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Implications to histories of the moon and parent meteorite bodies

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COMPARISON OF LUNAR ROCKS AND METEORITES: IMPLICATIONS TO HISTORIES OF THE MOON AND PARENT METEORITE BODIES

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ABSTRACT

There are many similarities between lunar samples and stone meteorites. Lunar samples, especially from the highlands, indicate that they have been affected by complex and repeated impact processes that can result in breccias with a wide variety of features produced by crushing; grinding; comminution; cataclasis; mixing (with other rock types and meteorites); partial or complete melting and mobilization; production of glass as matrix, agglutinates, spherules, fragments, and chondrules; solid state recrystallization; impact melt as matrix or as essentially wholly new igneous rocks with ophitic, intersertal, poikilitic, or other textures; etc. Similar complex and repeated impact processes have also been operative on the achondritic and chondritic meteorites, but there has been much less detailed study of the effects of these processes and discussion of their implications. In this study, we draw attention to a number of similarities between lunar and meteoritic rocks and suggest that this comparison is essential for a clear understanding of meteorites as probes of the early history of the solar systems:(1) Monomict and polymict breccias occur in lunar rocks, as well as in achondritic and chondritic meteorites, having resulted from complex and repeated impact processes. (2) Chondrules are present in lunar, as well as in a few achondritic and most chondritic meteorites. They apparently crystallized spontaneously from molten highly supercooled droplets

which may have formed from impact melts or, perhaps, volcanic processes (as well as from the solar nebula, in the case of meteoritic chondrites). It is pointed out that because chondrules may form in several different ways and in different environments, a distinction between the different modes of origin and an estimate of their relative abundance is important if their significance as sources of information on the early history of the solar system is to be clearly understood. (3) Lithic fragments are very useful in attempts to understand the pre- and post-impact history of lunar and meteoritic breccias. They vary from little modified (relative to the apparent original texture), to partly or completely melted and recrystallized lithic fragments. Their detailed study allows conclusions to be drawn about their parent rock types and their origin, thereby gaining insight into pre-impact histories of lunar and meteoritic breccias. There is considerable evidence that cumulate rocks were involved in the early history of both the moon and parent meteorite bodies. By continued study of meteoritic samples, in the light of knowledge derived from the lunar program, we should learn more about the pre-impact history of both rock groups and thereby be more prepared to make comparative studies of planetary bodies, particularly regarding their early histories.

INTRODUCTION

One of the most important characteristics of lunar rocks, particularly from the lunar highlands, is that they have been greatly altered by intense, repeated impact bombardment. The histories of these rocks, both pre- and post-impact, are difficult to decipher and interpretation of their genesis is a major goal of lunar research. There is general agreement that the lunar highland rocks originated as cumulates, although very few original textures have survived the impact processes without major obliteration. About 90% of the highland rocks are polymict breccias (ref. 1) which are the result of complex impact processes. These breccias were produced by crushing; grinding; comminution; cataclasis; mixing (with other rock types as well as meteorites); partial or complete melting and mobilization; production of glass as matrix, agglutinates, spherules, fragments, and chondrules; solid state recrystallization; crystallization of impact melt as matrix or as essentially wholly new igneous rocks with ophitic, intersertal, poikilitic, or other textures, etc. In spite of all these complications, some aspects of the pre-impact history of the cumulate rocks have been deciphered, and great progress has been made in interpreting their origins, although there is still much to be learned and some basic problems to be resolved.

In the case of meteorites, particularly the ordinary chondrites, there is much less general agreement as to whether the textural features observed are "primary", i.e. were established during condensation from a solar nebula; or whether they are "secondary", having been formed on a parent body or bodies by secondary (i.e. impact, volcanic, etc) processes; or by some combination of the two. There is much evidence and general agreement that many meteorites have been involved in impact events. However, there are few studies of meteorites in terms of deciphering their pre- and post-impact histories, notably by Fredriksson et al. (ref. 2), who pointed out that black veins in stone meteorites are shock-wave produced; by Fredriksson and Keil (ref. 3), who showed that the light-dark structures in the Kapoeta achondrite and the Pantar chondrite are due to impact brecciation; by Fredriksson (ref. 4, 5), Fredriksson and Reid (ref. 6), Urey (ref. 7), and Kurat et al. (ref. 8), who maintained that ordinary chondrites formed in large-scale impact events on parent meteorite bodies. If impact processes were indeed involved with formation of chondrites and achondrites, one should expect to find the features observed in shock-modified lunar rocks (if meteorites constitute a representative sample).

At this writing, we are only at the beginning of an era of comparative research of lunar and meteorite samples, and this type of work holds much promise for the future. We have studied both lunar rocks and meteorites (ref. 9-16), and other workers have identified impact-produced features in stone meteorites (e.g. Van Schmus, ref. 17; Bunch and Stöffler, ref. 18; Wilkening, ref. 18; Wilkening and Clayton, ref. 20; Bunch, ref. 21; Fredriksson et al., ref. 22; Dodd, ref. 23).

Since meteorites may have originated on small parent bodies with essentially no atmospheric cushion, many of their textural features must be impact- and regolith-produced, similar to what can be seen in lunar samples. In the present paper we draw attention to some of the similarities between lunar and meteoritic samples, mostly in the form of photographic analogues. It is hoped that some of the analogies will provoke other workers into studies whereby lunar and meteoritic samples will be used in conjunction in deciphering the histories of both groups of rocks, and the processes that were effective on their parent bodies.

There are, of course, many ways of comparing lunar and meteoritic samples, but for the purpose of this paper we shall limit our examination to only three general areas: (1) Evidence of impact brecciation, either monomict or polymict; (2) modes of origin of chondrules; and (3) origin and history of lithic fragments and their host breccias.

LUNAR AND METEORITIC BRECCIAS

Many lunar highland rocks are complex monomict and polymict breccias and exhibit many of the characteristics associated with impact metamorphism. Several excellent examples of monomict breccias were found in the lunar highlands. One of the best known is anorthosite 15415, the "genesis rock" (e.g. ref. 24). A group of eight other very similar rocks, termed ferroan anorthosites, were found in the Apollo 16 rake samples (ref. 25), indicating a widespread distribution of this rock type. Another important monomict breccia is dunite 72415, described by Albee et al.(ref. 26) and shown in fig. 1. The matrix of the dunite formed as the result of crushing, without recrystallization, of the parent rock; other deformational characteristics are also present.

Several meteoritic analogs to lunar monomict breccias exist, particularly in achondritic meteorites. There, the enstatite achondrites and bronzite achondrites (terminology of Keil, ref. 27) consist mainly of what appear to be monomict breccias of enstatitite and bronzitite (orthopyroxenites). One example of a bronzite achondrite, or bronzitite, is Johnstown (fig. 2), which is texturally very similar to the lunar dunite (fig. 1). Portions of the Johnstown meteorite are unbrecciated and retain a pre-impact, coarsely recrystallized texture with triple-point junctions between the bronzite grains. Brecciated and unbrecciated portions of this meteorite have identical bulk chemical compositions (ref. 28), indicating that, at least in this one case, the mineralogy and bulk chemistry of a monomict brecciated rock is the same as its pre-impact parent.

Most lunar highland samples, however, are polymict breccias. They are particularly abundant at the Apollo 16 (ref. 29) and the Apollo 14 sites (ref. 30). One such polymict breccia (14318), with a chondritic texture, has been described by Kurat et al (ref. 31). This rock differs, of course, from a meteoritic chondrite in its mineral and bulk chemistry and especially in its paucity of metal and troilite, but is very similar to chondrites in its texture. It consists of a fine-grained matrix into which are embedded lithic fragments, glasses, and chondrules of ANT suite, high-alumina basalt, and dunite composition. The rock is annealed and has a partly glassy matrix analogous to many relatively unrecrystallized chondrites. A similar Apollo 14 breccia, 14315, is shown in fig. 3.

Analogs to this rock type exist in both achondritic and chondritic meteorites. Among the achondritic meteorites, the best examples of polymict breccias are the howardites. These have previously been considered to be polymict breccias by numerous workers (e.g. Duke and Silver, ref. 32), and the analogy to lunar breccias has reinforced the conclusion that they are impact produced breccias from meteorite parent-body regoliths (e.g. refs. 21, 33). Bunch (ref. 21) finds lithic fragments ranging from anorthositic gabbro to basalt to ferrobasalt in five howardites, which would appear to indicate stronger mineralogical and chemical similarity to lunar rocks than previously realized. An example of one of these howardites, Malvern, is shown in fig. 4.

Many chondrites, particularly those of the LL-group, are also brecciated, and it is sometimes difficult to determine whether they are monomict or polymict. One such example, Soko-Banja, is shown in fig. 5. In some cases, the complex impact-produced relationships are further obscured by metamorphism which causes recrystallization and may be a late stage of the impact event or a later event superimposed on the impact features . The clearly brecciated chondrites exhibit these textures on the hand specimen level, and microscopic studies indicate lithic fragments of varying textures, mineralogy, and chemistry, associated with chondrules, embedded in a finer grained, highly indurated or welded matrix. Since many chondrites consist of chondrules embedded in fine-grained matrices, and show evidence of shock features in the minerals, it is possible that all chondrites are breccias and those without a visibly brecciated texture were originally comminuted on a finer scale and metamorphosed. Thus, there are many unresolved major problems with regard to the interpretation of the history of chondrites, as seen by the petrologist. These histories must then be correlated with studies of many types before final interpretations are possible.

Wahl (ref. 34) stressed the importance of polymict brecciated meteorites, but his descriptions were based largely on petrographic studies without chemical data. Nevertheless, there are now some well established examples of polymict brecciated chondrites. Some of the more recent descriptions are given in references 5, 10, 12, 13, 14, 16, 17, 20, 35 and 36.

One of the best known examples of a meteoritic polymict breccia is Cumberland Falls which consists of an enstatite achondrite host into which are embedded fragments of chondritic material. However, Fodor et al. (ref. 13) recently showed that achondritic material may be found in a chondrite: the Adams Co. chondrite contains a large lithic fragment of regolithic material consisting of smaller lithic and mineral fragments derived from ureilites and enstatite achondrites. A photo of this fragment is shown in fig. 6. Another group of polymict breccias currently receiving wide attention are C3 chondrites, such as Allende, which contain white Ca-Al-rich inclusions.

Even now it is already apparent that meteorites, both achondrites and chondrites, show many of the impact features seen in lunar highland rocks. The conclusion appears therefore inescapable, namely, that parent meteorite bodies have been severely affected by impact processes, and that many of the textural features in achondrites and chondrites are the result of these complex and repeated impact processes, similar to the lunar case. It will be an important task of future lunar and meteoritic research to clearly describe these "secondary" features and distinguish them from "primary" features. Inevitably, this will lead to a clearer understanding of the history of parent meteorite bodies, and to a better appreciation of what meteorites can tell us regarding the early history of the solar system.

ORIGIN OF CHONDRULES

Chondrules are characteristic features of chondritic stone meteorites and are thought by some to be primary bodies that condensed from a nebula of solar composition and then agglomerated to form parent meteorite bodies (ref. 37-40), and by others to be secondary objects that formed from pre-existing material by either volcanism (refs. 41-44), lightning discharge (ref. 45), shock melting of primitive dust (ref. 46), or impact splattering (refs. 4-8).

Lunar chondrules were found in some breccias and soils from most Apollo and Luna sites (e.g. ref. 47). Their textures are similar to those found in some meteorites, especially in unequilibrated ordinary chondrites, which often have chondrules with glassy matrices. The lunar chondrules have textures which often appear to be due to a greater amount of supercooling as compared to those in chondrites, but quantification of this difference is difficult because of bulk compositions. Lunar and meteoritic chondrules are interpreted by most workers as being produced from molten droplets which have spontaneously crystallized from the highly supercooled state. However the critical and controversial question is the origin of the molten droplets especially in the case of meteorites. Recent experimental work has contributed significantly to an understanding of the origin of chondrules. In this work, silicates were melted with the use of a CO_2 laser and allowed to fall freely into a variety of atmospheres. The freely falling molten droplets supercooled highly and crystallized spontaneously from the highly supercooled state, with the resulting spherules having typical chondrule textures (refs. 48, 49). It is therefore concluded, that both meteoritic and lunar chondrules formed by spontaneous crystallization of highly supercooled molten droplets, but nothing can be said from the experiments as to the origin of the molten droplets (i.e. whether they formed by condensation or by secondary processes such as volcanism or impact splattering).

In the case of some lunar chondrules, the mode of origin of the molten droplets is uncontroversial, being interpreted as to have formed by impact spattering (e.g. ref. 47). An example of an impact-produced lunar chondrule is shown in fig. 7. All gradations between glass spherules and chondrules, with microcratered surfaces indicative of repeated impact processes, were found in the lunar samples. Although some workers do not refer to these objects as chondrules and use such terms as "devitrified glass spherules", there is little or no disagreement that the crystallization in the chondrules occurred in the same event which formed the molten droplet and thus the apparent difference in interpretation is merely a matter of terminology.

However, the origin of two other lunar chondrule types is somewhat uncertain and controversial. This is the green glass (one example of a great variety of textures is shown in fig. 8), which is most abundant at the Apollo 15 site, and the orange glass (one example is shown in fig. 9), which was found at the Apollo 11 and 17 sites. Most workers argue that orange glass was formed by a volcanic process (e.g. refs. 50-52), such as fire-fountaining, and we have suggested (ref. 53) that the volcanic event may have been triggered by a major impact event, because the composition implies a major amount of partial melting of the same source rock as for high-Ti mare basalts. It has also been suggested that the orange glass may have formed by impact into a lava lake (ref. 54). Cameron et al. (ref. 55) suggested that green glass may be of volcanic origin, and Bunch et al. (ref. 56) stressed their ultramafic character, distribution at other sites, and the abundance of chondrules. Since green glass has many of the same unique characteristics as orange glass, most workers would probably now assume a similar mode of origin. The character of the ill-defined volcanic process responsible for green and orange glass is of critical importance to the interpretation of lunar history. Adams et al. (ref. 52) have shown that orange glass has a wide distribution on the lunar surface and is found in belts along the edges of major mare basins. The distribution of green glass deposits is not yet known. If these chondrules are indeed of volcanic origin, then this process must be reexamined for a possible mode of origin of at least some meteoritic chondrules.

In case of meteoritic chondrules, the problem is even more complicated. Only a few chondritic meteorites, namely the howardites, contain chondrule-like glass spherules, presumably of impact origin. One example from Bununu, is shown in fig. 10. If impact-produced glass spherules are found, then a small percentage of chondrules should also be present. Brownlee and Rajan (ref. 57) have indeed found such objects with microcratered surfaces in the howardite Kapoeta, a gas-rich meteorite, formed as an impact-produced regolith breccia similar to the lunar regolith breccias. Noonan et al. (ref. 59) also found glass spherules in Bununu and Kapoeta and in addition, in Malvern.

Chondrules, often with glassy matrices, are an important constituent of chondritic meteorites. They occasionally also contain glass spherules, especially in unequilibrated ordinary chondrites. One example of a glass spherule in Chainpur is shown in fig. 11. Two chondrules from the same meteorite are pictured in fig. 12, and their textural similarity to the lunar orange-glass chondrule (fig. 9) should be noted. Thus, these similarities in texture for glass spherules and chondrules in meteoritic and lunar samples appear to imply that at least some of the spherules and chondrules in some meteorites may be the result of impact splattering (as in most lunar spherules) or volcanism (as possibly in green and orange glasses). However, this does not imply that chondrules derived by other processes are not also present in meteorites. However, since we have shown that impact processes have been extremely important in the history of chondrites, it is inescapable that at least some of the spherules and chondrules must have been derived by this process. It should be noted that McDougall et al. (ref. 58) recently reported evidence that the H-group chondrite Fayetteville probably formed as a regolith on a parent meteorite body.

It is also interesting to note that Fredriksson et al. (ref.60) have shown that regolithic breccias, impact glasses and glass spherules can form terrestrially in terrestrial meteorite impact-events. Also, chondrules were found in glassy microtektites from a sea floor core in the Venezuela basin (ref. 61). These additional occurrences confirm our earlier conclusion that chondrules are not unique to chondrites, but that they may form in a number of different ways and in different environments.

One of the arguments against lunar chondrules having an origin which may be relevant to meteorite chondrules has been that impact-produced chondrules make up only a small proportion of a lunar breccia, whereas meteoritic chondrules often constitute a very large proportion of a chondrite. While this argument does appear to be a strong one with regard to impact-produced glass, it is not the case for presumably volcanic-produced lunar chondrules, such as green and orange glass. A breccia consisting largely of green glass spherules and chondrules is shown in low magnification in fig. 13. There is a strong similarity in texture with that of many chondrites, although the abundance of glass is much greater and there is very little metal and troilite, as compared to chondrites. Although it is not necessarily implied that chondrites formed in a manner analogous to green and orange glass breccias, it should be recognized that the mode of origin of green and orange glass has not previously been recognized as a process for making meteoritic chondrules.

In summary, it may be said that chondrules and glass spherules in lunar rocks, meteorites, and on earth, can form in a variety of ways. All that is required is a process which produces molten silicate droplets which are given a chance to supercool and crystallize spontaneously from the highly supercooled state. In case of lunar chondrules and glass spherules, this process is largely impact splattering, but volcanism or impact into a liquid cannot be ruled out. Because of the many indications for impact modification of chondrites and achondrites (e.g. brecciation), some meteoritic chondrules and glass spherules must have formed by impact as well. It is the subject of future studies to derive parameters which will allow one to distinguish between impact-produced meteoritic chondrules and those which may have formed by other processes (e.g. condensation, volcanism).

LITHIC FRAGMENTS AND THE ORIGIN OF THEIR PARENTS

Lithic fragments in lunar breccias and soils vary widely in textures; some appear to be only little modified, retaining their original (sometimes cumulate) textures, whereas others have partly modified textures, such as the cataclastic textures of monomict breccias, or are partly or completely melted or recrystallized. The lithic fragments are daughter products of an original parent rock or rocks (perhaps mixed together), and are sometimes in a matrix that may or may not be directly related to the parent. This makes any interpretation of the nature of the parental rocks an exceedingly difficult task, although some progress has been made.

One example of a possible parent in a parent-daughter relationship is that of spinel troctolite 67435 (fig. 14), described by Prinz et al. (ref. 62). This is an important lunar rock type, but one that has rarely survived impact processes without major textural alterations. A large number of lithic fragments derived from spinel troctolites (perhaps with some addition of KREEP and/or ANT component) were found in the Luna 20 sample (ref. 63) and have a wide variety of textures. One example of a spinel-troctolite daughter derived by total melting and quenching is shown in fig. 15; it consists of spinel, olivine and glass with the bulk chemistry of a spinel troctolite.

Analogs to this lunar situation also exist in meteorites. Some lithic fragments found in brecciated achondrites and chondrites apparently were derived from cumulate parent rocks, such as the olivine achondrite, or dunite, Chassigny (ref. 64; fig. 16), and the bronzite achondrite, or bronzitite, Johnstown (ref. 28; fig. 2). Chassigny is shocked and unbrecciated, and basically retains its partly igneous, partly recrystallized metamorphic (not by impact) texture, whereas Johnstown is mostly brecciated (monomict), but retains some of its originally coarsely recrystallized texture. The LL-group polymict-brecciated chondrite Olivenza contains numerous lithic fragments (unpublished data), two of which may be of interest because their parent rocks may be similar to Chassigny or Johnstown. One fragment (fig. 17) is an olivine-rich monomict breccia (of dunite composition) and could have been derived from a rock such as Chassigny. The other fragment (fig. 18) consists almost entirely of orthopyroxene and could have been derived from a meteorite such as Johnstown. The orthopyroxene-rich fragment has a bulk composition of: SiO_2, 52.3%; FeO, 16.9%; MgO, 24.5%, Cr_2O_3, 0.35% (ref. 65). A comparison with the bulk chemistry of Johnstown (ref.66) shows a striking similarity; Cr_2O_3 is somewhat lower, but Johnstown has more-chromiferous orthopyoxene than the other bronzite achondrites. Although it is possible that these two fragments may have been derived from a chondrite, the near-absence of metal and troilite in the fragment makes this possibility appear to be less likely. We have previously (fig. 6) referred to the presence of ureilite and enstatite achondrite (enstatitite) fragments in a regolithic fragment in the Adams Co. chondrite, indicating a similar parent-daughter relationship.

Sometimes the parent rock or rocks were only partly melted and relicts of the parent rock(s) are retained in a matrix of molten material. This appears to be the case in some of the lunar breccias which have a poikilitic-textured matrix with unmelted relict crystals (fig. 19). In meteorites, unmelted relict crystals in an igneous matrix are also found. One such meteorite (fig. 20), the H-group chondrite Plainview, shows a lithic fragment with relict olivine crystals (and minor pyroxene) in a fine-grained igneous groundmass that represents impact melt. In some cases the impact derived melt rocks represent a melt formed from a mixture of two or more rock types. Some examples were cited by Dowty et al. (refs. 25,67) and further work is planned to check this hypothesis with regard to these and other samples. Melt rocks derived from mixtures of various rock types should be common products from regoliths on the moon and on parent meteorite bodies. One meteoritic example of a possible mixture of two or more rock types, to produce an igneous-textured lithic fragment, is shown in fig. 21. This fragment is from the LL-group chondrite Bhola which contains numerous fragments of this type. The fragments consist predominantly of olivine set in a groundmass of K_2O-rich glass (5%) with minor pyroxene crystallites; the texture is similar to those of the most-supercooled lunar pyroxene-phyric rocks (ref. 68). Fredriksson et al. (ref. 22) suggest that these fragments indicate that the chondrite is probably a polymict breccia. Fodor et al. (ref. 14) suggest that the fragments are most reasonably explained as having crystallized from impact shock melts into an olivine-rich rock (such as dunite; a chondrite is less reasonable because the fragments are essentially free of metal and troilite) and a K_2O-rich rock (such as "granite"; chondrites have very low K_2O contents). Thus, these fragments, which are also present in other meteorites (unpublished data) may represent impact melting of a regolith with at least these two major rock components represented.

One of the most important results of the lunar program has been the realization that impact melting can produce abundant quantities of igneous-textured rocks which are very difficult to distinguish texturally from internally-generated igneous rocks. One of the best examples is

14310, although this conclusion remains controversial with some workers. A very similar lunar rock is 15382 (ref. 69) which is shown in fig. 22. Even for rocks of this type, meteoritic analogs exist: a lithic fragment with a very similar texture from the eucrite Pasamonte is shown in fig. 23. Although it is not certain, at this time, that either the lunar or meteoritic examples given here are really impact melts, their textures are strikingly similar to some rocks that have been interpreted as impact melts on the moon, based on compositional data and evidence of meteoritic contamination. More quantitative criteria for distinguishing internally-derived from externally-generated melts are badly needed.

Another type of texture commonly seen in lunar lithic fragments and larger samples, is granoblastic or equigranular. This is commonly seen in entire samples, or in matrices of samples, especially in feldspathic rocks. These rocks may retain relict, unrecrystallized crystals, but sometimes these are difficult to distinguish from newly crystallized grains. An example is shown in fig. 24. This type of texture is also observed in lithic fragments in meteoritic breccias, such as howardites and eucrites. One example of such a lithic fragment from the eucrite Bialystok is shown in fig. 25. The fragment appears to be feldspar-rich, but has not yet been studied in detail.

Finally, there are similarities between lunar and meteoritic lithic fragments in the case of poikilitic or poikiloblastic textures. Detailed studies of poikilitic- or poikiloblastic-textured rocks, with relict crystals, were published by Simonds et al. (ref. 70), Bence et al. (ref. 71), Albee (ref. 72), and others on rocks from the Apollo 16 site.

There is still some controversy as to the details of the processes involved, although most workers agree that the textures are related to impact events. An example of one of these rocks is shown in fig. 19. Similar textures are also found in lithic fragments in meteorites. We have found such fragments in several LL-group chondrites (ref. 15) and one example, from the H-group chondrite Plainview, is shown in fig. 26. Impacted melt rocks with poikilitic textures have also been identified in terrestrial impact structures, such as at Lake Mistasin, Canada (ref. 73). There, the target rock is known to be anorthositic, and the poikilitic melt rock is clearly an impact-generated derivative. Although it can be said with some confidence that some poikilitic- or poikiloblastic-textured rocks or fragments were derived as the result of impact processes, it should not be concluded that all material with these textures, especially meteoritic examples, formed in such a way. Some could have been derived from internally-generated melts as well, and, again, more criteria are needed that allow to distinguish between the two processes.

CONCLUSIONS

1. By comparing structures and textures of lunar rocks and meteorites, it can be shown that monomict- and polymict-brecciation caused by complex and repeated impacts is recorded in both rock types. Sometimes the brecciation may be so intense, resulting in such fine-grained rocks, that it is difficult to recognize the brecciated nature. In meteorites, this includes both achondrites and chondrites. A very important part of future research is to disentangle the features that impact events left on meteorites from features caused by previous histories (i.e. planetary accretion, igneous

differentiation), or from possibly still-later histories, such as metamorphic recrystallization and re-equilibration. We emphasize that any interpretation of the origin and history of meteorites and their parent bodies that does not take into account the complexities of their impact histories (which may or may not be easily recognizable) may be in serious error.

2. The origin of chondrules, both lunar and meteoritic, is not yet resolved. It does seem certain, however, that more than one process has been responsible for the chondrules present in both lunar and meteoritic rocks. On the moon, chondrules appear to have formed by supercooling of molten droplets derived by impact and possibly volcanic processes (perhaps triggered by impact processes). In places they are very abundant, such as at green glass and orange glass sites. In meteorites, it seems clear that at least some chondrules and chondrule-like objects must have formed by impact processes; these are present in both achondrites and chondrites. Possibly some chondrules are also of volcanic origin, and others may have developed by remelting condensates from the solar nebula. The task for future research is to develop criteria for distinguishing between chondrules of different modes of origin and to estimate their relative abundances. This is a very important task indeed, if the significance of stone meteorites and, particularly, chondrites, as probes into the early history of the solar system is to be clearly understood.

3. Impact processes can produce a variety of rock types from a parent rock. Applying the same type of interpretations as used for the moon, it appears that polymict brecciated achondrites contain lithic fragments which preserve some history of their igneous (often cumulate) origin, and other

achondrites are entirely made up of this material, some of which are monomict breccias. The cumulates are olivine-rich, pyroxene-rich, plagioclase-rich and, in fact, involve generally the same mineralogy as lunar rocks. Some achondrites contain lithic fragments of mafic rock types which obviously crystallized from melts, but the origin of these melts, either from within the planet, by impact melting of a rock, or by impact melting of a mechanical mixture in the regolith, has not yet been established. After this question has been solved, we can begin to better reconstruct the history of the parent body or bodies. Chondrites are also brecciated and, therefore, could not have escaped some of the inevitable effects of an impact history. Some lithic fragments may have been derived by impact brecciation and melting, or brecciation of cumulate rocks, but this is not at all certain yet. Detailed studies of individual chondrites, especially brecciated ones, are necessary to determine the effects of the variety of processes that have been operative.

Thus, the time has come to take a new look at meteorites, taking into account the results of the lunar programs. It is already apparent that meteorite parent bodies, just like the moon, have been affected by complex and repeated impact processes, and all the complexities that such processes have caused in lunar rocks, appear to be present in meteorites. It is therefore of the utmost importance that workers from many different disciplines unite in an effort to decipher these complex histories in stone meteorites, and compare them to lunar rocks. Only when these processes and their resulting textural and compositional features are clearly understood, can the significance of meteorites as probes for the early history of small planetesimals in the solar system be clearly recognized.

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FIGURE CAPTIONS

Fig. 1: Monomict brecciated lunar dunite (72415). Plane polarized light. (Photo by A. Albee). Scale bar equals 0.25 cm.

Fig. 2: Monomict brecciated Johnstown bronzite achondrite, or bronzitite. Note similarity in texture to lunar brecciated dunite (fig.1). Plane polarized light; scale bar equals 0.5 mm.

Fig. 3: Polymict brecciated Apollo 14 breccia 14315, containing chondrules, angular glass, mineral and lithic fragments in a tightly welded matrix. Plane polarized light; scale bar equals 0.5 mm.

Fig. 4: Polymict brecciated achondrite Malvern, a howardite, containing dark angular breccia fragments, glass, mineral, and igneous lithic fragments in a tightly welded matrix. Plane polarized light; scale bar equals 0.5 mm.

Fig. 5: Brecciated LL-group chondrite Soko Banja, showing lithic fragments of various sizes, shapes, and textures. White lines around some fragments are fractures. Plane polarized light; scale bar equals 3 mm.

Fig. 6: Polymict brecciated H-group chondrite, Adams Co. Regolithic achondritic breccia fragment is right-hand 2/3 of photo (dark line is boundary). Left 1/3 of photo is chondritic host. Achondritic breccia fragment contains enstatite achondrite or enstatite subfragment (large white area) and smaller ureilite fragments. Plane polarized light; scale bar equals 1 mm.

Fig. 7: An Apollo 16 chondrule, with plagioclase microphenocrysts, in a light matrix breccia (66036). Plane polarized light; scale bar equals 0.5 mm.

Fig. 8: An Apollo 15 green glass chondrule containing crystals of olivine, and dark microcrystalline areas, in sample 15425. Plane polarized light; scale bar equals 0.15 mm.

Fig. 9: An Apollo 17 orange glass chondrule containing crystals of olivine and an Fe-Ti phase (probably ilmenite), in sample 74220. Plane polarized light; scale bar equals 0.05 mm.

Fig. 10: Polymict brecciated achondrite Bununu, a howardite, with an impact-produced glass spherule (upper right) together with glass, mineral, and lithic fragments in an indurated matrix. Plane polarized light; scale bar equals 0.25 mm.

Fig. 11: A glass spherule in the unequilibrated LL-group chondrite, Chainpur. Fragmental material in spherule suggests that the spherule was impact produced. Plane polarized light; scale bar equals 0.5 mm.

Fig. 12: Two chondrules from the unequilibrated LL-group chondrite, Chainpur. Chondrules are similar in texture to the orange glass chondrule (fig. 9). Plane polarized light; scale bar equals 0.2 mm.

Fig. 13: Apollo 15 green-glass breccia 15427, consisting largely of green glass spherules and chondrules. Note one large chondrule at top. The texture of this breccia is similar to that of many chondrule-rich chondrites, except for paucity of metal and troilite, and differences in chemical composition. Plane polarized light; scale bar equals 1 mm.

Fig. 14: Apollo 16 spinel troctolite 67435 lithic fragment. Dark euhedral crystals are Mg-Al spinel, light gray crystals are euhedral olivine, and both are poikilitically set in light-colored plagioclase

matrix. Plane polarized light; scale bar equals 0.5 mm.

Fig. 15: Impact melt-rock lithic fragment in the Luna 20 fines, containing quench crystals of olivine (Fo_{95}) and Mg-Al spinel in a glassy matrix. Bulk chemistry is that of spinel troctolite. Plane polarized light; scale bar equals 0.025 mm.

Fig. 16: The meteorite Chassigny, an olivine achondrite, or dunite, consisting mainly of olivine crystals poikilitically included in exsolved pyroxene (striped areas), constituting a cumulate texture. In part, olivine crystals have triple junctions, indicating subsolidus recrystallization, probably immediately following igneous crystallization. Plane polarized light; scale bar equals 1 mm.

Fig. 17: A subrounded olivine-rich (dunite) lithic fragment in the brecciated LL-group chondrite, Olivenza. Plane polarized light; scale bar equals 1 mm.

Fig. 18: A subrounded orthopyroxene-rich (bronzitite) lithic fragment in the brecciated LL-group chondrite, Olivenza. Plane polarized light; scale bar equals 0.5 mm.

Fig. 19: An Apollo 16 polymict breccia 65778 with relict crystals and lithic fragments in a poikilitic matrix of low-Ca pyroxene oikocrysts. Crossed nicols; scale bar equals 0.25 mm.

Fig. 20: A lithic fragment in the polymict brecciated H-group chondrite, Plainview, consisting of partly-melted relict olivine crystals in a fine-grained olivine-feldspar (melt) matrix. Plane polarized light; scale bar equals 0.5 mm.

Fig. 21: A large lithic fragment in the brecciated LL-group chondrite Bhola consisting mostly of euhedral olivine crystals in a dark matrix of pyroxene crystallites and high K_2O (∿5%) glass. Porphyritic texture is the result of supercooling of the igneous melt. Plane polarized light; scale bar equals 0.5 mm.

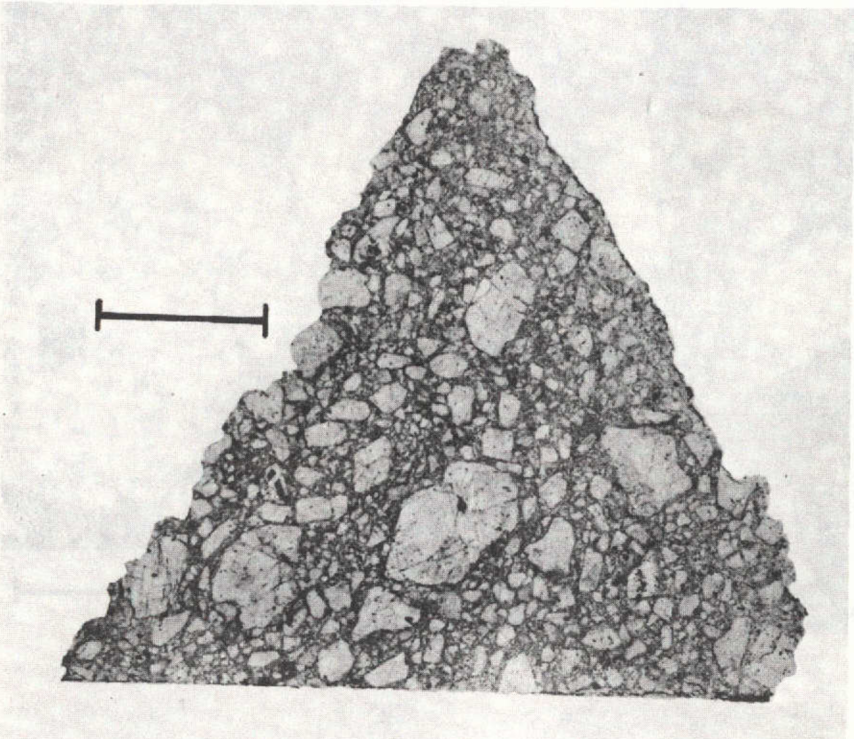
Fig. 22: A lunar melt rock (15382) with ophitic texture, of alkalic high-alumina basalt (KREEP) composition. Plane polarized light; scale bar equals 1 mm.

Fig. 23: A lithic fragment with ophitic texture, a probable impact melt rock, in the eucrite Pasamonte. Plane polarized light; scale bar equals 0.5 mm.

Fig. 24. An Apollo 16 anorthosite (60619) with granoblastic texture. Crossed nicols; scale bar equals 0.5 mm.

Fig. 25. A feldspar-rich granoblastic-textured lithic fragment in the eucrite, Bialystok. Compare with fig. 24. Crossed nicols; scale bar equals 0.5 mm.

Fig. 26: A large poikilitic-textured lithic fragment in the polymict brecciated H-group chondrite, Plainview, consisting mainly of olivine grains poikilitically enclosed in orthopyroxene. Crossed nicols; scale bar equals 0.25 mm.



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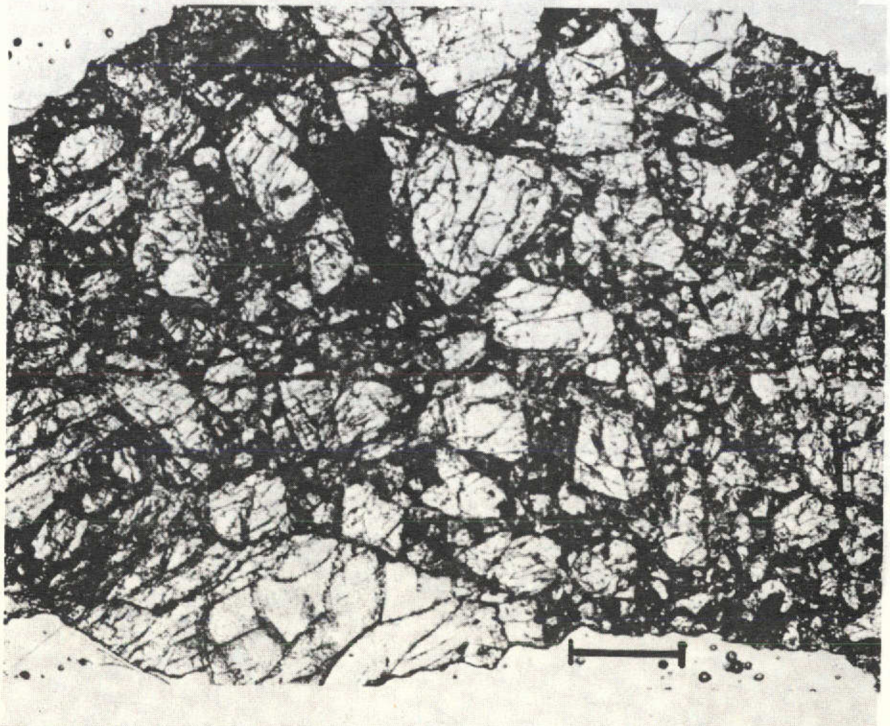

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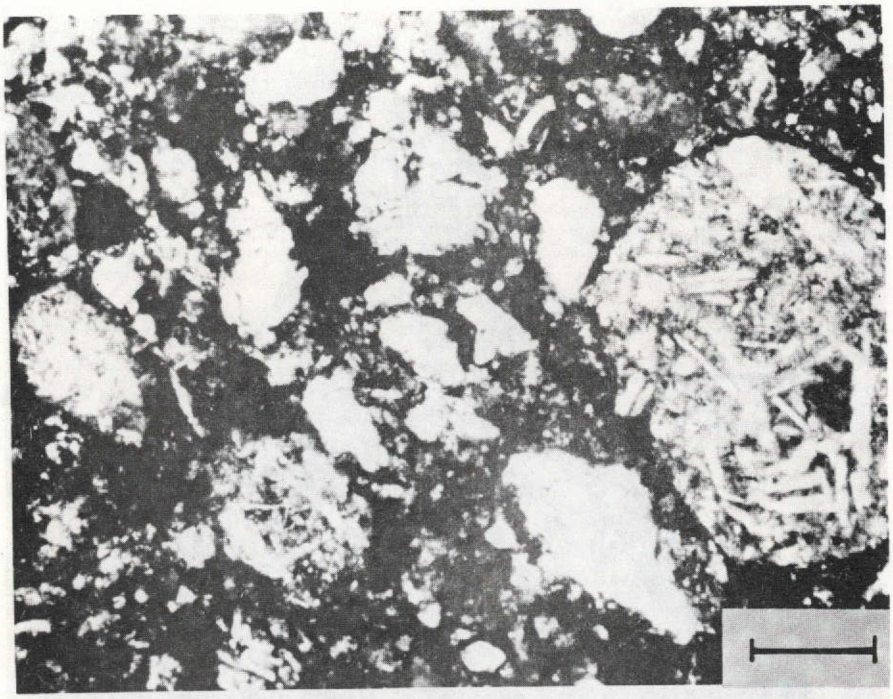

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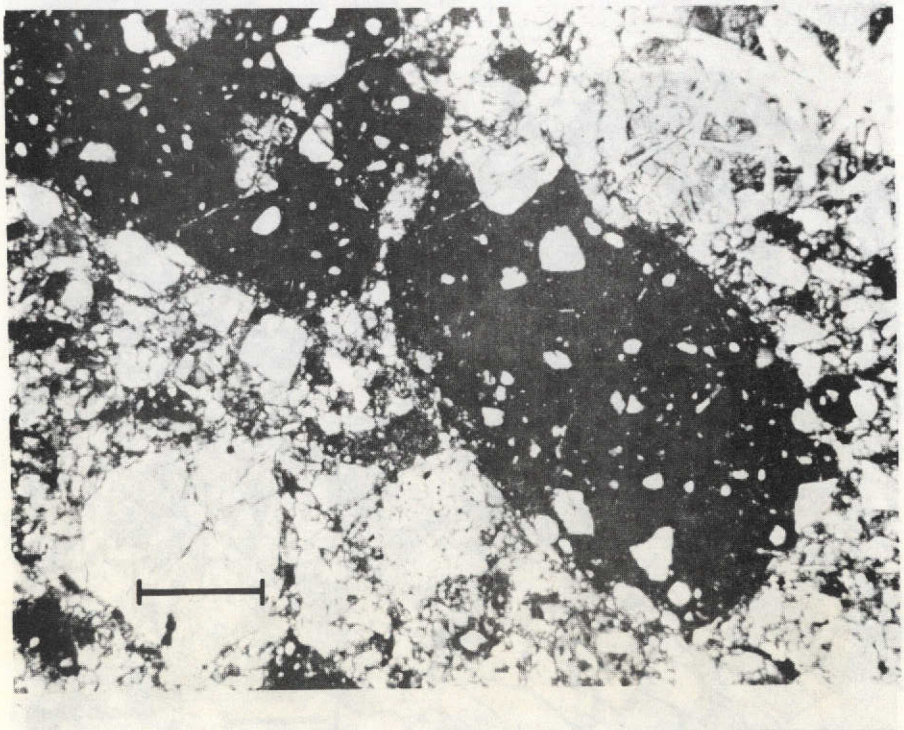

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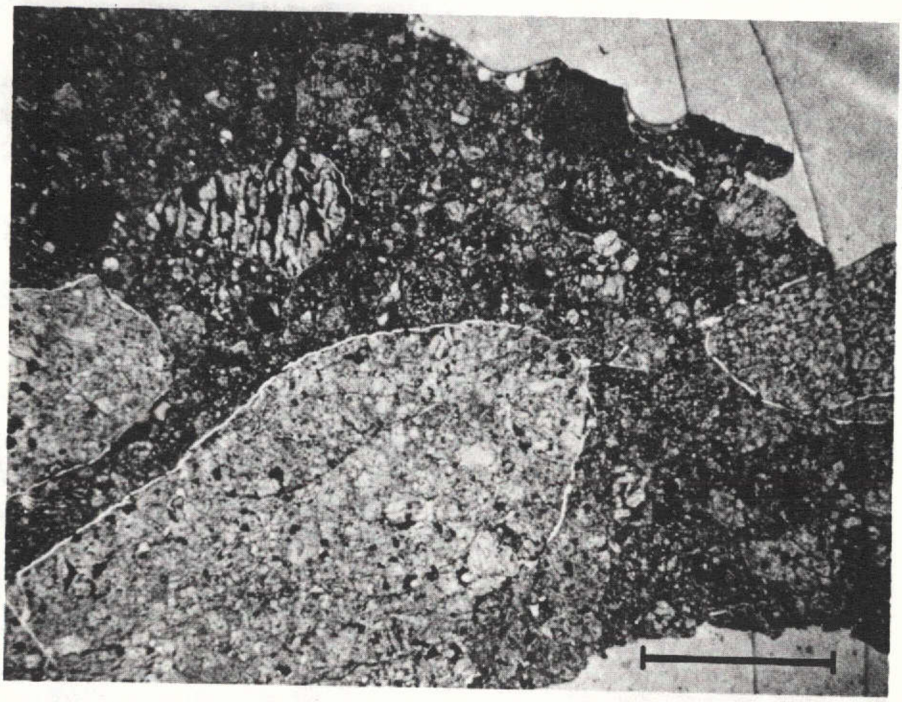

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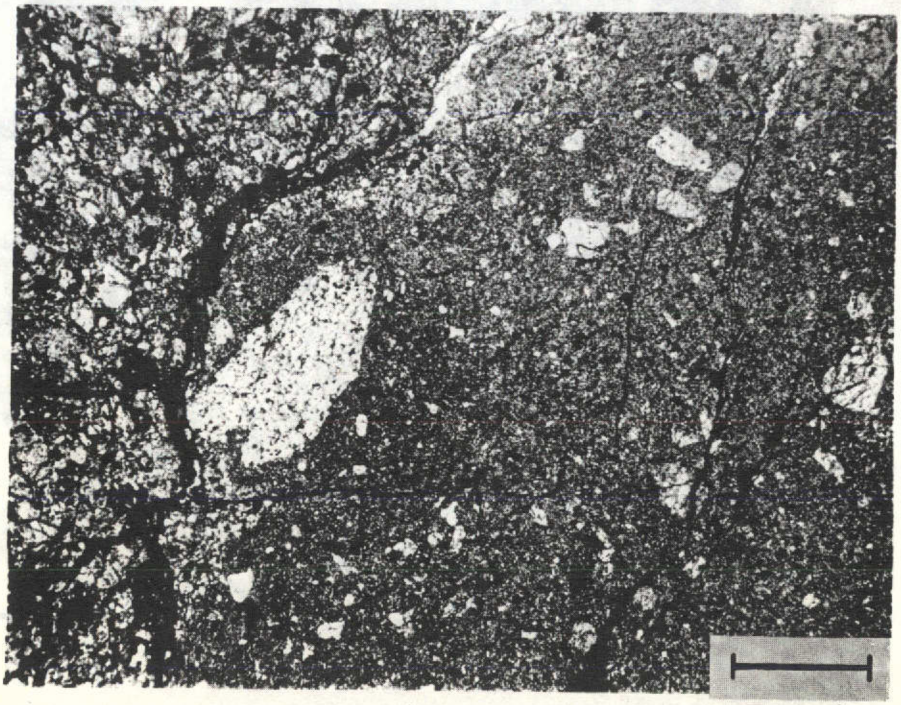

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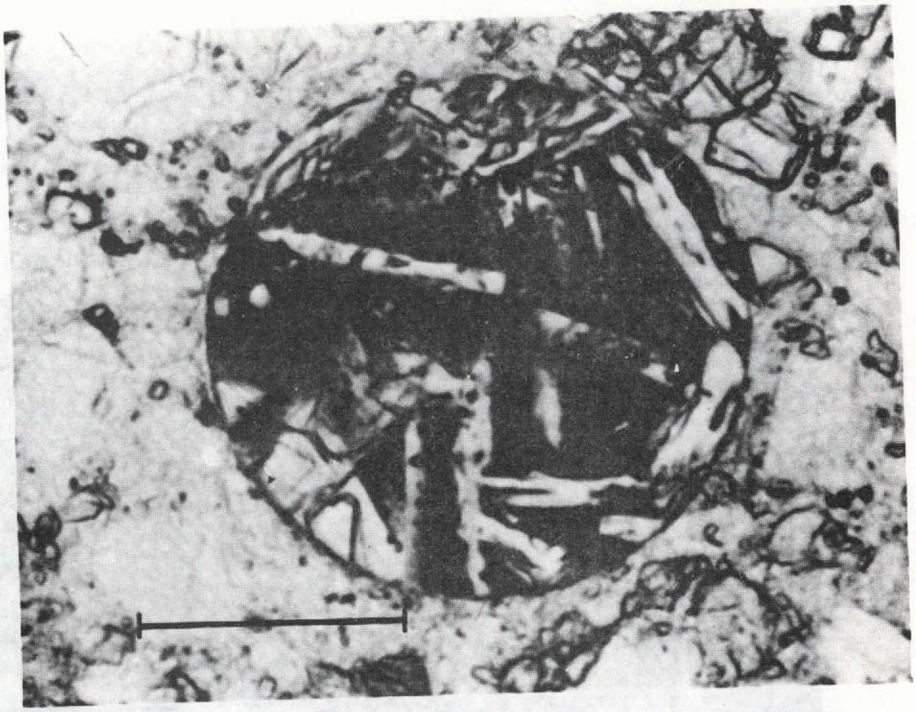

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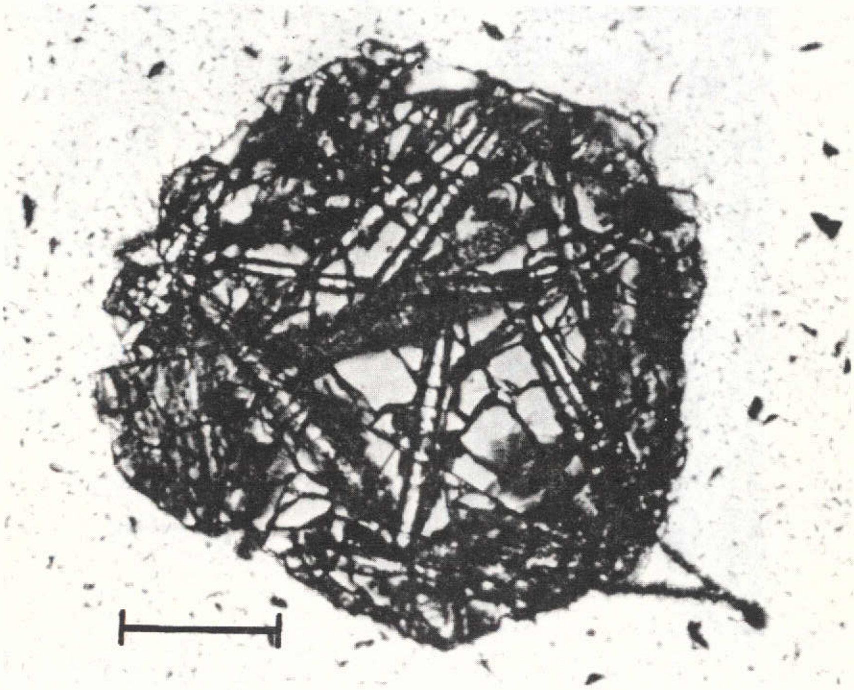

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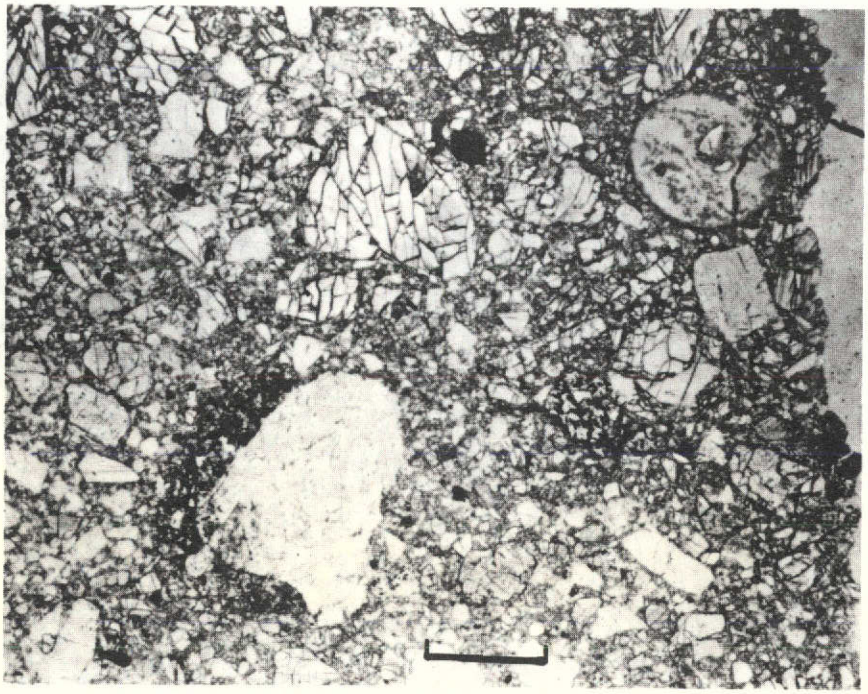

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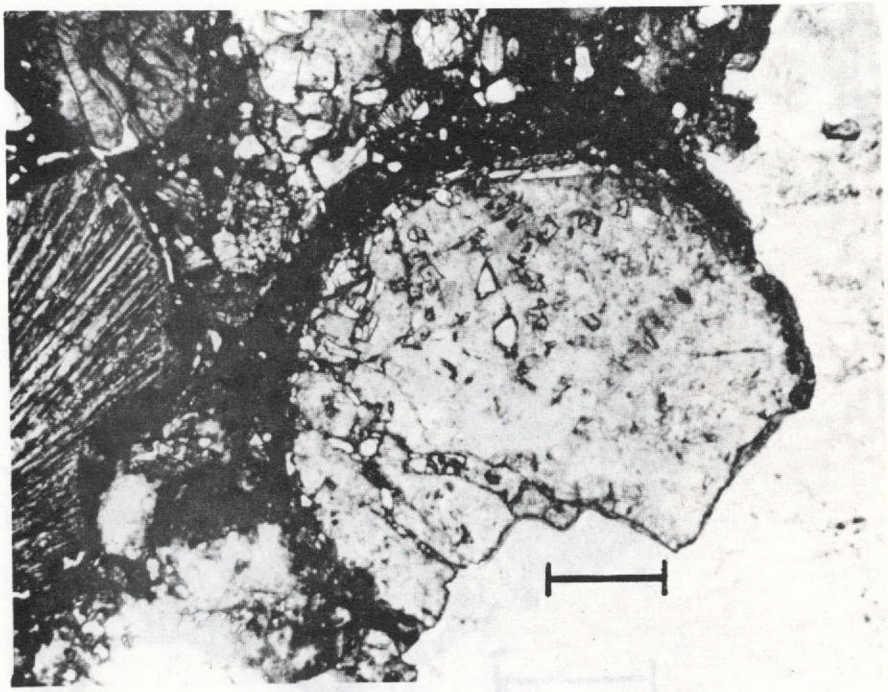

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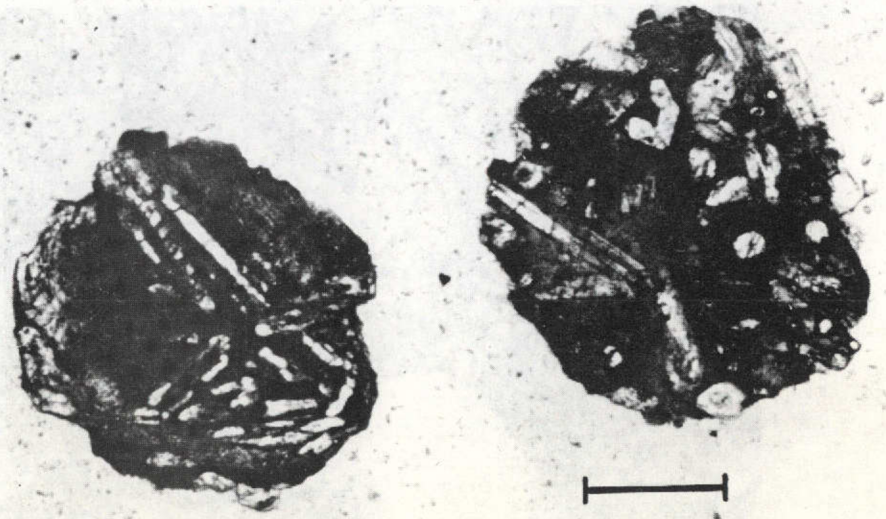

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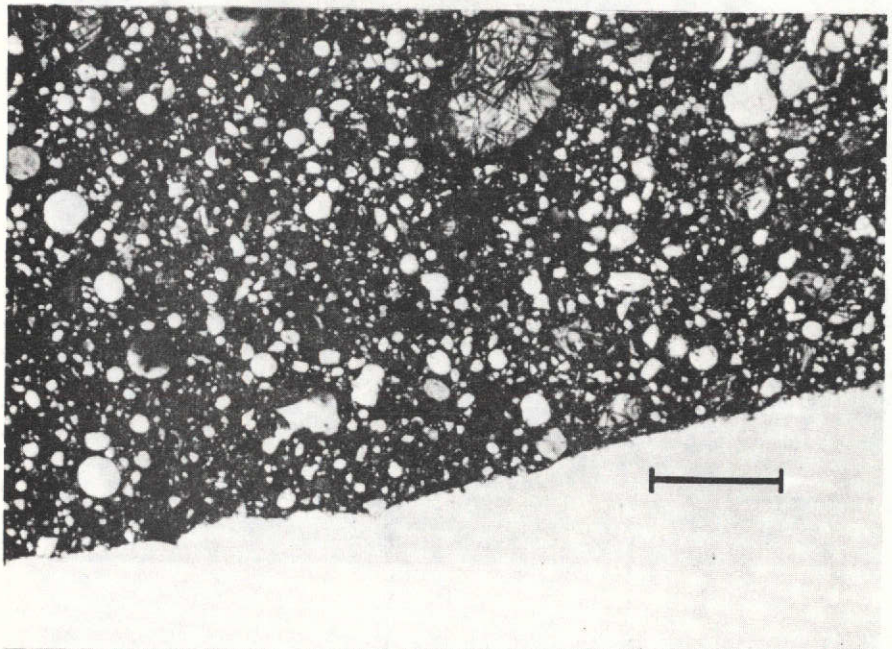

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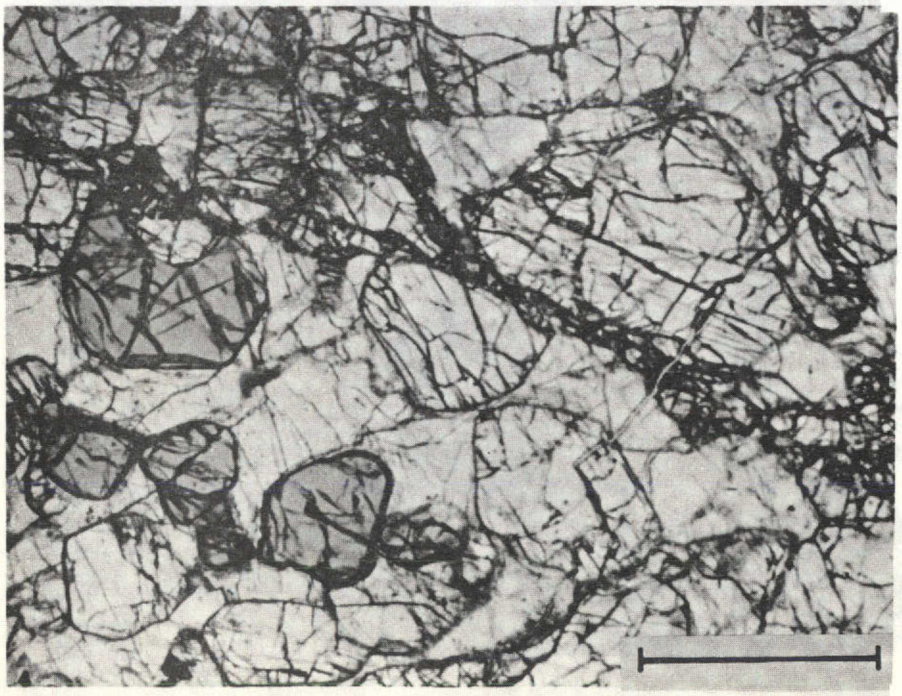

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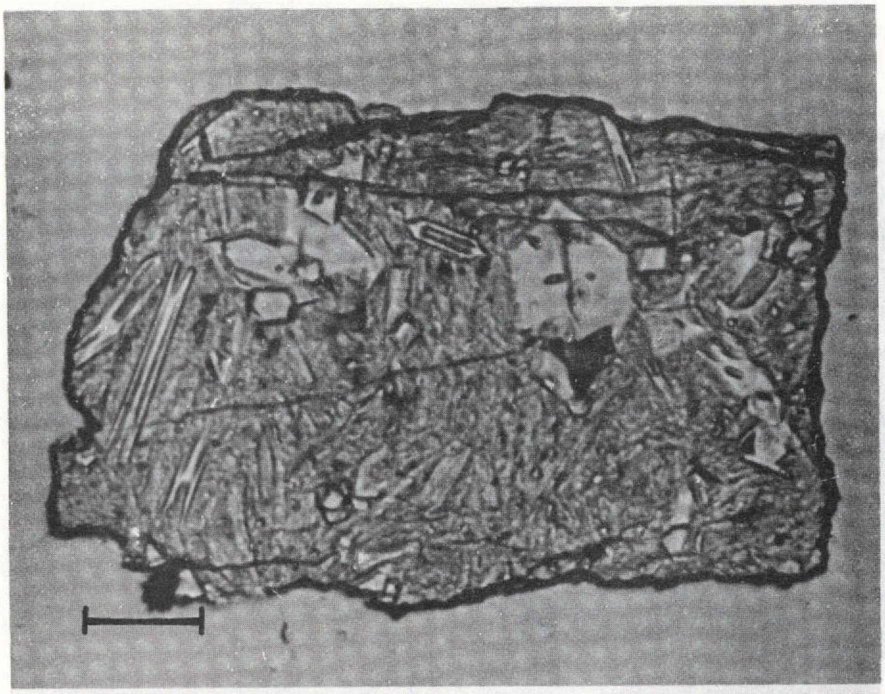

Fig. 15

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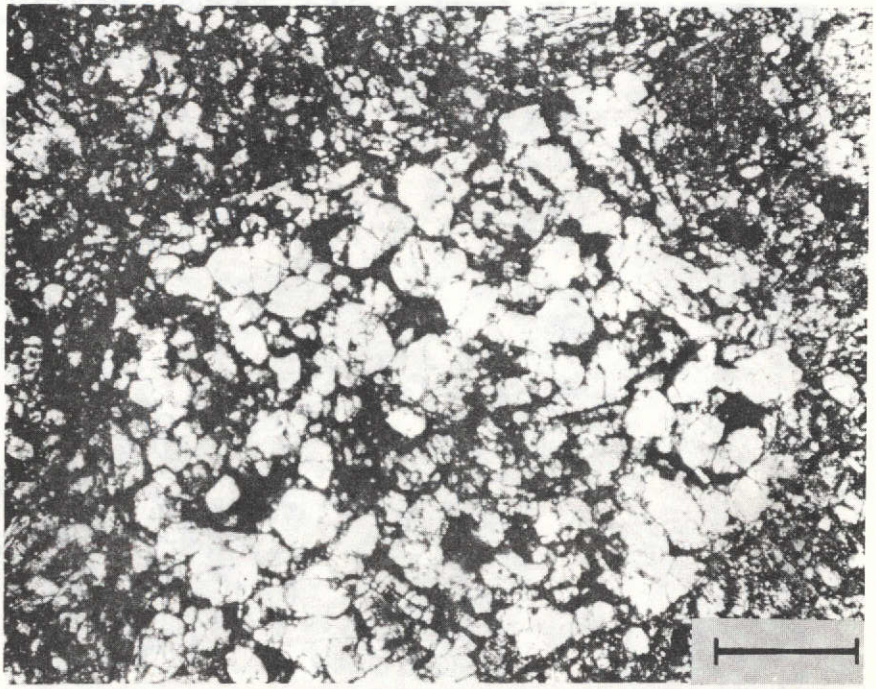

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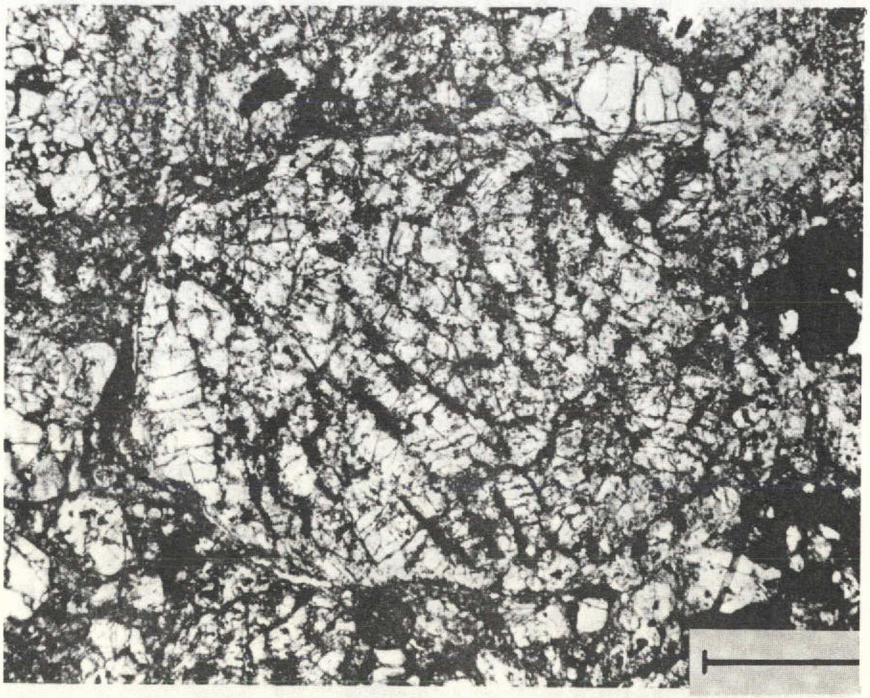

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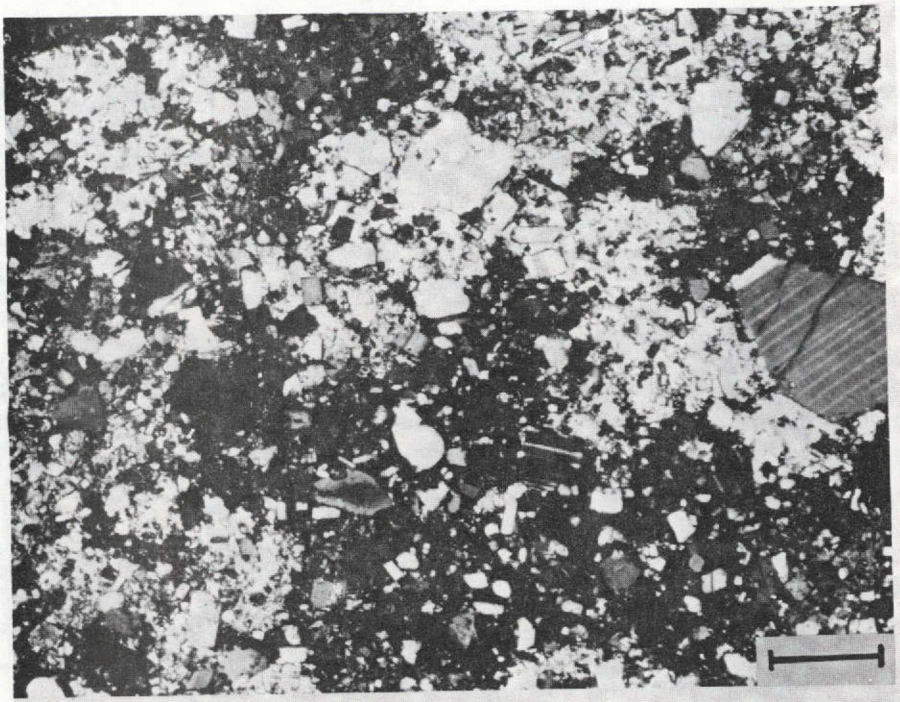

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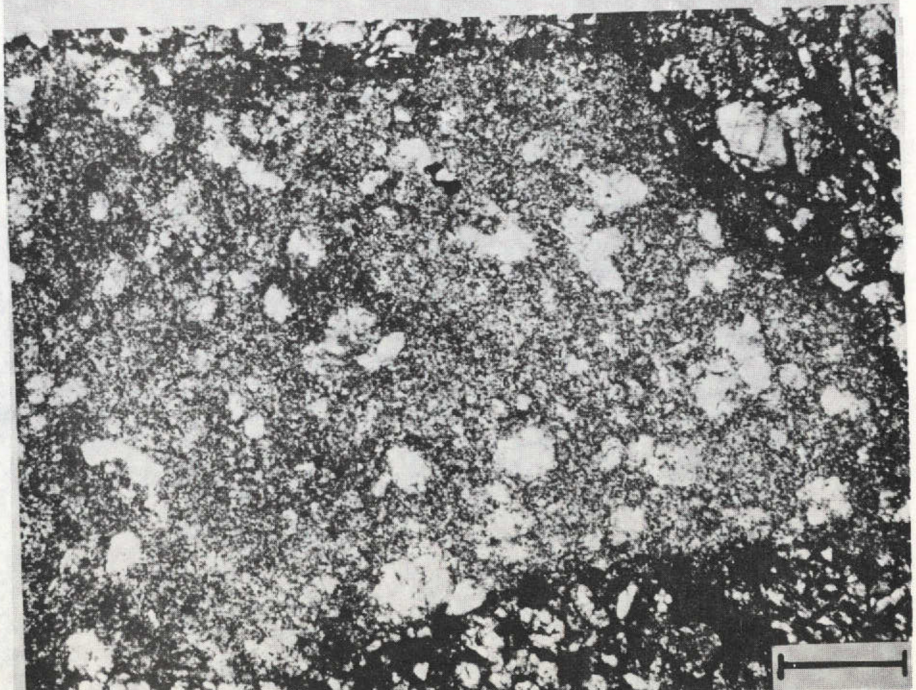

Fig. 20

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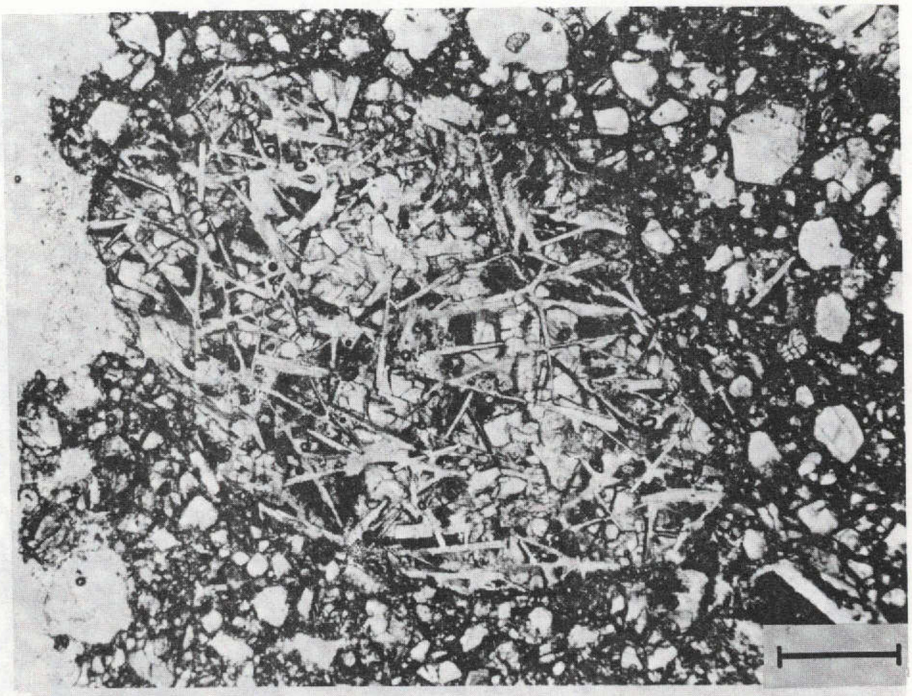

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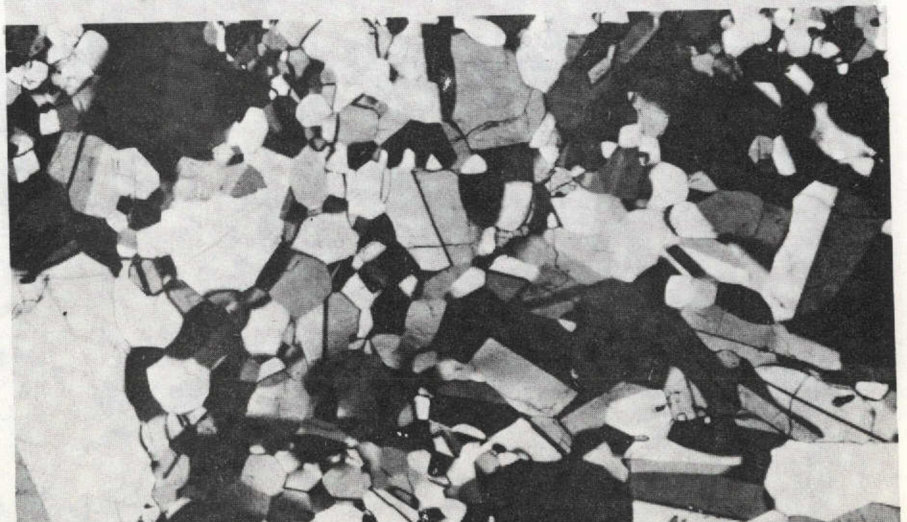

Fig 24

Fig 25.

Fig. 26.