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Petrography and classification of Apollo 17 non-mare rocks with emphasis on samples from the Station 6 boulder

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Abstract—The Apollo 17 non-mare rock collection consists largely of polymict breccias lithified by impact. These rocks are characterized by a variety of types of lithic clasts, concentrations of siderophile elements that indicate substantial meteoritic contamination, and contents of metallic iron well above those of mare basalts. A small fraction of the non-mare collection consists of isolated rocks and lithic clasts that lack these characteristics and are potentially igneous or meta-igneous rocks derived from unknown depths in the lunar interior. The polymict, impact-lithified materials may be subdivided into two compositional groups, one with 70–80% feldspar and the other with 50–60% feldspar. The high-feldspar group includes two characteristic textures: (1) coarsely poikilitic and (2) granulitic. The low-feldspar group includes (1) fragmental breccias with the most diverse lithic clast populations of all breccias and (2) crystalline breccias with poikilitic and subophitic to micropoikilitic textures containing tabular feldspar, granular textures with anhedral feldspar, and clast-rich ophitic textures containing less euhedral feldspar. In the poikilitic and subophitic to micropoikilitic textures, the clast population is dominated by the high-feldspar lithologies and An_{94-97} plagioclase grains, characteristic of the more feldspathic group, indicating that these more refractory lithologies were abundant in the material from which the less feldspathic crystalline rocks formed.

INTRODUCTION

THE APOLLO 17 non-mare rocks consist of fragmental matrix breccias, crystalline matrix breccias, a small number of granulitic textured rocks and a very small number of samples that do not appear to have been formed by mechanical mixing during impact events. This paper presents a textural classification of thin sections from Apollo 17 rocks emphasizing the study of samples from the boulder at Station 6, but correlating the boulder lithologies with the non-mare rocks from the entire landing site. As in our other classifications of non-mare lithologies (Warner, 1972; Phinney *et al.*, 1972; Warner *et al.*, 1973; and Phinney *et al.*, in preparation) emphasis is placed on matrix texture and correlated variations in major element composition. Although mineral and lithic clast populations are discussed, they are not used for classification, but rather to complement the bulk chemical data in placing limits on the composition and textural state of the material from which the breccias formed. No attempt will be made to place the lithologies in their stratigraphic context.

The objective of the classification scheme presented below is to present a set of petrographic criteria for separating rocks with potentially different origins. One of the most critical problems in lunar highland petrogenesis is to identify those rocks which were formed by impact lithification of complex mixtures of debris, and to distinguish them from rocks which were formed by endogenic igneous processes. Most of the small number of rocks that were potentially chemically fractionated and lithified by nonimpact processes have been subsequently crushed and brecciated and incorporated as clasts into impact breccias. But these later events have apparently not disturbed the sample chemistry of such clasts. The following criteria are suggested to be useful in identifying the polymict rocks lithified by impact:

(1) The petrographic texture should consist of mineral and lithic clasts dispersed in a fine-grained matrix. The lithic clasts should be of more than one petrographic type, and some may display shock-induced features.

(2) Siderophile-element concentrations should be above those proposed to be characteristic of the primitive rocks (Morgan *et al.*, 1974). The excess siderophile elements are ascribed to chemical remnants of meteorites which have struck the moon.

(3) Metallic iron should be in excess of the amounts found in mare basalts (Pearce *et al.*, 1973).

These criteria provide circumstantial evidence that the rocks formed as the result of cratering and are presented more for definition than as positive indication of the source of the energy for lithification. The high concentrations of siderophile elements and metallic iron indicate that the rock was formed from meteorite contaminated, and chemically reduced material. The inference is made that this material was lithified by impact because no other reasonable energy sources for lithification have been suggested. Petrographic data on sufficiently large thin sections to identify a variety of clast types, measurements of siderophile-element concentrations, and determinations of metallic iron content are not available for all Apollo 17 non-mare materials. Therefore, the textures observed in thin sections of extensively studied samples will be used to correlate and tentatively extrapolate the criteria listed above to samples lacking part of the appropriate data. At present, little data on the metallic iron content of Apollo 17 samples has been published and this criterion cannot be adequately applied.

There are a few samples, for which data are available, in the Apollo 17 non-mare collection that fail to meet the three criteria listed above for being polymict rocks formed by impact. But even these few have been affected by impact as most are clasts in polymict breccias. They include: 72415, a dunite clast in a subophitic to micropoikilitic matrix with KREEP-like chemistry, described in detail by Albee *et al.* (1974b), however, siderophile-element data have not yet been published; 76535, a granulitic textured troctolite with evidence of an inferred high-pressure reaction, described by Gooley *et al.* (1974); the crushed norite ("Civet Cat") clast in 72255 and the pigeonite basalt clast in 72275 as described by Stoeser *et al.* (1974). The last is similar to the Apollo 15 basaltic-textured KREEP fragments described by Meyer *et al.* (1972) and Phinney *et al.* (1972). In addition, sample 78235 (LSPET, 1973a,b) appears to be an intensely shocked norite texturally similar to 76535. Sample 77215 (Chao *et al.*, 1974) is similar texturally and in major element chemistry to the "Civet Cat" clast. The number of samples, that are recognized to have formed potentially outside the realm of impact processes, will undoubtedly increase as study of the Apollo 17 collection continues, but the petrographic and chemical evidence presented below argues that most of the Apollo 17 non-mare rocks formed by impact processes.

The Classification

The first subdivision of our classification of rocks of inferred impact origin at Apollo 17 is based on plagioclase content. One group has 50–60% feldspar, and the other has 70–80% feldspar. There appears to be a general lack of rocks with 60–70% feldspar, and no impact lithified rocks with less than 50% or more than 80% feldspar. The two groups separated on the basis of the amount of modal feldspar are further subdivided on the basis of matrix texture. The classification system is the following:

Mineralogy	Clast-matrix relations	Matrix texture
70–80% feldspar	crystalline rocks lacking macroscopic clasts	granulitic poikilitic
50–60% feldspar	crystalline rocks, with abundant clasts (matrix supported breccias)	poikilitic micropoikilitic–subophitic–granular clast-rich ophitic
	fragmental rocks (clast supported breccias)	fragmental

The term poikilitic is used as a purely descriptive term, referring to the presence of relatively large grains enclosing smaller grains. Table 1 presents the assignment of the matrix of each individual rock to the above-listed categories.

Rocks with 70–80% feldspar

The modal mineralogy of rocks in this group is 70–80% anorthitic plagioclase (An_{94-97}), variable proportions of magnesian olivine and low-calcium pyroxene and much smaller amounts of augite. Fe–Ni metal is usually the dominant opaque phase with smaller amounts of ilmenite and/or armalcolite and spinel also present. All rocks in the 70–80% feldspar group have coarser textures (feldspar grain size is 25–500 μm) than rocks in the 50–60% feldspar group, and the feldspar morphology in the 70–80% feldspar group ranges from equant polygonal feldspar grains with 120° angles at triple junctions to nearly equant but blocky feldspar grains with rounded corners. These shapes and sizes contrast with the smaller (1–25 μm) tabular grains in the matrix of 50–60% feldspar group rocks. Pyroxene morphology allows subdivision of the more feldspathic group into those with a simple granulitic texture and those with poikilitic pyroxene.

Table 1. Textural classification of samples.

Sample	Al_2O_3 wt.%	K_2O wt.%	Textural classification	Matrix feldspar grain size μm	Matrix mafic grain size μm
72215			Fragmental breccia	<5	<5
72235			Fragmental breccia	<5	<5
72255	14.5	.27	Fragmental breccia	<5	<5
72275	17.9	.22	Fragmental breccia	<5	<5
72315	18.8*	.31*	Clast-rich ophitic	10–40	20–80
72335	27.3	.13	Granulitic	25–500	10–30, rare 100
72355	18.8*	.31*	Clast-rich ophitic	10–50	10–100
72395	18.8*	.31*	Clast-rich ophitic	10–80	10–100
72395	18.8*	.31*	Clast-rich ophitic	10–40	20–100
72415	1.53	.01	Crushed dunite		
72435	19.23	.23	Micropoikilitic	5–30	25–50
73215		.2	Granular	1–10	1–10
73235	21.28	.21	Subophitic	5–15	125 (oikocrysts)
73255		.19	Granular	1–10	1–10
73275	18.49	.27	Subophitic–micropoikilitic	10–50	10–100
76015	17.78	.26	Poikilitic	5–20	Pyx. <700
76055	16.47	.20	Subophitic–micropoikilitic	5–20	20–50
76215		.26	Poikilitic	5–20	Pyx. <1000
76235	27.01	.06	Poikilitic	20–80	Pyx. <600
76255		.35	Fragmental breccia	<10	<10
76275		.27	Subophitic	<10	<25
76295		.27	Subophitic	<15	10–25
76315	18.01	.27	Subophitic–micropoikilitic	10	25–30
76535	20.72	.03	Granulitic		
77017	26.59	.06	Poikilitic	40–400	Pyx. <1500
77035			Micropoikilitic	25–50	25–50
77075	18.17	.23	Subophitic	10	5–25
77115	19.6	.35	Subophitic	15	25–75
77135	18.01	.22	Poikilitic	25	Pyx. <750
77215	15.06	.14	Granulated norite		
78155	25.94	.08	Granulitic	30–150	5–25
78235		.049	Shocked-Coarse norite		
79215			Granulitic	25–100	10–30, rare 100

*Data presented as an average.

Granulitic texture. In rocks with granulitic texture the feldspar grains occur as equant polygons with a seriate size distribution over the range 25–150 μm. The much less abundant mafic minerals are confined to space at triple junctions between feldspar grains where the mafics occur as equant grains typically 10–30 μm across and rarely over 100 μm (Fig. 1a). The rocks lack any porosity and have a mosaic texture with many grains approximating regular poly-

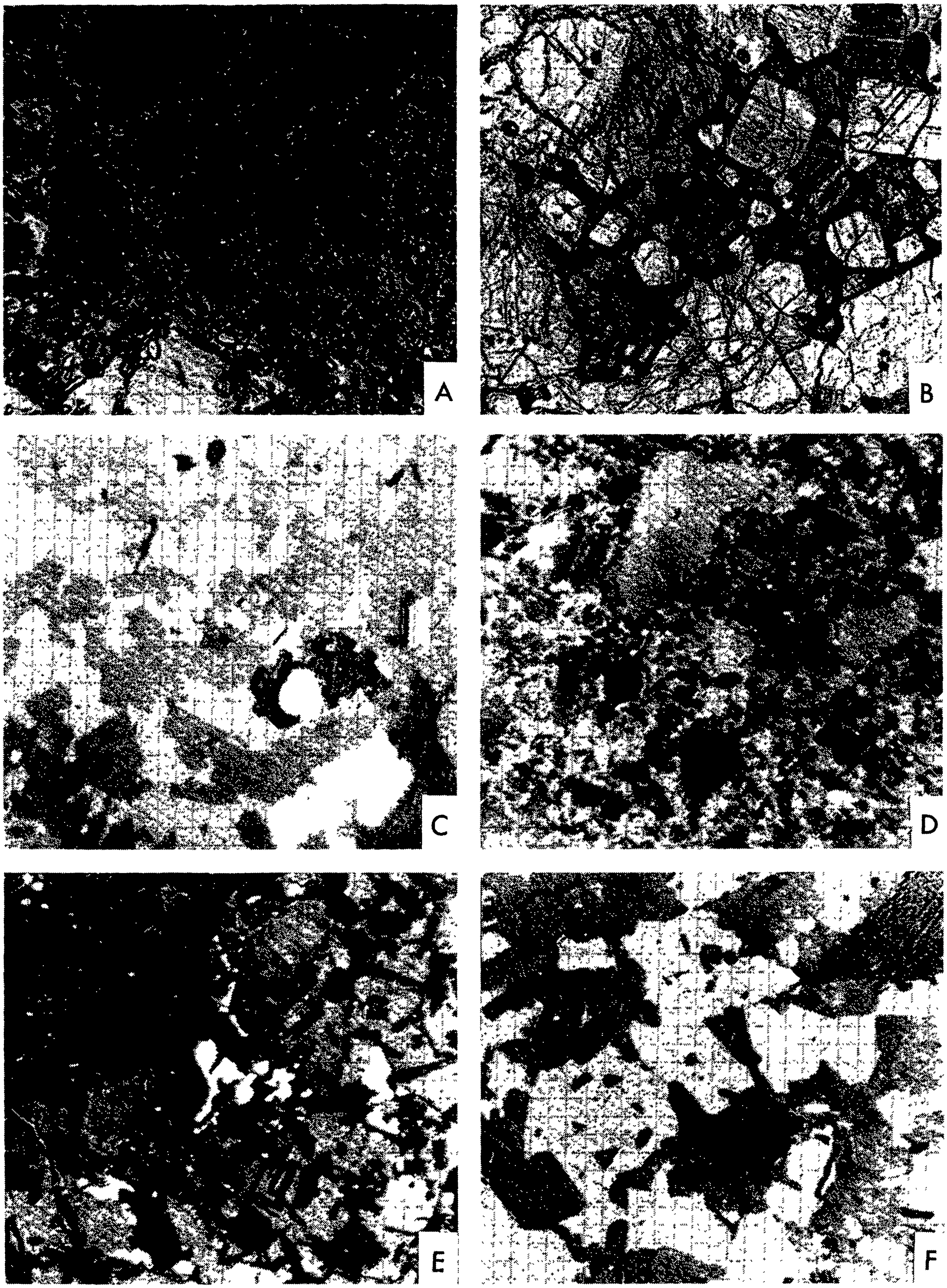

Fig. 1. Photomicrographs: (a) Granulitic sample 76315,14, field of view .67 mm; (b) poikilitic sample 77017,26, field 1.7 mm; (c) poikilitic 76215,12 field, .14 mm; (d) finest subophitic 73215,189, field .14 mm; (e) coarse micropoikilitic 72435,7, field .14 mm; (f) clast-rich ophitic 72355,4, field .14 mm.

gons in cross sections typical of textural equilibrium. Although mineral clasts are not obvious, they may be represented by the largest 5–10% of the feldspar grains and the much less abundant large mafic grains. There is no textural evidence that any of these rocks are polymict breccias; however, the extensive recrystallization responsible for the high-grade metamorphic texture might effectively obscure the recognition of most lithic clasts. Analyzed rocks of this group have high-siderophile contents suggesting meteoritic contamination (Morgan *et al.*, 1974).

This textural group is represented in the Station 6 boulder by a white rind, either a thin edge of a clast or a vein, along one face of 76315. This rind contains plagioclase (An_{93-97}) (Fig. 2), orthopyroxene ($Wo_{2-4}En_{80-83}Fs_{16-18}$), augite ($Wo_{37-43}En_{47-52}Fs_{8-11}$) and olivine ($Fo_{80-82}$) (Fig. 3). The restricted compositional range of all phases is as expected for well-annealed rocks. Microprobe data suggest that the cores of coarser feldspar grains (possible clasts) are 1% more anorthitic than the smaller feldspars (Fig. 2), but that observation is at the limit of analytical precision.

Poikilitic texture. High-feldspar group rocks with poikilitic texture are characterized by relatively large but isolated pyroxene grains enclosing much smaller grains of plagioclase known as chadacrysts. The pyroxene oikocrysts are completely surrounded by equant polygonal feldspar grains and do not touch one another (Fig. 1b). The texture is coarser and the feldspar more abundant than in the poikilitic rocks from both Apollo 16 (Simonds *et al.*, 1973; Albee *et al.*, 1973; Bence *et al.*, 1973; Crawford 1974) and the 50–60% feldspar poikilitic group from Apollo 17.

Although this lithology and the granulitic variety commonly occur as clasts, the matrices of two individual large samples, 76235 and 77017, fall in this group. Sample 76235 was collected from a clast in a subophitic–micropoikilitic 50–60% modal feldspar unit in the Station 6 boulder (Heiken *et al.*, 1973). Sample 77017 is described in some detail by Helz and Appleman (1974), who note a complex history of brecciation and veining after formation of the poikilitic matrix. The pyroxene oikocrysts in the large rocks and clasts are typically round to prismatic forms, 600–1500 μm in the maximum dimension. The feldspar has a narrow range in composition (An_{94-97}) (Fig. 2: 76230; and 76315 white clast) as does the olivine (Fo_{74-77}) and pyroxene ($Wo_4En_{75}Fs_{21}$ and $Wo_{3-6}En_{73-75}Fs_{19-21}$) (Fig. 3). Olivine occurs both within pyroxene oikocrysts (as in 77017) and as <40 μm isolated blebs at the triple junctions between the coarser (up to 400 μm) polygonal to tabular feldspar grains that occur between oikocrysts. The largest 5–10% of feldspar and pyroxene grains outside the oikocrysts are the only features that could be called clasts or xenoliths, and as with the granulitic rocks, the cores of the largest feldspars are 1% more anorthitic than the cores of the smaller grains (Fig. 2: 76315 white rind). These rocks lack any porosity.

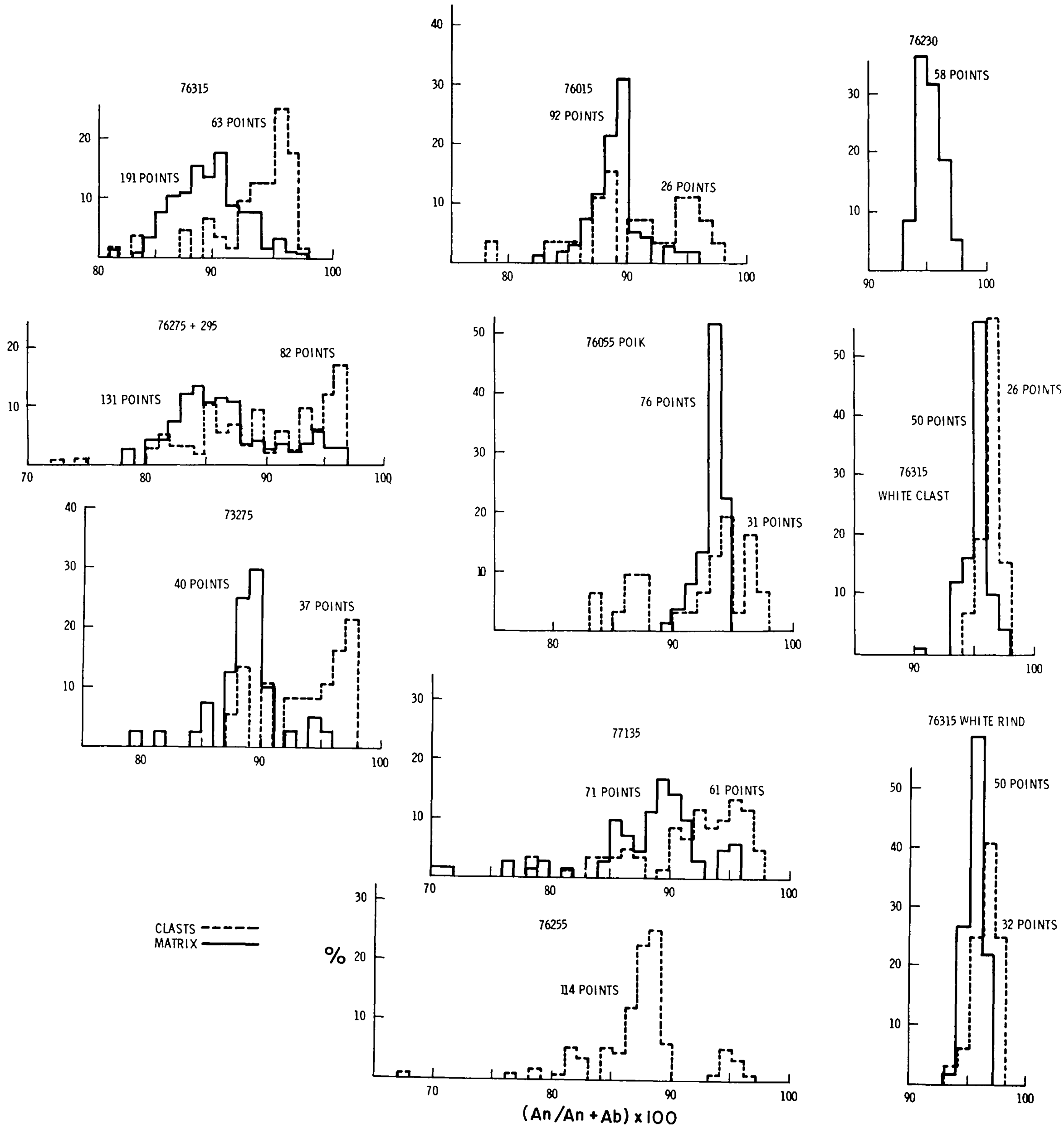

Fig. 2. Microprobe analyses of feldspar comparing a random selection of matrix grains with cores of large mineral clasts. The vertical scale is the percentage of the total clast or matrix analyses falling in each 1% An/An + Ab group. First column for subophitic to micropoikilitic rocks, second column for 50–60% feldspar poikilitic rocks, third column for 70–80% feldspar rocks and 76255, at bottom, is a fragmental breccia. Specific thin top to bottom, left to right: 76315,16, 108, 111; 76275,4; 76295,11, 13; 73275,60; 76015,15, 17; 76055,13; 77135,19; 76255,10, 12, 14, 15, 16; 76235 = 76230,12; 76315,14; 76315,76.

Rocks with 50–60% feldspar

The largest fraction of the returned non-mare rocks from Apollo 17 fall in the 50–60% feldspar group. This group displays a greater textural variety than the more feldspathic group including fragmental breccias and crystalline rocks with matrices having grain sizes showing a hundredfold variation and textures ranging

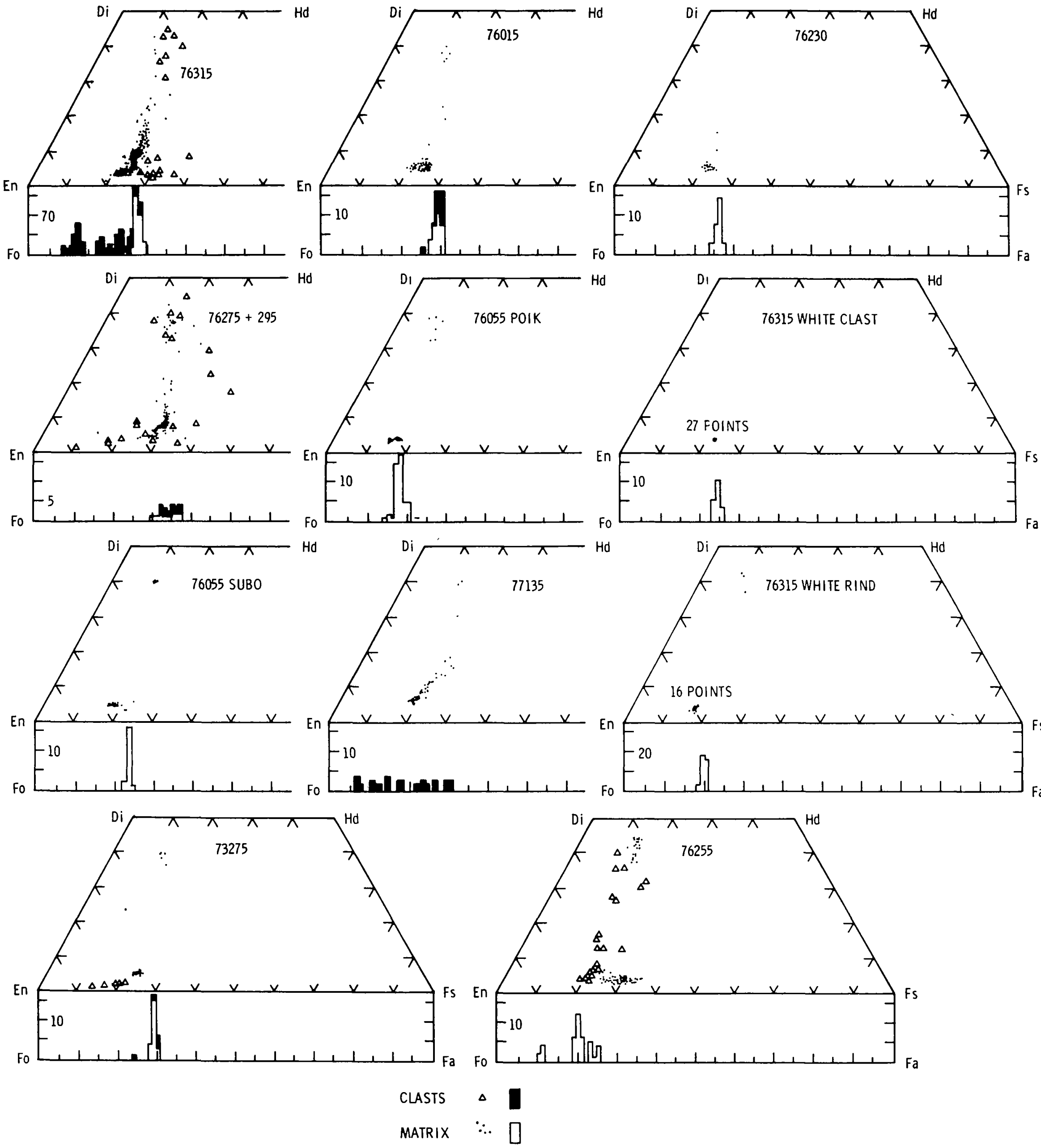

Fig. 3. Microprobe analyses of olivine and pyroxene comparing a random selection of matrix grains with cores of large mineral clasts. First column for subophitic to micropoikilitic rocks, second column for 50–60% feldspar poikilitic rocks, third column for 70–80% feldspar rocks and 76255, at bottom, is a fragmental breccia. Specific thin section analyses are: 76315,16, 108, 111; 76275,4; 76295,11,13, 76055,13; 73275,60; 76015,15, 17; 76055,13; 77135,19; 76255,10, 12, 14, 15, 16; 76235 = 76230,12; 76315,14; 76315,96.

from poikilitic to subophitic or granular. The matrices of these rocks contain about 50% feldspar, 40% low-calcium pyroxene, 5% augite, and small amounts of magnesian olivine. The dominant opaque mineral (up to 2% of each rock) is ilmenite and/or armalcolite containing chromite and rutile lamellae. Minor amounts of K feldspar, iron sulfide, Fe–Ni metal, pink or colorless spinel, and phosphate are also present. Invariably a mesostasis-like phase with very low optical reflectivity and as yet undefined chemistry is present as a late-forming phase confined between faces of feldspar and pyroxene grains, in the matrix.

Rocks in the less feldspathic group fall into two clearly defined categories:

(1) Crystalline rocks that are matrix-supported breccias with dense holocrystalline matrices and 5–25% mineral and lithic clasts. Further subdivision of crystalline breccias is based on both the relative size of pyroxene and feldspar grains and the extent of development of euhedral, tabular feldspar grains into (a) poikilitic, (b) micropoikilitic–subophitic–granular, and (c) clast rich ophitic subdivisions.

(2) Clastic or fragmental rocks that are clast-supported breccias bonded by material similar to the matrices of the finest grained crystalline breccias.

Poikilitic texture. The subdivision of the crystalline group is distinguished by a nearly continuous network of low-calcium pyroxene grains, 0.5–2 mm or more in length. The pyroxenes contain grains or chadacrysts of tabular feldspar a few tens of micrometers long (Fig. 1c). These rocks are very similar in texture to the poikilitic rocks from Apollo 16 such as 60315, 62235, and 65015. This texture occurs rarely in clasts in the 50–60% feldspar rocks with a subophitic to micropoikilitic texture, such as 76055 and 76315.

The matrix of the poikilitic rocks is typified by 76015 which consists of a nearly continuous mass of elongated, and occasionally aligned, 0.2–0.3 by 0.7–1.5 mm low-calcium pyroxene oikocrysts ($Wo_{4-9}En_{61-76}Fs_{19-25}$). Tabular feldspar 10–50 μm long occurs both within and between the pyroxene grains, and ranges from An_{82} to An_{96} with a distinct peak at An_{89} (Fig. 2). Small amounts of augite ($Wo_{35-40}En_{42-46}Fs_{12-15}$) are found as <20 μm grains both within and between the low-calcium pyroxene oikocrysts (Fig. 3). Both poikilitic ilmenite and/or armalcolite grains up to 200 μm long with spinel and rutile lamellae are concentrated between the pyroxene oikocrysts as is also the mesotasis phase with low optical reflectivity. Fifty matrix feldspar grains were analyzed in each of five 1 mm^2 areas on thin sections from regions separated by several centimeters. Each set of analyses is identical, indicating a high degree of homogeneity of the matrix of this rock.

The poikilitic rocks have two distinct types of cavities. The first type are the larger smooth-walled vesicles which range in size from 0.08 to over 100 mm long; the largest are noted in lunar surface photographs of the Station 6 boulder and one entire side of 76215 is part of the wall of one vesicle several centimeters long. Vesicles over a few millimeters long are flattened and elongated defining a foliation in samples 76015 and 76215 as well as in the lunar surface photos. These large vesicles have a small number of protruding euhedral feldspar and phosphate grains. The second type are the irregular cavities, at most 20 μm across, bounded by crystal faces of pyroxene and feldspar, and confined to the regions between oikocrysts.

Mineral and lithic clasts comprise 5–15% of the poikilitic rocks. Mineral clasts are recognized because they are typically over 50 μm across, much larger than the matrix grains. Lithic clasts that were studied in 22 thin sections of 76015 are predominantly granoblastic and poikilitic lithologies with 70–80% feldspar. Others include a brecciated troctolite with equal proportions of olivine and feldspar, a mesostasis-rich feldspathic troctolite with tabular feldspar, and an unusual porous clast composed of coarse pigeonite, augite, and minor feldspar which has reacted with the matrix and has about 1% K-feldspar inclusions, 1–10 μm across, in the feldspar and both pyroxenes.

The cores of feldspar mineral clasts are somewhat bimodal in composition (Fig. 2) with one peak at An_{89} similar in composition to the matrix. The second peak at An_{95-96} resembles the composition of plagioclase in rocks with 70–80% feldspar. The only mafic mineral clasts present in the poikilitic rocks we have studied are olivine. No evidence was found of the small amounts of relic pyroxene reported in some poikilitic rocks (Bence *et al.*, 1973).

Micropoikilitic–subophitic–granular texture. Rocks having these textures are the most abundant non-mare group at Apollo 17 and may form part of a continuous textural and genetic sequence with the poikilitic, 50–60% feldspar rocks. The major difference is that in the subophitic group, matrix pyroxene grains rarely exceed 50 μm in length and range from completely enclosing feldspar tablets to being merely intergrown with the feldspar. The two finest grained rocks of this group, 73215 and 73255 (Fig. 1d) have the poorest development of tabular feldspar and have an almost granular texture, while the much coarser grained rock, 72435 (Fig. 1e), has more euhedral feldspars. Hand specimens for this group appear massive; however, sawn faces of 76315 reveal that the rock has well-developed banding defined by variations in the degree of poikilitic pyroxene formation. The banding parallels the alignment of round <1 mm cavities. Sample 76315 appears to be flow foliated and was collected from a contact between two units in the Station 6 boulder.

A major unit of the Station 6 boulder, represented by samples 76295 and 76275, is classified in the subophitic–micropoikilitic textural type as is sample 76315 from the contact between a poikilitic 50–60% feldspar unit and an unsampled unit in this same boulder (Heiken *et al.*, 1973). The matrix of 76275 and 76295 consists dominantly of low-calcium pyroxene ($Wo_{4-22}En_{60-73}Fs_{19-26}$), augite ($Wo_{30-40}En_{44-57}Fs_{12-15}$), olivine ($Fo_{70-76}$), and feldspar ($An_{81-97}$) (Figs. 1 and 2). The grain sizes of matrix feldspar and pyroxenes for this group are presented in Table 1, and these sizes indicate the textural range in the group. The metal grains are typically only a few micrometers across and the Fe–Ti oxide phase ranges from 1–3 μm in the fine-grained rocks to 15–20 μm across in the coarser rocks. About 50 mafic and feldspar grains in the matrix of 76315 were analyzed in each of five 1 mm^2 areas separated by several centimeters, including both the more and less poikilitic bands; the compositions of minerals in each area were identical to those in the other areas, within analytical precision.

Lunar surface photos indicate that smooth cavities up to 50 mm across occur in the Station 6 boulder unit which yielded 76275 and 76295. However, round vesicles >0.5 mm are rare in the hand samples. Sample 76315 has less than 1%

round cavities of >1 mm diameter. Rare euhedral feldspar or phosphate grains protrude into a small number of cavities. The subophitic portion of 76055, not from the boulder, has abundant elongate, smooth-walled vesicles over a centimeter long. Cavities less than 20 μm long, bounded by feldspar or pyroxene crystal faces, are much less abundant than in the poikilitic 50–60% feldspar rocks.

Mineral and lithic clasts make up 5–25% of each rock. Examination of 20 thin sections of 76315 shows a wide variety of lithic clasts including: two poikilitic 70–80% feldspar fragments; three granulitic 70–80% feldspar fragments; one crushed feldspar or anorthosite fragment; three intersertal feldspar–pyroxene–olivine fragments; one crushed olivine or dunite; one poikilitic 50–60% feldspar fragment; two crushed spinel–olivine fragments; one crushed troctolite fragment; and three aphanitic feldspathic fragments.

The cores of feldspar mineral clasts show a similar bimodal compositional pattern (Fig. 2) to that present in the poikilitic 50–60% feldspar rocks. One peak at the matrix composition, between An_{85-90}, and a second peak at An_{95-96}. In contrast to the mineral clast population in the poikilitic 50–60% feldspar rocks, pyroxene relics (mostly of the low-calcium variety) are abundant with both higher and lower Fe/Mg ratios that the matrix pyroxene. Olivine clasts are abundant and range to higher forsterite composition than those of the matrix (Fig. 3).

Samples 73215, 76275, 76295, and 77115 have concentrations of mineral clasts in sheet of vein-like segregations less than a millimeter thick and up to several centimeters in maximum linear dimension. The segregations appear in photos of fresh surfaces of rocks as thin tan lines or surfaces, cutting through darker material. Part of the external surface of 76295 appears to have formed by fracturing along some of these segregations. The relative abundance of feldspar, olivine, and pyroxene in the segregations is similar to that of the mineral clasts more evenly distributed throughout the matrix. A small amount of matrix material surrounds mineral clasts in the segregations. The segregations have a degree of porosity typical of the remainder of the rock.

Clast-rich ophitic texture. This textural group of 50–60% feldspar rocks contains more blocky feldspar grains than the poikilitic or subophitic groups (Fig. 1f), ophitic to poikilitic pyroxene and ilmenite, armalcolite and ulvospinel. Only irregular cavities, commonly with drusy linings, occur. All samples in this suite, 72315, 72355, 72375, and 72395, are confined to a single boulder, at Station 2.

The matrix mineralogy and texture of this group is like the other low-feldspar rocks with low-calcium pyroxene forming some oikocrysts 25–100 μm across enclosing blocky feldspar grains 10–40 μm long with slightly rounded corners. The poikilitic pyroxene was noted in 72315,7 by Wilshire and 72355,4 by Morrison (LSPET, 1973a) as well as by us; however, sections examined by Albee *et al.* (1974a) are described as lacking poikilitic pyroxenes. A mesostasis with low reflectivity is confined to the areas between the larger feldspars. Fe–Ti oxides with rutile and chromite lamellae occur as poikilitic grains up to 100 μm long. Details of the mineral compositions and textures are given in Albee *et al.* (1974a) and LSPET (1973a).

The rocks contain a few percent irregular cavities, some with drusy linings. Smaller cavities (<20 μm) bounded by feldspar and pyroxene crystal faces form up to 1% of some thin sections.

Fragmental breccias. Samples in this group are clast-supported breccias with a wide range in clast types, including many not seen in other samples. The breccias consist largely of angular clasts, typically over 30 μm across, with small amounts of fine-grained 50–60% feldspar material, similar to the granular texture shown in Fig. 1d. The fine-grained material is concentrated at points where clasts almost touch. Samples 72215, 72235, 72255, and 72275 from a boulder at Station 2 vary widely in the degree of coherence; Stoeser *et al.* (1974) ascribe this to variable amounts of the fine-grained material which binds the rocks together. A clast within the subophitic to micropoikilitic portion of the Station 6 boulder, 76255, is also a clast-supported breccia, bound by small amounts of fine-grained, granular material and like the Station 2 rocks, it contains a diverse clast population including materials unique in the Apollo 17 collection.

The amount of fine-grained non-clast material in 76255 varies widely over distances of a few millimeters, and correlates inversely with porosity. Pores rarely exceed 30 μm across and range from angular where the amount of matrix is small, to relatively smooth, but irregular, where the amount of matrix is large. The matrix consists of plagioclase An_{88-96} with most in the range An_{89-90}, low-calcium pyroxene ($Wo_{2-7}En_{65-73}Fs_{23-30}$), high-calcium pyroxene ($Wo_{37-40}En_{41-47}Fs_{12-16}$), and olivine ($Fo_{73-80}$) (Figs. 2 and 3).

Mineral clasts in 76255 in order of abundance are: feldspar, exsolved pigeonite, augite, olivine, and Fe–Ti oxides. The composition of the mineral clasts are plotted on Figs. 2 and 3. The coarsely exsolved pigeonites consist of augite blebs and lamellae ($Wo_{42}En_{42}Fs_{14}$) in orthopyroxene ($Wo_{3.2}En_{63.4}Fs_{33.4}$).

The lithic clasts in one Station 2 boulder (72215, 72235, 72255, and 72275) are particularly important because many are texturally and chemically distinct from lithologies seen in the matrix of individual Apollo 17 rocks with masses over 50 g. They include the pigenoite basalt or basaltic-textured KREEP fragment, and granitic material. Stoeser *et al.* (1974) describe the wide variety of lithologies in considerable detail.

CHEMICAL VARIATIONS IN NON-MARE ROCKS

Figure 4 is a plot of K_2O versus Al_2O_3 of all published analyses of Apollo 17 non-mare rocks and clasts. Potassium oxide is used as an indicator of the content of incompatible elements and alumina is used as a measure of feldspar content. The figure reveals two concentrations of analyses: one with 17–20% Al_2O_3 and .15–.32% K_2O corresponding to the rocks with 50–60% modal feldspar, and the second, at 25–28% Al_2O_3 and 0.05–0.15% K_2O corresponding to the rocks with 70–80% modal feldspar group. The former group also corresponds to the Medium-K Fra Mauro Medium-K KREEP basalt group of glasses of Reid *et al.* (1972) or High Alumina Basalt composition of Prinz *et al.* (1973). The second group

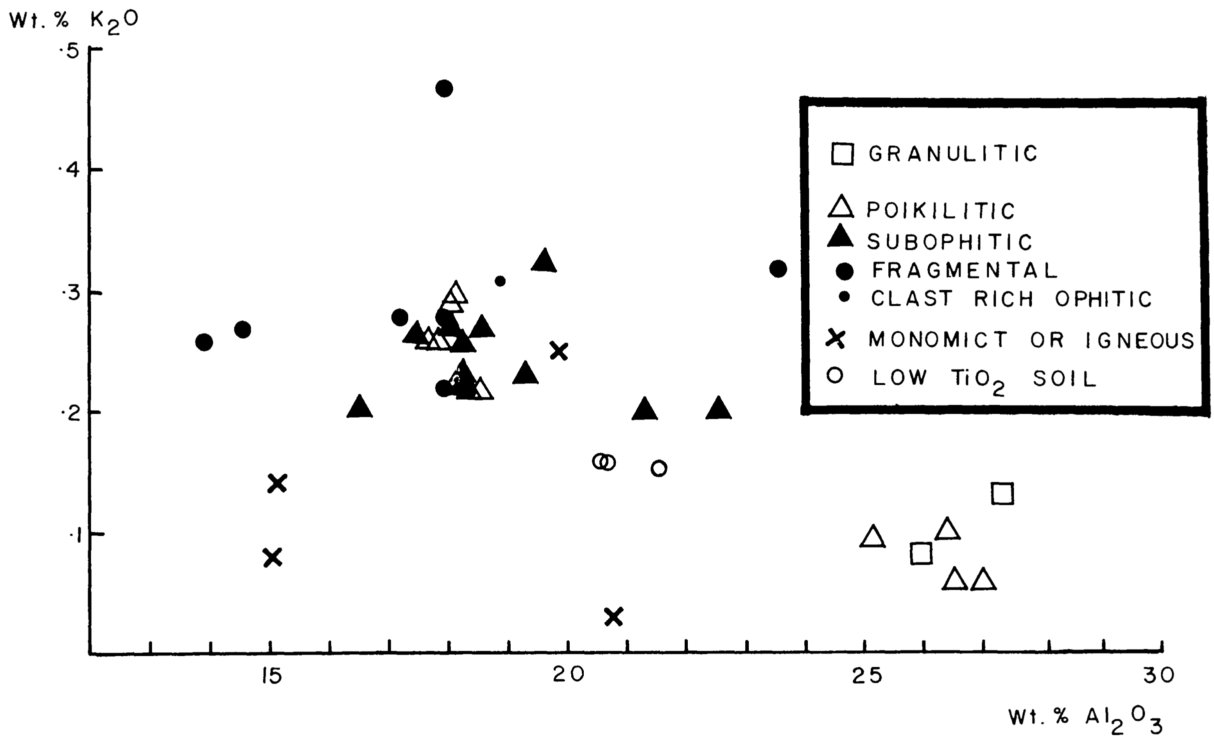

Fig. 4. Plot of K_2O versus Al_2O_3 for all published Apollo 17 non-mare analyses. Data from Chao *et al.* (1974), Duncan *et al.* (1974), Haskin *et al.* (1974), Laul *et al.* (1974), LSPET (1973b), Phinney *et al.* (1974), and Rhodes *et al.* (1974).

corresponds to the Highland Basalt glass (Reid *et al.*, 1972) or the LKAS (Hubbard *et al.*, 1974) compositional groups.

Four of the five analyses of nonimpact generated rocks, the dunite, 72415 (plotting off Fig. 4 to the left, see Table 1 for analysis), the troctolite, 76535, the "Civet Cat" norite from 72275 (15.0% Al_2O_3, 0.08% K_2O), and sample 77215 plot outside of either cluster. The fifth, the pigeonite basalt clast in 72275 (19.8% Al_2O_3 and 0.25% K_2O) falls at the high alumina extreme of the 50–60% feldspar group. It should be noted that the analyzed portions of the fragmental breccias 72255 and 72275 plot at the extremes of the 50–60% feldspar group. However, since thin sections corresponding to the analyzed samples were not available to the authors, these clasts and matrices are not discussed further. Both published analyses of 73235 fall between the two clusters, a fact which correlates with the unusually high abundance of feldspathic clasts in thin sections of that sample. The matrix is texturally similar to that of the subophitic 50–60% feldspar group. Note that the Apollo 17 soils, all from Station 2, with least TiO_2, which indicates the smallest degree of mixing of non-mare material with local mare basalts and orange glass, plot approximately equidistant from the two clusters, in a field almost devoid of rock or clast analyses. This observation suggests that rocks from the 50–60% and 70–80% feldspar groups are present in approximately equal abundance in the South Massif soils as pointed out by Duncan *et al.* (1974) and Rhodes *et al.* (1974).

DISCUSSION

Comparison with other non-mare sample suites

Although most non-mare samples returned by Apollos 14, 15, 16, and 17 are clastic or crystalline breccias of inferred impact origin and contain 50% or more feldspar, rock suites returned from each non-mare region have unique textural and compositional features. Both the Apollo 17 and 14 suites of samples have basically bimodal compositions with one group dominated by KREEP-rich breccias containing 12–18% Al_2O_3 and the second by more feldspathic light-colored breccias or crystalline rocks. The more feldspathic group has 20–23% Al_2O_3 and high K_2O at Apollo 14 and 25–28% Al_2O_3 and low K_2O at Apollo 17. The concentrations of the incompatible elements is higher in the Apollo 14 suite than at Apollo 17. In contrast to the large fraction of crystalline breccias at Apollo 17, the Apollo 14 collection consists mostly of fragmental breccias. Apollo 15 samples lacking any mare components are rare, and a statistical comparison between Apollo 15 and 17 non-mare rocks is not yet possible. In contrast to the Apollo 17 non-mare suite, the Apollo 16 rocks have a nearly continuous compositional spectrum from 15 to 36% Al_2O_3. Also, for rocks with 15–20% Al_2O_3 (50–60% modal feldspar), most from the Apollo 16 site have a poikilitic texture, in contrast to the wider variety of textures found at the Apollo 17 site. Furthermore, Apollo 16 crystalline breccias inferred to have crystallized from melts contain up to 28% Al_2O_3 but Apollo 17 rocks with similar textures all contain less than 20% Al_2O_3.

Petrogenesis

As indicated previously there are a small group of individual samples (72415, 76535, 77215, and 78235) plus some clasts in the clastic breccias which formed by processes that are not impact related. However, all of those samples have undergone various degrees of crushing, presumably shock-induced, subsequent to their primary crystallization.

Lithification of the various breccias can be explained in terms of purely thermal processes that occurred both before and after deposition. However, it may also be possible to explain the same lithologies by a combination of shock and shock-thermal effects resulting from events which post-date the deposition of the material.

The granulitic and poikilitic textures of the samples with 25–27% Al_2O_3 are typical results of annealing or recrystallization and must have developed as a result of intense metamorphism. The mineral homogeneity in these rocks is in accord with such an origin. Although some of these samples contain a meteoritic addition (Morgan *et al.*, 1974), the extent of original brecciation and mixing has been obliterated by the annealing which developed textures similar to those found in terrestrial pyroxene–feldspar rocks of high metamorphic grade. Compositions of the pyroxene oikocrysts in 77017 have led Helz and Appleman (1974) to suggest that small areas of melt developed in this rock during a reheating cycle in which some plagioclase rims and pyroxene oikocrysts formed from the melt. However, they point out that the textural variety of plagioclase chadacrysts must be relict.

The series of textures in the 17–20% Al_2O_3 rocks, from poikilitic through the micropoikilitic to the finest granular textures as well as the fragmental breccias, may be explained by a variety of thermal histories similar to those presented by Warner *et al.* (1973). However, slight textural transitions from micropoikilitic to subophitic across distances of less than 1 mm, in regions of identical composition, in 76315 indicate that the cause of the variation may be extremely subtle, and not purely due to variations in thermal history.

Nature of the protolith

One of the critical problems in the interpretation of chemical analyses of chips of non-mare rocks containing mixtures of clasts and matrix is the determination of the nature of the material which lithified to form the analyzed breccias. Samples of crystalline rocks in the 50–60% feldspar group that we have studied, consist of 5–25% petrographically recognizable mineral and lithic clasts. The most abundant mineral clasts are plagioclase with a bimodal compositional spectrum of the cores of the grains; one peak is An_{85-90}, typical of the matrix and clast rims, and the other is An_{94-97}, typical of Apollo 17 rocks with 70–80% modal feldspar. Extremely diverse types of lithic clasts occur in the two rocks studied most extensively, 76315 (a subophitic to micropoikilitic rock) and 76015 (a poikilitic rock) but the most abundant lithologies are the granulitic- and poikilitic-textured materials with 70–80% modal feldspar, and most of the remaining fragments are characterized by the assemblage anorthite–olivine–spinel–mesostasis. Pyroxene-bearing lithic clasts and pyroxene mineral clasts were found only in 76315. It is important to note that the relic lithologies, in their observed abundances, cannot be mixed to yield the matrix composition. The compositions of the cores of feldspar clasts, indicate a much higher abundance of the highly feldspathic material, about $\frac{1}{2}$ the total clasts, than could be mixed into the amount of KREEP-like material indicated by the feldspar clast population and still preserve the KREEP-like chemistry of the 17–20% Al_2O_3 group. A possible explanation for this general biasing of the relic clast population toward a greater abundance of An_{95-96} plagioclase is that the observed relic lithologies have an intrinsic ability to survive the processes which formed the two rocks. Our study of many samples of shocked non-mare rocks indicates that anorthite is more resistant to shock crushing and vitrification than are olivine or pyroxene. Badly cracked pyroxene is commonly associated with feldspar showing only shock lamellae. This mechanical result may work in combination with the phase equilibrium result that the liquidus temperature in the non-mare compositions increases with feldspar, or Al_2O_3, content. Thus, the matrices of crystalline rocks with 17–20% Al_2O_3 could have been formed by thermal or shock-thermal partial melting of the more finely crushed, more porous, complexly mixed debris whose composition is biased by a mechanical process toward a greater abundance of pyroxene, olivine, and the fine-grained interstitial or accessory minerals than occurred in the original rocks. Such partial melting would produce a less aluminous, KREEP-enriched matrix, but leave the less crushed, more refractory anorthite-rich debris as clasts.

However, at least two other models exist for explaining the same observations in the crystalline rocks with 17–20% Al_2O_3: (1) Material was totally fused by meteorite impact and the clasts are xenoliths picked up by the moving impact melt, stirred in, and to some extent, equilibrated with the melt: (2) the melts are volcanic derivatives from the lunar interior but contaminated by large numbers of xenoliths as they pass up through the brecciated surficial layer of debris (Bence *et al.*, 1974; Crawford, 1974). At present we know of no unambiguous tests which can conclusively delineate any of the above models. However, the ubiquitous meteoritic component, the even distribution and thorough mixing of the clasts in the crystalline breccias, especially the poikilitic rocks, and the total lack of coarse-grained plutonic equivalents to the very fine-grained rocks proposed to be of volcanic origin, seems most easily explained by shock fusion or recrystallization of the more easily melted portion of a mass of debris, leaving the more refractory material as clasts.

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