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MATRIX CHARACTERISTICS AND ORIGIN OF LUNAR BRECCIA SAMPLES NO. 12034 AND 12073

by

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ABSTRACT

The transmission electron microscope was used to investigate the nature of the matrix in two samples of lunar breccia. This matrix is composed largely of tiny (0.5 microns) grains of unaltered glass which are plastically fitted against one another, and tightly welded to the clastic fragments with which they are in contact.

The breccias have an open framework of angular clastic particles composed mainly of anorthositic, basaltic and glassy fragments. Most of the anorthositic fragments have been shock metamorphosed. Over half of the glassy clasts, and also the former diaplectic glass particles produced from shocked plagioclase, were partly or wholly devitrified before inclusion in the present breccias.

We suggest that each breccia was deposited from a hot base-surge cloud of impact debris, and that the tiny bits of glass in the matrix condensed from rock that was volatilized by the heat of major meteorite impact.

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INTRODUCTION

Lunar sample 12034 is a breccia collected from the bottom of the 6-inch trench dug on the northwest rim of Head Crater by Apollo 12 Astronauts Conrad and Bean. It is known as documented sample 6-D and was photographed on the lunar surface (Hasselblad photos AS12-49-7195 and AS12-49-7196). Materials submitted to us for examination from this sample were one polished thin section, and a few firmly consolidated chips taken from the interior of the specimen. Lunar sample 12073, reported to be a part of the same rock as sample 12074, was collected near the north rim of Surveyor Crater. Material submitted included a polished thin section and a few consolidated, but somewhat fragile chips. The location of both samples at the time they were collected is shown in Shoemaker, et al. (1970, Fig. 10-1, p. 114).

In the descriptions of Brett and Lofgren transmitted along with the material, both rocks are reported to be more firmly consolidated than Apollo 11 microbreccias, and both are said to have had splashes of glass on their outer surfaces.

We noted at the beginning of our study that the material shows a layering or stratification - clearly visible in the thin section of 12034 (Figure 1), but much more subtle in 12073 where it is photographically apparent only on high magnification of the matrix. In general both rocks may be described as poorly sorted to unsorted, although in an outcrop the subtle stratification might show clearly. Both rocks are characterized by an open framework of angular to subrounded particles. The larger clasts are quite varied in composition, texture, and other physical parameters. They comprise broken fragments of lithic, crystal, and glassy material of several kinds. Clasts of earlier breccias, some of which are not unlike the present breccia, are included in the rock.

In the material at our disposal the clasts range in size from 5 mm to particles not clearly resolvable with the petrographic microscope. The material filling interspaces between the large fragments of the open framework consists mainly of smaller clasts of the same kinds, but as the average grain size approaches 0.05 mm the proportion of glass to lithic and mineral particles increases notably, and the sorting of the material becomes more uniform. At magnifications of 60 to 100 diameters' under the petrographic microscope the finer grained layers appear as dark gray, black, or yellowish-brown bands composed only partly of broken bits of mineral and rock. Intermingled with and plastered upon these clastic particles is a nearly irresolvable matrix of well sorted and closely fitted glass particles. It requires the use of the transmission electron microscope to reveal the fabric of these tiny, oriented, and mutually accommodating particles. (See Figs. 2A and 2B). Our electron micrographs (Figs. 2-5, 7 and 8) are of replicas taken from polished and lightly etched (in HF) thin sections and rock mounts; replication was by the two-stage method (Honjo and Fischer, 1965).

THE MATRIX

As shown in Figures 2A and 2B the most striking feature of the matrix in these two lunar breccias is the abundance of minute particles of glass that are molded plastically against the clastic fragments of the rock, and also against one another until they fill almost every available open space. The texture of this matrix somewhat resembles that of the earth rocks called welded tuffs or ignimbrites, but the glass shards of earth ignimbrites show bubble wall textures (Fisher, 1963), whereas those of the lunar breccias contain few or no bubbles. Moreover, most of them are more irregular in outline and of stubbier shapes - although the rod-like and platy forms common in volcanic shards are also common. Both in earth ignimbrites and in these lunar breccias, however, the mutual space accommodation, the plastic behavior on deposition, and the preferred orientation testify to accumulation from a hot cloud of soft glass particles, and also to the operation of compaction or of lateral flow of the fluidized material during the period of deposition and solidification.

Yet, the absence of collapsed and pulled out pumiceous particles, and of the extreme draping effects over the sharp corners of foreign rock and mineral particles - features which are so typical of welded tuffs on earth - argues against the formation of these rocks by lunar volcanism. It appears that the attainment of a plastic state in the lunar shards was followed by an almost immediate quench. Indeed the general shape of the lunar particles is more like that of sideromelane granules formed by the quenching of basalt magma in water during eruptions of maar volcanoes (Waters and Fisher, 1970; Fisher and Waters, 1970) than it is like the typical bubble-wall shards in most ignimbrites. Unlike the immediately quenched particles of sideromelane breccias, however, the matrix shards of the moon breccias appear to have stayed hot long enough to undergo some plastic accommodation with their neighbors, but were quenched too quickly to assume the extreme welding of many ignimbrites.

Nevertheless, the plastic adjustment of the matrix shards in lunar breccias 12034 and 12073 clearly indicates that the glass shards were hot enough to plaster onto and weld with sharply defined broken surfaces. Furthermore about 20% of the smaller clastic particles were also softened on one or more edges by the transient high temperature attained at the time of emplacement. These show evidence of partial melting, and some have merged and flowed with the plastic matrix granules (Fig. 2A).

On the other hand numerous clastic particles, including many pieces of broken glass which would soften at approximately the same temperatures as the matrix shards, retain sharp clear-cut boundaries against the plastic shards fitted tightly against them. These relations can be clarified further after descriptions of the various kinds of clasts and their characteristics.

THE CLASTIC MATERIALS

The framework materials of the lunar breccias consist of broken, mostly angular fragments. Petrographically they include several different kinds of glasses, and abundant lithic fragments of which basalts (mostly variolitic and tachylitic varieties), and anorthosites are most abundant. Many fragments are themselves microbreccias: some of these are much like the breccias under investigation, others are quite different in appearance, and a few consist of breccia which contains still other breccia fragments. Chips of ophitic gabbro, troctolite, and anorthositic gabbro were noted. The mineral fragments are almost entirely pyroxene and plagioclase, and could be derived from the rock types listed. Small amounts of ilmenite, green spinel, apatite, and several other unidentified minerals were noted.

The lithic fragments, and the clasts of glass are not uniformly distributed, either by size or by kind. Modal studies by point counting were started, but abandoned when it became apparent that the distribution varies in erratic ways, as well as with the stratification. It is clear that a small thin section is a completely inadequate sample of the rock as a whole, although the matrix material appears far more uniform than the framework material.

Glass, and Devitrified Glass

B. P. Glass (1970) has analyzed by microprobe 130 particles of glass from the fines of Apollo 12 sample 12057. He reports a "strong correlation between composition, color and refractive index". Some of the glasses, including some spherules, are anorthositic in composition, but most are "similar to the published analyses of Apollo 12 crystalline rocks except that many of the glass particles are richer in SiO_2". Our observations, which are of reconnaissance nature and entirely qualitative, are in line with Glass' results. The glass fragments in samples 12034 and 12073 vary greatly in texture, in the degree of devitrification, in the time at which devitrification occurred, and in the amount and nature of included debris - as well as in composition and color.

Fragments of fresh glass are abundant. They range from colorless or pale green to various shades of yellow, yellow-brown, brownish red, and mauve; a few are variegated with a streaky banding. Most are massive, but a few have strongly developed flow banding, and one is an obsidian-like welded tuff. Phenocrysts are almost non-existent, the few observed were plagioclase. On the other hand, about half of the larger glass particles contain foreign inclusions. The most striking and largest inclusions are shock-metamorphosed anorthosites, or are microbreccias rich in plagioclase. Inclusions of basalt and of fresh to dirty yellowish-gray pyroxene are also common. Inclusions of glass within glass also occur; some are well formed glass spherules embedded in glass of a different color. Vesicles are sparse or absent.

At least half of the glass fragments are partially or wholly devitrified. Devitrification takes many forms (Figs. 3A, 3B, 4B, 5). Most common is the growth of small variolitic clusters of plagioclase from many centers (Figs. 3A, 3B, 4A). Some of the new plagioclase sprouts from the edges of seed crystals, and may then spread into feathery scopulites much like those from the famous Arran pitchstones. Subhedral to shapeless grains of pyroxene and feldspar fill the left-over spaces, or may be scattered through a still unaltered matrix of glass. In contrast to the open varioles of feldspar, much more tightly packed spherulites and sheaves made of pyroxene needles (and plagioclase?) sprout from centers (Fig. 4B) and grow until they may encompass an entire grain. In still other pieces of glass, devitrification has proceeded inward from the surface of the grain, the well oriented and tightly packed crystalline products growing at right angles to the surface until they meet from opposite sides (Fig. 5); this is the well-known kind of devitrification that produces the axiolitic structure in glass shards from volcanic tuffs on earth.

Most significant for the present study is that devitrification effects can be used to demonstrate that the different glass particles in these lunar breccias are of widely different ages and histories. Nearly all are fragments that were already devitrified before they were incorporated into the rock: their broken edges sharply transect the devitrification structures, and both the matrix glass and a variety of clastic particles are plastered against the broken surfaces (Figs. 3A and 4A). Broken parts of spherulitic and axiolitic glass are common. Some pieces of glass have devitrified along structural defects: a large fragment of yellow glass in the thin section of sample 12073 had been completely shattered (by shock?) and then partly devitrified along these shatter cracks. After devitrification it was incorporated into this rock, the devitrification products having sealed the former cracks so that the mass remained coherent. Except for the characteristic yellow color of this formerly shattered glass fragment, it would be nearly impossible to distinguish the separate shattered fragments which forms this coherent chunk from the finer clastic debris which now encloses it. Indeed, the edges of the fragment, clearly visible without polarizer in the petrographic microscope, are almost impossible to find in replicas prepared for the transmission electron microscope.

In general, little devitrification appears to have affected the glasses of sample 12034 after the rock was formed. Many clasts of fresh glass show no signs of devitrification. The tiny fitted glass shards which form the matrix of this rock also appear to be undevitrified, but in places the electron micrographs reveal a few needle-like crystals that nail two or more of the tiny matrix shards together. By contrast, electron micrographs of the matrix in sample 12073 show a dusting of tiny incipient crystallites between and across glass shards.

Devitrification products after maskelynite[1/] are also common in these breccias. They are described in the next section.

LITHIC AND CRYSTAL FRAGMENTS

Lithic fragments abound in these breccias, and it is unlikely that nearly all the broken fragments of single crystals which are

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1/ Maskelynite is an old term for isotropic or nearly isotropic material which has the morphology and composition of plagioclase; recently the terms diaplectic glass, and plagioclase thetamorphs (or thetamorphic glass) were introduced to describe plagioclase (and other minerals as well) that have been isotropized, but not melted, by the action of shock waves.

scattered through the samples were derived from the same kinds of rocks. The lithic debris can be roughly classified into three main kinds: anorthosites, basalts, and microbreccias. Each of these categories, however, is a wastebasket with quite varied material included.

Anorthosites, and Plagioclase Clasts

For example, although a few small bits of typical anorthosite and anorthositic gabbro with clear and unstrained crystals of plagioclase are present, most of the fragments here called anorthosite are intensely battered and partly recrystallized. Many plagioclase crystals are blackened, rendered grainy by disseminated alteration products, and show aberrant optical properties. Radial growths of new plagioclase and pyroxene partly destroy the old texture (Fig. 6C); even some normal plagioclase crystals have nearly isotropic edges that are segmented into small beads and rod-like masses (Fig. 2A). Some fragments are completely recrystallized - one of these is a mosaic of tiny plagioclase and spinel crystals.

We hold that the battered and disorganized condition of the plagioclase in these rocks can be attributed to recurrent episodes of shock metamorphism (Chao, 1967; French, 1968). Plagioclase in the anorthosites, however, does not show the striking planar structures, nor the limpid clear isotropic plagioclase (maskelynite) like that seen in Figs. 6A and 6B, photographs of shock-metamorphosed anorthosite from the central uplift of Manicougan Crater, Quebec. But even in Figs. 6A and 6B patches of new feldspar needles are seen penetrating both birefringent plagioclase and isotropic maskelynite. Exactly the same kind of recrystallization pervades the largest anorthosite inclusion in sample 12034 (Fig. 6C). The area corresponding to the maskelynite is now a blackened nearly opaque mass crowded with spherulitic feldspar needles.

Micrographs taken with the transmission electron microscope reveal clear evidence of the former presence of maskelynite, both in other anorthosite fragments, and in scattered broken feldspar grains throughout the lunar breccias. Most of it, however, is sufficiently recrystallized so that it is slightly birefringent. The devitrification of this diaplectic glass proceeds in a different manner than in glasses formed by fusion. In the diaplectic glass some relics of unchanged feldspar survive, and it is also probably that even some istoropic parts were not completely changed in coordination. As a result, many of the long needle-like growths of new feldspar mimic the old crystal. They extend along crystallographic lines, and many are in optical continuity with surviving parts of the old crystal. The nature of this mimicing is clearly seen in electron micrographs (Figs. 7 and 8). In Fig. 7 a fragment of devitrified normal fusion glass is in contact with a larger area of devitrified diaplectic glass: the differences in texture may be compared directly (also compare Figs. 7 and 8 with Figs. 3A and 4A).

This complicated history of shock metamorphism and devitrification before incorporation of the feldspathic fragments into the lunar breccia explains why Short (1970) was unable to find the planar structures and thetamorphic glass that he expected when he examined Apollo 12 samples 12034 and 12073 for shock effects.

Basalt and Microbreccia Clasts

The clastic fragments grouped under basalt are chiefly tachylitic and variolitic lavas which closely resemble quenched earth basalts. Texturally they are like lava from the variolitic rims of pillow lavas, or the fine grained intersertal lava typical of the glass-rich hackly entablatures of some basalt flows. Two holocrystalline fragments with ophitic textures were also seen. Vesicles are rare or absent. In contrast to the anorthositic fragments few of the basalts show marked evidence of shock metamorphism or of pre-incorporation devitrification and recrystallization. It is tempting to conclude from this difference that the anorthosites have been transported in several hops from the greatly impacted distant highlands whereas the basalts are of local derivation.

Samples 12034 and 12073 each contain several fragments of earlier microbreccias. We have not studied them in detail.

GLASS-ARMORED LAPILLI

A feature noted in both breccia samples is that many clastic fragments have concentric rings of glassy particles and of fine grained clastic debris stuck on their surfaces. They resemble, although with some major differences, the accretionary lapilli (Moore and Peck, 1962) and mud-armored lapilli (Water and Fisher, 1970) found in some kinds of earth pyroclastic deposits. McKay, Greenwood, and Morrison (1970) and Richardson et al. (1970) have also noted features resembling accretionary lapilli in lunar breccias recovered during the Apollo 11 mission.

The glass-clastic armors in our samples appear to be present on about 5% of the clasts, but because they are difficult to see, and because they apparently are more abundant in the fine grained parts of the rock, this estimate may be far too low. The first layer coating a clast is chiefly very fine grained shards and splatters of glass, much of which is identical with or else coarser than the tiny fitted shards of plastic glass that make up most of the matrix of the breccias. This layer also appears to be a favorite lodging place for the sparse small glass spheres. This dark colored glassy layer is generally followed by a coarse layer composed mostly of fine grained clastic debris. Then the sequence may be repeated a few times, although outer rings can rarely be traced through a full circle.

We were surprised to find that many of these glass-armored clasts show up under the electron microscope, indicating that they are more abundant in the glass-rich fine grained matrix of the rock. Examples of partial rings may be seen in Figs. 4A, 5 and 8.

ORIGIN OF THE BRECCIAS

Since M. N. Short (1966, 1968) demonstrated that "Instant Rock" is produced through induration of unconsolidated alluvium by the shock pressure and heat of underground nuclear explosions, one theory for formation of lunar breccias has been consolidation of parts of the lunar regolith by local meteorite impacts. Certain features of the two Apollo 12 breccias, however, demand a different interpretation. One obvious objection to the application of Short's theory to these breccias is that the extremely delicate structures in the matrix, and also within some of the clastic fragments, would be destroyed, or at least greatly modified by the shock and heat necessary to cement loose lunar regolith. Moreover the shock features present in these rocks are old ones; most of them had undergone partial recrystallization and devitrification before incorporation into the present rock.

Other objections which we find overwhelming are: 1) the small grains of well-fitted (hence) plastic glass which are so abundant in the matrix of the rock; 2) the successive rings of glassy particles (resembling accretionary lapilli) which are plastered over the surfaces of clastic particles; 3) the apparently preferred accumulation of the rare glass spheres in the matrix and in the glass-armored coatings; and 4) the subtle stratification of the breccias. All these combine to give evidence of dispersal and deposition from a turbulently moving hot cloud of shattered rock debris and plastic droplets of molten glass in which an internal "atmosphere" of vaporized rock material was condensing into tiny spherules and shard-like glass fragments. Condensed vapor and hot glass splatters coated the surfaces of some flying clastic particles, and on deposition they tended to accumulate in the matrix of the rock.

From photogeologic studies of the linear ridges, dunes, and "patterned ground" adjacent to Mare Oriental and around certain lunar craters Masursky (1968) and Fisher and Waters (1969) have predicted that these lunar deposits will show the bedding characteristics and dunes associated with base-surge deposits on earth. In a comprehensive paper (published posthumously in 1969) J. Hoover Mackin had worked out several years ago the theoretical consequences of a large meteorite impact on the moon. One necessary consequence, he deduced, is that a hot cloud of impact debris would surge out radially from the impact site as "a density flow of dust comminuted by explosion". This, he held, would be followed by frothy nuées ardentes generated by impact induced volcanism. The hypothesis of hot base-surge deposits from the partly vaporized rock formed during a major lunar impact explains the origin of breccia samples 12034 and 12073. The critical evidence in our work, has come from studies of the fine material by means of the electron microscope.

In advancing this hypothesis we do not mean to imply that a continuous sheet of base-surge ignimbrite from which these samples were derived, necessarily once covered the Apollo 12 site. It is probable that when removed from their final resting place on the lunar surface on November 18, 1969, these rocks were already seasoned travelers, kicked from place to place by several transient lunar events.

Acknowledgments

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CAPTIONS FOR ILLUSTRATIONS

Fig. 1 Preferred shape orientation of birefringent plagioclase and pyroxene clasts. Sample 12034, crossed nicols, scale bar is 400 microns.

Fig. 2 A matrix of tightly fitted particles of glass encloses clasts of plagioclase and glass. Note softening and destruction into small elongate grains of the rims of feldspar clasts in the upper part of the view, whereas the larger feldspar at the bottom of the view has sharp borders. Sample 12034, electron micrograph, scale bar is 10 microns.

Fig. 2B A matrix composed of stubby glass grains shows the plastic fit of shards against one another, and against clasts of plagioclase and broken glass (at bottom and left). Sample 12034, Electron micrograph, scale bar equals 10 microns.

Fig. 3A Clast of devitrified brown glass. Note varioles of new plagioclase (enlarged in Fig. 3B), and the intricately fitted border of the fresh glass shards which compose the matrix along the left side of photo. Sample 12034, electron micrograph, scale bar is 10 microns.

Fig. 3B Enlarged view showing two varioles from the center part of Fig. 3A. Scale bar equals 10 microns.

Fib. 4A Devitrified clast of glass in sample 12034. Note that fragments of the fresh matrix glass are plastered upon the lower edge of the devitrified glass, forming a tightly welded rim. Electron micrograph, scale bar is 10 microns.

Fig. 4B Spherulites and sheaves of closely packed pyroxene? Needles in a devitrified glass clast. Note how the lower left sheaf of the large cluster at upper right has been stopped and bent in its growth by a foreign inclusion in the original glass. Feldspar varioles sprout from seed crystals above the plagioclase in the left central part of the photo. Sample 12034, electron micrograph, scale bar equals 10 microns.

Fig. 5 Paddle-shaped primary glass particle which has undergone axiolitic devitrification. Sample 12073, electron micrograph, scale bar equals 10 microns.

Fig. 6A and 6B Maskelynite in shock metamorphosed garnet anorthosite from the central uplift in Manicougan Crater, Quebec. A, plain light, B crossed polarizers. Note recrystallization patches of new needle-like plagioclase near center. Scale bars equal 400 microns.

Fig. 6C The lower left 1/3 of the photograph shows a fragment of shocked and partly recrystallized anorthosite in sample 12034. Plagioclase in the upper part of the fragment is feebly birefringent, that in the lower part is blackened, almost isotropic, and is laced with needles of recrystallized plagioclase. Scale bar equals 200 microns.

Fig. 7 Devitrified maskelynite in a shock metamorphosed plagioclase grain, sample 12034. Note the crystallographic control of the new devitrification products. A clast of devitrified fusion glass borders the devitrified maskelynite in the upper right part of the photo. Electron micrograph, scale bar equals 10 microns.

Fig. 8 A clast of recrystallized maskelynite in sample 12073. Note the preferred orientation of the devitrification products. Note also that the already devitrified maskelynite is rimmed by a thin border of tiny fresh glass splashes and fitted shards, and then by a partial ring of coarser glass and clastic particles.

FIG 1 TOP

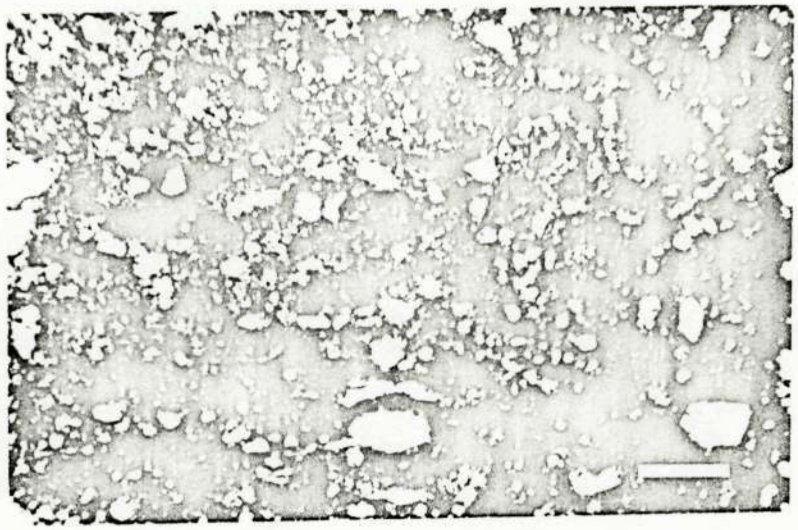
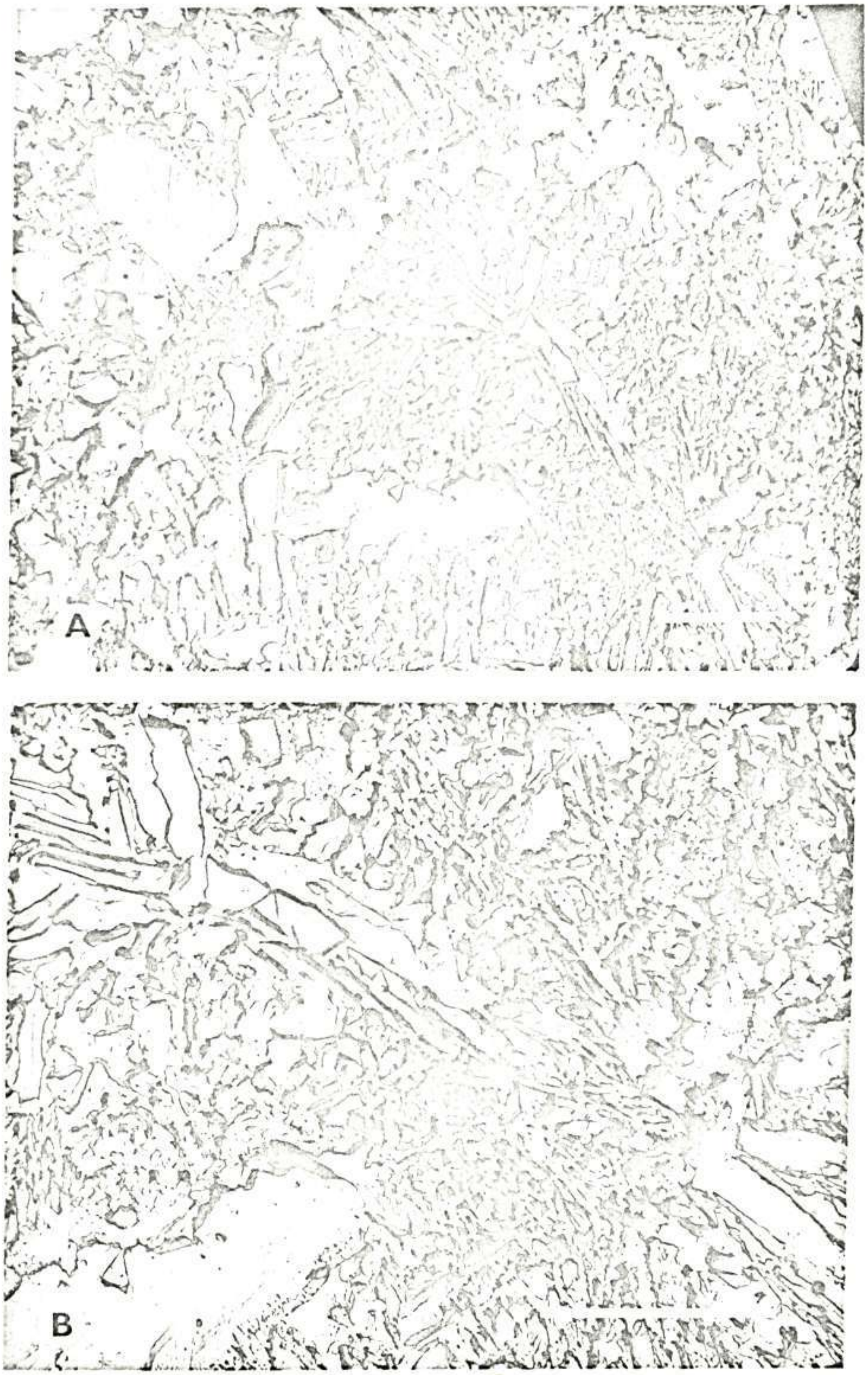


FIG. 2 TOP

FIG 3 TOP



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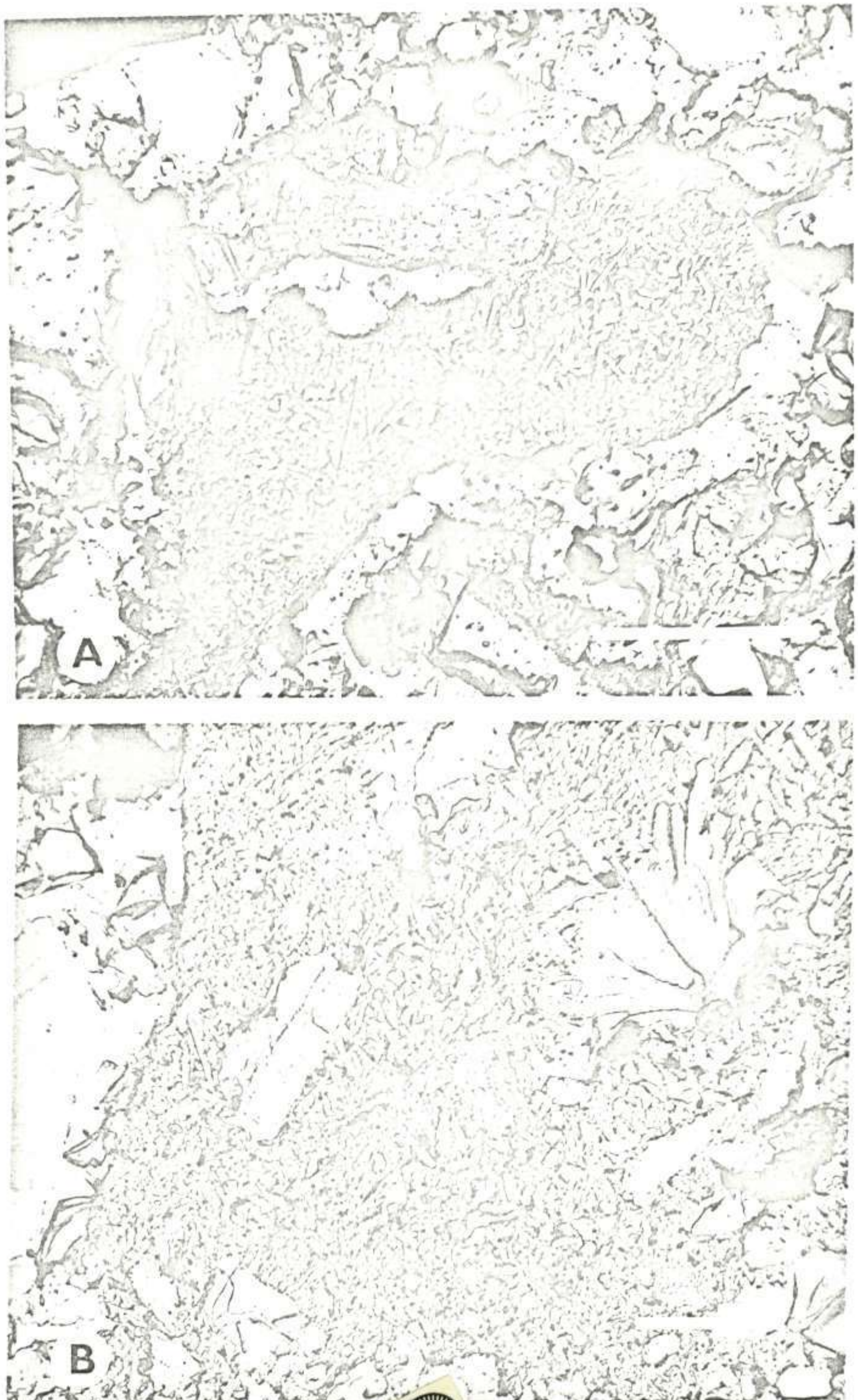

FIG 5 TOP

FIG. 6 TOP

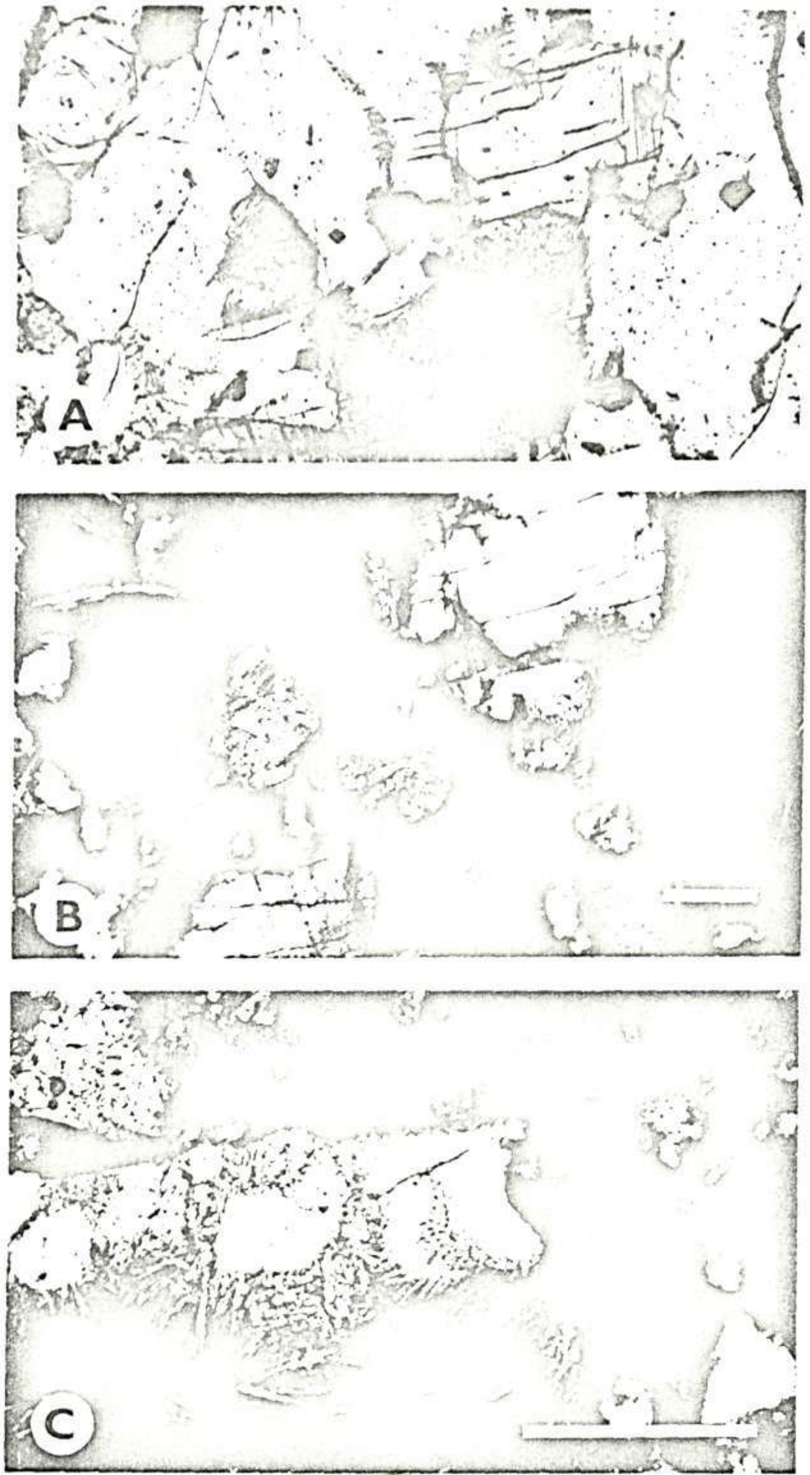

FIG. 7 TOP

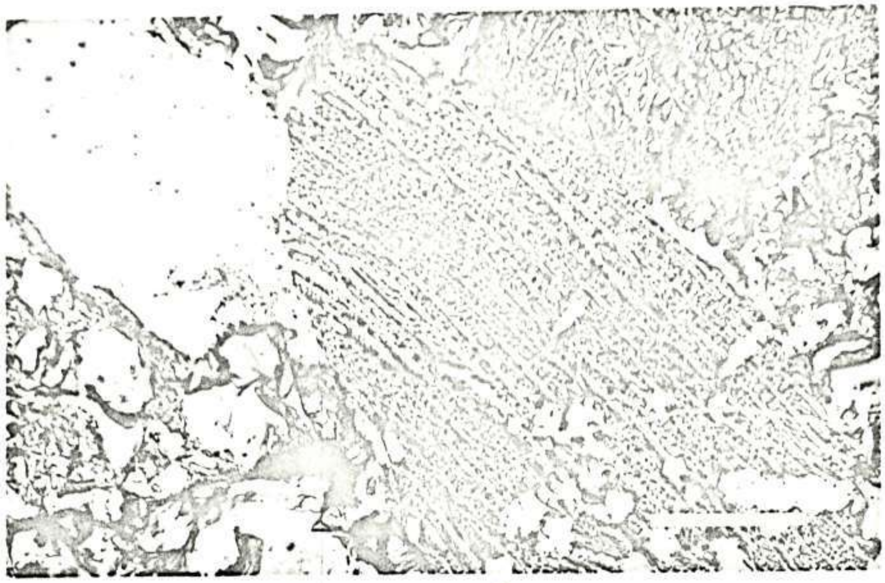

FIG 8 TOP