Exhumation of Deep-Level Metamorphic Rocks: 
A Window into the Ancient Lunar Crust

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Abstract. Among the Apollo samples there exists a distinct suite of rocks that probably formed after the initial 
differentiation of the early lunar crust (~4.4 Ga), yet before the final bombardment period that began around 4.0 Ga. 
However, few ages have been conclusively determined for this suite. These rocks are known as granulitic impactites or 
granulitic breccias and have been found at most Apollo highland sites, either as hand samples, clasts in breccias, or 
fragments in the lunar regolith. These samples reveal important information regarding the nature of the lunar crust 
during the first 0.5 Ga of the Moon’s history and the processes affecting it at that time.

INTRODUCTION

Breccias with granoblastic or poikilitic textures, suggestive of some degree of thermal metamorphism, have been 
found at most highland Apollo sampling sites. They occur as hand samples, clasts in breccia, fragments in the lunar 
regolith, and as clasts in lunar meteorites (e.g., SaU 300, ALHA81005). These rocks have been known by many 
names: lunar granulites, feldspathic granulitic breccias and “Early Impactites”, to name a few (e.g., Korotev and 
Jolliff, 2001; James, 1980; Cushing et al., 1999). The term “granulitic impactite” will be used in this paper. This 
termology may be somewhat confusing as the term “granulite” is misleading; these rocks are actually hornfelses. 
Terrestrial hornfelses are defined as fine- to medium-grained, granulose rocks produced by thermal metamorphism 
at shallow depths, while terrestrial granulites are rocks that formed at low temperatures and high pressures, often 
near the base of the crust (Cushing et al., 1999). Lunar and terrestrial processes differ; therefore, it is necessary to 
modify these traditional definitions. I will use the term “granulitic impactite” to describe feldspathic rocks with 
granulitic textures (granoblastic or poikiloblastic) derived from the recrystallization of impact-formed breccias. The 
term “impactite” is used to denote lithified deposits of an impact event.

These samples are chemically and petrologically distinct and are thought to have formed after the differentiation of 
the early lunar crust (~4.4 Ga), but before the final lunar bombardment, a period of intense meteorite impacts, which 
began around 4.0 Ga. Unfortunately, few conclusive ages have been determined for these rocks. If they did indeed 
form at this time, the granulitic impactite suite would reveal important information regarding the chemical and 
thermal environment of the lunar surface during the first 0.5 Ga of the Moon’s evolutionary history and the 
processes affecting it at this time.

PETROGRAPHY AND MINERAL CHEMISTRY

The granulitic impactite suite exhibits a great deal of textural and chemical variety. Warner et al. (1977) developed a 
set of criteria to identify granulitic impactites: they must exhibit a clast/matrix structure; be enriched in trace 
siderophile elements of meteoritic origin by at least an order-of-magnitude over indigenous lunar abundances; have 
granulitic (metamorphic) matrix textures, consisting of anhedral, equant crystals and triple junctions; and, finally, 
they must contain between 70 and 80% modal plagioclase and ~25% Al₂O₃. Well-studied samples are mostly from 
the Apollo 16 and 17 sites, but samples are also known from the Apollo 11 and 15 sites (Korotev and Jolliff, 2001).
Granulitic impactites normally contain calcic plagioclase, low-Ca pyroxene, high-Ca pyroxene, and olivine with minor (<1%) amounts of FeNiCo metal, ilmenite, Cr-spinel, phosphates, and other accessory minerals. Mineral chemistry is homogeneous on a millimeter scale and the composition of most mineral clasts matches the composition of the same mineral in the adjacent matrix (Warner et al., 1977). Pyroxene and olivine have Mg# ranging from >50<85 (Papike et al., 1998). Lithic clasts are almost entirely feldspathic and dominantly from the ANT (anorthosite-norite-troctolite) suite. In some samples, lithic clasts are distinct from the matrix, while in others the edges of the clasts grade into the comminuted matrix, making them difficult to identify (Ostertag et al., 1984).

Bickel and Warner (1978) concluded that rocks from this suite have bulk and mineral compositions that fall within and between two major pristine groups: the Mg-suite rocks (consisting of dunites, troctolites, norites, and gabbronorites) and the ferroan anorthosites (Fig. 1). This suggests that the original polymict breccias probably contained clasts from both suites as a result of thorough mixing by bombardment (James, 1980).

All granulitic impactites are contaminated with meteoritic siderophiles, indicating an impact origin for this suite of rocks. Their pre-metamorphic textures point to a brecciated protolith, which also suggests an impact origin (Cushing et al., 1999). Their siderophile spectrum is unique and does not fall into any of the ancient meteoritic groups (AMGs) of Higuchi and Morgan (1975), which suggests that they pre-date the final bombardment (Warner et al., 1977b). Granulitic impactites have low but variable abundances of incompatible trace elements indicative of KREEP (2-20x chondritic levels), distinguishing them from most other Apollo polymict breccias (Fig. 2) (Lindstrom and Lindstrom, 1986). KREEP is a chemical component named for its high abundance of potassium, rare-earth elements, and phosphorus. Granulitic impactites define a group that is compositionally distinct from KREEP and from the average lunar crust. Their pattern is indicative of much less fractionation from chondritic material and may, in fact, be indicative of the true rare-earth element pattern for the lunar crust. Impactites known to have been generated during the final bombardment period show a REE pattern characteristic of KREEP, implying that KREEP arrived at the lunar surface following the formation of the granulitic impactites. Its arrival probably coincided with the onset of the final bombardment period. The chemical composition of the lunar surface, as recorded by impactites, appears to have undergone a major change around the time of the final bombardment (Fig. 3). Large, basin-forming impacts
resulted in an intense mixing of lithologies and the impactites produced record the average composition of the target material of these impacts (Warner et al., 1977).

**FIGURE 2.** Plot of the rare-earth element spectra normalized to chondritic abundances. The seven patterns with La between 7 and 14 times chondrite represent granulitic impactites and the average pattern for the matrix of the Apollo 17, station 6 boulder (a typical KREEP sample) is shown for comparison. (Warner et al., 1977).

**FIGURE 3.** Schematic illustration of the chief events in lunar evolution that are recorded in samples (Warner et al., 1977).

Mg/Fe ratios among granulitic impactites are variable and almost dichotomous, which led Lindstrom (1985) to classify rocks from the suite as either ferroan or magnesian. The abundance of Sc defines these two groups more precisely; ferroan granulites have about twice as much Sc as magnesian granulites. Ferroan varieties have Mg# 50-70 and mineral compositions that fall in the ferroan anorthosite field. Magnesian granulites are more common and have Mg# 72-80 (Lindstrom and Lindstrom, 1986). Korotev and Jolliff (2001) believe that the two compositional
end-members originated from two different precursor lithologies: the ferroan granulites from the ferroan anorthosite suite of plutonic rocks and the magnesian granulites from magnesian intrusions into the Feldspathic Highlands Terrane.

As noted by many authors (e.g. Lindstrom and Lindstrom, 1986), there exists extreme variations in major and trace element compositions within the granulitic impactite suite. Elements in plagioclase (e.g., Ca, Al, Na) show little variation, while elements in mafic minerals (e.g., Mg, Fe) exhibit large variations. Compatible trace elements vary by a factor of two to three, incompatible trace elements vary by up to a factor of seven, and siderophile elements vary by up to a factor of fourteen. REE concentrations for magnesian granulites (15-20x chondrites) and ferroan granulites (2-5x chondrites) also vary significantly (Lindstrom and Lindstrom, 1986). Differences in siderophile element concentrations reflect the nature and amount of meteoritic contamination. Variations in trace elements reflect the different compositions of the precursor rocks, and, therefore, can provide clues to the origin of granulitic impactites (Lindstrom and Lindstrom, 1986).

TEXTURES

Variable textures make granulitic impactites difficult to classify; they can be from fine- to coarse-grained, homogeneous to heterogeneous, and have poikiloblastic to granoblastic textures. Most samples consist of a mosaic of grains whose boundaries meet at 120°, a texture produced through subsolidus recrystallization (Papike et al., 1998). The final texture of a granulitic impactite depends on the texture of its protolith, the degree of crushing and mixing it underwent, and its thermal history (Bickel and Warner, 1978). Different textures reflect different degrees of thermal metamorphism. Features indicative of a low degree of metamorphism include fine ilmenite stringers, small poikiloblasts, and a small matrix grain size. More pronounced metamorphism is suggested by an increase in matrix grain size, larger poikiloblasts, skeletal ilmenite crystals, and recrystallization textures in shocked clasts (Ostertag et al., 1984). Granulitic matrix textures and homogeneous mineral chemistry are indicative of a high-grade metamorphic event characterized by complete solid-state annealing or recrystallization (Warner et al., 1977).

The debate over the origin and the thermal history of these rocks arose because the suite is composed of two distinct textural varieties: coarse poikiloblastic types and finer-grained granoblastic types (Warner et al., 1977). The poikiloblastic impactites consist of subhedral to euhedral plagioclase crystals with smooth boundaries, which enclose olivine blebs and are themselves enclosed in pyroxene oikocrysts. The oikocrysts are irregular to subrounded and variable in size (Cushing et al., 1992). Olivine inclusions commonly form trains or “necklaces” inside the larger plagioclase crystals; possibly indicating the location of the pre-metamorphic grain boundaries (Papike et al., 1998). Matrices consist of subangular, comminuted grains with some recrystallized areas. Examples of this variety include 67955 and 77017. Granoblastic varieties are dominated by mosaics of polygonal to rounded, equant grains of annealed plagioclase (70-80 vol %) that meet at triple junctions. Small, rounded mafic minerals are concentrated along grain boundaries and at junctions and may occur as “necklaces” along the edges of plagioclase grains; again, possibly indicating the location of the pre-metamorphic grain boundaries. Matrices tend to be finer grained. Examples include 78155 and 79215 (Cushing et al., 1992). Cushing et al. (1999) also identified a group of rocks with textures intermediate between the two end members, which they refer to as the poiko-granoblastic variety. These rocks are medium-grained and contain smaller, subrounded pyroxene oikocrysts with small, round inclusions of plagioclase and olivine. Their matrices exhibit a granular texture with abundant triple junctions. These rocks bear a stronger resemblance to the granoblastic group than to the poikiloblastic group (Cushing et al., 1999).

It is still unclear if the two textural end-members formed via the same mechanism, but Cushing et al. (1999) suggest they originated in fundamentally different ways. They believe that the granoblastic and poiko-granoblastic groups formed by thermal metamorphism and recrystallization of a precursor and that the poikiloblastic group formed as a result of impact melting. However, the poikiloblastic granulites are clast-poor and KREEP-poor, in contrast with most of the Apollo poikilitic impact-melt breccias (Cushing et al., 1999). For that reason, other authors (e.g., Warner et al., 1977; Bickel and Warner, 1978; Lindstrom and Lindstrom, 1986) suggest that the poikiloblastic textures indicate a metamorphic paragenesis.

Pyroxene thermometry calculations carried out on co-existing pyroxenes in granulitic impactites reveal that they last equilibrated around 1000±50°C. Poikiloblastic and granoblastic varieties have similar equilibration temperatures, suggesting that they were probably physically associated during the metamorphic event (Cushing et al., 1999).
Based on average grain size and calculated equilibration temperatures, Cushing et al. (1999) determined that granoblastic granulites were annealed for $<10^5$ a. James (1980) estimated annealing time at ~1-10 Ma.

Based on their chemical, petrological, and textural features, Warner et al. (1977) concluded that granulitic impactites are probably recrystallized monomict (e.g., 67215 and 67415) or polymict (e.g., 79215 and 78155) impact breccias from the early lunar crust. Their clast-matrix structure and their meteoritic contamination suggest that they were derived from even older breccias that were metamorphosed and recrystallized by prolonged heating. These KREEP-poor precursors would have been present early in lunar history (Papike et al., 1998). Chemically, these rocks are anorthositic norite or anorthositic troctolite and were probably derived from an anorthositic norite parent. Both their feldspathic bulk composition and their low concentration of incompatible elements resemble the estimated average lunar highlands composition and the composition of “highland basalt” (Lindstrom and Lindstrom, 1986).

**SAMPLE DESCRIPTIONS AND PREVIOUS WORK**

Nine polished thin sections from seven different granulitic impactites were loaned by the NASA Johnson Space Center: 15418,154, 60035,19, 67955,53, 76235,19, 77017,70, 77017,85, 77539,13, 78155,8, and 78155,41. The petrography and chemistry of these seven samples, based on previous work as well as ongoing study by the author, will be discussed in detail.

**Sample 15418:** a strongly shocked granulitic breccia collected from the rim of Spur crater. Compositionally, it is a gabbroic anorthosite (Ryder, 1985). It is surrounded by a vesicular, glassy rind and its texture is granoblastic. The interior has a fragmental, recrystallized texture with polycrystalline grains of plagioclase and olivine up to 5 mm in a fine-grained, recrystallized matrix of plagioclase, olivine, and pyroxene (Ryder, 1985). These polycrystalline grains were produced by shock and exhibit aggregate extinction. Plagioclase grains have plumose texture, suggesting recrystallization via thermal metamorphism. Based on their petrographic study, Nord et al. (1977) propose that 15418 is a slowly cooled igneous rock that equilibrated at 1000°C and subsequently underwent two episodes of brecciation and recrystallization. Ryder (1985) also suggests that 15418 underwent initial crystallization and slow cooling followed by two episodes of brecciation and recrystallization. 15418 has very low REE concentrations and low but detectable siderophile element concentrations (Lindstrom and Lindstrom, 1986). Stettler et al. (1973) determined Ar plateau ages of 3.99±0.07 Ga and 4.04±0.06 Ga for subsample 15418,50.

**Sample 60035:** a fine-grained, clast-rich polymict breccia containing abundant clasts of anorthositic troctolite with granoblastic texture and anorthositic norite with poikiloblastic texture and minor clasts of cataclastic ferroan anorthosite, basalt, and Mg-rich troctolite (Ma and Schmitt, 1982). The matrix is cataclastic to poikiloblastic with very fine-grained plagioclase intergrown with pyroxene oikocrysts that enclose plagioclase and olivine chadacrysts. The matrix makes up 65% of the rock, lithic clasts make up 10%, and 25% of the rock is mineral fragments up to 1 mm, mainly plagioclase. Portions of the rock have been comminuted and exhibit undulose extinction. Warner et al. (1979) suggest this rock is a polymict ANT breccia, which has not undergone prolonged annealing. Cataclastic anorthosite clasts, large shocked plagioclase grains, and plagioclase-rich melt areas are evidence for their suggestion.

**Sample 67955:** a friable, white to grey, shocked poikiloblastic breccia from Outhouse rock. It contains coarse pyroxene oikocrysts surrounding plagioclase and olivine chadacrysts grading into a very fine-grained cataclastic to hornfelsic matrix (Lindstrom and Lindstrom, 1986). The matrix consists of finely comminuted and recrystallized grains from lithic and mineral clasts. Mineral fragments are dominantly (90%) single crystals of plagioclase, averaging 250 µm. Rare olivine and pyroxene fragments are generally less than 100 µm. Lithic clasts include coarse-grained, shocked, and annealed anorthositic norite and noritic anorthosite up to 2 mm wide with textures ranging from granoblastic to poikiloblastic. The sample has been pervasively shocked, which resulted in extensive fracturing and mosaicism. Mineral compositions are homogenous throughout the rock, suggesting that the last brecciation event involved only crushing of the precursor without significant introduction of foreign material (Ashwal, 1975). Interpretations as to its origins vary. Hollister (1974) and Ashwal (1975) conclude that it was derived from a single plutonic rock, based on its coarse-grained clasts, but Warner et al. (1977) reason that it is a metamorphosed polymict breccia, based on its textural homogeneity and recrystallized matrix. Norman and Ryder (1980) suggest that 67955 was extensively annealed, recrystallized, and subsequently brecciated. Siderophile concentrations are high and REE patterns are flat at nearly 10x chondrite (Ashwal, 1975).
Sample 76235: a feldspathic granulite clast from the Station 6 boulder with poikiloblastic to granoblastic texture. It contains plagioclase, pigeonite, and olivine as well as possible relict megacrysts of anorthosite, providing evidence for a polymict origin (Meyer, 1994). The section is 60% poikiloblastic and 40% granoblastic. Granoblastic plagioclase, averaging 150 µm, and minor finer-grained olivine and clinopyroxene are intergrown with coarse (<1 mm) pyroxene oikocrysts, both clinopyroxene and orthopyroxene. The oikocrysts enclose many rounded plagioclase and olivine chadacrysts, averaging 50 µm. The bulk composition of 76235 falls in between the two major pristine rock fields and all mineral compositions have been homogenized (Meyer, 1994). Lindstrom and Lindstrom (1986) conclude that the rock underwent a complex history of brecciation, melting, and recrystallization and that it is likely a mixture of a limited number of feldspathic precursors. Cadogan and Turner (1976) determined two Ar plateau ages of 3.93±0.06 Ga and 3.95±0.06 Ga for a troctolite clast in subsample 76235,3.

Sample 77017: a coarse-grained, annealed, poikilitic breccia with a fine-grained cataclastic matrix from the base of the North Massif. It contains relic coarse-grained lithic clasts from the ANT suite and angular mineral clasts of plagioclase, olivine, spinel, and accessory minerals enclosed in pyroxene oikocrysts (McCallum et al., 1974). Average grain size is as follows: plagioclase ~750 µm, olivine ~500 µm, and pyroxene oikocrysts ~1.5 mm. Mineral fragments show evidence of shock deformation and grade into the cataclastic matrix. The matrix is similar in composition to the mineral fragments and lithic clasts and is arbitrarily defined as all grains less than 100 µm. Mineral compositions are homogeneous and ferroan and all original texture was destroyed by intense meteorite bombardment (Lindstrom and Lindstrom, 1986). Helz and Appleman (1974), McCallum et al. (1974) and Ashwal (1975) all agree that the precursor of 77107 was a plagioclase-rich cumulate; however, their interpretations of the rock's texture vary. Ashwal (1975) interprets the rock as having crystallized in a plutonic environment, while Helz and Appleman (1974) and McCallum et al. (1974) favor a metamorphic origin. McCallum et al. (1974) conclude that the rock was formed by subsolidus recrystallization of a monomict breccia in a thick ejecta blanket. Finally, Meyer (1994) proposes that 77017 formed as a hot impactite sheet covered by younger, hotter ejecta early in lunar history. 77017 is enriched in siderophile elements and has a REE pattern flat at 10x chondrite (Ashwal, 1975). A high siderophile content and presence of vesicles indicate that the sample formed in a near-surface, low pressure environment (McCallum et al., 1974). Kirsten and Horn (1974) determined an Ar plateau at 4.04±0.03 Ga for the “white material” in subsample 77017,46.

Sample 77539: a vesicular, poikilitic impact-melt breccia from Station 7 containing a subangular “anorthite” clast that makes up ~30% of the sample. The impact-melt breccia has a poikiloblastic texture with irregular pigeonite oikocrysts enclosing euhedral plagioclase laths and minor rounded olivine crystals. Mineral clasts are abundant and mostly plagioclase, lithic clasts are rare (Meyer, 1994). The large, white clast has a fine-grained, sugary texture and is composed of 97% plagioclase and 3% mafics and opaques. Plagioclase averages 75 µm, is subangular, and meets at triple junctions. Mafic grains are concentrated near the plagioclase grain boundaries and are generally less than 1 µm.

Sample 78155: a holocrystalline, granoblastic, polymict breccia of anorthositic norite composition from Station 8. It contains scattered, shocked mineral grains and relic lithic clasts in a fine-grained, granoblastic matrix. Mineral grains include plagioclase, pyroxene, olivine, and accessory minerals. Lithic clasts include fine-grained anorthites with felty, shocked plagioclase and coarser-grained clasts with variable composition and texture. The rock also contains a substantial amount of crushed material (1-100 µm), up to 15% of the rock, in veins or irregularly shaped regions. This material was derived directly from the matrix and the clasts, indicating that brecciation occurred after metamorphism. The matrix makes up over 60% of the rock and occurs in subrounded fragments up to a few millimeters across that are separated by curved fractures and regions of crushed material. Grain size is on average 75 µm for plagioclase and 20 µm for mafic minerals. The rock is contaminated with meteoritic siderophile elements and contains no appreciable amount of KREEP (Bickel, 1977). Bickel (1977) concluded that the precursors of 78155 were plutonic ferroan anorthites that underwent at least two episodes of crushing and brecciation, one before and one after thermal metamorphism of the rock. Turner and Cadogan (1975) determined a whole rock Ar plateau age of 4.22±0.04 Ga, which was confirmed by Oberli et al. (1979) who determined an age of 4.17±0.03 Ga for subsample 78155,53.
TABLE 1. Average bulk compositions of selected granulitic impactite samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>Cr₂O₃</th>
<th>FeO</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>15418,51a</td>
<td>44.97</td>
<td>0.27</td>
<td>26.73</td>
<td>-</td>
<td>5.37</td>
<td>-</td>
<td>5.38</td>
<td>16.10</td>
<td>0.31</td>
<td>0.03</td>
</tr>
<tr>
<td>60035</td>
<td>46.49</td>
<td>0.20</td>
<td>26.00</td>
<td>0.11</td>
<td>4.00</td>
<td>0.05</td>
<td>8.40</td>
<td>14.30</td>
<td>0.38</td>
<td>0.07</td>
</tr>
<tr>
<td>67955,8</td>
<td>45.01</td>
<td>0.49</td>
<td>27.15</td>
<td>0.11</td>
<td>3.84</td>
<td>0.05</td>
<td>7.69</td>
<td>15.30</td>
<td>0.40</td>
<td>0.05</td>
</tr>
<tr>
<td>76235</td>
<td>44.52</td>
<td>0.20</td>
<td>27.01</td>
<td>0.14</td>
<td>5.14</td>
<td>0.05</td>
<td>7.63</td>
<td>15.17</td>
<td>0.35</td>
<td>0.06</td>
</tr>
<tr>
<td>77017,2</td>
<td>44.09</td>
<td>0.41</td>
<td>26.59</td>
<td>0.13</td>
<td>6.19</td>
<td>0.06</td>
<td>6.06</td>
<td>1.43</td>
<td>0.30</td>
<td>0.06</td>
</tr>
<tr>
<td>77539,15</td>
<td>44.08</td>
<td>0.11</td>
<td>34.20</td>
<td>0.02</td>
<td>0.67</td>
<td>0.08</td>
<td>0.90</td>
<td>18.90</td>
<td>0.45</td>
<td>0.05</td>
</tr>
<tr>
<td>78115,2</td>
<td>45.57</td>
<td>0.27</td>
<td>25.94</td>
<td>0.14</td>
<td>5.82</td>
<td>0.10</td>
<td>6.33</td>
<td>15.18</td>
<td>0.33</td>
<td>0.08</td>
</tr>
</tbody>
</table>


CHRONOLOGY

Chronological data for granulitic impactites are scarce. Few conclusive ages have been determined for these samples. Most samples are too fine-grained to permit the mineral separations necessary for Rb-Sr or Sm-Nd internal isochron age determinations (Papike et al., 1998). However, several have been found to have ⁴⁰Ar-³⁹Ar plateau ages of >4.2 Ga, suggesting that they formed prior to the final bombardment period (Cushing et al., 1999). Unfortunately, there is rarely an indication as to what part(s) of the rock were dated. Warner et al. (1977) summarized the Ar age data for Apollo 17 granulitic breccias and established that they range in age between 3.94-4.26 Ga. Many samples exhibit two age plateaus, one around 4.2 Ga and the other near 4.0 Ga. The younger age may have been reset by thermal metamorphism or by the event that exhumed the rocks, possibly the basin-forming impacts of the final bombardment (Korotev and Jolliff, 2001).

These degassing ages have been interpreted to represent a variety of geological processes, including crystallization and differentiation, thermal metamorphism, excavation, and brecciation. It is not fully understood whether granulite ages reflect the time of impact metamorphism or whether granulite metamorphism causes only incomplete degassing of ⁴⁰Ar. Cohen (2004) modeled experimental results and showed that the high temperatures and moderate cooling rates experienced by granulitic impactites were sufficient to fully degas plagioclase; therefore, the ages of the granulitic impactites should represent the date of the metamorphic event (Cohen, 2004).

Although most authors agree that granulitic impactites formed before the final lunar bombardment, it still remains puzzling that some samples have been reset and others have not. For example, at the Apollo 17 site, two large samples are completely reset, while centimeter-sized clasts retain evidence of their original ages (Warner et al., 1977). Further isotopic work on these samples will provide important clues to the thermal history of the lunar crust.

DISCUSSION: ORIGINS

Granulitic impactites have low lithophile element concentrations and REE patterns that are only slightly fractionated, suggesting a brecciated plutonic, perhaps cumulate, parent rock (Warner et al., 1977). Their bulk compositions, high siderophile element concentrations, and pre-metamorphic textures are also consistent with a polymict, meteoritically contaminated protolith (Cushing et al., 1999). These samples represent aggregates of rock and mineral fragments that were heated to near solidus temperatures and recrystallized or partially melted as a result (James, 1980). The equilibrated textures of these rocks make it difficult to determine the textures of their precursors. Major constraints on the nature of the precursors are based on bulk and mineral compositions, although trace element abundances can also provide important constraints.

Due to their varied textures, there have been many interpretations for the origin of granulitic impactites. Hollister (1973) and Ashwal (1975) have interpreted two of the samples (67955 and 77017, respectively) as plutonic igneous...
rocks that crystallized from silicate magma. However, most authors (e.g., Warner et al., 1977, Bickel and Warner, 1978, Lindstrom and Lindstrom, 1986) emphasize the metamorphic features of the rocks, especially the granoblastic texture of their matrices. Based on their calculations, Cushing et al. (1999) propose that granoblastic granulites were plutonic rocks excavated in large basin-forming events, brecciated, heated, and subsequently cooled and recrystallized beneath or within an ejecta blanket up to 200 m thick. Similarly, Korotev and Jolliff (2001) propose that granulitic breccias were assembled by one or several large impacts into the Feldspathic Highland Terrane that penetrated down to mid- or even deep-crustal levels and produced thick ejecta blankets, and that later basin-forming events brought these rocks to the surface. Bickel and Warner (1978) conclude that granulites originated by metamorphism of breccias made up of mixtures of igneous rocks from the Mg-suite and the ferroan anorthosite suite. James (1980) provides several lines of evidence that metamorphism occurred in the upper few kilometers of the lunar crust: 1) Most of the samples have been comminuted and recrystallized more than once, suggesting an origin greatly affected by impacts. 2) Grain size is fine and mineral compositions are not entirely homogeneous, suggesting a relatively short duration of recrystallization. 3) The global distribution of the rocks also suggests a level of origin affected by frequent lunar-wide impacts. 4) Their average bulk composition is close to the average composition of the lunar crust.

Granulitic impactites are only found as clasts in breccias that formed during the final bombardment, suggesting that the high temperatures and prolonged heating times required to develop their textures were only achieved before the final bombardment (Warner et al., 1977). The source of heat, however, still remains unknown. The impact events that granulated the precursor rocks would not alone have provided sufficient heat for metamorphism; an additional heat source would have been required. Cushing et al. (1999) suggest that it may have been provided by the remnants of the lunar magma ocean and retained by the megaregolith. Warner et al. (1977) propose that the early, brecciated lunar crust was hot enough for high-temperature metamorphism within a few kilometers of the surface due to higher heat flow or an increased flux of meteorite impacts. If such conditions were achieved more recently, the granulites produced were not sampled by the Apollo program, perhaps because basin-sized impacts, which are required to excavate these rocks, did not recently occur (Warner et al., 1977).

**CONCLUSIONS**

1. Granulitic impactites are metamorphosed and recrystallized monomict or polymict breccias that are KREEP-free and contaminated by meteoritic siderophiles. They have average compositions of anorthositic norite or troctolite, similar to the average composition of the lunar highland crust. These rocks are abundant, widespread, and thought to pre-date the final bombardment period.

2. Although the textures of granulitic breccias reveal complex histories of repeated brecciation and metamorphism, their compositions suggest that most are not complex mixtures of pristine rocks types. Instead, some represent a single annealed precursor rock type, most often an anorthositic norite. Others contain evidence of several precursors, but still appear to be dominated by ferroan or magnesian anorthositic norite parents (Lindstrom and Lindstrom, 1986).

3. Granulites must have been located at shallow crustal levels, probably in the megaregolith, to have been both 1) exposed to high enough internal heat flow to generate granulite metamorphic conditions and 2) excavated by large impacts, most likely those of the final bombardment period. Although the source of heat is still unknown, it is speculated that higher heat flow in the early lunar crust and a higher influx of meteorite impacts could have provided sufficient heat to metamorphose these breccias.

4. The extensive compositional variety seen in these rocks indicates that the ancient lunar highlands crust was far from being homogeneous and that impact events followed by thermal metamorphism were common processes operating on various lithologies. The existence of this rock type at a number of sampling sites implies that they were not formed solely by local processes (Lindstrom, 1985). The close resemblance of granulitic impactites to the average highlands composition suggests that plutonic anorthositic norites are more important in lunar crustal evolution than is implied by their under-representation in the Apollo and Luna samples (Lindstrom and Lindstrom, 1986).
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