American Mineralogist, Volume 60, pages 1086–1091, 1975

Mineralogy of Lunar Norite 78235; Second Lunar Occurrence of $P2_1ca$ Pyroxene from Apollo 17 Soils

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Abstract

Thin section 78235,40 is a coarse (1–2 mm), highly-shocked norite composed of ~30 percent low-Ca pyroxene (En 78 Fs 19 Wo 3), ~55 percent Ca-rich plagioclase ($An_{93}Ab_6$, mol %; Fe = 0.04–0.09, Mg = 0.05–0.08, K = 0.08 wt %), 15 percent glass and traces of an SiO_2 mineral, Ca-rich pyroxene (En 50, Fs 7, Wo 43), Fe-metal (Co ~ 1.6, Ni ~ 1.7 wt %), troilite, Cl-apatite, REE-whitlockite, baddeleyite, chromite, and Nb-rutile (Nb-10.7 wt %). The numerous glass veins with vesicles result from shock melting of the norite. Layering is apparent and may result from a cumulate origin, and/or shock deformation. Re-examination of low-Ca pyroxene from coarse pyroxene-plagioclase fragments from Station 8 soils shows the second lunar occurrence of $P2_1ca$ symmetry, and it is inferred that 78235 pyroxene has this symmetry based on similarities between the two samples. This and the coarse grain size indicate a plutonic origin for 78235.

The 78235 pyroxene is the most magnesian of noritic pyroxenes from the moon, implying that it may result from early lunar differentiation. Noritic breccias are considered to be mixtures because they do not correspond to mineralogies of inferred plutonic norites such as 78235.

Introduction

The noritic character of many lunar breccias and glasses was first recognized during the study of Apollo 11 and 12 samples (*e.g.*, Prinz, Bunch, and Keil, 1971; Wood, 1972), but these and later missions returned no samples with preservation of primary texture. Thus all inferences regarding the detailed chemistry of the primary norite have been based on data from breccias or glasses which may actually be mixtures of components each having different chemistries. Metamorphism, which has affected most lunar samples, may have altered the chemistry of individual phases or possibly the bulk composition of these breccias.

It was hoped that norite samples would be found with primary texture and chemistry to test petrogenetic relationships between lunar rock types. Two recent studies reported at least partial preservation of texture. Marvin and Stoeser (1974) observed norite clasts in breccia 72255 with an estimated original grain-size of 1–2 mm. They suggested that such norites were parental to numerous large clasts of orthopyroxene and plagioclase found elsewhere in this breccia. Irving, Steele, and Smith (1974) suggested that large (1–2 mm) orthopyroxene grains with attached plagioclase and diopside veins in Apollo 17 soils represented a coarse-grained noritic precursor, but textural evidence was poor. They also suggested that rock 78235, which was described as a coarse (1–5 mm) plagioclase—(?) orthopyroxene rock (LSPET, 1973), might be a parental norite. A thin section of this rock was examined optically and with the electron-microprobe, and indeed 78235 is a coarse norite, but highly shocked.

Thin Section 78235,40

Thin-section 78235,40 (~0.9 cm²) is light-colored with several buff to very dark glass veins less than 1 mm wide (Fig. 1). In polarized light all minerals show shock effects, mostly as wavy extinction, but also as fracturing.

Regions of plagioclase composition up to 1.5 mm wide (dark areas, Fig. 1) comprise about 55 percent of the section. Many areas appear isotropic but wavy extinction is most common; no good extinction was observed. Analysis of eight plagioclase areas showed a uniform composition of An 93 Ab 6 (mole percent) with Fe 0.04–0.09, Mg 0.05–0.08, and K–0.08 wt percent. This composition falls within the range reported for other plagioclase-rich rocks (Steele and Smith, 1973). The uniformity in composition suggests that

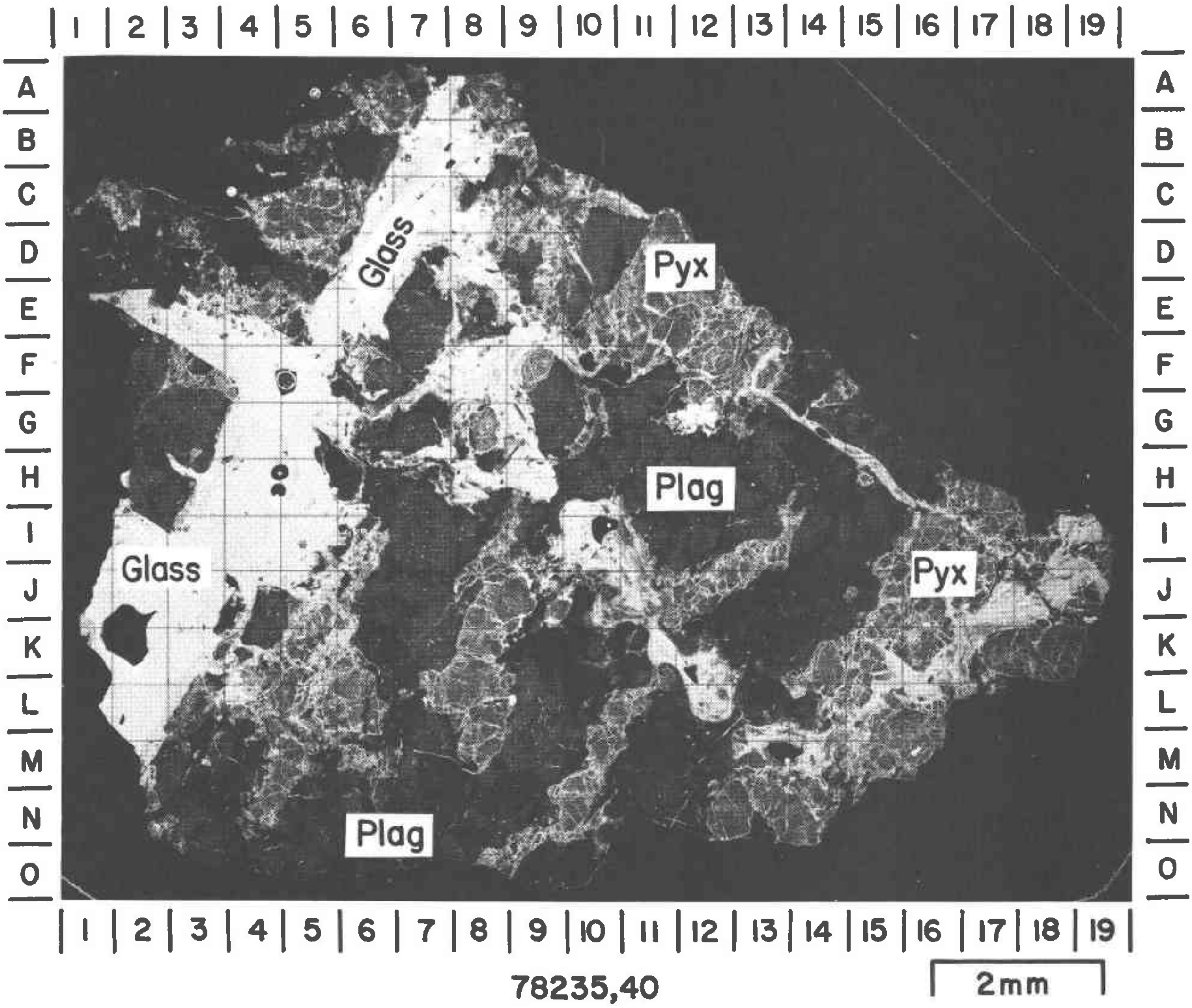

FIG. 1. Plain-light photograph (negative) of 78235,40. Dark, glass veins appear as white, plagioclase appears dark gray, and low-Ca pyroxene light gray (see labels).

the isotropic material is maskelynite glass uncontaminated by other components.

Low-Ca pyroxene up to 2 mm across (gray areas, high relief, Fig. 1) comprises about 30 percent. Most grains show poor extinction and fractures, while a few show no extinction. Analyses for low-Ca pyroxene (Table 1, nos. 1–3) are essentially identical for major elements (En 78, Fs 19, Wo 3), but TiO_2, Al_2O_3, and CaO vary. No exsolution features were observed either optically or with the electron probe. Although the texture is severely modified, some pyroxene grains appear to preserve sharp, curved boundaries with other pyroxene grains (Fig. 2a) which may represent a pre-shock texture.

Glass veins (white to light gray, Fig. 1) comprise the remaining 15 percent. Their color varies greatly, producing streaks parallel to the length of the larger veins. The lighter-colored narrow veins appear to associate with pyroxene while the darker glass forms the larger veins, but this may not be a general correlation. Analyses, like color, are highly variable. The *mg* (= Mg/(Mg + Fe) atom ratio) of averaged analyses of three areas (Table 1: analyses 6–8) range from 0.77 to 0.83, which brackets that of the low-Ca pyroxene in the section (0.81). Minor element concentrations are less than those of the pyroxene and roughly proportional to the absolute MgO and FeO content, suggesting that the glass is a simple shock melt of a portion of the norite. The dark glass based on analysis 6, Table 1, contains a higher percentage of

TABLE 1. Pyroxene and Glass Analyses from Thin Section 78235,40*

Analysis #	1	2	3	4	5	6	7	8
Coordinates	C-11	L-6	E-12	G-12	G-12	L-2	I-10	J-17
Type	Opx	Opx	Opx	Augite	Augite	Dark Glass	Light Glass	Light Glass
SiO_2	54.8	54.8	54.5	52.4	52.3	48.8	47.0	47.0
TiO_2	0.71	0.49	0.44	0.98	0.46	0.26	0.16	0.17
Al_2O_3	0.98	0.87	1.14	0.95	0.68	18.8	27.6	25.9
Cr_2O_3	0.59	0.65	0.58	0.49	0.31	0.34	0.14	0.22
FeO	12.7	12.3	12.8	4.73	5.42	7.32	2.06	4.72
MgO	29.5	29.7	30.1	18.1	18.2	13.9	5.81	8.92
CaO	1.61	1.32	1.59	22.0	22.3	10.8	15.9	13.1
	100.9	100.1	101.1	99.6	99.7	100.2	98.7	100.0
Cations based on 6 Oxygens								
Si	1.940	1.935	1.928	1.926	1.933			
Ti	0.019	0.014	0.012	0.027	0.013			
Al	0.041	0.037	0.047	0.041	0.029			
Cr	0.017	0.019	0.017	0.014	0.009			
Fe	0.377	0.373	0.379	0.146	0.167			
Mg	1.558	1.597	1.586	0.994	1.001			
Ca	0.061	0.051	0.060	0.869	0.882			
En(%)	78.1	79.0	78.3	49.5	48.8			
Fs	18.9	18.5	18.7	7.3	8.2			
Wo	3.0	2.5	3.0	43.2	43.0			
mg	0.805	0.810	0.807	0.871	0.856	0.772	0.834	0.771

* *Coordinates of analyses refer to Figure 1.*

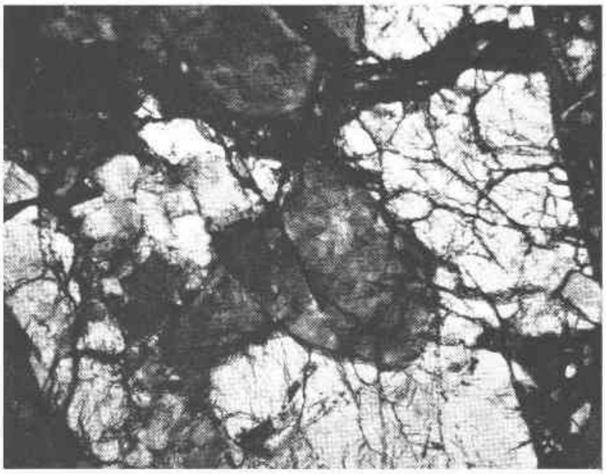

FIG. 2a. Textural relationship of pyroxene grains. Note curved boundaries which may represent primary texture (max. dimension = 2 mm).

pyroxene component or composition than the light glass (analyses 7 and 8) and more closely represents the bulk composition of the crystalline portion of this section. Numerous vesicles (coordinates G-14, K-2, I-10, F-5) and mineral fragments (coordinates G-8, E-8) occur within the glass veins, indicating formation in a low pressure environment—possibly on the lunar surface.

The coarse texture indicated above is unusual for lunar samples. Close examination of Figure 1 indicates a number of linear features. First, the glass veins at the left appear to form two perpendicular trends and probably result from melting along conjugate fracture surfaces formed during shock (see Wilshire and Moore, 1974, for other examples). Second, the pyroxene areas tend to be elongated from northeast to southwest; this was also noted on a macroscopic scale (LSPET, 1973) and interpreted as a cumulate texture. Although this last interpretation may be correct, the texture may result at least in part from shock deformation.

Although the three phases described above constitute about 99 percent of the thin section, one small area (coordinates G-12, Fig 1) contains nine other phases (Fig. 2b). A silica phase, Fe-metal (Co = 1.4–1.7, Ni = 1.6–1.8 wt %), and troilite form large (~0.2 mm) discrete grains. Three phases are intimately intergrown in the remaining area (Figs. 2c and d): they are apatite (CaO = 54.1, P_2O_5 = 40.2, MgO = 0.7 wt percent, Cl detected), whitlockite (CaO = 42.6, P_2O_5 = 43.5, MgO = 3.4 wt percent, REE detected), and augite (analyses 4–5, Table 1) in approximately equal amounts. One small grain of baddeleyite, several of Nb-rutile (Nb_2O_5 = 14.0%, Cr_2O_3 =5.7%, TiO_2 = 75.5%, + REE) and one grain of chromite (Cr_2O_3 = 58%, FeO = 25%, Al_2O_3 = 6.0%, MgO = 3.2%, TiO_2 = 1.3%) were recognized. The Nb content of the rutile is much higher than for other Nb-rutiles from the Moon (Hlava, Prinz, and

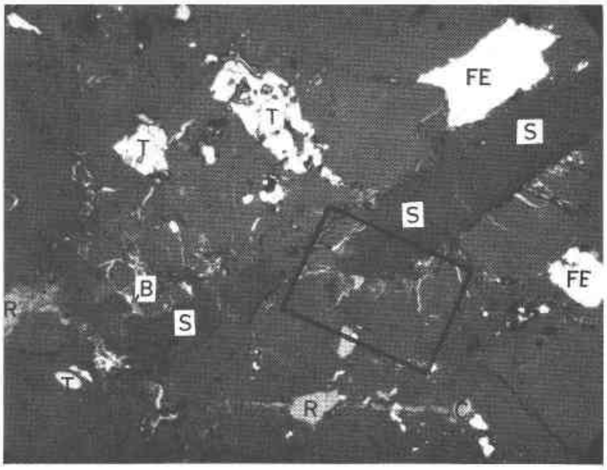

FIG. 2b. Reflected light photograph of minor phases in 78235,40 (Area G-12 on Fig. 1). Dark phase (s) = SiO_2, FE = iron metal, T = troilite, R = Nb-rutile, C = chromite, B = baddeleyite. Interstitial area is composed of apatite, whitlockite, and augite (max. dimension = 0.7 mm). Outlined rectangle shows area of Figures 2c and 2d.

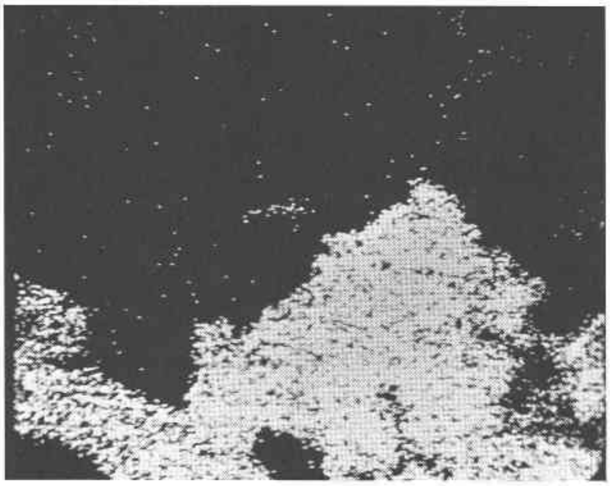

FIG. 2c. Scanning image of interstitial area of Figure 2b, using P$K\alpha$ radiation. Light area, phosphate; dark area, silica and augite (max. dimension = 0.2 mm).

Keil, 1972; Marvin, 1971). One other small grain of augite (coordinates E-12, Fig. 1), and several minute grains of troilite occur elsewhere in the section.

Re-examination of Apollo 17 Orthopyroxene Grains

Irving, Steele, and Smith (1974) reported chemical and X-ray data from pyroxene-plagioclase fragments collected at Station 8. Because Smyth (1974) reported a previously unrecognized orthopyroxene space group in lunar sample 76535, a re-examination of the Station 8 orthopyroxene grains was carried out. Indeed, on long exposure *a*-axis precession photographs, violations of the *b* glide were observed (violations include diffractions *014, 015, 031, 032, 071, 072*) and the true space group is $P2_1ca$ rather than *Pbca* reported by Irving *et al* (1974).

Discussion A: Comparison with Other Noritic Rocks

Several reasons strongly suggest that rock 78235 and the norite fragments described by Irving *et al* (1974) have the same origin: (1) both were collected at station eight within 50 meters of each other (ALGIT, 1973); (2) major element chemistry of both pyroxene and plagioclase are almost identical; (3) several minor phases (augite, chromite, iron, troilite, silica) occur in both samples, and these phases have similar chemistry—especially the chromite. Differences between the two samples include: (1) minor element concentration, especially TiO_2, in the pyroxenes; however, within either sample type the variation is large and there is usually overlap in the ranges; (2) several minor phases (baddeleyite, Nb-rutile, phosphates) were not observed within the single grains, but because of the large difference in sample size, all minor phases may not have been sampled; (3) sample 78235 showed numerous shock features while the single grains showed none; this may simply indicate that the shock features occurred after separation of the two samples. Direct confirmation of pyroxene symmetry probably is not possible because of shock effects; it is assumed, based on the above similarities between 78235 and pyroxene grains from soils, that 78235 pyroxene had $P2_1ca$ symmetry.

Noritic breccias are common in returned samples (*e.g.*, Wood, 1972; Powell and Weiblen, 1972), but few, if any, represent the bimineralic character, homogeneity, and chemistry of 78235. Keeping in mind the impact nature of the lunar surface, the evidence for metamorphism (Albee, Gancarz, and Chodos, 1974b), and the petrologic and experimental evidence for partial melting (Walker *et al*, 1974), the lack of breccias with mineralogies equivalent to 78235 is easier to reconcile by concluding that the vast majority of lunar samples are reworked and do not represent primary materials. Therefore samples such as 78235 could represent one example of rare parental material for the common lunar samples, the rarity of which is most easily explained by difficulty in sampling unmodified material which occurs at depth.

The thermal history of 78235 is apparently quite different from the noritic breccias. Assuming that 78235 pyroxene has $P2_1ca$ symmetry, long annealing times (Smyth, 1974) are implied; other features of

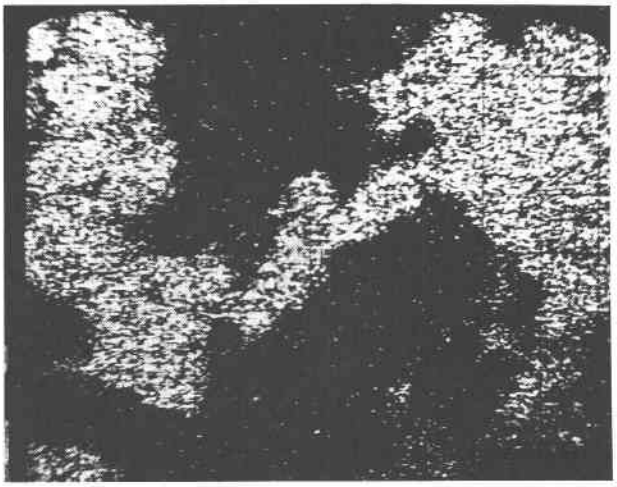

FIG. 2d. Scanning image of intersitial area of Figure 2b, using Mg$K\alpha$ radiation. Light area is augite. Area is same as Figure 2c.

78235 suggest plutonic conditions. Although crystallographic studies on other norites are not common, several studies have not recognized this new pyroxene symmetry in breccia or igneous rocks (Ghose, Ng, and Walter, 1972; Ghose, McCallum, and Tidy, 1973). Possibly this crystallographic feature is a general indication of rocks which formed under plutonic conditions; rocks modified by impacts have the conventional *Pbca* symmetry. Other postulated plutonic rocks (*e.g.*, dunite 72415, Albee *et al,* 1974a) should be checked for pyroxene symmetry.

Compositional data for low-Ca pyroxene from noritic rocks (*e.g.*, Powell and Weiblen, 1972; Floran *et al,* 1972; Cameron and Delano, 1973) and from random soil analyses (*e.g.*, Simkin *et al,* 1973) have a maximum enstatite component of about En 81 which is only slightly higher than in 78235. Exceptions have been reported (*e.g.*, Anderson 1973; Steele and Smith, 1972), but these are not noritic. This correspondence with the most-common Mg-rich composition may be only fortuitous, but in normal crystal-liquid differentiation the earliest crystallizing pyroxenes would be expected to be the most Mg-rich. In turn this suggests that of noritic samples, 78235 could represent the mineralogy of the earliest formed norites. It was argued above that most noritic samples probably represent samples altered by impact and that their chemistry reflects a mixture; possibly this mixture is with an early norite (cumulate) and the complementary more Fe-rich rocks. Alternatively, there could be a series of norites which, when mixed by impact, produce a range of noritic breccia or impact melts.

Discussion B: Origin of Minor Phases

The minor phases in 78235, in the norite grains of Irving *et al* (1974), and in norite clasts (Marvin and Stoeser, 1974) indicate that this material is common in norite. A similar mineralogy was noted by Gooley *et al* (1975) in troctolite 76535. Irving *et al* (1974) noted that an explanation of the origin is not simple, and invoked liquid or vapor intrusion to explain the observed veins. The occurrence in 78235 is not as vein structure, but rather as a localized area and evidence of intrusion is not present. What is more puzzling, however, is the textural relationship among the phosphates and the augite (Fig. 2b) which suggests co-crystallization because of the intimate, intergrown texture. There appears to be no relationship between the augite and the orthopyroxene, and the former cannot be attributed to exsolution. The presence of metallic iron and Mg-rich silicates suggests that the assemblage was highly reduced.

The minor mineralogy has strong KREEP affinities, being rich in P, REE, Nb, and Zr. Although K-rich phases are not present in 78235, K-Ba feldspar was recognized by Irving *et al* (1974). This assemblage cannot be considered as a sample of liquid from which the norite crystallized because of the extreme enrichment in normally trace elements; secondary growth of pyroxene and plagioclase from an intercumulus fluid may have concentrated these trace elements as suggested by McCallum *et al* (1975), or possibly metamorphism has remobilized a portion of the intercumulus material to form the minor assemblages. This occurrence does provide evidence of a KREEP-rich material existing with a cumulate as proposed by Prinz *et al* (1973). The ultimate source and mechanism of intrusion, however, is unknown.

Acknowledgments

NASA grant NGL-14-001-171. J. V. Smith and A. J. Irving offered many suggestions for improvement of this manuscript, and Mrs. I. Baltuska typed the many versions.

References

Albee, A. L., A. A. Chodos, R. F. Dymek, A. J. Gancarz, D. S. Goldman, D. A. Papanastassiou, and G. J. Wasserburg (1974a) Dunite from the lunar highlands: petrography, deformational history, Rb-Sr age. In, *Lunar Sci.* **5,** 3–5. The Lunar Science Institute, Houston.

———, A. J. Gancarz, and A. A. Chodos (1974b) Metamorphism of Apollo 16 and 17 and Luna 20 metaclastic rocks at about 3.95 AE: Samples 61156, 64423, 14-2, 65015, 67483, 15-2, 76055, 22006, and 22007. *Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4,* **1,** 509–595. MIT Press.

Algit (1973) Preliminary geologic investigation of the Apollo 17 landing site. Nasa sp-**330**.

Anderson, A. T. (1973) The texture and mineralogy of lunar peridotite, 15445,10. *J. Geol.* **81,** 219–226.

Cameron, K. L., and J. W. Delano (1973) Petrology of Apollo 15 consortium breccia 15465. *Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4,* **1,** 461–466. MIT Press.

Floran, R. J., K. L. Cameron, A. E. Bence, and J. J. Papike (1972) Apollo 14 breccia 14313: A mineralogic and petrologic report. *Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 3,* **1,** 661–671. MIT Press.

Ghose, S., G. Ng, and L. S. Walter (1972) Clinopyroxenes from Apollo 12 and 14: exsolution, domain structure, and cation order. *Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 3,* **1,** 507–531. MIT Press.

———, I. S. McCallum, and E. Tidy (1973) Luna 20 pyroxenes: exsolution and phase transformation as indicators of petrologic history. *Geochim. Cosmochim. Acta,* **37,** 831–839.

Gooley, R., R. Brett, J. Warner, and J. R. Smyth (1974) A lunar rock of deep crustal origin: sample 76535. *Geochim. Cosmochim. Acta,* **38,** 1329–1339.

HLAVA, P. F., M. PRINZ, AND K. KEIL (1972) Niobium rutile in an Apollo 14 KREEP fragment. *Meteoritics*, **7**, 479–485.

IRVING, A. J., I. M. STEELE, AND J. V. SMITH (1974) Lunar noritic fragments and associated diopside veins. *Am. Mineral.* **59**, 1062–1068.

LSPET (1973) Apollo 17 lunar samples: chemical and petrographic description. *Science*, **182**, 659–672.

MARVIN, U. B. (1971) Lunar niobian rutile. *Earth. Planet. Sci. Lett.* **11**, 7–9.

———, AND D. B. STOESER (1974) The civet cat clast, a new variety of lunar norite (abstr.). *Trans. Am. Geophys. Union*, **55**, 323.

MCCALLUM, I. S., E. A. MATHEZ, F. P. OKAMURA, AND S. GHOSE (1975) Petrology of noritic cumulates: samples 78235 and 78238. In, *Lunar Sci.* **6**, 534–536. The Lunar Science Institute, Houston.

POWELL, B. N., AND P. W. WEIBLEN (1972) Petrology and origin of lithic fragments in the Apollo 14 regolith. *Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 3*, **1**, 837–852. MIT Press.

PRINZ, M., T. E. BUNCH, AND K. KEIL (1971) Composition and origin of lithic fragments and glasses in Apollo 11 samples. *Contrib. Mineral. Petrol.* **32**, 211–230.

———, E. DOWTY, K. KEIL, AND T. E. BUNCH (1973) Mineralogy, petrology, and chemistry of lithic fragments from Luna 20 fines: origin of the cumulate ANT suite and its relationship to high-alumina and mare basalts. *Geochim. Cosmochim. Acta*, **37**, 979–1006.

SIMKIN, T., A. F. NOONAN, G. S. SWITZER, B. MASON, J. A. NELEN, AND W. G. MELSON (1973) Composition of Apollo 16 fines 60051, 60052, 64811, 64812, 67711, 67712, 68821, and 68822. *Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4*, **1**, 279–289, MIT Press.

SMYTH, J. R. (1974) Low orthopyroxene from a lunar deep crystal rock: A new pyroxene polymorph of space group *P*2₁*ca*. *Geophys. Res. Lett.* **1**, 27–29.

STEELE, I. M., AND J. V. SMITH (1972) Ultrabasic lunar samples. *Nature Phys. Sci.* **240**, 5–6.

———, AND ——— (1973) Compositional and X-ray data for Luna 20 feldspar. *Geochim. Cosmochim. Acta*, **37**, 1075–1077.

WALKER, D., J. LONGHI. T. L. GROVE, E. STOLPER, AND J. F. HAYES (1974) Experimental petrology and origin of rocks from the Descartes Highlands. *Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4*, **1**, 1013–1032. MIT Press.

WILSHIRE, H. G., AND H. J. MOORE (1974) Glass-coated lunar rock fragments. *J. Geol.* **82**, 403–417.

WOOD, J. A. (1972) Fragments of terra rock in the Apollo 12 soil samples and a structural model of the Moon. *Icarus*, **16**, 462–501.

Manuscript received, February 26, 1975; accepted for publication, May 21, 1975.