bonaceous chondrite material around 400° to 600°C. Sample 61221 did not evolve any sulfur-containing gases until temperatures above 900°C, and these high-temperature sulfur gases are reaction products of sulfur-bearing phases found in the soils with the silicate phases (*8*).

If the soil 61221 is associated with North Ray crater, as suggested by morphological and chemical characteristics, we suggest that the volatile material may have been brought to this site by the object that formed North Ray crater. Whipple (*10*) and Wurm (*11*) noted that the neutral molecules CN, C_2, C_3, NH, CH, OH, and NH_2, along with the ionized molecules CO^+, N_2^+, CH^+, CO_2^+, and OH^+, are characteristic components of comets. The possible parent compounds (H_2O, CO_2, HCN, H_2, CO, CH_4, N_2) of all these cometary species have been identified in lunar soil 61221. The large abundance of HCN in soil 61221, as compared to other lunar soils, is particularly strong evidence for this hypothesis. Hydrogen cyanide and hydrocarbon fragments have been previously identified in lunar soils and as exhaust products of the lunar module (LM) (*12*), but their abundance and temperature release profiles are distinctly different from the pattern observed for sample 61221. The subsurface location of sample 61221 further reduces the possibility of LM exhaust contamination. Kopal (*13*) points out that the total amount of gas which can be acquired by the moon in a catastrophic encounter with a comet is far from negligible. Although the exact composition of the gases associated with a cold cometary nucleus is not known at the present time, those gases identified in the spectra of cometary tails provide us with evidence of possible constituents that might be derived from a comet during impact.

If North Ray crater was formed by a cometary impact, it is possible that portions of the volatiles in the comet were retained in ray material thrown out as a result of the impact. Had the impact occurred during the cold lunar night the retention of volatiles would have been even more efficient. If the Apollo 15 heat flow measurements can be extrapolated to the Apollo 16 site (*14*), that part of the crater ray at a depth of 30 to 35 cm would have had a mean temperature of approximately 0°C after it cooled. Further burial would result from the base surge deposits emanating from younger craters, such as South Ray crater and secondary craters in the area immediately surrounding Plum crater. The probability of the retention of gases and volatiles from the comet after impact is quite low, but rapid burial might allow a small portion of them to be preserved. The presence of HCN, the low-temperature release of CH_4, and the unique weight-loss profile of sample 61221 suggest that it may have formed in the manner outlined. Studies of the abundances of such volatile elements as bismuth, lead, and thallium in sample 61221 may further test the proposed unique origin of this volatile-rich lunar soil.

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References and Notes

1. "The Moon Issue," *Science* **167** (1970); "Proceedings of the Apollo 11 Lunar Science Conference," *Geochim. Cosmochim. Acta* **1–3** (Suppl. 1) (1970).
2. E. Anders, *Science* **169**, 1309 (1970).
3. C. B. Moore, E. K. Gibson, Jr., J. W. Larimer, C. F. Lewis, W. Nichiporuk, *Geochim. Cosmochim. Acta* **2** (Suppl. 1), 1375 (1970).
4. C. Duke, personal communication; Apollo Lunar Geology Investigation Team, *Astrogeology 51* (Interagency report, U.S. Geological Survey, Washington, D.C., 1972).
6. Apollo 16 Preliminary Examination Team, *Science* **179**, 23 (1973).
7. D. S. McKay, D. A. Morrison, U. S. Clanton, G. H. Ladle, J. F. Lindsay, *Geochim. Cosmochim. Acta* **1** (Suppl. 2), 755 (1971); D. S. McKay, G. H. Heiken, R. M. Taylor, U. S. Clanton, D. A. Morrison, *ibid.*, in press; U. S. Clanton, D. S. McKay, R. M. Taylor, H. Heiken, *The Apollo 15 Samples* (Lunar Science Institute, Houston, Texas, 1972).
8. E. K. Gibson, Jr., and S. M. Johnson, *Geochim. Cosmochim. Acta* **2** (Suppl. 2), 1351 (1971); E. K. Gibson, Jr., and G. W. Moore, *ibid.*, in press; E. K. Gibson, Jr., and S. M. Johnson, *Thermochim. Acta* **4**, 49 (1972); E. K. Gibson, Jr., *ibid.*, in press.
9. J. Hayes, personal communication.
10. F. J. Whipple, in *The Moon, Meteorites and Comets*, B. M. Middlehurst and G. P. Kuiper, Eds. (Univ. of Chicago Press, Chicago, 1963), pp. 639–664.
11. K. Wurm, in *ibid.*, pp. 573–617.
12. B. R. Simoneit, A. L. Burlingame, D. A. Flory, I. D. Smith, *Science* **166**, 733 (1969); P. T. Holland, B. R. Simoneit, P. C. Wszolek, W. H. McFadden, A. L. Burlingame, *Geochim. Cosmochim Acta*, in press; D. A. Flory, S. Wikstrom, S. Gupta, J. M. Gibert, J. Orò, *ibid.*, in press.
13. Z. Kopal, *Man and His Universe* (Morrow, New York, 1972), pp. 182–188.
14. M. G. Langseth, Jr., S. P. Clark, Jr., J. L. Chute, Jr., S. J. Keihm, A. E. Wechsler, *Apollo 15 Preliminary Science Report* (NASA SP-289, National Aeronautics and Space Administration, Washington, D.C., 1972), p. 11-1.
15. We thank J. Hayes for confirming our suspicion as to the unusual nature of sample 61221. The authors acknowledge the invaluable assistance of astronaut C. Duke and discussions with P. W. Gast, P. R. Brett, S. Chang, D. S. McKay, G. H. Heiken, D. A. Flory, K. Kvenvolden, and C. B. Moore.

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Breccias from the Lunar Highlands: Preliminary Petrographic Report on Apollo 16 Samples 60017 and 63335

Abstract. *Lunar samples 60017,4 and 63335,14 are composed of microbreccias and devitrified glass. These components are predominantly anorthositic, with the exception of a cryptocrystalline clast found in the microbreccia portion of 63335,14 which contains 2.7 percent potassium oxide and 66.7 percent silicon dioxide. The samples have been subjected to extreme shock and thermal metamorphism. The parent materials of the microbreccias include both a coarse-grained anorthosite and a fine-grained subophitic anorthositic gabbro.*

Breccia 63335 was collected from Shadow Rock, a 5-m boulder at station 13 on the Cayley Plains of the lunar highlands. The collection site of 60017 is known with less certainty, although it too was probably collected from Shadow Rock (*1*). Thin sections 60017,4 and 63335,14 (shown in Fig. 1, a and b) were studied by using the petrographic microscope and the electron microprobe. Although no complete mineral analyses are presented in this paper, they are available from the authors on request.

60017. Sample 60017,4 consists of two distinct lithologies. One corner of the section (Fig. 1a) consists of a light gray devitrified anorthositic glass, while the rest of the section consists of a darker gray microbreccia. It is impossible to determine from this particular thin section whether either of these lithologies is incorporated within the other.

The devitrified anorthositic glass contains variolitic plagioclase with 93 to 95 mole percent anorthite ($An_{93\text{-}95}$), which decreases in grain size from the outer edge of the section inward toward the contact with the microbreccia. In addition, the glass contains interstitial olivine with 68 mole percent forsterite (Fo_{68}), ilmenite, and metallic iron.

The microbreccia is composed primarily of well-rounded anorthositic gabbro clasts, mosaically recrystallized

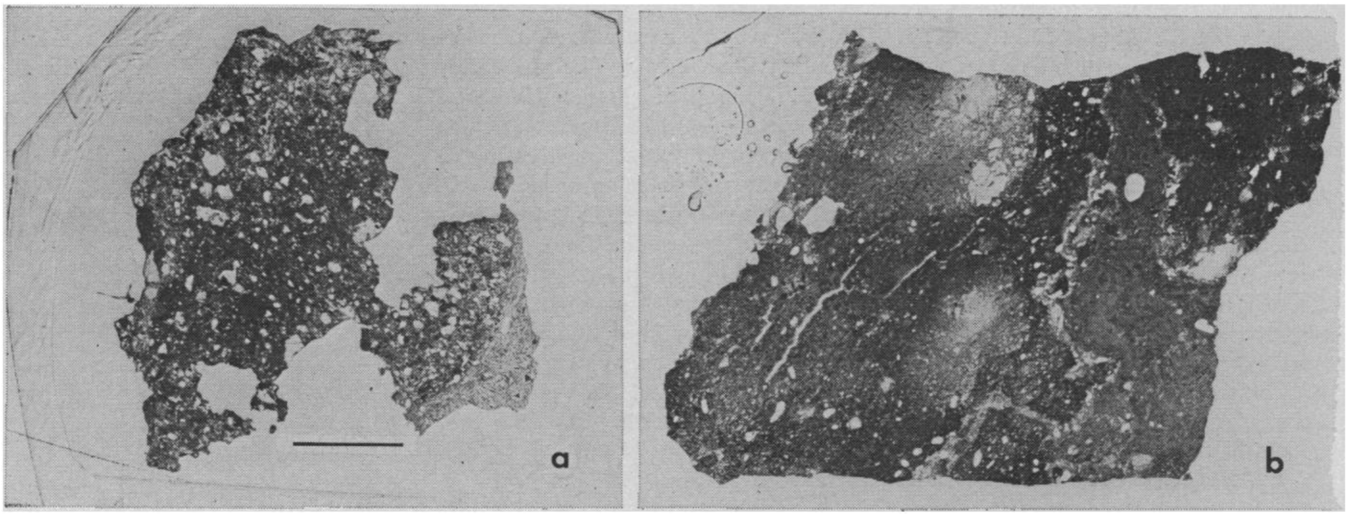

Fig. 1. (a) Photomicrograph of sample 60017,4. The section consists primarily of microbreccia with an area of devitrified anorthositic glass in the lower right corner. Scale bar, 2.5 mm. (b) Photomicrograph of sample 63335,14 [same scale as (a)]. The section consists primarily of microbreccia, which is transected from top to lower right by a vein of devitrified anorthositic glass. The recrystallized nature of the microbreccia matrix is most readily apparent in the upper left.

anorthosite clasts (possibly devitrified diaplectic glass), and rare crystal clasts, largely olivine, set in a cryptocrystalline matrix. The bulk composition of the matrix, based on defocused beam analyses, is that of gabbroic anorthosite (Table 1, A). A least-squares mixing calculation (*2*) provides an excellent fit for the bulk chemical composition of the microbreccia matrix with a mixture of 35 percent of the anorthositic gabbro clasts (Table 1, B) and 65 percent of the recrystallized anorthosite fragments (An_{94-96}) found in sample 60017.

The anorthositic gabbro clasts included in the microbreccia are well rounded, subophitic in texture (Fig. 2), and reach a maximum diameter of about 300 μm. Frequently they have a thin rim, which is fine grained and dark in color and is clearly the product of reaction of the clasts with the matrix (Fig. 2). The clasts are composed primarily of small (5 by 20 μm) plagioclase laths (An_{95}), interstitial olivine (Fo_{62-74}), and fine-grained mesostasis. Accessory minerals include ilmenite, iron metal, and troilite. Fifty ferromagnesian grains from the anorthositic gabbro clasts were analyzed in the course of this investigation, and no pyroxenes were found. Hence, if pyroxene is present, it is extremely fine grained (less than 2 μm).

The average bulk composition of the anorthositic gabbro clasts is given in Table 1, B, along with the compositions of an Apollo 12 mare type basalt (*3*), a Fra Mauro type basalt (*4*), the proposed "highland basalt" of Reid *et al.* (*5*), anorthosite 15415 (*6*), and gabbroic anorthosite 15418 (*6*) for comparison. The anorthositic gabbro in 60017 is much richer in normative anorthite than the mare basalts, and

Table 1. Compositions of Apollo 16 samples 60017 and 63335 and of other lunar materials. Samples 60017 and 63335 were analyzed by defocused beam microprobe; all compositions are given as percent by weight. The samples are: (A) Matrix of the microbreccia in 60017 (average of eight 50-μm spots); (B) gabbroic anorthosite clasts from the microbreccia in 60017 (average of 19 50-μm spots); (C) matrix of the microbreccia in 63335 (average of six 50-μm spots); (D) spherulitic devitrified glass in 63335 (average of two 50-μm spots); (E) Apollo 12 mare basalt (*4*); (F) Fra Mauro basalt (*5*); (G) proposed highland basalt (*6*); (H) anorthosite 15415 (*8*); (I) gabbroic anorthosite 15418 (*8*); (J) cryptocrystalline portion of potassium-rich clast from the microbreccia in 60017 (average of six 20-μm spots) (includes 2.4 percent corundum).

Component	A	B	C	D	E	F	G	H	I	J
SiO_2	45.69	45.94	45.63	46.23	45.0	46.82	44.35	44.08	44.97	66.71
TiO_2	0.22	1.07	1.34	1.38	2.9	2.33	0.43	0.02	0.27	0.09
Al_2O_3	31.16	22.92	26.91	30.60	8.6	13.81	27.96	35.49	26.73	19.61
FeO	3.26	9.17	6.66	3.43	21.0	15.92	5.05	0.23	5.37	0.29
MgO	2.39	6.37	3.10	1.46	11.6	6.30	6.86	0.09	5.38	0.07
CaO	17.42	14.03	15.43	17.18	9.4	11.57	15.64	19.68	16.10	5.77
Na_2O	0.03	0.76	0.83	0.75	0.2	0.80	0.19	0.34	0.31	2.49
K_2O	0.43	0.05	0.10	0.08	Trace	0.25	0.01	< 0.01	0.03	2.74
P_2O_5	0.02	0.06	0.06	0.04		0.25		0.01	0.03	
Total	100.62	100.37	100.06	101.2	99.3	98.52	100.57	99.95	99.37	97.75
				Molecular (one cation) norms						
Apatite	< 0.1	0.1	0.1	0.1		0.6		< 0.1	0.1	
Ilmenite	0.3	1.5	1.8	1.9	4.2	3.4	0.6	< 0.1	0.4	0.1
Orthoclase	0.2	0.3	0.6	0.5		1.6	0.1	0.1	0.2	16.7
Albite	3.8	6.9	7.6	6.7	1.9	7.5	1.7	3.1	2.8	23.1
Anorthite	82.7	59.2	70.1	79.6	23.6	34.8	74.5	95.3	72.1	29.5
Quartz	0.4			1.8		0.8		0.1		27.8
Wollastonite	1.3	4.1	2.7	2.0	10.1	9.6	0.9	0.9	3.3	
Enstatite	6.6	11.8	8.3	4.0	26.2	18.3	8.2	0.2	10.3	0.2
Ferrosilite	4.7	8.5	8.2	3.4	22.9	22.3	3.1	0.3	5.5	0.3
Forsterite		4.4	0.3		5.5		7.9		3.5	
Fayalite		3.2	0.3		4.8		3.0		1.9	

more closely resembles the proposed highland basalt and the gabbroic anorthosite 15418. In the report of the Preliminary Examination Team (PET) on the Apollo 16 rocks (*7*), rock 60017 has been classified as a type 4 rock: a partially molten breccia. It has been suggested that the anorthositic gabbro clasts may be a product of partial melting (*8*). Although origin by partial melting remains a possibility, we feel that the discrete nature of the areas of anorthositic gabbro favors a clastic origin for this material in 60017,4.

Virtually all the anorthosite clasts contained within the microbreccia exhibit mosaic recrystallization, indicating that they have been subjected to severe shock metamorphism (*9*). The presence of unshocked plagioclase in the anorthositic gabbro clasts, which are also contained within the microbreccia, implies that the mosaic anorthosite clasts must have been shocked before their incorporation in the microbreccia. It is impossible to determine whether the mosaically recrystallized anorthosite clasts were originally single plagioclase grains or polycrystalline fragments. These anorthosite clasts, which appear as light gray patches in the dark microbreccia in Figs. 1a and 2, show no significant variation in composition ($An_{94\text{-}96}$) either within individual clasts or from one clast to another. Usually the boundaries of the anorthosite clasts are well defined. However, some of the clast boundaries are very indistinct, and the clasts appear to grade into the matrix. In some cases, small fragments of anorthositic gabbro are partially enclosed in the mosaically recrystallized anorthosite clasts. A possible explanation of these textural relationships is that some of the anorthosite "clasts" may have grown during an episode of thermal metamorphism, and that some of the metamorphic overgrowths may have partially surrounded the anorthositic gabbro clasts.

63335. The bulk of the thin section 63335,14 consists of a dark gray microbreccia, which is cut by a vein of light gray devitrified glass. The microbreccia, comprising about 75 percent of the section, contains several types of clasts, including anorthosite, plagioclase, and gabbroic anorthosite. It also contains a few small (less than 30 μm) fragments of olivine, ilmenite, troilite, and iron metal, all of which are set in a cryptocrystalline matrix. The proportion of matrix to crystal and lithic clasts is very high (about 80 percent). The bulk composition of the matrix (Table 1, C) is that of a gabbroic anorthosite. This composition is similar to that given in the PET report for a 250-mg sample of the same rock [table 1 in (*7*)].

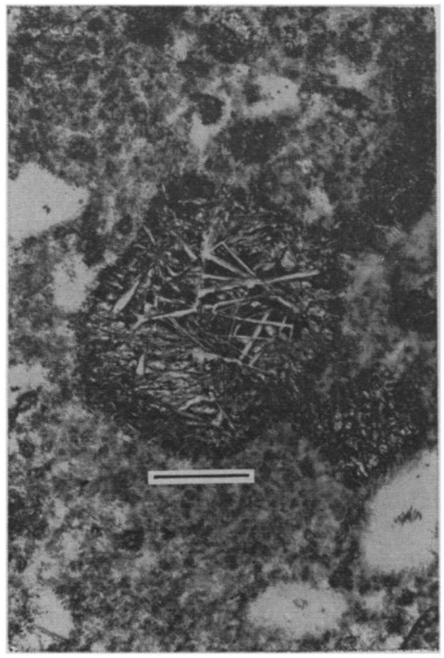

Fig. 2. Photomicrograph of a gabbroic anorthosite clast in the microbreccia portion of 60017,4, showing the reaction rim. The white areas are the mosaically recrystallized anorthosite, and the mottled gray areas the cryptocrystalline matrix. Scale bar, 100 μm.

Dark dendritic laths about 30 μm in width (see the upper left portion of Fig. 1b) appear to have crystallized from the matrix. The crystals have a high index of refraction, and are probably olivine or pyroxene, but the dendritic arms are too fine to permit probe analysis or optical identification. The growth of these dendritic crystals indicates that the microbreccia underwent an episode of extreme thermal metamorphism.

Two large, coarse-grained (1 to 2 mm) anorthosite clasts ($An_{93\text{-}97}$) are included within the microbreccia. They are located in the centers of the top and right edges of the section (Fig. 1b). Although they appear slightly shocked, these clasts do not show the extreme mosaic recrystallization displayed by the anorthosite clasts in 60017. The anorthosite clasts in 63335 are heavily fractured, and appear to have been abraded at their margins, with seams of microbreccia matrix frequently separating the broken fragments. The presence of large anorthite fragments within these clasts indicates that a coarse-grained anorthosite was among the parent materials of microbreccia 63335.

A single clast of gabbroic anorthosite (located just to the left of the anorthosite fragment along the right edge of the thin section, Fig. 1b) is included within the microbreccia portion of 63335. The clast is granular in texture, consisting of equant grains of anorthite (An_{95}) and normally zoned olivine ($Fo_{72\text{-}85}$).

Numerous small (50 to 100 μm) clasts of plagioclase within the microbreccia appear to have reacted strongly with the matrix. In some cases, the plagioclase fragments are partially embayed, and the embayments filled with cryptocrystalline matrix. In other cases, several neighboring fragments of plagioclase are in optical continuity, even though separated by bands of matrix. The origin of this texture is not clear. It is possible that the matrix selectively replaced portions of the plagioclase grains during the thermal metamorphic event. Perhaps severely shock-damaged domains underwent replacement reaction more readily than less damaged domains within the same grain.

Several plagioclase-rich areas with indistinct boundaries are present in the dark microbreccia of 63335. These areas may represent resorbed clasts, again suggesting severe thermal metamorphism.

A single highly vesicular, largely cryptocrystalline clast, about 400 μm in diameter, which contains 2.7 percent K_2O and 66.7 percent SiO_2 (Table 1, J), is present in the microbreccia portion of 63335,14. This clast contains a 200-μm subhedral grain of silica (polymorph unknown). The cryptocrystalline portion of the clast is richer in K and Si than KREEP (*10*), but poorer in these elements than the potassium microgranite found in microbreccia 14321 (*4*) and the granitic component of 12013 (*11*).

The light gray vein of devitrified glass cutting across the microbreccia portion of 63335,14 (Fig. 1b) is spherulitic near the top of the section and grades to variolitic near the bottom. It is composed primarily of elongate plagioclase laths (An_{95}), with minor interstitial olivine. The bulk composition of the spherulitic portion is that of gabbroic anorthosite (Table 1, D).

Samples 60017,4 and 63335,14 are similar in several respects. Both samples are composed predominantly of microbreccia and devitrified anorthositic glass. The areas of devitrified glass from the two samples are mineralogically very similar and may share a common 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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References and Notes

1. Apollo Lunar Geology Investigation Team, *Interagency Report: Astrogeology 51* (open-file report, U.S. Geological Survey, Washington, D.C., 1972).
2. W. B. Bryan, L. W. Finger, F. Chayes, *Science* **163**, 926 (1969).
3. R. Brett, P. Butler, Jr., C. Meyer, Jr., A. M. Reid, H. Takeda, R. Williams, *Geochim. Cosmochim. Acta* **1** (Suppl. 2), 301 (1971).
4. R. Grieve, G. McKay, H. Smith, D. Weill, S. McCallum, in *Lunar Science III*, C. Watkins, Ed. (Contribution No. 88, Lunar Science Institute, Houston, Texas, 1972), p. 338.
5. A. M. Reid, J. Warner, W. I. Ridley, R. W. Brown, *Geochim. Cosmochim. Acta*, in press.
6. Apollo 15 Preliminary Examination Team, *Science* **175**, 363 (1972).
7. Apollo 16 Preliminary Examination Team, *ibid.* **179**, 23 (1973).
8. J. Warner, personal communication.
9. N. M. Short, *Icarus* **13**, 383 (1970).
10. C. Meyer, Jr., R. Brett, N. H. Hubbard, D. A. Morrison, D. S. McKay, F. K. Aitken, H. Takeda, E. Schonfeld, *Geochim. Cosmochim. Acta* **1** (Suppl. 2), 393 (1971).
11. M. J. Drake, I. S. McCallum, G. A. McKay, D. F. Weill, *Earth Planet. Sci. Lett.* **9**, 103 (1970).
12. S. J. Kridelbaugh, R. A. F. Grieve, D. F. Weill, in *The Apollo 15 Lunar Samples*, J. Chamberlain and C. Watkins, Eds. (Lunar Science Institute, Houston, 1972), p. 123.
13. We thank A. R. Duncan, whose constructive criticism greatly improved this manuscript. Supported by NASA grants NGL 38-003-022 and NGL 38-003-020.

11 September 1972

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-

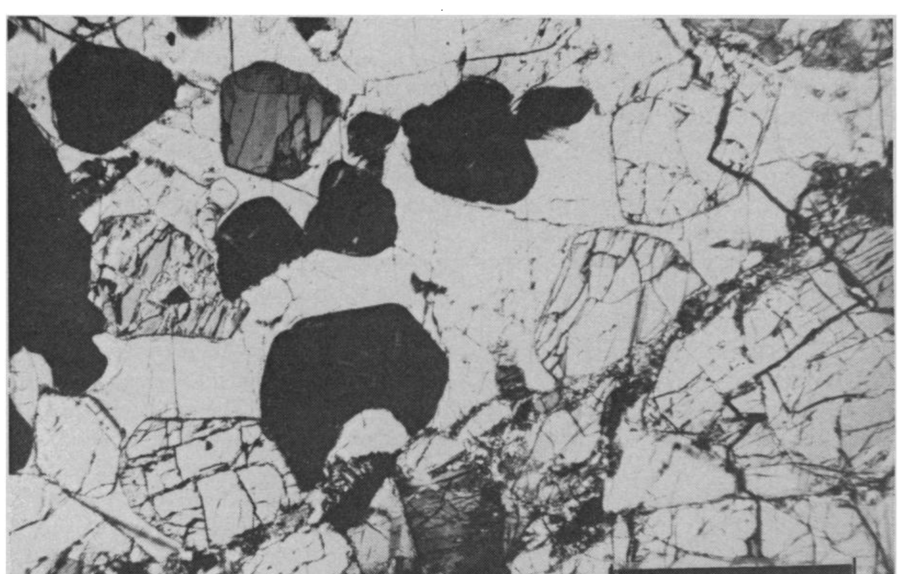

Fig. 1. Photomicrograph, with crossed polarizers, of a portion of the spinel troctolite lithic fragment in Apollo 16 microbreccia 67435,14. Subhedral crystals of spinel (black, in the center) and subhedral olivine (light to dark, in high relief) are poikilitically enclosed within a large single crystal 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.