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LUNAR HIGHLANDS BRECCIAS GENERATED BY

MAJOR IMPACTS*

by

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ABSTRACT:

Lunar missions have returned a variety of different types of breccias. These rocks differ greatly in their mechanisms of formation, source materials, and histories after formation; but all are related in that all were generated by impact processes. In this paper I discuss the impact processes involved in formation of several major types of breccias and identify some types that may have originated in large impacts. Such breccias are extremely important. The impacts that formed them penetrated deeply into, and perhaps through the lunar crust and brought up materials that had previously experienced little or no impact modification. Detailed studies of such breccias can permit partial reconstruction of their pre-impact source terranes and yield information on the nature of the early lunar crust (and possibly the upper mantle as well).

Breccia types discussed

Type	Site	Examples	Possible Terrestrial Equivalents
Regolith breccias	All	14042, 14047, 14049, 14313	None
Cataclastic anorthosites	Major type at Apollo 16	60015, 60025, 62237, 67075	Crushed bedrock lining crater cavity and forming fragments within throwout deposits
Black and white rocks	Important type at Apollo 15, 16, 17	15455, 64475, 61015, 77075 + 77215	Crushed bedrock (containing injected dikes) lining crater cavity and forming fragments within throwout deposits
Light gray breccias	Minor type at Apollo 17	72215, 72255, 73215, 73255	Fallout and fallback deposits
Blue-gray breccias	Major type at Apollo 17	73235, 76315, 77115	Fallout and fallback deposits and dikes injected into crater walls and floor
Thermally metamorphosed breccias	Major constituent of Fra Mauro formation at Apollo 14	14270, 14303, 14305, 14306, 14311, 14321	?
Glass-poor feldspathic breccias	Apollo 14 white rocks on Cone crater rim, bed-rock at Apollo 16 North Ray crater	14063, 14082, 67015, 67016, 67455	?

The most widespread type of lunar breccia is regolith (or soil) breccia, representing lithified lunar regolith. Fragment assemblage and chemistry strongly reflect a history of extensive reworking and mixing at the lunar surface. Apollo 14 regolith breccias are good examples from a highlands site. In composition they are nearly identical to Apollo 14 fines. They show diagnostic characteristics of long exposure as particulate matter at the lunar surface: relatively high contents of Fe metal, of siderophile and volatile elements associated with meteorites, of solar-wind implanted C and N and trapped rare gases, of galactic and cosmic ray tracks and of O^{18} (1). The suite of clasts they contain is highly heterogeneous in texture and composition, and many have experienced multiple impacts. The fragments tend to be small, and clasts of fragment-free glass are abundant (2).

Most types of highland breccia, however, do not show characteristics of extensive reworking at the lunar surface. To aid in determining which of these may be related to major impacts, it is of value to compare them to terrestrial impact breccias. Terrestrial impact breccias are of three main types (3): brecciated bedrock lining crater cavities; throwout breccias; and fallout and fallback breccias. Brecciated bedrock samples are sheared and granulated and may contain dikes of injected materials. Throwout breccias are composed of crushed but largely unshocked rocks and contain little or no melt or glass; the clasts come from relatively high in the pre-impact stratigraphic sequence. These breccias have the widest lateral extent of all ejecta deposits (analogous to Bunte breccia of Ries Crater). Fallout and fallback breccias contain abundant shocked as well as crushed rocks and large amounts of melt; the fragments and melts mostly come from rocks relatively deep in the pre-impact sequence, though materials from higher levels are also present. These breccias are concentrated on the rim and within the cavity of the crater (analogous to suevite of Ries).

One suite of lunar breccias does appear to represent brecciated bedrock that once lined the cavities of large craters and may also have formed fragments in throwout deposits surrounding such craters. These are the "cataclastic anorthosites" (4) and "black and white rocks" (5). The rocks termed "cataclastic anorthosites" include granulated plutonic anorthosites, gabbroic anorthosites, and norites; some were recrystallized after granulation, some were only crushed, and some had several episodes of deformation and recrystallization. The "black and white rocks" consist of two lithologies: white rock identical to the "cataclastic anorthosites" and aphanitic black rock. The black rock appears to represent a mixture of impact melt and crushed bedrock injected into the white rock during cataclasis. The classic example is 15455. Here the black rock has very fine-grained igneous texture and is laden with fragments. Some of the fragments are of shocked plagioclase and devitrified plagioclase glass; other fragments are clearly derived from parent rocks that had different textures and compositions than the host white rock. Siderophile element studies show that the black rocks contains a meteoritic component whereas the white rock does not (6). Thus this black rock cannot be derived from the surrounding white rock alone, and some injection of material from within the crater cavity is required to explain the chemistry and fragment suite.

Another suite of examples may represent fallout breccias from a large impact, and these rocks are now being intensively studied to determine whether or not this is the case. They are the Apollo 17 light gray breccias, collected from near South Massif (7). 73255 and 73215 are good examples. 73255 consists of devitrified fragment-laden glass which is locally highly vesicular. 73215 is similar, except that it appears to have initially contained more fragments and less glass, and it underwent considerable shearing and recrystallization after consolidation. Preliminary studies of the fragment assemblage in 73215 suggest that these rocks may consist of ejecta from one of the basin-forming impacts. Most fragments appear to have been derived from only a few major suites of parent rocks; one of these suites consisted of coarse-grained plutonic troctolites and troctolitic anorthosites. Clasts that show the effects of multiple impacts are rare, and clasts of fragment-free glass are absent. Thus the clast assemblage suggests a deep source not previously plumbed by impact. The glass that binds the fragments together may represent impact melt that penetrated the cloud of ejected debris and cemented the ejecta after deposition.

Breccias with textures and fragment populations like the light gray breccias 73215 and 73255 are widespread on the lunar surface. Similar types that occur as large samples are the black lithology within the "black and white rocks" described above, and the Apollo 17 blue-gray breccias (7). Most breccias like these, however, occur as small fragments in fines samples and clasts in other breccias. (It is significant that such rocks form the most abundant type of clast in the > .1 mm size range in the Apollo 14 thermally metamorphosed breccias (2).) Where such rocks are uniform or occur as small clasts it cannot be established whether they originated as fragment-laden melts ejected from crater cavities or injected into basement rocks. However, their abundance and widespread distribution suggests that they represent an important facies of impact-produced breccias.

There are two other types of highlands breccias that may represent lithified debris deposits from major impacts: thermally metamorphosed breccias and glass-poor feldspathic breccias. Identification of these rocks as major-impact breccias is not as certain as for the rocks described above, and much additional study will be required to confirm or disprove this hypothesis.

Thermally metamorphosed breccias appear at the Apollo 14 site to be a major constituent of the Fra Mauro formation, a unit which formed as a deposit of Imbrian ejecta (8). These rocks either represent lithified and metamorphosed Imbrian ejecta (9, 2), or they are clasts of Pre-Imbrian metabreccias in the Imbrian deposit (3, 10). The published studies of the characteristics of these breccias cast some light on the preaggregation histories of the fragments they contain, but these studies are by no means complete enough to be definitive. The fragment suites (2) are much different from those typical of regolith breccias. The suite of lithic fragments is not as diverse as in regolith breccias but not as homogeneous as in the Apollo 17 light gray breccias. Clasts that show effects of multiple impacts are present in significant numbers. Clasts that were initially fragment-free glass are sparse, and clasts of recrystallized fragment-laden glasses (like the Apollo 17 blue gray and light gray breccias) are abundant; this is the reverse of the case in regolith breccias. In the .1-1 mm size range, fragments of single mineral grains are twice as abundant as in regolith breccias. The rocks show no appreciable O^{18} enrichment (11), in contrast to regolith breccias, but they do show sparse unannealed particle tracks ascribed to irradiation of fragments prior to breccia aggregation (12). Thus it appears that the fragments in these breccias have undergone more complex histories of multiple impacts than fragments in the Apollo 17 light gray breccias, but they have probably had less extreme reworking than fragments in regolith breccias.

Glass-poor feldspathic breccias at the Apollo 14 site are probably derived from within the Fra Mauro formation, and at the Apollo 16 site similar rocks form a layer 100-250 m thick underlying the northern part of the sampling area (13). Evidence for origin during large impacts is the compositional homogeneity of the fragment suite and the apparent deep-seated source of many of these fragments. The breccias consist largely of crushed debris derived from relatively coarse-grained, highly feldspathic rocks. Most clasts are of single mineral grains. Clasts of devitrified fragment-free glass are sparse, but present, and clasts of dark devitrified fragment-laden glasses are common. Only sparse glass is present binding fragments together. Chemistry and track data suggest that the particles had little or no exposure to the lunar surface environment prior to breccia aggregation (14).

Relations of this type of breccia to other types are unclear. At Apollo 14, these rocks formed irregular layers and patches in boulders of darker rock, and the dark rocks were not sampled. At Apollo 16 there is no clear association with other breccias. At Apollo 17, however, glass-poor feldspathic breccias form schlieren included within light gray breccias, and the association is now under study in samples 73215 and 73255. Here it is possible that the two lithologies are different facies of ejecta of the same impact.

Studies now in progress of the fragment suite of the light gray breccia 73215 provide an example of the type of information on the nature of the early lunar crust that may be obtained from such breccias. For the purposes of illustration, I will assume here that it has been demonstrated that the sample consists of major impact ejecta, and I will attempt to reconstruct its source terrane from the observed fragment assemblage.

The most abundant clasts are of single mineral grains, and it appears that a large number of these were derived from relatively coarse-grained plutonic rocks (up to 4 mm grain size observed). Fragments of plagioclase are greatly dominant; fragments of olivine and pyroxene (containing optically prominent exsolution lamellae) are subordinate, with the former more common than the latter. Most lithic fragments are derived from three major suites: 1) coarse-grained plutonic troctolites and troctolitic anorthosites; 2) fine-grained anorthositic-noritic-troctolitic hornfelses; and 3) fine-grained igneous-textured spinel troctolites.

Most of the large lithic clasts are of plutonic troctolites and troctolitic anorthosites. Most of these were granulated prior to incorporation in the breccia, but they show relict grain sizes up to 4 mm. The troctolites appear to be like the troctolite sample 76535. It has been proposed that such rocks are from a source more than 10 km deep and they may have formed 4.3-4.4 billion years ago (15); thus, they may be some of the original rocks of the lunar crust.

Most of the smaller lithic clasts are of fine-grained hornfelses whose textures range from microgranular to micropoikiloblastic. Some are of deep-seated origin and formed by recrystallization of sheared zones in coarse-grained parent rocks; others are probably of shallower origin and represent recrystallized impact debris deposits. The spinel troctolites are of shallow origin and crystallized from rapidly cooled melts. It is not certain whether these melts were endogeneous or generated by impact.

One major contributor to 73215 is an enigma. This is the source material for the glass that binds the fragments together. Bulk composition of the glass appears to be that of feldspathic or low-alkali high-alumina basalt, in which plagioclase and low-calcium pyroxene are the dominant minerals and are about equal in abundance. The glass is also relatively rich in potassium and rare earth elements. No lithic fragments of similar composition are found within the breccia, but clasts of "granitic" rocks are present (plagioclase laths with coarse interstitial intergrowths of a silica mineral and potassium feldspar). The source for the glass could have been a noritic rock that was completely melted, or it could have been a mechanical mixture of troctolite plus "granitic" rocks.

Thus the fragment suite of the light gray breccias suggests that the source crust from which they were derived had a layered structure. The deepest material excavated came from greater than 10 km below the surface; the rocks were coarse-grained plutonic troctolites and anorthosites, "granitic" rocks, and possibly norites. They had not previously been excavated by impact and may represent samples of early lunar crust. Locally, however, these rocks had been sheared and deformed by impacts in overlying rocks and the sheared zones had later recrystallized. Above these plutonic basement rocks lay a series of metamorphosed ejecta deposits, perhaps interlayered with fine-grained spinel troctolites.

Much of the material presented in this paper is speculative, and much more work remains to be done before many of these suggestions can be either confirmed or disproved. However, the method of approach to the study of lunar highlands breccias outlined herein is potentially of great value. Although the fragment suite of a single sample of major-impact breccia will not be representative of the entire pre-impact source area, studies of such samples can permit partial reconstruction of that source. By such an approach we may eventually be able to decipher some of the history of the moon's crust and upper mantle during the first half billion years of lunar history.

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INTRODUCTION

The lunar missions have returned a variety of types of breccias. These rocks differ greatly in their mechanisms of formation, source materials, and histories after formation, but all have a common factor involved in their genesis in that all formed by processes related to impact bombardment of the lunar surface. Among all these types of breccias, there is one particular class (if it can be identified) that holds great potential for study of the early history of the lunar crust. This is the class of breccias that formed as a result of major impacts -- the impacts that generated the mare basins and the largest of the lunar craters. Impacts of this magnitude would have penetrated deeply into the lunar crust, and perhaps even though it into the lunar mantle. They would have excavated both materials of the upper parts of the crust and deep-seated rocks; among the latter might have been rocks that had originated in the early stages of crustal evolution and had not been greatly disturbed by impact since they formed. If some breccias can definitely be established as representing little-reworked ejecta from large events, studies of the materials they contain could permit a partial reconstruction of the pre-impact lunar crust at the site of impact. In this paper I discuss the processes that may have been involved in the formation of most of the major types of lunar breccias (Table 1), and I identify some of the types of highlands breccias that may have originated in large impacts.

TERRESTRIAL IMPACT BRECCIAS

To aid in determining which of the lunar breccias may be related to major impacts, it is of value to compare them with terrestrial impact breccias. The general characteristics of terrestrial impact breccias are briefly described below; the discussion is based mainly on the characteristics of breccias associated with the Ries Crater in Germany (Chao, 1973b; Dennis, 1971), but data from other structures are also included.

Breccias associated with the Ries Crater are of three main types: 1) brecciated bedrock, 2) Bunte breccia and Gries, and 3) suevite. The brecciated bedrock is material that was deformed during the impact event but remained in place, whereas the Bunte breccia, Gries and suevite are deposits of different kinds of ejected materials.

Brecciated bedrock lines the floor and walls of the crater cavity. The rocks are sheared and granulated and their minerals locally show weak shock-induced plastic deformation.

Bunte breccia and Gries ejecta deposits form a blanket of wide lateral extent surrounding the crater. These breccias consist of the earliest deposited of the ejected materials. They are composed of crushed but largely unshocked rocks and contain little or no impactite glass or melt rocks. The clasts they contain come from relatively high in the pre-impact stratigraphic sequence.

Suevite ejecta deposits are concentrated on the rim and within the cavity of the crater, and they overlie deposits of the Bunte-breccia type. They consist of the last of the ejected materials. The deposits are poorly sorted and unstratified, but the fragments within them show planar preferred orientations. Abundant clasts of shocked as well as crushed rocks are present. Also present are large proportions of impactite glass, most of which represents impact melt that solidified in flight prior to deposition. Most of the material in the deposit cooled considerably in the time interval between ejection and deposition, and there was little or no consolidation of the breccia by sintering or cementation by hot interstitial glass. Most of the fragments and melt are derived from rocks relatively deep in the pre-impact stratigraphic sequence, although materials from higher levels are also present. Glass content of the breccia and depth of source of the fragments it contains show a rough positive correlation. (Fragment population studies of Ries suevite have been reported by Ackermann (1958) and Chao (1973b). Ackermann found that 80% by volume of the suevite he studied was fine-grained matrix; of the remaining volume of the rock, 55%-90% was glass bombs, 10%-35% was fragments of deep-seated rocks, and less than 5% was fragments of shallow origin. Data on fragment abundances given by Chao are as follows: for most suevites he studied he found 62%-75% glass bombs, 18%-30% fragments of deep-seated rocks and 2%-8% fragments of shallow origin, but one suevite contained 52% glass bombs, 15% fragments of deep-seated rocks, and 27% fragments of rocks from shallow levels.)

Impactite glass was incorporated in the suevite in the form of small fragments, bombs, and coatings on lithic clasts. Much of this glass is vesicular (fig. 1) and there is evidence that the impact melt from which it formed possessed a considerable degree of superheat; Hörz (1965) and El Goresy (1964) estimated original temperatures in excess of 1500°C and 1700°C, respectively, for these melts. The melts incorporated highly variable proportions of lithic and mineral fragments. Many of these fragments are of broken but undeformed rocks and mineral grains, but significant numbers of grains of thetomorphic glass and shock-deformed mineral grains are also present. The fragments show large variations in thermal history that may reflect variations in the post-shock temperatures they attained prior to being incorporated in the melt. Many grains show no evidence of being strongly heated, despite the high temperatures of the surrounding impact melts, and they may have been quite cool when incorporated. In contrast, some of the fragments of thetomorphic glass and shocked minerals have recrystallized, and some of the unshocked lithic fragments show partial melting at grain boundaries (fig. 2); such fragments may have been strongly heated during the impact so that the added heating they received after incorporation in the impact melt produced the recrystallization and partial melting.

LUNAR BRECCIAS

Regolith Breccias

The most widespread type of lunar breccia is regolith breccia (also referred to as soil breccia by many investigators). These rocks are not related to single impacts but they instead represent consolidated lunar surface debris that had been reworked by countless impacts prior to lithification. Such breccias are strongly preponderant at mare sites, but they have been returned from all highlands sites as well. The features diagnostic of this type of rock are illustrated below by an outline of the characteristics of the Apollo 14 regolith breccias, the most extensively studied group of highlands regolith breccias.

The nature of the fragment assemblage and matrix strongly reflects the fact that the particles had a history of extensive impact reworking and mixing at the lunar surface prior to consolidation of the breccia (fig. 3). Clasts tend to be small because they have been subjected to several episodes of fragmentation (Wilshire and Jackson (1972) found that no more than 10%, and usually less than 5% of the clasts are larger than 1 mm across). Size distribution of fragments tends to be seriate. Among the clasts are particles of diverse textures and compositions derived from many different source areas, but most of the clasts come from local bedrock. The breccias are very rich in glass that is free of included fragments; this glass forms much of the matrix material and a very great proportion of the larger clasts (Wilshire and Jackson reported that chips and spheres of fragment-free glass form 35%-50% of clasts in the 0.1-1-mm size range). Several types of clasts are characteristic (figs. 3 and 4), including: angular chips and spheres of fragment-free glass; devitrified glasses, some with chondrule-like textures; glasses with flow structures; glass-coated clasts; and fragments that show the effects of multiple impacts.

Bulk composition and physical characteristics reflect the mixing, incorporation of meteoritic matter, and exposure to solar-wind and extra-lunar particle bombardment that took place while the breccia constituents formed loose particulate materials in the regolith. The breccias are very similar in bulk composition to fines samples (LSPET, 1971; Laul et al., 1972). They have relatively high contents of iron metal and of the siderophile and volatile trace elements associated with meteorites (Morgan et al., 1972). They are rich in solar-wind implanted C and N (Moore et al., 1972; Goel and Kothari, 1972) and in trapped solar-wind rare gases (Megrue and Steinbrunn, 1972; Alexander and Kahl, 1974). O^{18} is enriched relative to O^{16} (Clayton et al., 1972), and the clasts contain solar-flare and cosmic-ray tracks (Hutcheon et al., 1972; Hart et al., 1972).

Light gray breccias

One suite of lunar breccias may be analogous to terrestrial suevites; if so, these breccias were probably produced in a very large impact event. The rocks of this suite are the Apollo 17 samples that have been termed light gray breccias (LSPET, 1973b). Only six hand samples were returned; four were collected from a single large boulder at the base of South Massif (72215, 72235, 72255, 72275), and two were picked up as loose rock samples from regolith developed on the light mantle avalanche deposit (73215, 73255). It appears that both the boulder and the avalanche were derived from a layer that caps

South Massif, and it has been suggested that this layer represents a deposit of Serenitatis or Imbrian ejecta (H. H. Schmitt and W. R. Muehlberger, oral communication).

The light gray breccias may be divided into three types. Rocks of the first type (represented by 73255) appear to consist of fragment-laden devitrified glass; they may be analogous to the impactite glass bombs that are found within suevite. Rocks of the second type (represented by 73215, 72255, and 72215) appear to consist of aggregates of fragments bonded by variable amounts of devitrified and recrystallized glass; no analogous materials are found in suevite. Rocks of the third type (represented by 72275 and part of 72235) are poorly consolidated aggregates of mineral and lithic debris, contain clasts of the other two types of light gray breccia, and may be analogous to bulk suevite.

Light gray breccia of the first type in hand specimen is a gray aphanite that contains sparse xenocrysts and xenoliths. 73255, the only large sample of this type, has a vesicular outer rind, a non-vesicular interior, and an ovoid shape that appears to be close to the primary shape of the rock. In thin section (fig. 5), these breccias are composed of abundant small xenocrysts and xenoliths set in a dark groundmass, and grain size distribution appears bimodal rather than seriate. The groundmass consists of minute mineral fragments cemented by material that has a texture suggestive of devitrified glass (fig. 6). It is difficult to distinguish the finest mineral fragments in the groundmass because of possible modification of their outlines by recrystallization; their proportions can only be roughly estimated and may be very great.

Most clasts in light gray breccias of this type are of angular unshocked mineral grains and show no evidence of strong heating, significant equilibration with groundmass, or partial melting. A small proportion of the clasts, however, do show thermal and deformational effects: some of the lithic clasts show interstitial partial melting that was induced by thermal heating after they were incorporated in the fragment-laden melt (fig. 7); and some of the monomineralic clasts are of recrystallized shocked plagioclase and devitrified maskelynite (these appear to be more abundant than in other types of detrital lunar breccias, such as regolith breccias). Most of the fragments appear to have been derived from only a few suites of parent rocks. The two major parent suites were: 1) coarse-grained plutonic troctolites and troctolitic anorthosites; and 2) anorthositic-noritic-troctolitic hornfelses. Clasts of fragment-free glass and clasts that show the effects of multiple impact are rare. This clast assemblage suggests part of the source terrane was deep and not previously plumbed by impact. (The clast assemblage is described in greater detail in a later section, where an attempt is made to reconstruct the source terrane of the light gray breccias of types 1 and 2.)

Rocks of the second type of light gray breccia are similar to the fragment-laden devitrified glasses of the first type, except that they appear to have initially contained more fragments and less glass, and they underwent considerable shearing and recrystallization during or following consolidation. From relations visible in the boulder from which two of these samples were collected, it appears that they were probably deposited as large "clots" or clasts within a matrix of light gray breccia of the third type.

Breccias of the third type are friable aggregates of mineral and lithic debris, in which only sparse interstitial glass is present binding fragments together. However, the dominant kind of clast in these rocks is of fragment-laden devitrified glass equivalent to light gray breccia of the first type (Stoeser et al., 1974b). Significant numbers of these clasts are composite: they have large cores consisting of lithic fragments and rinds of fragment-laden devitrified glass, and in some of these composite clasts the rinds are vesicular.

In the characteristics described above, the fragment-laden devitrified glass that forms the first type of light gray breccia is remarkably like impactite glass from terrestrial suevite. The shape of the one hand-specimen-sized example, 73255, suggests that this rock may be a lunar analog of the glass bombs from suevite deposits. This type of breccia is very different from regolith breccia, and it probably cannot be interpreted as reheated regolith material. In this type of light gray breccia the most abundant clasts are of single mineral grains, and fragments of glass are rare, whereas in regolith breccias the most abundant clasts are of glass. The mineral and lithic fragments do not show the diversity of sources that characterizes the regolith breccias; instead they appear to have been derived from only a few major suites of parent rocks, and deep-seated rocks were abundant in the source terrane. Grain sizes have a bimodal-appearing distribution, in contrast to the seriate-appearing distribution in the regolith breccias. The evidence for variable heating of clasts suggests that not all the clasts had the same thermal history; some may have been hot when incorporated into the glassy groundmass, but others may have been relatively cool. The presence of vesicles establishes that the groundmass was at or near melting temperature, so it is necessary that the entire rock have cooled rapidly to avoid equilibration of clasts with their surroundings.

All these characteristics of this fragment-laden devitrified glass suggest that its genesis is best interpreted in terms of processes operating during a very large impact event. In this interpretation, the xenocrysts, xenoliths, and fine-grained mineral powder in the groundmass represent debris ejected as a cloud during the impact event. The devitrified glass that binds the fragments together represents impact melt that penetrated this debris cloud while it was still in flight and cemented the particles together. Some fragments in the cloud were hot while others were cool. The entire aggregate solidified and cooled rapidly so that only the hot fragments partly melted, whereas those that were incorporated while cool were unable to react with surrounding material. (An interpretation nearly identical to the one proposed here has also been suggested for similar rocks by members of the consortium studying the light gray breccia samples from the boulder (Stoeser et al., 1974a)). The major difference in textures between these lunar fragment-laden glasses and terrestrial impactite glasses is that the lunar glasses seem to have contained much larger proportions of fragments and much smaller proportions of melt. It may be that this difference is a function of differences in conditions of formation, or it may simply be that the markedly lower viscosities of impact melts of the compositions of lunar rocks permitted them to incorporate far larger proportions of debris.

In this interpretation, rocks of the second type of light gray breccia could have formed by the same process as the fragment-laden glasses of the first type, only with the ejected debris penetrated to a lesser extent by impact melt. The friable, glass-poor matrix of rocks of the third type might represent ejected debris that was only sparsely penetrated by impact melt. Thus the glass-rich rocks of the first type would be analogous to impactite glass bombs deposited within suevite, rocks of the second type would have a somewhat similar origin, and rocks of the third type would be analogous to bulk samples of suevite.

Other breccias similar to glass-rich (types 1 and 2) light gray breccias

Breccias with textures and fragment populations like the glass-rich light gray breccias are widespread on the lunar surface. The types that occur as large samples are: the black material within "black and white rocks" (described in the following section), and the Apollo 17 blue-gray breccias (LSPET, 1973b). Most samples of breccias like these, however, do not occur as large hand specimens; they instead occur as small fragments in fines fractions and as clasts in other breccias. Such rocks form the most abundant type of clast in the greater-than-0.1-mm size range in the Apollo 14 thermally metamorphosed breccias (Chao, 1973b; Wilshire and Jackson, 1972). They make up the dark material in the highly potassic and siliceous thermally metamorphosed breccia 12013, and they are also important as clasts in glass-poor feldspathic breccias from the Apollo 14 and 16 sites. The abundance and widespread distribution of such rocks suggests that they represent an important facies of lunar impact-generated breccia.

The Apollo 17 blue-gray breccias (fig. 8) are similar to the glass-rich light gray breccias in that they have a bimodal-appearing grain size distribution (clasts set in an aphanitic groundmass) and they have similar types of fragment suites (derived from fairly restricted source terranes; mineral fragments dominant, glass fragments rare). Also they are locally vesicular. In the blue-gray breccias, however, equilibration between fragments and groundmass was more extensive, and groundmass crystallization was better developed than in the similar light gray breccias. Blue-gray breccias are themselves quite variable in fragment assemblage and extent of groundmass-clast reactions. One of the samples, 73235, has a fragment assemblage nearly identical with that of light gray breccia 73215 (type 2): 73235 seems to differ from 73215 primarily in that it was more plastic during its episode of late shear, and its postconsolidation crystallization produced a denser, more coarsely crystalline groundmass. Another sample, 77115, differs considerably from light gray breccia 73215 both in fragment suite and in groundmass texture. Although the relative proportions of mineral versus lithic clasts are roughly similar in 73215 and 77115, the suite of parent rocks from which the fragments were derived appears to have been different. 77115 also shows evidence of very extensive equilibration of clasts with groundmass: for example, some fragments of plagioclase show partial melting textures and overgrowths, and others are zoned; fragments of olivine are zoned; and fragments of subcalcic augite show partial melting textures, resorption of exsolution lamellae, and broad overgrowths of pigeonite.

Possible explanations for the differences between glass-rich light gray breccias and blue-gray breccias might be that: the latter were formed by the same processes as the former, but they had 1) higher initial temperatures, 2) larger initial proportions of melt, 3) longer cooling times, and/or 4) slightly higher confining pressures during cooling. There may have been considerable variation in these parameters even within the suite of blue-gray breccias; in samples like 77115, the initial groundmass melt may have been even hotter or present in even larger proportions, or cooling may have been even slower than in others of the blue-gray breccias like 73235.

In Apollo 14 thermally metamorphosed breccias, the types of clast that are similar to blue-gray and glass-rich light gray breccias are those that were termed fine-grained hornfelsed noritic microbreccias and annealed fragment-laden glasses by Chao (1973b) and were designated as type D_4 by Wilshire and Jackson (1972). The similar material in 12013 (fig. 9) was referred to as the dark lithology (Drake et al., 1970), "black end member" (Lunatic Asylum, 1970), and dark aggregate (James, 1970). Textures of these materials are essentially similar to those of the blue-gray and glass-rich light gray breccias (though bulk compositions are different). Most fragments they contain are of unshocked, undeformed mineral grains, but significant proportions of devitrified maskelynite and recrystallized shocked plagioclase are present. (In the dark material in 12013, volume percentages of fragments larger than 0.1 mm are as follows (James, unpublished): 36% undeformed plagioclase, 2% shocked plagioclase, 12% pyroxene, and 13% other minerals, for a total of 63% mineral fragments; and 5% anorthositic-noritic-troctolitic hornfels, 9% anorthosite, and 20% quartzo-feldspathic rock, for a total of 34% lithic fragments.) Reactions of clasts with groundmass are well developed, as in the blue-gray breccias. Locally, the groundmass is vesicular. The major textural difference between these rocks and the glass-rich light gray and blue-gray breccias is that the groundmass has very fine granoblastic texture rather than subophitic, poikilitic, or devitrified glass texture.

Cataclastic anorthosites and "black and white rocks"

One suite of lunar breccias is probably analogous to the terrestrial impact breccias that line crater cavities and make up most of the fragments in deposits of the Bunte-breccia type. Large samples of this suite were collected at the Apollo 15, 16 and 17 sites. Among them are the rocks that were termed cataclastic anorthosites by the Apollo 16 LSPET (1973a) and "black and white rocks" by the Apollo 15 LSPET (1972); some of the Apollo 16 samples called "partially molten breccias" (LSPET, 1973a) are probably also members of this suite.

The cataclastic anorthosites and the white materials of the "black and white rocks" are sheared and granulated samples that were originally medium- to coarse-grained plutonic crystalline rocks (fig. 10). (Here the name "anorthosite" is used as a general term to indicate that most of the samples are anorthosites and troctolitic, noritic, and gabbroic anorthosites; in fact the suite also includes norites, olivine norites, and troctolites.) Many, perhaps most of the breccias appear to be monomict or composed of fragments of a few related types of plutonic rocks. Deformation history varies considerably from sample to sample; some were only crushed, some were recrystallized after crushing, and some had several episodes of deformation and recrystallization. Most samples, however, retain some relict areas of medium-grained to coarse-grained textures and mineralogies that indicate they had equilibrated at subsolidus temperatures prior to granulation. (In many samples, compositions and structures of the minerals suggest that, during formation of the coarse-grained texture, the rocks were equilibrated over large volumes at subsolidus temperatures on the order of 600 to 800 degrees Centigrade.)

The nature and degree of deformation shown by these rocks is typical of brecciated bedrock lining crater cavities or of blocks forming Bunte-breccia-type deposits. Shear and granulation dominate, shock effects are absent or weak, and relict textures are abundantly preserved. The textures, mineral compositions, and mineral structures show that most of these samples cannot have been deformed and recrystallized more than a few times in the period between the impact event that excavated them and the episode of magmatic crystallization or metamorphic equilibration that formed the initial coarse-grained texture. D. B. Stewart (oral communication) estimates that times on the order of hundreds of millions of years were necessary to achieve the degree of equilibration that was attained during the formation of the initial texture. Because the times involved are so long, the rocks may be relicts preserved from the early stages of crustal evolution. These rocks must have resided during their equilibration period at deep levels within the lunar crust, in order to have been protected from the effects of intense impact bombardment at the highlands surface. The events required to deform and excavate them must have been very large in order to penetrate to plutonic bedrock that had been little disturbed by previous impacts.

<u>The black materials in the "black and white rocks"</u> appear to represent fragment-laden melts that intruded the white rocks. Evidence leading to this interpretation comes from the characteristics of 15455 (one of the first of the "black and white rocks" to be returned) and 77075 plus 77215 (black dike and white crushed norite in a boulder at the Apollo 17 South Massif). Relationships between the black and white materials seen in the hand specimens and at the outcrop clearly show that the black materials intrude and include the white

materials (Apollo 15 Lunar Sample Catalog; AFGIT, 1973b). In both 77075 and 15455, the black rocks are dense and aphanitic; they consist of abundant xenocrysts and xenoliths set in a very fine-grained groundmass that has igneous texture (fig. 11). The xenocrysts and xenoliths are from diverse rock types, and some are clearly not derived from the immediately surrounding white rock. (In 77075, for example, olivine fragments are abundant and clasts of fine-grained hornfels are present, although these materials are rare or absent in the surrounding white norite 77215; conversely, fragments of the orthopyroxene that typifies the norite are not abundant in the dike.) In both 77075 and the black material in 15455, some of the xenocrysts are of rounded and spherulitic devitrified maskelynite (fig. 11); these grains had a history of more intense shock than the immediately surrounding white rock. In black material in 15455 particles of nickel-iron are present; analyses of siderophile trace elements and Ni show that these are of meteoritic origin and that the associated white rock does not contain any similar material (Ganapathy et al., 1973).

The Apollo 16 "partially molten breccias" that may be related to the "black and white rocks" differ from the samples described above in several significant respects. Two examples are 61015 and 64475 (fig. 12). In these breccias the black dike rocks were nearly all melt when emplaced and contained only sparse fragments. Most of the silicate clasts could have been derived from the white host rocks, but large nickel-iron globules that are probably from an exotic source are also present. These breccias show evidence of a complex injection and deformation sequence (hence the name "partially molten breccias"). Textures and structures visible in the hand specimens and thin sections suggest the following interpretation of the history of these rocks: The black dikes were injected into the white rocks while the latter were undergoing cataclastic deformation. The dike rocks were quenched and solidified rapidly. The solidified dikes were fragmented by later deformation in the surrounding white rocks, and this deformation separated the fragments of dike rock and injected them with remobilized white rock. Thus, in such samples the black and white materials mutually intrude and include one another.

The black materials in the "black and white rocks" are very similar to the glass-rich light gray breccias in many respects and most likely formed by similar processes. Thus, they probably represent mixtures of impact melt, material derived from the impacting body, and granulated country rock. They canno have been derived solely from melting of the surrounding white rocks, for the characteristics of their chemistry and fragment suite require that they contain some material generated within an impact crater cavity. Nor is it likely that they are remobilized regolith breccias; in fragment assemblage and nature of fragment-matrix relationships they resemble the glass-rich light gray breccias rather than regolith breccias. In most "black and white rocks" these fragment-laden melts probably were injected into the white cataclasites during their deformation; in others, they may have been ejected from the craters along with large clasts of cataclasite and may have penetrated fractures in these clasts after ejection. The complex injection and deformation sequence observed in the "partially molten breccias" could have originated in two ways: either the last stages of deformation in the large events that brecciated the cataclasites and generated the black dike materials involved fragmentation of early injected dikes and ejection of the brecciated rocks from the crater cavity; or the deformation of dikes and ejection took place as a result of subsequent impact events.

A similar interpretation of the cataclasites, "black and white rocks", and related "partially molten breccias", which differs only in minor details from the one outlined above, has been proposed by Wilshire and Moore (in press).

Thermally metamorphosed breccias

Thermally metamorphosed breccias are one of the lunar breccia types that may possibly represent lithified debris deposits from major impacts. In these rocks, however, the thermal metamorphism has obscured many of the characteristics that might have been diagnostic of origin, and much additional study will be required before any definite conclusion can be reached on their genesis.

The first sample of thermally metamorphosed breccia that was returned was the unique potassic and silica-rich 12013. Minor numbers of thermally metamorphosed breccias were found at the Apollo 15 and 16 sites, but at the Apollo 14 site such breccias were abundant. Here it appears that these rocks are a major constituent of the Fra Mauro Formation, a unit that formed as a deposit of Imbrian ejecta (Eggleton, 1970). Either they represent lithified and metamorphosed Imbrian ejecta (Warner, 1972; Wilshire and Jackson, 1972), or they are breccias metamorphosed in pre-Imbrian time and transported to the Apollo 14 site to form clasts in the Imbrian deposit (Dence and Plant, 1972; Chao, 1973b).

Fragment assemblages in the Apollo 14 thermally metamorphosed breccias (fig. 13) are unlike those in either the Apollo 14 regolith breccias or the Apollo 17 glass-rich light gray breccias and blue-gray breccias. Clast sizes tend to be larger than in the regolith breccias, possibly suggesting fewer episodes of fragmentation (Wilshire and Jackson (1972) found that on the average 25% of the clasts in these samples are larger than 1 mm across). Clasts that were initially fragment-free glass (indicators of a regolith history) are sparse; and clasts of recrystallized fragment-laden glasses (similar to glass-rich light gray breccias) are abundant (Wilshire and Jackson reported that these average 28% of the clasts in the 0.1-1-mm size range, and Chao (1973b) found that 55% by volume of one thermally metamorphosed breccia he studied consisted of such clasts). Fragments of single mineral grains are much more abundant than in the regolith breccias (Wilshire and Jackson reported an average of 56% mineral fragments in the 0.1-1-mm size fraction in thermally metamorphosed breccias in contrast to a range of 15%-33% in this same size fraction in regolith breccias). The suite of lithic fragments is not as diverse as in regolith breccias but not as homogeneous as in the Apollo 17 light gray breccias, and clasts that show the effects of multiple impacts are present in significant numbers.

Many of the compositional and physical indicators that might be used to evaluate whether or not the constituents of these breccias had ever passed through an episode as particles in a regolith have been obscured by thermal metamorphism. During metamorphism at high temperatures or over long periods of time, solar-wind-implanted C and N and trapped solar-wind rare gases are driven off and particle tracks are annealed out; however, one indicator of surface exposure that is not affected by metamorphism is enrichment of O^{18} relative to O^{16}. In the Apollo 14 thermally metamorphosed breccias, C and N contents are low and either were always low or were lowered during metamorphism; however, the rocks may retain a trace of trapped solar-wind rare gases (Kirsten et al., 1972). Particle track contents are also low, but some of the sparse unannealed tracks that are present have been ascribed to irradiation of fragments in a regolith prior to breccia aggregation (Hutcheon et al., 1972). O^{18} does not appear to be significantly enriched relative to O^{16} (Clayton et al., 1972). In sum, the rare gas and track data indicate some surface exposure, but the particles in these breccias probably have not been as extensively exposed and reworked in the lunar surface debris layer as particles in regolith breccias.

As outlined above, the published studies of the characteristics of the thermally metamorphosed breccias give some indication of the preaggregation histories of the fragments they contain, but these studies are by no means complete enough to be definitive. About all that can be said at present is that the fragments in these rocks probably have undergone more complex histories of multiple impacts than fragments in the glass-rich light gray breccias, but they have probably had much less extreme reworking than fragments in regolith breccias.

Glass-poor feldspathic breccias

Glass-poor feldspathic breccias are another of the lunar breccia types that may have originated as debris deposits from large impacts. The characteristics of these rocks and their relations to other types of breccias are not yet well enough known to permit anything more than speculation about this possibility, however.

Samples of glass-poor feldspathic breccias were collected at the Apollo 14, 16 and 17 sites. At the Apollo 14 site they formed white rocks (represented by 14063 and 14082) and irregular layers and patches in boulders of darker rock on the rim of Cone Crater (Swann et al., 1971); as the dark rock was not sampled, we do not know that lithology it is. In any case, however, it is likely that the white rocks and the associated darker rocks were derived from deep within the Fra Mauro Formation. At the Apollo 16 site similar breccias (for example 67015, 67016, 67455) form a layer 100-250 m thick underlying the northern part of the sampling area (AFGIT, 1973a); here there is no clear association with other types of breccia. At the Apollo 17 site, only very minor amounts of such breccias were found; they form schlieren included within light gray breccias such as 73215.

These breccias consist largely of crushed debris derived from highly feldspathic rocks (fig. 14). The fragment suite is variable, being quite homogeneous in some rocks and much more heterogeneous in others. In all the samples, most fragments are of single mineral grains, with plagioclase greatly dominant (in the Apollo 14 feldspathic breccias Wilshire and Jackson (1972) found that 45%-55% of the fragments in the 0.1-1-mm size range were of plagioclase grains and about 15% were of other minerals, for a total of 60%-70% mineral fragments). Many of these fragments are coarse, and pyroxene clasts show broad exsolution lamellae; these characteristics suggest plutonic source rocks. Fragments of recrystallized shocked plagioclase and devitrified maskelynite are also present. The most abundant lithic fragments in most samples are of brown devitrified fragment-laden glasses and granulated coarse-grained anorthositic rocks. Highly variable amounts of clasts of other rock types and of brown fragment-free glasses are present.

Generally the rocks are friable and contain very little groundmass glass binding the fragments together; but the amount of such glass varies considerably from sample to sample, and in some cases it is variable within single samples. Compositional and track studies suggest that in many of these rocks the fragments had little or no exposure to the lunar surface environment prior to consolidation of the breccia (Clayton et al., 1973; Moore et al., 1973; MacDougall et al., 1973), but in other rocks the fragments may have had some history prior to exposure (Dran et al., 1972).

The major evidence that some of these breccias may be devris from single large impacts is as follows: 1) The suite of parent rocks from which their fragment assemblage was derived was apparently fairly homogeneous in texture and composition and contained coarse-grained deep-seated rocks as a major constituent; and 2) the fragments appear to have had very little reworking by multiple impacts. However, it is not clear why some of these feldspathic breccias are less homogeneous than others and how the different variants might be related to one another. It is also unclear how breccias of this type might be related to the other breccias that could represent major-impact debris. In this regard, it is significant that one of the most abundant types of lithic clast in the feldspathic breccias is devitrified or recrystallized fragment-laden glass similar in texture to Apollo 17 glass-rich light gray breccia. In relationships shown in 73215, where glass-poor feldspathic breccia is included within glass-rich light gray breccia, it appears that the feldspathic debris may have been formed in the same impact that generated the fragment-laden glass. Thus, in some cases glass-rich light gray breccia and glass-poor feldspathic breccia may be two different facies of ejecta of the same impact. On the other hand, it is not yet possible to rule out the alternative that the feldspathic breccias are derived from loose deposits of feldspathic debris that had not experienced extensive reworking prior to consolidation. The relationships seen in 73215 could conceivably have been produced if preexisting loose debris had simply been caught up in the glass-rich light gray breccia during its formation. It is hoped that the studies now in progress of feldspathic breccia lithologies in the light gray breccias will clarify these relationships.

Green-gray breccias, or poikilitic-poikiloblastic rocks

One other type of lunar rock that has been termed breccia is worth noting briefly here. These are the rocks that were designated green-gray breccias (fig. 15) by the Apollo 17 LSPET (1973b) and poikilitic rocks by the Apollo 16 LSPET (1973a). They appear to represent fragment-laden melts and glasses that crystallized or devitrified at temperatures above or just below the solidus (Simonds et al., 1973; Bence et al., 1973; Chao and Minkin, 1974). Clast proportions are low and clast-groundmass equilibration is extensive in these rocks; thus studies of the fragments they contain do not have as great a potential for determining nature of source terrane as do studies of the breccia types described in previous sections. For this reason I will not present here a detailed discussion of these rocks, but I will only indicate what alternatives have been proposed for their origin and which alternative I prefer. It has been suggested that these rocks represent: clast-laden impact melts (Dence, oral communication); clast-laden melts of uncertain origin (Chao and Minkin, 1974); clast-laden endogenous melts of deep origin (Crawford, 1974); breccias heated by impact to temperatures just above or below the solidus (Simonds et al., 1973; Bence et al., 1973); or thermally metamorphosed glassy-matrix breccias (Albee et al., 1973). The rocks are texturally gradational with blue-gray breccias and they show simple fragment suites much like those characteristic of the blue-gray breccias. They also contain particles of nickel-iron of meteoritic origin (Ganapathy et al., 1973). Because of the similarities to blue-gray breccias, I favor the interpretation that both types of rock had similar origins: that is, both represent fragment-laden impact melts, but the green-gray breccias initially contained much higher proportions of melt and much lower proportions of fragments than did the blue-gray breccias. In this interpretation, the clasts were included in this melt and are not relicts from a melting episode that heated the whole rock, although they may have reacted extensively with the melt after incorporation.

SOURCE TERRANE OF LIGHT GRAY BRECCIAS

Studies are now in progress of the fragment suites in several samples of glass-rich light gray breccia, for example 73255 and 73215 (consortium led by myself) and 72255 and 72215 (consortium led by J. A. Wood). These studies are only beginning, and among their first objectives will be to determine the amount of reworking of the fragments prior to consolidation of the breccia, and to establish whether or not the analogy to suevites is truly valid. In the discussion below, however, I will assume that it has already been demonstrated that these samples consist of major-impact ejecta and I will attempt to reconstruct the source terrane of this ejecta, in order to illustrate the potential of breccia studies in determining the nature of the early lunar crust. The data presented consist of a combination of my own observations on 73215 and the observations of Stoeser et al. (1974b) on 72255.

Fragment Assemblage

The most abundant clasts are of single mineral grains. Fragments of plagioclase are greatly dominant; fragments of olivine and pyroxene are subordinate, and the former is more abundant than the latter. Fragments of recrystallized shocked plagioclase and devitrified maskelynite are common (fig. 16). Sparse fragments of silica minerals, pink to red spinels, opaque minerals, and zircon are also present.

It appears that a significant number of the mineral clasts may have been derived from plutonic parent rocks. Fragments of single grains as much as 4 mm across have been observed in 73215. All the fragments of pyroxene contain optically prominant exsolution lamellae which are quite coarse in some grains, suggesting deep-seated equilibration.

Clastic lithic material consists primarily of: 1) fine-grained anorthositic-noritic-troctolitic hornfelses and granoblastic plagioclase; 2) fine-grained "troctolites" with igneous textures; 3) granulated medium-grained plutonic anorthosites, norites, troctolites, and troctolitic anorthosites; and 4) aggregates of poorly consolidated feldspathic debris (glass-poor feldspathic breccia described above) (fig. 17). Minor numbers of other types of lithic clasts are also present. Stoeser et al. (1974b) have reported abundance data on lithic clasts in 72255. They find that, for clasts larger than 0.2 mm, the proportions are as follows: 49% fine-grained granulitic anorthositic-noritic-troctolitic hornfels; 12% fine-grained granoblastic plagioclase; 15% devitrified maskelynite; 7% granulated anorthosite; 4% fine-grained "troctolite"; 5% devitrified rock glass; 4% felsite and felsic glass ("granitic clasts"); 2% recrystallized pyroxene and olivine; 1% basalt; and 1% plutonic norite. No quantitative data are available for lithic clast abundances in 73215 at present, but rough visual estimates suggest that, in this rock, clast proportions differ from those in 72255 in that fragments of granulated medium-grained troctolite and troctolitic anorthosite are common and fragments of devitrified rock glass are very rare.

The hornfelses occur as small competent clasts, and their textures range from microgranoblastic to micropoikiloblastic. Many are inequigranular, with variable proportions of xenocrysts and small xenoliths set in a very fine grained recrystallized matrix (fig. 18). Some of these rocks are probably of relatively deep-seated origin and formed by recrystallization of sheared zones in coarse-grained parent rocks. Others, those that have heterogeneous textures and contain xenoliths, probably represent recrystallized impact debris deposits and are of shallower origin.

The fine-grained "troctolites" occur as small competent clasts, and they range in texture from devitrified vitrophyres (bearing spinel and plagioclase phenocrysts), to basaltic-textured rocks (fig. 19), to remelted troctolitic cataclasites (in which large deformed and recrystallized grains of olivine and plagioclase are set in a fine-grained matrix that has igneous texture). The finest grained members of this suite are probably of very shallow origin and crystallized from rapidly cooled melts. At present it is not known whether these melts were endogenous or generated by impact. Source depth and processes of origin of the remelted cataclasites are also unknown.

In 73215 most of the large lithic clasts are of plutonic troctolites and troctolitic anorthosites. Most of these were granulated prior to incorporation in the breccia, but they show relict grain sizes as large as 4 mm. Others were not deformed, and they preserve original granular textures. The troctolites appear to be like the troctolite sample 76535. It has been proposed by Gooley et al. (in press) and Bogard et al. (1974) that troctolites of this type are from a source more than 10 km below the lunar surface and that they may have formed 4.3-4.4 billion years ago; thus, they may be some of the original rocks of the lunar crust.

The devitrified rock glasses that are common in 72255 and very rare in 73215 are deep red-brown, xenocryst-poor, and have very fine grained devitrification textures.

Most of the felsitic (or "granitic") clasts consist of either: 1) oriented and graphic intergrowths of a silica mineral and potassium feldspar, with or without plagioclase feldspar and glass (fig. 20); or 2) glasses of granitic composition that contain variable amounts of crystals of silica minerals and feldspars. The crystalline felsites tend to be fine grained, and it is unlikely that they were derived from a large body of plutonic granite; they may instead come from small crystallized segregations of late immiscible "granitic" melts formed during igneous differentiation or partial melting processes in the lunar crust (R. W. Wolfe, oral communication).

One of the lithic types present in trace amounts is worth noting here. This is basalt in which pyroxene is dominant over plagioclase. The clasts of these basalts are metamorphosed, but they preserve relict subophitic or vitrophyric textures, indicating that they initially crystallized at shallow depths. Bulk compositions (Stoeser et al., 1974b) are intermediate between those of highlands rocks and mare basalts. Studies of such basalts may shed some light on the relationships between mare and highland rocks and the processes of origin of the lunar crust.

One major contributor to the glass-rich light gray breccias is an enigma. This is the source material for the glass that binds the fragments together. Bulk composition of this glass (Stoeser et al., 1974b; Haskin et al., 1974) appears to be that of feldspathic or low-alkali, high-alumina basalt (terminology of Prinz et al., 1973), containing about 19% Al_2O_3, 10% MgO, 10% FeO, 0.3% K_2O and rare-earth element concentrations about 100 times those in chondrites (with negative Eu anomaly). Plagioclase and low-calcium pyroxene are the dominant normative minerals and are about equal in abundance. No lithic fragments of similar composition have been found within the breccias. Two possible alternatives for the source for the glass are: 1) a noritic rock that was completely melted by impact; or 2) a completely melted mechanical mixture of clasts of the anorthositic-noritic-troctolitic suite and clasts of felsite.

Source Terrane

The fragment suite of glass-rich light gray breccias such as 73215 and 72255 suggests that the source crust from which they were derived had a layered structure. The deepest material excavated probably came from more than 10 km below the surface; the parent rocks were medium-grained and coarse-grained plutonic troctolites, anorthosites, and norites. They had not previously been excavated by impact and may represent samples of early lunar crust. Locally, however, these rocks had been sheared and deformed by impacts in overlying rocks and the sheared zones had later recrystallized. Above the plutonic rocks lay a series of metamorphosed ejecta deposits, perhaps interlayered with igneous-textured rocks that had crystallized from impact-generated and endogenous melts. Among these igneous-textured rocks were fine-grained spinel-bearing "troctolites" and pyroxene-dominant subophitic basalts and vitrophyres. Material from this upper layer was subjected to varying amounts of impact reworking and some of it may have been deformed or melted, excavated, buried, and subsequently metamorphosed many times.

SUMMARY AND CONCLUSIONS

The most widespread type of lunar breccia is regolith breccia, representing lithified material from the lunar surface debris layer. Fragment assemblage, nature of the matrix, bulk composition, and physical characteristics of these rocks reflect the fact that the particles they contain had histories of extensive impact reworking and mixing in the regolith prior to being consolidated into a breccia.

Most breccias returned from highlands sites, however, do not show characteristics of extensive reworking at the lunar surface. Some of these may be samples of brecciated bedrock and ejecta deposits related to major impacts. The following is a list of the types of highlands breccias discussed in this paper (other than regolith breccias) with suggestions as to their possible genetic relationships to large impacts.

1. Cataclastic anorthosites: probably represent rocks granulated by shock-induced deformation in the walls and floors of large impact crater cavities and in blocks of ejecta thrown out from such crater cavities.

2. "Black and white rocks": white material is like cataclastic anorthosites. Black material probably represents fragment-laden melts (mixtures of impact melt, material derived from the impacting body, and crushed bedrock) injected into the white cataclasites during their deformation or filling fractures in them after deformation ceased.

3. Light gray breccias: probably analogous to terrestrial suevites. The glass-rich members of this suite (types 1 and 2) probably formed as fragment-laden impact melts and are somewhat analogous to impactite glass

bombs in suevites. Other samples (type 3) are mixtures of small glass-rich clasts and debris from crushed and shocked bedrock and may be analogous to bulk suevite.

4. Blue-gray breccias (and the similar fragments that form clasts in thermally metamorphosed and glass-poor feldspathic breccias): probably similar in origin to glass-rich light gray breccias (types 1 and 2) and black materials within "black and white rocks".

5. Thermally metamorphosed breccias: possible relationship to major impacts is unclear. Fragments in these breccias appear to have had more complex histories of reworking than fragments in glass-rich light gray breccias but less complex histories than fragments in regolith breccias.

6. Glass-poor feldspathic breccias: possible relationship to major impacts is unclear. Samples of this type may be major impact ejecta deposits, or they may come from deposits of loose feldspathic debris that was reworked but not extensively; it is also possible that samples with both these origins may be represented in this suite.

7. Green-gray breccias and poikilitic-poikiloblastic rocks: possibly represent fragment-laden impact melts generated in large impacts.

The glass-rich light gray breccias appear to represent one end member of a gradational series of lunar breccias, and the members of this series are widespread and abundant on the lunar surface. Glass-rich light gray breccias are gradational in texture, nature of fragment assemblage, and nature of clast-matrix relations with blue-gray breccias and with the black materials in "black and white rocks". Similar rocks are common as clasts in thermally metamorphosed breccias, clasts in glass-poor feldspathic breccias, and fragments in fines fractions. Blue-gray breccias are in turn gradational with green-gray breccias (or poikilitic-poikiloblastic rocks). In this paper I propose a hypothesis for a genetic relationship between all the members of this gradational series: that is, that all represent mixtures of varying proportions of impact melt and finely crushed debris ejected during large impact events. Under this hypothesis, mixing takes place during ejection of melts and debris from the crater cavity; the differences between the various types of breccia are a function of ratio of melt to included particles, initial temperatures of melt and inclusions, and post-aggregation cooling history.

Many of the ideas presented above are speculative, and much more work remains to be done before they can be either confirmed or disproved. Such work is essential, for any breccias that can definitely be established as having been formed in major impacts are potentially of great importance to lunar research. Although the fragment suite of a single sample of major-impact breccia will not be representative of the entire pre-impact source area, studies of such samples can permit partial reconstruction of that source. By such an approach we may eventually be able to decipher some of the history of the moon's crust and upper mantle during the first half billion years of lunar history.

Acknowledgements

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Table 1: Types of lunar highlands breccias

Type	Designations used by other investigators	Site	Examples
Regolith breccia[1,12]	Soil breccia Apollo 14 group F_1[2] Apollo 14 metamorphic group 1[3] Vitric matrix breccias[7]	All	14042, 14047, 14049, 14313
Cataclastic anorthosite[4,5]	Cataclastic rocks[7] Samples are included in Apollo 16 groups C_1 and B_1[8] Brecciated anorthositic rocks[12]	Major type at Apollo 16	60015, 60025, 62237, 67075
Black and white rocks[6] White fraction Black fraction	 Cataclastic rocks[7] Basaltic matrix breccia[7] Blue-gray breccia dike[9]	Important type at Apollo 15, 16, 17	15455, 77075 + 77215
Partially molten breccias[4] (does not include all samples of this class) White fraction Black fraction	Samples are included in Apollo 16 group B_2[8] Cataclastic rock[7] Basaltic matrix breccia[7]	Minor type at Apollo 16	61015, 64475
Light gray breccias[10]		Minor type at Apollo 17	72215, 72255, 73215, 73255, 72275
Blue-gray breccias[10]	Blue-gray matrix-rich breccia[11] Basaltic matrix breccia[7]	Major type at Apollo 17	73235, 76315, 77115
Thermally metamorphosed breccias	Annealed Fra Mauro breccias[1] Apollo 14 group F_4[2] Apollo 14 metamorphic groups 4-8[3] High grade breccias[7]	Major type at Apollo 14	14270, 14303, 14305, 14306, 14311, 14321, 12013
Glass-poor feldspathic breccias	Unannealed Fra Mauro breccias[1] Apollo 14 group 14 F_3[2] Apollo 14 metamorphic group 3[3] Light matrix breccia[7] Apollo 16 group B_2[8] Polymict breccia[4] Feldspathic breccia[12]	Apollo 14 white rocks on Cone Crater rim, bedrock at Apollo 16 North Ray Crater	14063, 14082, 67015, 67016, 67455
Green-gray breccia[10] or Poikilitic rock[4]	Poikilitic matrix breccia[7] Samples included in Apollo 16 group C_2[8]	Minor type at Apollo 16, major type at Apollo 17	60315, 65015, 76015, 77135, 62235

[1]Chao, 1973b; [2]Wilshire and Jackson, 1972; [3]Warner, 1972; [4]LSPET, 1973a; [5]Warner et. al., 1973; [6]LSPET, 1972; [7]Phinney et. al., this conference; [8]Wilshire, Stuart-Alexander, and Jackson, 1973; [9]AFGIT, 1973b; [10]LSPET, 1973b; [11]Schmitt, 1973; [12]Chao, 1973a.

FIGURE CAPTIONS

Figure 1: Photomicrograph of impactite glass bomb from Ries Crater (sample courtesy of E. C. T. Chao). (Width of field of view is 2.2 mm; crossed polarizers.) The glass (black and gray) contains fragments of unshocked and shocked mineral grains (white) and clay-lined vesicles (ovoids rimmed in white). Flowage in the impact melt flattened the vesicles and aligned and oriented the included fragments.

Figure 2: Photomicrograph of anorthositic lithic clast in impactite glass from Clearwater Lake, Canada (sample courtesy of M. R. Dence). (Width of field of view is 2.2 mm; plane-polarized light.) The clast snows partial melting along internal grain boundaries (induced by heating after incorporation in the melt). Matrix of the sample is devitrified glass (black) that contains abundant small fragments of unshocked, shock-deformed, and recrystallized mineral grains.

Figure 3: Photomicrograph of regolith breccia 14313. (Width of field of view is 2.2 mm; plane-polarized light.) Diverse lithic, mineral, and glass clasts are set in a glass-rich matrix. Grain size distribution is roughly seriate. Spheres of fragment-free glass (bottom and center left) and fragments of devitrified glass (lower center) are characteristic of such breccias. Lithic fragments in the field of view are fine-grained hornfelses.

Figure 4: Photomicrograph of particles in regolith breccia 14313. (Width of field of view is 2.2 mm; plane-polarized light.) The fragment at the left is a fine-grained hornfels. The fragment at the right is a spherule of devitrified glass with chondrule-like texture.

Figure 5: Photomicrograph of glass-rich light gray breccia 73255. (Width of field of view is 2.2 mm; plane-polarized light.) Grain size distribution appears roughly bimodal, with clasts clearly distinguishable from the dark, very fine grained groundmass. Most clasts are of mineral fragments, and they show planar preferred orientation (NE to SW) produced by flow of the glassy groundmass. The rock is locally vesicular (clear ovoids in upper left part of field).

Figure 6: Photomicrograph of matrix of glass-rich light gray breccia. (Width of field of view is .22 mm; reflected light.) Dark ovoids with textured appearance are vesicles. Angular and rounded fragments of mafic minerals (high reflectivity) and plagioclase (low reflectivity) are enclosed by material that has minute grain size and a texture suggestive of devitrified glass.

Figure 7: Photomicrograph of anorthositic lithic clast in glass-rich light gray breccia. (Width of field of view is 2.2 mm; plane-polarized light.) The clast shows partial melting along internal grain boundaries.

Figure 8: Photomicrograph of blue-gray breccia 77115. (Width of field of view is 2.2 mm; plane-polarized light.) Fragments are dominantly of mineral grains and are set in a fine-grained dark matrix.

Figure 9: Photomicrograph of dark material in thermally metamorphosed breccia 12013. (Width of field of view is 2.2 mm; plane-polarized light.) As in light gray breccia 73255 (see fig. 5), most clasts are of single mineral grains, and fragments and groundmass have the appearance of being two distinct materials. Fragment sizes are similar to those in 73255, and the fragments show rough planar preferred orientation (NE to SW). This rock is unusually rich in material of the composition of lunar "granite" and a veinlet of such material cuts the field of view (NW to SE).

Figure 10: Photomicrograph of white cataclasite in 15455. (Width of field of view is 2.2 mm; plane-polarized light.) The rock is an intensely sheared and granulated norite in which plagioclase (white, low relief) and orthopyroxene (gray, higher relief) are the dominant minerals. The white and gray areas are composed of minutely granulated aggregates of plagioclase and pyroxene, respectively; size of these areas reflects the original grain size of the rock. Two intersecting sets of shear planes are prominent in this field of view (E-W and NNW-SSE).

Figure 11: Photomicrograph of contact of black and white materials in 15455. (Width of field of view is 2.2 mm; plane-polarized light.) The contact is sharp, and the black rock (right) consists of an aggregate of fragments in a dark groundmass that has very fine grained igneous texture. Rounded fragments of spherulitic devitrified maskelynite (top right) are present; such fragments may have originated as ejecta and their presence suggests an ejection history of some of the material in the black rock.

Figure 12: Photomicrograph of "partially molten breccia" 61015. (Width of field of view is 3.52 mm; plane-polarized light.) The white rock (lower right) is a sheared and granulated anorthosite. The black rock (top and lower left) has fine grained igneous texture and contains sparse xenocrysts and xenoliths. Contacts between the two materials are smoothly curved shear boundaries.

Figure 13: Photomicrograph of thermally metamorphosed breccia 14312. (Width of field of view is 2.2 mm; plane-polarized light.) Dark patches are clasts of recrystallized fragment-laden glasses similar to glass-rich light gray breccias. Matrix and clasts are gradational and grain size distribution appears more seriate than bimodal. Clasts of fragment-free glasses and devitrified fragment-free glasses are sparse.

Figure 14: Photomicrograph of glass-poor feldspathic breccia 14063. (Width of field of view is 2.2 mm; plane-polarized light.) The dark areas are clasts of devitrified fragment-laden glass. The bulk of the rock consists of a poorly-consolidated light-colored aggregate of mineral fragments; the light color is due to the strong predominance of feldspar over mafic minerals among the fragments.

Figure 15: Photomicrograph of green-gray breccia 77135. (Width of field of view is 2.2 mm; plane-polarized light.) Xenocrysts and xenoliths are set in a groundmass that has fine-grained poikilitic texture. Light-colored areas in the groundmass are poikilitic grains of low-calcium pyroxene, and darker-colored areas are interstitial

to the poikilitic grains and contain concentrations of small ilmenite grains. Much of the plagioclase is euhedral to subhedral (small white laths). The rock is vesicular and a large vesicle is visible at bottom center. The large xenocryst at top right is of olivine.

Figure 16: Photomicrograph of glass-rich light gray breccia 73215. (Width of field of view is 2.2 mm; crossed polarizers.) Two large rounded grains of partly recrystallized shock-deformed plagioclase are included within the dark aphanitic matrix.

Figure 17: Photomicrograph of poorly consolidated feldspathic debris included with glass-rich light gray breccia 73215. (Width of field of view is 2.2 mm; plane-polarized light. The most abundant clasts are of single mineral grains, dark fragment-laden devitrified glasses, and crushed anorthosites (white clasts to right of center). Only sparse interstitial glass is present binding fragments together. The light color of the matrix is a reflection of the lack of cementing glass and the highly feldspathic bulk composition of the rock. This material is very similar to glass-poor feldspathic breccias described in the text as one of the major lunar breccia types.

Figure 18: Photomicrograph of hornfels clast in glass-rich light gray breccia 73215. (Width of field of view is 2.2 mm; plane-polarized light.) The rock consists of a very fine grained recrystallized granoblastic matrix that contains xenocrysts (such as the angular one of plagioclase below center) and small xenoliths (such as the oval

one to the left of the prominent plagioclase xenocryst.)

Figure 19: Photomicrograph of clast of fine-grained basaltic-textured "troctolite" in glass-rich light gray breccia 73215. (Width of field of view is 2.2 mm; plane-polarized light.) Plagioclase grains are lath-shaped and olivine grains are roughly equant. A few partly resorbed phenocrysts of aluminous spinel are present (dark gray skeletal grains near top left and bottom left of clast).

Figure 20: Photomicrograph of felsite clast in glass-rich light gray breccia 73215. (Width of field of view is 0.88 mm; crossed polarizers.) The felsite consists of a fine-grained graphic intergrowth of a silica mineral (white) and potassium feldspar (gray). Matrix of the surrounding light gray breccia is visible in the lower left corner and along the bottom edge of the field of view.

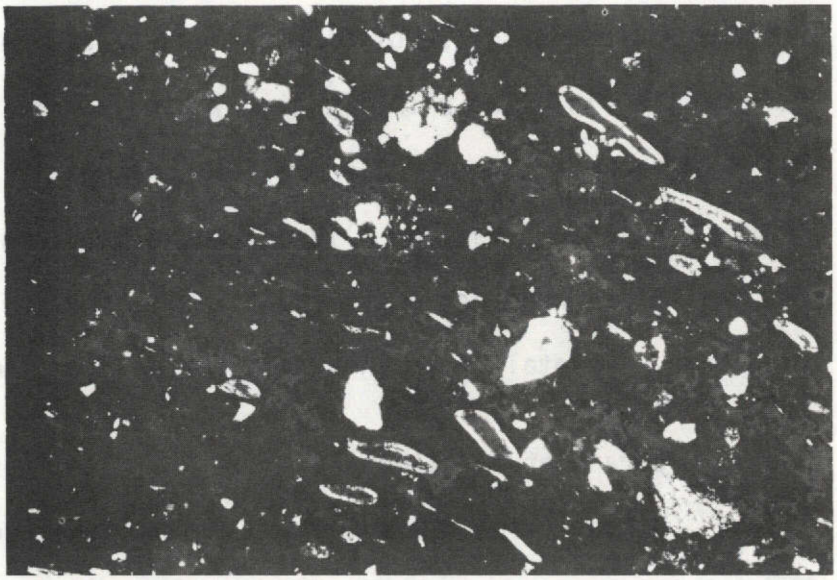

FIG. 1

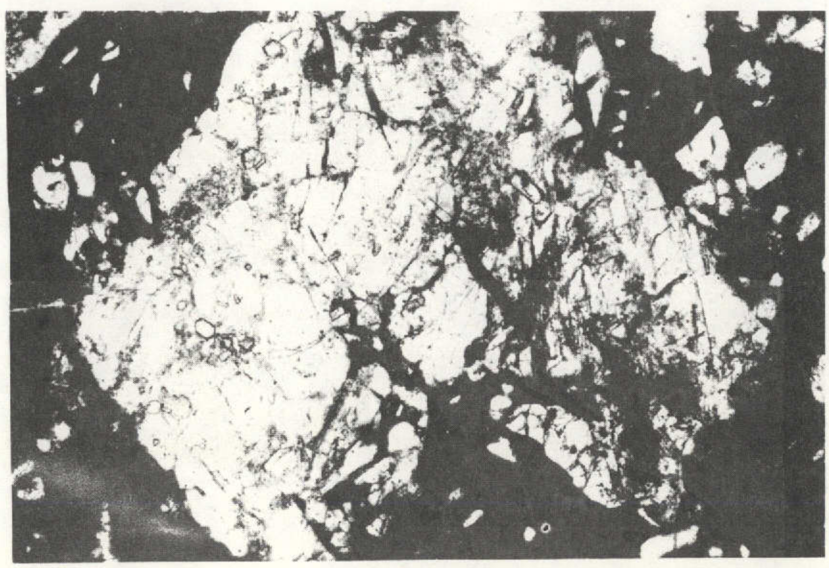

Fig. 2

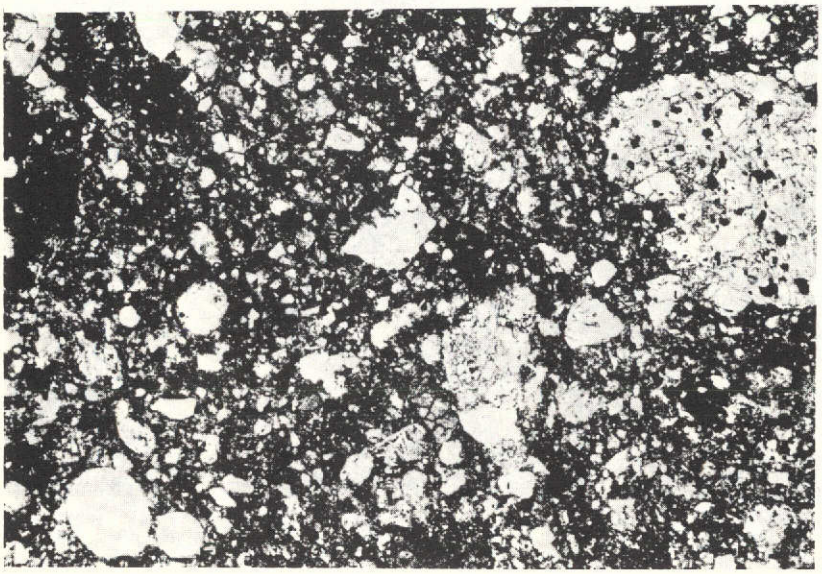

Fig. 3

Fig. 4.

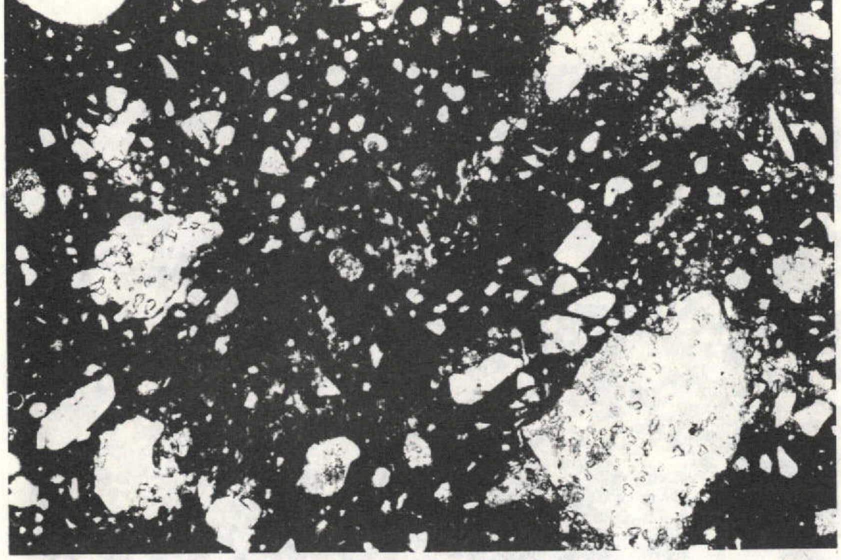

Fig. 5

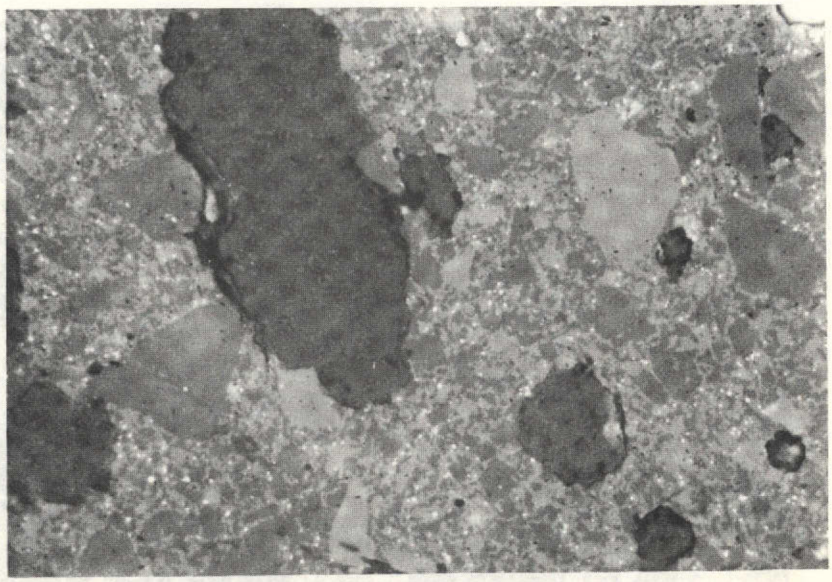

Fig. 6

Fig. 7

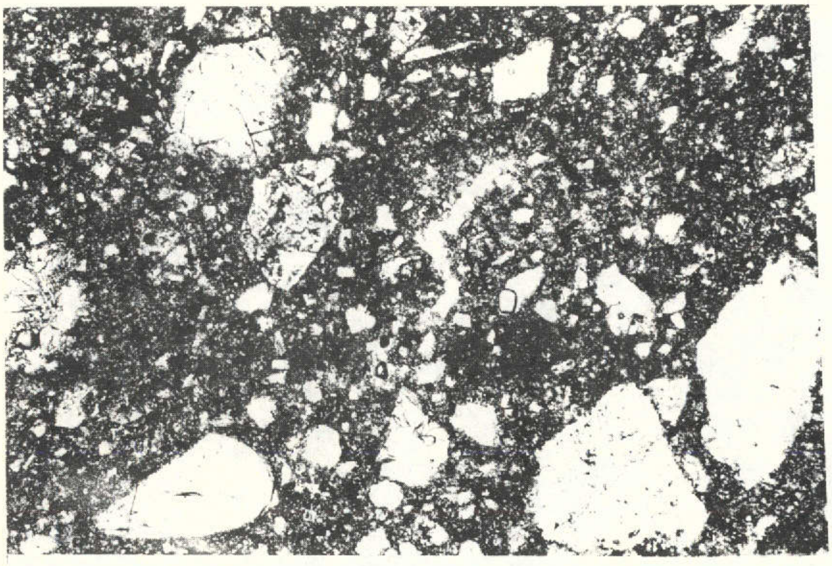

Fig. 8

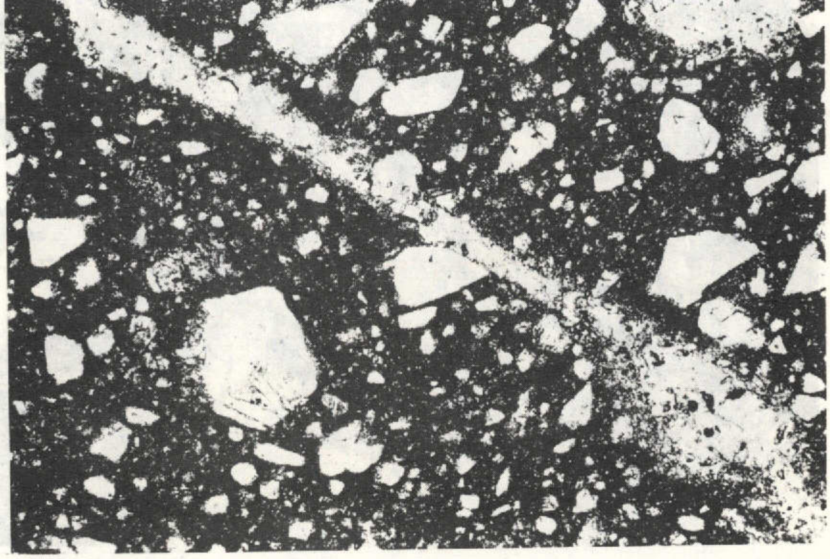

Fig. 9

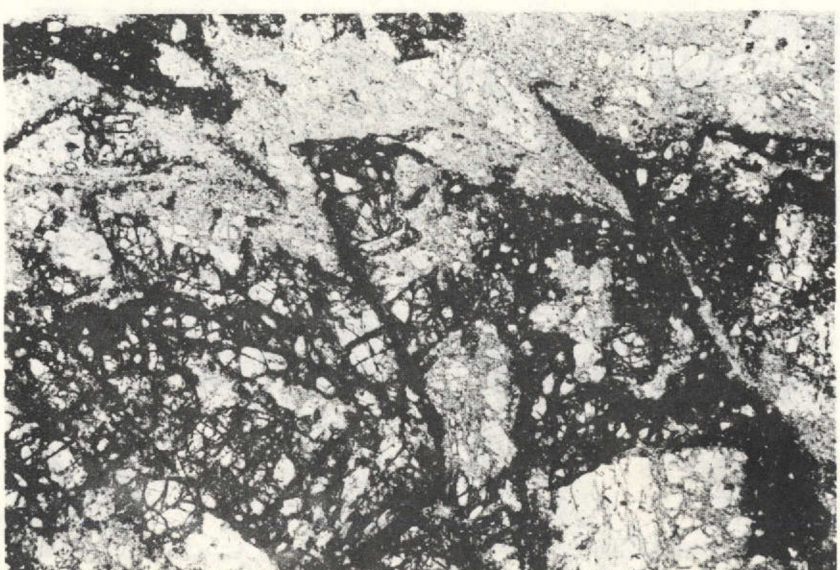

Fig. 10.

Fig. 11

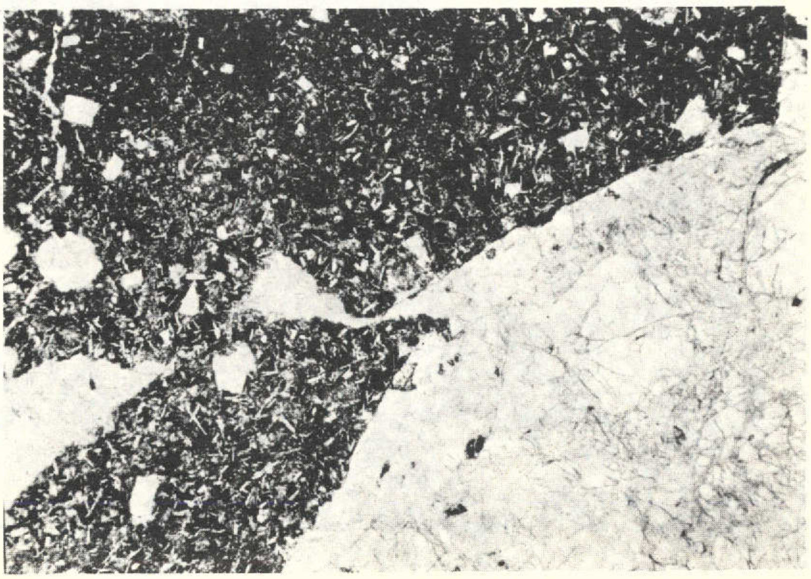

Fig. 12

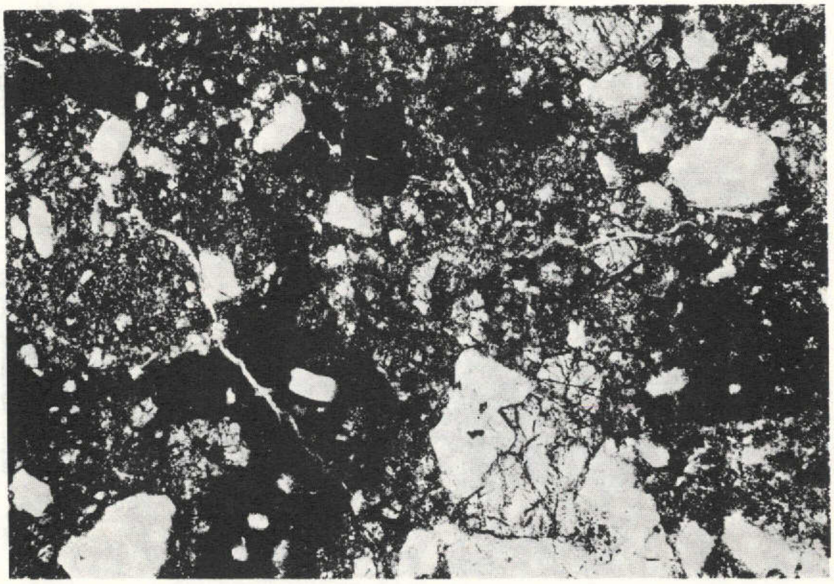

Fig. 13

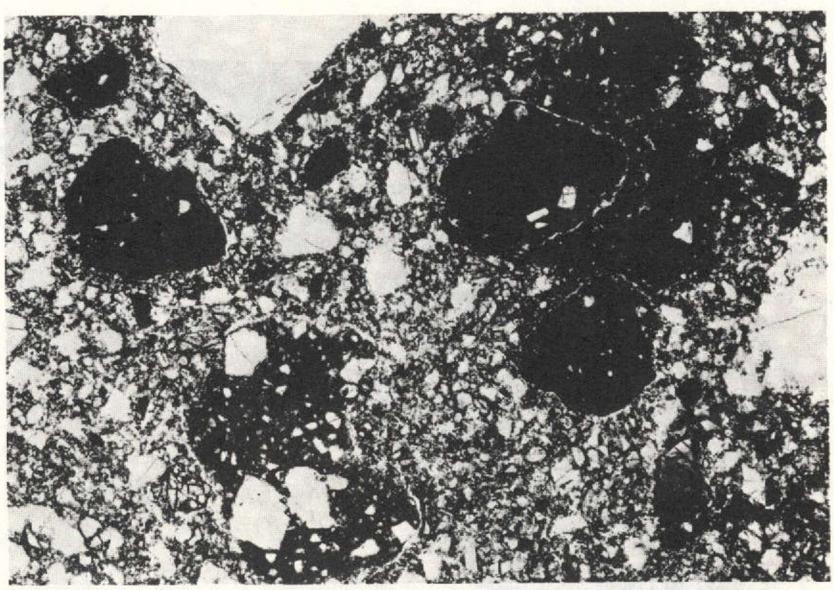

Fig. 14

Fig. 15

Fig. 16

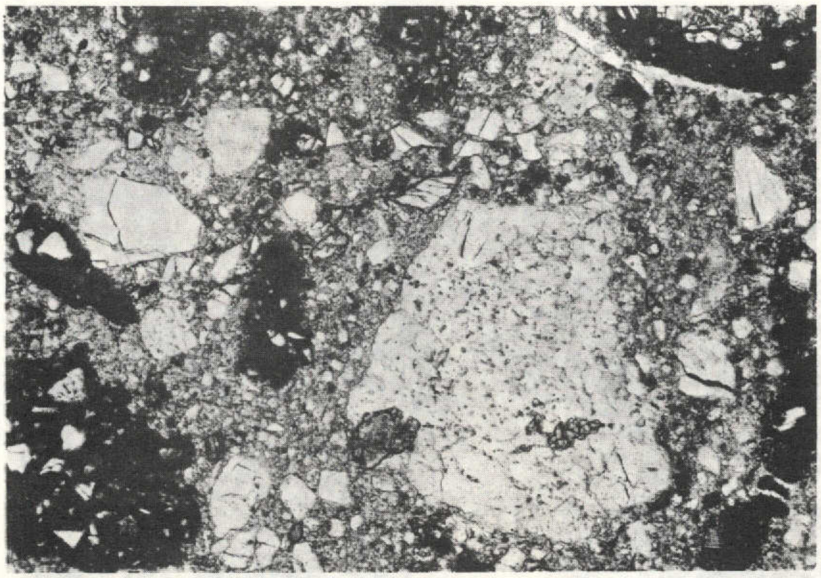

Fig. 17

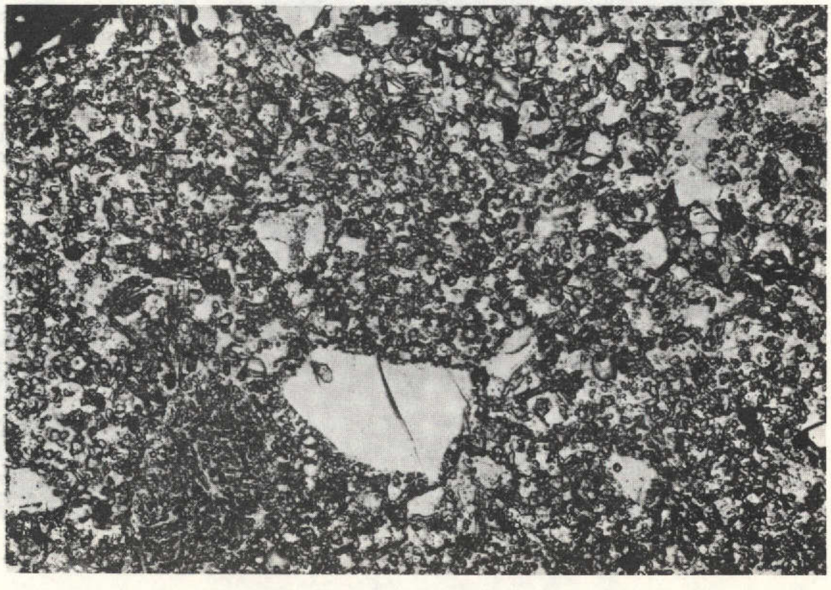

Fig. 18

Fig. 19

Fig. 20