Impact-induced fractionation in the lunar highlands

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Abstract—A synthesis of the relevant data concerning lunar highland polymict breccias from the fields of petrography, chemistry, photogeology, and impact studies compels the prediction that the breccias should have homogeneous matrices from rock to rock within regions of the highlands of limited size where impact mixing has been efficient and extensive. But the matrices of returned breccias, even from one landing site, display a wide range in composition. This incompatibility between prediction and observation is a paradox that may be resolved by a process that acts after impact mixing to cause a differentiation of the breccia compositions. Partial melting of the local surficial material, and separation of melt and residue in ejecta and/or fall-back blankets, is compatible with the reviewed data and may resolve the paradox.

INTRODUCTION

This paper examines the possibility that the chemical diversity of lunar highland polymict breccias is the result of impact processes. Petrographic observations, combined with photogeologic and geochemical results, show that the lunar highlands have been subjected to continuous, extensive meteorite bombardment that has crushed, ground, and mixed the autochthonous and allochthonous material into a series of polymict breccias. We use petrologic and geologic arguments to suggest that those processes should have produced breccias with relatively homogeneous matrix compositions. Since the matrices, even within one landing site, are not homogeneous, there must be a differentiation process that accompanies the crushing, grinding, and mixing of the impact process. Using phase equilibrium and geochemical data as support, we suggest that partial melting, accompanied by some separation of melt from residue, takes place within ejecta and/or fall-back blankets or in the wall rock of craters. This partial melting can account for the geochemical trends and the fact that the polymict breccias at each landing site have diverse compositions.

DEFINITION OF ROCK TYPES

The lunar rock samples collected during the Apollo and Luna missions fall into three broad categories: coarse-grained igneous rocks, fine-grained igneous (volcanic) rocks, and polymict breccias. Statistically valid samples (e.g. rake samples and the coarser fractions of the fines) indicate that volcanic rocks make...
up about 90% of the mare basins and polymict breccias make up about 90% of the highlands. A detailed classification of lunar highland rocks is presented by Phinney et al. (1974a) and is abstracted below with some examples.

Coarse-grained igneous rocks have hypidiomorphic granular textures with a grain size generally greater than 1 mm, have old ages (crystallization ages tend to be greater than 4.0 AE), have anorthositic compositions or have high Mg/Fe ratios suggestive of a cumulate origin, have flat rare-earth spectra with low values and positive Eu anomalies, and have low-siderophile element concentrations. The spinel troctolite clast in 67435 described by Prinz et al. (1973a) is an example. Included within this group are cataclastic and granulitic rocks that contain evidence that they once had coarse-grained textures such as cataclastic anorthosites 15415, 15418, 67075; cataclastic dunite 72415; and granulite 76535.

Fine-grained igneous (volcanic) rocks include the mare basalts, associated pyroclastic rocks, and highland samples with basaltic textures. These samples have igneous textures, lack mineral and lithic clasts, have low-siderophile element concentrations, and contain relatively little metallic iron (Pearce et al., 1973). These include the Apollo 15 igneous KREEP fragments described by Meyer (1972), Morgan et al. (1973), and Phinney et al. (1972) and samples 15382 and 15386, and the pigeonite basalt clasts in 72275 described by Stoeser et al. (1974) and Morgan et al. (1974).

Polymict breccias contain angular to subrounded clasts set in a fine-grained matrix of clastic or igneous origin. Breccias contain lithic and mineral clasts that are uniformly distributed throughout the rocks, siderophile element concentrations above those indigenous to the highlands, and more metallic iron than do the fine-grained or coarse-grained igneous rocks. Polymict breccias are the product of meteorite impacts and formed in ejecta and/or fall-back blankets. Because evidence bearing on the processes that produce breccias is best preserved in the matrix and the relations between clasts and matrix, polymict breccias are subdivided according to the nature of the matrix into fragmental matrix and crystalline matrix breccias. The fragmental matrix breccias are further subdivided into vitric matrix (formally called glassy) and light matrix breccias, and the crystalline matrix breccias are further subdivided into recrystallized matrix, basaltic (or ophitic) matrix, and poikilitic matrix breccias. The last two subdivisions are referred to as melt-rock breccias.

Poikilitic matrix rocks such as 65015 and 77135, and basaltic (ophitic) matrix rocks such as 66095 and 76315 are considered polymict breccia impact melts because they contain abundant, evenly spaced lithic and mineral clasts and have high concentrations of siderophile elements and metallic iron. Basaltic (ophitic) matrix rocks such as 14310 and 68415/416 are also considered polymict breccia impact melts because they contain high concentrations of siderophile elements and metallic iron and mineral and lithic clasts either in the rock or in the boulder the rocks were chipped from. Other workers have informally suggested that these rocks are volcanic and that the siderophile elements, metallic iron, and clasts have been picked up as regolith contamination. The presence of evenly spaced clasts in most argues against that origin. The abundance of craters in the lunar highlands
suggest that impact melts should be present, and these rocks have textures similar to terrestrial impact melts such as those found at Manicouagan, Lake Mistasis, and Clearwater Lakes. If rocks such as these are not impact melts, then it is unclear which highland samples are the result of impact melting.

**Petrographic Observations**

Petrographic study of most lunar highland breccias that have been thin sectioned (Phinney *et al.*, 1972; Simonds *et al.*, 1974; Warner, 1972; Warner *et al.*, 1973) yields several generalizations: (i) the breccias are polymict, (ii) most breccias show evidence of multiple impact events, (iii) the matrix of each breccia is homogeneous, and (iv) breccias were deposited hot.

*Breccias are polymict*

The multiparent origin of highland breccias may be established from mineral, glass, and lithic clasts. The mineral clasts in any one breccia show a wide range of composition that would not be expected in a single igneous rock (Warner, 1972). One example of this diversity is found in rock 76255, a fragmental matrix breccia clast in a basaltic matrix breccia from Station 6 at Apollo 17. This rock contains clasts of inverted pigeonite alongside clasts of orthopyroxene, pigeonite, and augite (Simonds *et al.*, 1974).

Lithic clasts are not as numerous as mineral and glass clasts, especially in a single thin section, and therefore evidence from lithic clasts that lunar breccias are polymict is more difficult to obtain. However, it is common to find lithic clasts of both coarse-grained igneous rock and one or more different types of breccia in a single thin section. The lithic clast population has been studied in many thin sections of melt-rock breccias 76015 and 76315. Results are presented in Simonds *et al.*, 1974, and indicate that each sample contains clasts that represent a wide range of lunar highland rock types. Similar results have been obtained from a Station 2 boulder (Stoeser *et al.*, 1974) and from Apollo 14 breccias (Wilshire and Jackson, 1972).

Vitric breccias contain glass clasts ranging in color from yellow to brown to red. Moreover, the glass clasts generally do not display a continuum of colors, but rather exhibit several discrete colors. For example, 15294, from the Apennine Front, contains yellow, deep orange, green, light brown, and tan glasses. These glasses, of different colors and compositions, must have formed from different parents.

The matrices of vitric breccias contain fragments of the same minerals, glasses, and rock types as found in the clasts, except the proportion of these materials is different. Lithic fragments are more abundant as clasts, whereas glass fragments are more abundant in the matrix. The similarity in types of material in clasts and matrix and the seriate grain size distribution of the matrix and clasts suggest that the matrix and the clasts are derived from the same set of parents. The extremely fine grain size of the matrix of fragmental matrix polymict breccias
(on the order of $<1-5$ microns) illustrates the pervasiveness, extent, and multiplicity of impact comminution.

**Evidence for multiple events**

Petrographic evidence that many breccias represent multiple events has been well documented by Wilshire and Jackson (1972). They found that breccia clasts within breccia clasts within the main breccia were common, and in rare cases they documented occurrences of breccia within breccia within breccia within breccia. Each generation of breccia clasts has different compositions and textures from one another which indicate different parents and thermal histories. The number of observed breccia-in-breccia relations must be taken as a minimum number of brecciation cycles for a given rock, because the intense recrystallization and melting that the current, and preexisting, breccias underwent would obscure the recognition of the preexisting breccia clasts. Breccia-in-breccia texture is observed in single impact events (e.g. at the Ries Crater). However, the scale of Ries breccia-in-breccia texture is meters (Hüttner, 1969), whereas in the lunar case the scale is millimeters.

**Breccia matrix is homogeneous**

The matrices of polymict breccias are petrographically homogeneous on the scale of millimeters. That is, the texture, grain sizes, mineral abundances, and mineral compositions are the same within several 1 mm square areas across a single thin section, and from thin section to thin section of one rock (e.g. Warner, 1972). Homogeneity studies have been carried out on the matrices of two samples (76015 and 76315) from a large boulder and reported in detail by Phinney et al. (1974b) and Simonds et al. (1974). These studies include major element chemistry, minor element chemistry, trace element chemistry, mineral chemistry, and petrographic observations of the texture and modal abundances of minerals. Data from several samples separated by several centimeters in each rock yield essentially identical results indicating that the matrix of each sample is homogeneous on the scale of one aliquots studied—$30 \text{ mm}^3$ for chemistry and $1 \text{ mm}^2$ for petrography. The chemistry of 76015 and 76315 is nearly the same indicating chemical homogeneity on a scale of meters between two textural units of a large boulder. That the matrix of breccias is homogeneous is not surprising in view of the fact that analyses of many lunar breccias performed by different laboratories, on different aliquots of the same rock, for a variety of elements are about the same. For example, there are nine determinations of $\text{Al}_2\text{O}_3$ from sample 14310 which range from 20.0 to 21.7 wt.%, and eight from sample 60315 range from 16.4 to 17.8 wt.% (data from the Lunar Sample Curator’s data base).

**Breccias were deposited hot**

Analysis of petrologic and geochemical data for vitric and recrystallized breccias (Williams, 1972), combined with the experimental sintering data of
Simonds (1973), suggest that vitric breccias were deposited at temperatures on the order of 700°C, and the recrystallized breccias at progressively higher temperatures up to approximately 1000°C. Warner et al. (1973) and Simonds et al. (1973) demonstrated that many of the Apollo 16 breccias contain matrices that were clast-laden liquids. Statistical studies of 2–4 mm soil fragments by Delano et al. (1973) indicate that melt-rock breccias constitute about \( \frac{1}{3} \) of the Apollo 16 site. Bence et al. (1974) show that a similar fraction of the Apollo 17 highlands are melt-rock breccias. Phase equilibrium studies on these compositions by Walker et al. (1973a) and Hodges and Kushiro (1973) show that the matrices of these breccias must have reached 1200°C or 1300°C. Although the details of processes that heat ejecta and fall-back blankets are not understood, the data are irrefutable that the breccias were formed in hot ejecta blankets. This suggests that abundant thermal energy is available in ejecta blankets.

**EXTENT OF MIXING IN THE LUNAR HIGHLANDS**

Petrographic evidence indicates that lunar breccias, which comprise about 90% of the returned lunar highland rocks, were formed by multiple meteorite impacts from any parents. The physical processes involved are crushing, grinding, and mixing. The rarity of nonmixed (i.e. fine-grained and coarse-grained igneous) rocks, the wide range of lithic clasts types found in several breccias, and the chemical and petrographic homogeneity of breccia matrices suggest that impact mixing has been an extensive and efficient process in the lunar highlands. This is not surprising in view of supporting data from photogeology, cratering studies, geochemistry, and the abundance of mixed versus unmixed rocks.

The numerous overlapping meteorite-impact craters observed on any photograph of the lunar highlands attests to the pervasiveness of impact induced mixing. Head (1973) has emphasized the importance of the many local 10 km and larger craters to the Apollo 16 samples. Hartmann (1972) has shown that the cratering rate prior to the deposition of the Fra Mauro Time. Short and Foreman's (1972) calculations show that ejecta from only the visible craters average out to a uniform layer 1–2 km thick. Secondary impacts will enhance the mixing effects of primary impact. Oberbeck (1971) and Oberbeck et al. (1973) show that the total mass of material moved by the secondaries may be larger than the mass moved by the primary impact. Thus virtually all material in the upper few kilometers of the moon should be thoroughly mixed.

Siderophile element (e.g. Au) concentrations in the polymict breccias and soils are 1–2 orders of magnitude higher than equivalent values for fine-grained and coarse-grained igneous rocks (Morgan et al., 1973, 1974). Following Ganapathy et al. (1973) the Au content of igneous rocks is a measure of the siderophile element concentrations that are indigenous to the moon, and the higher values in soils and polymict breccias represent contamination by meteorites. Thus, siderophile element concentrations may be used as an index to the mixed versus the nonmixed rocks. The uniformly high concentrations of Au and other siderophile elements in all analyzed polymict breccias (except 15205, Baedecker et al., 1973) is further
corroborative evidence that the highlands have been extensively mixed by impacts.

At the Apollo 14 and 16 sites where there is no nearby mare material the rocks show a wider composition range than the soils (Table 1). Soils are about 95% degraded local bedrock, and the rocks are samples of the local bedrock. The narrower range of soil compositions is thus an indication of the effectiveness of the mixing process during the last $10^9$ yr, when the impact rate has been much less intense than during the time of formation of highland rocks. Further, because the soils appear to be well-mixed local material, they are used to approximate the composition of the local crust.

The Apollo 15 and 17 sites straddle mare–highland boundaries, and the rock–soil relations are obscured. The soils define a linear trend from the field of mare rocks to the field of highland rocks (as illustrated in Fig. 1 for Apollo 17).

![FeO-MgO plot of Apollo 17 rock and soil analyses.](https://example.com/apollo_17_plot.png)

This is due to recent mixing between a “mare average” and a “highland average.” The “highland average” composition, as set out in Table 1, may be used to approximate the local highland crust at Apollo 15 and 17.

The abundance of various highland rock types also provides supporting evidence as to the extent of highland impact mixing. The only nonmixed highland samples are the fine-grained and coarse-grained igneous rocks. Nonmixed materials (both as individual rocks and as clasts in polymict breccias) make up less than 15% of the mass of returned highland samples. Further, the nonmixed rocks...
Impact-induced fractionation in the lunar highlands

Table 1. Range of composition of selected elements and oxides in highland polymict breccias and soils.

<table>
<thead>
<tr>
<th></th>
<th>Apollo 14</th>
<th>Apollo 15</th>
<th>Apollo 16</th>
<th>Apollo 17</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Breccias(^a)</td>
<td>Soils(^a)</td>
<td>Breccias(^a)</td>
<td>Soils(^b, c)</td>
</tr>
<tr>
<td>TiO(_2) (%)</td>
<td>1.4–1.7</td>
<td>1.6–1.8</td>
<td>1.3–1.4</td>
<td>1.27</td>
</tr>
<tr>
<td>Al(_2)O(_3) (%)</td>
<td>14.8–22.3</td>
<td>16.2–17.7</td>
<td>15.2–23.5</td>
<td>17.38</td>
</tr>
<tr>
<td>FeO (%)</td>
<td>6.7–11.0</td>
<td>10.0–10.9</td>
<td>5.9–15.0</td>
<td>11.65</td>
</tr>
<tr>
<td>MgO (%)</td>
<td>8.3–13.7</td>
<td>9.2–10.2</td>
<td>9.4–13.3</td>
<td>10.36</td>
</tr>
<tr>
<td>CaO (%)</td>
<td>9.1–12.8</td>
<td>10.2–11.3</td>
<td>10.3–13.7</td>
<td>11.52</td>
</tr>
<tr>
<td>K(_2)O (%)</td>
<td>.15–.87</td>
<td>.50–.60</td>
<td>.08–.17</td>
<td>.17</td>
</tr>
<tr>
<td>P(_2)O(_5) (%)</td>
<td>.22–.63</td>
<td>.40–.58</td>
<td>.02–.55</td>
<td>.13</td>
</tr>
<tr>
<td>Sm (ppm)</td>
<td>20–42</td>
<td>29–31</td>
<td>3–13</td>
<td>~10</td>
</tr>
</tbody>
</table>

\(^a\)Data from Curator's Data Base, Curator's Office, J.S.C., Houston.
\(^b\)Data presented is “highlands average” as described in text.
\(^c\)Data from LSPET (1973b) and Rhodes et al. (1974).

Themselves are generally small—a few centimeters across or less (sample 61016, a black-and-white rock, is an exception—the catalastic anorthosite part is about 10 cm thick).

The extent of impact mixing in the lunar highlands suggest a low probability that large amounts of nonmixed rock could survive on or near the surface of the lunar highlands for a long time. This does not imply that no nonmixed rock can survive. Impact comminution is a random process and a few nonmixed rocks can survive numerous impact events, but nonmixed rocks cannot form a major proportion of the highland samples. One exception, which should be rare and local, is if the formation and/or emplacement of the nonmixed rock onto the lunar surface was near the end of the evolution of the highlands.

The petrographic and chemical homogeneity studies suggest that the upper limit for effective mixing is greater than tens of cubic meters and the lower limit is less than a cubic centimeter. Obviously, a few grains at a time, taken in sets, should not be homogeneous. The lower limit thus appears to be less than a cubic centimeter but more than a few grains, probably a few thousand grains.

Because soils at each highland landing site are very similar in composition, and thus relatively homogenized (except for later local mixing at contacts with nearby mare material), the upper limit for effective mixing must be larger than a landing site (which is on the order of several square kilometers). Without a doubt there are major lateral heterogeneities in the lunar highlands as evidenced by the orbital XRF and gamma-ray experiments (Adler et al., 1973; Metzger et al., 1973). Because the local average crust (soil) composition is different at each landing site, the limit must be less than the inter-landing site distances (which are on the order of 10\(^3\) km). The resolution element of the orbital XRF and gamma-ray experiments is not clearly defined, but it is on the order of tens of kilometers across, and the orbital data as plotted (Adler et al., 1973; Metzger et al., 1973) suggests that these resolutions are close to the scale of lunar surface homogeneity. The upper limit of effective mixing thus appears to be about tens of kilometers across.
The arguments and data cited in this section suggest that within most regions of the lunar highlands that are on the order of several hundred square kilometers, there should have been adequate impact mixing to produce polymict breccias with relatively homogeneous matrices. That is, we predict that within any small area (up to 100 km$^2$) of the lunar highlands that is chosen at random, the bedrock will consist of polymict breccias that are all of about the same composition. Reference to Table 1 shows that this prediction is wrong.

**Paradox and a Solution**

The diversity of breccia compositions at each highland landing site has been well established (e.g. LSPET, 1971, 1972, 1973a, and 1973b). We use Apollo 16 as an example since it contains the most diverse highland rock compositions and the landing site lies well within the lunar highlands. Figure 2 shows that the diversity of Apollo 16 rock compositions forms a linear trend from aluminous basalt (KREEP) (CaO = 10–12 wt.%; Al$_2$O$_3$ = 17 wt.%) to anorthosite (CaO = 19–20 wt.%; Al$_2$O$_3$ = 35 wt.%). The one sample that plots off this trend at 6 wt.% CaO and 16 wt.% Al$_2$O$_3$ (a spinel troctolite (Prinz et al., 1973a)) and several of the rocks at the anorthositic end are coarse-grained igneous rocks; the remainder are polymict breccias (Warner et al., 1973). Soil compositions lie on the rock trend, but with a much narrower composition range (15–16.5 wt.% CaO; 26–29 wt.% Al$_2$O$_3$). The average soil composition is taken to approximate the local average crustal material, and is used as the starting point for petrochemical processes that take place after impact mixing.
We have shown above that meteorite impacts crush, grind, and mix material; that this material is deposited hot; and that it lithifies into polymict breccias. We argue that impact mixing is so efficient it compels the prediction that breccia matrices should be homogeneous from rock to rock within some ill-defined sized region of the lunar highlands. Yet the rock analyses, which are essentially matrix analyses because clasts larger than about 2 mm are separated from the analyzed material from any landing site, are not homogeneous. This incompatibility between prediction and observation presents a paradox.

There are two explanations for this paradox. First, the prediction that the highland breccias are well mixed is wrong; second, the diversity of breccia compositions is due to some differentiation process that takes place after impact mixing.

The first explanation that impact mixing is not extensive has two alternatives: (i) the diversity of rock compositions is old (it either dates from crustal formation or pre-4.3 AE volcanism) and the subsequent impact events have not caused significant chemical mixing, or (ii) the diversity of rock compositions is young (3.9–4.3 AE volcanism) and the breccia petrography is due to contamination with, and/or partial assimilation of, regolith. The evidence for mixing set out above makes alternative (i) unlikely. If alternative (ii) were the explanation, we would expect to find volcanic rocks that were not contaminated by regolith; and essentially none has been found in the highlands. The even distribution of mineral and lithic clasts does not suggest that they are xenoliths and xenocrysts. If the melt-rock breccias were volcanic, we would expect some coarser grained equivalents; the latter are not found, and in fact, the breccias are an order of magnitude finer grained than the mare basalts suggesting a formational process other than volcanism. For these reasons, and others discussed in the last paragraph of the “Definition of Rock Type” section, we do not accept the first explanation for the paradox.

The second, and favored explanation for the paradox calls for a differentiation process to take place during formation of the breccias so that the repeated mixing is partially undone. The fact that the breccias were formed between 700°C and 1300°C suggests the presence of adequate thermal energy (within ejecta and fall-back blankets and in the heated wall rock of craters) to drive petrochemical processes. Processes that may be associated with impacts and could cause differentiation are: selective volatilization, crystal fractionation in pools of impact melt, and partial melting.

Volatilization does not appear to be a significant process since the trend in the breccia compositions is not the trend of vaporization. Volatilization would selectively remove alkali elements, but the breccias show a covariant trend in CaO and Al₂O₃ and no evidence of alkali loss. Furthermore, the alkali element concentrations are so low in lunar material (even KREEP) that volatilization loss should not be a major process of highland petrogenesis. The necessity of bringing a large fraction of lunar surface material to within 1 mm of the lunar vacuum, while that material is hot, in order for volatilization to be effective seems impossible.
Crystal fractionation in a pool of impact melt of the local average crustal composition could adequately account for the chemistry of the breccias; the observed trend is essentially due to feldspar enrichment plus minor Fe/Mg variation. A major problem with crystal settling is that an impact melt would not be a conducive environment for such a process to take place. Melt-rock breccias are glassy to very fine-grained, which suggests cooling rates so rapid that crystal settling could not be effective. Terrestrial basalts, which are coarser grained, and thus may have cooled more slowly, do not show crystal settling in lava lakes tens of meters thick. Also, impact melts are laden with mineral and lithic clasts which would hinder crystal settling, and in fact, should themselves settle.

Partial melting processes are controlled by the phases melted: the first melt from the Apollo 16 local average crustal composition should appear at the olivine–pyroxene–feldspar peritectic. Walker et al. (1973b) have shown that the peritectic has an aluminous basalt (KREEP) major element composition (CaO ≈ 12: Al₂O₃ ≈ 16 wt.%) which plots at one end of the trend in Fig. 2. Further partial melting will produce melts along the olivine–plagioclase cotectic and toward the local average crust, and the rocks that fall in this range are melt-rock breccias. The residue will be more anorthositic, and that is where the potential residue candidates among the Apollo 16 rocks lie on Fig. 2.

Statement of the model

The model we propose to explain the variety of breccia compositions is illustrated in Fig. 3 and outlined below:

(1) Continuous grinding, crushing, and mixing of surface and near-surface materials as a result of primary and secondary impacts from the time of crustal formation to about 3.85 AE. This step is represented in Fig. 3 by the MIXING oval and the arrows leading into it. The product is a homogeneous mixture of fine-grained and coarse-grained igneous rocks, preexisting polymict breccias, and regolith material deposited in ejecta and fall-back blankets. This mixture, which approximates THE LOCAL AVERAGE LUNAR CRUST in composition, is the material that further processes act upon.

(2) Those parts of the mixed deposits that do not attain temperatures of about 700°C form regolith or SOIL.

(3) Those parts of the mixed deposits that attain temperatures above 700°C but below about 1200°C lithify into VITRIC BRECCIAS and RECRYSTALLIZED BRECCIAS.

(4) Those parts of the mixed deposits that attain temperatures above about 1200°C will start MELTING following the normal rules of phase equilibrium. There will be at least a partial separation of MELT (with included mineral and lithic clasts) from RESIDUE. The melt will crystallize into basaltic matrix and poikilitic matrix (MELT-ROCK) breccias, and the residue will form some sort of breccia, perhaps a LIGHT MATRIX BRECCIA.

(5) There will be many impacts that aid in homogenizing the deposits, whereas there will be relatively few impacts that are accompanied by partial melting and separation of melt and residue.
FUNCTIONAL MODEL IMPACT PROCESSES

Fig. 3. Schematic representation of the impact mixing and partial melting model that explains the diversity of polymict breccia compositions. Boxes represent material and ovals represent processes.

(6) The partial melting may take place in an ejecta blanket, a fall-back blanket, or within the deposits that form the wall rock of craters.

Such a partial melting process can explain the observed diversity of breccia compositions. Below we examine if partial melting of the local average crustal composition is consistent with the chemical data, and discuss evidence bearing on the problem of separation of melt from residue and identification of the residue. As is pointed out below, there are problems with this model, especially in regards to Fe/Mg ratio evolution. Although some details of the model are surely wrong, we stress that the data demands that some sort of chemical fractionation process must take place in ejecta and fall-back blankets.

CHEMICAL TESTS OF PARTIAL MELTING

There are six points of chemical data used to test impact partial melting. None of these proves that impact partial melting is the major process responsible for the diversity of highland breccia compositions. Rather, they show that a low-pressure partial melting model is consistent with the chemical data.

The range of rock compositions at each highland site has some major similarities. The local crustal average composition would yield an aluminous basalt (KREEP) as the first liquid during partial melting, and rocks with that
composition are found at each site. Two sites, Apollo 16 (see Fig. 2) and Luna 20 (Prinz et al., 1973b), have rocks that are more aluminous than the first melt but less aluminous than the parent composition. Those rocks may have formed by larger amounts of partial melting than that required to form the aluminous basalt. Finally, each site contains rocks that are more aluminous than the parent composition. These rocks may be residues.

The general major element variations that would be expected in this series are not completely present. The Fe/Mg ratio decreases from the aluminous basalts to the rocks formed by larger amounts of partial melting, but the decrease does not continue through the local average crustal composition to the residue. This problem could be explained if impact crushing and grinding systematically biased the finer grain size fractions to more mafic compositions, and this finer fraction was the first material melted. There is evidence that mafic minerals (Butler et al., 1973; Finkelman, 1973) and trace elements (Evensen et al., 1973) are fractionated into finer grain sizes.

The aluminous basalt at each landing site is different in detail in both major and trace elements (Hubbard et al., 1973). This difference shows up in the Fe/Mg ratio and the trivalent lithophile trace elements. In the impact-generated partial melting model these small, but significant, differences may be accounted for by corresponding differences in the trace element content and Fe/Mg ratio of the local average crust and different partial melting histories.

There is a correlation between the trivalent lithophile trace elements and major elements at each site as shown by Haskin et al. (1973) and Hubbard et al. (1973) for Apollo 16. For example, the total rare-earth element content decreases with increasing Al$_2$O$_3$ content in the breccias. Since the trivalent lithophile trace elements occur in accessory minerals, the first liquid generated during partial melting will contain most of these elements, and the first liquid contains the lowest Al$_2$O$_3$, yielding a liquid with high trace elements and low Al$_2$O$_3$. If we use local soil as a model of the material that was partially melted, an enrichment factor of only five or less is needed to produce the trace element concentrations in the low Al$_2$O$_3$ breccias. With increased partial melting, the Al$_2$O$_3$ content of the liquid increases, and the trace element contents are lowered by dilution.

Taylor et al. (1973) have demonstrated that highland-wide, positive, one-to-one correlations exist among total rare earth elements, Ba, Hf, Nb, Th, and Zr. Hubbard (1973) and Haskin et al. (1973) have pointed out the consistency of the slope of the rare-earth elements when normalized to chondrites, which corresponds to the one-to-one correlations found by Taylor et al. (1973). Because these elements occur in the accessory minerals, the first melt will contain most of them and there will be no differential fractionation of the trivalent lithophile trace elements. Further partial melting will simply dilute the abundances that occur in the first liquid. The partial melting model does not specify the slope of the rare-earth elements, but once that slope is established as characteristic of the lunar highlands, the partial melting model propagates it.

Although these interelement correlations between major and trivalent lithophile trace elements do not constitute proof of the proposed impact partial
melting, the relations are so striking that they demonstrate a general genetic relationship among the highland breccias. The weight of geochemical evidence argues for partial melting as the basic process. If the diversity of compositions of highland breccias was due to partial melting of different source regions in the lunar interior, the chemical relations would be expected to show discontinuities in the correlations and these discontinuities do not exist. Partial melting in homogenized ejecta blankets would not produce discontinuities.

The $^{39}$Ar--$^{40}$Ar and Rb--Sr data for highland breccias yield crystallization ages between 3.85 and 4.05 AE for the majority of the samples, with a few measurements as old as 4.25 AE (Schaeffer and Husain, 1973, 1974; Tera et al., 1974). This spectrum of ages would be expected for continuous impact mixing and partial melting in ejecta blankets. The sharp cutoff of ages at 3.85 AE indicates the time that meteorites large enough to cause extensive mixing and partial melting stopped impacting the moon on a regular basis. The range in ages of about 200 m.y. suggests that toward the end of highland formation, meteorites large enough to cause partial melting impacted the moon with a frequency such that there was an effective thermal cycle time in the highlands of about 200 m.y.

Rb--Sr and U--Pb data on highland breccias yield "whole-rock isochrons" of about 4.3--4.4 AE (Nyquist et al., 1973; Tera et al., 1974). Nyquist has suggested that these model ages indicate a major lunar differentiation at that time. Tera et al. (1974) give two explanations for the data. Either the model age is the age of the lunar crust for a simple two-stage model, or "...about one-half of the crust formed between 4.6 to 4.5 AE, and the remainder evolved uniformly down to $\sim$3.9 AE." In the latter case the initial ratios (of both Pb and Sr), and the age, would "represent an average of the rocks sampled and mixed during ... impacts." This latter interpretation is consistent with our model of continuous impact mixing and partial melting.

We have performed calculations of Rb--Sr evolution to test our geologic model. Visualize that all Rb$^{87}$, Sr$^{86}$, and Sr$^{87}$ are contained in one or more "pots." The calculations start with one "pot" that contains Sr$^{87}$/Sr$^{86} = 0.6990$ (BABI) and Rb$^{87}$/Sr$^{86} = 0.05$ at 4.6 AE. The calculations iterate every 0.1 AE from 4.6 AE to 3.9 AE. Within each iteration the following processes are calculated:

1. All existing "pots" are allowed to age for 0.1 AE.
2. The mechanical aspects of impact are simulated by sampling all existing "pots" and combining the sampled material into one "temporary pot." The sampling algorithm removes half of the material in 0.1 AE old "pots," half of the remaining material in 0.2 AE old "pots," and all of the remaining material in 0.3 AE old "pots." Thus at any time there are "pots" of three ages with a spread of 200 m.y. to agree with the spread in observed crystallization ages.
3. The chemical aspects of impact (i.e. partial melting) are simulated by fractionating the "temporary pot" into a new Rb-rich (melt) "pot" and a new Rb-poor (residue) "pot." This part of the calculation contains two variables: (i) the partitioning of Rb between the two new "pots," and (ii) the partitioning of Sr between the two new "pots." There is no Sr isotopic fractionation.
At this stage of the calculation the formation of the highlands is essentially complete, and the systems are allowed to age for 3.9 AE to the present. We have calculated models that use various expressions for the Rb and Sr partition variables, and many of these yield similar results (Fig. 4). Although the results do not provide a perfect match to the observed data, they show that no major problems exist with our model of impact partial melting. For example, the calculations demonstrate that the residues will not have extremely high (>5.0 AE) model ages with BABI.

**Separation of Melt and Residue**

Physical separation of partial melt and residue is necessary for the proposed model to be effective. However, the reader should keep in mind that the mechanical details of separation are not really understood for the case of terrestrial migmatites or basalts, although evidence is exceedingly strong that such separations do take place. We hope that this model will not be judged on how well
the separation process is specified. The scale of separation of partial melt within an ejecta blanket is small compared to separating basaltic magma from the earth’s mantle; the largest known mass of rock that could be considered formed by impact partial melting is the boulder at Station 6 on Apollo 17. That boulder represents about 10 stratigraphic meters and contains three layers (Heiken et al., 1973)—perhaps suggesting that each layer represents a separate event. Calculations by Brett (1974) based on petrologically derived cooling rates indicate that layers of melt-rock breccia were not more than several meters thick.

Returned samples display partial melts (presumably formed during impact) that have separated. Samples 64455 and 65075 show partial melting and separation of the melt on the millimeter scale (Grieve and Plant, 1973). Similar separation of partial melt and residue has been documented by Phinney et al. (1972) from KREEP fragments found at Station 7 on Apollo 15. Segregation of a partial melt into small pods and 100 micron veins has been suggested for 67075 by LSPET (1973).

The black-and-white rocks from Apollo 15 and 16 consist of angular veins of clast-laden melt-rock breccia (black) that intrude cataclastic anorthosites and cataclastic norites (white) and are examples where melt has migrated some unknown distance (but at least 1 cm) and injected a fractured, refractory rock.

The small size of returned lunar samples precludes finding examples of separation on the meter scale. Pools of melt on the kilometer scale occur on the floors and ejecta blankets of highland craters (e.g. King and Tycho; Howard, 1972). These pools may be total impact melts or separated partial melts, but in any case, they occur in an ejecta environment.

Finally, if there were mechanical fractionation of the lower melting material into the finer grain sizes as was suggested above, that process itself would accomplish much of the required separation of partial melt and residue.

**Identification of the Residue**

The residue from the proposed partial melting in an ejecta blanket must meet well-defined chemical criteria. Phase equilibrium relations dictate that the residue must be higher in $\text{Al}_2\text{O}_3$ and $\text{CaO}$, and lower in $\text{TiO}_2$, $\text{K}_2\text{O}$, Fe/Mg ratio, and all trivalent lithophile trace elements.

We cannot predict what the texture of the residue should be. Rocks that meet the chemical criteria include cataclastic anorthosites (e.g. 61016), light matrix breccias (e.g. 67955), melt rocks (e.g. 68815), and metamorphosed breccias (e.g. 61295). Hubbard et al. (1971) have suggested that there are two types of anorthosite with higher and lower $\text{Sr}^{87}/\text{Sr}^{86}$. Perhaps the low-$\text{Sr}^{87}/\text{Sr}^{86}$ anorthosites are derived from the moon’s original crust and the high-$\text{Sr}^{87}/\text{Sr}^{86}$ anorthosites are partial melting residues. However, the monomict nature of the anorthosites is not consistent with them being the residue from the impact partial melting of a polymict breccia, unless they were the clasts. We suggest that the residue is probably a polymict breccia or granulite of some type—the light matrix breccias appear to be prime candidates. This is a subject that demands considerable study.
CONCLUSIONS

The general petrogenesis of the moon is best understood by the interpretation of primary rock types returned by the Apollo and Luna missions. It is therefore imperative that we can unambiguously identify the primary rocks. This paper shows how difficult that problem is. Although fine-grained and coarse-grained igneous rocks are probably primary, the bulk of the returned highland rocks are polymict breccias, and this paper demonstrates that the polymict breccias are not primary rocks. Polymict breccias were formed in impacts, and the crushing, grinding, and especially, mixing that takes place during impact does not allow the preservation of original chemistry, but should produce homogeneous breccias.

There is a paradox between compelling evidence that the breccias should be about the same composition, and the wide range of compositions displayed by the returned highland breccias. This paradox demands a differentiation process after the impact mixing. A process that may explain the heterogeneity is partial melting and separation of melt and residue in ejecta and fall-back blankets, or in the wall rock of craters. We are now investigating the possibility of even better fits of chemical, petrographic, and impact data resulting from a mechanical concentration of mafic and accessory minerals into the finer grained fraction of regolith and preferential melting of this lower melting temperature material.

Finally, the processes that we discuss are not of major importance on earth, but seem to be on the moon. Recent photographs of the surface of Mars and Mercury show those planets to be intensely cratered like the moon. Perhaps the processes discussed in this paper will have application to those planets.

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REFERENCES


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