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ABSTRACT

The first step in a petrologic study must be a classification based on observed textures and mineralogy. Lunar rocks may be classified into three major groups: I. Coarse-grained igneous rocks, II. fine-grained igneous rocks and III. breccias. Group I is interpreted as primitive lunar crustal rocks that display various degrees of crushing and/or annealing. Group II is interpreted as volcanic rocks. Group III is interpreted as resulting from impacts on the lunar surface and is subdivided on the basis of matrix textures into fragmental breccias, crystalline breccias that have been annealed, and crystalline breccias with igneous matrices.

A synthesis of the relevant data concerning lunar highlands polymict breccias from the fields of petrography, chemistry, photogeology, and impact studies compels the prediction that the breccias should have homogeneous matrices from rock to rock within regions of the highlands of limited size where impact mixing has been efficient and extensive. But the returned breccias, even from one landing site, display a wide range in composition. This incompatibility between prediction and observation is a paradox that may be resolved by a process that acts after impact mixing to cause a differentiation of the breccia compositions. Partial melting of the local average crustal composition (as modeled by the average soil composition for each site), and separation of melt and residue in ejecta and/or fall-back blankets is compatible with the reviewed data and may resolve the paradox.

Introduction

Lunar samples have now been returned by eight missions, Apollos 11, 12, 14, 15, 16 and 17 and Lunas 16 and 20. From many hand specimen-sized rocks, but mostly from smaller fragments separated from soils, thousands of thin sections of lithic fragments have been made and studied (e.g., Delano, et al., 1973; Taylor, et al., 1973; Warner, et al., 1973; Prinz, et al., 1973; Warner, 1972; Phinney, et al., 1972; Bence, et al., 1972). Lithic types returned from mare areas are largely Fe-Ti-rich basalts, or breccias comprised largely of such basalts. Those returned from highland areas are more complex; most are breccias of various types and a small number are partially crushed and annealed, coarser-grained igneous rocks. An initial attempt is made in this paper to classify the highland lithologies and explain their petrogenesis. Previous studies of limited suites of samples from individual missions have resulted in several lithologic classifications; commonly these are based on objective and interpretive combinations of chemical, mineralogic, and textural criteria. Although a thorough understanding of lunar rocks should eventually include a wide variety of petrogenetically significant criteria, the first step in a petrologic study must be a classification based on observed textures and mineralogy as was historically developed for terrestrial rocks. Further refinements may include chemical, experimental, or other data. Table 1 is a classification based solely on petrographic observations. Because there are gradations between most groups the divisions between groups are somewhat arbitrary. The texture of an individual thin section may overlap more than one group and not be clearly assignable to one group or the other. Some rocks may contain more than one distinct petrographic type, and the proximity of these various types may be petrogenetically significant. For example; the black and white rocks of Apollos 15 and 16 are irregularly banded mixtures of basaltic-textured breccias and light matrix breccias or cataclastic rocks. In spite of this complexity the groupings in this classification represent reasonably well the major rock types required to describe the returned highland samples.

Several ground rules were used in developing this classification:

1. Terminology is based primarily on study of thin sections.

2. Existing terrestrial or lunar rock names and terminology are used when possible.

3. When several terms have been used to classify a particular rock type the term having the least ambiguity in the literature is utilized.

4. New names are not invented

5. Although it is impossible to avoid some degree of genetic connotation in many rock terms, the terms utilized are those considered as having the least genetic connotation.

6. Assignment to a group in the classification must be possible on the basis of binocular and petrographic microscope examinations and not require chemical or isotopic data which is available for only a small fraction of the samples for which thin sections exist.

Classification

The rocks are divided into three major groups: Coarse-grained igneous rocks, fine-grained igneous rocks, and breccias. Each of the three major groups is further subdivided into several subgroups.

Group I. Coarse-grained igneous rocks.- Grain-sizes in this group are generally greater than 1 mm and occur in various intergrowths of euhedral to subhedral minerals as in terrestrial gabbroic and granitic rocks (Fig. 1). Applicable terrestrial terms such as troctolite and anorthositic gabbro are appropriate for these coarse igneous lithologies that are more common as clasts in breccias than as separate rock fragments. A few coarse mare basalts attain dominant, or average, grain sizes of up to 1 to 2 mm thus overlapping with the coarse-grained group, but they contain less than 35% plagioclase, significant augite and ilmenite, continuous gradations to much finer-grained or vitrophyric textures, and greater than 14% FeO, all of which are characteristic of mare basalts which are classed as fine-grained igneous rocks.

Most of the coarse-grained igneous rocks have been partly to extensively crushed. If there are petrographically recognizable remnants of previous coarse-grained igneous textures, the rock is classified as the cataclastic equivalent of the appropriate predecessor: e.g., cataclastic gabbro, cataclastic anorthosite. As in the terrestrial equivalents the greater the degree of crushing the more difficult it is to deduce a coarse-grained igneous origin. To be a cataclastic igneous rock, the minerals may be crushed but not mixed with material from other source rocks. Lithologies which are most clearly in this category are those with seriate monomineralic matrices enclosing multigrain clasts of the same mineral (Fig. 2a). Monomineralic matrices with large single mineral grains of the same mineral (Fig. 2b) are also included in this group. Lithologies containing seriate polymineralic matrices enclosing multigrain clasts, all of which have the same coarse-grained lithology and minerals as those in the matrix, would also be placed in this group. More equivocal are those textures in which crushed zones are irregularly interspersed with coarse grains which are themselves fractured and partly crushed (Fig. 3). If no relic igneous texture remains then the rock would be categorized as a breccia.

In other coarse-grained igneous rocks partial to extensive annealing, or recrystallization, has resulted in granulitic textures. The grains display equigranular, polyhedral morphology with triple junctions of 120°. The rock may have been a coarse-grained igneous rock that has been intensely crushed and then recrystallized (Fig. 3). Such histories can commonly be verified by studies of textural variations in both hand specimens and thin sections. If remnants of a coarse-grained igneous precursor are present the rock may be classed as a granulitic troctolite, granulitic anorthosite, etc. The hand specimen may clearly show the rock to have a coarse-grained, cumulus texture, yet the thin section may show granulitic texture as is the case with troctolite 76535 and anorthosite 15415 (Fig. 4). Again, as in terrestrial equivalents, the more extensive the recrystallization the more equivocal the initial rock type. In cases where the rock initially may have been a polymict or detrital breccia and then recrystallized, there may be some heterogeneities or relic clasts suggesting such an origin and the rock would be termed a high grade breccia under the crystalline matrix category. In the absence of any petrographic evidence of an igneous or detrital origin it is suggested that the rock be termed a granulite with constituent mineral names as adjectives: e.g., plagioclase-olivine granulite. Further studies of petrologic, chemical, and physical properties might allow a more definitive determination of origin.

Group II. Fine-grained igneous rocks.- This group consists of vitrophyric to fine-grained (<1 mm) crystalline rocks with ophitic, subophitic, diabasic, intersertal, and porphyritic textures similar to those of terrestrial volcanic rocks. Most of the returned fine-grained igneous rocks are mare basalts containing less than 50% feldspar, greater than 50% ferromagnesian silicates, several percent opaque minerals largely as ilmenite, significant amounts of augite or other clinopyroxenes, and essentially no orthopyroxenes (Fig. 6). The high content of ferromagnesian minerals is reflected in the high FeO content (>14% of the chemical analyses of mare basalts.

Pyroclastic rocks consist of aggregates of small (<1 mm), glassy to devitrified fragments most of which are spheroids or fragments of spheroids. The fragments are extremely homogeneous, some contain phenocrysts, many are composite, and a few contain vesicles (Fig. 7). A review of these materials from Apollo 17 (Heiken, et al., 1974) presents the arguments for a pyroclastic origin. The green rocks of Apollo 15 (15425, 15426, and 15427), the orange clods and soil of Apollo 17 (74220), and the black soil of Apollo 17 (74001) are all in this group.

Rocks with basaltic texture, 50% plagioclase, predominantly Ca-poor pyroxene including orthopyroxene, about 1-2% opaques, and no obvious relic fragments are termed feldspathic basalts (Fig. 8). In some cases they have been considered as volcanic in origin, but some may be impact units representing totally melted matrices that contain fragments on a scale too large (cm co m) to observe in the returned samples, and certainly too large to observe in a single thin section. Therefore, this group appears with queries in two places on Table 1. For example thin sections of a 370 gm feldspathis basalt from the Apollo 16 site (68415) contains no obvious relic fragments yet the lunar surface photos show this to be a sample of the matrix from a fragment-laden rock and the description of the overall specimen in the Apollo 16 lunar sample catalog contains the following comment: "no clear-cut inclusions and clasts observed; however, patchy distribution of light and dark colored parts is suggestive of almost completely resorbed clasts." Although another feldspathic basalt (68416) was collected from the matrix of the same boulder only 20 to 30 cm from 68415, it has different mineral compositions and textures (Hodges and Kushiro, 1973; Helz and Appleman, 1973; Gancarz, et al., 1972) indicating significant meterogeneity in the matrix. Crystalline KREEP basalt fragments (Meyer, 1972) from the Apollo 15 site contain no obvious clasts but are all less than 2 cm across and could also be breccia matrix fragments. The much larger but similar feldspathic, or KREEP, basalt from the Fra Mauro site (14310) has been interpreted both as of volcanic origin (Brown, et al., 1972) and as an impact melt derived from the lunar regolith

(James, 1973; Dence and Plant, 1972; LSAPT, 1972). Such rocks might be placed in either the fine-grained igneous rock or basaltic matrix breccia groups during the initial petrographic observations, but further study of petrologic, chemical, and physical properties may allow a more definite assignment to a group.

Group III. Breccias.- As with terrestrial equivalents the breccias consist of various sized, angular to rounded, clastic fragments from more than one source rock set in a finer-grained matrix of either clastis or igneous origin. The ratio of clasts to matrix may vary considerably and the clastic fragments represent a polymict source. Clast types may vary from one geographic area to another or with depth of origin, making them important in provenance studies. Information about the processes that formed breccias is best preserved in the matrix and reactions between clasts and matrix. Temperatures, cooling rates, fugacities of certain volatile components such as O_2 and CO_2, pressures, and mechanical processes involved in the lithification of breccias are best deduced from the mineralogy, texture, composition, and physical properties of the matrix. Therefore, the breccia groups of Table 1 are based on the petrography of matrices. Further modifications of these groups to include clast content could be accomplished by having clast terms precede the matrix name: e.g., troctolite and gabbro-bearing vitric matrix breccia.

Fragmental, crystalline, and glassy matrix breccias are common. Because of the great variety of breccias and their importance to interpretation of the evolution of the lunar highlands, the classification of this major group is subdivided more extensively than were the other major groups.

Among the fragmental breccias there are two subdivisions: 1. Light matrix breccias containing a seriate distribution of mineral, lithic, and, rarely, glass fragments and 2. Vitric matrix breccias containing a large proportion of tiny glass fragments in their matrices (Fig. 9). The light matrix breccias consist of crushed and mixed mineral and lithic debris with minor amounts of glass in some samples. There is no clear-cut distinction between matrix and clasts because of a continuous gradation in grain size as though comminution and accumulation were the major processes involved in formation. There are varying degrees of coherence in the light matrix breccias ranging from crumbly, clod-like lumps to quite coherent fragments that may be partly cemented by very small amounts of glass at the grain boundaries causing fritting of the grains. The fine-grained, crushed silicate debris imparts a light gray color to the matrix.

The vitric matrix breccias are dark brown. The matrix consists largely of small, brown glass fragments about 0.5 to 2 μm in longest dimension (Fig. 10). Waters, et al. (1971) showed that these glass particles are mostly irregular to stubby in shape although rod-like and platy forms are also common. The particles are molded plastically against one another and against mineral, lithic, and glass clasts indicating that the material accumulated while still reasonably soft and hot. Mineral and lithic fragments occur in seriate distribution ranging from fine debris mixed with the minute glass fragments to much larger discrete clasts.

Crystalline matrix breccias are subdivided into two groups based on crystal morphology in the matrix. Feldspars are particularly useful because of their distinct flat-sided, lathy to tabular forms when euhedral in contrast to their more equant, rounded to polygonal forms when anhedral. Pyroxenes have similar but less distinctive contrasts in morphology while olivine is roughly equidimensional in both its euhedral and anhedral forms. Because feldspars have the most distinctive morphology the crystalline breccias are divided into two groups, one with equant feldspar and the other with tabular to lathy feldspar in the matrix. Irregularly-shaped mineral clasts of predominantly plagioclase with subordinate olivine, pyroxene, and spinel and a variety of lithic clasts are generally present in both groups in quantities ranging from 5 to 45% of the total rock.

Crystalline matrix breccias with equant feldspar display distinct discontinuities in grain size distribution for each mineral in the matrix: i.e., each matrix mineral has a fairly restricted size-range. For example in some Apollo 14 breccias (Warner, 1972) the plagioclase and pyroxene of the matrix are restricted to the range 3 to 6 μm. For mineral fragments greater than 25 μm there is a seriate distribution. Warner (1972) suggested that this distribution resulted from recrystallization of the finest grained material (<25 μm) in an originally detrital matrix.

Further textural distinctions allow three subdivisions of the crystalline matrices containing equant feldspar: low grade, high grade, and poikilitic. Low grade breccias (Fig. 11) display no particular pattern in the matrix minerals: i.e., there is no mosaic pattern of polygonal grains as in the high grade breccias nor poikilitic mineral development as in the poikilitic breccias. There is less than 5% glass in the low grade breccias corresponding to grades 3 and 4 of Warner (1972). High grade breccias contain silicate minerals as regular polygons in a mosaic pattern with 120° triple junctions. Figure 12 shows some fine-grained versions of this texture which may also be much coarser-grained. There is no glass in the matrix of high grade breccias corresponding to grades 5 and 6 of Warner (1972). When the original rock cannot be shown to have been a breccia it may be equivalent to the granulitic igneous rocks of Group I. Poikilitic breccias contain ferromagnesian silicates, particularly low-calcium pyroxenes, as oikocrysts enclosing rounded, equant to irregular chadacrysts of plagioclase and ferromagnesian silicates (Fig. 13). This texture is quite distinct from the polygonal mosaics of high grade breccias.

Crystalline matrix breccias containing tabular plagioclase in their matrix display poikilitic texture and several varieties of basaltic textures (Warner, et al., 1973). The matrices of the mesostasis-rich basaltic breccias contain greater than 10% brownish mesostasis consisting of very fine intergrowths of glass, phosphates, opaque minerals, pyroxene, and accessory minerals (Fig. 14). With increasing content of mesostasis these grade into devitrified glass matrix breccias. At about 50% mesostasis most of the crystal development is in the spherulitic or dendritic patterns typical of the devitrified glass matrix breccias. The plagioclase of mesostasis-rich basaltic breccias ranges from H-shaped to tabular, commonly with hollow cores, olivine is the most common mafic mineral and displays a subophitic relationship with plagioclase. Pyroxene is rather rare outside the mesostasis and the subophitic texture occurs in olivine-plagioclase combinations rather than in clinopyroxene-plagioclase as is usually required by the term ophitic. Ophitic basaltic breccias contain matrices of plagioclase, olivine, augite, and pigeonite in subophitic to ophitic textures (Fig. 15). A few percent of the mesostasis described above may be present in this subgroup. These textures are dominated by an interlocking network of tabular plagioclase with interstices occupied by pyroxene and olivine crystals that extend over areas 2 to 4 times as large as the plagioclase tablets. Grain sizes of each mineral are usually restricted to a fairly narrow range varying little more than a factor of 2 to 3. Porphyritic basaltic breccias are similar to the ophitic basaltic breccias except for the presence of plagioclase phenocrysts (Fig. 16). Grain sizes vary considerably more than in the ophitic basaltic breccias. Some of the basaltic textures contain orthopyroxene as the predominant ferromagnesian silicate (Warner, et al., 1973; Chao, 1973). To distinguish these from the previously discussed basaltic matrices they are termed micronoritic breccias (Fig. 17). Feldspathic basalts which may represent extensively melted breccia matrices were discussed under fine-grained igneous rocks.

Poikilitic matrix breccias contain poikilitic ferromognesian minerals,usually low-calcium pyroxene but also high-calcium pyroxene and olivine (Simonds, et al., 1973; Bence, et al., 1973; Chao and Minkin, 1974). They consist of oikocrysts,generally of orthopyroxene or pigeonite but also of olivine, up to 3 mm across enclosing up to 50% of their volume as chadacrysts, predominantly of plagioclase tablets but also a few mafic silicates (Fig. 18). The regions between oikocrysts contain the same minerals as occur in the chadacrysts plus accessory minerals such as potassium feldspar, apatite, and opaques. In some cases the plagioclase tablets are well-alined both in and around the oikocrysts (Fig. 18d).

Glassy matrix breccias contain a coherent, usually vesicular, mass of glass that forms a bonding medium for mineral and lithic clasts (Fig. 19). This contrasts with the vitric matrix breccias that contain tiny fragments rather than coherent masses of glass in their matrices. Because cooling of relatively large fragments (> a few cm) from melt temperatures (~1300°C) to 600 or 700°C would take tens of minutes to hours these larger fragments would be expected to commence crystallizing (or devitrifying) and not remain as glass. Therefore, the glassy matrix breccias occur as small fragments, primarily as agglutinates, rarely larger than a few centimeters across.

Devitrified glass-matrix breccias consist of integrowths of very fine dendritic to spherulitic crystals and glass (Fig. 20). The crystals often develop in fan and bow-tie patterns nucleated on relic grains. As the crystalline development becomes more extensive this group grades into the basaltic matrix types of crystalline matrix breccias.

Interpretation

On the basis of our knowledge of previous studies, plus our studies of textures and mineralogy, the summary interpretations of various lunar rock groups are shown in the right hand column of Table 1. In combination with chemical data the textural diversity of breccias is attributed to various degrees of metamorphism or annealing in the non-melted group (Warner, 1972) and various peak temperatures and cooling rates in the melt-derived group (Warner, 1973).

The remainder of this paper examines the possibility that the chemical diversity of lunar highland polymict breccias is the result of impact processes. Petrographic observations, combined with photogeologic and geochemical results, show that the lunar highlands have been subjected to continuous, extensive meteorite bombardment that has crushed, ground, and mixed the autochthonous and allochthonous material into a series of polymict breccias. We use petrologic and geologic arguments to suggest that those processes should have produced breccias with relatively homogeneous matrix compositions. Since the matrices, even within one landing site, are not homogeneous, there must be a differentiation process that accompanies the crushing, grinding, and mixing of the impact process. Using phase equilibrium and geochemical data as support, we suggest that partial melting, accompanied by some separation of melt from residue, takes place within ejecta and/or fall-back blankets or in the wall rock of craters. This partial melting can account for the geochemical trends and the fact that the polymict breccias at each landing site have diverse compositions.

PETROGRAPHIC OBSERVATIONS

Petrographic study of most lunar highlands breccias that have been thin sectioned (Phinney et al., 1972; Simonds et al., 1974; Warner, 1972; Warner et al., 1973) yields several generalizations: i) the breccias are polymict, ii) most breccias show evidence of multiple impact events, iii) the matrix of each breccia is homogeneous, and iv) breccias were deposited hot.

Breccias are Polymict

The multiparent origin of highlands breccias may be established from mineral, glass, and lithic clasts. The mineral clasts in any one breccia show a wide range of composition that would not be expected in a single igneous rock (Warner, 1972). One example of this diversity is found in rock 76255, a fragmental matrix breccia clast in a basaltic matrix breccia from Station 6 at Apollo 17. This rock contains clasts of inverted pigeonite alongside clasts of orthopyroxene, pigeonite and augite (Simonds et al., 1974).

Lithic clasts are not as numerous as mineral and glass clasts, especially in a single thin section, and therefore evidence from lithic clasts that lunar breccias are polymict is more difficult to obtain. However, it is common to find lithic clasts of both coarse-grained igneous rock and one or more different types of breccia in a single thin section. The lithic clast population has been studied in many thin sections of melt-rock breccias 76015 and 76315. Results are presented in Simonds et al., 1974, and indicate that each sample contains clasts that represent a wide range of lunar highlands rock types. Similar results have been obtained from a Station 2 boulder (Stoeser et al., 1974) and from Apollo 14 breccias (Wilshire and Jackson, 1972).

Vitric breccias contain glass clasts ranging in color from yellow to brown to red. Moreover, the glass clasts generally do not display a continuum of colors, but rather exhibit several discrete colors. For example, 15294, from the Apennine front, contains yellow, deep orange, green, light brown, and tan glasses. These glasses, of different colors and compositions, must have formed from different parents.

The matrices of vitric breccias contain fragments of the same minerals, glasses, and rock types as found in the clasts, except the proportion of these materials is different. Lithic fragments are more abundant as clasts whereas glass fragments are more abundant in the matrix. The similarity in types of material in clasts and matrix and the seriate grain size distribution of the matrix and clasts suggest that the matrix and the clasts are derived from the same set of parents. The extremely fine grain size of the matrix of fragmental matrix polymict breccias (on the order of <1 to 5 microns) illustrates the pervasiveness, extent, and multiplicity of impact comminution.

Evidence for Multiple Events

Petrographic evidence that many breccias represent multiple events has been well documented by Wilshire and Jackson (1972). They found that breccia clasts within breccia clasts within the main breccia were common, and in rare cases they documented occurrences of breccia within breccia within breccia within breccia. Each generation of breccia clasts has different compositions and textures from one another which indicate different parents and thermal histories. The number of observed breccia-in-breccia relations must be taken as a minimum number of brecciation cycles for a given rock, because the intense recrystallization and melting that the current, and pre-existing, breccias underwent would obscure the recognition of pre-existing breccia clasts. Breccia-in-breccia texture is observed in single impact events (e.g., at the Reis Crater). However, the scale of Reis breccia-in-breccia texture is meters (Hüttner, 1969), whereas in the lunar case the scale is millimeters.

Breccia Matrix is Homogeneous

The matrices of polymict breccias are petrographically homogeneous on the scale of millimeters. That is, the texture, grain sizes, mineral abundances, and mineral compositions are the same within several 1mm square areas across a single thin section, and from thin section to thin section of one rock (e.g., Warner, 1972). Homogeneity studies have been carried out on the matrices of two samples (76015 and 76315) from a large boulder and reported in detail by Phinney et al.(1974) and Simonds et al.(1974). These studies include major element chemistry, minor element chemistry, trace element chemistry, mineral chemistry, and petrographic observations of the texture and modal abundances of minerals. Data from several samples separated by several cm in each rock yield essentially identical results indicating that the matrix of each sample is homogeneous on the scale of the aliquots studied--30 mm^3 for chemistry and 1 mm^2 for petrography. The chemistry of 76015 and 76315 is nearly the same indicating chemical homogeneity on a scale of meters between two textural units of a large boulder. That the matrix of breccias is homogeneous is not surprising in view of the fact that analyses of many lunar breccias performed by different laboratories, on different aliquots of the same rock, for a variety of elements are about the same. For example, there are nine determinations of Al_2O_3 from sample 14310 which range from 20.0 to 21.7 wt%, and eight from sample 60315 range from 16.4 to 17.8 wt% (data from the Lunar Sample Curator's data base).

Breccias were Deposited Hot

Analysis of petrologic and geochemical data for vitric and recrystallized breccias (Williams, 1972), combined with the experimental sintering data of Simonds (1973), suggest that vitric breccias were deposited at temperatures on the order of 700°C, and the recrystallized breccias at progressively higher temperatures up to approximately 1000°C. Warner et al.(1973) and Simonds et al. (1973) demonstrated that many of the Apollo 16 breccias contain matrices that were clast laden liquids. Statistical studies of 2-4 mm soil fragments by Delano et al.(1973) indicate that melt-rock breccias constitute about 1/3 of the Apollo 16 site. Bence et al.(1974) show that a similar fraction of the Apollo 17 highlands are melt-rock breccias. Phase equilibrium studies on these compositions by Walker et al. (1973a) and Hodges and Kushiro (1973) show that the matrices of these breccias must have reached 1200 or 1300°C. Although the details of processes that heat ejecta and fall-back blankets are not understood, the data is irrefutable that the breccias were formed in hot ejecta blankets. This suggests that abundant thermal energy is available in ejecta blankets.

EXTENT OF MIXING IN THE LUNAR HIGHLANDS

Petrographic evidence indicates that lunar breccias, which comprise about 90% of the returned lunar highlands rocks, were formed by multiple meteorite impacts from many parents. The physical processes involved are crushing, grinding, and mixing. The rarity of non-mixed (i.e., fine-grained and coarse-grained igneous) rocks, the wide range of lithic clasts types found in several breccias, and the chemical and petrographic homogeneity of breccia matrices suggest that impact mixing has been an extensive and efficient process in the lunar highlands. This is not surprising in view of supporting data from photogeology, cratering studies, geochemistry, and the abundance of mixed vs unmixed rocks.

The numerous overlapping meteorite impact craters observed on any photograph of the lunar highlands attests to the pervasiveness of impact induced mixing. Head (1973) has emphasized the importance of the many local 10 km and larger craters to the Apollo 16 samples. Hartmann (1972) has shown that the cratering rate prior to the deposition of the Fra Mauro Formation was 1.5 to 2 orders of magnitude greater than since Fra Mauro Time. Short and Foreman's (1972) calculations show that ejecta from only the visible craters average out to a uniform layer 1 to 2 km thick.

Secondary impacts will enhance the mixing effects of primary impact. Oberbeck (1971) and Oberbeck, et al. (1973) show that the total mass of material moved by the secondaries may be larger than the mass moved by the primary impact. Thus virtually all material in the upper few km of the moon should be thoroughly mixed.

Siderophile element (e.g., Au) concentrations in the polymict breccias and soils are 1 to 2 orders of magnitude higher than equivalent values for fine-grained and coarse-grained igneous rocks (Morgan et al., 1973, 1974). Following Ganapathy et al. (1973) the Au content of igneous rocks is a measure of the siderophile element concentrations that are idigenous to the moon, and the higher values in soils and polymict breccias represent contamination by meteorites. Thus siderophile element concentrations may be used as an index to the mixed vs the non-mixed rocks. The uniformly high concentrations of Au and other siderophile elements in all analysed polymict breccias (except 15205, Baedecker, et al., 1973) is further corroborative evidence that the highlands have been extensively mixed by impacts.

At the Apollo 14 and 16 sites where there is no nearby mare material the rocks show a wider composition range than the soils (Table 2). Soils are about 95 percent degraded local bedrock, and the rocks are samples of the local bedrock. The narrower range of soil compositions is thus an indication of the effectiveness of the mixing process during the last 10^9 years, when the impact rate has been much less intense than during the time of formation of highland rocks. Further, because the soils appear to be well-mixed local material, they are used to approximate the composition of the local crust.

The Apollo 15 and 17 sites straddle mare-highland boundaries, and the rock-soil relations are obscured. The soils define a linear trend from the field of mare rocks to the field of highland rocks (as illustrated in Figure 21 for Apollo 17). This is due to recent mixing between a "mare average" and a "highland average." The "highland average" composition, as set out in Table 2, may be used to approximate the local highland crust at Apollo 15 and 17.

The abundance of various highland rock types also provides supporting evidence as to the extent of highland impact mixing. The only non-mixed highlands samples are the fine-grained and coarse-grained igneous rocks. Non-mixed materials (both as individual rocks and as clasts in polymict breccias) make up less than 15 percent of the mass of returned highlands samples. Further, the non-mixed rocks themselves are generally small--a few cm across or less (sample 61016, a black and white rock, is an exception--the cataclastic anorthosite part is about 10 cm thick).

The extent of impact mixing in the lunar highlands suggests a low probability that large amounts of non-mixed rock could survive on or near the surface of the lunar highlands for a long time. This does not imply that no non-mixed rock can survive. Impact comminution is a random process and a few non-mixed rocks can survive numerous impact events, but non-mixed rocks cannot form a major proportion of the highlands samples. One exception, which should be rare and local, is if the formation and/or emplacement of the non-mixed rock onto the lunar surface was near the end of the evolution of the highlands.

The petrographic and chemical homogeneity studies suggest that the upper limit for effective mixing is greater than 10's of cubic meters and the lower limit is less than a cm^3. Obviously a few grains at a time, taken in sets, should not be homogeneous. The lower limit thus appears to be less than a cm^3 but more than a few grains, probably a few thousand grains.

Because soils at each highland landing site are very similar in composition, and thus relatively homogenized (except for later local mixing at contacts with nearby mare material), the upper limit for effective mixing must be larger than a landing site (which is on the order of several km^2). Without a doubt there are major lateral heterogeneities in the lunar highlands as evidenced by the orbital XRF and γ-ray experiments (Adler, et al., 1973; Metzger, et al., 1973). Because the local average crust (soil) composition is different at each landing site, the limit must be less than the inter-landing site distances (which are on the order of 10^3 km). The resolution element of the orbital XRF and γ-ray experiments is not clearly defined, but it is on the order of 10's of km across, and the orbital data as plotted (Adler, et al., 1973; Metzger, et al., 1973) suggest that these resolutions are close to the scale of lunar surface homogeneity. The upper limit of effective mixing thus appears to be about 10's of km across.

The arguments and data cited in this section suggest that within most regions of the lunar highlands that are on the order of several hundred km^2, there should have been adequate impact mixing to produce polymict breccias with relatively homogeneous matrices. That is, we predict that within any small area (up to 100 km^2) of the lunar highlands that is chosen at random, the bedrock will consist of polymict breccias that are all of about the same composition. Reference to Table 2 shows that this prediction is wrong.

PARADOX AND A SOLUTION

The diversity of breccia compositions at each highland landing site has been well established (e.g., LSPET, 1971, 1972, 1973a, and 1973b). We use Apollo 16 as an example since it contains the most diverse highlands rock compositions and the landing site lies well within the lunar highlands. Figure 22 shows that the diversity of Apollo 16 rock compositions forms a linear trend from aluminous basalt (KREEP) (CaO - 10-12 wt%; Al_2O_3 = 17 wt%) to anorthosite (CaO = 19-20 wt%; Al_2O_3 = 35 wt%). The one sample that plots off this trend at 6 wt% CaO and 16 wt% Al_2O_3 (a spinel troctolite (Prinz, et al., 1973a)) and several of the rocks at the anorthositic end are coarse-grained igneous rocks; the remainder are polymict breccias (Warner, et al., 1973). Soil compositions lie on the rock trend, but with a much narrower composition range (15-16.5 wt% CaO; 26-29 wt% Al_2O_3). The average soil composition is taken to approximate the local average crustal material, and is used as the starting point for petrochemical processes that take place after impact mixing.

We have shown above that meteorite impacts crush, grind, and mix material; that this material is deposited hot; and that it lithifies into polymict breccias. We argue that impact mixing is so efficient it compels the prediction that breccia matrices should be homogeneous from rock to rock within some ill-defined-sized region of the lunar highlands. Yet the rock analyses, which are essentially matrix analyses because clasts larger than about 2 mm are separated from the analysed material, from any landing site are not homogeneous. This incompatibility between prediction and observation presents a paradox.

There are two explanations for this paradox. First, the prediction that the highland breccias are well mixed is wrong, or second, the diversity of breccia compositions is due to some differentiation process that takes place after impact mixing.

The first explanation that impact mixing is not extensive has two alternatives: (i) the diversity of rock compositions is old (it either dates from crustal formation or pre-4.3 AE volcanism) and the subsequent impact events have not caused significant chemical mixing, or (ii) the diversity of rock compositions is young (3.9 - 4.3 AE volcanism) and the breccia petrography is due to contamination with, and/or partial assimilation of, regolith. The evidence for mixing set out above makes alternative (i) unlikely. If alternative (ii) were the explanation, we would expect to find volcanic rocks that were not contaminated by regolith; and essentially none have been found in the highlands. The even distribution of mineral and lithic clasts does not suggest that they are xenoliths and xenocrysts. If the melt-rock breccias were volcanic, we would expect some coarser-grained equivalents; the latter are not found, and in fact, the breccias are an order of magnitude finer-grained than the mare basalts suggesting a formational process other than volcanism. For these reasons, and others discussed in the last paragraph of the Definition of Rock Type section, we do not accept the first explanation for the paradox.

The second, and favored explanation for the paradox calls for a differentiation process to take place during formation of the breccias so that the repeated mixing is partially undone. The fact that the breccias were formed between 700 and 1300°C suggests the presence of adequate thermal energy (within ejecta and fall-back blankets and in the heated wall rock of craters) to drive petrochemical processes. Processes that may be associated with impacts and could cause differentiation are: selective volatilization, crystal fractionation in pools of impact melt, and partial melting.

Volatilization does not appear to be a significant process since the trend in the breccia compositions is not the trend of vaporization. Volatilization would selevtively remove alkali elements, but the breccias show a covarient trend in CaO and Al_2O_3 and no evidence of alkali loss. Furthermore, the alkali element concentrations are so low in lunar material (even KREEP) that volatilization loss should not be a major process of highland petrogenesis. The necessity of bringing a large fraction of lunar surface material to within 1 mm of the lunar vacuum, while that material is hot, in order for volatilization to be effective seems impossible.

Crystal fractionation in a pool of impact melt of the local average crustal composition could adequately account for the chemistry of the breccias; the observed trend is essentially due to feldspar enrichment plus minor Fe/Mg variation. A major problem with crystal settling is that an impact melt would not be a conducive environment for such a process to take place. Melt-rock breccias are glassy to very fine-grained, which suggests cooling rates so rapid that crystal settling could not be effective. Terrestrial basalts, which are coarser-grained, and thus may have cooled more slowly, do not show crystal settling in lava lakes tens of meters thick. Also, impact melts are laden with mineral and lithic clasts which would hinder crystal settling, and in fact, should themselves settle.

Partial melting processes are controlled by the phases melted: the first melt from the Apollo 16 local average crustal composition should appear at the olivine-pyroxene-feldspar peritectic. Walker,et al. (1973b) have shown that the peritectic has an aluminous basalt (KREEP) major element composition ($CaO \approx 12$; $Al_2O_3 \approx 16$ wt%) which plots at one end of the trend in Figure 12. Further partial melting will produce melts along the olivine-plagioclase cotectic and towards the local average crust, and the rocks that fall in this range are melt-rock breccias. The residue will be more anorthositic, and that is where the potential residue candidates among the Apollo 16 rocks lie on Figure 12.

Statement of the Model

The model we propose to explain the variety of breccia compositions is illustrated in Figure 13 and outlined below:

1. Continuous grinding, crushing, and mixing of surface and near surface materials as a result of primary and secondary impacts from the time of crustal formation to about 3.85 AE. This step is represented in Figure 13 by the MIXING oval and the arrows leading into it. The product is a homogeneous mixture of fine-grained and coarse-grained igneous rocks, pre-existing polymict breccias, and regolith material deposited in ejecta and fall-back blankets. This mixture, which approximates the LOCAL AVERAGE LUNAR CRUST in composition, is the material that further processes act upon.

2. Those parts of the mixed deposits that do not attain temperatures of about 700°C form regolith or SOIL.

3. Those parts of the mixed deposits that attain temperatures above 700°C but below about 1200°C lithify into VITRIC BRECCIAS and RECRYSTALLIZED BRECCIAS.

4. Those parts of the mixed deposits that attain temperatures above about 1200°C will start MELTING following the normal rules of phase equilibrium. There will be at least a partial separation of MELT (with included mineral and lithic clasts) from RESIDUE. The melt will crystallize into basaltic matrix and poikilitic matrix (MELT-ROCK) breccias, and the residue will form some sort of breccia, perhaps a LIGHT MATRIX BRECCIA.

5. There will be many impacts that aid in homogenizing the deposits, whereas there will be relatively few impacts that are accompanied by partial melting and separation of melt and residue.

6. The partial melting may take place in an ejecta blanket, a fall-back blanket, or within the deposits that form the wall rock of craters.

Such a partial melting process can explain the observed diversity of breccia compositions. Below we examine if partial melting of the local average crustal composition is consistent with the chemical data, and discuss evidence bearing on the problem of separation of melt from residue and identification of the residue. As is pointed out below, there are problems with this model, especially in regards to Fe/Mg ratio evolution. Although some details of the model are surely wrong, we stress that the data demands some sort of chemical fractionation process must take place in ejecta and fall-back blankets.

CHEMICAL TESTS OF PARTIAL MELTING

There are six points of chemical data used to test impact partial melting. None of these prove that impact partial melting is the major process responsible for the diversity of highland breccia compositions. Rather, they show that a low pressure partial melting model is consistent with the chemical data.

The range of rock compositions at each highland site has some major similarities. The local crustal average composition would yield an aluminous basalt (KREEP) as the first liquid during partial melting, and rocks with that composition are found at each site. Two sites, Apollo 16 (see Figure 22) and Luna 20 (Prinz et al., 1973b), have rocks that are more aluminous than the first melt but less aluminous than the parent composition. Those rocks may have formed by larger amounts of partial melting than that required to form the aluminous basalt. Finally, each site contains rocks that are more aluminous than the parent composition. These rocks may be residues.

The general major element variations that would be expected in this series are not completely present. The Fe/Mg ratio decreases from the aluminous basalts to the rocks formed by larger amounts of partial melting, but the decrease does not continue through the local average crustal composition to the residue. This problem could be explained if impact crushing and grinding systematically biased the finer-grain size fractions to more mafic compositions, and this finer fraction was the first material melted. There is evidence that mafic minerals (Butler et al., 1973; Finkelman, 1973) and trace elements (Evensen et 1973) are fractionated into finer grain sizes.

The aluminous basalt at each landing site is different in detail in both major and trace elements (Hubbard et al., 1973). This difference shows up in the Fe/Mg ratio and the trivalent lithophile trace elements. In the impact generated partial melting model these small, but significant, differences may be accounted for by corresponding differences in the trace element content and Fe/Mg ratio of the local average crust and different partial melting histories.

There is a correlation between the trivalent lithophile trace elements and major elements at each site as shown by Haskin et al. (1973) and Hubbard et al. (1973) for Apollo 16. For example, the total rare earth element content decreases with increasing Al_2O_3 content in the breccias. Since the trivalent lithophile trace elements occur in accessory minerals, the first liquid generated during partial melting will contain most of these elements, and the first liquid contains the lowest Al_2O_3, yielding a liquid with high trace elements and low Al_2O_3. If we use local soil as a model of the material that was partially melted, an enrichment factor of only 5 or less is needed to produce the trace element concentrations in the low Al_2O_3 breccias. With increased partial melting, the Al_2O_3 content of the liquid increases, and the trace element contents are lowered by dilution.

Taylor et al. (1973) have demonstrated that highland-wide, positive, one-to-one correlations exist among total rare earth elements, Ba, Hf, Nb, Th, and Zr. Hubbard (1973) and Haskin et al. (1973) have pointed out the consistency of the slope of the rare earth elements when normalized to chondrites, which corresponds to the one-to-one correlations found by Taylor et al. (1973). Because these elements occur in the accessory minerals, the first melt will contain most of them and there will be no differential fractionation of the trivalent lithophile trace elements. Further partial melting will simply dilute the abundances that occur in the first liquid. The partial melting model does not specify the slope of the rare earth elements, but once that slope is established as characteristic of the lunar highlands, the partial melting model propagates it.

Although these inter-element correlations between major and trivalent lithophile trace elements do not constitute proof of the proposed impact partial melting, the relations are so striking that they demonstrate a general genetic relationship among the highland breccias. The weight of geochemical evidence argues for partial melting as the basic process. If the diversity of compositions of highland breccias was due to partial melting of different source regions in the lunar interior, the chemical relations would be expected to show discontinuities in the correlations and these dicontinuities do not exist. Partial melting in homoginized ejecta blankets would not produce discontinuities.

The Ar^{39-40} and Rb-Sr data for highland breccias yield crystallization ages between 3.85 and 4.05 AE for the majority of the samples, with a few measurements as old as 4.25 AE (Schaeffer and Husain, 1973 and 1974; and Tera et al., 1974). This spectrum of ages would be expected for continuous impact mixing and partial melting in ejecta blankets. The sharp cut-off of ages at 3.85 AE indicates the time that meteorites large enough to cause extensive mixing and partial melting stopped impacting the moon on a regular basis. The range in ages of about 200 million years suggests that towards the end of highland formation, meteorites large enough to cause partial melting impacted the moon with a frequency such that there was an effective thermal cycle time in the highlands of about 200 million years.

Rb-Sr and U-Pb data on highland breccias yield "whole rock isochrons" of about 4.3-4.4 AE (Nyquist et al., 1973; Tera et al., 1974). Nyquist has suggested that these model ages indicate a major lunar differentiation at that time. Tera et al. give two explanations for the data. Either the model age is the age of the lunar crust for a simple two-stage model, or "...about one-half of the crust formed between 4.6 to 4.5 AE, and the remainder evolved uniformly down to ∿3.9 AE." In the latter case the initial ratios (of both Pb and Sr), and the age, would "represent an average of the rocks sampled and mixed during...impacts." This latter interpretation is consistent with our model of continuous impact mixing and partial melting.

We have performed calculations of Rb-Sr evolution to test our geologic model. Visualize that all Rb^{87}, Sr^{86}, and Sr^{87} are contained in one or more "pots." The calculations start with one "pot" that contains $Sr^{87}/Sr^{86} = 0.6990$ (BABI) and $Rb^{87}/Sr^{86} = 0.05$ at 4.6 AE. The calculations iterate every 0.1 AE from 4.6 AE to 3.9 AE. Within each iteration the following processes are calculated:

1. All existing "pots" are allowed to age for 0.1 AE.

2. The mechanical aspects of impact are simulated by sampling all existing "pots" and combining the sampled material into one "temporary pot." The sampling algorithm removes half of the material in 0.1 AE old "pots," half of the remaining material in 0.2 AE old "pots," and all of the remaining material in 0.3 AE old "pots." Thus at any time there are "pots" of 3 ages with a spread of 200 million years to agree with the spread in observed crystallization ages.

3. The chemical aspects of impact (i.e., partial melting) are simulated by fractionating the "temporary pot" into a new Rb-rich (melt) "pot" and a new Rb-poor (residue) "pot." This part of the calculation contains two variables: i) the partitioning of Rb between the two new "pots," and ii) the partitioning of Sr between the two new "pots." There is no Sr isotopic fractionation.

At this stage of the calculation the formation of the highlands is essentially complete, and the systems are allowed to age for 3.9 AE to the present. We have calculated models that use various expressions for the Rb and Sr partition variables, and many of these yield similar results (Figure 14). Although the results do not provide a perfect match to the observed data, they show that no major problems exist with our model of impact partial melting. For example, the calculations demonstrate that the residues will not have extremely high (>5.0 AE) model ages with BABI.

SEPARATION OF MELT AND RESIDUE

Physical separation of partial melt and residue is necessary for the proposed model to be effective. However, the reader should keep in mind that the mechanical details of separation are not really understood for the case of terrestrial migmatites or basalts, although evidence is exceedingly strong that such separations do take place. We hope that this model will not be judged on how well the separation process is specified. The scale of separation of partial melt within an ejecta blanket is small compared to separating basaltic magma from the earth's mantle; the largest known mass of rock that could be considered formed by impact partial melting is the boulder at Station 6 on Apollo 17. That boulder represents about 10 stratigraphic meters and contains three layers (Heiken et al., 1973) - perhaps suggesting that each layer represents a separate event. Calculations by Brett (1974) based on petrologically derived cooling rates indicate that layers of melt-rock breccia were not more than several meters thick.

Returned samples display partial melts (presumably formed during impact) that have separated. Samples 64455 and 65075 show partial melting and separation of the melt on the mm scale (Grieve and Plant, 1973). Similar separation of partial melt and residue has been documented by Phinney et al. (1972) from KREEP fragments found at Station 7 on Apollo 15. Segregation of a partial melt into small pods and 100 micron veins has been suggested for 67075 by LSPET (1973).

The black and white rocks from Apollo 15 and 16 consist of angular veins of clast-laden melt-rock breccia (black) that intrude cataclastic anorthosites and cataclastic norites (white) and are examples where melt has migrated some unknown distance (but at least 1 cm) and injected a fractured, refractory rock.

The small size of returned lunar samples precludes finding examples of separation on the meter scale. Pools of melt on the km scale occur on the floors and ejecta blankets of highland craters (e.g., King and Tycho; Howard, 1972). These pools may be total impact melts or separated partial melts, but in any case, they occur in an ejecta environment.

Finally, if there were mechanical fractionation of the lower melting material into the finer grain sizes as was suggested above, that process itself would accomplish much of the required separation of partial melt and residue.

IDENTIFICATION OF THE RESIDUE

The residue from the proposed partial melting in an ejecta blanket must meet well-defined chemical criteria. Phase equilibrium relations dictate that the residue must be higher in Al_2O_3 and CaO, and lower in TiO_2, K_2O, Fe/Mg ratio, and all trivalent lithophile trace elements.

We cannot predict what the texture of the residue should be. Rocks that meet the chemical criteria include cataclastic anorthosites (e.g., 61016), light matrix breccias (e.g., 67955), melt rocks (e.g., 68815), and metamorphosed breccias (e.g., 61295). Hubbard et al. (1971) have suggested that there are two types of anorthosite with higher and lower Sr^{87}/Sr^{86}. Perhaps the low Sr^{87}/Sr^{86} anorthosites are derived from the moon's original crust and the high Sr^{87}/Sr^{86} anorthosites are partial melting residues. However, the monomict nature of the anorthosites is not consistent with them being the residue from the impact partial melting of a polymict breccia, unless they were the clasts. We suggest that the residue is probably a polymict breccia or granulite of some type--the light matrix breccias appear to be prime candidates. This is a subject that demands considerable study.

CONCLUSIONS

The general petrogenesis of the moon is best understood by the interpretation of primary rock types returned by the Apollo and Luna missions. It is therefore imperative that we can unambiguously identify the primary rocks. This paper shows how difficult that problem is. Although fine-grained and coarse-grained igneous rocks are probably primary, the bulk of the returned highland rocks are polymict breccias, and this paper demonstrates that the polymict breccias are not primary rocks. Polymict breccias were formed in impacts, and the crushing, grinding, and especially, mixing that takes place during impact does not allow the preservation of original chemistry, but should produce homogeneous breccias.

There is a paradox between compelling evidence that the breccias should be about the same composition, and the wide range of compositions displayed by the returned highland breccias. This paradox demands a differentiation process after the impact mixing. A process that may explain the heterogeneity is partial melting and separation of melt and residue in ejecta and fall-back blankets, or in the wall rock of craters. We are now investigating the possibility of even better fits of chemical, petrographic, and impact data resulting from a mechanical concentration of mafic and accessory minerals into the finer-grained fraction of regolith and preferential melting of this lower melting temperature material.

Finally, the processes that we discuss are not of major importance on earth, but seem to be on the moon. Recent photographs of the surface of Mars and Mercury show those planets to be intensely cratered like the moon. Perhaps the processes discussed in this paper will have application to those planets.

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REFERENCES

ADLER I., TROMBKA J. I., SCHMADEBECK R., LOWMAN P., BLODGET H., YIN L., ELLER E., PODWYSOCKI M., WEIDNER J. R., BICKEL A. L., LUM R. K. L., GERARD J., GORENSTEIN P., BJORKHOLM P., and HARRIS B. (1973) Results of the Apollo 15 and 16 X-ray experiment. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 3, pp. 2783-2791. Pergamon.

BAEDECKER P. A., CHOU C. L., GRUDEWICZ E. B., and WASSON J. T. (1973) Volatile and siderphilic trace elements in Apollo 15 samples: Geochemical implications and characterization of the long-lived and short-lived extralunar materials. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 2, pp. 1177-1195. Pergamon.

BENCE A. E., PAPIKE J. H., SUENO S., and DELANO J. W. (1973) Pyroxene poililoblastic rocks from the lunar highlands. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 1, pp. 597-611.

BENCE A. E., DELANO J. W., and PAPIKE J. J. (1974) Nature of the highland massifs at Taurus Littrow: An analysis of 2-4 mm soil fraction. (abstract) In Lunar Science-V, pp. 51-53, The Lunar Science Institute, Houston, TX.

BRETT R. and MENDELL W. (1974) Thickness of some lunar mare basalt flows and ejecta blankets based on chemical kinetics (abstract) Meteoritics, in press.

BROWN G. M., EMELEUS C. H., HOLLAND J. G., PECKETT A., and PHILLIPS P. (1972) Mineral-chemical variations in Apollo 14 and Apollo 15 basalts and granitic fractions. Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 3, v. 1, pp. 141-147.

BUTLER J. C., GREENE G. M., and KING E. A., JR. (1973) Grain size frequency distribution and modal analysis of Apollo 16 fines. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 1, pp. 267-278. Pergamon.

CHAO E. C. T. (1973) The petrology of 76055,10, a thermally metamorphosed fragment-laden olivine micronorite hornfels. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 1, pp. 719-732.

CHAO E. C. T. and MINKIN J. A. (1974) The petrogenesis of 77135, a fragment-laden pigeonite feldspathic basalt-a major highland rock type. (abstract) Lunar Science-V, pp. 112-114. The Lunar Science Institute, Houston, TX.

DELANO J. W., BENCE A. E., PAPIKE J. J., and CAMERON K. L. (1973) Petrology of the 2-4 mm soil fraction from the Descartes region of the moon and stratigraphic implications. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 1, pp. 537-551. Pergamon.

DENCE M. R. and PLANT A. G. (1972) Analysis of Fra Mauro samples and the origin of the Imbrium Basin. Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 3, Vol. 1, pp. 379-399.

EVENSEN N. M., MURTHY V. R., and COSCIO M. R., JR. (1973) Rb-Sr ages of some mare basalts and the isotopic and trace element systematics in lunar fines. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 2, pp. 1707-1724. Pergamon.

FINKELMAN R. B. (1973) Analysis of the ultrafine fraction of the Apollo 14 regolith. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 1, pp. 179-189. Pergamon

GANAPATHY R., MORGAN J. W., KRÄHENBÜHL U., and ANDERS E. (1973) Ancient meteorite components in lunar highland rocks: Clues from trace elements in Apollo 15 and 16 samples. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 2, pp. 1239-1261. Pergamon.

GANCARZ A. J., ALBEE A. L., and CHODOS A. A. (1972) Comparative petrology of Apollo 16 samples 68415 and Apollo 14 samples 14276 and 14310. Earth Planet Sci. Lett. 16, 3, pp. 307-330.

GRIEVE R. A. F. and PLANT A. G. (1973) Partial melting on the lunar surface, as observed in glass coated Apollo 16 samples. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 1, pp. 667-679. Pergamon.

HARTMANN W. K. (1972) Paleocratering of the moon: Review of post-Apollo data. Astrophysics and Space Sci. 12, pp. 183-199.

HASKIN L. A., HELMKE P. A., BLANCHARD D. P., JACOBS J. W., and TELANDER K. (1973) Major and trace element abundances in samples for the lunar highlands. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 2, pp. 1275-1296. Pergamon.

HEAD J. W. (1974) Stratigraphy of the Descartes region (Apollo 16): Implications for the origin of samples. The Moon, in press.

HEIKEN G., BUTLER P., JR., SIMONDS C. H., PHINNEY W. C., WARNER J. L., SCHMITT H. H., BOGARD D. D., and PEARCE W. G. (1973) Preliminary data on boulders at station 6, Apollo 17 landing site. NASA Tech. Memor. TM X-58116, pp. 1-56, Johnson Space Center, Houston, TX.

HEIKEN G., MCKAY D. S., BROWN R. W. (1974) Lunar deposits of possible pyroclastic origin. Geochim. Cosmochim. Acta. (in press).

HELZ R. T. and APPLEMAN D. E. (1973) Mineralogy, petrology, and crystallization history of Apollo 16 rock 68415. Proc. Fourth Lunar Sci. Conf. Geochim. Cosmochim. Acta, Suppl. 4, Vol. 1, pp. 643-659.

HODGES F. N. and KUSHIRO I. (1973) petrology of Apollo 16 lunar highland rocks. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 1, pp. 1033-1048. Pergamon.

HOWARD K. A. (1972) Ejecta blankets of large craters exemplified by King Crater. Apollo 16 Preliminary Science Report, Chapter 29, pp. 70-77, NASA SP-315.

HUBBARD N. J., GAST P. W., MEYER C., NYQUIST L. E., SHIH C., and WIESMANN H. (1971) Chemical composition of lunar anorthosites add their parent liquids. Earth Planet. Sci. Lett. 13, 71-75.

HUBBARD N. J., RHODES J. M., GAST P. W., BANSAL B. M., SHIH C. Y., WIESMANN H., and NYQUIST L. E. (1973) Lunar rock types: The role of plagioclase in non-mare and highland rock types. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 2, pp. 1297-1312. Pergamon.

HÜTTNER R. (1969) Bunte Trümmermassen und suevit. Geologica Bavarica 61, pp. 142-200.

JAMES O. B. (1973) Crystallization history of lunar feldspathic basalt 14310. USGS Prof. Pap. 841, 29pp.

LSAPT, Lunar Sample Analyses Planning Team (1972) Third Lunar Science Conf., Science, v. 176, no. 4038, pp. 975-981.

LSPET (Lunar Sample Preliminary Examination Team) (1971) Preliminary examination of lunar samples from Apollo 14. Science 173, pp. 681-693.

LSPET (Lunar Sample Preliminary Examination Team)(1972) The Apollo 15 lunar samples: A preliminary description. Science 175, pp. 363-374.

LSPET (Lunar Sample Preliminary Examination Team (1973a) The Apollo 16 lunar samples: Petrographic and chemical description. Science 179, pp. 23-34.

LSPET (Lunar Sample Preliminary Examination Team) (1973b) Apollo 17 lunar samples: Chemical and petrographic description. Science 182, pp. 659-672.

METZGER A. E., TROMBKA J. I., PETERSON L. E., REEDY R. C., and ARNOLD J. R. (1973) Lunar surface radiactivity: Preliminary results of the Apollo 15 and Apollo 16 gamma-ray spectrometer experiments. Science 179, pp. 800-803.

MEYER C. (1972) Mineral assemblages and the origin of non-mare lunar rock types. (Abstract) In Lunar Science-III, pp. 542-544, The Lunar Science Institute, Houston, TX.

MORGAN J. W., KRÄHENBÜHL U., GANAPATHY R., ANDERS E., and MARVIN U. B. (1973) Trace element abundances and petrology of separates from Apollo 15 soils. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 2, pp. 1379-1398. Pergamon.

MORGAN J. W., GANAPATHY R., HIGUCHI H., KRÄHENBÜHL U., and ANDERS E. (1974) Lunar basins: Tentative characterization of projectiles, from meteoritic elements in Apollo 17 boulders. (Abstract) In Lunar Science-V, pp. 526-528, The Lunar Science Institute, Houston, TX.

NYQUIST L. E., HUBBARD N. J., GAST P. W., CHURCH S. E., BANSAL B. M., and WIESMANN H. (1972) Rb-Sr systematics for chemically defined Apollo 14 breccias. Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 3, Vol. 2, pp. 1515-1530, MIT Press.

NYQUIST L. E., HUBBARD N. J., GAST P. W., BANSAL B. M., WIESMANN H., and JAHN B. (1973) Rb-Sr systematics for chemically defined Apollo 15 and 16 materials. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 2, pp. 1823-1846. Pergamon.

OBERBECK V. R. (1971) A mechanism for the production of lunar crater rays. The Moon, 2, pp. 263-278.

OBERBECK V. R., MORRISON R. H., HÖRZ F., QUAIDE W. L., and GAULT D. E. (1974) Smooth plains and continuous deposits of craters and basins. Proc. Fifth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 5, Vol. 3. Pergamon.

PAPANASTASSIOU D. A. and WASSERBURG G. J. (1971) Rb-Sr ages of igneous rocks from the Apollo 14 mission and the age of the Fra Mauro Formation. Earth Planet. Sci. Lett. 12, pp. 36-48.

PAPANASTASSIOU D. A. and WASSERBURG G. J. (1972a) The Rb-Sr age of a crystalline rock from Apollo 16. Earth Planet. Sci. Lett. 16, pp. 289-298.

PAPANASTASSIOU D. A. and WASSERBURG G. J. (1972b) Rb-Sr systematics of Luna 20 and Apollo 16 samples. Earth Planet. Sci. Lett. 17, pp. 52-63.

PEARCE G. W., GOSE W. A., and STRANGWAY D. W. (1973) Magnetic studies on Apollo 15 and 16 lunar samples. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 3, pp. 3045-3076. Pergamon.

PHINNEY W. C., WARNER J. L., SIMONDS C. H., and LOFGREN G. E. (1972) Classification and distribution of rock types at Spur Crater. The Apollo 15 Lunar Samples, pp. 149-153, The Lunar Science Institute, Houston, TX.

PHINNEY W. C., ANDERS E., BOGARD D., BUTLER P., GIBSON E., GOSE W., HEIKEN G., HOHENBERG C., NYQUIST L., PEARCE W., RHODES M., SILVER L., SIMONDS C., STRANGWAY D., TURNER C., WALKER R., WARNER J., and YUHAS D. (1974) Progress report: Apollo 17, station 6 boulder consortium. Lunar Science-V, Suppl. A, pp. 7-13, The Lunar Science Institute, Houston.

PRINZ M., DOWTY E., KEIL K., and BUNCH T. E. (1973a) Spinel troctolite and anorthosite in Apollo 16 samples. Science 179, pp. 74-76.

PRINZ M., DOWTY E., KEIL K., and BUNCH T. E. (1973b) Mineralogy, petrology and chemistry of lithic fragments from Luna 20 fines: Origin of the cumulate ANT suite and its relationship to high-alumina basalts. Geochim. Cosmochim. Acta, 37, pp. 979-1006.

RHODES J. M., RODGERS K. V., SHIH C., BANSAL B. M., NYQUIST L. E., and WIESMANN H. (1974) The relationship between geology and soil chemistry at the Apollo 17 landing site. (abstract) In Lunar Science-V pp. 630-632, The Lunar Science Institute, Houston, TX.

SCHAFFER O. A. and HUSIAN L. (1973) Early lunar history: Ages of 2 to 4 mm soil fragments from the lunar highlands. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 2, pp. 1847-1863. Pergamon.

SCHAEFFER O. A. and HUSIAN L. (1974) Chronology of lunar basin formation and ages of lunar anorthositic rocks. (abstract) In Lunar Science-V pp. 663-665, The Lunar Science Institute, Houston, TX.

SHORT N. M. and FOREMAN M. L. (1972) Thickness of impact crater ejecta on the lunar surface. Modern Geol. 3, pp. 69-91.

SIMONDS C. H. (1973) Sintering and hot pressing of Fra Mauro composition glass and the lithification of lunar breccias. Am. J. Sci. 273, pp. 428-439.

SIMONDS C. H., WARNER J. L., and PHINNEY W. C. (1973) Petrology of Apollo 16 poikilitic rocks. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 1, pp. 613-632. Pergamon.

SIMONDS C. H., PHINNEY W. C., and WARNER J. L. (1974) Petrography and classification of Apollo 17 non-mare rocks with emphasis on samples from the station 6 boulder. Proc. Fifth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 5, Vol. 1. Pergamon.

STOESER D. B., WOLFE R. W., MARVIN U. M. WOOD J. A., and BOWER J. F. (1974) Petrographic studies of a boulder from the South Massif. (abstract) In Lunar Science-V, pp. 743-745, The Lunar Science Institute, Houston, TX

TAYLOR G. J., DRAKE M. J., WOOD J. A., and MARVIN U. B. (1973) The Luna 20 lithic fragments, and the composition and origin of the lunar highlands. Geochim.Cosmochim. Acta, 37, pp. 1087-1106.

TAYLOR S. R., GORTON M. P., MUIR P., NANCE W., RUDOWSKI R., and WARE N. (1973) Lunar highlands composition: Apennine Front. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 2, pp. 1445-1459. Pergamon.

TERA F., PAPANASTASSIOU D. A., and WASSERBURG G. J. (1973) A lunar cataclysm at 3.95 AE and the structure of the lunar crust. (Abstract) In Lunar Science-IV, pp. 723-725, The Lunar Science Institute, Houston, TX.

TERA F., PAPANASTASSIOU D. A., and WASSERBURG G. J. (1974) The lunar time scale and a summary of isotopic evidence for a terminal lunar cataclysm. (Abstract) In Lunar Science-V, pp. 792-794, The Lunar Science Institute, Houston, TX.

WALKER D., LONGHI J., GROVE T. L., STOLPER E., and HAYS J. F. (1973a) Experimental petrology and origin of rocks from the Descartes Highlands. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 1, pp. 1013-1032. Pergamon.

WALKER D., GROVE T. L., LONGHI J., STOLPER E. M., and HAYS J. F. (1973b) Origin of lunar feldspathic rocks. Earth Planet. Sci. Lett. 20, pp. 325-336.

WARNER J. L. (1972) Metamorphism of Apollo 14 breccias. Proc. Third Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 3, Vol. 1, pp. 623-643. MIT Press.

WARNER J. L., SIMONDS C. H., PHINNEY W. C., and GOOLEY R. (1973) Petrology and genesis of two "igneous" rocks from Apollo 17 (76055 and 77135). EOS Transactions, Am. Geophys. Union 54(6) pp. 620-621.

WARNER J. L., SIMONDS C. H. and PHINNEY W. C. (1973) Apollo 16 rocks: Classification and petrogenetic model. Proc. Fourth Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 4, Vol. 1, pp. 481-504. Pergamon.

WATERS A. C., FISHER R. V., GARRISON R. E., and WAX D. (1971) Matrix characteristics and origin of lunar breccia samples 12034 and 12073. Proc. Second Lunar Sci. Conf., Geochim. Cosmochim. Acta, Suppl. 2, Vol. 1, pp. 893-907.

WILLIAMS R. J. (1972) The lithification of metamorphism of lunar breccias. Earth Planet. Sci. Lett. 16, pp. 250-256.

WILSHIRE H. G. and JACKSON E. D. (1972) Petrology and stratigraphy of the Fra Mauro Fromation at the Apollo 14 site. U.S. Geological Survey Prof. Paper 785, pp. 1-26.

TABLE 1: PETROGRAPHIC CLASSIFICATION OF LUNAR ROCKS

Groups and Subgroups	Interpretation
I. Coarse-grained Igneous Rocks (intergrown crystals, >1 mm, typical of terrestrial equivalents)	Early crustal cumulate rocks some of which have been partly crushed and/or annealed.
A. Plutonic Rocks (anorthosite, troctolite, etc.)	
B. Cataclastic Rocks (cataclastic anorthosite, etc.)	
C. Granulitic Rocks (granulitic troctolite, etc.)	
II. Fine-grained Igneous Rocks (glassy to fine-grained (<1 mm) intergrown, crystalline textures typical of terrestrial equivalents)	Melts from the lunar interior
A. *Mare Basalts (ferromagnesian silicates plus opaques comprise >50% and plagioclase <50% of minerals, essentially no orthopyroxene)	
B. Pyroclastic Rocks (aggregates of vitric to devitrified ash)	
C. (?) Feldspathic Basalts (?) (plagioclase comprises >50% of minerals, orthopyroxene is common; e.g., 14310, Apollo 15 KREEP, 68415)	
III. Breccias (angular to rounded relic fragments in a fragmental, crystalline, or glassy matrix; polymict)	
A. Fragmental Matrix Breccias (no sutured or interlocking minerals in matrix as in crystalline textures)	Non-melted, crushed and mixed breccias formed directly from impact events (matrix never consisted of coherent melt although matrix may have contained many fragments of glass) Some may have undergone one or more subsequent heating events.
1. Light Matrix Breccias (seriate distribution of lithic and mineral fragments)	
2. Vitric Matrix Breccias (matrix is largely 0.5 - 2.0 mμ glass fragments)	
B. Crystalline Matrix Breccias	
1. Crystalline Matrix Breccias with equant feldspar in matrix	
a. Low Grade Breccias (grain size distribution is discontinuous, no obvious mosaic pattern to minerals)	
b. High Grade Breccias (grain size distribution is discontinuous, minerals form mosaic pattern, silicates as regular polyhedra)	
c. Poikilitic Breccias	
2. Crystalline Matrix Breccias with tabular feldspar in matrix	Melt-derived breccias formed directly from impact events (matrix at some stage consisted of reasonably coherent melt)
a. Basaltic Matrix Breccias	
i Mesostasis-rich Basaltic Breccias (matrix contains plagioclase, olivine, >10% cryptocrystalline mesostasis of glass, phosphates, opaque minerals, pyroxene, and other accessory minerals)	
ii Ophitic Basaltic Breccias	
iii Porphyritic Basaltic Breccias	
iv Micronoritic Breccias	
v (?) Feldspathic Basalts (?)	
b. Poikilitic Matrix Breccias	
C. Glassy Matrix Breccias (primarily agglutinates; matrix consists of coherent glass)	
D. Devitrified Glass-Matrix Breccias	

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*Mare Basalts may be further subdivided but this paper is concerned more with Highland rock types.

Table 2. Range of composition of selected elements and oxides in highland polymict breccias and soils.

	Apollo 14		Apollo 15		Apollo 16		Apollo 17	
	Breccias[1]	Soils[1]	Breccias[1]	Soils[1,2]	Breccias[1]	Soils[1]	Breccias[1]	Soils[1,3]
TiO_2 (%)	1.4-1.7	1.6-1.8	.3-1.4	1.27	.3-1.7	.4-.7	.2-1.5	1.24
Al_2O_3 (%)	14.8-22.3	16.2-17.7	15.2-23.5	17.38	17.2-31.2	26.0-29.0	17.0-27.0	21.42
FeO (%)	6.7-11.0	10.0-10.9	5.9-15.0	11.65	3.2-10.5	4.1-6.2	5.1-11.6	8.14
MgO (%)	8.3-13.7	9.2-10.2	9.4-13.3	10.36	2.3-15.1	4.2-6.3	6.1-16.3	9.94
CaO (%)	9.1-12.8	10.2-11.3	10.3-13.7	11.52	10.4-18.3	15.0-16.5	9.9-15.2	13.06
K_2O (%)	.15-.87	.50-.60	.08-.17	.17	.03-.49	.05-.16	.06-.30	.15
P_2O_5 (%)	.22-.63	.40-.58	.02-.55	.13	.02-.48	.06-.15	.03-.35	.12
Sm (ppm)	20-42	29-31	3-13	~10	2-27	3-7	2-25	-
Sr (ppm)	180-230	177-181	113-268	142	139-235	167-188	111-177	151

1. Data from Curator's Data Base, Curator's Office, J.S.C., Houston.
2. Data presented is "highlands average" as described in text.
3. Data from LSPET(1973b) and Rhodes et al.(1974).

Figure Captions

Fig. 1: Clast of spinel-bearing troctolite from 67435 which is a poikilitic matrix breccia with tabular feldspar. (a) plane light view of plagioclase (very light gray) subhedral olivine (light gray), and subhedral spinel (gray); (b) cross polars view illustrating isotropic nature of spinel and poikilitic nature of plagioclase. The troctolite has the cumulate texture of igneous rocks (long dimension = 2.4 mm).

Fig. 2(a): Cataclastic dunite, 72415,56 (plane light). This rock is essentially all olivine in seriate grain size distribution. Note clast of multigrain olivine at lower left (long dimension = 7.2 mm).

(b): Cataclastic anorthosite, 60025,110 (crossed polars). This rock is essentially all plagioclase both as large grains and fine-grained matrix (long dimension = 1.8 mm).

Fig. 3: White area of black and white breccia 15455 showing plane light view (a) of zones of crushed plagioclase (light gray) containing larger fragments of plagioclase (white) enclosing zones of crushed orthopyroxene (black) and larger fragments of orthopyroxene (medium gray, high relief). Crossed polars view of same area (b) shows continuity of twinning from one plagioclase fragment to another, especially at right center and lower center. Similar pair of plane light (c) and crossed polars views (d) show that orthopyroxene fragments (medium gray in c) in crushed orthopyroxene (dark gray in c) form one optically continuous grain as shown by their simultaneous extinction in d (long dimension = 7.2 mm).

Fig. 4(a): Crossed polars view of troctolite 76535,51 showing polyhedral grain development with triple junctions. Gray, irregularly cracked grains are olivine; remainder is plagioclase (long dimension = 7.2 mm).

(b): Crossed polars view of chip from anorthosite 15415,30 showing polyhedral grain development of smaller plagioclase grains within much larger plagioclase grains (long dimension = 7.2 mm).

Fig. 5: Plane light (a) and crossed polars (b) views of 79215,58. Light area in center is large plagioclase grain that has developed extensive ~~zone of~~ small polyhedral grains in its outer zone. Top left and top right are similar zones of polyhedral grains but entirely of olivine. Light areas in lower half of fragment consist of polyhedral plagioclase grains (long dimension = 7.2 ~~1.8~~ mm). Plane light (c) and crossed polars (d) views of another thin section of 79215,50 at lower magnification showing polyhedral grain development from a large plagioclase (lower left) and in zones of olivine between plagioclase crystals (upper right) (long dimension = 1.8 ~~7.2~~mm).

Fig. 6: Plane light views of mare basalts. (a) Coarse grained basalt 15555,206 showing olivines and clinopyroxenes (gray) poikilitically enclosed in plagioclase. Opaque minerals are primarily ilmenite. Large clinopyroxene grain with opaque inclusions occurs along right margin. (b) Crystals of armalcolite or ilmenite (black) and pyroxene (white) in matrix of glass and spherulitic crystals in 70215,160 (long dimension = 1.8 mm).

Fig. 7: Plane light views of orange clod, 74220,78 (a) and green rock 15427,29 (b). Both are very similar in that they contain spheroids or fragments of spheroids that are primarily glass but also a few are devitrified. The gray matrix is mostly finer fragments of the same material. Note the euhedral olivine grain in the large glass fragment in the upper right of 15427 (b) (long dimension = 1.8 mm).

Fig. 8: (a) Plane light and (b) crossed polars views of KREEP feldspathic basalt 15434,37 consisting of elongate plagioclase laths (white) some of which are slightly curved, tabular orthopyroxene (gray), and fine-grained mesostasis (dark gray) containing glass, opaques, phosphates, and other accessories. (c) Plane light and (d) crossed polars views of feldspathic basalt 68415,130 consisting mostly of feldspar laths and irregularly-shaped, interstitial grains of pyroxene much of which is orthopyroxene. (e) Plane light and (f) crossed polars views of feldspathic basalt 14310,183 consisting of plagioclase laths (white), orthopyroxene phenocryst (light gray, upper left), interstitial pyroxene (light gray), opaques (black), and a trace of fine-grained mesostasis (dark gray in e) (long dimension = 1.8 mm).

Fig. 9: (a) Plane light and (b) crossed polars views of light matrix breccia 61516,4 showing seriate grain-size distribution and crystalline nature of fragments. (long dimension = 1.8 mm).

(c) Plane light and (d) crossed polars views of light matrix breccia 14082,10 at much greater magnification than (a) and (b) showing seriate grains and their crystalline nature in the very fine fraction (long dimension = 0.44 mm).

Fig. 10: Plane light views of vitric matrix breccias at intermediate magnification (long dimension = 0.44 mm) of 14042,7 (a) and high magnification (long dimension = 0.18 mm) of 15314,45 (b). Matrix consists of micromillimeter-size particles of brown glass which can be resolved in (b).

Fig. 11: Low grade crystalline matrix breccia, 15314,43, showing lack of regular pattern and restricted grain-size range of matrix in plane light (a) and crystalline nature of matrix in cross polars (b) (long dimension = 0.44 mm).

Fig. 12: High grade crystalline matrix breccias showing development of equant matrix grains in plane light, sample 14311,13 (a) (long dimension = 0.44 mm), and mosaic arrangement of polygonal grains in a small area of matrix in reflected light, sample 14305,95 (b) (long dimension = 0.18 mm).

Fig. 13: Crossed polars views of poikilitic breccias with equant feldspar grains (a) 77017,76 contains areas of low-calcium pyroxene as oikocrysts (black) enclosing equant feldspar grains of various size (white to light gray) (long dimension = 2.0 mm) (b) A clast, 76315,96, contains areas of low calcium pyroxene as oikocrysts (white) enclosing many plagioclase grains most of which are equant and rounded (long dimension = 0.44 mm).

Fig. 14: Plane light views of mesostasis-rich basaltic breccias. (a) 64477,13 shows mesostasis (black) amid clusters of small equant olivine grains (gray) and elongate plagioclase laths (white to light gray). A few larger mineral clasts are visible.

(b) 15314,40 contains a greater proportion of mesostasis (gray) with equant olivine (light gray) and lathy plagioclase (light gray) grains (long dimension = 0.44 mm).

Fig. 15: Ophitic basaltic breccias. (a) Plane light view of 66095,86 showing tabular plagioclase (light gray), equant olivine and pyroxene (gray) and opaques (black). Large irregular grains in lower half are clasts. (b) Crossed polars view of (a) to show ophitic texture. Upper half of photo shows several ophitic pyroxenes (larger irregular white patches) containing a few plagioclase laths (long dimension = 0.44 mm). (c) Plane light and (d) crossed polars views of 63585,4 one of the coarser grained versions of this group showing the relatively uniform grain-size distribution (long dimension = 1.8 mm).

Fig. 16: Porphyritic basaltic breccia 64817,3 (a) plane light and (b) crossed polars, showing the larger plagioclase grains developing a porphyritic texture. Note the much greater variation in grain size than in the ophitic basalts of Fig. 15 (long dimension = 1.8 mm).

Fig. 17: (a) Plane light and (b) crossed polars views of noritic breccia 63598,4. Note the barely resolvable to clearly seen laths of plagioclase (light gray) throughout the matrix. Most of the remaining light gray material is orthopyroxene. A few large plagioclase clasts are present (long dimension = 0.44 mm). The lath-shaped plagioclase is best seen in high magnification under reflected light as in 73435,7 (c)

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(long dimension = 0.18 mm). Dark gray is plagioclase and light gray is largely orthopyroxene.

Fig. 18: Poikilitic matrix breccia 15414,11 (a) in crossed polars showing the pyroxene oikocrysts (large light gray and dark gray patches) (long dimension = 1.8 mm) and (b) in plane light at higher magnification showing the tabular to lathy forms of plagioclase (long dimension = 0.44 mm). Similar texture occurs in 76055,13 (c) in plane light showing oikocrysts (light gray and medium gray patches) (long dimension = 1.8 mm) and (d) in crossed polars showing the plagioclase laths in one of the oikocrysts. Note the alignment of plagioclase grains (long dimension = 0.44 mm). (e) Sample 66035,2 in crossed polars showing several oikocrysts with plagioclase laths having consistent alignment through all of them (long dimension = 1.8 mm).

Fig. 19: Plane light views of glassy matrix breccias from 14003,28. Dark areas are brown glass, white areas are vesicles, and gray areas are clasts (long dimension = 0.34 mm).

Fig. 20: Plane light views of devitrified glass-matrix breccias. (a) 67435,17 shows glass (light gray) at bottom left and various spherulitic crystal growths. (b) 64579,4 shows nucleation around margins of clasts (long dimension = 1.8 mm).

FIGURE CAPTIONS

Figure 11. FeO – MgO plot of Apollo 17 rock and soil analyses. "Average mare" and "Average highlands" soils are described in the text. Data are from the Curator's Data Base.

Figure 12. CaO – Al_2O_3 plot of Apollo 16 rock and soil analyses. Data are from the Curator's Data Base.

Figure 13. Schematic representation of the impact mixing and partial melting model that explains the diversity of polymict breccia compositions. Boxes represent material and ovals represent processes.

Figure 14. Rb-Sr evolution diagram showing whole rock data for lunar highlands rocks. The results of our calculated Rb-Sr evolution are shown for camparison. The calculations are based on the impact mixing and partial melting model and are described in the text. Data from Nyquist et al. (1972 and 1973), Papanastassiou and Wasserburg (1971, 1972a, and 1972b), and Tera et al. (1973).

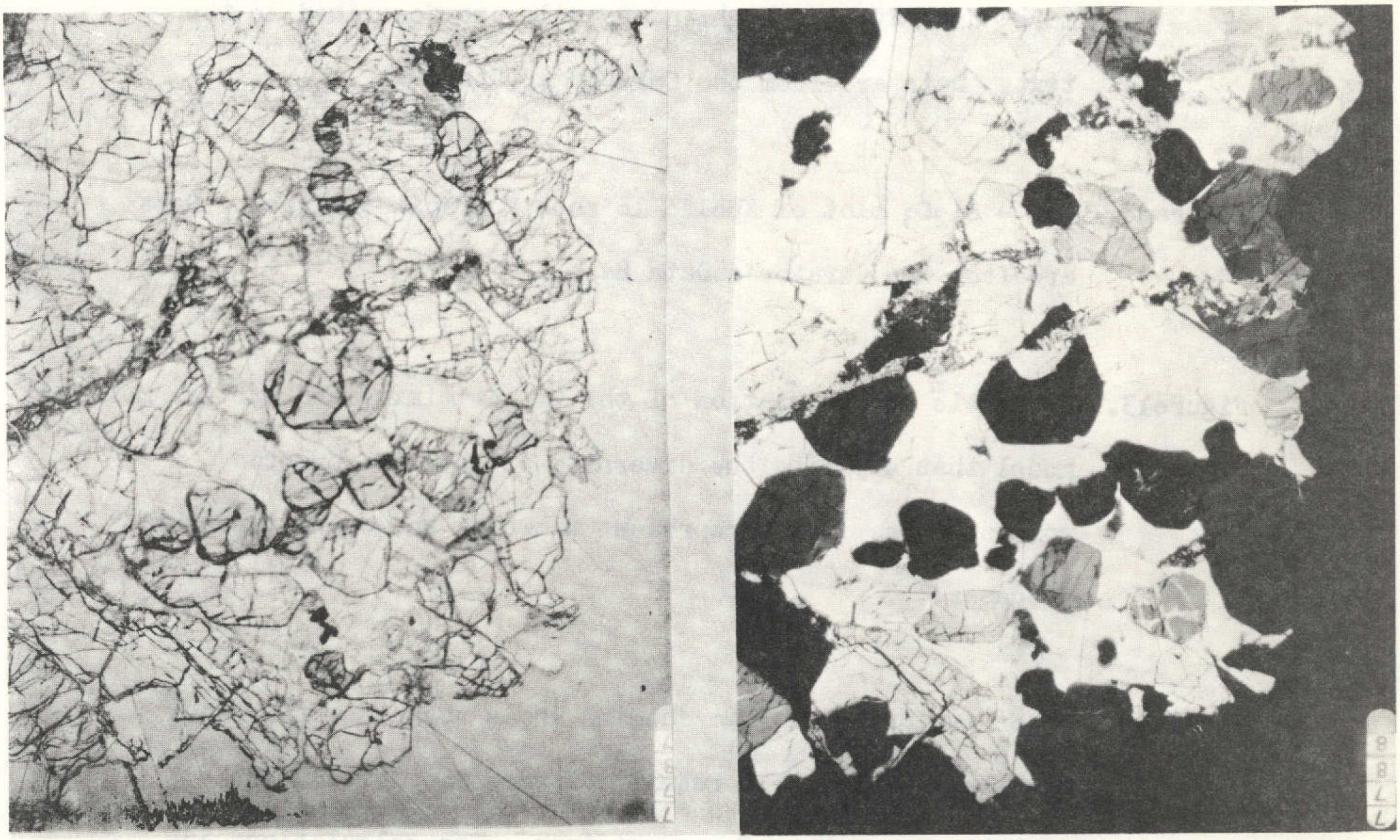

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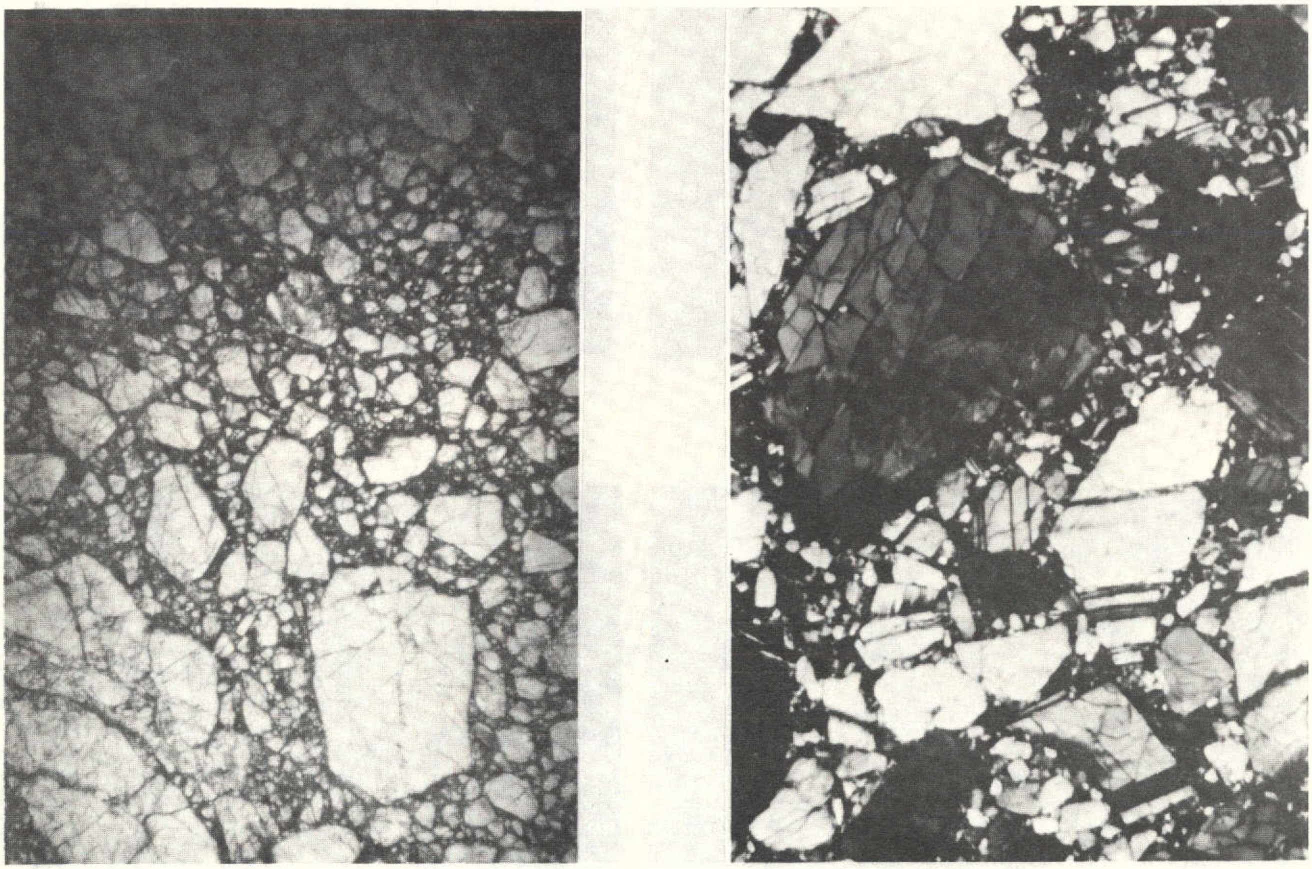
Figure 1



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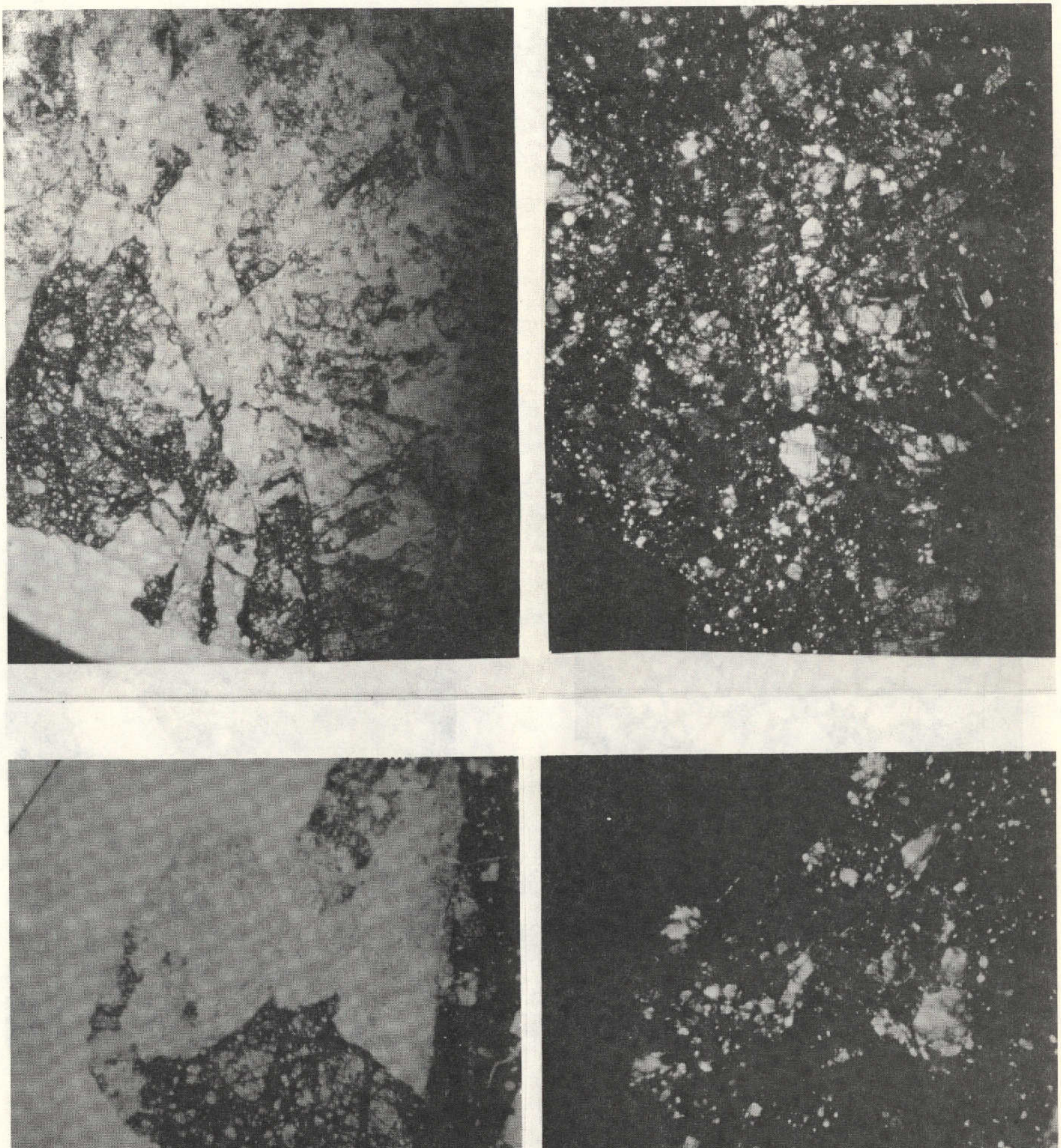

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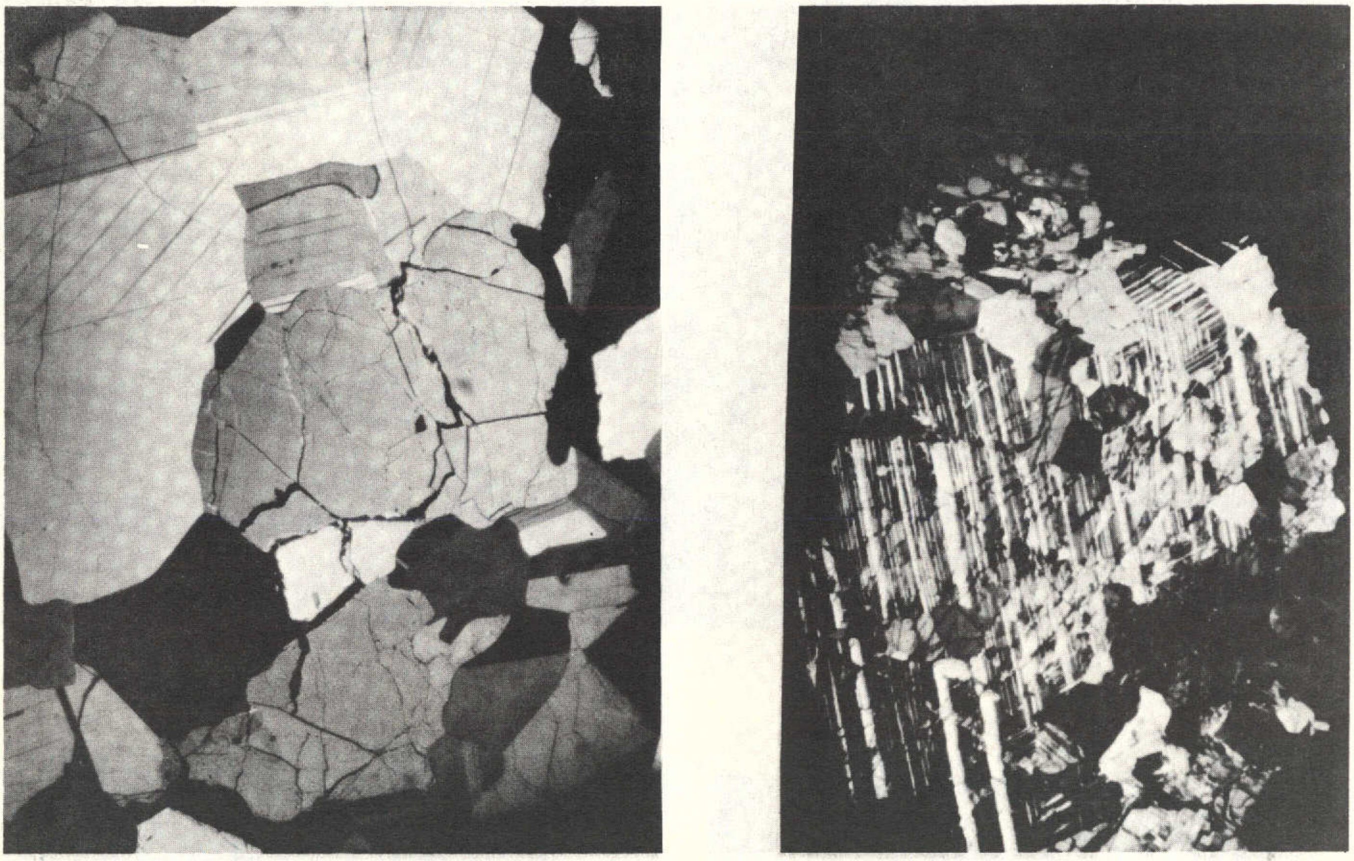

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Figure 4

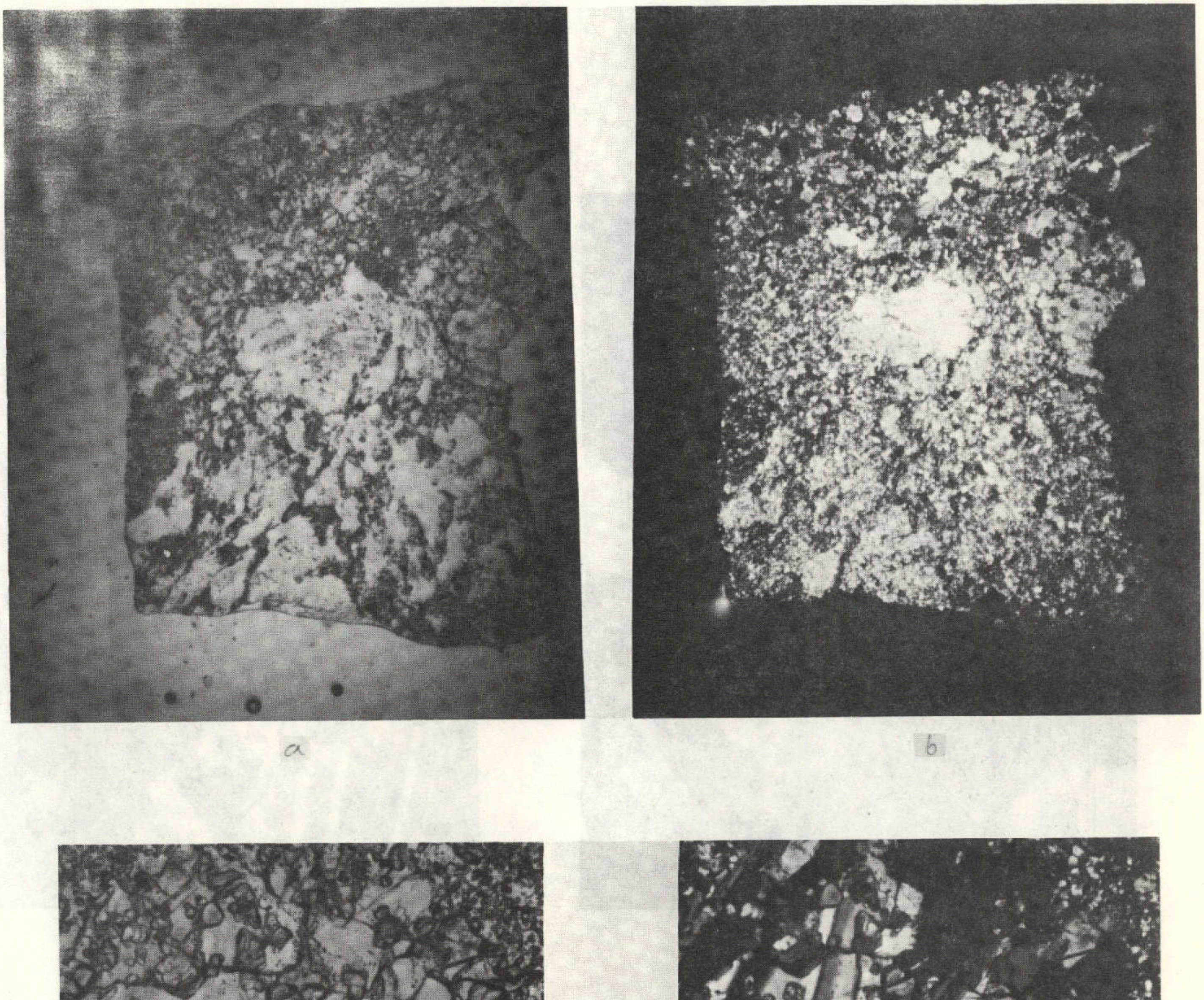

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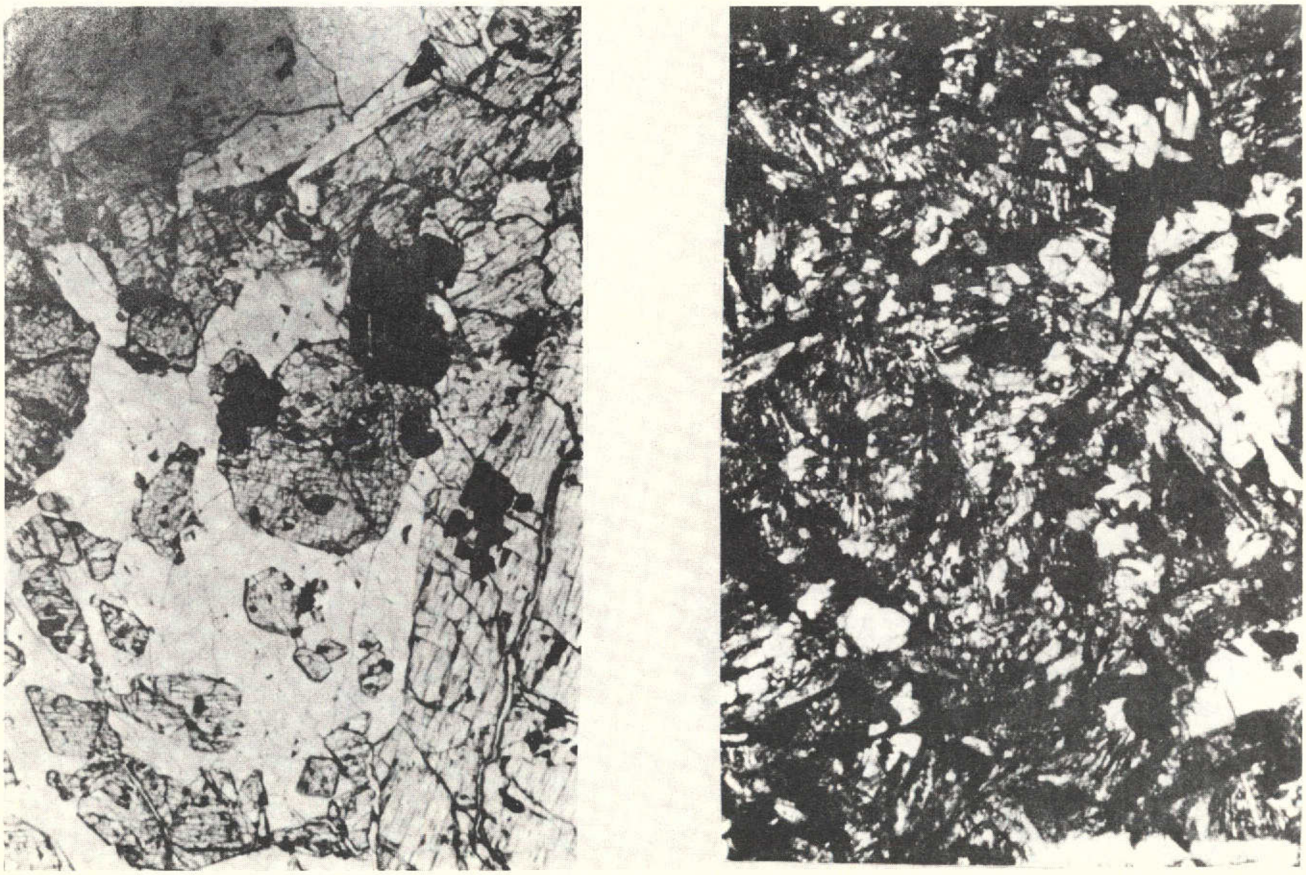
Figure 5



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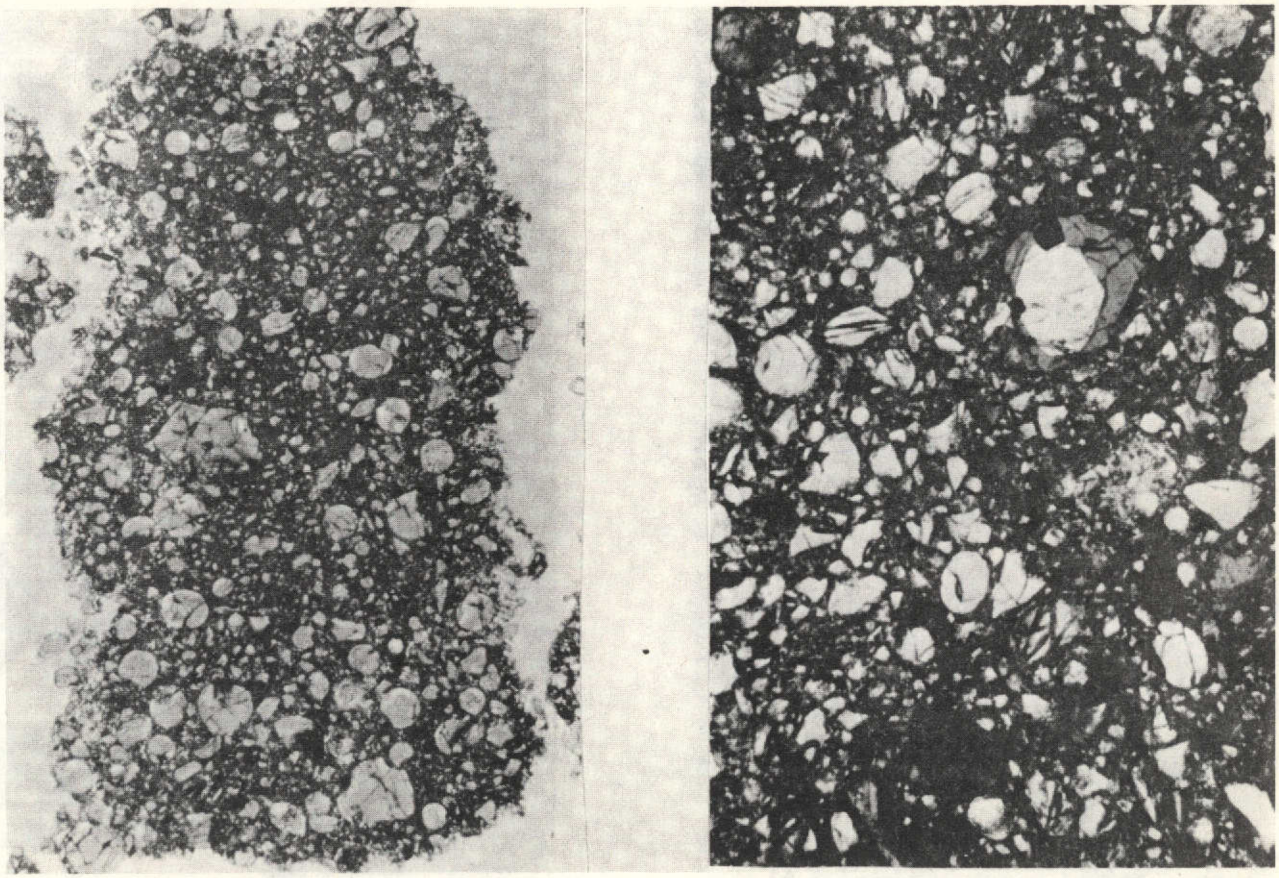

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Figure 7

Figure 8


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Figure 8 (continued)

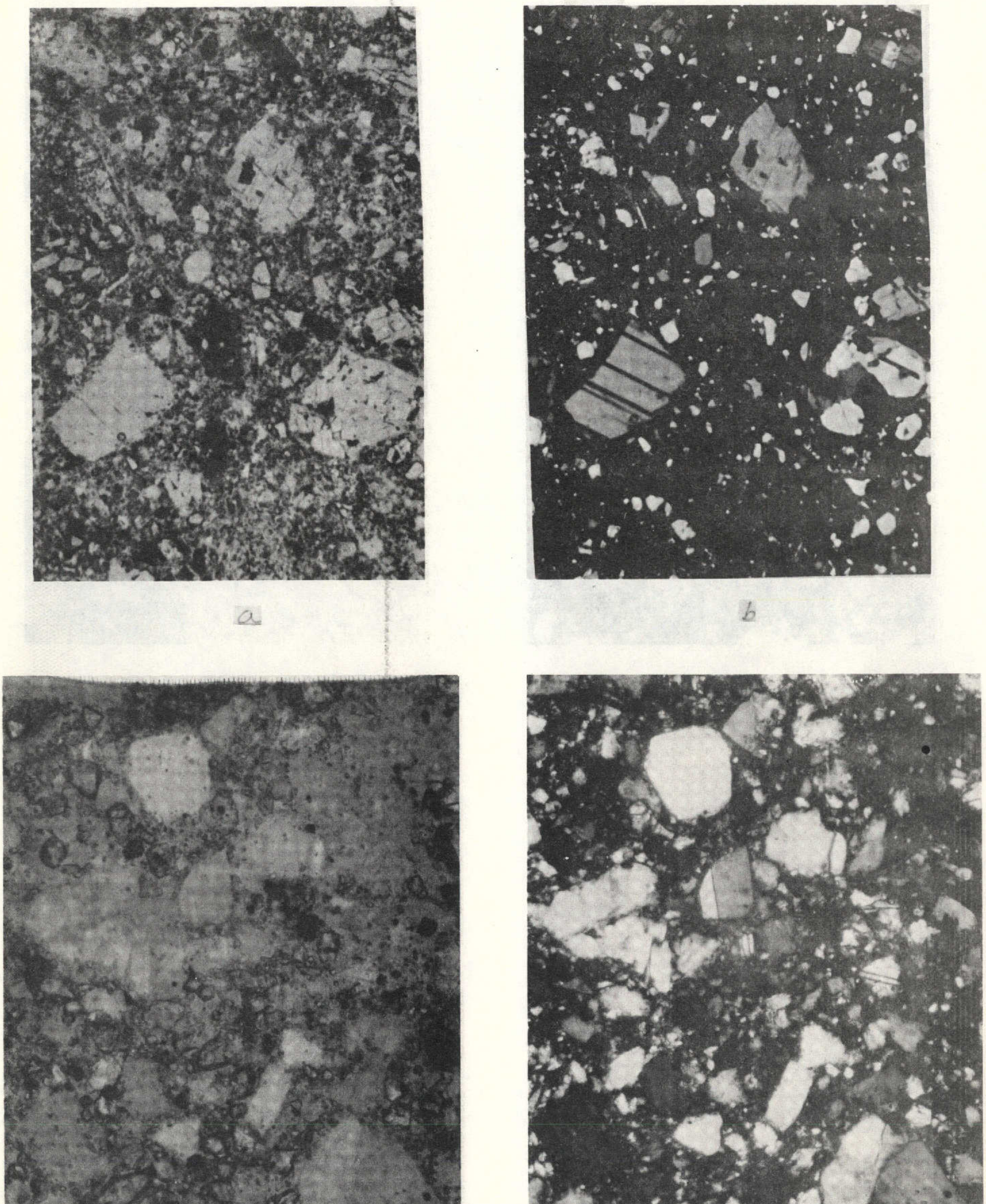

Figure 9

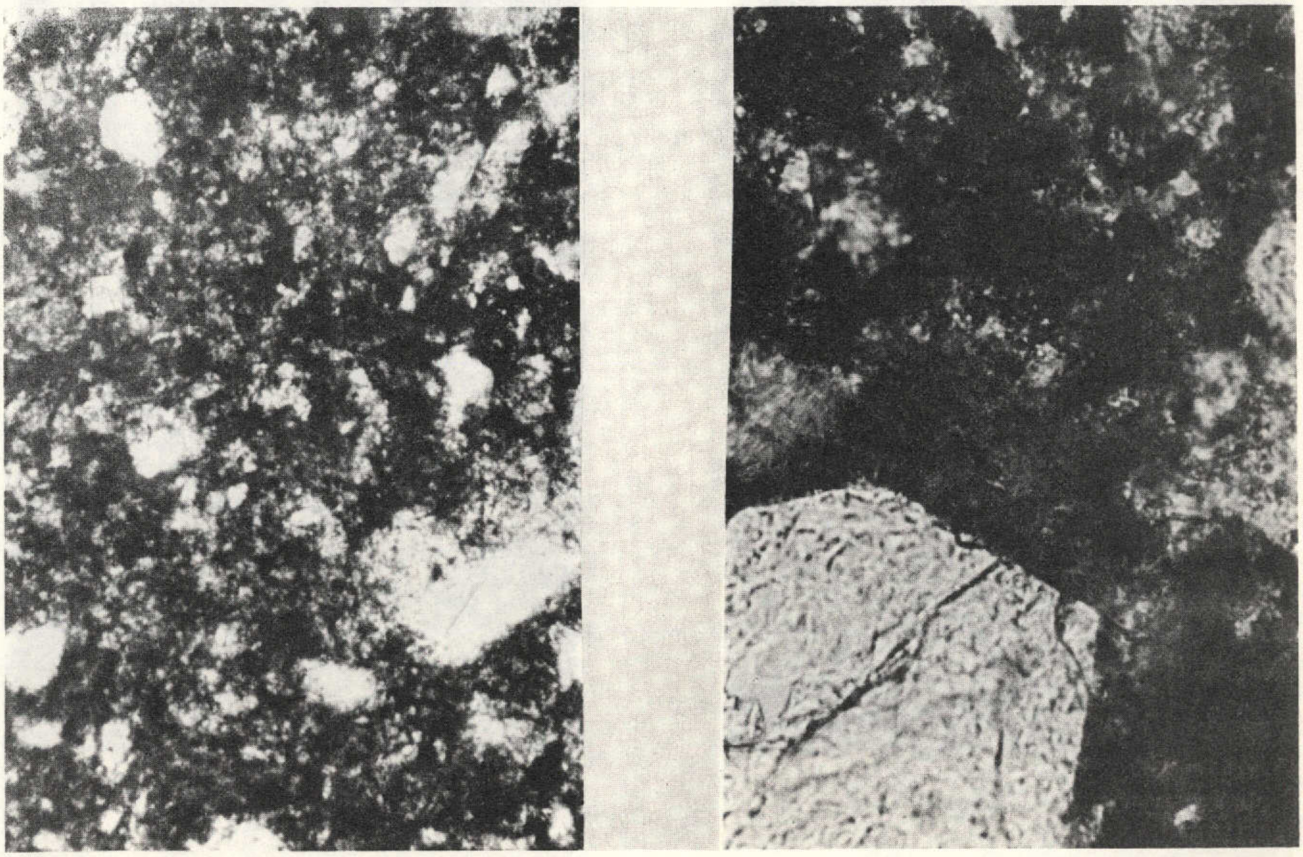

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Figure 10

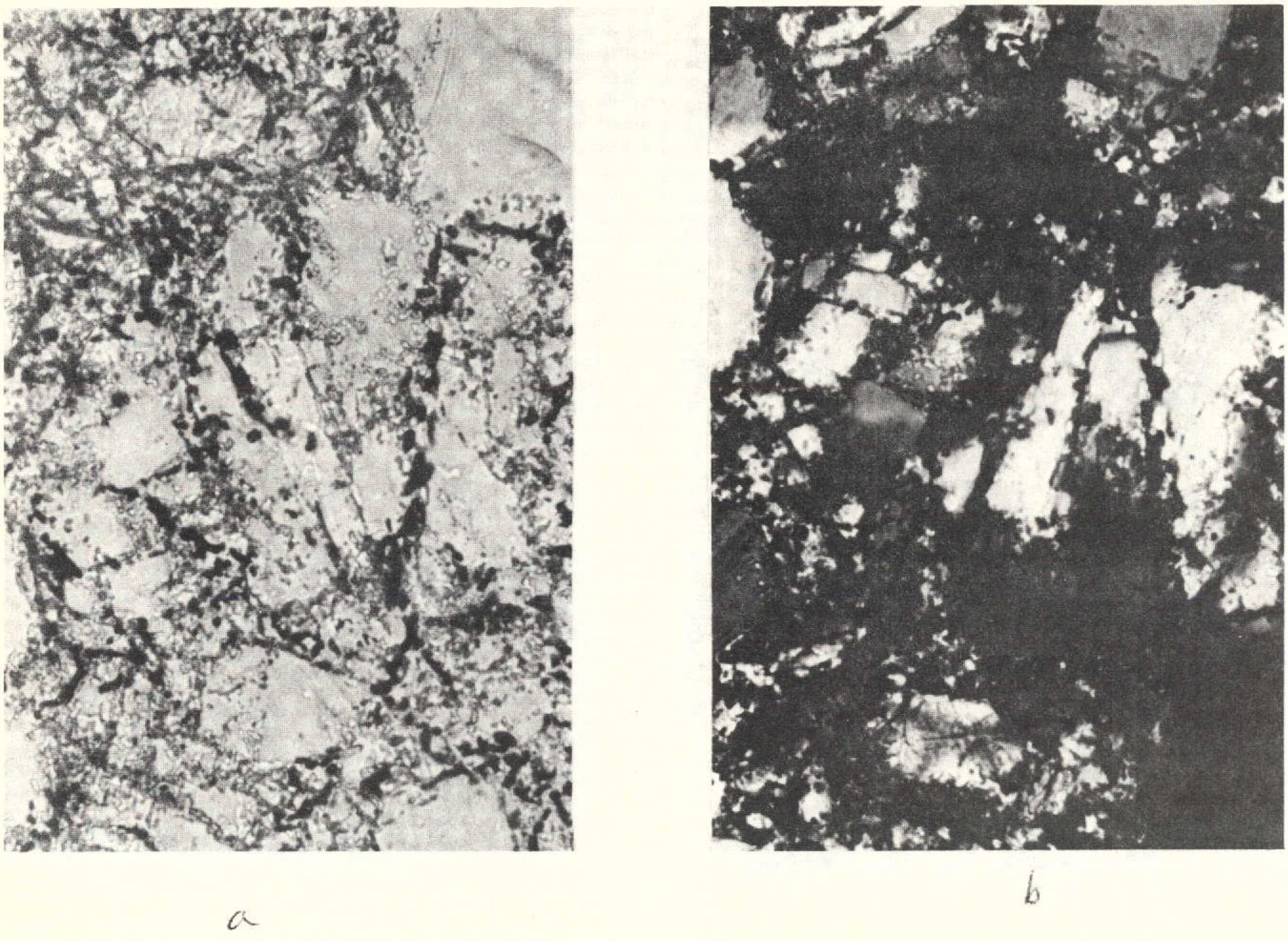


Figure 11

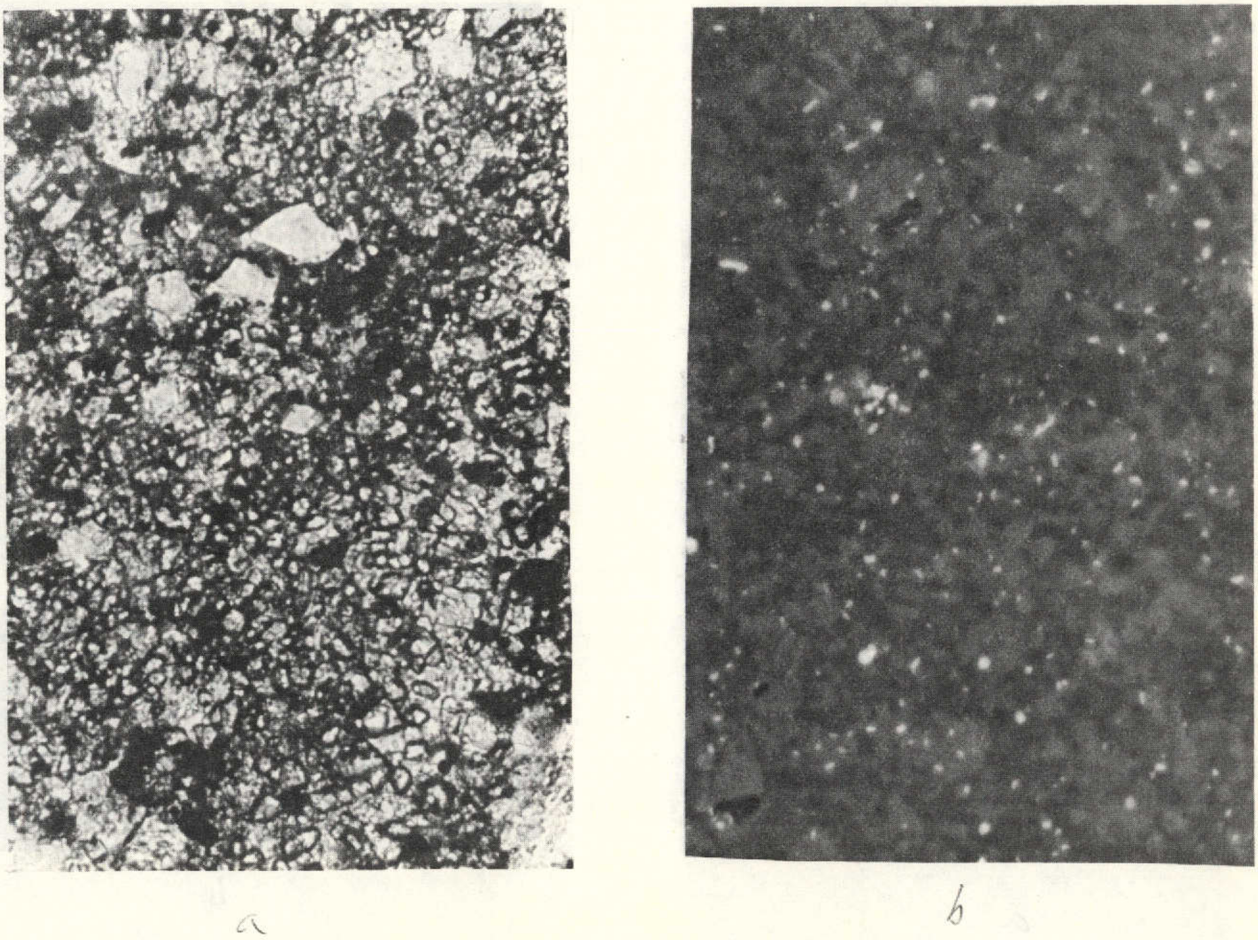
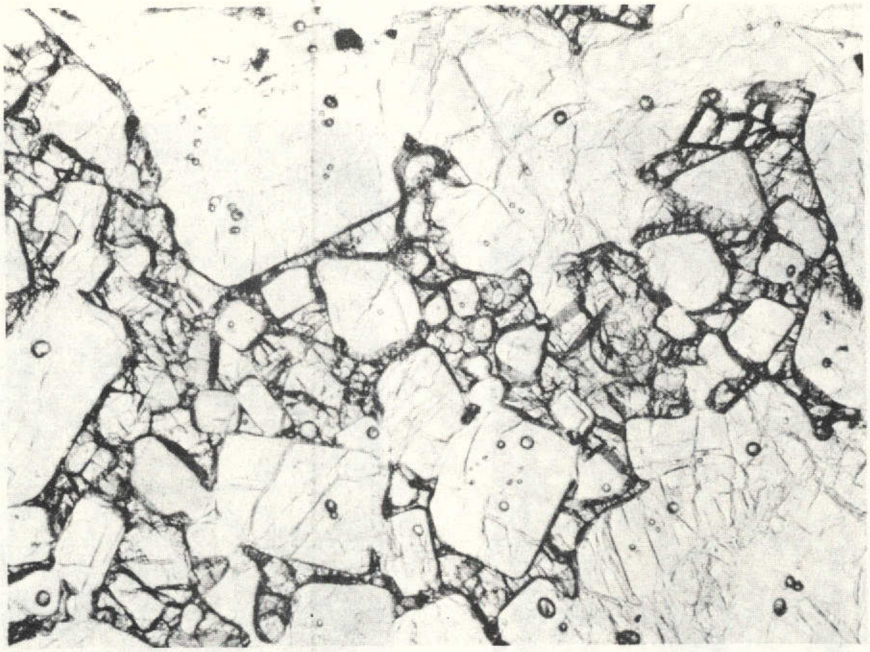


Figure 12



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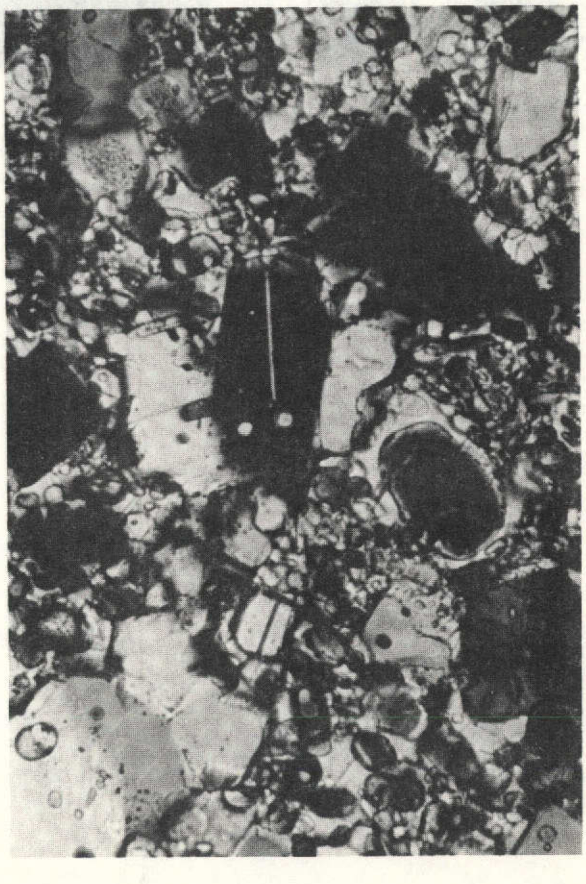
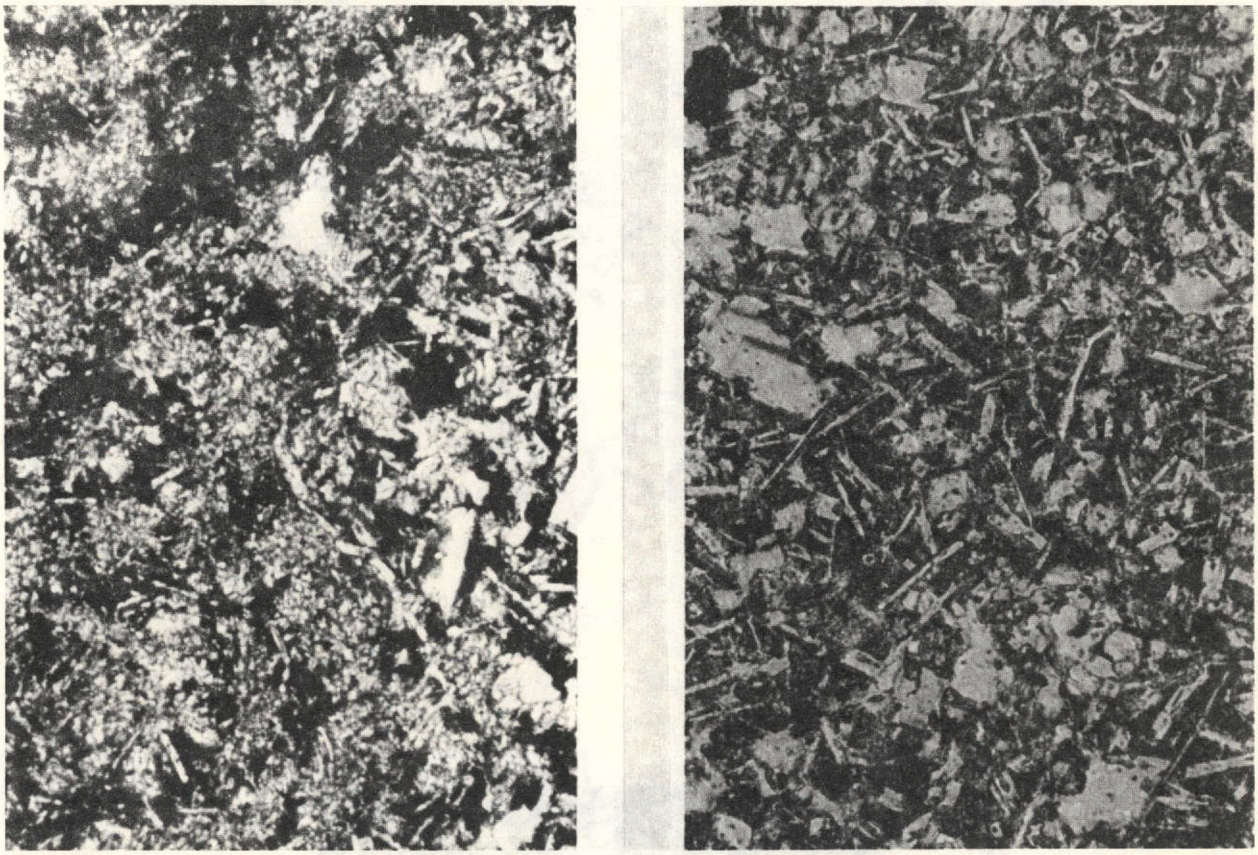


b

Figure 13



a

b

Figure 14

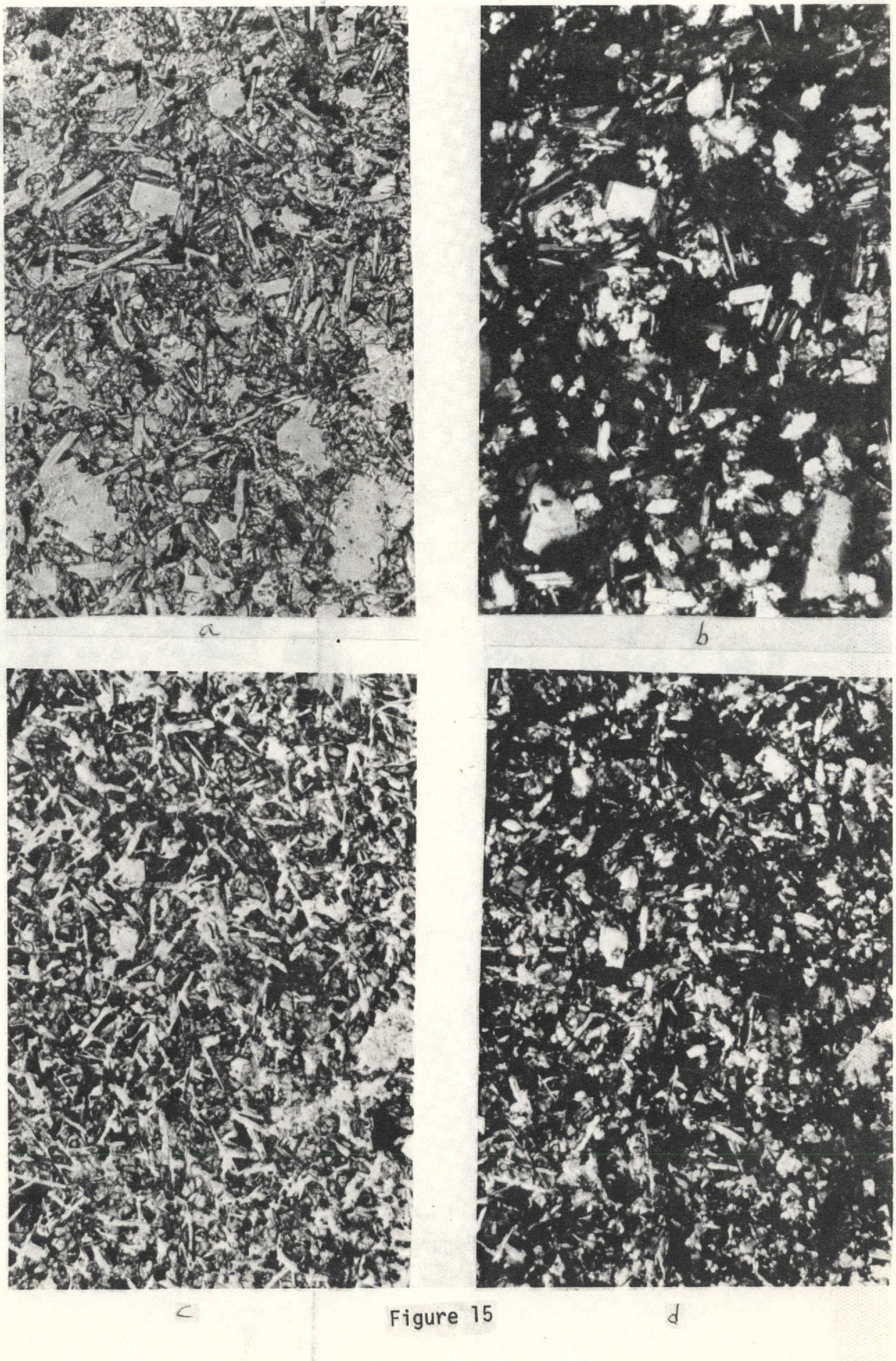
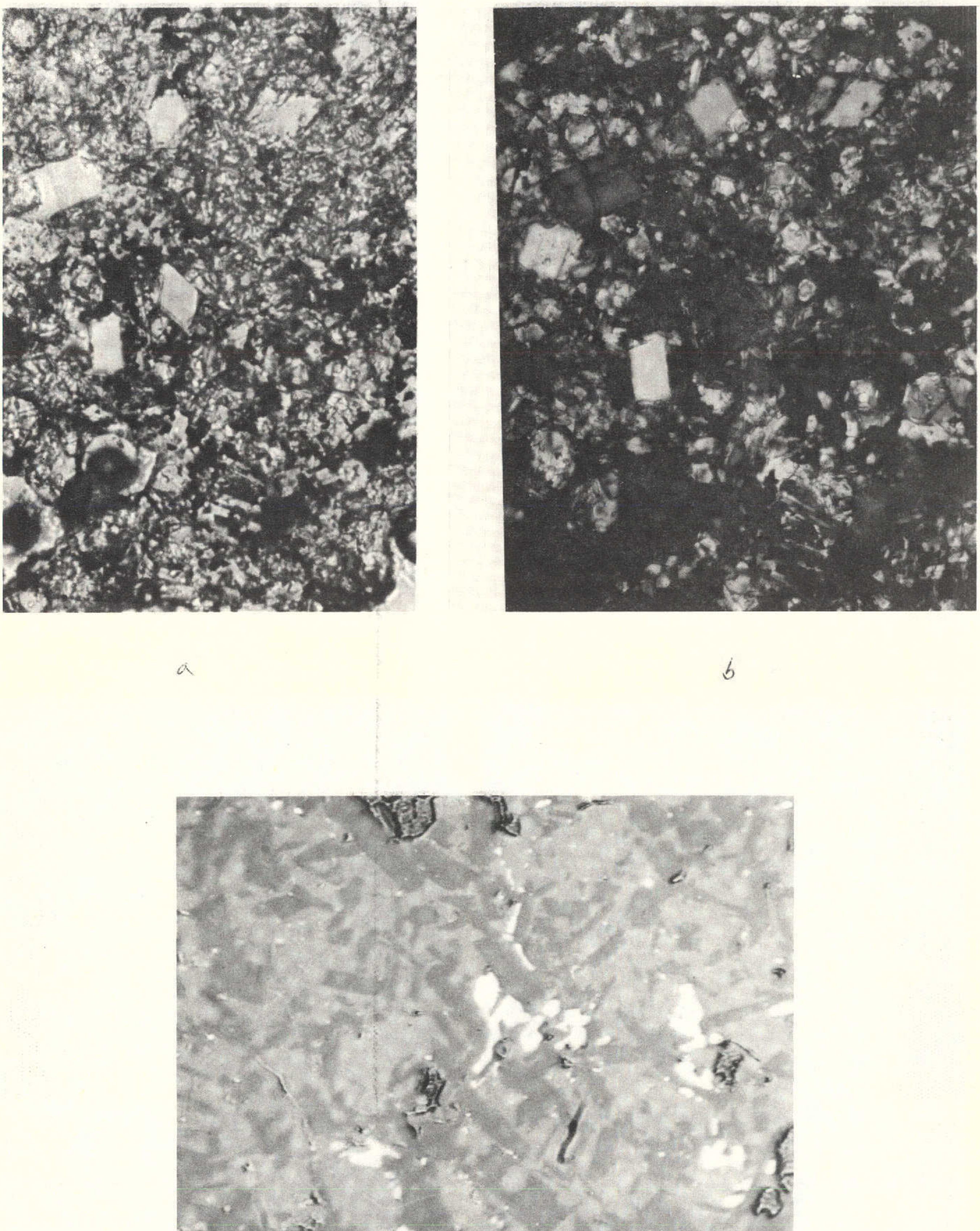


Figure 15

a

b

Figure 16



a

b

c Figure 17

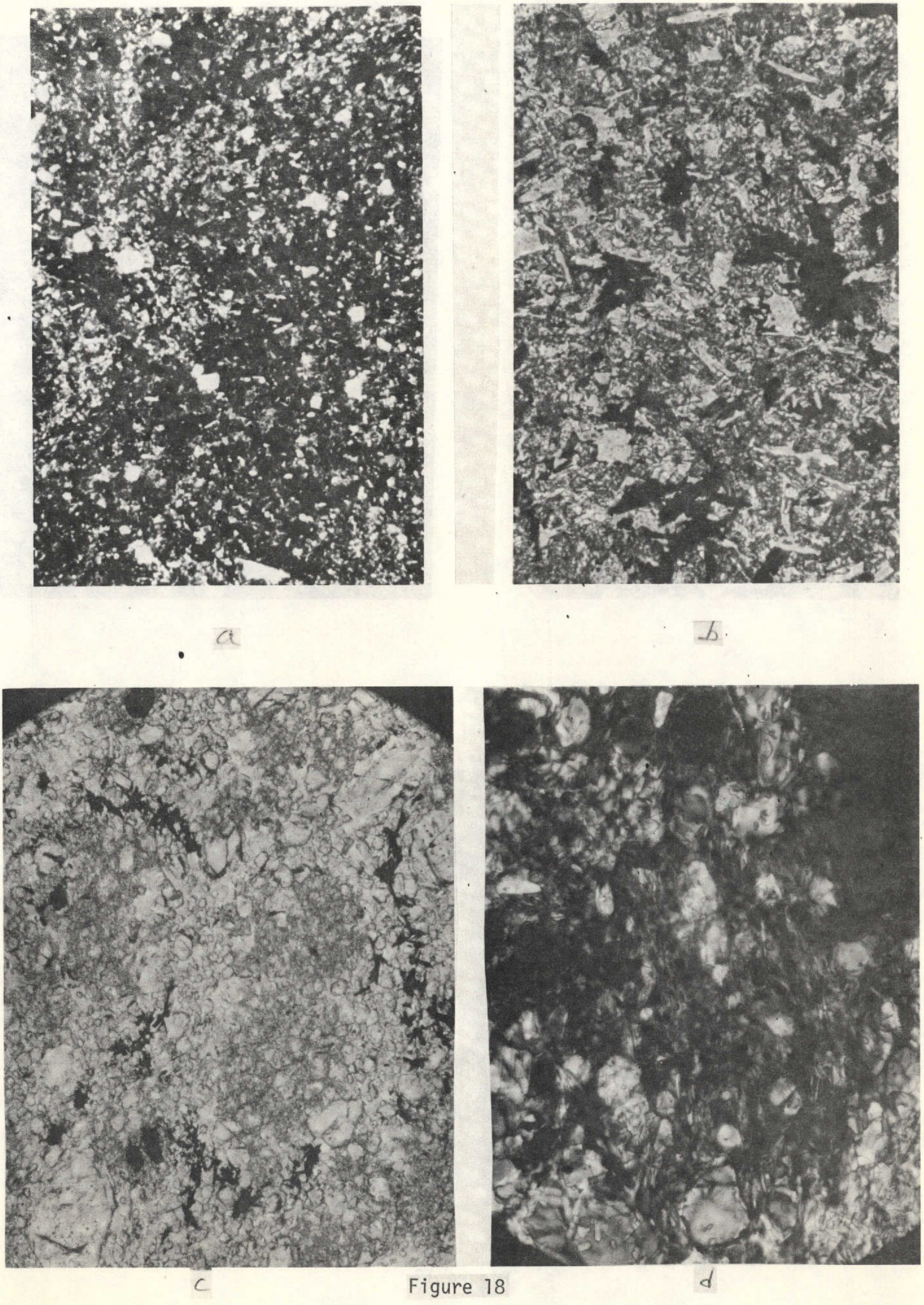
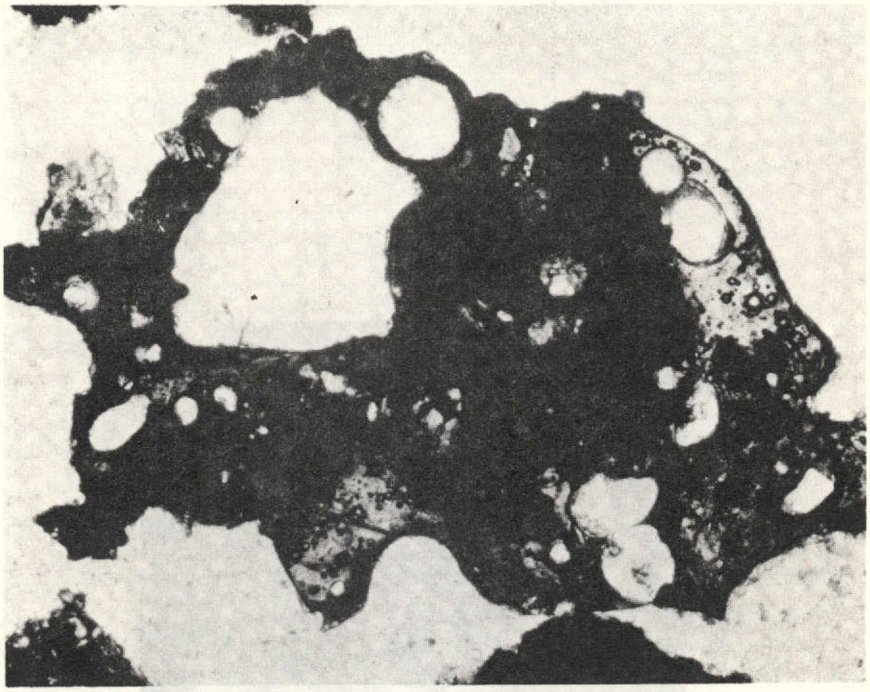
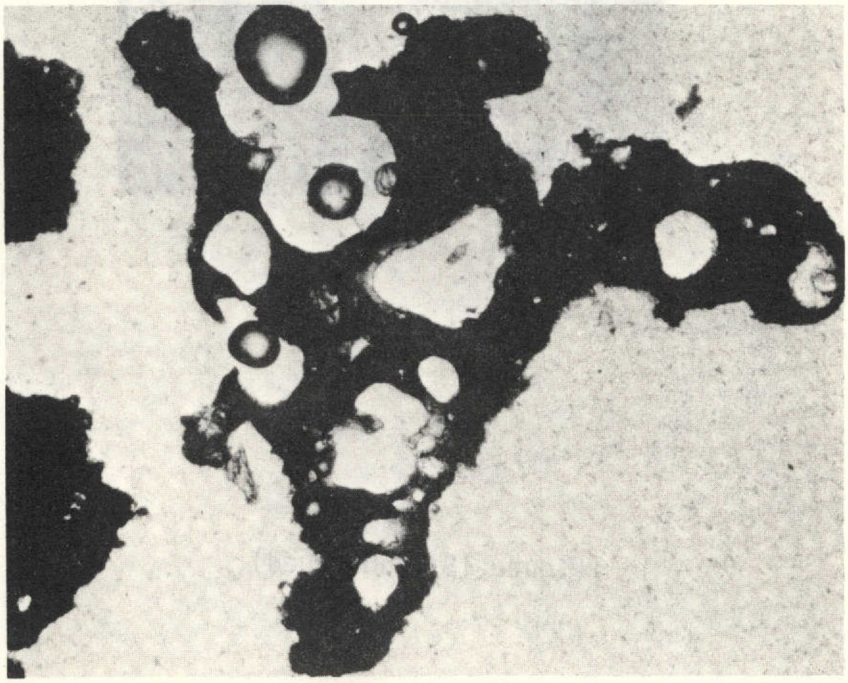


Figure 18

Figure 18 (continued)

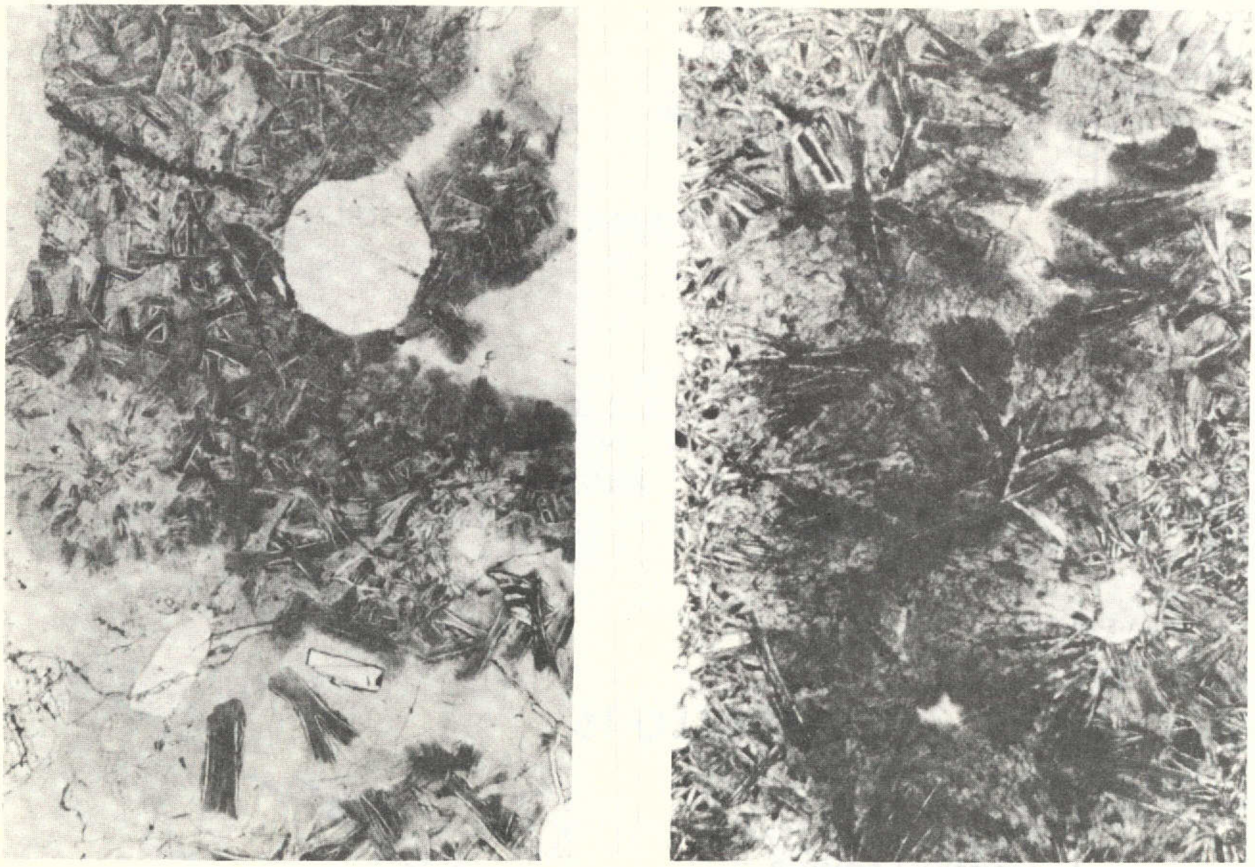


a



b

Figure 19



a

b

Figure 20

NASA-S-74-3281

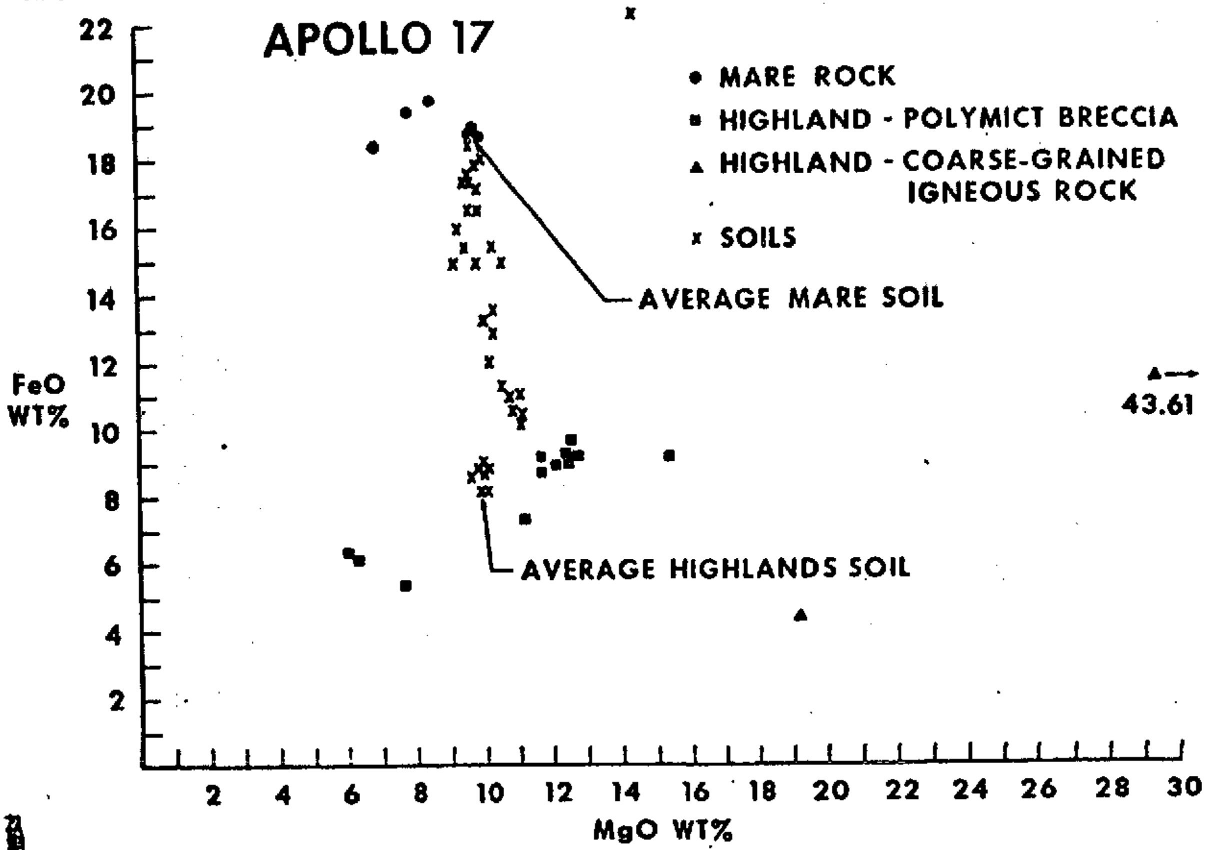


FIGURE 21

NASA-S-74-3282

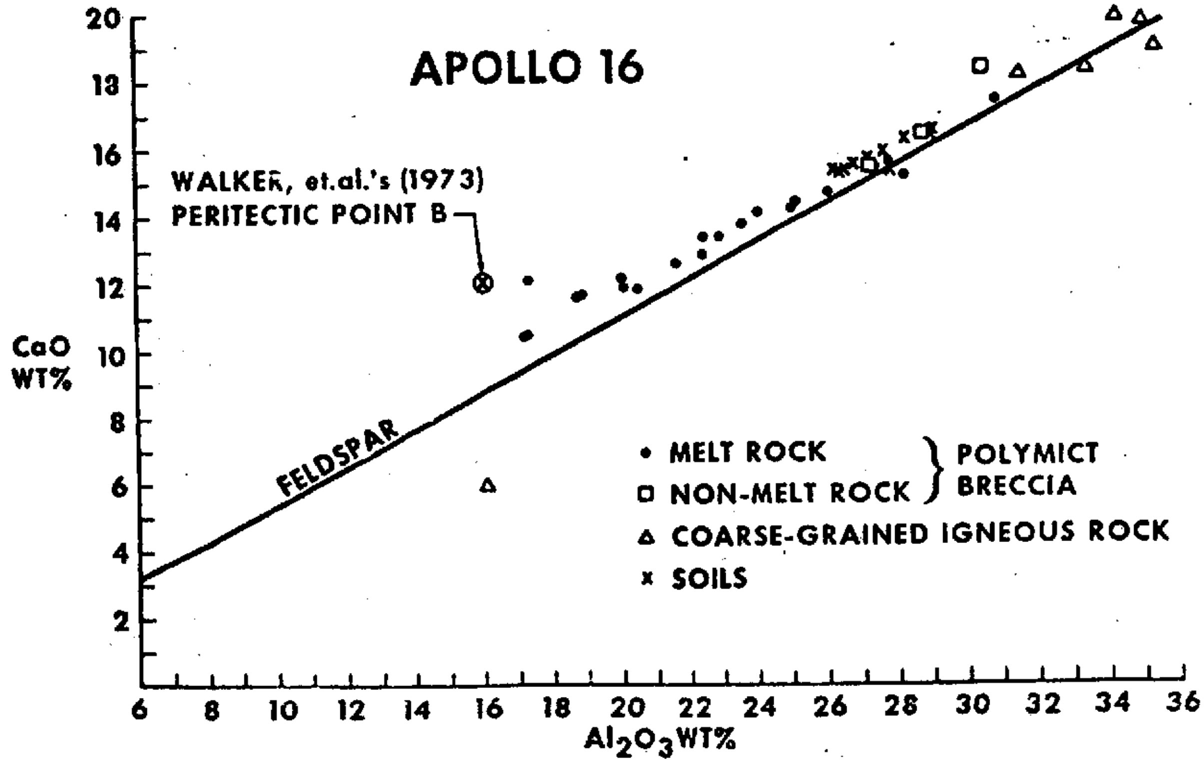


FIGURE 22

NASA-S-74-3433

FUNCTIONAL MODEL IMPACT PROCESSES

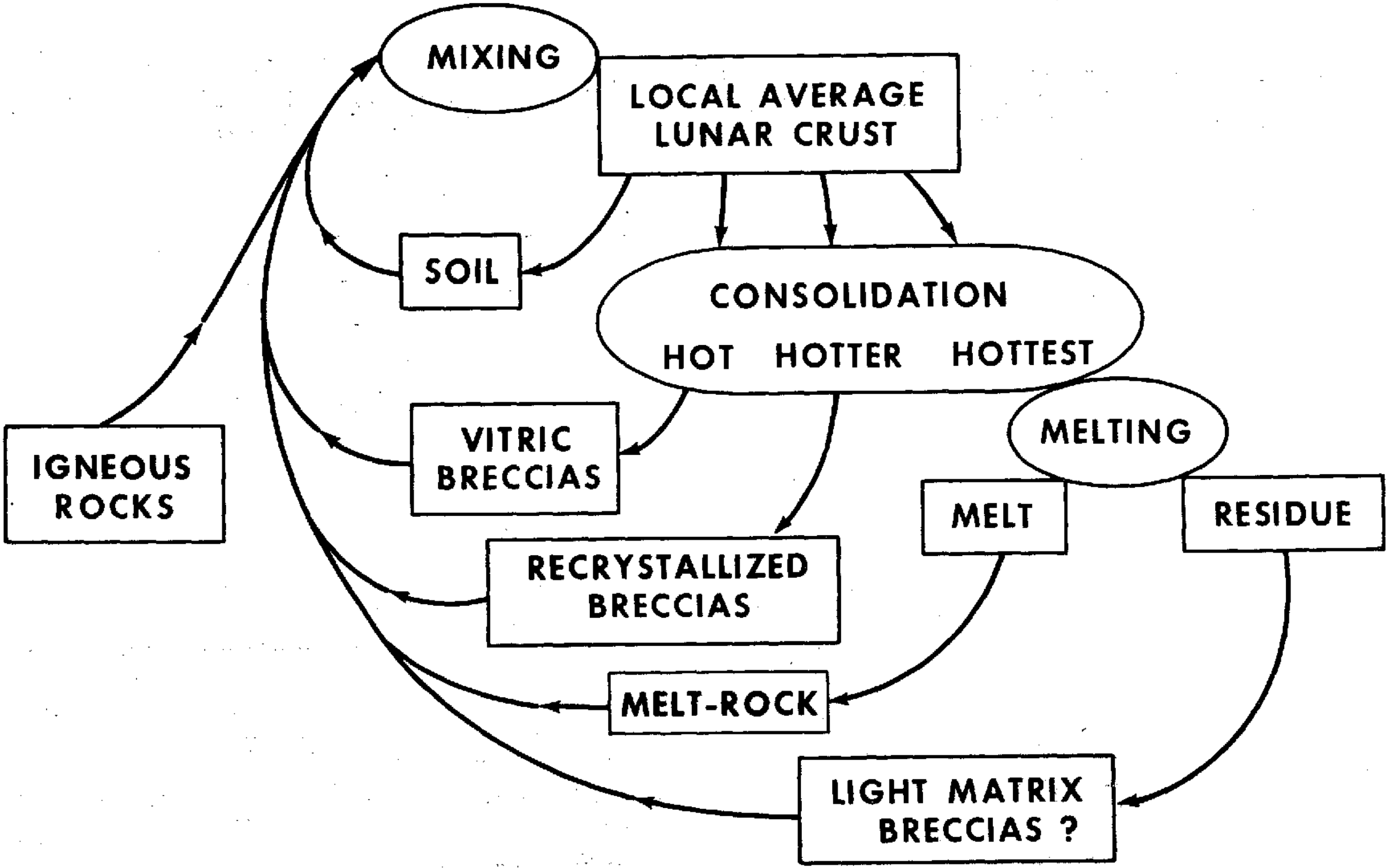


Figure 23

NASA-S-74-3435

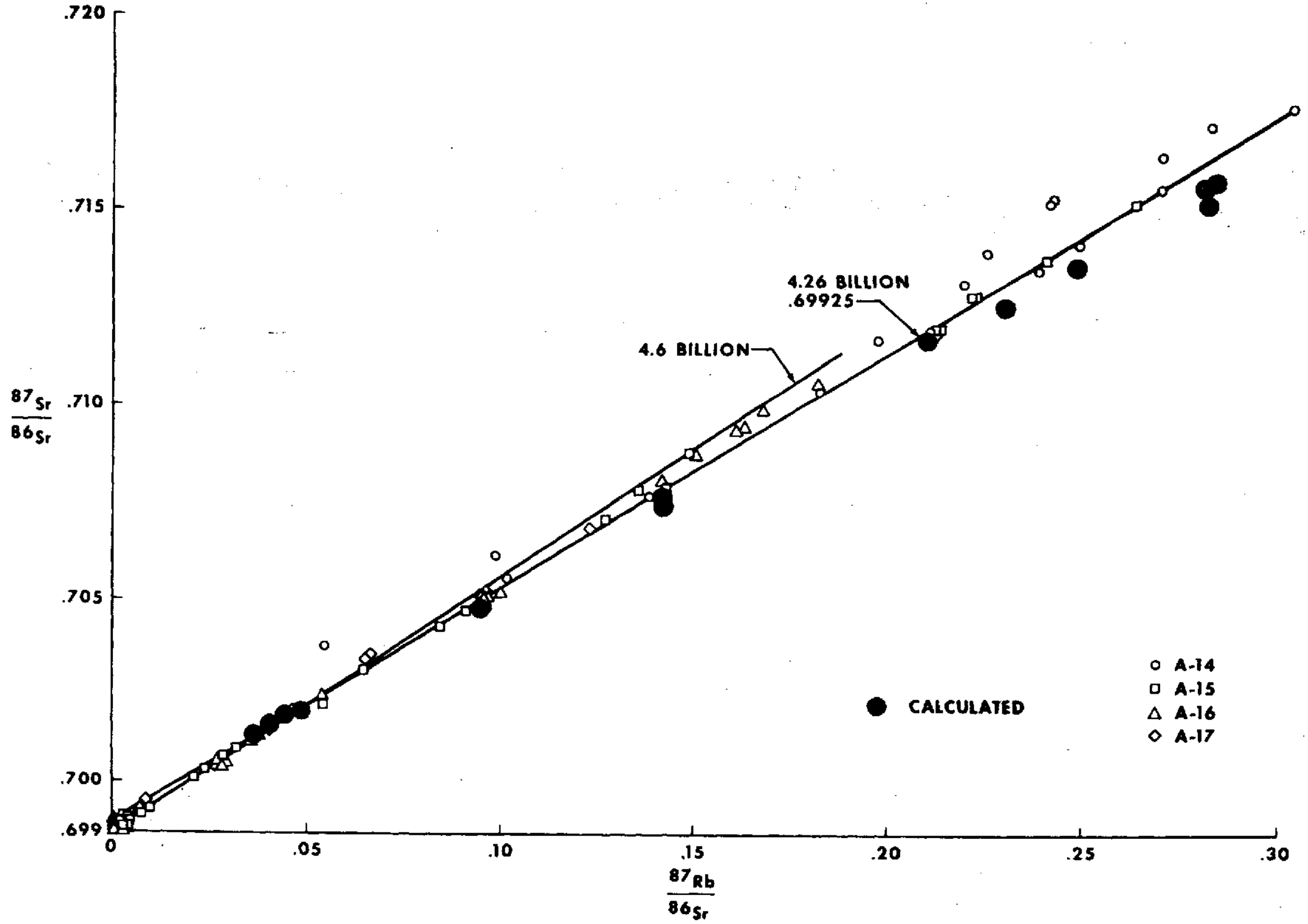


Figure 24