ACCRETION OF
MURRAY CARBONACEOUS CHONDRITE
AND IMPLICATIONS REGARDING
CHONDRULE AND
CHONDRITE FORMATION

DONALD P. ELSTON

NININGER METEORITE AWARD PAPER

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CENTER FOR
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ARIZONA STATE UNIVERSITY
T E M P E • A R I Z O N A

ACCRETION OF MURRAY CARBONACEOUS CHONDRITE AND IMPLICATIONS REGARDING CHONDRULE AND CHONDRITE FORMATION

by
DONALD P. ELSTON
U. S. Geological Survey
Flagstaff, Arizona
and
Department of Geology
University of Arizona
Tucson, Arizona

Revision of a Co-Winning Student Paper for the
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NININGER AWARD PAPERS

The Nininger Meteorite Award of $1,000 was established in 1961 by Dr. and Mrs. H. H. Nininger for the best paper or papers written by undergraduate or graduate students. The papers are written by the student only and specifically for competition. Any subject matter relating to any aspect of meteorites is acceptable. The judges are recognized professional scientists working in meteorite research. Professor Carleton B. Moore, Director of the Center for Meteorite Studies, is Executive Secretary of the Award Committee of Arizona State University which administers the Award. Starting with the 1965 Awards the Center will occasionally publish outstanding papers which have not been previously published. Winners and titles of the Nininger Award are as follows:

1961-62 Mr. Michael E. Lipschutz, University of Chicago
"On the Origin of Diamonds in Iron Meteorites"

Mr. Craig M. Merrihue, University of California (Berkeley)
"Meteoritic Xenon and the Origin of Meteorites"

Mr. Michael Fernandez, Beloit College*
"Locating Meteorite Falls from Micro-Meteorites in Soil Samples"

1962-63 Mr. James L. Setsee, University of Kentucky
"Determination of the Abundances of Zirconium and Hafnium in Meteorites, Tektites and Terrestrial Materials"

Mr. Michael B. Duke, California Institute of Technology
"Petrology of the Basaltic Achondrite Meteorites"

1963-64 Mr. Marvin W. Rowe, University of Arkansas
"Gamma Radioactivity and Rare Gases in Meteorites and Terrestrial Materials"

Mr. Ned Read, Carleton College±
"The Determination of the Orientation of the Cut-Plane Through an Iron Meteorite Relative to its Crystal Structure"

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*A special award was given Mr. Fernandez, an undergraduate student.
±Mr. Read was an undergraduate.

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1964-65 Mr. Joseph Goldstein, Massachusetts Institute of Technology
"The Growth of the Widmanstätten Pattern in Metallic Meteorites"

Mr. William K. Hartmann, University of Arizona
"Terrestrial and Lunar Flux of Large Meteorites through Solar System History"

1965-66 Mr. Marvin W. Rowe, University of Arkansas
"Xenomalies"

Mr. John W. Larimer, Lehigh University
"The Petrology of Chondritic Meteorites in the Light of Experimental Studies"

1966-67 Mr. Billy P. Glass, Columbia University
"Microtektites and the Origin of the Australasian Tektite Strewn Field"

Mr. Donald P. Elston, University of Arizona
"Accretion of the Murray Carbonaceous Chondrite and Implications Regarding Chondrule and Chondrite Formation"

1967-68 Mr. Jeffrey G. Taylor, Rice University
"On the Thermal History of Chondrites"

Mr. Benjamin N. Powell, Lamont Geological Observatory of Columbia University
"Extinct Radioactivities in Meteorites"

Mr. Patrick S. Freeman, Monmouth College
"Versailles Cryptoexplosive Structure"

George A. Boyd, Editor
Associate Director of the Center

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ABSTRACT

Detailed mapping of two surfaces of a specimen of the Murray carbonaceous chondrite (Type II of Wiik) has revealed three discrete mineral assemblages, or components. They are: 1) a pre-accretionary, volatile-rich, low-temperature assemblage (component 1 - carbonaceous matrix); 2) a pre-accretionary high-temperature assemblage (component 2 - discrete, relatively coarse grains and chondrules of magnesium silicate, and associated finely granular metal that is probably nickel-iron); and, 3) an accretionary high-temperature assemblage (component 3 - aggregates and chondrules of very finely granular magnesium silicate).

Component 3 aggregates characteristically contain intergranular component 1 matrix material, and range from tiny, highly irregular disseminations to comparatively large ovoidal chondrules. Some component 3 aggregates contain, as nuclei, grains of component 2 olivine or pyroxene, and metal. A few component 3 aggregates contain compound nuclei of both component 1 and 2 grains.

Textural and paragenetic relations suggest that component 1 and 2 grains were mechanically incorporated in the component 3 aggregates. Hollow, thin-walled component 1 matrix spherules are present in several relatively large component 3 aggregates. The matrix spherules are soft and can be easily broken. One component 3 chondrule contains several whole matrix spherules that exhibit oriented, raised, equatorial sutures. Some matrix spherules in component 3 aggregates are broken and incomplete; a few spherules appear to have been partly crushed. One spherule was sharply broken across its central void before it was incorporated as the nucleus of a component 3 aggregate. To account for crisp, pre-aggregation fracturing, the matrix spherules are inferred once to have been stronger and more brittle than they are now. The surface of the central void of one matrix spherule is smooth and shiny. The void may have been once occupied by a filling material, possibly an ice, which was lost through evaporation or ablation. Preservation of central voids in matrix spherules in component 3 aggregates is evidence for low pressures at, and since, the time of formation of Murray.

Textural and paragenetic relations suggest that the accretion of Murray occurred in a dynamic environment at the time of formation of component 3 aggregates. It is proposed that the tiny magnesium silicate grains of the component 3 aggregates were precipitated abruptly from a high-temperature gas--a gas that was injected into a cold environment that contained dispersed low- and high-temperature materials (components 1 and 2). Accretion possibly resulted from brief, partial melting of icy volatiles associated with component 1, followed by refreezing into icy chondritic material.

Component 1 is inferred to represent the material of a primitive dust cloud. Component 2 includes pre-accretionary refractory materials possibly formed in a high-temperature, near-central region of the primitive solar system. Component 3 includes "accretionary" high-temperature materials, the source of which may have been gas derived from the high-temperature environment of component 2. The injection of dispersed component 2 materials and component 3 gas into dispersed component 1 material is inferred to have given rise to the observed mix of high- and low-temperature materials, and to the paragenetic relations displayed by Murray.

0   .5   1 cm
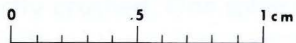
MURRAY CARBONACEOUS CHONDRITE

(Arizona State University specimen No. 635.1;
weight, 32.7g)

INTRODUCTION

Chondrule formation and chondrite accretion have long been recognized as key problems in meteoritics. Several mechanisms have been proposed for the primary origin of chondrules, and several models exist for chondrite formation. Recent reviews and discussions are found in Mason (1962), Wood (1963a), Anders (1964), Urey (1964), and Ringwood (1966). No solution yet proposed accounts for the textural, mineralogical, and chemical characteristics of the five chondrite classes (carbonaceous, olivine-pigeonite, olivine-hypersthene, olivine-bronzite, and enstatite chondrites).

Any hypothesis that deals with the origin of chondrules and the accretion of chondrites should be founded on evidence in both the chondrules and the chondrites. Not yet considered in any model for accretion are textural characteristics of the mineral assemblages, and paragenetic relationships between grains, aggregates of grains, chondrules of various types, and mineral assemblages.

The chondrites display some common textural characteristics, and certain mineralogical and chemical regularities (see, for example, Mason, 1962, 1967). Because of this, chondrule formation and chondrite accretion may be expected to have been interrelated. Furthermore, the process or processes involved in chondrule formation and chondrite accretion were responsible for formation of both the volatile-rich (carbonaceous) and the volatile-poor chondrites.

The volatile-rich carbonaceous chondrites (Type II of Wiik, 1956) texturally appear to be the least altered or metamorphosed of the chondrites. Because of this, key relationships between chondrules and matrix should be best preserved in them. It is the purpose here to review some detailed paragenetic and textural relations in the Murray carbonaceous chondrite that shed new light on chondrule and chondrite formation.

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CIRCUMSTANCES OF FALL

Murray fell as a shower of stones on September 20, 1950, at approximately 1:35 a.m., central standard time, following the explosion of a brilliant fireball over western Kentucky. The specimen of Murray described here (page 6) is in the collection at Arizona State University, Tempe (No. 635.1, weight 32.7 g). It is a fragment from the largest stone recovered (H. H. Nininger, personal commun., 1967), which was about 15 cm in the longest dimension (Horan, 1953, Fig. 2). The stone, which was heard to fall, embedded itself to a depth of about 15 cm in a hardpacked path about 26 feet from a house.

The fireball traveled from north to south across southern Illinois before exploding over western Kentucky at an altitude of about 46 km (Horan, 1953). Its trajectory through the atmosphere and its orbital elements were calculated by C. P. Olivier under the assumption of parabolic heliocentric velocity (Horan, 1953). On the basis of six estimates, the bolide was traveling at about 71 km per sec., and its path was inclined 68° to the ecliptic. The high inclination and great heliocentric velocity suggest that the bolide consisted of cometary material in a near-parabolic orbit. Evidence for a low-pressure environment of preservation, which is reviewed later, suggests that Murray may have resided in the outer or crustal part of its parent body.

GENERAL CHARACTERISTICS

Murray is a dark, compact meteorite that has a specific gravity of 2.81±0.02 (Horan, 1953). The fusion crust is a fraction of a millimeter thick; material directly underlying it appears to have been unaffected by the ablation process. About four-fifths of the meteorite is black, very fine-grained to locally sooty-appearing, hydrous matrix material. The matrix serves as a bonding agent for disseminated grains, compound particles, and finely granular aggregates of olivine, pyroxene, and metal (nickel-iron?). Most of the anhydrous, high-temperature magnesium silicates are in very fine grains, occuring in tiny aggregates that are pervasively disseminated in the matrix, and in scattered larger aggregates of irregular to nearly spherical outline. Several of the larger aggregates, or clusters, are partly to wholly limonite stained. Except for this very local staining, the meteorite appears to be extremely fresh.

The Arizona State University specimen of Murray is closely similar in texture and in general appearance to the several dozen specimens of Murray in the collection of the U.S. National Museum, Washington, D.C. Murray also is closely similar in texture to a specimen of the Mighei carbonaceous chondrite (Arizona State University Collection), and to specimens of the Crescent and Bells carbonaceous chondrites that were examined through the courtesy of Mr. O. E. Monnig, Fort Worth, Texas. Components 1, 2, and 3, which are described for the Arizona State University specimen of Murray, were observed in the other specimens of Murray, and in the specimens of Mighei, Crescent, and Bells. This suggests that the textural and paragenetic relations described here for Murray are representative of Type II carbonaceous chondrites.

The chemical composition of Murray (Table 1) has been determined by Wiik (1956); its water content, about 12.5 weight percent, is very near the average value reported for the carbonaceous chondrites. The black carbonaceous matrix consists mainly of "layer lattice silicates" (Fredriksson and Keil, 1964, p. 208); its composition is summarized in Table 1. Fredriksson and Keil (1964) reported that nickel is fairly homogeneously distributed in the matrix. Where

TABLE 1.

Analyses of Murray carbonaceous chondrite

<div align="center">Whole Rock [1]/   Matrix [2]/</div>

Oxides	Weight Percent	Metals	Weight Percent	Elements	Percent
SiO_2	28.69	Fe	0.00[3]/	Si	13-14
MgO	19.77	Ni	0.00[3]/	Mg	9-10
FeO	21.08	Co	0.00	Fe	~22
Al_2O_3	2.19			Al	0.5-1
CaO	1.92		Other	Ca	~0.5
Na_2O	0.22			Ni	~1-4
K_2O	0.04	FeS	7.67	S	~1-4
Cr_2O_3	0.44	C	2.78		
MnO	0.21				
TiO_2	0.09	Loss on			
P_2O_5	0.32	ignition	0.62		
H_2O+	9.98				
H_2O-	2.44				
NiO	1.50	Sum	100.04		
CoO	0.08				

[1]/ From Wiik (1956, Table 1, p. 280-281). Wiik noted that the FeO is only a calculated number, obtained by subtraction of the metallic iron and the troilite from the total iron. Wiik also noted that the FeS tends to be too high because all S was calculated to that compound.

[2]/ From Fredriksson and Keil (1964); electron-microprobe analysis.

[3]/ A small amount of metallic nickel-iron actually is present in Murray.

they found strong positive correlations between nickel and sulfur, they considered the fine-grained material to be pentlandite; where the sulfur content was too low for pentlandite, the material was considered to be a sulfate rather than a sulfide. They also reported that some sulfur can be leached from the matrix with cold distilled water.

Murray contains abundant rare gases as well as water (see, for example, Signer and Suess, 1963). Serpentine (Mason, 1962), chlorite (Kvasha, 1948), and chlorite- and chrysotile-like silicates (DuFresne and Anders, 1963, p. 504) are constituents of the carbonaceous chondrites. The water and the rare gases reported for the carbonaceous chondrites may be retained in these silicates.

Electron-microprobe investigations of randomly selected silicate grains in Murray have shown that olivine is about four times more
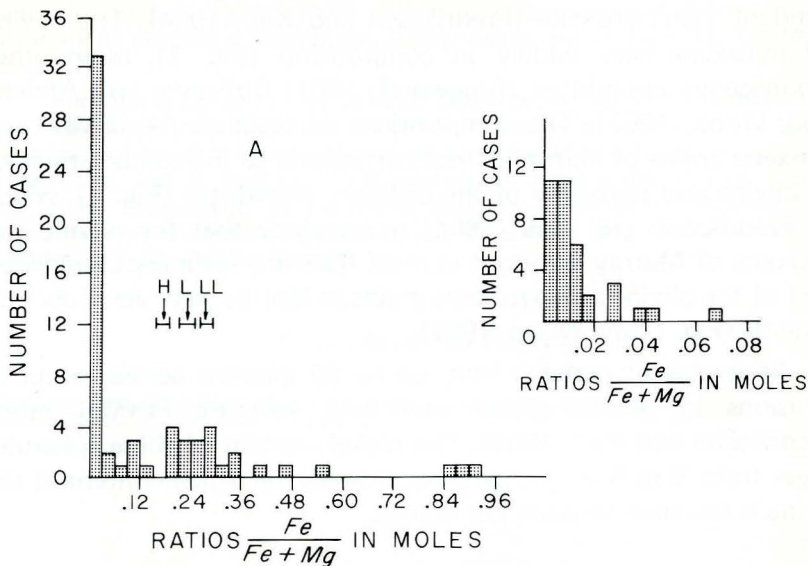
Figure 1a. Frequency distribution of the mole-ratios Fe/(Fe+Mg) in 63 individual olivine grains, Murray carbonaceous chondrite. Inset shows the values from 0 to 0.08 moles at a larger scale. H, L, and LL represent the averages and ranges in composition of olivines in H-, L-, and LL-group chondrites (Keil and Fredriksson, 1964). From Fredriksson and Keil (1964, Fig. 1, p. 207).
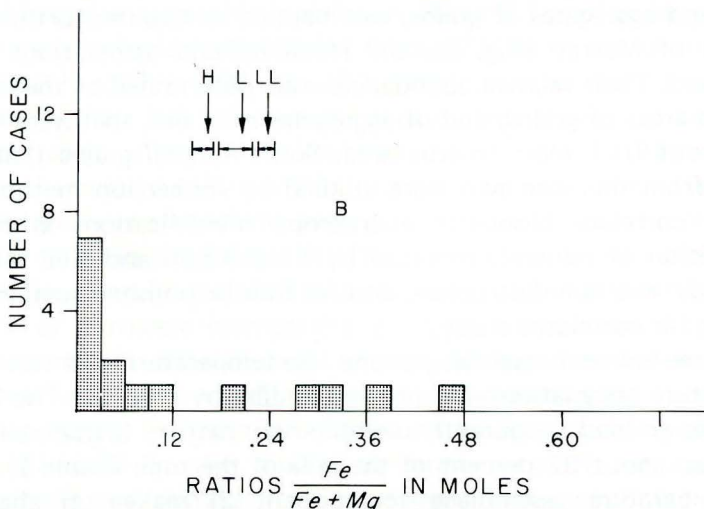
Figure 1b. Frequency distribution of the mole-ratios Fe/(Fe+Mg) in 16 individual pyroxene grains, Murray carbonaceous chondrite. H, L, and LL represent the averages and ranges in composition of orthorhombic pyroxenes in H-, L-, and LL-group chondrites (Keil and Fredriksson, 1964). From Fredriksson and Keil (1964, Fig. 2, p. 208).

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abundant than pyroxene (Fredriksson and Keil, 1964). The olivine and pyroxene vary widely in composition (Fig. 1), as in other carbonaceous chondrites (Ringwood, 1961; DuFresne and Anders, 1963; Wood, 1967). The compositions of most of the olivine and pyroxene grains of Murray do not correspond to the compositions of the olivine and pyroxene of the ordinary chondrites (Fig. 1), which led Fredriksson and Keil (1964) to conclude that the olivine and pyroxene of Murray were not derived from the ordinary chondrites. Most of the olivine and pyroxene grains in Murray have very low iron contents (Fig. 1; and Wood, 1967).

Spherules of metallic iron, up to 20 microns across, occur as inclusions in olivine grains that have low $Fe/(Fe+Mg)$ ratios (Fredriksson and Keil, 1964). The nickel content of these spherules ranges from 5 to 9 weight percent, whereas the nickel content of the olivine is less than 50 parts per million.

PARAGENETIC AND TEXTURAL STUDIES

RECOGNITION OF THREE MINERAL ASSEMBLAGES (COMPONENTS)

The distribution of matrix material, and of included fragments, grains, and aggregates of grains, was mapped on two near-orthogonal surfaces of Murray (Fig. 2a, b). Three mineral associations were recognized. Their relative abundances were determined by measuring the map areas of grains, and of aggregates of grains, that were larger than about 0.05 mm^2 in true area. Some mineral grains that had spalled from the specimen were studied by immersion methods to broadly correlate binocular microscope identifications with the composition of minerals reported by Fredriksson and Keil (1964). The study was non-destructive, and no thin or polished section was available for correlated study.

Three mineral assemblages--one low-temperature and two high-temperature associations--are present in Murray (Fig. 2). The black very fine-grained, apparently volatile-rich matrix (component 1) makes up about 82 percent of the area of the rock (Table 2). One high-temperature assemblage (component 2) makes up about 1 percent of the area of the rock (Table 2). Component 2 consists of scattered, relatively large (mostly 0.2 to 0.8 mm) grains of olivine and pyroxene, and a single large (2 mm) compound chondrule. Metal (component 2d) appears to be genetically associated because it

Figure 2. Maps and photographs of Murray carbonaceous chondrite showing distributions of mineral assemblages (components) are on pages 17, 18, 19, 21, 22, and 23.

End view is shown in Figs. 2a1-2a3; side view, in Figs. 2b1-2b3. Maps show the distribution of component 3 and 2 materials in component 1 matrix material, and the distribution of component 1 material as flakes, granules, and spherules in, and as sheaths around, component 3 aggregates. In Figs. 2a3 and 2b3, most component 3a aggregates have been deleted to emphasize the distribution of compound aggregates and chondrules, and the distribution of component 2, 3b, and 3c materials.

Explanation for Maps

Component 3:   Accretionary high-temperature silicates
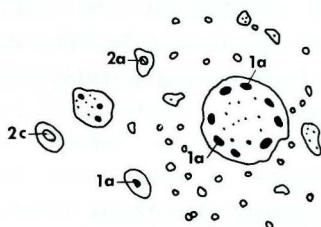
a.   Unstained, finely granular low-iron magnesium silicates.
Small irregular aggregates (commonly about 0.1 mm) to large ovoidal and nearly spherical chondrules (about 2.5 mm), consisting of tiny (commonly about 0.01 to 0.02 mm), clear unstained grains of essentially iron-free magnesium silicate that appears to be mainly olivine; some intergranular material may be glassy. Aggregates of grains characteristically contain intimately admixed black flakes, and locally granules and hollow spherules of matrix material (component 1) that range in size from about 0.01 to 0.3 mm. Some component 3 aggregates contain nuclei of relatively large (0.2 to 0.6 mm) grains of olivine or pyroxene (component 2). A few component 3 aggregates contain matrix spherules as central nuclei; one hollow matrix spherule was fractured before it was incorporated as the nucleus. In a few aggregates, hollow matrix spherules are irregularly to symmetrically disposed in the medial to outer parts of the aggregates. Paragenetic and textural relations suggest that component 1 and 2 materials were mechanically incorporated in component 3 aggregates. Component 1 granules and spherules may have been shaped by the process that caused precipitation and aggregation of component 3 silicates.
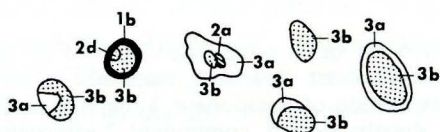
b. Stained, finely granular low-iron magnesium silicates.

Texturally identical with component 3a, but aggregates and chondrules of essentially iron-free magnesium silicate grains are partly to entirely stained various shades of brown, yellow, orange and red. Some aggregates appear to contain rusty relicts of component 1 matrix material; in most stained aggregates, matrix material is not present. Most stained aggregates are relatively large, and several are partly to wholly enclosed by component 3a materials. Paragenetic relations suggest that aggregation and staining mostly occurred before precipitation of component 3a. The staining may be due to limonite derived from iron-bearing sulfides associated with formerly included matrix material.
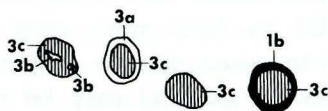

c. Finely granular high-iron magnesium silicates.

Texturally identical with components 3a and 3b. Consists of relatively large (0.2 to 2 mm) aggregates and chondrules of finely granular, medium- to dark-brown, probably iron-rich magnesium silicates. Included matrix material is not apparent, possibly because of the general darkness of the aggregates. One aggregate is locally limonite stained. The dark aggregates tend to be clustered (Fig. 2b). Several are enclosed by thin, dense, dull-black rinds of matrix material, and in turn are embedded in sooty-appearing matrix that is deficient in disseminated component 3a material. One component 3c aggregate is enclosed by a sheath of component 3a material, indicating, as in the case of several component 3b aggregates, formation before the precipitation of component 3a materials.

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Component 2: Pre-accretionary high-temperature materials

Relatively large, discrete grains and chondrules of olivine and pyroxene, and finely granular metal. Irregularly disseminated in component 1 matrix material; locally forms the nuclei of component 3 aggregates.
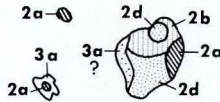

a. Grains and fragments of grains of clear to very pale brown (iron-free to iron-poor) olivine and pyroxene; mostly about 0.2 to 0.7 mm across. Occurs as isolated grains in component 1 matrix; as the nucleus of several component 3 aggregates; and as relatively coarsely granular material that encloses components 2b and 2d in a compound component 2 chondrule.

b. Fragment of "zoned" or barred, clear silicate, which by analogy with barred chondrules in volatile-poor chondrites is probably olivine. Forms an apparently fragmented nucleus of a 2 mm compound chondrule in which zoned silicate is overlain by components 2d and 2a. Consists of thin, parallel, resistant layers of clear silicate, separated by soft, milky-white bands of what may be Na- and Al-rich glass.
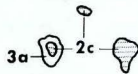
c. Grains and fragments of grains of pale to moderately dark-brown (probably iron-rich) olivine and pyroxene, mostly about 0.2 to 0.8 mm. Occurs as isolated grains in component 1 matrix and as the nucleus of a component 3a aggregate.
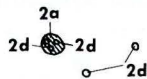

d. Metal, probably nickel-iron from data of Fredriksson and Keil (1964). Occurs as sparse tiny droplets (about 0.01 mm) disseminated in component 1 matrix; as droplets in a component 2a grain; and as a finely granular deposit on component 2b silicate in a compound component 2 chondrule.

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Component 1: Pre-accretionary low-temperature materials

Black, carbonaceous, very fine-grained, hydrous matrix material consists mainly of layer silicates and subordinate nickel-bearing sulfides (Fredriksson and Keil, 1964). The composition is summarized in Table 1. The layer silicates presumably contain the approximately 12.5 weight precent H_2O reported by Wiik (1956), and they also may be the sites of retention of Murray's abundant rare gases (Signer and Suess, 1963).

Matrix material serves as a general fine-grained cement, and also occurs as:
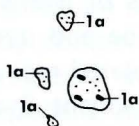
a. Flakes, granules, and hollow spherules ranging in size from about 0.01 to 0.3 mm in component 3a aggregates. In the smallest component 3a aggregates, the enclosing component 1 material may be traced into included component 1 material.
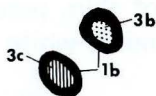
b. Shiny-black, crudely-layered sheath, and compact, dull-black rinds that enclose, respectively, component 3b and component 3c aggregates.

c. A compact, black, subangular fragment, about 0.7 mm long, in the matrix; may be a pre-solar system rock fragment.

d. Sooty-appearing material that is deficient in disseminated component 3a aggregates and grains; encloses a cluster of component 3c aggregates.
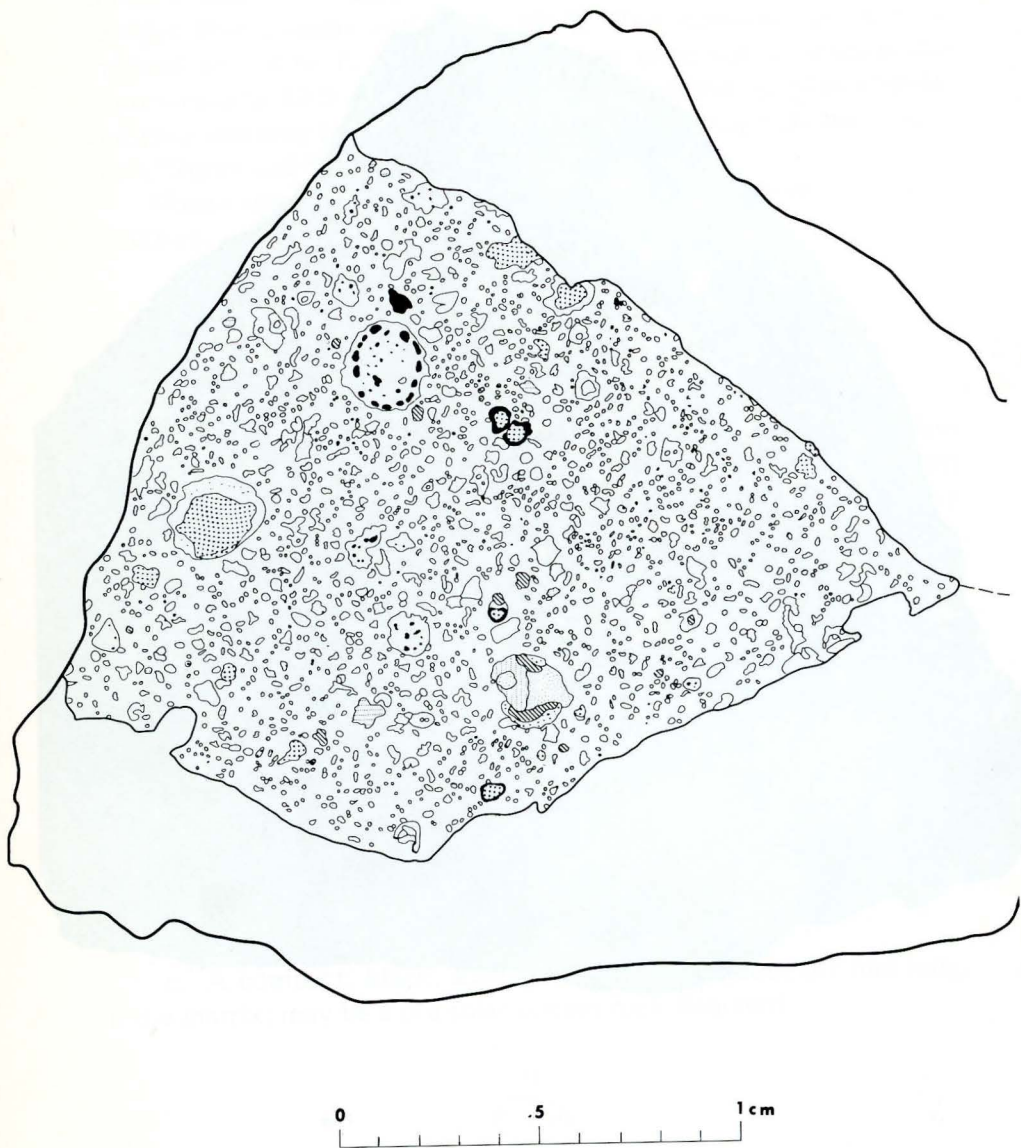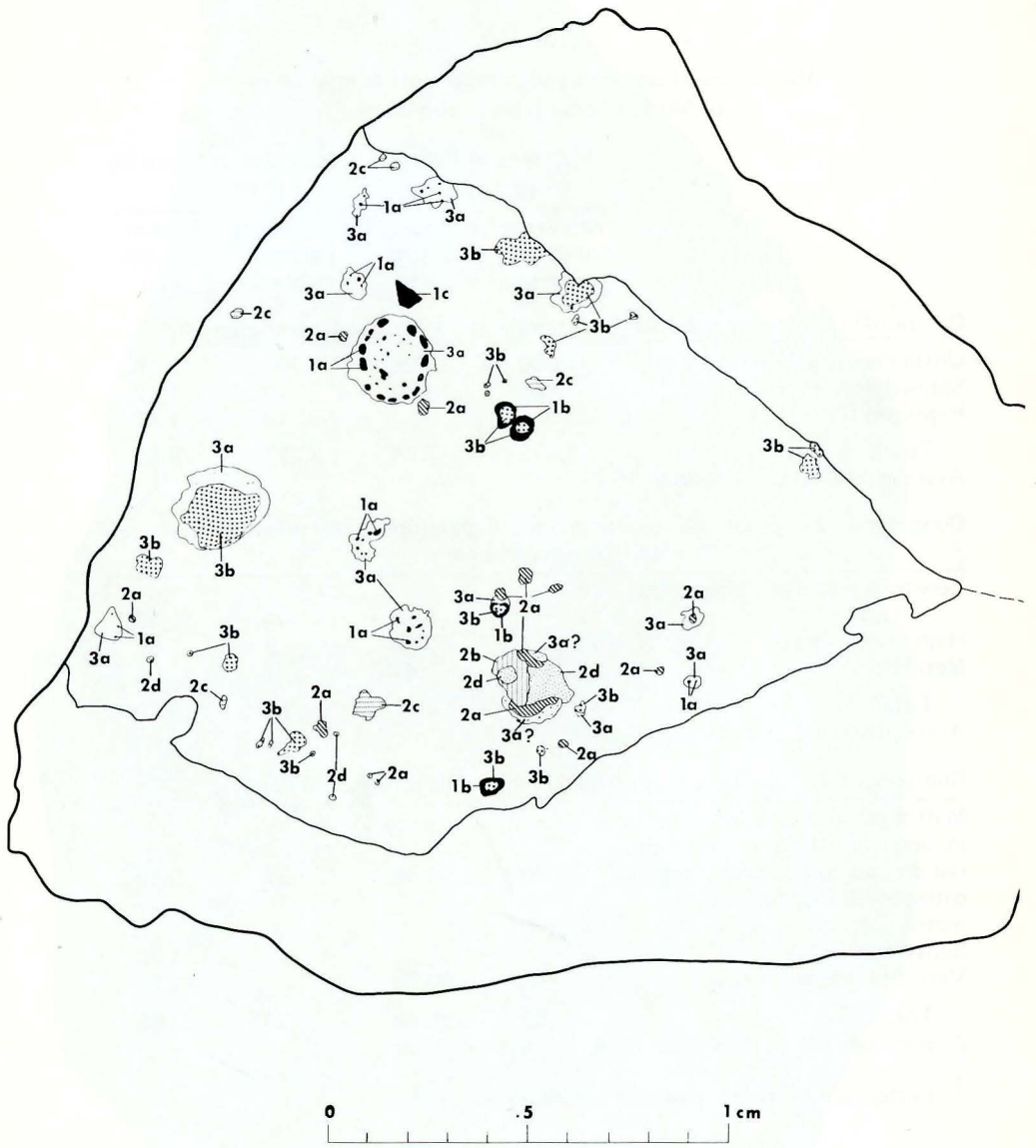
16

0   .5   1 cm

Figure 2a1.

Figure 2a2.

Figure 2a3.

TABLE 2.

Abundance of particles and components in map areas of Murray carbonaceous chondrite

	Map area of figure 2a (2.27 cm^2)		Map area of figure 2b (6.62 cm^2)	
	Number of particles or grains	Percent of total area	Number of particles or grains	Percent of total area
Component 3: Finely granular, high-temperature silicates (accretionary)				
Unstained, low-iron (a) [1]/	1,600	15.95	3,207	12.99
Stained, low-iron (b)	23	1.89	46	1.17
High-iron (c)	—	—	18	1.47
Total	1,623	17.84	3,271	15.63
Average percent of total area: 16.7				
Component 2: Relatively coarse grained high-temperature silicates, and finely granular metal (pre-accretionary)				
Low-iron grains and chondrules (a,b)	14	0.63	44	0.38
High-iron grains (c)	7	.26	6	.07
Metal (d)	5	.41	7	.04
Total	26	1.30	57	0.49
Average percent of total area: 0.8				
Component 1: Low-temperature matrix materials (pre-accretionary)				
Matrix granules and spherules (a) in, and rinds (b) of matrix material around component 3 aggregates; black fragment in matrix (c)	59	0.56	31	0.40
Sooty matrix (d)	—	—	2	1.28
Very fine-grained matrix	—	80.30	—	82.20
Total	59	80.86	33	83.88
Average percent of total area: 82.4				

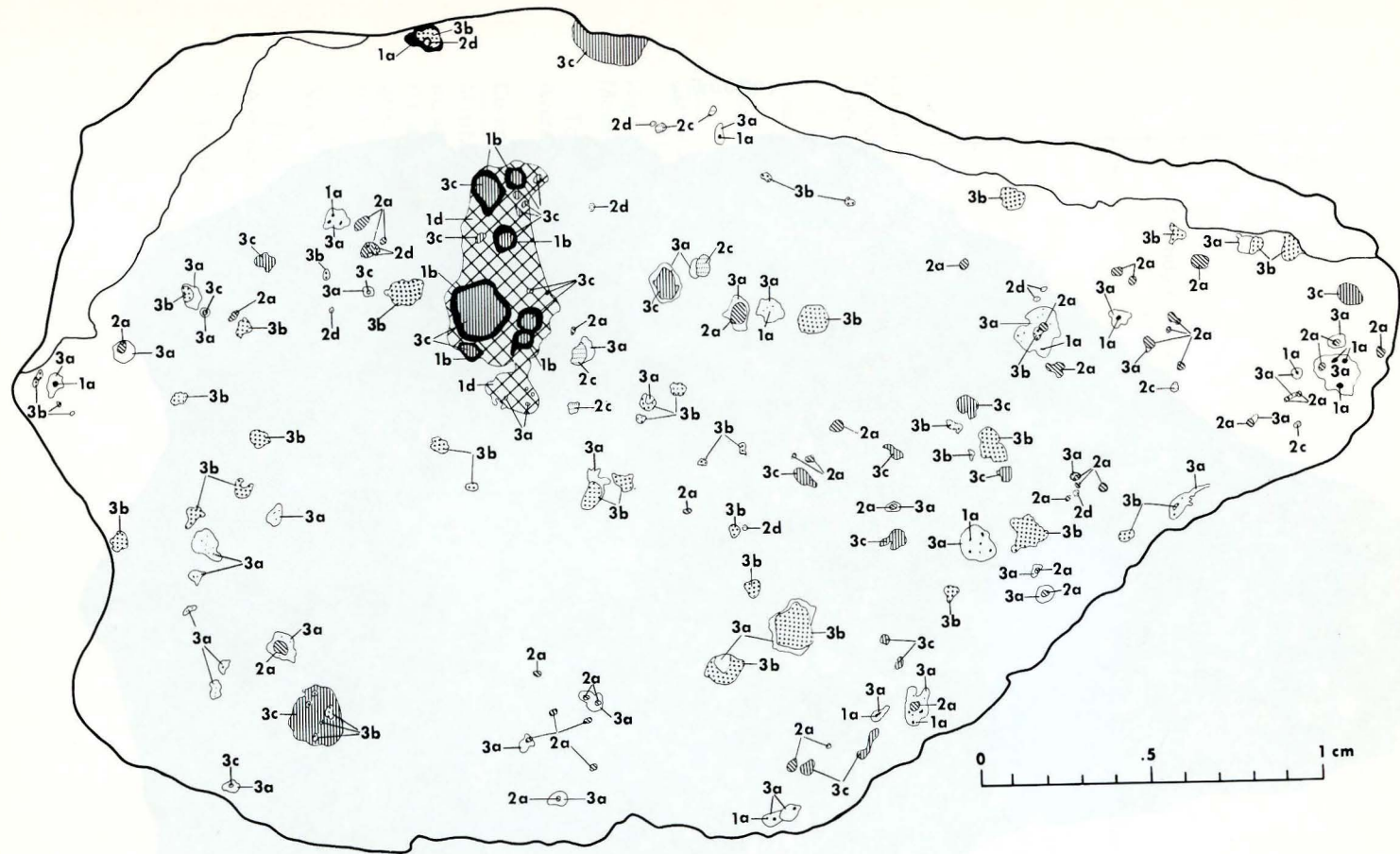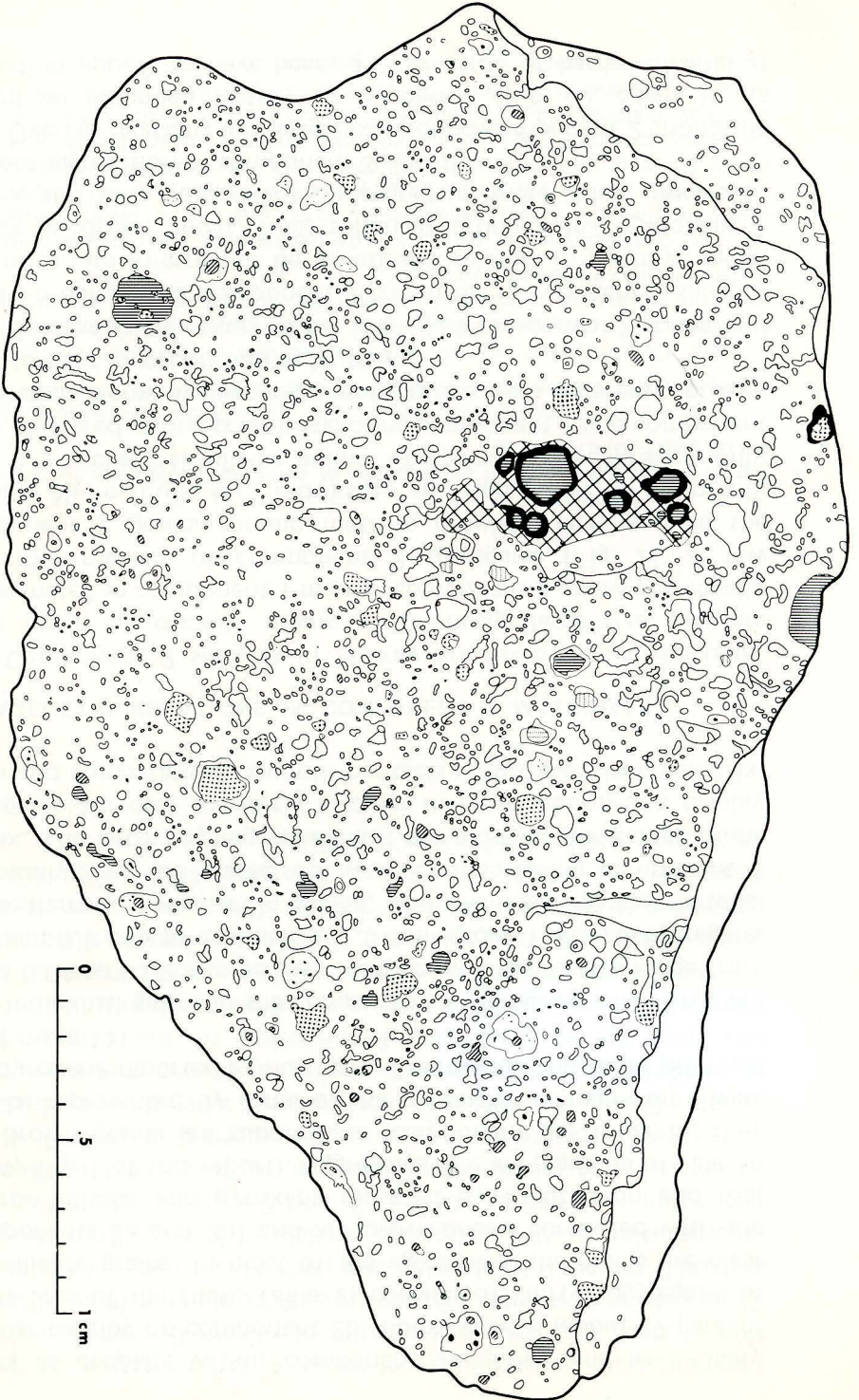[1]/ Letters are keyed to materials described in Fig. 2.

Figure 2b1.

Figure 2b2.

Figure 2b3.

occurs as droplets within component 2a grains, and as a finely granular coating on component 2b. Component 3 (about 17 percent of the area of the rock; Table 2) consists of "dirty" aggregates of tiny silicate grains. In most of the aggregates, the grains are clear (components 3a and 3b) and are provisionally correlated with the low-iron olivine and pyroxene reported by Fredriksson and Keil (1964; Fig. 1 of this report). Aggregates that are made up of pale- to dark-brown grains are subordinate (component 3c; Table 2); they may be represented by some of the moderate- or high-iron olivine and pyroxene reported in Murray by Fredriksson and Keil (1964; see Fig. 1, page 11).

Individual grains in the component 3 aggregates commonly are about 0.01 to 0.02 mm across. Component 3 aggregates range from less than 0.1 mm to as much as 2.5 mm across. The small aggregates are extremely irregular in shape, and included matrix material commonly may be traced outward into enclosing component 1 matrix. The largest aggregates exhibit the most regular shapes. Some aggregates are oval to nearly circular in cross section and display sharp and comparatively smooth contacts with the enclosing matrix.

PARAGENETIC RELATIONS IN COMPONENT 2 MATERIALS

Component 2 silicates in Murray are texturally conspicuous. They occur as discrete grains of relatively large size that are disseminated in component 1 matrix; component 2 grains also locally form the nucleus of component 3 aggregates (Fig. 2). A few component 2 grains contain metallic droplets, analogous to the metallic Ni-Fe found by Fredriksson and Keil (1964) in essentially iron- and nickel-free olivine grains. Component 2 grains show only crisp unaltered contacts with enclosing component 1 and component 3 materials. Some of the component 2 grains were apparently broken prior to their incorporation in Murray.

Because metal occurs within individual component 2 grains, and within a compound component 2 chondrule, component 2 silicates and metal are inferred to be genetically related. In contrast, metal occurs as disseminated, free, spherical droplets in component 1 matrix and in a component 3b aggregate; metal thus appears to predate aggregation of component 3 silicates.

Overlap relations in a single compound component 2 chondrule record an extended history of formation (Fig. 3). Steps in its formation appear to have been; 1) formation of barred silicate; 2)

fragmentation; 3) deposition of metal; 4) fragmentation; 5) deposition of clear, relatively coarse grains of silicate; 6) fragmentation(?); 7) deposition of a soft, light gray sheath containing finely dispersed matrix(?) material; 8) abrasion and partial loss of the sheath; and, 9) incorporation of the compound particle in Murray. Formation and deposition recorded in steps 1, 3, and 5 may be inferred to have occurred in the environment that gave rise to the high-temperature component 2 materials; fragmentation recorded in steps 2, 4, and possibly 6, may be inferred to have occurred when the chondrule was in a relatively low-temperature environment, one that presumably was near the environment of formation of the component 2 materials. Similar, possibly analogous compound chondrules occur in the volatile-poor chondrites. Some relatively large compound chondrules display diversely oriented, fragmented barred silicates, and aggregates of relatively coarsely granular silicate that are enclosed by metal (Wood, 1963a, pl. 2a, c; Wlotzka, 1963, Fig. 10a, b.; Tschermak, 1885 [1964], Figs. 41, 75).

Figure 3. **Sketch maps and photographs of compound component 2 chondrule are on pages 26, 27, and 28.**

a. General view of part of area of Fig. 2a showing selected grains, aggregates, and chondrules of component 2 and 3 materials.

b. Detailed view of compound component 2 chondrule and adjacent materials. Three fragments of light-gray, punky component 3a? material that reside in the matrix appear to have been derived from nearby component 3a? material in the compound chondrule.

c. Detailed view of barred silicate (component 2b) showing crystalline layers of olivine(?) (dark), separated by softer milky-white layers (white) that may be Na- and Al-rich glass. Finely granular metal (component 2d) lines the cavity in upper part of chondrule. Component 3a? sheath consists of punky, dove-gray material $(3a_1)$, which encloses finely granular, fresher-appearing, buff-gray material $(3a_2)$. Component $3a_2$ contains very tiny black specks of matrix(?) material (component 1). Component $3a_2$ grains are about 0.01 mm across. Contact between $3a_1$ and $3a_2$ is gradational.
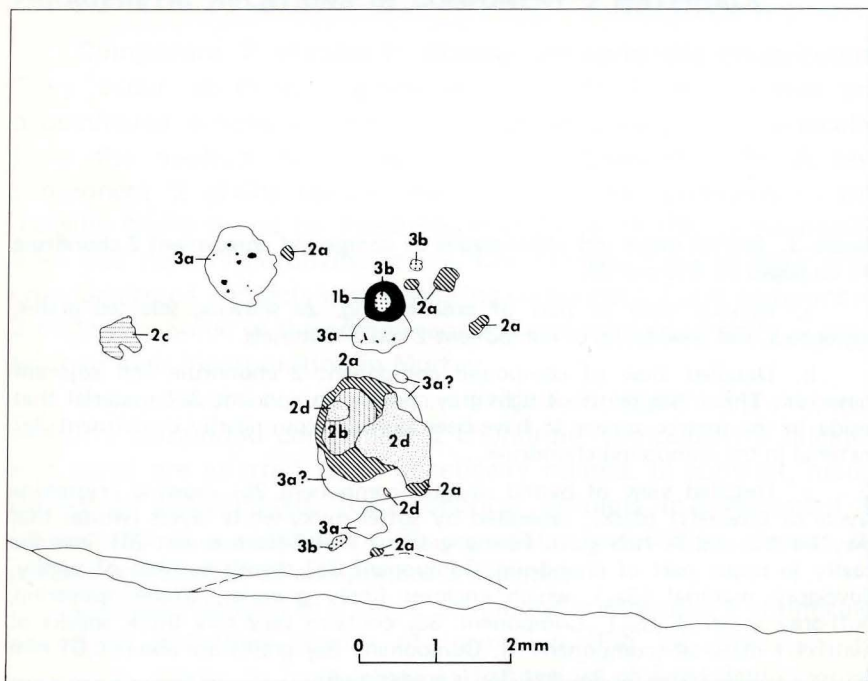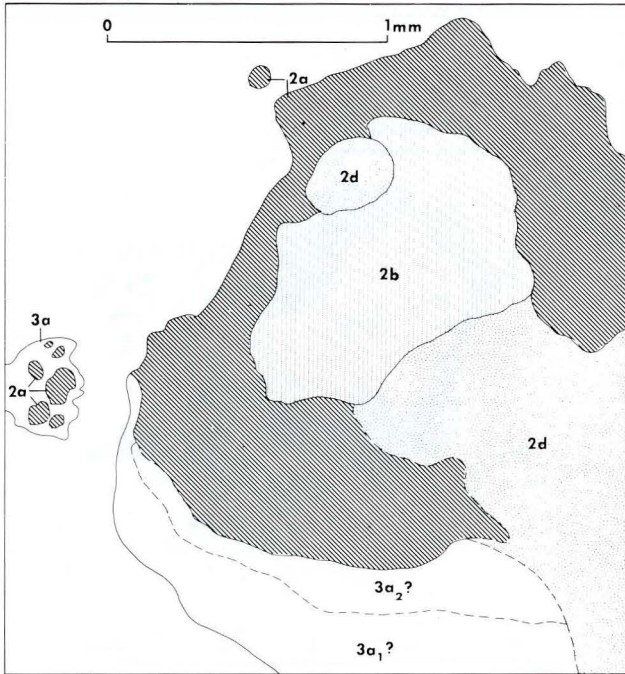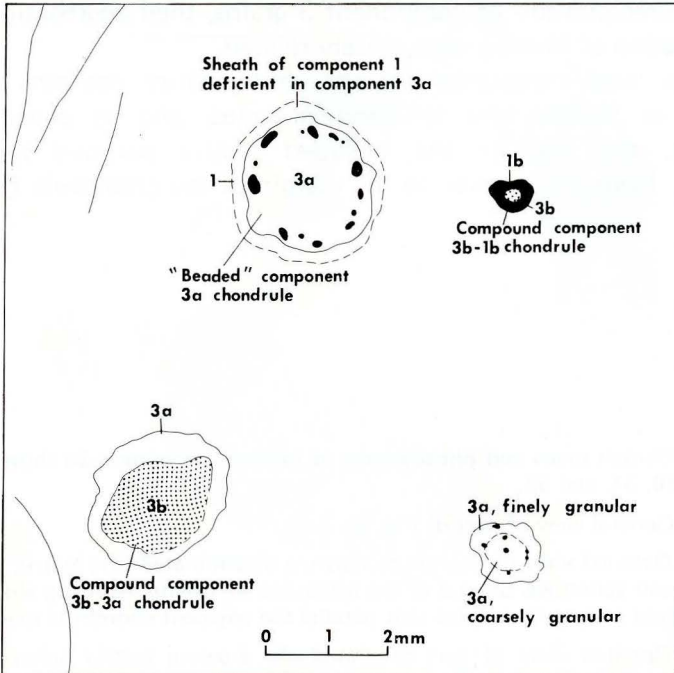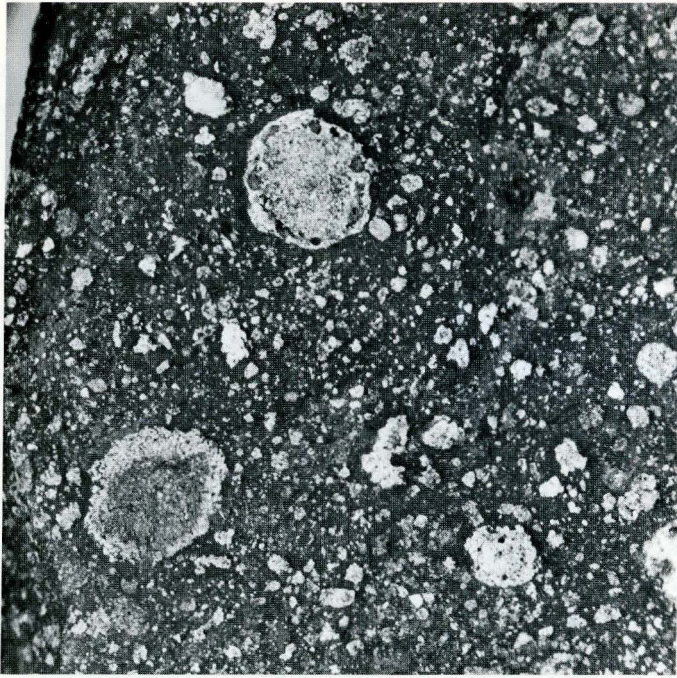
Figure 3a (Photo and Map)

Figure 3c (Photo and Map)
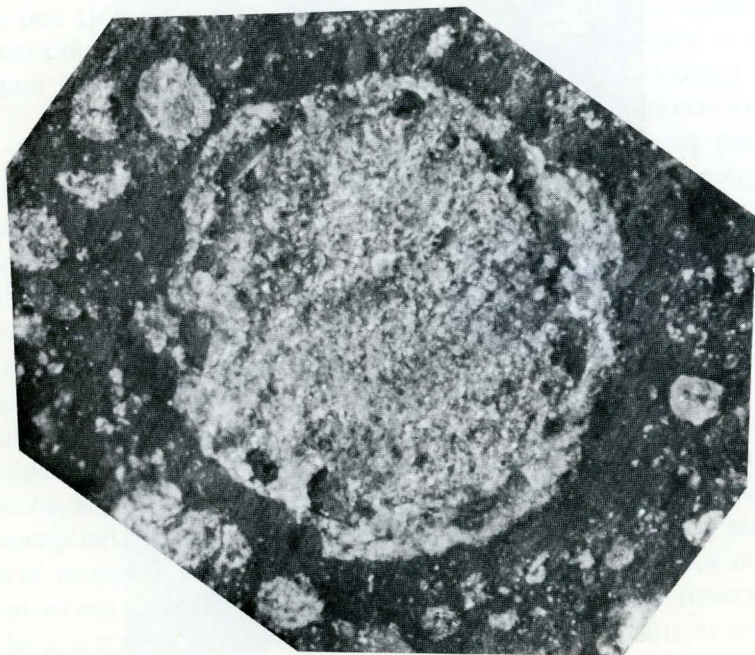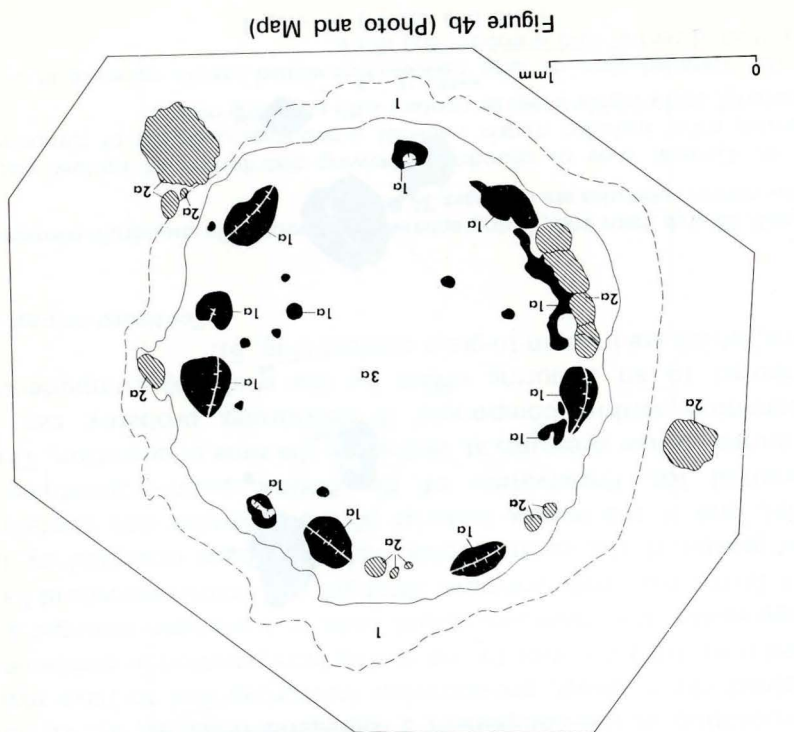
Figure 4a (Photo and Map)
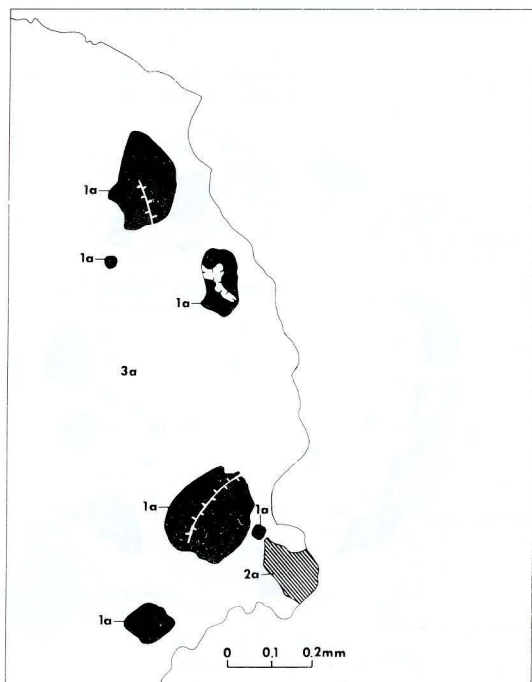
Figure 4b (Photo and Map)

0 |___| 1mm

Figure 4c (Photo and Map)

Several relatively large matrix spherules, about 0.1 to 0.3 mm across, are present as a bead-like girdle, band, or sheath inside the periphery of the chondrule. Some of the spherules appear teardrop shaped. Several are slightly oblate, and their short axes are perpendicular to the adjacent chondrule margin. Some of the spherules display raised equatorial rims or sutures, which are oriented parallel to the adjacent chondrule margin. The outer part of the chondrule appears to terminate in a "step," and component 1 matrix material that directly encloses the chondrule is deficient in finely disseminated component 3a material (Fig. 4a, b). The relations suggest that the matrix spherules are not the product of in situ processes, but rather were mechanically incorporated in a layer that was deposited around more typical component 3a material-- before the component 3 chondrule was incorporated in Murray. The matrix spherules and granules thus formed before aggregation of the component 3 chondrule, and before accretion of Murray.

Hollow matrix spherules, some with very thin walls and one with a smooth, shiny interior, occur in a few component 3a aggregates (Figs. 4, 5, 6). The matrix spherules are soft and break easily. A few were broken across their central voids prior to their incorporation in the component 3 aggregates (Figs. 4c, 6). To have sustained clean, sharp, pre-accretion fracturing, and to have maintained their integrity prior to and during incorporation in component 3a aggregates, the spherules would have to have been stronger and more brittle than they are now. Strength and brittleness would have been greater if the central voids had once been occupied by icy nuclei, and if the matrix material of the spherules also contained interstitial ice. Preservation of the hollow matrix spherules is attributed to low pressures at, and since, the time of accretion. Their preservation within component 3 chondrules probably can be attributed to an armoring effect by the enclosing component 3 grains, which are in grain-to-grain contact (Fig. 5).

Figure 5. Sketch maps and photographs of a component 3a chondrule containing hollow matrix spherules are on pages 34 and 35.

    a. General view of chondrule, showing distribution of hollow matrix spherules, other included matrix material, a two-stage character of component 3a material, and a highly irregular contact with enclosing matrix.

    b. Detailed view of large hollow, thin-walled matrix spherule in chondrule. Wall of central void is smooth and shiny.
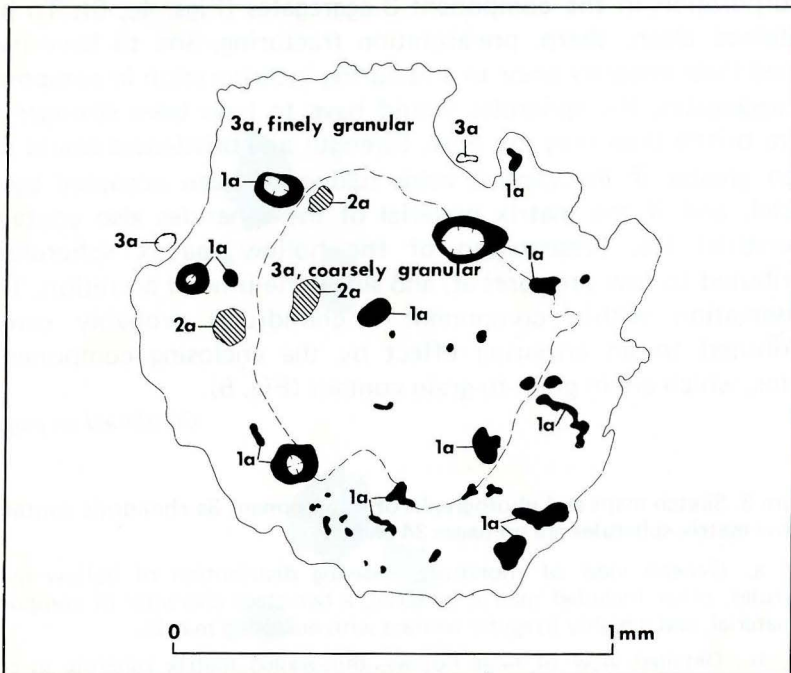
Figure 5a (Photo and Map)

Figure 5b (Photo and Map)

3a, finely granular

1a

3a, coarsely granular

2a

2a

0   0.1   0.2 mm
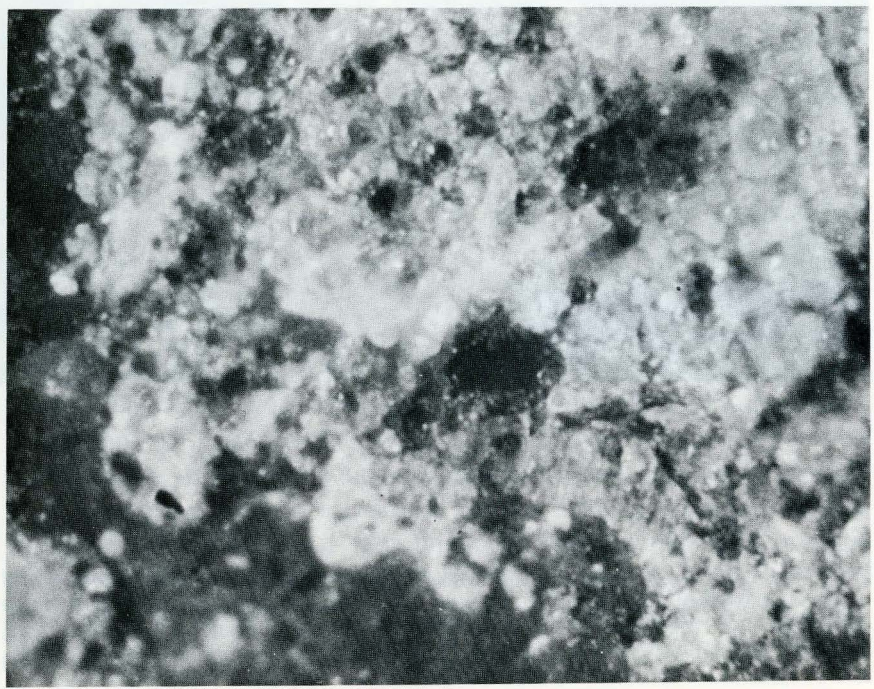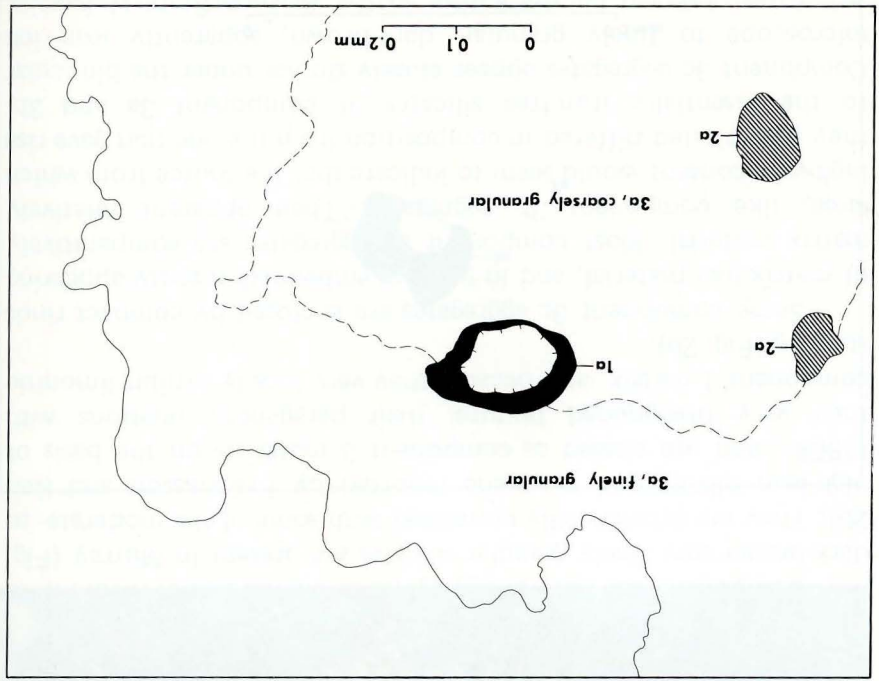
Figure 6. Sketch map and photograph of fragmented, hollow matrix spherule that forms the nucleus of an irregular, component 3a aggregate. The aggregate appears near the left-central edge of the meteorite (in Fig. 2b). Matrix material is present as intergranular inclusions in the aggregate.
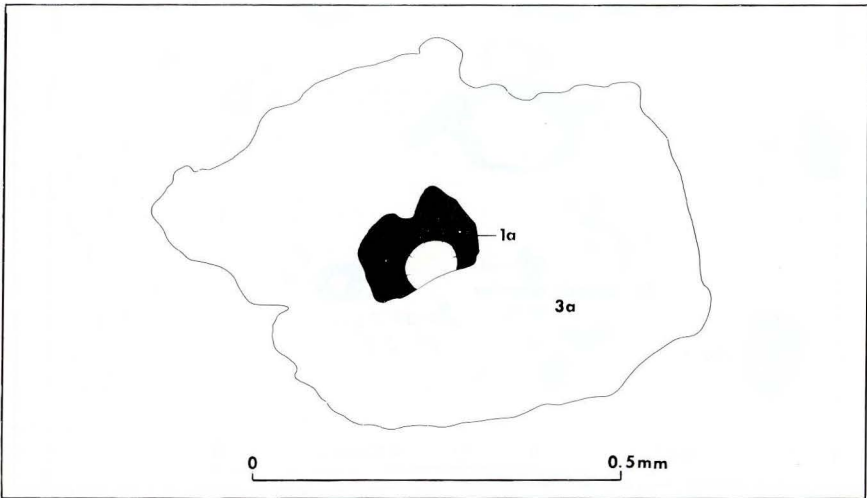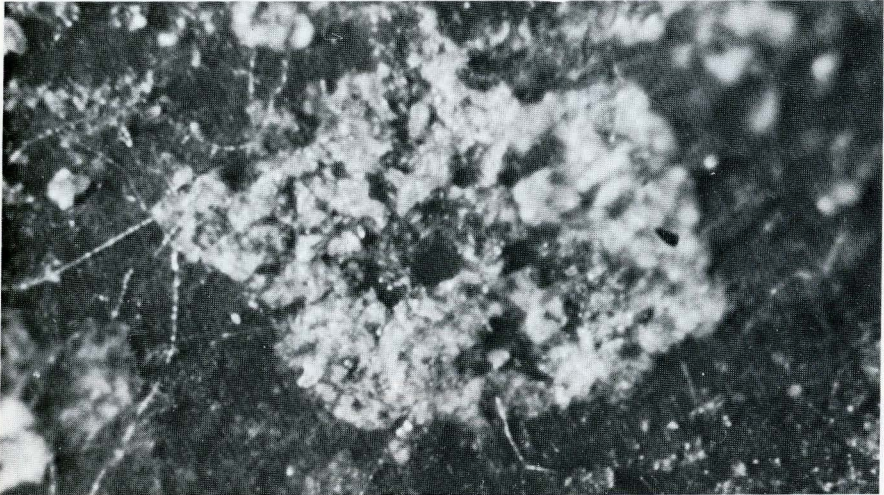
Figure 6 (Photo and Map)

Component 3b.--Most component 3b aggregates are comparatively large, and several are partly to entirely enclosed by component 3a materials (Fig. 2). Component 3b consists of grains of clear silicate that display limonitic staining; fresh, finely disseminated matrix is lacking. In most stained aggregates, alteration effects do not appear to extend into enclosing matrix. However, in a compound component 3b-1b chondrule (Fig. 7), a nucleus of red-stained component 3b material is enclosed by a shiny black, crudely layered sheath of matrix-like material. Dull black, very fine-grained matrix in turn encloses the compound chondrule and displays a subtle alteration halo that appears as a diffuse, gray patch in Fig. 4a.

In a compound component 3b-3a chondrule (Fig. 8), limonitic staining in the component 3b nucleus has apparently soaked through part of the enclosing component 3a sheath. Alteration halos are lacking around most component 3b aggregates, which suggests that alteration may have occurred principally before component 3b aggregates acquired component 3a sheaths and before the aggregates were incorporated in Murray. Nonetheless, there is evidence that local alteration occurred after the precipitation of component 3a materials and after the accretion of Murray. Solutions or vapors emanating from the component 3b aggregates may have been responsible for the local alteration effects.

Component 3c.--Several aggregates or chondrules of medium- to dark-brown very finely granular silicates are present in Murray (Fig. 2b). They are provisionally correlated with some of the moderate- to high-iron olivine and pyroxene reported by Fredriksson and Keil (1964), and are classed as component 3 materials on the basis of their very fine-grained texture, their paragenetic relations with component 1 matrix, and because they very locally exhibit limonitic staining (Fig. 2b).

Some component 3c aggregates are enclosed by compact rinds of matrix-like material, and in turn are embedded in sooty-appearing matrix material. Most component 3c aggregates are comparatively large, like component 3b aggregates. Their apparent relatively high-iron content would seem to indicate that the source from which they precipitated differed in composition from the one that gave rise to the essentially iron-free silicates of component 3a and 3b. Component 3c aggregates appear closely similar under the binocular microscope to finely granular, dark-brown, apparently iron-rich aggregates observed by the author in the Arizona State University

Figure 7. Sketch map and photograph, compound component 3b-1b chondrule. Red, limonite- or hematite-stained component 3b aggregate is enclosed by a sheath of black matrix- like material that contains very sparse component 3a grains. "Murray F" material (DuFresne and Anders, 1963) is reported to have enclosed olivine or pyroxene, possibly analogous to the sheathing material shown here.
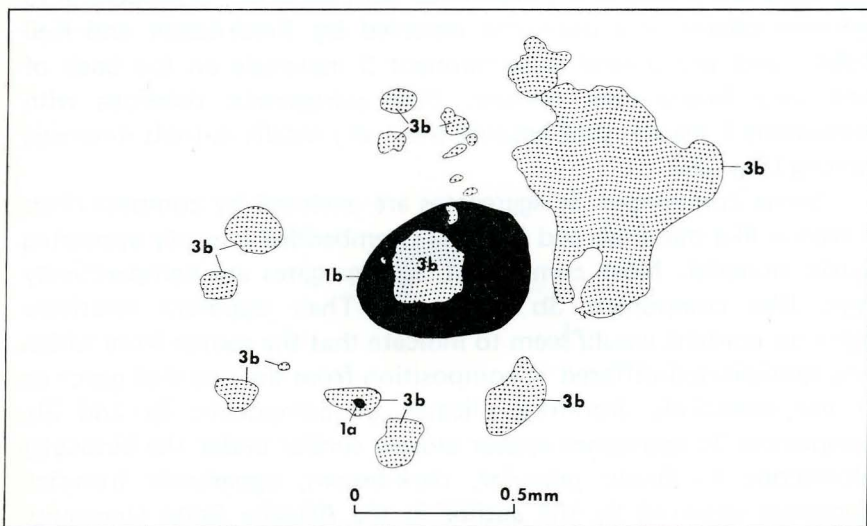
Figure 7 (Photo and Map)

Figure 8. Sketch map and photograph, compound component 3b-3a chondrule. Unstained component 3a sheath contains fresh, disseminated matrix material. "Altered," yellowish to reddish stained component 3b core contains irregularly distributed matrix(?). "Altered" part of component 3a sheath is superficially stained a pale yellowish-brown. The staining appears to have soaked through the component 3a sheath from the interior of the chondrule.
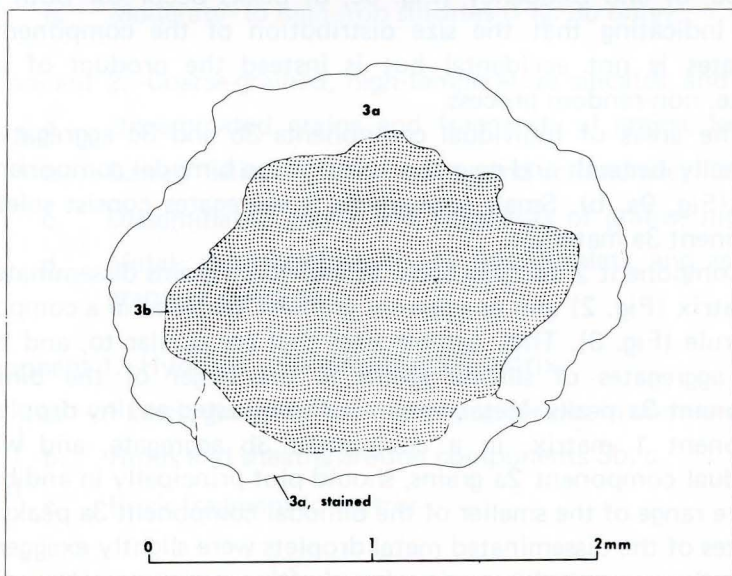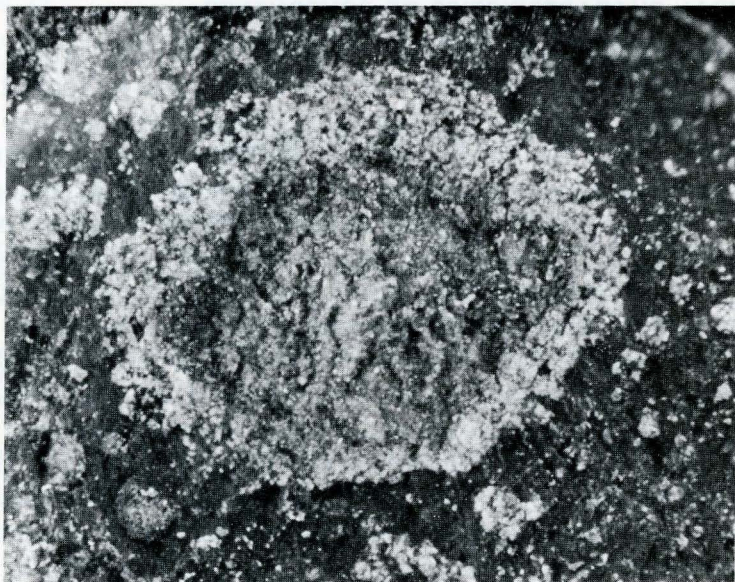
Figure 8 (Photo and Map)

specimen of the Vigarano pigeonite chondrite. In Murray, component 3a is more abundant than component 3c, whereas in Vigarano the reverse appears to be the case.

TEXTURAL CHARACTERISTICS OF COMPONENTS

The abundances and size distributions of particles, grains, and aggregates of components 1, 2, and 3 are summarized in Table 2 and in Figs. 9a-9d. Component 3a aggregates occur mainly in three size groupings: 1) as a few comparatively large (1-2 mm diam) ovoidal to nearly spherical chondrules in the area of Fig. 2a; 2) as abundant irregular to subovoidal aggregates, which commonly are on the order of about 0.2 mm across; and, 3) as very abundant tiny aggregates of highly irregular outline, which would have diameters of about 0.1 mm and less if they were circular in cross section. The second and third size groupings occur in both map areas, and their plots exhibit remarkably similar forms. About 7.5 percent of the area shown in Fig. 2a is occupied by component 3a grains in small aggregates that lie in narrow size intervals under the two prominent peaks at about 0.008 and 0.035 mm^2 in Fig. 9a; this comprises nearly one-half of the total area (16 percent, see Table 2) occupied by component 3a aggregates in the map area of Fig. 2a. Highly similar bimodal size (Fig. 9a, b) and frequency (Fig. 9c, d) peaks occur for both map areas, indicating that the size distribution of the component 3a aggregates is not accidental but is instead the product of some discrete, non-random process.

The areas of individual components 3b and 3c aggregates lie principally beneath and near the larger of the bimodal component 3a peaks (Fig. 9a, b). Small component 3 aggregates consist solely of component 3a materials.

Component 2 silicates occur as individual grains disseminated in the matrix (Fig. 2) and as coarsely granular material in a compound chondrule (Fig. 3). They exhibit sizes that are similar to, and larger than, aggregates of silicate grains in the larger of the bimodal component 3a peaks. Metal, which is disseminated as tiny droplets in component 1 matrix, in a component 3b aggregate, and within individual component 2a grains, should plot principally in and below the size range of the smaller of the bimodal component 3a peaks, but the sizes of the disseminated metal droplets were slightly exaggerated during the course of mapping for drafting purposes. Very finely granular metal in a compound component 2 chondrule is plotted in

Figure 9. Size distributions and abundances of components in Murray carbonaceous chondrite are in graphs on pages 42, 43, 44, 45.

a. Plot of particle size against percent of total area in area of Fig. 2a.

b. Plot of particle size against percent of total area in area of Fig. 2b.

c. Plot of particle size against particle frequency for component 3a in area of Fig. 2a.

d. Plot of particle size against particle frequency for component 3a in area of Fig. 2b.

Explanation for Graphs

Component 3a aggregates display three peaks in the map area of Fig. 2a and two peaks in the map area of Fig. 2b. The large-size component 3a peak in Fig. 9a reflects the existence of two prominent accretionary chondrules in the map area of Fig. 2a. Components 3b and 3c, and materials of components 2 and 1, mainly lie under and near the larger (0.2 mm) of the bimodal peaks. If the aggregates that form the peaks in Fig. 9a were circular in cross section, their areas would correspond to the three diameters (0.1, 0.2, and 2 mm) shown in parentheses in that figure.

Component 3.--Finely granular aggregates of high-temperature silicates.

○ a. Unstained, low-iron silicates

● b. Stained, low-iron silicates

□ c. Moderate- to high-iron silicates (Fig. 9b only)

Component 2.--Coarse-grained, high-temperature silicates, and metal.

x { a. Disseminated grains and fragments of grains, low-iron

    b. Barred silicate in a compound chondrule, low-iron

+ c. Disseminated grains and fragments of grains, high-iron

△ d. Metal, as disseminated very fine droplets, and as finely granular deposits

Component 1.--Hydrous, low-temperature matrix.

    a. Flakes, granules, and hollow spherules in component 3a

■ { b. Rinds and sheaths around components 3b, c

    c. Rock fragment in matrix
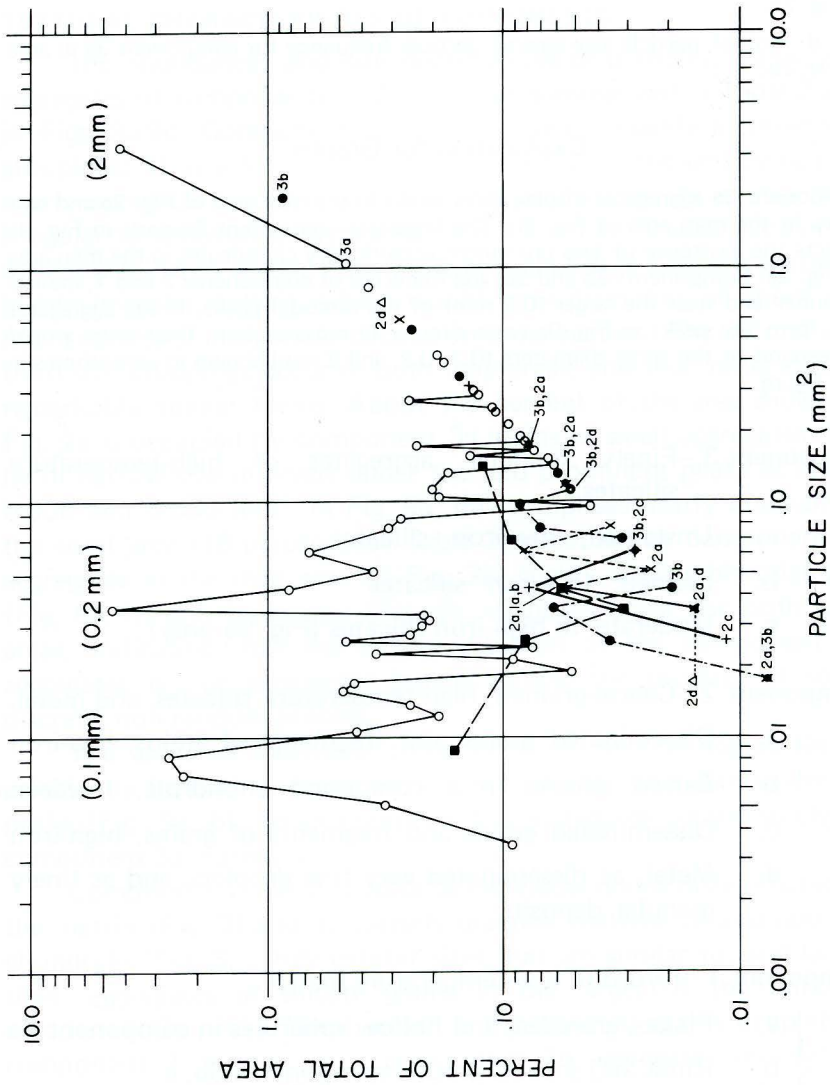
Figure 9a

PARTICLE SIZE (mm²)

PERCENT OF TOTAL AREA

42

Figure 9b

PARTICLE SIZE (mm^2)

NUMBER OF PARTICLES
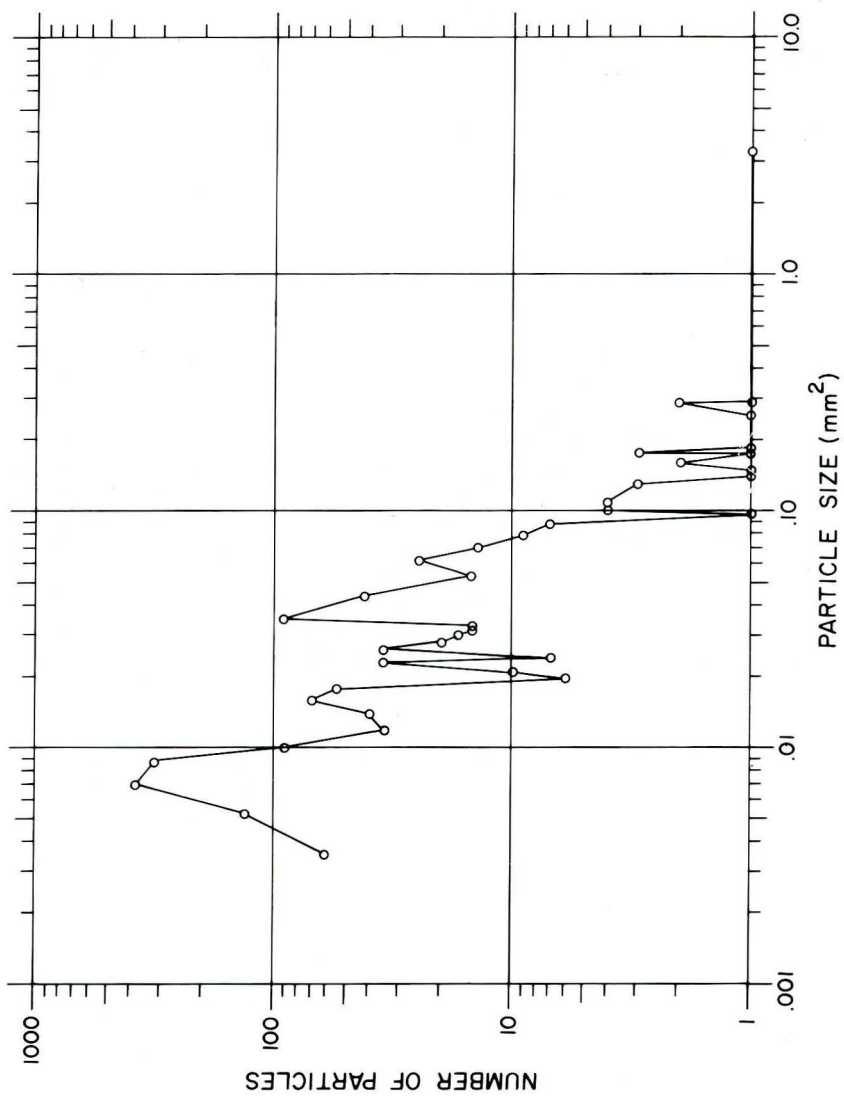
Figure 9c

44

NUMBER OF PARTICLES
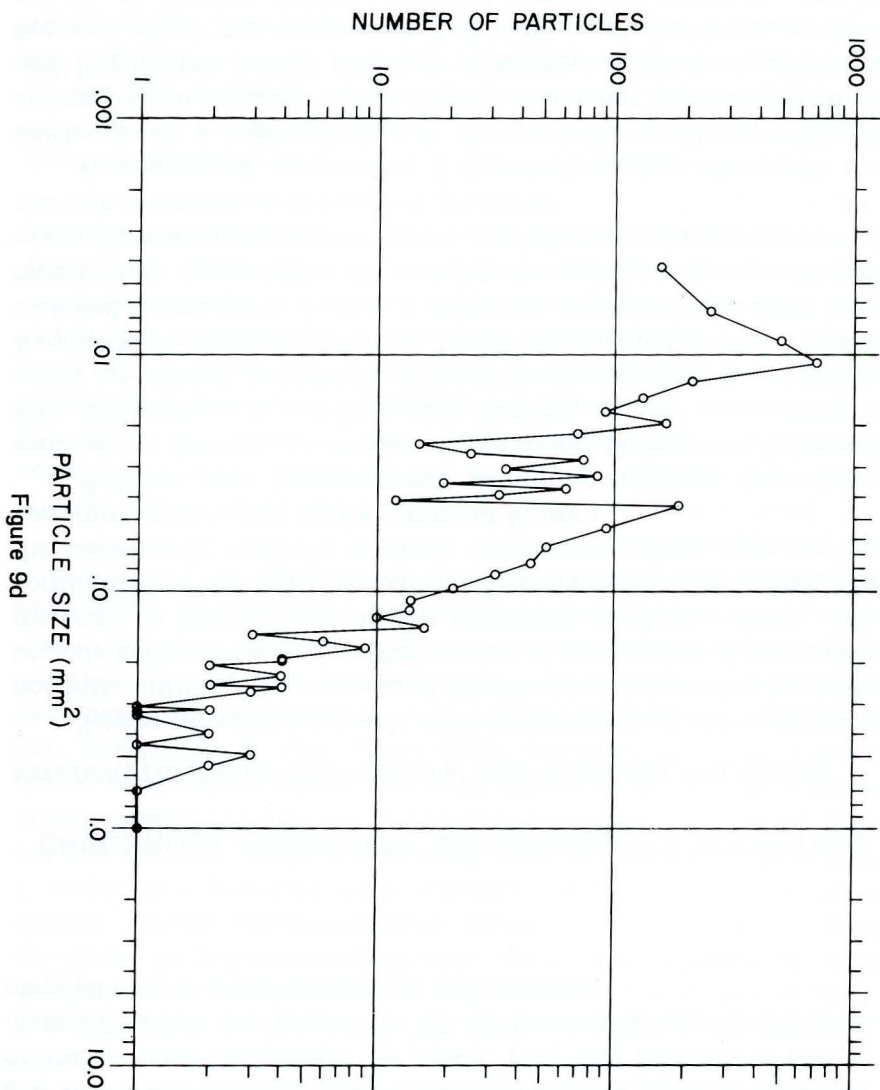
PARTICLE SIZE (mm²)

Figure 9d

Fig. 9a as a single deposit of metal. If disaggregation were possible, the metal would plot as abundant very finely granular material, the size of which would be below the scale of resolution of the maps.

Component 1 matrix material, which occurs as particles, grains, and sheath-like coatings, plots principally under the area of the larger of the bimodal component 3a peaks. Very tiny particles of matrix material, which are present in all component 3a aggregates, were mapped only in a few component 3 chondrules.

CHONDRULE FORMATION AND CHONDRITE ACCRETION

INTERPRETATION OF PARAGENETIC AND TEXTURAL RELATIONS

Salient physical intra- and inter-relationships of the three components, outlined on the maps and described in the preceding sections, provide evidence bearing on the manner of aggregation of particulate materials in Murray, and on the formation of Murray itself. Discontinuities in the size distribution of component 3a aggregates, and the paragenetic relations between components, shed light on the conditions that led to the formation of Murray.

Relative ages between and within components have been assigned on the basis of paragenetic relations. Component 3 formed after components 1 and 2 because materials of both components 1 and 2 are present in component 3 aggregates as discrete grains and as fragments of grains. The diverse, locally fragmented character of the included component 1 and 2 materials indicates that both low-temperature (component 1) and high-temperature (component 2) materials were in existence before precipitation and aggregation of the high-temperature component 3 silicates.

A compound component 2 chondrule appears to record the existence of a high-temperature environment in which relatively coarse-grained silicates, barred silicate, and metal, were precipitated, and fragmented, before accretion of Murray. A genetic relationship between metal and component 2 silicates is inferred because metal occurs as droplets within individual component 2 grains, and as finely granular deposits on and in a compound component 2 chondrule. Metal does not appear to be genetically related to components 1 and 3 because it occurs only as discrete, randomly disseminated droplets in component 1 matrix and in a component 3b

aggregate. Grains of metal display the same paragenetic relations to component 1 matrix and to component 3 aggregates as do component 2a and 2c silicate grains.

Component 1 material predates the formation of component 3 aggregates because flakes, granules, and hollow spherules that are texturally identical with enclosing matrix occur within component 3a aggregates. Locally, the form and distribution of included matrix granules and spherules suggest that the matrix material was mechanically incorporated in the component 3 aggregates (Fig. 4). Relatively large component 3 chondrules characteristically display smooth external forms and sharp contacts with enclosing component 1 matrix (Figs. 4, 8). The gross form, the contact relations, and the local presence of internal gradations in the size of included matrix material (from fine to coarse from the central to the outer parts), suggest that the relatively large component 3 chondrules and aggregates formed mechanically in an environment that contained dispersed matrix material, following which they became mechanically incorporated in Murray. The presence of soft, hollow matrix spherules in component 3a chondrules indicates that aggregation occurred at low pressures, possibly on the order of 1 atmosphere, and perhaps much less.

Small component 3a aggregates, those which make up the smaller bimodal peak of Figs. 9a and 9b, display extremely irregular contacts with the enclosing component 1 matrix, and locally the matrix may be traced into the aggregates. Because of the intimate association of components 1 and 3a, the formation of the small component 3 aggregates and the accretion of Murray are inferred to have been essentially contemporaneous. Neither external form nor internal structure exists to suggest that the small, pervasively disseminated component 3a aggregates formed before the accretion of Murray.

The peaked abundance distributions of component 3a material (Fig. 9) may reflect dynamic conditions at the time of formation of the aggregates and the accretion of Murray. Component 3b and 3c aggregates are comparatively large, and their sizes correspond to the larger component 3a aggregates. Component 3b and 3c aggregates are locally enclosed by sheaths of component 1 and component 3a materials, which suggests that they formed during the general aggregation process but before the moment of accretion of Murray. In contrast, small aggregates are restricted solely to component 3a material. Thus, aggregates that are about 0.2 mm and larger, which

include those that display subovoidal to ovoidal shapes, are inferred to have undergone transport during aggregation, prior to their incorporation in Murray. Aggregates about 0.1 mm and smaller are inferred to have precipitated and formed at essentially the time and place of accretion of Murray.

ACCRETION OF MURRAY

The textural characteristics and paragenetic relationships of Murray cannot be explained by the hypothesis that high-temperature magnesium silicates precipitated from an igneous melt that was in intimate association with volatile-rich matrix materials, such as might be inferred from the autoreduction-volcanism hypothesis of Ringwood (1966, p. 163-166). Rather, relatively large, ovoidal, matrix-bearing component 3 chondrules, and smaller irregular to subovoidal component 3 aggregates appear to have formed mechanically during the course of accretion. The moment of accretion in Murray was apparently marked by the precipitation of grains, and tiny aggregates of grains, of component 3 silicate that are disseminated in component 1 matrix. The relations appear to be best explained if the very fine grained component 3 silicates precipitated abruptly from a high-temperature gas, at low pressures, in a low-temperature environment that contained dispersed component 1 and component 2 materials.

Fragmented, hollow matrix spherules that are incorporated in "accretionary" chondrules perhaps once contained nuclei of ice. If free volatiles, as ices, were associated with dispersed, hydrous, low-temperature matrix materials, brief thawing and abrupt refreezing of volatiles during the precipitation of component 3 materials could have been at least partly responsible for chondrite accretion.

The anhydrous, high-temperature component 3 silicates, on the basis of their very small grain size and their intimate association with component 1 matrix material, are inferred to have precipitated abruptly from a high-temperature source medium (gas). The formation of accretionary chondrules, and the process of accretion, may have a terrestrial analogy in the rolling up of a dirty snowball where fresh snow overlies relatively warm ground. In the terrestrial situation, dirt is picked up at the contact between cold accreting material (the snowball) and warm background material (earth). In the case of chondrite accretion, the temperature roles appear to have been reversed. Dispersed, very fine-grained, presumably cold back-

ground materials appear to have adhered to presumably warm, but cooling, grains and aggregates of grains of component 3 magnesium silicate. Accretion of Murray perhaps may be visualized as having occurred as a warm "snow storm" of fine magnesium silicate crystals, in the course of precipitating from a gas into a cold, "dusty" environment, briefly raised the temperature of the cold "background" materials to above the melting points of associated ices, following which there was abrupt refreezing into icy chondritic material. The formation of nearly spherical "accretionary" chondrules perhaps occurred where component 3 aggregates were virtually rolled along interfaces between the precipitating high-temperature gas and the environment that contained the cementing low-temperature background material. To preserve Murray and its accretionary textures, the chondritic material then needed to be inserted into a path that lay to the side of and away from the direction of movement of the inferred high-temperature gas. Accretionary materials then could presumably coalesce, in an eddy of material, to form a small, volatile-rich planetesimal- or cometary-sized parent body.

INFERRED SOURCES OF COMPONENTS

Because component 1 and 2 materials existed prior to accretion, a low-temperature dust cloud and a high-temperature region of chondrule and metal formation, and storage, may be inferred to have co-existed in the primitive solar system prior to chondrite formation. Wood (1963b, 1967) has suggested that chondrules formed in the solar nebula, with reduction occurring before accretion by reaction with hydrogen:

$$FeO + H_2 \longrightarrow Fe + H_2O$$

FeO	+	H_2	$\longrightarrow$	Fe	+	H_2O
(dissolved in silicate droplets)		(gas)		(metal droplets)		(gas)
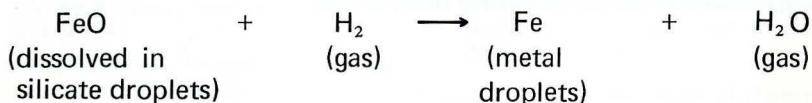
The precipitation of chondrules as liquid droplets condensing from a gas of solar composition requires high pressures, about 100 to 1000 atm. total pressure (Wood, 1967, Fig. 4). These pressures are much higher than those estimated for the primordial nebula (probably no greater than 10^{-5} to 10^{-4} atm. near the present asteroid belt; Cameron, 1966). They also appear to be higher than lithostatic pressures which accretionary chondrules of Murray have been

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subjected to, judging from the inclusion and preservation of hollow matrix spherules in component 3a chondrules.

The relatively large size and the textural complexities of component 2 grains and chondrules may be explained if they formed under the temperature and pressure conditions proposed by Wood (1967). However, to satisfy these requirements for a moderately high pressure of formation, and to account for the co-existence of component 1 and 2 materials before accretion, component 2 silicates and metal may have formed in the region of the protosun rather than in the solar nebula. Formation and temporary storage of refractory component 2 silicates and metal in and adjacent to the protosun during the contraction and gravitational heating of a component 1 dust cloud conceivably could have given rise to a proto-solar system in which a dust cloud of volatile-rich component 1 materials enclosed a ring of component 2 chondrules and metal. Such a model might explain the existence of components 1 and 2 not only in the carbonaceous chondrites, but also apparently in unequilibrated (Van Schmus and Wood, 1967), carbon- and water-bearing pigeonite, bronzite, hypersthene, and enstatite chondrites (Wiik, 1956; Jarosewich, 1967).

The foregoing model also could provide a source for component 3 silicates. The inferred component 3 gas could have had its origin in the protosun, and developed partly depleted to very low iron contents as a consequence of the formation of component 2 metal. The shedding of a filament of component 3 gas from the protosun, accompanied by concomitant shedding of an inferred enclosing ring of component 2 chondrules and metal, then conceivably could have resulted in the precipitation of component 3 silicates at low pressures, and in accretion at low temperatures, across a region occupied by a low-temperature dust cloud.

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2. Catalog of Meteorites, Arizona State University*	Carleton B. Moore and Charles F. Lewis	1964
3. Terrestrial and Lunar Flux of Large Meteorites Through Solar System History	William K. Hartmann	1966
4. Xenomalies	Marvin W. Rowe	1967
5. The Petrology of Chondritic Meteorites in the Light of Experimental Studies	John W. Larimer	1967
6. Microtektites and the Origin of the Australasian Tektite Strewn Field	Billy P. Glass	1968
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8. Accretion of Murray Carbonaceous Chondrite and Implications Regarding Chondrule and Chondrite Formation	Donald P. Elston	1969

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