15086 contains 41.5% monomineralic fragments in the size range 20-500
um and soil 15601 contains 41.6 percent monomineralic fragments in the same size range. The plagioclase/pyroxene ratio in this breccia is 0.31 in this size range compared to 0.19 in soil 15601. The greatest difference is in the more abundant KREEP basalt in the breccia (10%) compared to this soil (1%), and the lower agglutinate content in the breccia (5%) compared to this soil (28%). As the surface maturity of soil decreases, the noble gases and fine-grained metal are observed to be preferentially enriched in the finest size fraction of the soil. We measured concentrations of solar gases and $I_g$/FeO in the <20 um and 90-150 um grain sizes of disaggregated breccias 15265 and 15086, and these data offer further evidence that the pre-breccia material was irradiated as finely disseminated grains. The ratios of concentrations of these maturity parameters in the two grain sizes are compared to core soils in Table 1. Because noble gases in the 90-150 um grain size were not measured for these core soils, we compare to the bracketing size ranges of 75-90 and 150-250 um measured for the soils. Comparison of gas concentrations of whole rock and grain size data show no evidence of appreciable loss of solar gases during the disaggregation. The five noble gases and $I_g$/FeO have very similar concentration ratios for a given disaggregation experiment, e.g. the ratios are all about four for the freeze-thaw disaggregation of 15265. The concentration ratios for 15265 disaggregated by freeze-thaw are somewhat lower than the ratio of about 7 expected from core soil data, and the ratios for 15265 disaggregated by ultrasonic and 15086 disaggregated by freeze-thaw are somewhat higher than those shown by the soils. These concentration ratios are known to vary with soil maturity and relative retentivity of solar gases (6,7). Lower ratios could result if the disaggregation caused breakage of larger grains and production of small grains with a deficiency of original grain surfaces enriched in solar gases. Higher enrichment factors could result if the disaggregation did not fully break the breccia into its original soil component so that some fraction of the larger grains contain solar gases on interior surfaces. Completely random breakage of the breccia during disaggregation without regard to the original soil grains is expected to produce a concentration ratio of one.

Breccia-Soil Differences: Comparisons of petrologic components, grain size distributions, surface maturity parameters, and chemical composition (8) show that the Apollo 15 regolith breccias are quite similar to Apollo 15 soils. Korotev (8) found the chemical composition of breccias and soils recovered from the same collecting station to be even more correlated. In spite of these similarities, several breccias show significantly higher trapped $^{40}$Ar/$^{36}$Ar ratios than the soils, which suggests that the breccias were formed at significantly earlier times when this ratio was larger at the lunar surface (e.g. 9,1). The five breccias from station 8 have $^{40}$Ar/$^{36}$Ar ratios <1, as do local soils. Five breccias from station 7 near Spur Crater have ratios of 3.3-5, far greater than local surface soil with a ratio of 0.7. Five breccias collected at station 6, some distance from a small crater, have ratios of 0.6-1.3, similar to local soils, whereas, breccias collected near the crater rim, including two chipped from boulders, have ratios of 1.4-2.4. Apparently deeper and older breccias were deposited near the crater rim. One breccia collected at station 9 at some distance from the rim of Hadley Rille has a ratio identical to local soil (0.6). Three breccias collected on the rim of the Rille have $^{40}$Ar/$^{36}$Ar of 1.4-2.3, considerably higher than the range of 0.6-1.1 seen in soils of the 15010/11 core also collected at the rille rim. Higher Ar ratios in these breccias and in the less mature soils of the core are consistent with older regolith being exposed by downslope movement of regolith into the rille.

Table 1. A Comparison of $I_5$/FeO and Noble Gas Concentration Ratios as a Function of Grain Size for Disaggregated Breccias 15265 and 15086 and for Twelve 15010-11 Core Soils

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>BRECCIA 15265</th>
<th>BRECCIA CORE SOILS 15010-11</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;20/90-150</td>
<td>15086</td>
</tr>
<tr>
<td></td>
<td>FT</td>
<td>US</td>
</tr>
<tr>
<td>$^4$He</td>
<td>4.3</td>
<td>11.7</td>
</tr>
<tr>
<td>$^{22}$Ne</td>
<td>3.4</td>
<td>9.8</td>
</tr>
<tr>
<td>$^{36}$Ar</td>
<td>3.5</td>
<td>9.8</td>
</tr>
<tr>
<td>$^{84}$Kr</td>
<td>4.4</td>
<td>10.3</td>
</tr>
<tr>
<td>$^{132}$Xe</td>
<td>4.2</td>
<td>9.3</td>
</tr>
<tr>
<td>$I_5$/FeO</td>
<td>3.7</td>
<td>11.5</td>
</tr>
</tbody>
</table>

* $I_5$ values are <20/90-150 for 5 drill core soils.
FT= freeze thaw; US= ultrasonic

Fig. 1 (below left) $I_5$/FeO versus solar $^{36}$Ar for Apollo 15 and 16 regolith breccias

Fig. 2 (below right) Modal percents of major components in several Apollo 15 regolith breccias
EXTRACTION OF INFORMATION FROM MAJOR ELEMENT CHEMICAL ANALYSES OF LUNAR BASALTS

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When the history of igneous petrology is written in the year 2,100, students of the subject will note that the first hundred and twenty five years or so (1865 to 1990) marked a time when advances in analytical capabilities far exceeded advances in the ability of the petrologist to display and interpret the variability present in chemical analyses of rocks and minerals. One may argue that the quality of the data in today's publications exceeds that of any time in the past with respect to accuracy and precision. Does the fact, however, that the most common forms of displaying petrochemical variability in the past - the binary and ternary scatter diagrams imply that they have been shown to be superior to all other possible forms? I think not. Many authors have expressed the concern that focusing attention upon a subset of the available information is tantamount to ignoring a great deal of the total amount of available information. There is no doubt that this presents a problem for the petrologist to wrestle with but there remains a more fundamental foe. Namely, the form of the data itself.

Major element chemical analyses often form the framework within which one attempts to recognize similarities and differences among analyzed specimens and either to speculate upon the suitability of previously proposed genetic models or to devise a new genetic model to explain the observations. Although some authors have advocated multivariate models, there remains a reliance upon the binary and ternary scatter diagrams in spite of serious concerns voiced by Chaves (1) and others concerning all such analytical approaches when the data are presented as percentages or proportions. Given a set of M amounts (oxide weight percentages, for example) of the chemical constituents in a rock specimen, an increase in one must of necessity result in the reduction of at least one of the others as the sum of all M must remain a constant. A binary scatter diagram, for example, of MgO versus FeO may exhibit a strong negative relationship. How should the investigator interpret such a display? Is it "safe" to assume that one is "viewing" the results of crystal fractionation in which removal of early-formed Mg-rich phases produced a liquid in which Fe was enriched? Or, is it possible that the inverse variation is only a manifestation of the aforementioned constraint upon percentages and proportions in general? A third possibility obviously exists as the "correct" answer may in fact be that both mechanisms - petrogenetic and numeric - may be recorded by the observed variation. One may argue that the problem can be cast in the form of a null hypothesis which states that the variables are "independent" (uncorrelated in this note) and that a standard test of independence can be evaluated; for example,
testing the observed correlation coefficient against a null value of 0.0. Unfortunately, this is the crux of the problem.

Performing such a test (or worse yet, judging the strength of a variation on the basis of simplicity of observed variation) assumes that one knows how to recognize independence in percentages. As Chayes (1) and Aitchison (2,3) have demonstrated, however, such is not the case.

Aitchison (2,3) has proposed a statistical framework within which one may be able to answer questions such as those noted above. Preliminary studies (Butler and Woronow, in preparation) have been encouraging although there remain numerous questions as Aitchison style and notations are somewhat obscure to this geologist. When percentages are formed the ratios of pairs of the components are preserved whereas many of the familiar statistical and geometrical descriptors are likely to exhibit major changes. This ratio-preserving aspect forms the basis for much of Aitchison's proposals.

The set of 42 major element analyses of the "lunar reference samples" (4) was selected as part of a major investigation of Aitchison's proposals. A somewhat subjective decision was made to ignore those variables with mean values less than 0.35 weight percent which yields a set with seven "major variables": SiO₂, TiO₂, Al₂O₃, FeO, MgO, CaO and Cr₂O₃.

An analysis of compositional variability within this set of data must be prefaced by determining if the covariance structure present in this matrix could be the sole result of percentages having been formed from independent components; expressed by Aitchison (4) as a hypothesis of complete subcompositional independence. The computed chi-squared test statistic of 115.9 (with 14 degrees of freedom) greatly exceeds the tabulated chi-squared value of 23.7 at the 95% confidence level. Thus the null hypothesis is rejected and, in the opinion of the author, one can safely proceed with an analysis of the data set. Failure to reject such a null hypothesis should call a halt to such extensions as one would be assigning petrogenetic significance to variability most likely induced by forming percentages.

Following Aitchison's (3) suggestions, the set of 6 non-zero eigenvalues and associated eigenvectors were extracted from the variance-covariance matrix of the log-row-centered form of the data set. In effect, each component in a sample is normalized to the geometric mean of the sample.

A plot (Figure 1) of the first versus the second principal component scores (I and II) displays more than 96% of the total variability of this data set. No single pair of components in the set of oxide weight percentages or log-row-centered variates accounts for more than some 70% of the total variability of the array. The correlation coefficient between scores I and II is constrained to be zero yet "clusters" of similar specimens are evident. An analysis of the correlations among scores I and II and the raw data set (including the computed magnesium number) indicates that the first score is a measure of TiO₂ and Cr₂O₃.
MAJOR ELEMENT CHEMICAL ANALYSES OF LUNAR BASALTS
Butler, J.C.

variability whereas the second score correlated with Mg number and Al₂O₃ (see Figure 1). For example, within each outlined cluster there is a systematic variation of Mg number (given just for the set of Apollo 12 ilmenite basalts).

The potential utility of such a plot should be evident. First, it is based upon a data set in which one "knows" that the petrologic information content exceeds that expected from having formed percentages from independent variables. Second, very little information is not contained within the plane defined by the first two principal components. Although it may be comforting to note that the familiar groups of lunar samples are recognized in Figure 1, this in and of itself is not a justification for the process.


Figure 1. A plot of the first two principal components (I and II) from the set of 42 Lunar Reference Samples (4). GG and OG refer to Apollo 15 green glass and Apollo 17 orange glass respectively. VLT refers to the very low titanium basalts and the prefix L denotes Luna basalts. F refers to the feldspathic-rich basalts, PI to pigeonite-bearing basalts, OL to olivine basalts and IL to ilmenite-rich basalts.
Introduction

The Apollo 15 landing site contains mare volcanics in the form of crystalline basalts (open symbols in Figure 1) and pristine glasses (solid symbols), which form the framework for all models dealing with the mantle beneath that site. This abstract summarizes some of the major issues bearing on the petrology of the mare source-regions beneath that portion of Mare Imbrium.

Magmas at Apollo 15

Petrologists who study the Earth's upper mantle rely on (a) basaltic magmas and (b) ultramafic xenoliths. While that combination of samples has proven successful in furnishing first-order information about the chemistry of the terrestrial upper mantle, this dual approach has not been possible on the Moon due to the absence of ultramafic xenoliths. As a result, lunar petrologists have had to depend only on mantle-derived magmas (i.e. LIQUIDS). This has involved searching for volcanic samples with vitreous or aphanitic textures without accumulated mineral-phases (e.g. 15016; 15597; pristine glasses). Six major varieties of magma, plus four sub-varieties, have been identified by investigators since 1972 (Table). These magmas include: (a) quartz-normative basalt 15597; (b) olivine-normative basalt 15016; (c) five varieties of pristine green glass; (d) pristine yellow glass; (e) pristine orange glass, which is chemically indistinguishable from that found at Apollo 17; and (f) pristine red glass. These magmas can not have been derived from one another by crystal/liquid fractionation and hence represent 10 separate volcanic events (e.g. Chappell and Green, 1973; Ma et al., 1978; Walker et al., 1977).

The Apollo 15 magmas are compositionally diverse. For example, the range in Ti-abundance among these magmas is nearly as large as that observed for the entire collection of mare samples returned by all Apollo missions. Although this compositional variety in magmatic samples from one landing site probably has important implications for the chemical diversity in the lunar mantle, caution must be exercised since the eruptive sites of these magmas are not known. Consequently, local provenance is not assured for all ten magmas.

Primary versus Differentiated

Following the identification of samples that represent magmatic compositions, petrologists ascertain whether each magma was primary or differentiated. A magma is primary if it ascended from its source-region without undergoing changes in its original chemistry. A differentiated magma, however, underwent assimilation of wall-rock and/or crystal/liquid fractionation, such that its chemistry has been altered subsequent to leaving the source-region. Primary magmas possess vital petrologic information about their source-regions. However, primary magmas are rare. For example, fewer than 1% of the magmas erupted onto the Earth's surface are primary (Walker et al., 1979; p. 2009).

To determine whether a magma is primary, petrologists focus on the abundances of elements that are most sensitive to differentiation processes (e.g. Mg, Ni). While this approach in tandem with studies of ultramafic xenoliths has led to a consensus on the chemical nature of primary MORB's (mid-ocean ridge basalts) on Earth (e.g. Elthon and Scarfe, 1984; Green et
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al., 1979; Stolper, 1980), the absence of ultramafic xenoliths among lunar samples has made the task of identifying primary lunar magmas more difficult (Bence et al., 1980).

The Apollo 15 magmas are plotted in Figure 1a against an element that is sensitive to differentiation (Mg). Note that the basalts, 15016 and 15597, have lower Mg-abundances than the pristine glasses. A similar relationship also exists at Apollo 11, 14, and 17, and suggests that the magmas represented by the crystalline basalts appear to be differentiated compared to the pristine glasses (e.g. differentiation drives magmatic compositions to the left in Figure 1a). The pristine glasses are the best candidates for primary magmas yet identified (e.g. Binder, 1982, 1985a,b; Delano and Livi, 1981; Delano, 1985; Green and Ringwood, 1973; Marvin and Walker, 1978).

However, while the quartz-normative basalt 15597 can be confidently concluded not to be a primary magma (see next section), the olivine-normative basalt 15016 can not be completely excluded from consideration.

Depths of Mantle Source-Regions

To constrain the depths of source-regions, petrologists must (a) identify primary magmas and (b) assume that two-or-more minerals were present in the residue during partial melting. While it is generally agreed among terrestrial petrologists that olivine + pyroxene(s) were residual phases in the source-regions of MORB's (e.g. Elthon and Scarfe, 1984; Green et al., 1979; Stolper, 1980), this consensus has emerged only after years of investigations on MORB samples and ultramafic xenoliths. Unfortunate for lunar petrologists, the absence of mantle-derived xenoliths has severely restricted efforts to evaluate whether or not the "2+-phase assumption" is valid in the case of primary mare magmas. Consequently, the depth of the mare source-regions remains a contentious issue (e.g. Binder, 1982, 1985a,b; Delano, 1980, 1985).

IF the "2+-phase assumption" is correct, Figure 1b shows the experimentally determined depths of the source-regions for the Apollo 15 magmas. First, note that the depth indicated by quartz-normative basalt 15597 is only about 50 kilometers (i.e. within the anorthositic highlands crust). This result, in concert with this magma's low Mg-abundance (Figure 1a) prompted Walker et al. (1977) to conclude that the quartz-normative magma is not primary, and hence provides few direct constraints on the petrologic nature of the lunar mantle. Second, the experimental results derived from the pristine glasses (solid symbols in Figure 1b) suggest that these magmas were all derived from the limited depth-interval of 350 km to 450 km (e.g. Delano, 1980; Green et al., 1975; Grove and Lindsley, 1978; Kesson, 1975; Stolper, 1974). Since these Apollo 15 magmas have Ti-abundances that vary by a factor of 30, this implies that the lunar mantle is heterogeneous (e.g. Bence et al., 1980). Finally, Stolper et al. (1981), noting that the pressures in the source-regions of MORBs (25-35 kbars) and mare magmas (20-25 kbars) were similar, speculated that it may be related to melt compressibility and the resulting buoyant force. If that comparison is significant, it suggests a physical basis by which the depths experimentally inferred for the mare sources (Figure 1b) using the "2+-phase assumption" might be meaningful.

IF the "2+-phase assumption" is not correct for the primary mare magmas, as argued by Binder (1982, 1985a,b), then the experimentally derived depths shown in Figure 1b have no significance other than to be maxima. Binder has proposed that the mare source-regions were located at depths of about 200 km.
The Mg/(Mg + Fe) ratio in the silicate residuum of the source-regions can be determined using the chemistry of primary magmas. Based upon the compositional- and pressure-dependence of the Fe- and Mg-distribution coefficient (K_D) between olivine and liquid, the Mg/(Mg + Fe) ratios of the residuum have been determined for the Apollo 15 mare magmas (e.g. Delano, 1980; Green et al., 1975; Grover et al., 1980; Longhi et al., 1978). Differentiation of a magma would drive the calculated points in Figure 1c to the left toward lower values of the ratio. Note that the residual silicate(s) in the source-regions of the Apollo 15 pristine glasses have a range of only 10% (i.e. from 0.77 to 0.85), even though the Ti-abundance among these magmas differs by more than a factor of 30. This suppressed variation of the Mg/(Mg + Fe) ratio of the lunar mantle has been noted at other Apollo landing sites (e.g. Green et al., 1975; Walker et al., 1975). Since this parameter involves few assumptions, it is a reliable indicator of an important characteristic of the lunar mantle. In recognition of its importance, various models for the magma ocean have been proposed to account for it (e.g. Binder, 1982, 1985a,b; Longhi, 1981; Ringwood and Kesson, 1976).

Remaining Questions
(a) Were any ultramafic xenoliths carried to the lunar surface by mare volcanism?
(b) What process(es) suppressed variation of the Mg/(Mg + Fe) ratio in the differentiated lunar mantle?
(c) How deep were the mare source-regions?
(d) Where are eruptive sites of the chemically diverse magmas at Apollo 15?
(e) Why are mare magmas about 2x richer in FeO than terrestrial MORB’s?
(f) How thick was the magma ocean?
(g) Where did the volatiles associated with the basalts and pristine glasses come from?
(h) Are there pieces of the Eratosthenian-age basalts from Mare Imbrium (e.g. Boyce et al., 1974) in the Apollo 15 sample collection?
(i) What processes caused the unique fractionation trends in the Apollo 15 pristine green glasses (Basu et al., 1979; Delano, 1979; Delano and Lindsley, 1982; Grove, 1981; Ma et al., 1981)?

REFERENCES
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TABLE: Major-element compositions of Apollo 15 mare magmas.

<table>
<thead>
<tr>
<th></th>
<th>BASALTS</th>
<th>PRISTINE GLASSES</th>
</tr>
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<tr>
<td></td>
<td>1 2 3 4 5 6 7 8 9 10</td>
<td></td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>44.1</td>
<td>48.0 45.5 46.0 45.1</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>2.29</td>
<td>1.84 0.26 0.38 0.40</td>
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<tr>
<td>Al$_2$O$_3$</td>
<td>8.41</td>
<td>9.36 7.74 7.75 7.92</td>
</tr>
<tr>
<td>Cr$_2$O$_3$</td>
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<td>0.49 0.57 0.56 0.55</td>
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<tr>
<td>FeO</td>
<td>22.8</td>
<td>20.2 16.5 19.7 19.1</td>
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<tr>
<td>MnO</td>
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<td>0.28 0.19 0.22 0.22</td>
</tr>
<tr>
<td>MgO</td>
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<td>8.96 18.2 17.2 17.2</td>
</tr>
<tr>
<td>CaO</td>
<td>9.30</td>
<td>10.1 8.57 8.65 8.75</td>
</tr>
<tr>
<td>Na$_2$O</td>
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<td>0.32 n.d. n.d. n.d.</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.04</td>
<td>0.06 n.d. n.d. n.d.</td>
</tr>
</tbody>
</table>

[9] Pristine orange glass that is indistinguishable from 74220 (Delano and Livi, 1981).

FIGURE 1

APOLLO 15 MARE MAGMAS
INTRODUCTION. Prior to the Apollo missions, the origin of sinuous rilles— including the Hadley Rille—was a contentious topic. Although most workers agreed that a fluid of some sort was involved in rille origin, the nature of the fluid and of the process(es) involved in rille formation were debated. Hypotheses included origins related to volcanic ash flows (1), water, including periglacial and fluvial processes (2), fluidization of regolith resulting from outgassing (3), and to processes associated with basaltic lava flows (4). Based on comparisons with terrestrial analogs, it was proposed that the Hadley Rille (and similar lunar sinuous rilles) was a lava channel, parts of which were roofed to form lava tube segments (5). This interpretation was based on observations that Hadley and other lunar sinuous rilles (6): (a) appear to originate in irregularly-shaped depressions (inferred to be vents), (b) trend generally down slope, (c) have discontinuous channels and cut-off branches, (d) are fairly uniform in width, or narrow toward the terminous, (e) are restricted to mare surfaces and appear to be controlled by pre-mare topography, and (f) may form topographic highs along their axes. Moreover, lava tubes and channels are common in certain types of basaltic lavas; thus with determination of basaltic compositions for the mare lavas, the lack of extensive ash flows, and the lack of evidence for water, the hypothesis for rille origin narrowed to the now-generally-accepted lava channel/tubes origin.

GEOLOGY OF LAVA TUBES AND CHANNELS. Results from the Apollo 15 mission raised several key questions regarding the general geology and volcanic history for the site, and the role of the rille in the emplacement of lavas within the Hadley valley (7). Among these are questions related to: the sequence and style of emplacement of the mare lavas; thickness(es) of the flow unit(s) and total flow accumulation; possible ponding of lavas in the Hadley valley; sources of glasses and other volcanic materials near the landing site; and explanations for the topography along the rille. Consideration of the general geology of terrestrial lava tubes and channels (8) may shed light on some of these questions:

1. Lava tubes/channels typically form in flows of basaltic composition (although they could form in other flows of comparable rheological properties), erupted at moderate rates of effusion (lower than flood eruptions); this style of eruption ("Hawaiian") tends to produce thin (< 5m), flows that are produced by long-duration eruptive periods. However, the effusion of lava is sporadic, not continuous, and this results in surges of lava and the formation of multiple flow units.

In general, the longer a given eruption sequence is active, the better established and larger the feeding tube/channel system. Moreover, previous tube-channel systems are frequently reactivated by later flows, even after long periods of quiescence. Thus, one would expect to see multiple, thin flow units in the walls of Hadley Rille. Although the size of Hadley Rille exceeds the largest of terrestrial tubes/channels by an order of magnitude, one might infer that it was the consequence of a very long-duration eruptive sequence, perhaps more than 100 years.
2. Flows fed through tubes and channels are emplaced by secondary (distributary) tubes and channels, as well as by overflow from open channels. Because lunar lavas are so low in viscosity (9), they would be expected to spread out in thin sheets from the rille as surges and flow units, leaving little in the way of flow fronts. The roofs of lava tubes, including distributary tubes, often rupture and produce local flows and other volcanic material. There is often the appearance of local vents that may, in fact, be "rootless". Thus, samples obtained in the vicinity of the Apollo 15 landing site may resemble near-vent products, but may have been derived from the cleft-shaped source-vent for the rille.

3. The formation of a tube roof, or of a crust on channelized flow, retards heat loss from the active lava, allowing greater flow lengths, and also retards loss of volatiles (in some respects, lava tubes are extensions of the vent conduit). Thus, some flow units emplaced via tubes/channels are vesicular at long distances from their source vents. On the other hand, fountain-fed flows may also collect and be emplaced via previously-formed tubes and channels; during fountaining, degassing often occurs. Thus, some of the flow units may also be nonvesicular.

4. Lava tube flows may erode by thermal (i.e. partial melting) and mechanical processes, as has been documented in terrestrial flows (10, 11, 12); in one case, a tube entrenched into pre-flow materials to a depth 4x the thickness of the flow (13). In addition, numerical models (14,15,16) suggest that extensive thermal erosion may occur in the development of lunar sinuous rilles. Thus, Hadley Rille may be entrenched substantially below the flow contact with valley floor. Thermal erosion (melting) could, in principle, alter lava compositions by assimilation during the lava flow emplacement via the tubes/channels.

5. Lava tubes/channels are primarily constructional features in that they emplace lava flows, both laterally and at the flow front. Accretion of lava along the sides of open channels, and via distributary tubes and channels raise the topography along its axis. However, the position of the tube may shift as it migrates (meanders) during active flow, and the axis does not always coincide with the topographically highest part of the flow. With drainage of the tube/channel and collapse of the roof segments, one side of the structure may be higher than the other side. In addition, the final "trench" may expose flow units of different textures and possibly different compositions, and the trench may cut into pre-flow rocks.

HADLEY RILLE AND APOLLO 15. Hadley Rille trends northwest and then east over 120 km in a valley between the Apennine scarp of the Imbrium basin and large terra slump blocks from the front. The rille is almost completely confined within mare material, although the source crater straddles the mare-highlands boundary (5,17). At the Apollo 15 site, the east (near) rim of the rille is about 30 to 40 m higher than its corresponding farside. In this locality, the rille is about 300 m deep and 1500 m wide. Apollo 15 photographs and observations show that the rille walls expose at least three different mare units. The lowermost layered unit (~8 m thick) is overlain by talus and debris (~5 m). This sequence is overlain by a massive, poorly-jointed unit, about 17 m thick. On top of the massive unit is a thin (1-2 m) dark unit, on which regolith is developed (7). These exposures give direct evidence for at least 30 to 40 m thickness of basalt in the landing site area. On the basis
of geologic reconstruction of returned mare samples, it appears that Apollo 15 olivine-normative and quartz-normative basalts are representative of the upper dark unit and middle massive units, respectively (18,19).

On one of the traverses, Scott noted a dark band and topographic bench along the base of Mt. Hadley. This bench, clearly seen on orbital pan photographs, has been taken as evidence that the mare lavas in the site vicinity were ponded in this area to a thickness on the order of 900 m (7). If this interpretation is correct, the rille may have served to drain this ponded lava. Of the two Apollo 15 basalt groups, the olivine-normative basalts show an olivine fractionation trend (20). Moreover, "peridotitic" basalts, originally interpreted as from a separate lava flow (21) but in fact, possibly related to the olivine-normative group by olivine crystal accumulation, are found in Spur crater ejecta, 60 m above the current mean mare topographic level. This may be consistent with ponding of the olivine-normative basalts in the site area; if the rille served as a conduit to drain the lavas, the 1-2 m thickness of olivine basalt observed at Sta. 9A is not a simple flow unit, but a veneer of lava left by the draining lava lake. The present exposure of this unit within the rille wall would then be due to post-draining collapse of the rille walls inward (7).

A question of crucial importance to Apollo 15 site geology is the total thickness of basalt at the site. The actual LM site lies atop a low (5 m), broad ridge; at this location, only one (quartz-normative) mare basalt (15058) was collected. The remaining samples are regolith breccias (that contain comminuted mare basalt debris). Petrography of soils at this site indicate up to 50% non-mare material (22). Although this could be due to post-mare ray material (18), it is also possible that mare basalts in this area are very thin (23). This is not precluded by the observations of basalt in the rille walls; the LM site is ~2 km from Sta. 9A and if 60 m of basalt pinched out to zero at the LM site, it would imply an average pre-flow slope of less than 2°.

It is possible the exposed portion of basalt seen in the walls of Hadley Rille represent the entire thickness of basalt at the site. In this case, rille formation must have included downcutting and erosion of some type (14). Both thermal and mechanical erosion during rille formation may have occurred, but it is difficult to say which was dominant. Significant erosion by complete melting is unlikely because extruded mare lavas would not be superheated, as evidenced by phenocrysts in Apollo 15 mare basalts. However, some assimilation could produce partial melting of sub-mare, brecciated basement and this in turn would exacerbate mechanical erosion, which was probably already occurring during the high volume effusion of low-viscosity mare lavas (9). There is no evidence for a "delta" of eroded basement debris at the rille terminus, but this material could be covered by the late-draining lava pond, described above.

CONCLUSIONS. Hadley Rille appears to be a collapsed lava tube/channel, whose formational history may be more intimately related to the mare units sampled at Apollo 15 than had been previously thought. More work is needed relating samples and observations from Apollo 15 to the rille and its geologic evolution. As the only sinuous rille visited during the Apollo missions, Hadley Rille presents us with a data resource that is directly applicable to the deciphering of processes involved in lunar mare volcanism.
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This overview will be restricted to a discussion of the geologic history of the quartz normative (QNB) and olivine normative (ONB) basalt types at Hadley Rille. A model for the geology of the mare basalts has been constructed from a combination of field observations, sample chemistry, sample petrology and personal bias from terrestrial experience. This model is speculative and proposes that the QNBs are the only mare lava type that is present as outcrop in the area traversed by the astronauts during the Apollo 15 mission. The returned QNB samples formed during a single eruptive phase of the Hadley Rille lava tube system. The ONB lavas are an exotic component transported to the site by a cratering event, perhaps by the event that formed Aristillus or Autolycus craters, or the ONBs are samples excavated from older mare bedrock that was partly covered by the QNB lavas. This model differs from the conventional one, which interprets the ONB lavas as a younger flow that overlies the QNB lavas. Several investigators have proposed that Hadley Rille is a giant collapsed lava tube (1,2,3). Like terrestrial lava tubes the Hadley Rille follows older fault controlled topography. At bends in the rille the outside has less curvature than the inside, the rille is deepest where it is widest, and the rock benches and talus deposits in the rille are similar to those found in terrestrial collapsed lava tubes.

Chemical and isotopic variability of mare lavas at Apollo 15. Two distinct compositional types were identified in the Apollo 15 mare basalt collection (excluding the older KREEP basalts). Major and trace element analyses (4,5) indicated that the QNBs showed limited within group compositional variations which could be explained by a small amount of near surface fractionation of olivine, spinel and/or pyroxene (<7%). The ONB group showed within group compositional variability caused by olivine fractionation (<15%). The two basalt types are not related to one another by any simple fractional crystallization process. The ONBs have higher FeO, TiO2 and lower large ion lithophile element concentrations compared to the QNBs. Combined assimilation of anorthositic lunar crust and fractionation of an ONB-like parent can not produce the QNB compositional trend, because ONB lavas have higher normative plagioclase than the QNB lavas. The Rb-Sr ages and the initial 87Sr/86Sr of the ONB and QNBs overlap, and range from 3.28 to 3.44 AE and 0.69923±6 to 0.69937±4 (6).

Geology of mare lavas at Apollo 15.

QNB lavas. The dominant rock type sampled on the mare surface at Hadley Rille is QNB lava (7,8). The QNBs were sampled from the highest bedrock outcrop at the edge of the rille (sta. 9A). The textural characteristics of the samples obtained from the outcrop at sta. 9A indicate that this outcrop is the top of a lava flow (9). A large vesicular block at Dune Crater (sta. 4) is also a block of the QNB flow top. The thermal histories inferred for the QNB flow top vitrophyres are two stage, characterized by initial slow cooling followed by rapid cooling. The overbank deposits of a lava tube would be expected to experience similar thermal histories. At Elbow Crater (sta. 1) coarse-grained samples of QNB lava were excavated. These station 1 QNB microgabbros are samples of the slowly cooled interior of the QNB flow complex. Among the station 1 samples, 15065 and 15085 experienced the slowest
cooling histories (9,10) and crystallized in the center of (a) lava flow(s) >20 m in thickness. The layered outcrops in Hadley Rille were interpreted (8) as flows with thicknesses of 10 to 20 meters. LSPET (8) describes these flows as light colored, massive units which contain prominent vertical joints and horizontal partings. An upper dark unit overlies the massive outcrops, and some layering resembles pahoehoe draining from beneath cooled crust.

The estimated physical properties of the QNB magma (9) and the restricted chemical variability of the QNB samples favor this lava as the occupant of Hadley Rille. Near liquidus viscosity is low (<100 poise) and the density contrast between pyroxene and liquid is slight (+.10 gm/cm³). In this physical state the QNB lavas could flow in the tube system and undergo little change in bulk chemistry through differentiation by pyroxene settling. Presumably all liquidus olivine originally present in the QNB had settled out of the magma during an earlier upstream differentiation episode.

Terrestrial experience with collapsed lava tube systems at Medicine Lake Highland, California has shown that processes operating in a single lava tube system can create a complex range of cooling histories which results in substantial textural diversity in chilled lava samples. The QNB textural variations fall within the range sampled from a single flow in the 50 km long Giant Crater-Chimney Crater flow at Medicine Lake.

ONB lavas. The ONB lavas were sampled at all the mare sites, and this basalt component constitutes a substantial part of the soil at station 9A, and at the lunar module (11). The hand samples were commonly found to be isolated fragments; 15016 (sta. 3) was described as having been on the mare surface for a long time, while the sta. 9A samples (15535, 15536) were described as fresh crater ejecta. The textures of these ONB lavas are porphyritic to gabbroic, but no vitrophyric ONB samples have been identified from rake or hand samples (12). A textural characteristic of the gabbroic samples is that plagioclase poikilitically encloses sub-rounded olivine and pyroxene grains. The porphyritic samples contain radiate plagioclase and pyroxene intergrowths and olivine phenocrysts. An early and enduring interpretation of the ONB samples is that they represented a flow that had been degraded by meteorite impact (7,8). To explain the large proportions of ONB in the soil at stas. 9, 9A and LM, it was proposed that an ONB flow was stratigraphically above the QNB flows. This interpretation of an ONB-QNB flow contact is not consistent with textural characteristics of either basalt type. At Station 9A there are no ONB vitrophyres. Vitrophyres would be expected to form at the basal ONB chill margin. The vitrophyres at station 9A are QNBs, and these are fresh, and show no evidence of reheating by a later overlying flow. Terrestrial experience indicates that reheating of the proposed underlying QNB would be recorded by textural changes. The ONB samples with the plagioclase-poikilitic textures do show textural characteristics similar to those found in basalts heated by a later flow. Therefore, textures would suggest that the ONB flow was older. A simpler explanation is that the ONB lavas were transported mare ejecta from the Aristillus-Autolycus cratering event. The South Cluster and the bright ray that trends northwest across the Hadley Rille site were formed by this cratering event which impacted Mare Imbrium to the southeast. An alternative is that the ONB lavas are older bedrock that make up the NW trending ridge (Fig. 5-41, ref. 8) buried beneath younger QNB lava tube deposits.
GEOLOGIC HISTORY OF APOLLO 15 BASALTS

Grove, T. L.

The lunar regolith is a complex mixture of many components. A major goal of compositional studies of lunar regolith is to use the compositional data to identify and estimate the relative importance of the various chemical components of the regolith. This paper reviews the results and conclusions of four methods that have been applied to Apollo 15 regolith data and samples to determine the important chemical components: graphical techniques, analysis of individual soil particles, factor analysis, and multicomponent mixing models. This synthesis relies heavily on data and conclusions from the literature as well as new analyses on 28 regolith breccia samples, 28 soil samples, and 50 individual 1-2 mm particles from soil 15272 [Korotev, unpub.].

Graphical. Fig. 1 is a plot of the concentrations of Sm and Sc in soils and regolith breccias compared to those in some important rock types found at Apollo 15. The Sm vs. Sc plot, which is essentially equivalent to the plot of Sm vs. Cr [11] is useful because compared to many other two-element plots the overlap of fields for different rock types is minimal. Fig. 2 is a plot of Mg⁰ (mole % Mg/(Mg+Fe)) as a function of alumina concentration for the soils. These plots reflect most of the compositional variation observed in the Apollo 15 regolith. Although the variation among stations is considerable, soils from a given station are more similar in composition to each other than they are to soils from other stations (Fig. 1). The greatest range is seen in the stn. 7 soils from Spur Crater.

Most of the variation in soil compositions results because the soils are predominantly binary mixtures containing different proportions of mare material and highland material from the Apennine Front (AF). This is similar to what is observed at Apollo 17 which is also at the interface between the mare and highlands [e.g., 10]. At one extreme are the soils from station 9a at Hadley Rille which are the most similar in composition to the mare basalts. Even these soils, however, are richer in incompatible trace elements (ITEs) and generally less mafic than the basalts, indicating the presence of some nonmare material in the soil. At the other extreme, the least mafic and most feldspathic soils are samples from the bottom (55-57 cm) of the 15007/8 drive tube at stn. 2 on the AF [Korotev, unpub. data]. These soils are less mafic than the stn. 2 surface soils and are presumably the most representative of the AF in being the least 'contaminated' by mare basalt. Most of the other soils are intermediate in composition between these two extremes. Important exceptions are some samples from stn. 7. In both Figs. 1, 2 and 3 samples of soil 15421 and regolith breccia 15426 plot closest to the point for pure green glass separated from 15426. Other stn. 7 soils and breccias plot between the green glass and the stn. 2 soils. Another perturbation to the dominant mare-highlands mixing trend is that soils from stn. 6 (AF), stn. 9 (Hadley Rille), and the LM area plot to the high-Sm side (Fig. 1) of the mare-AF mixing line, suggesting that a KREEP-like material is also a component of these soils.

Regolith breccias collected at a given station are usually similar in composition to the soils from the same station (Fig. 1b). Some breccias have more extreme compositions than the soils, however. Station 9a sample 15688 is indistinguishable in composition from a mare basalt and thus contains a smaller nonmare component than any of the soils. Stn. 7 sample 15425 is more nearly similar to the pure green glass separated from it than soil 15421. Approximately a third of the breccias have higher concentrations of Sm and other ITEs than any soil, with four samples approaching the levels in Apollo 15 KREEP basalt. These Sm-rich breccias are found at both mare and AF stations and cannot be lithified local soil as no returned soil contains such high ITE concentrations. They may be exotic to the immediate Apollo 15 site.

Thus, in order to explain the trends on the variation diagrams of Figs. 1 and 2, a minimum of only four components is required. Three of these can be unambiguously associated with local materials represented by rock types which are regarded as primary (i.e., not polymict): Apollo 15 green glass (a rock type in the chemical sense), mare basalt, and KREEP basalt. The 4th component is a noritic component and is principally associated with the AF and the stn. 2 soils. The relationship of the AF component to local rock will be discussed in more detail later, but the similarity to the dark melt portions of breccias 15445 and 15455 is obvious from Figs. 1 and 2. The composition of these melts is often equated with, if not defined as, the 'LKFM composition' [9, 13].

Soil particles. Plotted in Fig. 3 are data for the 50 largest particles in a 225 mg allocation of station 6 (AF) soil 15272, the 1-2 mm grain-size fraction of 15270. About 21 of the particles are similar in composition to the <1 mm soils from stn. 6 and are probably small regolith breccias like the larger samples plotted in Fig. 1b. Three of the particles are mare basalts and two resemble soils from other stations (1 and 2). Eighteen are
CHEMICAL COMPONENTS OF THE REGOLITH
KOROTEV, R. L.

slightly to considerably more enriched in ITEs than the station 6 soils. Only six of the
particles are less mafic (and presumably more anorthositic) than the station 6 soils. Two of
these are troctolitic anorthosites and one has a composition somewhat similar to that of the
melt portions of 15445 and 15455. No particles similar to anorthosite 15415 or anorthositic
norite 15418 were found. These results and those of [6] for particles from the deep-drill
core (stan. 8/LM) indicate that >1 mm particles of mare basalt are common in the soil from
the mare but not from the AF and that >1 mm particles of KREEP-like material are common in
both mare and AF soils. In fact, the mean concentration of Sm in 15272 (1-2 mm) is 30%
greater than that in 15271 (<1 mm), indicating a significantly greater proportion of KREEP-
like components in the 1-2 mm size fraction. These KREEP particles may be relatively recent
ejecta from a local crater which sampled underlying KREEP basalt. Many appear to be dark
and crystalline; some have glass coatings. Note that several of the regolith breccias with
Sm concentrations greater than the soils in Figs. 1b and 3 are also richer in Sc than the
15272 particles plotting in the same area. This indicates that some of the non-soil-like,
ITE-rich regolith breccias (namely, 15025, 15028, 15205, 15528, and 15565) have only a small
component of AF material compared to the soils and, thus, are primarily KREEP - mare basalt
mixtures. This is basically the conclusion reached for 15205 on petrologic grounds [4].

For the 15272 particles the AF component is carried primarily by the glassy breccias of
bulk soil composition, but also in part by the few 'ANT suite' particles. There is little
information in these particles about what more primary rock types accounts for the overall
noritic composition of the AF soils. We can conclude, however, that unlike the KREEP compo-
nenent the Apennine Front soil component (AFSC) is fine grained and well mixed.

Factor Analysis. Two- and three-element variation diagrams are useful because they are
conceptually simple and geometrical arguments can be used to show mixing relationships. A
disadvantage is that conclusions based on one such diagram may be contradicted by another
when different elements are used. Compositional trends using all available data can be used
to imply end-member components with computer techniques of factor analysis or principle com-
ponent analysis. Despite the potential utility of these techniques there are very few
applications to lunar regolith studies. One of these is the study of Apollo 15 soil composi-
tions by Duncan et al. [3] in which factor analysis was applied to major and trace
element concentrations in Apollo 15 soils. This study concluded that most of the soils lie
on a mixing line between mare basalt and LKFM, but that soils from stations 6, 9, and LM
contained "more KREEP material than other soils". (The importance of the green glass in
stn. 7 soils is not evident in this study because the stn. 7 soil composition used was that
for the stn. 7 soils that resemble stn. 2 soils, not the 15421 extreme.)

An important conclusion from each of the techniques discussed above is that there is no
requirement in the soil data for components of anorthosite or anorthositic norite ('gabbro')
to explain the variation in the data. Although these rock types occur as particles in the
soil and are highly visible in the large rocks (15415 and 15418), the variation in composi-
tion of Apollo 15 soils is not primarily the result of variation in anorthositic components.

Mixing Models. Once the likely components of the soils are identified the validity of the
choice can be tested and the relative proportions of the various components estimated by
using 'mixing models'. The validity of the results of mixing model calculations depends on
the reasonableness of both the components selected and the compositions chosen to represent
the components. It is sometimes implied that a 'good fit' proves that the set of components
selected represents the reasonable and true components of the soil. This is not true. The
models can only 'prove' that a particular set of components does not fit the soil composi-
tion. Good fits can be obtained from unreasonable components. It is important to keep in
mind that components used to model a soil mixture and the compositions used to represent
those components are assumed input parameters to the calculations; they are not model
results or predictions.

The contents made above are easily demonstrated by Table 1 and 2. Table 1 presents
a summary of components used in nine different models which have been applied to Apollo 15
soils and breccias. No two models are the same in regard to either which components are
assumed to be the important components or which compositions are used to represent the com-
ponent. Each provided a sufficiently good fit to the data that the authors were confident
enough to publish the results, however. It is impossible to rigorously compare the good-
ness of fit of the various models because different elements were used in each and because
two models which may provide equally good fits in a mathematical sense may not be equiva-
cently good in a geochemical sense (the latter is more subjective). Table 1 represents
differences in model input assumptions.

Table 2 summarizes some model predictions for stn. 2 soils, i.e., those AF soils with
the lowest fraction of mare basalt. (Models in Table 1 which are not in Table 2 did not
include stn. 2 soils.) The differences in model predictions in Table 2 are a direct result
of the differences in input assumptions of Table 1. Despite the differences in the various models, there is some concensus. Mare basalt and green glass are clearly important components. Many models include both olivine- and quartz-normative basalts. Considering the similarity in composition of these two basalt types compared with their mutual difference in composition to the other rock types used in the models, it is unlikely that the models can truly predict the prevalence of one over the other for any but the most basalt-rich soils. For these, model results indicate a decided predominance of olivine basalt over quartz basalt of 5-10 to 1. Each of the soil models also includes KREEP, either Apollo 15 type (La = 230-250 times chondritic) or Apollo 14 type (La = 300-330 times chondritic). Because of the relatively small proportion of KREEP required to obtain mass balance for the ITEs, the models are not too sensitive to which kind of KREEP is used. The only effect is that models using Apollo 14 KREEP (high-K) predict a slightly lower proportion of KREEP in the best-fit mixture than those using 15386 KREEP (intermediate-K).

The major differences among the models is what rocks are used to represent the AF component. All models include some type of LKFM component as norites of this approximate composition are most nearly similar to the composition of the AF soils. However, some of the models do and others do not also include anorthositic components, either anorthosite such as 15415 or anorthositic norite ('gabbro') such as 15418. As noted earlier, there is no indication in the compositional data that such components are necessary to explain any of the variation in the soil data. This is not to say that anorthosites, anorthositic norites, and anorthositic troctolites, etc. are not components of the soils. If they are important components they must occur as well-mixed subcomponents of the AFSC. A multielement model that we have tested which accounts for the composition of Apollo 15 soils as well as any model listed in Table 1 requires only four components: mare basalt, green glass, KREEP, and an AF component represented by the least mafic soils from the 15007 (stn. 2) drive tube. These are the only four components needed to account for the variation in the soil data. Because the first three components are local rock types, the problem of modeling Apollo 15 soils in terms of mixtures of local rock types is thus reduced to modeling the AF soils.

The Apennine Front Soil Component (AFSC). The AF component is often identified as LKFM or other noritic compositions such as the dark melt portions of 15445 and 15455. The latter and other noritic rocks of similar composition are not alone sufficient to account for the soil data. As seen in Fig. 2, the stn. 2 soils are considerably more ferroan (Mg' = 61) than the 15455-type melt and other Apollo 15 norites (Mg' > 70). The AF soils must contain at least two ferroan components with a sufficiently high concentration of Fe to reduce the bulk Mg/Fe ratio. One of these is mare basalt. The curved line in Fig. 2 is the mixing line between stn. 9a soils (richest in mare basalt) and the stn. 2 soils (poorest in mare basalt). The line assumes that these two extreme soils are essentially binary mixtures of a mare basalt component (some mixture of olivine- and quartz normative basalt and green glass) and the AF soil component, but that neither soil is the 'pure' end member. Hence, removing the mare basalt component from the stn. 2 soils should yield a composition for the AFSC plotting on the extension of the curve to the high-Al side of the stn. 2 soils. This curve does not intersect the field for any known Apollo 15 noritic material. The AFSC component must be a mixture which also contains a component(s) plotting below the curve, such as anorthositic norite 15418. (The effect of KREEP is minimal on this diagram.) If 25% mare basalt is removed from the stn. 2 soils, as is indicated by several of the mixing models in Table 2, the composition obtained corresponds to point X on the curve. The fact that point X lies between the points for 15445-type melt and 15418 is not a coincidence, but a necessary result. Nearly every model in Table 2 which has included a noritic component with the 15445 composition has also required a more anorthositic and ferroan component with the 15418 composition in order to obtain a good fit to the stn. 2 soil data. This is essentially the same problem encountered with trying to model Apollo 16 soils using local melt rocks as the principle carriers of the ITEs and 'mafic' elements. Some type of ferroan norite or anorthositic norite is required [6,7].

An anorthositic norite with the composition of 15418 may, in fact, be the important ferroan subcomponent of the AFSC. An alternative possibility is that the ferroan subcomponent is actually more mafic (noritic) than 15418 (a unique sample) and, consequently, that there is less mare basalt in the stn. 2 soils than the 25% predicted by the mixing models. Note on Fig. 3 that a mixture of 15418, 15445-type dark melt, and a small amount of KREEP also satisfies the geometrical mixing requirements for the stn. 2 soils on the Sm-Sc diagram. Quantitative, multielement modeling of the AFSC is hampered by a lack of data for likely subcomponents [11]. Most modeling has been done on the basis of single analyses of unique rock types.

Summary and Conclusions. The variation in composition of Apollo 15 soils can be
explained by mixing of four chemical components, some of which may be mixtures themselves or be represented by more than one petrographic component. The chemical components are (1) mare basalt, (2) green glass, (3) KREEP, and (4) an Apennine Front soil component. The AFSC is a composition, defined here as stn. 2 soil minus any mare basalt resulting from mechanical mixing of local mare material. It is best represented the composition of the least mafic soils from the bottom of the 15007/8 double drive tube. The mass fraction of local mare material in these soils is unknown but it is less than that of the stn. 2 surface soils. The AFSC is surely a complex mixture of many subcomponents, but in terms of known Apollo 15 rock types, it appears to be primarily a mixture of a magnesian norite, some ferroan norite or anorthositic norite like sample 15418, and some type of KREEP norite or basalt (which does not have to be the same KREEP component as (3) above). Anorthosite and troctolite may also be minor components. The magnesian norite may be the dark melt rock associated with 15445 and 15455. However, like these melt rocks, even the analysis of 15306.23, a "probably" pristine norite of [16] resembles the composition associated with LKFM (Fig. 3). Considering the original definition of LKFM as the composition of certain glasses found in the soils [e.g., 9] it is probably misleading and counterproductive for the purpose of unravelling the geology of the Apollo 15 site to strictly identify 'LKFM' as the AFSC, 15445 melt, or any other rock type. LKFM has been used to refer to a wide variety of rock types and compositions (e.g., Table 1) and it is not clear which, if any, Apollo 15 rock type deserves the apellation LKFM (e.g., Fig. 3).

![Figure 1](image-url)  
Figure 1. Sm and Sc concentrations in Apollo 15 soils (a) and regolith breccias (b) compared to some local rock types. The lines in (a) represent the presumed mixing lines of stn. 2 soils with mare basalt and green glass. Data for Figs. 1, 2, and 3, are from many literature sources which will be referenced properly in a later publication and also from unpublished data of Korotev (soils and regolith breccias) and M. Lindstrom (15445, 15455 melt).

### Table 1. Apollo 15 Preciosa and Soil Mixing Models.

<table>
<thead>
<tr>
<th>Component</th>
<th>15418</th>
<th>15455</th>
<th>15445</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preciosa</td>
<td>15418</td>
<td>15455</td>
<td>15445</td>
</tr>
<tr>
<td>Soil 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil 3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2. Mixing Model Predictions: Mean percent mare component (basalt and green glass) and LKFM in Apollo 15 Apennine Front (stn. 2) soils.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Mare</th>
<th>LKFM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carr &amp; Meyer (1974)</td>
<td>20</td>
<td>44</td>
</tr>
<tr>
<td>Schonfeld (1974)</td>
<td>25</td>
<td>32</td>
</tr>
<tr>
<td>Fruchter et al. (1973)</td>
<td>26</td>
<td>34</td>
</tr>
<tr>
<td>Duncan et al. (1975)</td>
<td>26</td>
<td>59</td>
</tr>
<tr>
<td>Korotev et al. (1980)</td>
<td>27</td>
<td>50</td>
</tr>
<tr>
<td>Walker &amp; Papke (1981)</td>
<td>31</td>
<td>29</td>
</tr>
</tbody>
</table>

### References

Figure 3. Like Fig. 1, but with data for some soil particles ([8] and Korotev, unpub.). Data for average compositions of some rocks and soils from other stations are included for reference.

Figure 2. Mg' versus alumina in Apollo 15 soils and some rock types. Numbers are station numbers of soils. The curved line is the mixing line through the stn. 9a and stn. 2 mean soil compositions. The X on the line represents the composition obtained by removing 25% mare basalt component with the same composition as that in the stn. 9a soils from the stn. 2 soils. LKF1 glass composition from ref. [9].
PETROLOGY AND GEOCHEMISTRY OF HIGHLANDS SAMPLES FROM THE APENNINE FRONT; Marilyn M. Lindstrom, Department of Earth and Planetary Sciences and McDonnell Center for Space Sciences, Washington University, St. Louis, Mo.

At the Apollo 15 site, the lunar highlands are represented by Hadley Delta massif. It is part of the Apennine Front, an arcuate mountain belt which forms the most prominent ring of the Imbrium basin. The site also falls within the rings of the older Serenitatis basin. Samples returned from the front were therefore expected to consist mainly of Imbrium ejecta and possibly to contain some Serenitatis materials. As is the case for other highlands landing sites, the samples collected at the base of the Apennine Front are dominated by breccias. True highlands igneous rocks are rare, but because of the proximity to Palus Putredinis, mare basalts are common. The distribution of large rocks at the three stations is: 15 regolith breccias; 3 green glass clods; 3 impact melt breccias; 1 basalt breccia; 1 anorthosite; 1 recrystallized anorthositic norite. The distribution of rock types among rake and coarse soil particles is similar, except that mare basalts are more common and the polymict breccias are not separated into distinct categories. Geologic interpretations of the highlands samples from the Apennine Front rely upon detailed petrologic and geochemical studies of breccia clasts and matrices, which provide data on the rock types and their associations.

Descriptions of Samples.

Although regolith breccias are the most common rock type at the front, they are complex mixtures of many components. This description of individual rocks begins with the simplest samples and builds to the most complex regolith breccias.

15415. Anorthosite (269 g), the Genesis Rock, was collected at the rim of Spur Crater (Sta. 7), perched on a pedestal of regolith breccia 15435, one of the largest rock fragments in the vicinity. It consists of > 95% plagioclase (An97), accessory pyroxene (augite with Mg'72 > pigeonite with Mg'58) and trace ilmenite, silica, olivine and apatite. Its texture is cataclastic and granulitic, reflecting a complex metamorphic history[1]. It is a typical ferroan anorthosite, as shown by mineral compositions in Fig 1. Concentrations of REE (Fig 2) and other incompatible elements are very low and typical of ferroan anorthosites[2]. Rake sample 15362 is very similar to 15415.

15418. Granulitic breccia (1140 g), from Sta. 7, is an anorthositic norite with mineral compositions similar to 15415, yet a more complex texture. It is a shock-melted, devitrified and recrystallized breccia in which the equilibrated poikilitic rock was later modified by at least two episodes of brecciation and recrystallization [3]. REE concentrations are low, with a relatively flat pattern [4].

15256. Basaltic breccia (201 g), from Sta. 6, has the mineralogy and chemistry of a mare basalt, but a clastic texture[5].

15405. KREEP breccia (513 g), from a large boulder at Sta. 6a, is an impact melt of KREEP basalt containing clasts of the basalt, and its differentiates quartz monzodiorite and granite[6]. Mineral compositions of basalt clasts show normal crystallization trends, but are plotted as ranges in Fig 1. REE concentrations are high, with patterns similar to those of KREEP breccias [7]. Both basalt and QMD clasts are free of siderophile element contamination from meteorites. The QMD clast has been dated at 4.37 BY, the matrix at 1.25 BY. Rake samples 15382 and 15386 are also KREEP basalts.
15445 and 15455. Black and white breccias (287 & 937 g), representing a large boulder at Sta 7, are impact melt breccias containing clasts of Mg-suite norites, anorthositic norites, troctolites and spinel troctolites [8]. These clasts are among the best examples of pristine mafic rocks returned from Moon. They are highly magnesian (Fig 1), have low REE concentrations (Fig 2) and are ancient (norite dated at 4.52BY) [7,9]. No clasts of ferroan anorthosite or anorthositic norite, KREEP, or mare basalt are found in either breccia. The melt rock matrix has basaltic composition (Al2O3 17'), with moderately high Mg' (73) and REE concentrations (50 x chondritic), and has been dated at 3.9BY [7].

15425-7. Green glass clods (136, 224 & 116 g), from Sta. 7, are regolith breccias dominated by green glass spheres. Other clasts include yellow and red glasses, mare basalts, anorthositic and noritic fragments, and melt rocks. Although green glass is presumed to be a mare pyroclastic glass, it is found concentrated at Sta. 7 and not on the mare plain. The green glass and clods are rich in Fe, Mg and trace transition metals, and poor in REE [10].

Regolith breccias. (15 large samples, total 12,648 g) These brown glass matrix breccias are common at all three Apennine Front stations. They contain a diverse suite of clasts including anorthosites and other feldspathic rocks, KREEP basalts, mare basalts and green glass. Extreme variations in clast proportions are observed among the breccias, for example 15205 [11] is dominated by KREEP basalt, while 15459 [12] has little KREEP and is made up of feldspathic and mare components. Mineral compositions and REE patterns for clasts in the regolith breccias are shown in Figs 1b and 2b, for comparison with those of the simpler breccias. Although the KREEP and mare components of the regolith breccias are well characterized, the feldspathic components are not. Highly magnesian plutonic rocks like the clasts in the black and white breccias are rare in the regolith breccias. Ferroan anorthosites are found as clasts in several breccias, but are not abundant. The majority of feldspathic clasts are poikilitic norites or anorthositic norites whose textures have usually been interpreted as metamorphic [12,13], but which could also be the products of impact melting. Based on microprobe data, these clasts exhibit considerable range in composition (Al2O3 19-26%, Mg' 60-80). Detailed compositional characterization has not been done. Some of the clasts appear to resemble 15418, but most are much more magnesian.

Discussion
The samples collected from the Apennine Front are a diverse suite of breccias which include all three major classes of pristine highland rocks as well as mare basalts and glasses. Relationships among samples may be evaluated using Fig 3, a plot of Sc vs. Sm for Apennine Front samples. The Sm axis shows variations in the KREEP component (with the reminder that pure KREEP is itself variable). The Sc axis reflects variations in both the amount and composition of mafic minerals. Thus anorthositic norite 15418 has higher Sc than ferroan anorthosites because it has a higher proportion of mafic minerals, and higher Sc than Mg-suite troctolites and norites because it has ferroan composition. Endogenous lunar rocks occupy the extremes of the diagram, while melt rocks, breccias and soils scatter in the interior. Matrices of the black and white breccias occupy a field distant from both KREEP and mare basalt. Some samples trend away from the main group in the direction of the Mg-suite clasts from the breccias; these may represent dilution of the matrices with clast material. Regolith breccias scatter along two trends, one toward KREEP, the other toward green glass. (Regolith breccias from mare stations trend toward mare basalts.) The fields for Apennine Front
Soils [14] are shown for comparison with regolith breccias. Sta. 2 soils are adjacent to the matrices of the black and white breccias. The Sta. 6 regolith breccias cluster around the soils, while most Sta. 7 regolith breccias form a trend parallel to their soils. The most KREEP-rich breccias are found at Sta. 2 and 7. Regolith breccias and soils are obviously mixtures of a variety of components, but geologic interpretations depend on the choice of components. The question is whether the pristine components mix independently or are associated in some common polymict one. The enigmatic LKFM may be such a component since it falls near the point where the trends diverge.

**LKFM.** Reid et al. [14] used the term low K Fra Mauro (LKFM) basalt for a cluster of glass compositions in Apollo 15 soils. It is similar to KREEP basalt glass but has much lower K and Na, lower Si, higher Al, Mg and Mg'. They concluded that LKFM was a major component of the Apennine Front because it is more abundant in soils near the front. The ensuing search for rocks of LKFM composition produced no endogenous lunar rocks, but some impact melts [17]. Taylor [16] equated LKFM with the matrix of the black and white breccias, a definition which survives today. Glasses of LKFM composition are found in soils from all highland sites[15], but these glasses vary in composition from site to site, as do the compositions of melt rocks which most closely match the glass compositions [17]. Inspection of the original glass data shows that the LKFM cluster is not a tight compositional group as would be expected for an endogenous or impact melt of a single composition. LKFM composition closely resembles that of the Apennine Front soils [14], and based on remote geochemical data [18] is widespread in the Apennines. These variations in compositions and similarities to average surface compositions suggest that LKFM is a common mixture of components at the Apennine Front and not an endogenous rock or impact melt representing a limited assemblage of components. Ryder and Spudis [19] discussed problems with the use of LKFM for geologic interpretations and dismissed it in favor of individual samples. At present LKFM is a loosely defined term which will be useful in future interpretations only if it can be defined as a specific geologic association.

Geologic interpretations of the samples are speculative because of the limited dataset, but they provide models to be tested when additional data are available. Ryder[8,20] concluded that the black and white breccias are Imbrium melt rocks because of their age (3.9BY) and deep-crustal clast assemblage. KREEP breccia 15405 was rejected as a product of a major basin-forming event because of its young age (1.25BY) and lack of deep-crustal components. Spudis [21] accepted the Imbrium origin of the black and white breccias and suggested that LKFM represented Serenitatis ejecta because of its closer similarity to Apollo 17 melt rocks. In this scenario the feldspathic rocks are pre-Serenitatis materials. He also suggested that KREEP basalts originated as lava flows from the Apennine Bench formation which may underlie the mare basalts, rather than being ray material from young craters Aristillus and Autolycus. If these models are correct, the regolith breccias and soils, which are made up largely of Apennine Front debris, should have black and white breccias and LKFM as major components and feldspathic rocks as only very minor components. Indeed, the compositions of regolith materials do resemble these proposed basin components, but they are not present as recognizable clast assemblages. It is strange that the predominant lithologies of the two basin formations are not preserved in recognizable form when the feldspathic, KREEP, and mare clasts are. The resolution of this dilemma awaits detailed petrographic and compositional studies of clasts from the regolith breccias.
SAMPLES FROM THE APENNINE FRONT
Lindstrom, M.M.

and of rake and coarse soil particles. These studies will provide new data on the variety and distribution of rock types which are required before we understand the geology of the Apennine Front.


Fig 1. Mg' in mafic minerals vs. An in plagioclase for Apennine Front samples. A. Feldspathic rocks and clasts in impact melt breccias. B. Regolith breccia clasts.
Fig. 2. Chondrite-normalized REE plots for Apennine Front samples. A. Feldspathic rocks and impact melt breccias. B. KREEP breccia matrices and mare glass. Green glass and mare basalt.
The unaltered solidification products of basaltic magmas at the Apollo 15 site are present in two well-studied forms: fine-grained basalts and ultramafic glasses. The ultramafic glasses generally have higher Mg/Fe ratios than the fine-grained basalts and thus are judged to be more primitive (1). However, numerous workers, e.g. (2,3), have shown that the most common ultramafic glass at Apollo 15, the emerald green glass (4), cannot produce the observed basalt compositions by any reasonable combination of fractionation and melting processes. The present study extends these earlier studies to include the 25 chemical groups of ultramafic glasses recognized by (5), 8 of which have been collected at the Apollo 15 site. Consideration of simple MgO-TiO$_2$-Al$_2$O$_3$ systematics plus the results of calculations of fractional crystallization demonstrate that none parental magmas of the recognized groups of ultramafic glasses could have fractionated to produce the Apollo 15 basalts, nor conversely could any of the Apollo 15 ultramafic magmas have produced any of the low-Ti basalts collected at the other sites. The obvious question is whether this lack of correlation between ultramafic glasses and basalts is caused by limited sampling of a wide range of magma types or whether there is some more profound (and interesting) physical process operated to produce this lack of correlation.

Figs. 1 and 2 are plots of TiO$_2$ and Al$_2$O$_3$ respectively in which the compositions of the low to intermediate Ti ultramafic glass groups recognized by (5) are plotted along with the compositions of fine-grained mare basalts from several landing sites (the compositions of coarser-grained basalts or micro-gabbros are omitted). The compositional variation produced by fractional crystallization of olivine in some of the molten parents of the ultramafic glasses has been calculated by the methods of (6) and is shown by dashed lines in the figures. The low-MgO ends of these curves represent the liquid composition at the first appearance of low-Ca pyroxene during fractional crystallization. The calculated lines of fractional crystallization are sub-parallel to the arrays of the various basalt groups indicating that olivine fractionation is probably the dominant control on compositional variation within the groups. Chromite is likely to have fractionated as well from the ultramafic magmas, but only in small amounts with barely discernable effects on the TiO$_2$ and Al$_2$O$_3$ trends. Figure 1 illustrates an important point made previously by (7) that there are two major groups of low-Ti basalts collected at Apollo 15 -- ol-basalts (OBL5) and pigeonite + olivine-phyric quartz-normative basalts (QNB15) -- and neither group could be parental to the other. At the Apollo 12 site there are two similar groups of low-Ti basalts (ol and quartz-normative) that can be related by fractional crystallization (8). So it seems reasonable to assume that at the Apollo 15 site there are pigeonite-phyric quartz-normative
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derivatives of the Apollo 15 olivine basalts and olivine-rich parents of the quartz-normative basalts (QNB15) that were not sampled. Taken together Figs. 1 and 2 also preclude deriving ultramafic parents to OB15 and QNB15 by different degrees of partial melting of the same olivine-rich source: Mg-Ti relationships suggest that the QNB15 parent should have been produced by \( \sim \frac{1}{3} \) more melting than the OB15 parent, whereas Mg-Al relationships suggest that an ultramafic parent to QNB15 would have formed from similar or somewhat lower degrees of partial melting than the OB15 parent.

The same MgO-TiO\(_2\)-Al\(_2\)O\(_3\) systematics that preclude a similar parentage for OB15 and QNB15 also preclude deriving either of these two basalt groups from ultramafic liquids with compositions similar to any of the ultramafic glass groups recognized by (5). Figs. 1 and 2 suggest that the lack of relation between low-Ti basalts and ultramafic glass compositions at Apollo 15 is a feature of low-Ti mare basalts in general. The closest relationships appear to be between Apollo 17 VLT basalts and VLT17 glass, and between QNB15 and Apollo 14 green glass A (GA14), yet even in these cases lineages are distinct.

Another way of looking at the basalt/ultramafic glass problem is to note that of the 25 varieties of ultramafic glass identified by (5) only two (Y14 and Y15) have TiO\(_2\) concentrations between 1 and 6 wt%, the range of concentrations for low-Ti basalts from Apollo 12, 14, 15, and Luna 16. Is it merely an accident of sampling that produced a paucity of low-Ti ultramafic glasses and an abundance of low-Ti basalts? If so, then more categories of yellow to green ultramafic glasses await to be recognized in the Apollo 12 and 15 soils. Perhaps the ultramafic parents of the low-Ti basalts were less prone to the fire-fountaining that produced the glass balls and hence crystallized extensively upon eruption. If so, then there ought to be olivines present in the soils with a distinctive composition: Mg\(_{0.80-0.85}\) and CaO\(_{0.3-0.4}\) wt%. If neither of these tests is positive, then we must entertain the possibility the low-Ti basalts did not have ultramafic parents near the Moon's surface.

REFERENCES

(9) Basaltic Volcanism Study Project (1981).
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Fig. 1

![Graph showing TiO2 vs MgO in wt% oxides. Abbreviations: Il = ilmenite basalt; OB = olivine basalt; PB = pigeonite basalt; Al = aluminous basalt; QNB = quartz-normative basalt; L = Luna; VLT = very-low-Ti basalt. Glasses: R = red; Y = yellow; O = orange; G = green. Glass data from (5); basalt compositions from (7, 8, 9). Dashed lines are calculated paths of fractional crystallization of olivine (6).]

Fig. 2

![Graph showing Al2O3 vs MgO in wt% oxides. Symbols as in Fig. 1.]

Fig. 1. TiO2 vs MgO in wt% oxides. Abbreviations: Il = ilmenite basalt; OB = olivine basalt; PB = pigeonite basalt; Al = aluminous basalt; QNB = quartz-normative basalt; L = Luna; VLT = very-low-Ti basalt. Glasses: R = red; Y = yellow; O = orange; G = green. Glass data from (5); basalt compositions from (7, 8, 9). Dashed lines are calculated paths of fractional crystallization of olivine (6).

Fig. 2. Al2O3 vs MgO in wt% oxides. Symbols as in Fig. 1.

Introduction: Detailed information concerning the composition of surface material in the Hadley-Apennine region is necessary in order to understand the nature and origin of Imbrium basin-related units. Even though progress has been made in recent remote sensing studies (e.g., 1-6), many unanswered questions still remain. These include the compositions of Imbrium ejecta and pre-Imbrian material exposed both on the Imbrium backslope and in the Apennine Mts. (Apennine front), the variation in Imbrium ejecta composition as a function of distance from, and position around, the basin, and the nature of the material responsible for the thorium anomaly associated with the region. The purpose of this paper is to present results of an analysis of near-infrared spectral obtained for surface units in the Hadley-Apennine region.

Method: Twenty-three near-infrared spectra were recently obtained at the Mauna Kea Observatory 2.2-m telescope using the Planetary Geosciences Division indium antimonide spectrometer. Spectra were obtained for six relatively fresh surfaces in the Apennine Mts. (front), for five fresh crater deposits on the Imbrium backslope, and for a variety of highland units within the Apennine ring (Imbrium interior). The latter includes the following: 1) two fresh, small (D < 5 km) craters on the Apennine Bench and 2) the eastern wall deposits of Archimedes, Aristillus, Autolycus, and Timocharis craters. Four spectral parameters were derived from each spectrum after the methods of Lucey et al. (1985): the 1 micron band depth, width, and center and the infrared continuum slope.

Result: Examination of scatter diagrams which plot the six combinations of the four spectral parameters reveals the presence of two major spectral classes. Figure 1 shows a plot of band depth versus band width and illustrates the separation between the two classes on the basis of these parameters. Class 1, in the upper left, is characterized by a large band depth (9-15%), and bands narrow with respect to the rest of the region (0.15-0.24A). The spectra of Class 1 appear to be those of a mixture of low Ca pyroxene and feldspar. The plagioclase to pyroxene ratio of the areas determined from the spectra indicate these locations are anorthositic norite to norite. Class 2 is in the lower right of Figure 1. On the plot of band width vs band center (Figure 2), Class 2 members form a linear trend rather than a cluster. The trend is not consistent with maturing of an end member. Plots of the parameters sensitive to maturity, band depth and continuum slope, show that the trend does not exhibit an increase in continuum slope with decrease in band depth, systematics typical of the maturing process. The trend displayed by spectral Class 2 shows a correlation with location. Areas interior to the Apennine ring have both a longer band center and wider bands than those points on or beyond the Apennine front. The spectra of locations on the Apennine Bench Formation seem to represent a spectral end-member with the widest bands and longest band centers. Spectra of the walls of large craters interior to the Apennine ring show values intermediate between those of the Apennine Bench and Apennine exterior locations.

The Class 2 spectra and trend may be interpreted in several ways. One interpretation is that the spectra represent mixtures of low Ca pyroxene and olivine (with unknown amounts of feldspar) and the trend is caused by a decrease in olivine content with distance from the basin center. These
spectra are consistent with mixtures of olivine and pyroxene where the ol:pxn ratio varies from about 40:60 to 70:30 (Singer, 1981). However, two of the Class 2 spectra were collected for small craters (D=2 and 3 km) on the Apennine Bench. This mafic mineralogy is not consistent with the KREEP basalt composition of the Apennine Bench Formation as determined by the orbital geochemistry experiments (Spudis and Hawke, 1985; Clark and Hawke, 1981). Two alternatives present themselves. The small craters in the Apennine Bench Formation for which spectra have been obtained penetrated a thin (<200m) layer of KREEP basalt to excavate sub-Bench material which is more mafic than KREEP basalt. Alternatively, the spectral characteristics of the trend may be caused by variation in the amount of a glass which has a broad Fe²⁺ absorption feature, centered at 1.00μm.

Conclusions:

1) Spectra for features in the Hadley–Apennine region can be placed in two general classes.

2) Class 1 spectra are for some of the craters and massifs in the Apennine Mountains and backslope. Analyses of these spectra indicate that these terrains are composed of feldspar-rich rocks dominated by low-Ca orthopyroxene. Norites and anorthositic norites are suggested.

3) Class 2 spectra were collected for highlands features inside the Apennine ring (Imbrium interior) and for locations on the Apennine ring and on the Apennine backslope. These spectra have shallower, wider bands centered at longer wavelengths than those of Class 1. Class 2 spectra are consistent with the presence of relatively large amounts of olivine in the locations observed. However, at least two of the spectra are for units thought to contain abundant impact or volcanic glass. In addition, the orbital geochemistry data constrains the amount of mafic material in the region. Additional work is necessary to satisfactorily interpret the Class 2 spectra.

4) The material exposed in the Apennine Mts. and backslope should be dominated by Imbrium ejecta derived from several kilometers to tens of kilometers beneath the surface. The presence of two spectral classes in this region suggests that at least two distinct compositions were excavated by Imbrium basin.

5) Class 2 spectra show a compositional trend from interior to exterior of Imbrium which may be the result of decreasing abundance of olivine with distance from the basin center. The trend may be a reflection of a change in composition with depth in the Imbrium target site.

6) The spectrum of one crater on the backslope (Marco Polo F, D = 4 km) appears to be dominated by an olivine absorption.

References:

Figure 1. Scatter diagram plotting 1 μm band width versus percent band depth for spectra of Imbrium interior and exterior including the Apennine Bench Formation. Note the separation of two spectral types. The group in the upper left of the plot is referred to as Class 1. The group in the lower right is referred to as Class 2. Class 1 occurs on the Apennine front and on the Apennine backslope. Class 2 occurs in the interior, on the front, and on the backslope.

Figure 2. Scatter diagram of 1 μm band centers versus band width for Class 2 spectra. The linear trend shows a correlation with location as discussed in the text.
77 Kg of samples, consisting of more than 350 individually numbered samples of rock and regolith, were collected during the three EVA's on the Apollo 15 mission. The samples consist of rock specimens, and scooped, trenched, and cored regolith samples. Details of the collection of the samples were given in early reports [1,2,3], and an early catalog was published [4]. Those samples numbered as rocks are individually described, with analytical data summarized and complete referencing, in a new catalog [5]. A summary of data on the Apollo 15 regolith samples, not including cores, is included in the recent soil handbook [6].

The rock specimens were collected as individuals, some chipped from boulders, and as raked collections. The raked collections, with individuals ranging from about 0.5 cm to 6 cm, were taken at the edge of Hadley Rille (St. 9a) on the mare plains, and at St. George Crater (St. 2) and Spur Crater (St. 7) on the Apennine Front. Several of the samples collected and numbered as rocks are actually extremely friable regolith clods, and a few samples numbered as rocks are actually collections of small fragments of regolith breccias, regolith clods, and glassy materials which are not necessarily very closely related.

Regolith samples were collected at all sampling stations except 3, an unscheduled stop at which only one rock was picked up, and 10, at which no samples were collected. Most regolith samples were scooped, near-surface (upper few centimeters) materials, and include comprehensive samples picked up at the same localities as the raked rocks, and cover a range of environments. At St. 8 and 6, trenches were dug to about 30 cm depth, with samples taken from the top and the bottom. Regolith cores were taken at 4 locations: a deep drill at St. 8 (~2.4m; 6 x 40 cm), and drive tubes at St. 2 and 9a (~2 x ~30 cm) and St. 6 (~30 cm). The St. 6 core has not yet been opened. Three regolith samples were placed in Special Environment Sample Containers (SESC), which had pressure seals to preserve the extremely low pressures of the Moon. These SESCs were filled at St. 6 (15012), the LM (15013), and St. 8 (15014). 15013 failed to seal properly. 15012 and 15014 are trench bottom samples, but 15014 has never been allocated, under the mistaken impression that it is the LM exhaust gas sample (location correctly identified in refs. [2,4]; incorrectly in [1,3,6]).

**Rock Types**

Apollo 15 lithologies comprise several major types, including mare basalts, regolith breccias, green glass clods, glasses and agglutinitic breccias, anorthosites, KREEP basalts, and highland impact melts. Varied volcanic and impact glasses are constituents of breccias, as are mare and KREEP basalt fragments. Apart from the anorthosites, other pristine igneous highlands lithologies are present as clasts in breccias, and include norites, troctolites, and spinel-troctolites.

**Mare Basalts:**

As expected, mare basalts were collected on the mare plains, but a few were also collected on the Apennine Front (Figs. 1a, 6). They were sampled almost in situ at the rille edge (St. 9a), and the only observation of in situ bedrock ever made on the surface of the Moon were those on the Hadley Rille wall. The mare basalts are low-TiO₂ varieties generally similar to Apollo 12 olivine- and pyroxene-normative basalts, but chemically distinct from them. The Apollo 15 mare basalts form two main distinct groups: one is olivine-normative, the other quartz-normative. Within analytical error they have identical ages (Rb-Sr ages ~ 3.35 b.y. [8]; \( \lambda = 1.39 \times 10^{-11} \text{yr}^{-1} \)) and initial Sr-isotopic ratios (~0.69930, adjusted to C. I. T.). The rare earth element patterns are the same although the quartz-normative basalts have slightly higher rare earth element abundances (Fig. 2). However, the two groups cannot be simply related by fractional crystallization of a common parent or partial melting of a common source (e.g., [8]).

Olivine-normative mare basalts:

These basalts range from fine-grained olivine-porphyritic to coarser-grained (pyroxenes up to about 3 mm) subophitic varieties. Many are vesicular. Olivine, generally less than 10%, is subspherical. The pyroxenes (60-70%) have pigeonite cores and generally zone to ferroaugite and pyroxferroite. Plagioclase (20-30%) is lathy in finer-grained varieties, and poikilitic in coarser-grained varieties. The chemical variation and textural evidence suggests that the group forms a series related by a small amount of olivine fractionation, but whether the more Mg-variety are cumulative or equivalent to parental magma composition has not yet been established. The olivine-normative mare basalts are richer in iron, titanium, and magnesium, and lower in silicon and most LIL elements than the quartz-normative mare basalts. Dowty et al [9]

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Figure 1. Distribution of rock types around the Apollo 15 landing site. (1a) open triangles are "feldspathic peridite". On (1b), open triangle is "feldspathic microgabbro". Others as keyed. Numbers are stations.
divided the group into finer-grained olivine-phyric basalts and coarser olivine
microgabbros" (which they also divided into two subgroups), but at present there is
little chemical evidence suggestive of their being from different flows.

The olivine-normative basalts dominate the rake sample collected at St. 9a, and a few
were individually picked up at that location. They were also collected as a few small
fragments on the Apennine Front (Fig. 1a), and the single fragment collected at St. 3
because of its conspicuous vesicular nature is an olivine-normative basalt (15016). Two
samples (15385, 15387) from Spur Crater are "feldspathic peridotite" [9], similar to the
olivine microgabbros, but even coarser and with more olivine (~30%). Data for 15385
suggest they are closely related to the olivine-normative basalts: similar rare earth
pattern [8, 10], age [11], and a Sr-isotopic measurement compatible with the other mare
basalts [12]. One sample from the Apennine Front, 15296, is a shock-melted equivalent
of an olivine-normative basalt.

Quartz-normative mare basalts:

These basalts are porphyritic with pigeonite phenocrysts in all samples. They range
from vitrophyric with tiny phenocrysts to coarse-grained groundmasses containing
phenocrysts up to several centimeters long [13]. Tridymite is a conspicuous late-stage
mineral in the coarser samples. Olivine is only rarely present. The chemical variation
of the basalts is small and consistent with a small amount of pigeonite fractionation.
The glassy varieties (15597) have been taken to represent erupted liquid compositions and
have been the subject of many crystallization experiments, particularly to determine the
natural cooling rates and environments of samples (e.g. [13, 14]). The composition is
multiply saturated within lunar crustal pressures, suggesting that it is not a primary
magma [15].

The quartz-normative basalts are ubiquitous (Fig. 1b), but they were not found as
individual rocks in the Spur Crater region. At St. 9 they are poorly represented in the
rake sample, but were collected from boulders at a lower stratigraphic level. At Spur
Crater, a "feldspathic microgabbro" (15388), which lacks olivine and has coarsely
integradol pigeonite and feldspar, is a mare basalt which might be a member of the
quartz-normative mare basalt group, but present information is inadequate for positive
identification.

KREEP basalts:

Only two samples of volcanic KREEP basalt are present among individually numbered
samples (15382, 15386, from Spur Crater; Fig. 1c) but they are prominent clasts in boulder
samples 15405 and 15205, and occur commonly among coarser fines samples, in regolith
breccias, and as a chemical component of most regoliths. The basalts are subophitic to
intersertal to variolitic, and range from rather coarse-grained to aphanitic. They
contain roughly cotectic proportions of plagioclase and low-Ca pyroxene, and a glassy
mesostasis. They have the highest rare earths of Apollo 15 materials (Fig. 2), except for
fragments of "quartz-monzodiorite", found only with KREEP basalt fragments in sample 15405

Figure 2. Examples of rare earth patterns for Apollo 15 rock types. All
data from [12].
The KREEP basalts have an age indistinguishable from that of Imbrium (~3.85 b.y.; several sources), and are recognized as volcanic by their negligible siderophile concentrations, their clast-free, homogeneous textures, and their major and trace-element chemistry. Although they were originally believed to have been brought to the site in rays from a major impact (Aristillus or Autolycus) they are equally likely to be of more immediate origin, i.e., the Apennine Bench which may underlie the site [17]. The quartz-monzodiorite clasts have yielded zircon ages considerably older i.e., 4.35 b.y. [18].

Highland Impact melts:
Crystalline, clast-bearing impact melt samples of highland origin are not common, even on the Apennine Front (Fig. 1c). Two aphanitic samples, 15445 and 15455 (St. 7) are similar and appear to be representative of a nearby cm-boulder. They contain clasts of pristine igneous lithologies including norite, troctolite, and spinel troctolite, to the exclusion of shallow-level-derived materials, and have been proposed to be Imbrium impact melts [19, 20]. They have a low-K Fra Mauro composition (*LKF* on Fig. 2), slightly poorer in rare-earths and richer in magnesium than Apollo 17 impact melts proposed to be Serenitatis melt. One of the pristine clasts, the norite in 15455, yielded a Rb-Sr isochron age of 4.52 b.y. [21]. Other impact melt samples are generally much smaller and little work has been done on them; my own work (accompanying abstract) suggests a wide range in compositions ranging up to that of the 15405 matrix which is similar to Apollo 15 volcanic KREEP. Some may be Serenitatis-like. One has a flat rare-earth pattern at about 10 x chondrites with a positive Eu anomaly. These melts suggest that the Apennine Front is made up of material from a variety of sources. A few highlands impact melts have been found as clasts in regolith breccias.

Anorthosites and 15418:
A few small fragments, all from Spur Crater (Fig. 1c), are pristine anorthosites, all belonging to the ferroan anorthosite group. The best known is 15415 "Genesis Rock", which was sitting on a small regolith pedestal. This rock is not a typical ferroan anorthosite in that it contains high-Ca pyroxenes as its dominant mafic mineral [22, 23] rather than low-Ca pyroxene or olivine. It also had a complex history of fragmentation and metamorphism, resulting in a low Ar-Ar age of ~4.1 b.y. [24, 25]. The other fragments are less well-studied. 15418, also from Spur Crater, is unique. It is variably shock-melted, appears to have been essentially a granulitic rock prior to melting, and has an anorthositic norite bulk composition (about 26x Al2O3) [26]. Because of its deformation, little is yet known about the ultimate origin of this rock. Anorthosites and anorthositic norites are not as common a component in the Apennine Front as they are at the Apollo 16 landing site.

Regolith breccias, glassy breccias, agglutinates, and glass:
Regolith breccias were collected at all stations (except 3 and 10, Fig. 1d), and range from extremely friable clods, barely deserving designation as rocks, to coherent samples. They were originally subdivided on whether or not they contained mare basalt clasts [4] but that distinction appears to be unreal: virtually all contain a mare basalt component. Most regolith breccias contain rather fine-grained clasts (~2 mm), with only a few containing several conspicuous large fragments (e.g., 15205, 15459). Most contain at least some KREEP basalt fragments and green glass balls or other such debris. Agglutinates are generally uncommon. The chemistry of most regolith breccias is similar to the local soil, indicating a local derivation (Korotev, this volume) but several are conspicuously different, generally in that they contain greater amounts of incompatible elements. A smaller proportion of breccias are glassy or agglutinitic, and evidently of regolith origin. A few samples are glasses, ellipsoids or shells. Many rocks, including mare basalts and regolith breccias, have glass coats partially draping them. Little work has been done on such materials.

Green Glass Clods:
Two green clods were specifically collected at Spur Crater. These disintegrated into several pieces which were numbered 15425, 15426, and 15427, each consisting of several pieces, and none specifically the original two pieces collected. These clods vary from very pure green glass chunks (e.g., 15426, 26) to more typical mixed regolith. Several other green clods were sorted from the Spur Crater rake samples, and such were even found in the drill core at St. 2. The green glasses which constitute the clods are volcanic ultramafic glasses, distinct in composition and parentage from the crystalline basalts at the site (see Delano, this volume). Those richest in green glass appear to be pristine, unmixed deposits. The green glasses are not all identical, several slightly but distinctly different groups having been recognized [27].
APOLLO 15 SAMPLES

Ryder, G.

REGOLITH

The regolith has been the subject of intensive petrographic and chemical studies, particularly in deciphering the nature of its components (see Basu, this volume; Korotev, this volume). The chemistry (partially shown on Fig. 3) has geographical variations reflecting the dominance of mare basalts on the plain and especially at the rille edge (high Sc, Ti), and "LKFM" (low Sc, low Ti) and green glass (high Sc, low Ti) on the Apennine Front. KREEP basalts contribute much of the rare earths, and appear to be most common around the LM and on parts of the Front. The drive tube and drill core sections at least at the LM and St. 2 are fairly homogeneous in both chemistry and mode (e.g.,[28]). Apart from the lithologies briefly described above, the regolith samples also contain small amounts of yellow, red, and orange volcanic glasses (see Delano, this volume).

Impact glasses, including a distinctive yellow variety, are common regolith constituents.

FINALE

The Apollo 15 samples are consistent with an Apennine Front composed of feldspathic and "LKFM" (~basaltic) breccias, with ages of 3.9 b.y. and older, and including basin-derived materials. However, these are poorly represented in samples. In down faulted or depressed regions they were overlain by volcanic KREEP flows analytically indistinguishable in age from the Imbrium event. Exactly where these flows were emplaced at the site cannot be observed but must be inferred. Immediately prior to the emplacement of the mare basalt lavas at ~3.3 b.y. ago, the area, at least the Apennine Front, was partly blanketed with pyroclastic, ultramafic green glasses. The olivine-normative mare basalts appear to have been emplaced at least locally above the quartz-normative mare basalt, as a thin flow(s). At least the latest flows would seem to have been related to Hadley Rille, or the rille cut into them. Subsequently, the evolution of the site has been once again exogenic, with the development of regolith and glassy breccias. A few samples (e.g., boulders parental to 15205, 15405) are exotic but contain local samples types and may not have travelled very far.

Whether or not one believes we actually sampled a fairly complete sequence depends on ones concept of KREEP basalt; if it is local and underlies the mare basalts then we did. If it is exotic, then we may not have. Petrographic and chemical evidence suggests that there is so much KREEP it must be local. There is an abundance of KREEP on the LM "ridge"; possibly the unfortunately unvisited North Complex is a KREEP volcanic center or at least exposure.

REFERENCES


Figure 3. Summarized variation of regolith chemistry. Data from many sources.
Apollo 15 Mare basalts were first seen as two groups - olivine-normative and quartz-normative basalts. Early studies identified these groups based on major- and trace-element chemistry and different pyroxene compositional trends. Previous work interpreted the olivine-normative samples to be closely related members of a group whose major-element chemistry is controlled by olivine fractionation. Similarly, quartz-normative samples were thought to be related but controlled by pigeonite fractionation. However, an experimental study of the quartz-normative samples suggested fractional crystallization was unlikely. Some trace element modeling suggested subgroups within the samples. Thus, understanding petrogenesis is incomplete. A new study compiled data from 60 Apollo 15 samples with both major- and trace-element data, particularly the REE. Averaged data were used where available. The separation of samples on a chemical basis is shown in Figure 1. The two groups have distinct TiO2 and MgO concentrations. However, fractionation trends within the quartz-normative samples are weak, suggesting that other processes may be important. This study reevaluates previous interpretations.
istics to be ambiguous. Perhaps the trace element data will permit a more meaningful interpretation.

Figure 3 is a variation diagram of La vs. MgO. The effects of olivine or pigeonite fractionation should be evident on such a diagram since their removal will cause a decrease in MgO and an increase in La, as denoted by the arrow. (However, we note that fractional crystallization is not the only mechanism that will produce correlations on this diagram.) The quartz-normative samples do not display a clear trend on Figure 3, tending to confirm the proposal that this group may represent a number of unrelated flow units. The data points for the olivine-normative samples appear to form two trends. One trend, made up of the "main group" of samples, has relatively high La. The other trend is characterized by lower La. This group is denoted by different symbols on Fig. 3 to facilitate their recognition on following diagrams.

Figures 4 and 5 are plots of REE ratios against La. The utility of such plots is that the La concentration serves as an index of fractionation or partial melting, since it is not a compatible element in any likely fractionating (olivine, pigeonite) or residual (olivine, opx) phases. The element ratios, on the other hand, should remain unaffected by either process unless plagioclase or augite are involved, neither of which are primary liquidus phases. Some scatter is expected in the ratios plotted on Figures 4 and 5 due to analytical uncertainty. The horizontal lines on these two figures denote the maximum ranges of the average ratios of the olivine-normative samples if the uncertainty in the elements making up the ratios is 5%. A significant number of data points fall outside the ranges of uncertainty on both diagrams. Furthermore, the two groups tentatively identified in the olivine-normative samples tend to cluster together. There are trends in the data on Figures 4 and 5 showing increasing La/Sm and Sm/Eu ratios with increasing La concentrations. These trends might signify a series of unrelated flows, or they can be due to varying amounts of residu-
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A liquid in samples from the same flow (9,11). As discussed above, fractional crystallization and partial melting of a homogeneous source region are unlikely mechanisms to produce the patterns observed on Figures 4 and 5. Assimilation is equally unlikely. Increasing degrees of assimilation of ferroan anorthosite would decrease the concentrations of La while increasing the La/Sm ratio. Increasing degrees of assimilation of granite would produce a trend of decreasing La/Sm with increasing La. Increasing degrees of assimilation of KREEP should have no effect on the La/Sm ratio. Finally, assimilation of alkali anorthosite would produce the trend seen on Figure 4, but rather than increasing the Sm/Eu ratio with increasing La concentrations (Figure 5), this mechanism should decrease that ratio.

In conclusion, our analysis of major and trace elements in the expanded data set of Apollo 15 mare basalts is consistent with the existence of two broad categories of basalt: olivine normative and quartz normative. We recognize that the quartz-normative samples may represent a group of unrelated flows. Furthermore, olivine fractionation alone cannot account for the geochemical characteristics of the olivine-normative samples. Models have been developed which explain some of the trace-element characteristics of these samples as being consistent with their derivation from a single flow (e.g., 9,11). However, our treatment of the expanded data set indicates that they may have been derived from source regions with different chemical characteristics. The possibility of a large number of basalt types suggests a heterogeneous mantle beneath Apollo 15.

An important part of understanding the geology of a lunar landing site is understanding the evolution of the regolith at the site. Soils and regolith breccias contain clues to the geologic processes that contributed to the evolution of the local regolith over time. Thus we have conducted a study of a suite of ten regolith breccias from the Apollo 15 site and compared the results to previous studies on A-15 soils in order to learn more about the regolith evolution at that site.

One interesting feature of the A-15 regolith breccias is that they tend to be chemically similar to the soil at the station where they were collected [1], a strong indication of local formation of the breccias. Therefore the modal petrology of the breccias should be extremely useful in comparing the breccias and soils, and the breccia modal petrology is summarized in Fig. 1. The breccias average 52 vol.% <20 μm material and pore space; the 1000-20 μm fraction is summarized in Fig. 1, which shows the low fused soil contents which are typical of regolith breccias [e.g. 2, 3]. Ferromagnetic resonance maturity indices \( (I_S/FeO) \) measured by McKay et al. [3] on twenty-eight A-15 regolith breccias showed that half of the samples were immature, and only two were mature. Our observations agree with their results, in most cases. For example, we found the highest agglutinate content in 15086, and it has an \( I_S/FeO \) value in the 18-27 range (based on a range of assumed FeO contents) [3]. 15205 and 15015, with very low agglutinate contents, have \( I_S/FeO \) values of 0 and 3, respectively. Values that do not agree can be attributed to heterogeneity of the samples. Mineral clast contents are fairly high in the breccias, but glass contents vary. The averages of the breccia and soil modal data are illustrated in Fig. 2, which shows that overall the two sample suites are very similar except for the difference in fused soil content. This is a strong indication that the breccias were formed from the local soils when they were less mature.

Since the difference in maturities between breccias and soils makes detailed petrologic comparison of the two difficult, we present fused soil-free modes in Fig. 3. With this figure we compare breccias with soil from the same station. Station 2 soil has more plagioclase and less mare lithics than station 2 breccia 15205. The station 6 breccias are similar to each other and to soil 15271.
though the breccias again contain more mare basalt fragments. Conversely, the Rille (9A) and LM breccias have more highland lithics and plagioclase than the corresponding soils. Walker and Papike [4] found that station 9A drive tube 15010/15011 was depleted in highland materials relative to the deep drill core (LM area). They suggested that at station 9A regolith tends to be lost into Hadley Rille. Thus this regolith has become more mare-rich and highland-poor as the lost soil is replaced by new regolith derived from the underlying basalt. Regolith at the edge of the Rille remains thin and rich in mare basalt fragments. Regolith breccias, however, would not be affected by this erosional process, and now contain more highland lithics, that were added at an earlier time, than the present-day local soil. In contrast, soils at Front stations 2 and 6 have probably become more highland-rich with time, as material slumped down the side of Hadley Delta.

The chemical data provide further evidence of local formation, even on a station-by-station scale. Fig. 4 shows the correlation of two elements in breccias and soils from the same stations. The Apennine Front soils and breccias have higher $\text{Al}_2\text{O}_3$ and lower $\text{FeO}$ than samples from the mare stations. The uniformity of the chondrite-normalized rare earth element (REE) patterns (Fig. 5), with similar Eu anomalies and upward Th inflections, indicates that the breccias all contain the same KREEP component, in varying amounts. The pattern of station 6 breccia 15295 is almost identical to that of station 6 soil 15271 [5]. The overall similarity between the soils and breccias is summarized by a comparison of the chemical mixing models (Fig. 6). We used the same components as Walker and Papike [6] used for A-15 soils. Fig. 6 shows higher mare components at the Rille stations (1, 9, 9A) and lower mare components at the Front stations (2, 6, 7). The station 2 breccia (15205) is somewhat anomalous, however, having a very large (73%) $\text{FeO}$ KREEP component.

Fig. 2

Fig. 3
We conclude that since the ten breccias studied are of local origin, they are useful as recorders of regolith evolution at the site. Our data indicate that, since the formation of the breccias, the regolith at the edge of Hadley Rille has become more basalt-rich, whereas the soils at the base of Hadley Delta have gained highland lithic fragments. We looked for, but did not find, evidence for addition of other components (e.g. KREEP, green glass) to the soils after the breccias became closed systems.


Fig. 4

K, REE and Th in A-15 REGOLITH BRECCIAS

Fig. 5

Fig. 6 Schematic map of A-15 site.

Introduction. The Imbrium basin, prominently located on the lunar nearside, has been the focus of intensive investigation by lunar geologists ever since G.K. Gilbert recognized its impact origin in 1893. The deposits around the Imbrium basin form a widespread stratigraphic datum, to which other lunar geological units may be dated relatively [1]. More importantly, as a relatively well-preserved multi-ring basin, Imbrium provides an important testbed of geologic investigation to study the processes involved in lunar basin formation and evolution.

The Imbrium impact was considered such a key event in lunar history that two Apollo missions (Apollo 14 and 15) were sent to landing sites chosen specifically to address problems of Imbrium basin geology. The purpose of this paper is to review what we know about the deposits of the Imbrium basin, what we can infer about the formational mechanics of lunar basins in general and, in particular, relations of materials collected at the highlands adjacent to the Apollo 15 landing site to Imbrium and other basins.

Stratigraphy and Morphology of the Imbrium Basin. Although Imbrium is significantly modified by mare flooding, parts of the basin interior have not been flooded and its associated deposits outside the basin are well-preserved in many regions. Thus, a reasonably complete reconstruction of Imbrium basin stratigraphy and morphology is possible (Fig. 1), keeping in mind that several key relations among basin units may be obscured by post-basin geologic units.

Imbrium basin deposits are subdivided into several formal and informal rock-stratigraphic units that comprise the Imbrium Group ( provisionally named here; see also [2]). The informal massif materials are exposed as kipukas protruding through basin interior mare basalts and as segments comprising the main basin rim. Massifs consist of large mountains that are, in some cases, transitional with large hummocks included within other rock units. At Imbrium, no basin interior unit is recognized that corresponds to the Orientale Maunder Formation (basin impact melt [2,3]). Although it has been proposed that the planar Apennine Bench Fm. might be this basin impact melt unit [2,4], geologic studies (summarized in [5]) have shown that this material probably consists of post-basin volcanic KREEP basalt. Isolated pools of cracked material along the base of the Apennine scarp may be Imbrium impact-melt deposits [4,6].

Basin continuous deposits are subdivided on the basis of morphology. The informal Apenninus Fm. [7] consists of coarsely-textured deposits that occur only in the southern Apennines (Fig. 1). This material appears to be about 1-2 km thick near the Apennine crest [8,9]; its concentric texture in this area suggests that post-basin slumping may be partly responsible for the morphology of this unit [9]. Apenninus material appears to be gradational with the more widely distributed Fra Mauro Formation [7,10]. This unit varies in morphology, ranging from strongly-lineated textures (radial to basin) of the Motlis and Maunder Formation (basin interior mare basalts and as segments comprising the main basin rim) to more hummocky texture elsewhere (e.g., Apollo 14 landings site). The Fra Mauro Fm. appears to be about 1 km thick in the Apennine back slope and thins to a feather-edge south of Parry where it intercalates with smooth plains material. There is little evidence for flow lobes or melt ponds associated with the Fra Mauro Fm., but it commonly appears to have overridden previously-formed secondary impact craters and chains [10,11], suggesting that some type of downflow was important in its final emplacement.

Another extensive Imbrium stratigraphic unit (Fig. 1) is the knobby-textured Alpes Formation [12]. The knobs average on the order of 10 km in size and are set in a matrix of undulating terra plains. The Alpes Fm. extends locally up to 800 km from the basin rim (discussed below) and such a distribution is consistent with an origin by basin ejecta deposition. On the basis of morphologic similarity, some workers have equated the Imbrium Alpes Fm. with the Orientale basin's Montes Rook Fm. [2,3]. However, the distribution of the Alpes Fm. is much more extensive than the Orientale Montes Rook Fm., which is almost completely confined within the topographic basin (local occurrence beyond the Cordilleria rim rarely exceeds 50 km [3]).

Figure 1 shows that there is a concentric dependence upon which stratigraphic unit may be found outside the basin rim. Fra Mauro Fm./Apenninus material is found in the northwest and southeast quadrants of the basin deposits; Alpes Fm. is confined primarily to the northeast and southwest quadrants. This "bilateral symmetry" of basin deposits may be of great, although elusive, significance. Moreover, limited geochemical data for Imbrium basin deposits (discussed below) suggest that a real lithologic difference exists between the Fra Mauro and Alpes Formations.

The outermost deposits of the Imbrium basin consist of the light plains Cayley Fm. [13] and numerous basin secondary craters [4,14]. The Cayley Fm. is gradational with both Fra Mauro and Alpes materials. Results of the Apollo 16 mission and subsequent cratering studies [15] suggest that the Cayley plains were emplaced contemporaneously with deposition of basin ejecta by a "debris surge." The Cayley Fm. is widely distributed as fill deposits in both primary craters (only regional exposures are shown in Fig. 1) and frequently in large-basin secondary craters. The fraction of primary Imbrium ejecta in these plains is still under debate (cf. [15] and [16]).

The Imbrium basin displays one of the most complex ring systems of any lunar multi-ring basin. Controversy has arisen even over the location of the main basin ring, a parameter critical to modeling basin cavities and ejecta volumes. It was first proposed [17] that the Apennine Mts. represents the main Imbrium rim, but the rim is represented by the trough of Mare Frigoris to the north. Later, it was suggested [7] that the north shore of Mare Frigoris was the rim remnant in the north. My interpretation of the Imbrium ring structure is shown in Fig. 2; the main Imbrium basin rim consists of the Apennines in the southeast and the southern Caucasus, Alpes and Iridium rim to the north and west, resulting in a
main rim 1160 km in diameter. This arrangement, first proposed in [18] and later in [6], avoids eccentric, egg-shaped Imbrium rims [7]. If this interpretation is accepted, then mare ridge and massif patterns (Fig. 1) define five additional rings, two inside the basin topographic rim and three outside. Although the outer rings have been suggested by some workers to represent an older, mega-basin ("Procellarum"; [19, 20]), at least part of the reason for the postulation of this basin was the eccentric position of Imbrium within a large regional concentric pattern [19]. By redrawing the main Imbrium ring as shown (Fig. 2), this pattern is easily explained as Imbrium-related [21]. In this interpretation, Imbrium has six rings of 550, 790, 1160, 1700, 2250, and 3200 km diameter. As such, it is the largest multi-ring basin on the Moon.

Regional Composition of Imbrium Deposits. Orbital geochronological data for Imbrium basin deposits are very limited, being confined to the Apennines and Central highlands/Fra Mauro region. The large field of view of the chemical detectors results in the inclusion of post-basin units, such as mare basalts and pyroclastic deposits, in regional compositions. Even so, these data are our primary source of information about variations in the regional composition of Imbrium ejecta.

Geochemical mixing-model results for Imbrium basin deposits are presented in Table 1; models for the Apennines were made for this study and results for Fra Mauro and Ptolemaeus are from [22]. It can be seen from Table 1 that the composition of Imbrium deposits is regionally variable. Within the continuous deposits, the northern Apennines are dominated by Alpes Fm. materials and the southern Apennines contains Ptolemaeus Fm. (Fra Mauro) units (Fig. 1). These two units appear to be lithologically different (Table 1). The Alpes Fm. is dominated by norite with minor quantities of KREEP. The Apenninus material is more KREEP-rich at the expense of norite. Both units show substantial quantities of anorthosite and mare basalt, which is probably caused mostly by discontinuous dark-mantle deposits in the Apennines [7]. The discontinuous Imbrium deposits (Table 1) are even more diverse, probably a result of local mixing becoming dominant at the distal ends of the Imbrium ejecta blanket [15]. Even so, the dominance of KREEP at Fra Mauro and Ptolemaeus and in the southern Apennines (Table 1) suggests that at least some of this component may be related to Imbrium ejecta.

These results for Imbrium deposits suggest that the crustal target for the Imbrium impact was composed primarily of norite, with subequal amounts of KREEP and anorthosite. At least some mare basalt also contributed to this basin target [21], but this is difficult to quantify from the orbital data. The composition of the Imbrium basin deposits is in contrast to those of most lunar basin ejecta blankets, where anorthosite predominates over other rock types [24], but Imbrium deposits are not as noritic as Serenitatis basin ejecta [25], where anorthosite is almost totally absent.

The Imbrium Excavation Cavity. As the Imbrium basin is an impact crater, the problem of reconstruction of the impact event is tied to the more general problem of scaling complex craters [26]. There is wide disagreement among workers in this field as to the original cavity dimensions of basins. It is suggested by some [27, 26, 29] that the main basin rim (the Apennine ring at Imbrium; 1160 km dia.) corresponds to the original excavation crater rim. In contrast, evidence from terrestrial impact craters [30], analytical modeling [26] and lunar basins [24, 31, 32], suggests that the fundamental shape of an excavating crater is size-invariant; this is called the proportional-growth model. Such a model has been shown to be valid in size ranges over eight orders of magnitude [26, 31] and, in the absence of any compelling evidence to the contrary, is assumed to hold for the Imbrium basin in this discussion.

For a lunar basin with a crater rim diameter of 1160 km (Imbrium), the proportional-growth model suggests excavation cavity diameters (Dc) ranging from 604±200 km [26] to 685±88 km [32]; the relation of [30], derived from study of terrestrial impact structures, predicts a cavity 667±87 km in diameter. The maximum depth of excavation (dc) of material from this cavity is related to Dc as follows: dc = 0.09 to 0.12 Dc [30]. This relation suggests for the Imbrium basin (Dc = 685 km), that the maximum depth of crater excavation is on the order of 62 to 82 km. The geometry of the Imbrium cavity is not known, but the "Z"-model [33,34] suggests that a spherical cap segment excavating a spherical moon is a good approximation [31]. Analysis of this geometric figure suggests that the total excavated volume of Imbrium is on the order of 12 x 106 km; moreover, although such excavation depths would have excavated mantle material (assuming an average crustal thickness of 55 km; [32]), the mantle would constitute less than 4% of the total excavated volume. Additionally, 90% of the total excavate volume would be derived from depths of less than 45 km.

Thus, the proportional-growth model predicts that the Imbrium basin impact excavated most of the crustal column at its target site; it further predicts that most ejecta are derived from the upper two-thirds of the basin crustal target. This is consistent with what we know from lunar samples [29, 35]; it should be noted that basin-forming models that equate the main rim of the basin with the excavation cavity [27-29] must appeal to mechanisms that produce shallowing-cavities with increasing crater size [e.g. 6] to explain the paucity of deep-crustal or mantle material in the lunar samples. The search for evidence of such mechanisms at basin scales has been inconclusive.

Implications for Apollo 15 Highland Samples. The Apollo 15 sites lies close to the main (Apennine) ring of the Imbrium basin. The highlands were sampled at Hadley Delta, a massif that is part of the main basin ring. Mixing-model results for Imbrium deposits (Table 1; N. Apennines) suggest that noritic rocks are the dominant lithology in this region. This noritic component may be reflected by the "LKFM" composition of most Front Rognolith material [36, 37]. Anorthosite is present in minor amounts at the Apollo 15 site [37], and orbital data suggest that it may indeed be part of the Imbrium ejecta in this
IMBRIUM BASIN

Spudis, Paul D.

region. KREEP is a minor component in Imbrium deposits in this area (Table I), but geologic evidence suggests that the abundant KREEP at the Apollo 15 site is related mostly to post-Imbrium basin KREEP volcanism [5] and not to the Imbrium ejecta.

Because the total expected thickness of Imbrium ejecta at the crest of the Apennines (~1 km; [8]) is less than the 4 km relief of the Apennine scarp, it is likely that pre-Imbrian material would have been collected at Hadley Delta. At Apollo 15, this would consist mostly of Serenitatis ejecta, but because Serenitatis material is dominantly noritic [25], it may be difficult to identify purely clastic material. Impact melts may exist that could be identified [36], although the proportional-growth model predicts less total impact melt at this position in the basin than was sampled by Apollo 17. There is probably no coherent "melt sheet" mantling the massifs at the Apollo 15 site, but discontinuous patches and pods of ejected impact melt are probably present and were likely sampled at Apollo 15 [38]. Pre-Serenitatis material is probably present and may be represented in the samples by small, feldspathic granulitic breccias and rocks derived from them [39].

The Apollo 15 landing site provides us with key information on one of the most important lunar basins. Continued study of Apollo 15 samples will give crucial data to test models of basin formation and to help us decipher the complex history of the Moon.

References
Figure 1. Geologic sketch map of Imbrium basin deposits, adapted from [7, 14, 40, 41] and new mapping in progress by the author. Secondary crater field omitted for clarity. Base is a Lambert Equal-area projection centered on 35°N, 17°W (Imbrium basin center).
Figure 2. Ring map of the Imbrium basin. Six concentric rings of diameters 550, 790, 1160, 1700, 2250, and 3200 km are identified. Major radial mega-structures are indicated by dashed lines. Base is a Lambert Equal-area projection centered on 35°N, 17°W (Imbrium basin center).

Table 1. Geochemical mixing-model results for Imbrium Basin Deposits.

<table>
<thead>
<tr>
<th>Component</th>
<th>Continuous deposits</th>
<th>Discontinuous deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N. Apennines</td>
<td>S. Apennines</td>
</tr>
<tr>
<td>Anorthosite</td>
<td>21%</td>
<td>30%</td>
</tr>
<tr>
<td>Anorthositic gabbro</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Norite</td>
<td>42%</td>
<td>19%</td>
</tr>
<tr>
<td>Al4 KREEP</td>
<td>9%</td>
<td>30%</td>
</tr>
<tr>
<td>Mare basalt²</td>
<td>28%</td>
<td>21%</td>
</tr>
</tbody>
</table>

1. Results of [22]
2. Apollo 11 high-Ti basalt used in continuous deposits; Apollo 12 low-Ti basalt used by [22] for Fra Mauro.
THE APENNINE BENCH FORMATION REVISITED  P. D. Spudis, U.S. Geological Survey, Flagstaff, AZ 86001 and B. R. Hawke, HIG, University of Hawaii, Honolulu, HI 96822

Introduction. The Apennine Bench Formation consists of pre-mare light plains materials that crop out south of the crater Archimedes, inside the Imbrium basin [1]. This material has been ascribed either impact [2,3] or volcanic origins [1,4,5]. Several studies [4,5,6] have argued that the Apennine Bench Formation is represented in the lunar sample collection by Apollo 15 KREEP basalts, which have been interpreted as endogenically-generated volcanic rocks [e.g., 7,8]. Recently, Taylor [9] has challenged the concept that the Apennine Bench Formation consists of volcanic KREEP basalt flows on two grounds: 1) The Apollo 15 KREEP basalts are not volcanic; and 2) the Apennine Bench Formation morphologically resembles an expected "melt sheet" produced by the Imbrium impact. The purpose of this note is to briefly review the characteristics of both Apollo 15 KREEP basalts and the Apennine Bench Formation, demonstrate that their characteristics are compatible with a volcanic origin and that both topics are important cornerstones in the deciphering of Apollo 15 site geology and history.

Apollo 15 KREEP Basalts. Among other things, the Apollo 15 site is remarkable for a collection of numerous, small basaltic fragments with KREEP trace-element patterns. The petrology of these basalts is described in [7,8,10,11]; they consist of glassy intersertal to subophitic-textured basalts that totally lack clastic inclusions and have no detectable meteoritic siderophile element contamination. Modally, they consist of 40-50% plagioclase, 30-40% pyroxene (usually orthopyroxene rimmed with pigeonite or augite), and minor phases including cristobalite, ilmenite, apatite, and brown, Si- and K-rich glass [7,10]. In bulk chemistry, they are equivalent to high-Al basalt (Al₂O₃ >15-18%), with trace element concentrations at about the same level as Apollo 14 soils (="medium-K Fra Mauro basalt"). The Apollo 15 KREEP basalts have been dated by Rb-Sr (internal isochron age- 3.85 ± 0.02 b.y.; [12]), ⁴⁰⁴⁰Ar-³⁹Ar (3.85 ± 0.05 b.y.; [13]), and Sm-Nd (internal isochron age- 3.85 ± 0.08 b.y.; [14]) techniques. The isotopic data are consistent with crystallization of these basalts at 3.85 b.y., an age at present indistinguishable from that of the Imbrium basin impact [15].

Apollo 15 returned several unequivocal impact-melt rocks, none of which resemble the Apollo 15 KREEP basalts in any way. Moreover, clast-poor impact-melt rocks from elsewhere on the Moon (e.g., 14310; 68415) also differ from the Apollo 15 KREEP basalts in that: (1) they invariably contain xenocrystic debris, consisting of undigested (refractory) clasts; 2) they have high contents of siderophile elements, indicating meteoritic contamination. Taylor [9; p. 215] argues that lack of siderophile contamination does not prove an endogenic origin. While true, we contend that both the lack of clastic debris and low siderophile concentrations are strongly suggestive of an endogenic origin; such data certainly would be conclusive in the case of a mare basalt. Taylor [9; p. 216] further states that "model ages for KREEP point back to the initial differentiation of the Moon, not to more recent volcanic events" [9; p. 216]. But model ages for mare basalts also point back to initial lunar differentiation [16], yet no one doubts their volcanic origin. We conclude that all petrologic, chemical, and chronologic data are consistent with Apollo 15 KREEP basalts being true, endogenically-generated volcanic rocks, extruded onto the lunar surface at the time of or shortly after the Imbrium basin impact.
The Apennine Bench Formation. As shown by orbital geochemical data [6], an area strongly enriched in radioactive elements (indicative of KREEP) occurs southwest the Apollo 15 landing site. The dominant geologic unit in this area is the Apennine Bench Formation, a light plains unit originally interpreted to be of volcanic origin [1]. Intensive study of impact melt deposits in lunar craters and basins has resulted in a fuller appreciation of their importance in lunar history and some workers have assigned such an origin to the Apennine Bench Formation [e.g., 2,3,9]. However, comparison of the occurrence, distribution, surface texture, morphology, and stratigraphic relations displayed by the Apennine Bench Formation with recognized melt deposits in the Orientale basin [e.g., 4,5] suggests that the Apennine Bench Formation does not represent an Imbrium basin impact melt sheet.

The Apennine Bench Formation occurs within the Imbrium basin in the vicinity of the Archimedes ring (790 km diameter), the ring just inside the main basin ring (Apennine ring; 1160 km diameter). At the Orientale basin, the analogous geologic setting (i.e., Outer Rook/Cordillera rings) contains a knobby-textured unit, the Montes Rook Formation [3,17]. This unit is not similar to the Apennine Bench Formation [cf. 9; p. 38]; an Orientale unit which does bear superficial resemblance to the Apennine Bench material is the Maunder Formation [3], but this unit is totally confined within the Outer Rook ring [3,17,18] and does not extend outward to the main basin ring. Moreover, the Apennine Bench Formation has a relatively flat, smooth surface as opposed to the rough, pitted, and cracked texture of the Maunder Formation. The Apennine Bench Formation does not drape pre-existing topography, as does the Maunder Formation, but rather, displays an embayment relation with terra islands, as do the mare basalts [4,5].

A more important line of evidence for the origin of the Apennine Bench Formation comes from its chemical composition as determined from remote-sensing data (Table 1). Early studies [4,5,21] noted a rough chemical correspondence between the Apennine Bench Formation and Apollo 15 KREEP, based on early reductions of the orbital chemical data. In recent years, these data have been refined [6,18,19] and the resemblance of the Apennine Bench Formation to Apollo 15 KREEP is remarkable (Table 1). The Apennine Bench Formation does not correspond to the composition of probable Imbrium impact melt (15445 and 15455 black matrix; [22]), but closely resembles Apollo 15 volcanic KREEP basalt (Table 1). Taylor's argument that portions of the Apennines (Imbrium ejecta) possess the same Th concentrations as the Apennine Bench Formation [9, p. 215] is incorrect; the highest Th concentration in Apennine material is 7.6 ppm [6]. Thus, the orbital data strongly support the contention that Apollo 15 volcanic KREEP basalt and the Apennine Bench Formation have identical compositions.

Finally, we note that the KREEP-basalt composition of the Apennine Bench Formation (Table 1) precludes an Imbrium impact melt origin. If the Imbrium basin target had a pure Apollo 15 KREEP-basalt composition, much higher heat-flow values would be seen at the Apollo 15 landing site than are recorded [4,23]. In fact, the crust would have been so enriched in radiogenic elements, that it would have been partially molten. We conclude that considerations of the probable chemical nature of the Imbrium basin crustal target suggests that the presently exposed portion of the Apennine Bench Formation cannot represent an Imbrium basin impact melt sheet.

Conclusions. We contend that a variety of data support previous interpretations [1,4,5,21] that the Apennine Bench Formation consists of post-Imbrium, volcanic KREEP basalt lava flows. The observations leading to this conclusion
are: 1) petrologic, chemical, and isotopic data suggest Apollo 15 KREEP basalts are of volcanic origin; 2) the morphology of the Apennine Bench Formation is more consistent with a volcanic origin than with an impact-melt origin; and 3) the Apennine Bench Formation and Apollo 15 KREEP are chemically identical. Additionally, it has been found recently [24] that Apennine Bench Formation may be in the shallow subsurface within 10 km of the Apollo 15 site, supporting the likelihood that this material was probably sampled during the mission.

As a major, preserved surface exposure of post-Imbrium volcanic KREEP flows, the Apennine Bench Formation is an important target for future lunar exploration. At this locality, the geology and processes of lunar KREEP volcanism may be studied and eventually deciphered.

References

Table 1. Comparison of the compositions of the Apennine Bench Formation, Apollo 15 volcanic KREEP, and Imbrium basin impact melt.

<table>
<thead>
<tr>
<th></th>
<th>Apennine Bench Fm&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Apollo 15 KREEP&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Probable Imbrium Impact Melt&lt;sup&gt;3&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1.7-2.3%</td>
<td>1.8-2.3%</td>
<td>1.35-1.70%</td>
</tr>
<tr>
<td>Al&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;3&lt;/sub&gt;</td>
<td>16.0%</td>
<td>14.8-17.8%</td>
<td>16.2-17.5%</td>
</tr>
<tr>
<td>FeO</td>
<td>9.5-12.4%</td>
<td>8.6-11.1%</td>
<td>7.9-10.2%</td>
</tr>
<tr>
<td>MgO</td>
<td>5.7%</td>
<td>6.3-8.2%</td>
<td>13.4-16.0%</td>
</tr>
<tr>
<td>Th</td>
<td>10.7-12.0 ppm</td>
<td>10.5-12.0 ppm</td>
<td>2.4-2.9 ppm</td>
</tr>
</tbody>
</table>

1. Values from [18] (Al, Mg), [19] (Fe, Ti) and [6] (Th).
2. Values from [8,10].
3. Values for black matrix of 15445 and 15455, compiled in [20].
The Apollo 15 Lunar Module (LM) landed July 30, 1971, on the mare surface of Palus Putredinus at the eastern edge of Mare Imbrium. The major geologic objectives of the mission, in order of decreasing priority, were observations and sampling of the Apennine Front, Hadley Rille, and the mare. Apollo 15 was the first of three “JM” missions, which were devoted primarily to science. The first EVA, or stand-up EVA (SEVA), was performed by Commander Scott opening the top hatch of the LM and describing the surface from this vantage point. Three traverse EVAs were performed using the Lunar Roving Vehicle (LRV) for the first time (Fig. 1). A total of 27.9 km were traveled on the LRV, 77 kg of samples were collected, and 1,152 still photographs were taken on the surface. These photographs were supplemented by moving pictures taken with the Data Acquisition Camera (DAC), and television with pan and zoom controlled from the Mission Control Center. An Apollo Lunar Surface Experiments Package (ALSEP) consisting of an array of geophysical instruments was deployed near the LM. High resolution (panoramic) and high geometric fidelity (metric) photos were taken from orbit which included coverage of the landing site; in addition, gamma-ray and X-ray fluorescence spectroscopic measurements were made from orbit, to determine regional chemical compositions of the Moon.

During the SEVA and LM window descriptions, Scott described a rolling and hummocky surface, and commented that all of the rock fragments he could see were either white or light gray, with the exception of two black ones (one of which was subsequently collected and turned out to be a glassy regolith breccia). He also described lineaments on the mountains which are clearly visible on the photographs. With the exception of Silver Spur, these have been shown to be artifacts of illumination (Wolfe and Bailey, 1972). Those on Silver Spur appear to be topographic benches, but whether or not these benches are reflections of layering or structure remains uncertain.

During the first EVA, the crew traveled south, partly along the rim of Hadley Rille, to Station 1 at Elbow crater. Samples collected at Elbow are predominantly pyroxene basalt, presumably excavated from the mare near the rim of Hadley Rille by the impact which formed Elbow crater. They then proceeded up the “front,” or lower slopes of Hadley Delta, to Station 2, where they collected mostly breccias, many of them containing mare basalt clasts. They also sampled a 1 m breccia boulder, and took several soil samples.

They then returned to the LM, making one quick stop to collect a vesicular olivine basalt, at what was later designated as Station 3. Upon returning to the LM, they deployed the ALSEP.

On EVA II, they again traversed a southerly route to Stations 6, 6a, and 7, all on the lower slopes of Hadley Delta above the mare surface. Nearly all of the samples collected are regolith breccias, many containing mare basalt clasts. Apparently, most true "highlands" samples, including an anorthosite (15415), were collected at Spur crater (Sta. 7). They then started back toward the LM, stopping on the south rim of Dune crater in the South Cluster at Station 4. The crew sampled a large vesicular pyroxene basalt boulder on the rim of Dune, and collected other samples, mostly breccias, near the rim of Dune. Upon returning to the LM, they performed the "Station B" activities at the ALSEP site, which included a trenching operation for the Soil Mechanics Experiment, and the drilling of the "deep" (3m) core hole.

On the third EVA, they first removed, with some difficulty, the core barrel from the drill hole, and then proceeded west toward the rille. Station 9 is at a very fresh, 15 m diameter crater with clouded ejecta, about 300 m east of the rille edge. Samples taken there are all glassy, poorly indurated regolith breccias. Station 9a is in a basalt boulder field on the rille edge, and the boulders appear to be nearly in place, essentially bedrock. Olivine basalt samples were collected from one boulder, and pyroxene basalt from another at a slightly lower elevation and nearer the rille, and therefore probably at a lower stratigraphic level. Regolith at Station 9a is nearly absent because the rille serves as a repository for fines moved by meteorite impact (Swann and others, 1972). Station 10 was a stop to take photographs which would form stereo pairs with those taken at Station 9a of outcrops on the far side of the rille.
The primary interest in the Apennine Front stemmed from the hope of collecting "primordial" pre-Imbrian material. Prior to the Imbrium impact, the site was undoubtedly blanketed with ejecta from the Serenitatis basin, and beneath the Serenitatis ejecta were debris from older impact events. The search for "primordial" material is of necessity an almost random process of finding, and hopefully recognizing, a piece of such material among the many layers and mixtures of debris created by countless impacts of all sizes. Perhaps some place within the massifs such material exists, but it is not clear that it was collected by Apollo 15. Anorthosite 15415, the "Genesis Rock," is probably a pre-Imbrian rock, but how much of its "primordial" character has been altered by intense shock events after its original crystallization remains unclear.

Nearly all of the rock samples collected at the front are regolith breccias containing mare basalts. Station 2, however, is well within the range of ejecta from Elbow crater, and Stations 6, 6a, and 7 are within range of ejecta from the South Cluster and other craters in the mare. The regolith on the front is mature and thoroughly gardened, and in the areas sampled, ejecta from the nearby mare have been intermixed into the breccias.

It was expected prior to the mission that the mare surface in the vicinity of the landing site would be contaminated with non-mare materials. Material from impacts on the massifs would certainly be present in some undetermined amount, and most mappers thought that they could identify the presence of a very faint ray crossing the site either from Aristillus or from Autolycus. Spudis (1978a), however, has pointed out the that topographic highs (such as the North Complex) in the vicinity of the site, which are almost certainly Apennine massif material and possibly partly covered by a thin mantle of mare basalt, are probable contributors of non-mare materials by post-mare impact. He also suggests that the slight ridge upon which the LM landed (Fig. 2) may be a reflection of pre-mare topography covered by a thin mantle of mare basalt. The "high lava mark" on the side of Mt. Hadley (Fig. 2) described and photographed by
the crew suggests a drain-back of lava that would leave topographic highs draped with basalt (Swann and others, 1972). Significant segments of the EVA I and II traverse routes were along the aforementioned ridge, and craters penetrating into underlying pre-mare material could be the source of much of the non-mare materials at the surface.

KREEP basalts are abundant in the Apollo 15 samples. Spudis (1978b, 1985), and Hawke and Head (1978), have shown with remote sensing data that the Apennine Bench Formation exposed south of Archimedes (Hackman, 1966) is probably KREEP basalt. Carr and El-Baz (1971) show extensive exposures of Apennine Bench Formation 40 km northwest of the site that were not recognized by Hackman. Two more exposures of Apennine Bench Formation 50 and 100 km southwest of the site are apparent in Metric and Panoramic camera photographs. In addition, the large exposure of Apennine Bench Formation south of Archimedes extends to within 75 km west of the site, not 125 km as mapped by Hackman (1966). These determinations by Carr and El-Baz were made possible by Lunar Orbiter IV photographs, and by the author with Apollo 15 Metric and Pan camera photographs, none of which were available to Hackman at the time of his mapping. Furthermore, two areas, one 12 km north of the site and the other 6 km northeast of the site appear, from scarps and depression features of the type that typify the Apennine Bench Formation, to be Apennine Bench Formation covered by a thin mantle of basalt (Fig. 2). The proximity of widespread exposures of Apennine Bench Formation to the north, west, and south of the site, and of Apennine Bench-like structures even nearer, suggest that the site may be underlain in the shallow subsurface by Apennine Bench Formation. Additional Apennine Bench Formation material was probably introduced at the surface of the site by the Autolycus event 140 km to the north, which almost certainly impacted into the Apennine Bench Formation (Carr and El-Baz, 1971; Carr and Meyer, 1974).

A reasonable stratigraphic sequence for the site consists of pre-Serenitatis basin impact breccias, Serenitatis basin ejecta, Imbrium basin ejecta, Apennine Bench Formation, and mare basalts, the upper-most 60 m being the lower layered unit, middle massive unit, and upper dark unit exposed in the rille wall (Howard and others, 1972). The upper dark unit may be olivine basalt, and lower units pyroxene basalt (Swann and others, 1972).

The origin of sinuous rilles has long been debated, and a mechanism involving lava channels and/or collapsed lava tubes is probably the most widely accepted explanation. It has also been noted that some sinuous rilles consist of straight segments connected at rounded corners. This is the case for Hadley Rille, and suggests that the trends are structurally controlled (e.g., Howard and others, 1972).

Some of the most distinctive features of the Apennine Bench Formation are its northeast and northwest trending scarps, troughs, and elongate depressions. Mozart Rille, 100 km west southwest of the landing site, is a sinuous rille mostly confined to the Apennine Bench Formation, but extending 10 km into the mare. The zigs and zags of this rille appear to be controlled by scarps in the Apennine Bench Formation; it is also aligned with an apparent collapse structure a couple of kilometers to the east which extends at right angles from Bradley Rille. Structural control of Mozart Rille seems obvious.

The two main trends of Hadley Rille are northeast for the southern half, and northwest for the northern half. Individual segments of the rille also lie on these trends (Howard and others, 1972). These trends are consistent with the structural trends in the Apennine Bench Formation; furthermore, the northern terminus of Hadley Rille merges with two northeast- and northwest-trending straight rilles of the Fresnel system in the Apennine Bench Formation. It is proposed here that Hadley Rille is a lava channel or collapsed lava tube that first formed on the structurally controlled topography of the Apennine Bench Formation as did Mozart Rille, and that these trends were maintained as mare flooding continued and the rille completed its development.

References Cited
Figure 2. Geologic sketch map of Apollo 15 landing site area, from unrectified Apollo 15 Pan Camera photographs.


THE ORIGIN OF PRISTINE KREEP: EFFECTS OF MIXING BETWEEN URKREEP AND THE MAGMAS PARENTAL TO THE MG-RICH CUMULATES

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The two main varieties of lunar basalt, mare basalt and KREEP basalt, are seldom difficult to distinguish. Besides having far higher contents of incompatible elements, KREEP basalts generally have higher Al2O3 and lower Ca/Al (reflected in lower contents of high-Ca pyroxene). Both types of basalt are widely assumed to be derived by remelting of late products of the Moon's "magma ocean" (a.k.a. magmasphere). But the sharpness of the distinctions between the two basalt types, and more importantly the paradox that KREEP basalts have far higher contents of incompatible elements and yet have similar mg ratios, seem inconsistent with both basalt types having formed simply by remelting of a series of different products of a single former magma.

The mg ratio - incompatible elements paradox is also difficult to explain with a "serial magmatism" model, in which the Moon's crust forms in the absence of a magmasphere [Walker, 1983]. Under such a scenario, complexities such as assimilation and magma mixing would occasionally lead to geochemical anomalies, including basalts with high incompatible element contents and moderate mg ratios. But such cases would presumably be exceptional. Most basalts with high incompatible element contents would have low mg.

Assuming that KREEP is derived from magmasphere residual liquid (urKREEP), one possible means of raising its mg ratio is by assimilation reactions between urKREEP and lower crustal material [Warren and Wasson, 1979]. But this model, originally suggested by Hubbard and Minear [1976] and Dowty et al. [1976], has never been tested quantitatively. Most estimates of the bulk composition of the Moon hold that its mg is less than 0.84 [for a review, and arguments that these estimates are probably somewhat low, see Warren, 1985b]. Most estimates of the bulk mg of the crust are of course much lower still. Taylor's [1982] estimated bulk highlands crust composition has mg = 0.65. One way to estimate the mean mg of the upper nonmare crust is to consider the compositions of mare-free soils, which generally have mg in the range 0.66-0.69; including the ALHA81005 regolith breccia extends the range to 0.73 [Warren, 1985b]. Thus, it seems unlikely that the upper nonmare crust's mg is much greater than 0.70. In the simple magmasphere - plagioclase flotation model of crustal genesis, the crust grows from the top down, so the upper crust presumably acquires an mg ratio that is at least as high as that of the lower crust. As the final residuum of the magmasphere, urKREEP must have had a modest mg. It seems unlikely that any type of assimilation reaction with mg-0.70 material could transform urKREEP into liquids with the mg ratios of the Apollo 15 pristine KREEP basalts. Among pristine Apollo 15 KREEP basalts mg ranges from 0.35 to 0.73, and most are in the range 0.50-0.70 [Irving, 1977]. Irving [1977] even suggests that these basalts were all derived by fractional crystallization of a more magnesian parent melt with mg = approx. 0.72 (and K2O = approx. 0.5 wt%). The pristine KREEP basalt from Apollo 17 (72275c) also has a moderate mg ratio: approx. 0.52 [Ryder et al., 1977]. At equilibrium, assuming KD = 0.30 (numerous experimental studies, cited by Warren [1985b], indicate that KD for both olivine and pyroxene at low pressure and oxygen fugacity will be in the range 0.25-0.35), a solid with mg = 0.70 will coexist with a liquid with mg = 0.41. The numerous Apollo 15 KREEP basalts with mg >0.65 would only be in equilibrium, as melts, with solids with mg =0.86; the Apollo 15 KREEP basalt with mg = 0.73 would be in equilibrium
with solids with mg = 0.90. Even assuming $K_D = 0.35$, the basalts with mg $\leq 0.65$ would be in equilibrium with solids with mg $\geq 0.84$, and the basalt with mg = 0.73 would be in equilibrium with solids with mg = 0.89.

Dowty et al. [1976] appeal to assimilation as a process in which "equilibrium was strictly maintained only between the liquid and the outermost surface layer of the ANT crystals," as a result of which, these authors suggest, "the Fe/Fe+Mg ratio would tend to approach that of the melted ANT crystals." In this model, the assimilation process resembles continual ultralow-degree partial melting of the crustal rocks through which the urKREEP is supposed to percolate. However, in any partial melt, the melt mg ratio increases as the degree of melting increases. Thus, the transient sort of equilibrium invoked in this model would probably tend to yield liquids with modest mg ratios, even lower than in the case of a slower, more thorough type of assimilation; and in any case far below the mean mg ratio of the crust with which the liquid undergoes the assimilative reactions.

The magmasphere's urKREEP residuum must have initially collected as a "sandwich horizon" at the top of the mantle. Barring vigorous convective mixing of the mantle, assimilation reactions between urKREEP and the mantle would be unlikely to raise the mg ratio of the urKREEP, however, because the cumulates in the uppermost mantle (the presumed sources of the mare basalts) formed late in the differentiation of the magmasphere, and therefore had modest mg ratios; moreover, the low density of urKREEP probably caused it to slowly rise into the crust [Shirley and Wasson, 1981].

The mg ratio - incompatible elements paradox is readily explained by a model that considers not only the magmasphere, but also its aftermath. A widely accepted model for the origin of the Mg-rich cumulates (i.e., the nonmare cumulates other than ferroan anorthosites; the latter are presumed to have formed atop the magmasphere) holds that they formed in more or less conventional layered intrusions, emplaced into older, ferroan-anorthositic crust within a few hundred Ma of the origin of the Moon [e.g., Warren and Wasson, 1980; James, 1980]. As discussed by Warren and Wasson [1980], the source regions of these melts were probably concentrated in the lower-middle mantle, where the mg ratio was at least nearly as high as the bulk-Moon mg ratio. In any event, these melts yielded cumulates with olivine mg ratios frequently $\geq 0.90$, and occasionally as high as 0.92 [Warren, 1985b]. Assuming $K_D = 0.30$, olivine with mg = 0.90 implies the parent melt's mg was 0.73; olivine with mg = 0.92 implies the parent melt's mg was 0.78.

Pristine Mg-rich rocks range in age from 4100 to 4500 Ma, and thermal models suggest that the magmasphere completed 99% of its crystallization, yielding the ferroan anorthosites plus a thin layer of urKREEP immediately below, within 200 Ma of the origin of the Moon [Warren, 1985a]. Thus, the onset of Mg-rich plutonism apparently came shortly after, or even overlapped, the final stages of magmasphere crystallization. The magmasphere's final urKREEP residual liquid, representing only a few tenths of a percent of the original magmasphere, had such high contents of U, Th and K, it could have remained molten at the base of the crust for many hundreds of Ma. Left undisturbed, its low density would have caused it to slowly migrate toward the surface [Shirley and Wasson, 1981]. But soon after urKREEP formed, and perhaps even during its final stages of formation, Mg-rich magmas apparently plowed through the urKREEP collection layer (the crust/mantle boundary) on their way to the crust. These rising parcels of Mg-rich melt presumably mixed
ORIGIN OF PRISTINE KREEP

Warren, P. H.

with, or at least partly assimilated, whatever urKREEP that they passed through. Implications of this mixing for the composition of the melts parental to Mg-rich rocks have been appreciated for some time [e.g., Warren and Wasson, 1980]. But if mixing between urKREEP and Mg-rich melts was pervasive enough, the composition of most of the basalts derived from urKREEP would also have been affected.

As noted by Longhi and Boudreau [1979] in relationship to their model for crystallization of the magmasphere, systematic mixing of primitive, Mg-rich material with residual liquid could account for the paradox that KREEP basalts, despite their high incompatible element contents, have moderate mg ratios. For example, assume that urKREEP with a U content of 400 x chondrites was mixed into a 10 times more massive parcel of Mg-rich melt, with U = 5-10 x chondrites and an mg ratio of 0.75. The resultant mixture has a primitive major element composition, including mg ratio (assuming that the FeO content of the urKREEP is similar to that of the Mg-rich melt, the mg ratio of the mixture will be at least 0.73), but 5-10 times more U than the Mg-rich melt would otherwise have contained. As this melt proceeds to crystallize as a "mini magma ocean" in the crust, its residual, KREEP-like liquid (a sort of second-generation urKREEP) will have 5-10 times more U for any given reduction in its mg ratio. Again, the U, Th, and K enriched in the residual melt might produce enough heat to prevent complete, or in this case even nearly complete, crystallization, until finally the melt migrates (or is ejected by a mega-impact) to a cooler environment closer to the surface of the Moon. Alternatively, crystallization might go to completion, but the upper portion of the intrusion might later remelt (perhaps in the aftermath of heating of the lunar interior by a basin-forming impact). The melt produced by this process would have roughly 5-10 times more U than a melt of equivalent mg ratio produced by direct melting of magmasphere cumulates.

This mixing process could also help to account for the higher Al2O3 contents and Al/Ca ratios of KREEP basalts, in comparison to mare basalts. The Al2O3 content of melts co-saturated with a low-Ca mafic silicate plus plagioclase tends to correlate with the melt mg ratio [e.g., Longhi, 1977]. Thus, the Al2O3 content of a KREEP basalts derived from a mixture of urKREEP and primitive Mg-rich melt will tend to be higher than the Al2O3 contents of basalts produced by direct remelting of late-stage magmasphere cumulates. In addition, the Mg-rich melt will tend to assimilate plagioclase from ferroan anorthosite country rock as it solidifies [Warren, 1985c]. Besides increasing the melt Al2O3 content, plagioclase assimilation would have a moderating effect on the Ca/Al ratio of the residual liquid.

GEOLOGIC SETTING OF THE APOLLO 15 LANDING SITE; D. E. Wilhelms, U.S. Geological Survey MS-946, Menlo Park, CA 94025

General setting

Apollo 15 was a multi-purpose mission to investigate both the multi-ringed Imbrium impact basin, represented by Montes Apenninus, and the mare that fills the basin, represented by Palus Putredinis (PP) (Fig. 1). Although the sinuous rille Rima Hadley that cuts PP was actually the initial attractant to the site, the Apennines eventually became its prime object of geologic interest (1).

The landing site is at 26.10° N., 3.65° E., in an inlet of PP that is bordered on the SE by the Apennine front and almost enclosed on the NE by two outlying linear hills parallel to the front. The main part of PP is bordered on the NW by the mare-filled Upper Imbrian impact crater Archimedes (83 km diam., 29.7° N., 4.0° W.) and on the SW and NE by the Apennine Bench. The Bench consists of low hills and of the Apennine Bench Formation (ABF), a Lower Imbrian light-colored plains deposit (2). The ABF is overlain by secondary craters of Archimedes and floods hills of the Apennines and the rugged Montes Archimedes. The northern arm of the Bench lies south of the Copernican impact craters Autolycus (39 km, 30.7° N., 1.5° E.) and Aristillus (55 km, 33.9° N., 1.2° E.) and is overlain by deposits and secondary craters of Autolycus. Rays and the "South Cluster" of craters indicate that ejecta from one of these craters impacted near the site.

Imbrium basin

The Apennines, the lunar nearside's highest mountain range, are the most prominent component of the concentric ring system of the Imbrium basin. The Apennine front is a major topographic and geologic discontinuity and encloses the Imbrium topographic basin. PP and the adjoining belts of the Bench trend normal to the Apennines, that is, radial to the basin center. Faults on the basinward side of the Apennines are oriented both concentrically and radially; few Imbrium-related faults occur outside the Apennine front. Many hummocks atop the mountains and near the front are concentric with the basin, but those farther out are predominately radial (Fig. 1). South and SW of the Apennines, this crudely radial hummocky deposit, the Fra Mauro Formation (FMF), obliterates pre-Imbrian craters to distances of 350 to 600 km and extends to distances of 600 to 800 km (3,4,5). Many Imbrium secondary craters as large as 20 km and some as large as 30 km in diameter form giant clusters and chains beyond the FMF to as much as 2,600 km from the Apennines (5,6). A similar, though less well defined, transition from the FMF to secondaries occurs north and NW of Mare Frigoris. In the remaining sectors, NE and SW of the basin, the coarse, knobby variety of hummocky Imbrium material known as the Alpes Formation forms a belt as much as 600 km wide (3,5). Imbrium ejecta and secondaries therefore constitute a datum plane relative to which stratigraphic units can be dated over a large area. Thus, samples from both the Apennines and from the FMF at the Apollo 14 site 1,100 km SE of the Apollo 15 site can potentially provide absolute ages and compositional data relevant to the Imbrium basin, if the samples are primary basin ejecta. Premission modeling suggested that samples from the Apennines might represent deeper crustal layers than the Apollo 14 samples (1).
The nature and origin of the multiple concentric rings of Imbrium, including the Apennines, are less well understood than its ejecta and secondaries. The major arc on which the Apennines lie also includes Montes Carpatus and southern Montes Caucasus. Otherwise, even the connection among the exposed segments of the Imbrium rings is uncertain. The northern Caucasus diverge eastward from a circular extrapolation of the arc, so that the main ring may continue, alternatively, through the northern shore of Mare Frigoris, the Mare Frigoris trough, or Montes Alpes (3,7,8,9). Corresponding alternative diameters of the main basin ring are 1,500 km, 1,340 km, and 1,180 km, respectively. Centers have been plotted from 38° N., 19° W. to 34° N., 17° W. Lineations in the northern, deflected part of the Caucasus point to the latter center, suggesting that it is the true center and that the basin has a larger radius in the north than the south. Reconstructions of inner rings also vary. The most obvious topographic elements (including mare wrinkle ridges) suggest rings of 950 km-diameter (connecting Montes Archimedes and Alpes) and 670 km (connecting smaller peaks).

Significant unresolved questions concerning basin rings in general and the Apennines in particular include whether basins were shallow or deep when formed, and whether the rings (a) are unique features or are scaled up from central peaks and/or terraces of complex craters, (b) developed during or after the excavation, (c) formed by active processes such as undulations of the target material or by passive processes such as centripetal faulting or megaterracing, (d) formed inside or outside the excavation or in both positions, and (e) are influenced by the thickness and physical properties of the target rock (4,5,10,11,12). The identification of the original boundary of excavation and therefore of the original diameter of the basin is a particularly important and vexing unsolved problem. The currently most popular view is that the Apennines and other topographic basin rims were formed outside the excavation cavities and were isolated when the cavities collapsed. This origin is suggested by Apennine Bench and the slump features, which have been compared with the terraces of craters, whose formation enlarges the original cavity. The hypothetical smaller Imbrium cavity is now mostly buried by Mare Imbrium and is represented by one of the partly exposed rings or by no preserved ring. Another view, which prevailed during the planning for the Apollo 15 mission, is that the topographic basin rims are also the rims of the basins' excavation cavities. I still favor this hypothesis because the Apennines are such a massive ring segment and mark sharp discontinuities in topographic trend and ejecta textures. The mountain front is marked by a line of massifs that slope in both directions (Fig. 1), not by a simple scarp as would be the case in passive fault origins; the steep inward-facing slope is a complex, scalloped landslide slip surface. Mons Hadley delta is the nearest such massif to the site and the only sampled part of the front.

In most interpretations, the Apennines consist of uplifted prebasin rock overlain by Imbrium ejecta (2,3,13). The proportion between pre-Imbrian rock and Imbrium ejecta in the mountains is a premission question that remains unanswered.

Several subtypes of Imbrium-basin material overlie the mountains except, judging from the textures, on the tops of the most rugged massifs (Fig. 1; 3,14,15). Some of this Imbrium material might have dribbled down to the site in talus, which coats all the steep slopes and obscures the
original stratigraphy of the mountains. The samples that were collected from the front came from an apronlike accumulation of this doubtlessly highly mixed debris (which was noted before the mission; 13). The subtype of hummocky material called Material of Montes Apenninus lies in the intermassif terrain nearest the site; it consists of rugged elongate blocks roughly concentric with the front and has been interpreted as a mixture of structurally emplaced blocks and ejecta (14). Other hummocky facies of Imbrium material are the Alpes Formation, interpreted as Imbrium ejecta emplaced from high-angle trajectories, and the FMF, Imbrium ejecta emplaced at lower angles. These facies are geochemically different (16). Knowing the proportions of impact-melt rock and clastic debris in each facies would help in identification of sample provenance, interpretations of isotopic ages, and estimates of impact magnitude and velocity (10,11,12). Pools of cohesive material superposed on the Apennine flank suggest to me that considerable ejected impact melt is present (Fig. 1).

The rings of older basins apparently controlled the present form of the Imbrium rings and suggest what pre-Imbrian materials might be found in the Apennines. The Serenitatis basin to the east is the most obvious nearby older basin. Its topographic rim, represented by Montes Haemus, is truncated by the Apennines at 25° N., 5° E. Serenitatis material must constitute part of the Apennines or their basement at that point. Projection of the Serenitatis rim inside the Apennine-Caucasus arc shows that the depressed part of Serenitatis occupied the space between the Apennines and Caucasus, explaining the gap (3,15). The eastward deflection of the northern Caucasus is explained by the absence of resistance to the expansion of the Imbrium rim north of the Serenitatis rim. Another pre-Imbrian basin that affected the present structure of Imbrium is Insularum (3,4,5). Some of Insularum's outer flank material may be incorporated in the Imbrium rings. If present in Mons Hadley delta, the Insularum material would have been first incorporated in the deposits or uplifted in the massifs of the younger Serenitatis basin. Distinguishing among the contributions of Imbrium, Serenitatis, Insularum, and possibly other basins is a major challenge to petrologists and geochemists. These basin materials may be stratified in their sequence of formation or may be inextricably mixed.

The third and oldest basin that may have contributed to Imbrium has been called "Gargantuan" (17) or Procellarum (18). In my opinion, the Procellarum basin exists and had a profound effect on Imbrium by thinning the pre-Imbrian crust and lithosphere (4,5,17,18). The basin may have three rings, a diameter of 3,200 km, and a center under Mare Imbrium at 23° N., 15° W. (18). Such a basin would have been a site of pre-Imbrian basalt extrusions that became part of the Imbrium ejecta; a concentration of KREEP in the Procellarum-Imbrium region may reflect a KREEP-rich composition of this basalt (17). Alternatively, Procellarum could have exposed lower KREEP-rich layers of the terra crust, possibly explaining why the FMF at the Apollo 14 site is KREEP-rich and why many Apennine samples (and Serenitatis samples from Apollo 17) are richer in Mg-rich ANT and low-K KREEP than the Apollo 16 material (17).

Interpretations of the ABF have shifted back and forth between volcanic and impact-melt rock ever since it was first recognized. Its pre-mare, pre-Archean age shows that it is either contemporaneous with the basin (if impact melt; 14) or only slightly younger (if volcanic; 19).
Mare and related materials

Before the mission, the age of the mare near the landing site was estimated as late Imbrian or early Eratosthenian on the basis of crater frequencies, crater morphologies, and, mistakenly, albedo (13). No subdivisions had been recognized. The "reddish" reflectance spectra of the mare appears to result from their low TiO₂ content (20,21). Both in age and spectra, PP is typical of the units of the main part of Mare Imbrium on the west and north sides of the Archimedes-Apennine Bench barrier. Studies of the large collection pigeonite and olivine basalts from the landing site have not demonstrated their genetic or chronologic relation or shown whether which, if either, contained the flow that formed Hadley rille (21,22).

Like most lunar mare margins, the region has its share of dark mantling materials. The apparently dark-mantled hills called North Complex (which might possibly be a volcanic construct) were on the list of mission objectives but were not visited. The Apennines also are overlain by some dark-mantling material (3).

Sampling summary

Viewed in the context of the site's geology (22), the returned samples already have or potentially can provide a remarkably comprehensive sampling of the Moon's vertical profile and geologic history: (a) the deep mantle, probably represented by pyroclastic glasses; (b) a shallower zone or zones of the mantle, represented by the mare basalts (and possibly by fragments excavated directly by the basins); pre-Imbrian pristine rock from (c) KREEP-rich and (d) ANT layers or zones; (e) recycled crustal rock in the deposits of one or more pre-Imbrian basins; (f) Imbrium-basin ejecta; (g) the ABF of volcanic or Imbrium impact-melt origin (KREEP basalt), transported by impacts from exposures or buried beds of the ABF (19); (h) the target material of Autolycus and(or) Aristillus, possibly including geochronologically reset samples that can date the crates; and (i) the regolith.

Figure 1. Geologic map of the Apollo 15 landing site (arrow), based on Apollo 15 and 17 mapping-camera frames (Wilhelms, 1980).
SELECTION OF THE APOLLO 15 LANDING SITE; D. E. Wilhelms, U. S. Geological Survey MS-946, Menlo Park, CA 94025

Telescopic studies in the early 1960's pinpointed the future Apollo 15 landing site as a potential exploration site because it includes one of the largest lunar sinuous rilles, Rima Hadley, and some of the Moon's highest mountains, Montes Apenninus. Interest in the site was aroused largely by a striking photograph taken by G. H. Herbig with a primitive camera attached to the 120-inch telescope of Lick Observatory (while he was waiting for the bothersome Moon to set). The Apennines are the southeastern segment of the most prominent ring of the Imbrium basin. Imbrium is the most conspicuous ringed impact basin on the lunar nearside, and its deposits constitute a valuable stratigraphic datum plane for vast areas of the Moon. The Apennine-Hadley region also includes clearly determinable stratigraphic relations that proved that lunar basins and maria differ in age and origin.

Because of this early interest, the site was placed high on the list of targets for the Lunar Orbiter 5 mission in August 1967, whose purpose was to explore sites for advanced manned exploration. A mode of four widely spaced camera exposures was employed that left gaps in the high-resolution coverage.

Peculiar features often attracted more attention in the early stages of the site-selection process than did basic geologic units such as those of ringed basins. Thus, in 1967 many mission planners considered the rille to be the region's center of interest. Knowing the process of rille cutting was considered important for understanding lunar processes and materials; investigators alternatively favored an origin as a tectonic fissure, a lava channel or tube, or as a groove eroded by lava, nuées ardentes, or water. The head of the rille was thought to be a possible still-active source of, or trap for, volatiles. Other conspicuous rilles, such as Vallis Schröteri and Rimae Prinz, were also photographed by Orbiter 5 and were briefly considered as alternatives to the Hadley mission.

Interest in volatiles subsided, however, when earlier missions found no traces of them. Interest in the Apennines persisted and grew to prime importance. Their evident uplift indicated that they would expose a section of crustal rock several kilometers thick. Both Imbrium-basin and pre-Imbrian rock should be present, in unknown proportions. Analogy with the overturned ejecta flaps of simple terrestrial impact and explosion craters suggested that a complete section of Imbrium ejecta would be present in or on the massifs, and that the top of this section was derived from greater depths than was the Fra Mauro Formation at the Apollo 14 site. It was hoped that the very deep crust, or even the mantle, might have been excavated. Samples of the Imbrium ejecta would also provide an absolute age for the Imbrium basin by which the lunar stratigraphic column could be calibrated, and would help to elucidate basin-forming processes. The underlying pre-Imbrian section was predicted to include rock from such pre-Imbrian basins as Serenitatis or, many planners hoped, relatively undisturbed primitive crustal rock. These exciting possibilities kept Apennine-Hadley on almost all lists of potential landing sites.

Additional targets were identified once Apennine-Hadley emerged as a potential landing site. It offered another mare, Palus Putredinis, in addition to the two, apparently older, mare units that had been visited by
Apollos 11 and 12 in 1969. Constructional volcanic features were thought to occur at the arrowlike source of Rima Hadley, along the Apennine front, and in the "North Complex." The 5.5-km-diameter crater Hadley C presumably excavated a thick stratigraphic section that could be sampled in its ejecta. Some planners believed that Hadley C might be a maar because of its anomalously soft-textured rim and position near volcanic features; it would then expose materials from even greater depths than would an impact crater. Secondary craters of the distant Copernican impact craters Aristillus and Autolycus were recognized as potential sources of rock that could date the craters and of samples from units far from the landing site. Several alternative landing points within the Orbiter 5 coverage were considered to take maximum advantage of these objectives.

Before a specific site was assigned to it, Apollo 15 was planned as an "H" mission (with an ALSEP, two EVA's, and other improved capabilities over the Apollo 11 "G" mission, but with no roving vehicle). The small, young, very bright crater Censorinus (0.4° S., 32.7° E.) and a contact between mare material and dark mantling material near Rimae Littrow (21.7° N., 29.0° E., west of the eventual Apollo 17 site) were contenders for this Apollo 15 H mission almost until May 1970, when Fra Mauro was chosen for Apollo 14. However, the site favored by many scientists of the Group for Lunar Exploration for an H-type Apollo 15 mission was a spot along Rima Davy that could profitably be explored by walking (11.0° S., 6.4° W.). Rima Davy, a near-linear chain of small, closely spaced craters, is another eye-catching feature. It was widely thought to be a chain of maars and a likely source of deep lunar material. Representative samples of the uplands and "upland fill" (light plains or mantles) could also be reached in places along the Davy chain. A "J" (advanced capability) mission was even designed for Davy to exploit these multiple objectives and visit an adequate number of "vents."

The failure of Apollo 13 in April 1970 caused all later missions to be postponed. During the resulting breathing space, four developments shifted interest away from Davy. The first was extra time to fabricate the J-type Lunar Module (LM) and Rover (LRV), and by August 1970 these appeared near enough to completion that the next mission after Apollo 14 could be a J mission. Second, a steeper approach trajectory was devised, so that the LM could clear the high Apennine crest during an Apennine-Hadley landing from the east. Both these changes would have benefitted Davy, but they benefitted Apennine-Hadley even more. The third factor was the cancellation, in September 1970, of two Apollo missions, the original 15 and 19, in addition to the Apollo 20 mission that had already been dropped in January 1970 in favor of Skylab. The constricted mission schedule put pressure on planners to select the best possible sites for the three remaining missions. Apennine-Hadley was generally considered more interesting than Davy because of its obvious multiple objectives, as opposed to the more theoretical ones of Davy. Moreover, its high-latitude location gave Apennine-Hadley the advantages of a good geophysical spread and a high inclination of the orbit of the Command and Service Module (CSM). The inclined orbits would carry the CSM's geochemical and geophysical experiments and cameras over new parts of the Moon, over the mascon basins Serenitatis and Imbrium, and over a wider latitudinal belt than would orbits over the near-equatorial Davy. The fourth change that shifted interest away from Davy to Apennine-Hadley was in the requirements for photographic site-certification. Very high-
resolution photographs were no longer thought to be required. Therefore the gaps between the Orbiter 5 high-resolution frames were not a cause for rejecting the site as they would have been earlier. The safety of landings at scientifically interesting areas covered by moderate-resolution frames could now be certified by extrapolating terrain information from nearby high-resolution coverage. However, some good stereoscopic coverage at moderate resolution was still required, and this could not be provided for Davy in time to prepare an Apollo 15 mission for that site. Apollo 14 might have provided such coverage, but the new month-dependent orbital path chosen for it favored photography of Descartes instead. The Descartes photographs would be available in time to plan Apollo 16 but not Apollo 15.

There were four other leading contenders for the first J mission in addition to Apennine-Hadley and the ambitious J-type Davy mission. The first was Descartes, which was set aside because the Apollo 14 photography would not be available soon enough. The second was Copernicus, which lost out to Apennine-Hadley for reasons that were partly operational and partly scientific. Because of the economic need to space missions closely, a J mission would be flown in mid-1971 whether the LRV was ready or not. If the LRV were not developed in time for Apollo 15, or if it malfunctioned on the Moon, Apollo 15 would become a J-type walking mission. Palus Putredinis offered a smooth "landing field" for access to the Apennines and Rima Hadley even for a walking mission, whereas no such access lay close enough to the main object of interest in Copernicus, its central peaks. Copernicus was also considered the only good backup to Descartes for the Apollo 16 highland mission that was shaping up. The third site, Tycho, was every scientist's favorite as a sampler of a thick section of terra crust, a geophysical station far removed from the others, a datable young stratigraphic marker, and a calibration point for the Surveyor 7 compositional analysis. However, it was opposed and finally vetoed by operations specialists because of questions of safety and orbital-mechanics difficulty. It lay at one end of the cross-shaped area that was accessible to Apollo landings (arms along the prime meridian and equator), and its surface looked rough on the Orbiter 5 photographs. As a result, the only remaining strong contender besides Apennine-Hadley for the first J slot as of September 1970 was the Marius Hills, yet another eye-catching feature. Marius' steep, rugged cones and other rare landforms were considered likely to consist of young, highly differentiated volcanic rock. It finally lost to Apennine-Hadley mainly because of the latter's favorable high-latitude position and multiple surface and orbital objectives.

The mission planners settled on the northernmost (at 26.1° N., 3.6° E.) of the several alternative landing sites within the Apennine-Hadley region. The Apollo Site Selection Board approved Apennine-Hadley for Apollo 15 on 24 September 1970.

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