Spinel Troctolite and Anorthosite in Apollo 16 Samples

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origin. The bulk composition of both samples is dominated by normative anorthite. However, there are also significant differences between the two samples. The mosaically recrystallized anorthosite fragments in the microbreccia portion of 60017 appear to have undergone much more severe shock metamorphism than any of the materials in 63335. Both samples have undergone severe thermal metamorphism, but different results (growth of dendritic ferromagnesian crystals and apparent resorption of plagioclase fragments in the case of 63335, and apparent growth of plagioclase in the case of 60017) suggest that the samples were subjected to different thermal metamorphic conditions. The fine-grained subophitic anorthositic gabbro fragments that are present in the microbreccia portion of 60017 are completely absent in 63335. Hence, if the reported sample locations (*1*) are correct, Shadow Rock is a complex breccia incorporating several lithologically diverse components which have had different shock and thermal metamorphic histories.

Rocks 60017 and 63335 provide samples of a variety of material which has had a complex history of transportation, lithification, and metamorphism. Although the thin sections investigated were only a few square centimeters in area, previous investigations of small breccia samples have uncovered a wide variety of lithic types (*4, 11, 12*). Therefore, it may be significant that there is little compositional variety in the material observed in these samples. The samples are dominated by calcic plagioclase, and no material resembling the typical mare basalts was found. We conclude that the region of the Apollo 16 landing site is dominated by anorthositic rocks.

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Spinel Troctolite and Anorthosite in Apollo 16 Samples

Abstract. *A spinel troctolite and an anorthosite from the Apollo 16 landing site represent contrasting types of "primitive" lunar cumulates. The two rock types probably formed from the same parent magma type, a high-alumina magnesian basalt, with the troctolite forming earlier by crystal settling, and the anorthosite later, possibly by flotation.*

One of the principal topics of discussion in lunar petrogenesis has been the possibility of early, large-scale differentiation and the importance of cumulate-type rocks. We report here on two Apollo 16 rocks recovered from the lunar highlands which probably represent contrasting types of "primitive" lunar cumulates. Rock 67435 (polished thin sections 67435,14 and 67435,16) is a microbreccia containing a large (4 by 4.5 mm) lithic fragment of spinel troctolite. Rock 62275 (polished thin section 62275,4) is a shock-brecciated anorthosite.

The spinel troctolite lithic fragment in section 67435,14 is an ultramafic rock with a cumulate texture (Fig. 1). The cumulus phases are subhedral to euhedral olivine and pink spinel poikilitically included in plagioclase. The grain size is variable, with spinel ranging from 0.1 to 0.7 mm and olivine from 0.2 to 1.1 mm; the poikilitic plagioclase is much coarser, ranging from 2 to 3 mm. Spinel is unevenly distributed and sometimes occurs in clusters (Fig. 1). The only other phases present are minor Fe-Ni-Co metal grains ranging from minute specks to 0.1 mm in diameter, and fine veinlets of troilite. No pyroxene was found. Spinel and olivine were the first phases to crystallize, with some spinel probably preceding the olivine; these were followed by plagioclase. The mode is given in Table 1 and indicates a high abundance of olivine. However, because of the coarseness of the grain size relative to the size of the fragment the mode may not be representative of the entire rock.

The rock has been mildly shocked, as indicated by the presence of fracture zones with finely recrystallized min-

Fig. 1. Photomicrograph, with crossed polarizers, of a portion of the spinel troctolite lithic fragment in Apollo 16 microbreccia 67435,14. Subhedral crystals of spinel (black, in the center) and subhedral olivine (light to dark, in high relief) are poikilitically enclosed within a large single crystal of plagioclase (white). A fracture zone, with recrystallized minerals, crosses the fragment (right center to bottom center of the photograph). Scale bar, 0.5 mm.

erals (one such zone is shown in Fig. 1). Other indications of shock are the presence of mosaic patterns of optical extinction of some olivine and portions of some feldspar grains, as well as the fine veinlets of troilite.

Compositions of minerals were determined with an Applied Research Laboratories EMX-SM electron microprobe by using methods described by Keil (*1*). The spinel is enriched in $MgAl_2O_4$ (85 mole percent; Table 1). This analysis is typical of other spinel in this rock (*2*), with a few grains differing slightly. The olivine is highly magnesian (Table 1); analyses of ten crystals give a range of 91.9 to 92.4 mole percent forsterite ($Fo_{91.9}$–$Fo_{92.4}$). This olivine is among the most magnesian reported from the moon; minor occurrences with values near this were found in Apollo 14 and Apollo 15 samples (*3*). The plagioclase is highly calcic (Table 1); analyses of ten crystals give a range of 96.6 to 97.4 mole percent anorthite ($An_{96.6}$ –$An_{97.4}$). In the plagioclase, the concentration of FeO is low (0.16 percent) and that of MgO high (0.65 percent), reflecting the bulk chemistry of the rock. The Fe-Ni-Co grains are remarkably high in Ni (Table 1). The troilite is too small to be analyzed.

A bulk analysis of the spinel troctolite fragment by the broad beam electron microprobe technique (*4*), is given in Table 1. The high concentrations of MgO (33.7 percent) and Al_2O_3 (15.9 percent) reflect the abundant magnesian olivine and spinel. Even if the rock generally contains a greater amount of plagioclase than is present in this fragment, the magnesian nature of the mineral assemblage would still result in a highly magnesian rock.

The spinel troctolite is embedded in a dense, highly annealed microbreccia consisting of major amounts of plagioclase, minor amounts of olivine and orthopyroxene, and traces of clinopyroxene, Fe-Ni-Co, and troilite. The plagioclase ranges in composition from $An_{93.0}$ to $An_{97.2}$ with one large oval grain being $An_{65.8}$. The olivine ranges from $Fo_{73.9}$ to $Fo_{81.5}$, with a few grains being more magnesian; one grain is of special note in having a $Fo_{95.0}$ composition. The orthopyroxene has a limited range with an average composition of $En_{78.4}$. One grain of clinopyroxene, found in an anorthosite fragment, has a composition of 39.9 mole percent wollastonite, 43.1 enstatite, and 17.0 ferrosilite. Electron microprobe bulk analyses of three chips of the microbreccia showed their compositional similarity to one another; the average of the analyses is given in Table 1.

The microbreccia is polymict in that it includes the spinel troctolite, as well as minor anorthositic and troctolitic fragments. However, the limited compositional range of the minerals indicates that only a few rock types, of the anorthositic-noritic-troctolitic (ANT) group (*5*), are included.

Rock 62275 is a brecciated, shock-metamorphosed anorthosite. In thin section it consists of isolated transparent fragments, most of which are fractured, in a finely brecciated matrix. Most of the large transparent fragments are not feldspar, but brownish glass of near-feldspar composition. Only about one-third of the feldspathic fragments are crystalline plagioclase. The glass is not thetomorphic, as indicated by its contents of FeO and MgO, but must have been produced by melting of both plagioclase and mafics. Smaller fragments of olivine, pyroxene, and spinel are present in minor quantities. Our best estimate of the mode, including feldspathic glass with plagioclase, is given in Table 2.

A bulk analysis of this rock is also shown in Table 2. The anorthositic character of this rock is reflected in the high Al_2O_3 (33.1 percent) and CaO

Table 1. Bulk analysis and representative mineralogical data for the spinel troctolite lithic fragment and microbreccia from Apollo 16 sample 67435,14. Ten grains of Fe-Ni-Co were analyzed. The results of the bulk analysis of the troctolite fragment were recalculated to 100 percent by weight; all data are percent by weight. The modal analysis for the troctolite fragment (in percent by volume) is: spinel (5), olivine (69), plagioclase (26), Fe-Ni-Co (trace), and troilite (trace). The molecular proportions (mole percent) are: for plagioclase, anorthite (97.3), albite (2.4), orthoclase (0.3); for olivine, forsterite (92.4), fayalite (7.6); and for spinel, spinel (84.9), hercynite (7.0), chromite (7.9), ulvospinel (0.2); nd, not determined.

Constituent	Bulk analysis	Plagioclase	Olivine	Spinel	Fe-Ni-Co	Microbreccia
SiO_2	37.5	44.4	41.2	0.25		45.4
TiO_2	0.05	0.02	0.03	0.10		0.89
Al_2O_3	15.9	35.7	0.38	62.9		24.1
Cr_2O_3	0.49	nd	0.01	7.9		0.12
FeO	5.8	0.16	7.5	6.9		6.1
MnO	0.16	0.03	0.08	0.03		0.17
MgO	33.7	0.65	51.3	22.5		9.6
CaO	6.2	19.4	0.24	0.22		13.2
Na_2O	0.14	0.27	nd	nd		0.53
K_2O	0.04	0.05	nd	nd		0.23
P_2O_5	0.02	nd	nd	nd		0.17
Totals	100.00	100.68	100.74	100.80		100.51
Fe					47.0–70.4	
Ni					26.7–50.8	
Co					0.64–1.26	

Table 2. Bulk analysis and representative mineralogical data for Apollo 16 anorthosite 62275,4. The results of the bulk analysis were recalculated to 100 percent by weight; all data are percent by weight. The modal analysis (percent by volume) is: feldspathic glass and plagioclase (93), olivine (6), orthopyroxene (1), clinopyroxene (trace), spinel (trace). The molecular proportions (mole percent) are: for plagioclase, anorthite (98.8), albite (1.2); for olivine, forsterite (59.8), fayalite (40.2); for clinopyroxene, wollastonite (45.1), enstatite (38.1), ferrosilite (16.8); for orthopyroxene, wollastonite (3.1), enstatite (67.0), ferrosilite (29.9); and for spinel, chromite (59.3), hercynite (21.5), spinel (12.0), ulvospinel (7.2); nd, not determined.

Constituent	Bulk analysis	Plagioclase	Feldspathic glass	Olivine	Clinopyroxene	Orthopyroxene	Spinel
SiO_2	43.7	43.4	44.3	35.2	51.4	53.5	0.58
TiO_2	0.04	nd	0.13	<0.01	0.46	0.16	2.73
Al_2O_3	33.1	36.2	30.2	0.65	1.43	1.38	16.2
Cr_2O_3	0.29	nd	0.06	0.03	0.24	0.10	42.0
FeO	2.20	0.10	3.4	34.2	10.4	18.8	31.5
MnO	<0.01	nd	0.04	0.42	0.30	0.39	0.24
MgO	1.91	<0.02	3.1	28.5	13.2	23.7	3.5
CaO	18.4	20.3	18.6	0.43	21.7	1.51	0.57
Na_2O	0.30	0.13	0.34	nd	0.07	<0.01	nd
K_2O	0.06	<0.01	0.03	nd	nd	nd	nd
Totals	100.00	100.13	100.20	99.43	99.20	99.54	98.23*

* The total includes 0.86 weight percent V_2O_3.

(18.4 percent) contents. The low FeO and MgO contents reflect the low abundance of mafics. The plagioclase ranges from $An_{97.1}$ to $An_{99.0}$; MgO in the plagioclase is below detection, in contrast with the high MgO content in the plagioclase of the spinel troctolite. The feldspathic glass has an Al_2O_3 content too low for plagioclase, and its FeO (0.1 to 4.1 percent) and MgO (0.10 to 3.3 percent) contents are higher than those found in lunar plagioclase. The olivine grains are small, ranging from minute specks to 0.2 mm; compositionally they are in the range $Fo_{59.0}$ to $Fo_{61.4}$ (Table 2). Orthopyroxene is a minor phase and clinopyroxene is very rare; the grains are found as small discrete crystals. The orthopyroxene ranges from $En_{54.6}$ to $En_{69.8}$ (Table 2). The clinopyroxene has a very limited range and the analysis in Table 2 is typical; compositionally it is transitional between augite and salite. Spinel is a rare constituent, and only two grains large enough to analyze were found. The analysis given in Table 2 shows that it is enriched in $FeCr_2O_4$.

The spinel troctolite described here confirms earlier suggestions (*4*) that troctolite is a lunar igneous rock type. It is the best example to date of a cumulate texture in a "primitive" rock. Cumulate textures noted previously in lunar igneous rocks, especially in Apollo 12 samples, are in rocks that appear to be related to mare basalts. A lunar spinel troctolite assemblage was first reported as a fragment in an Apollo 11 microbreccia (*6*), and other troctolitic lithic fragments were described in the same samples (*4*). An olivine-plagioclase (troctolite) lithic fragment was found in an Apollo 12 sample, but with no spinel (*7*), and rare spinel troctolite fragments were found in Apollo 14 samples (*8, 9*). When a spinel phase is present in these troctolites it is enriched in $MgAl_2O_4$. In addition, olivine is rather magnesian (Fo_{74}–Fo_{88}), plagioclase is highly calcic (An_{94}–An_{98}), and no pyroxene or ilmenite is found.

Lunar anorthosites differ from the troctolites, not only in containing more plagioclase, but in the nature of the mafic minerals. Anorthosites usually contain pyroxene, whereas spinel troctolites do not. When spinel is found in anorthosites it is enriched in $FeCr_2O_4$, as shown in Apollo 11 and Apollo 12 fragments (*7, 10*), and in an Apollo 15 rake sample specimen very similar to 15415 (Genesis Rock) (*11*). Olivine is usually relatively iron-rich, and opaque phases present in anorthosites include ilmenite, armalcolite, troilite, and metallic Fe-Ni.

The data reported in the literature and the results of the present study indicate that there are essential mineralogical differences between spinel troctolite and anorthosite, which are suggestive of genetic relationships between the two. Such genetic relations may be inferred from a consideration of the system diopside-forsterite-anorthite (*12*), which offers a first approximation to the parent magmas of these rocks. A $MgAl_2O_4$ spinel field is present on the liquidus of the system on and near the forsterite-anorthite join, and certain liquids in this vicinity would crystallize spinel as one of the earliest phases. On cooling, the liquid would move toward the diopside field with spinel reacting with the liquid to form olivine and plagioclase, unless it is removed by settling, or armored by other crystals. Although $MgAl_2O_4$ spinel is thus removed from later liquids in this differentiation process, the presence of some FeO and Cr_2O_3 in the liquid would probably allow spinel rich in $FeCr_2O_4$ to remain in coexistence with the forsterite-anorthite-diopside (anorthosite) assemblage. The higher Fe/Mg ratios of mafics as well as the presence of ilmenite and armalcolite in anorthosites is also indicative of their formation at a lower temperature, compared to spinel troctolite assemblages.

Thus, if the two rock groups formed from the same parent magma type, the spinel troctolite must have formed early in the differentiation sequence as the result of crystal settling in the melt, whereas the anorthosite must have formed as a later cumulate, possibly by flotation. A similar suggestion has also been made by Roedder and Weiblen (*9*). It appears that the parent magma must have been a high-alumina magnesian basalt melt.

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Early Cultivated Beans (Phaseolus vulgaris) from an Intermontane Peruvian Valley

Abstract. *Examples of fully domesticated common beans* (Phaseolus vulgaris) *and lima beans* (Phaseolus lunatus) *were recovered from deposits in Guitarrero Cave (PAn 14-102) in the Callejón de Huaylas, Ancash, Peru. Carbon-14 dates for stratum II, in which the earliest beans were found, range from 7,680 ± 280 to 10,000 ± 300 years before the present.*

Preceramic cultural and skeletal remains from Guitarrero Cave (PAn 14-102) in the Callejón de Huaylas, Ancash, Peru, have been described in their stratigraphic and chronological context (*1*). Partial analysis of the vegetal remains has disclosed the presence of fully domesticated common beans (*Phaseolus vulgaris*) at an early level in the dry deposits.

The vegetation around the cave is a thorn-scrub formation in which the