

SILICATE METEORITE STRUCTURES  
AND THE ORIGIN OF THE METEORITES

by

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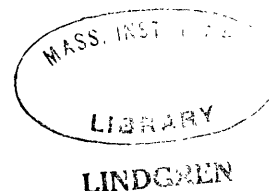
ABSTRACT

The purpose of this study is to consider the implications of the petrography (particularly textures) and petrology of stony meteorites. The meteorites are of great importance to geologists and geophysicists, because they are a key to the origin, evolution and constitution at depth of the earth.

A classification, and descriptions of the types of meteorites are given. Nineteen microphotographs are included, with brief descriptions.

It is concluded that some chondrites are analogous to sedimentary rocks, others to metasediments. The question of the source of the chondrules is posed. The possibility that they represent primary condensations from cooling solar matter is investigated: pressures and temperatures within a contracting cloud of gas (Emden sphere) are plotted; on the basis of assumptions made about the angular momentum of the cloud, the approximate size of the cloud becomes unstable is predicted; assuming that the gas spun off cooled adiabatically, it is shown that it would pass through the liquid field in the SiO<sub>2</sub> and Fe phase diagrams, allowing the condensation of liquid droplets (chondrules). It is proposed that differences in composition between the various particle size fractions might account for the terrestrial planetary densities, and the meteoritic iron groups. Measurements of the composition of olivine crystals by optical means, in fifteen chondrites, appear to support the postulated compositional difference between the chondrules and the finer dust particles.

The possibility that the non-chondrites are the product of re-melting of the core of a parent meteorite planet (initially of homogeneous, chondritic composition) is explored. Two major difficulties present themselves. It is seen that the melting and fractional crystallization of chondritic material would produce rock types in grossly different proportions than those found in the achondrite and iron falls. And, it is seen that if a planet were large enough for diamonds to be stable in its core, half or more of its volume would be in the stability field of the eclogite minerals (pyrope garnet, omphacite, coesite) instead of the basaltic minerals (plagioclase, forsterite, diopside); eclogite minerals have never been observed in meteorites. It is suggested that this volume in the parent meteorite planet was occupied by dunites and pyroxenites, which do not have the proper composition to form eclogite minerals, and that proportions of rock types based on falls are enormously biased because of the relative weakness of these deep-seated stony meteorites.





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SILICATE METEORITE STRUCTURES  
AND THE ORIGIN OF THE METEORITES

I. INTRODUCTION

A. THE STUDY OF METEORITES\*

The phenomenon of stones and iron falling from the sky has been observed and recorded since the beginning of history. However, not until 1803, when a fall of stones at L'Aigle, France, was exhaustively reported on by the physicist Biot, was the skeptical scientific community convinced that meteorites are of extra-terrestrial origin.

From this time meteorites became objects of curiosity, and were avidly collected by museums. Their study became the domain of the mineralogists and metallurgists, who described them and conceived systems of classification according to chemical composition, mineralogy and texture.

The work of astronomers was largely confined to the fall phenomenon. Eye-witness reports of many falls have been critically evaluated and studied. From these, approximate orbits of the bodies in space could be calculated. Most of the orbits are clearly elliptic, and there is almost universal agreement that none are indisputably hyperbolic; thus the meteorites are a solar system phenomenon.

Meteorites apparently are not related to the meteor

\* Mostly from Smith, 1950 and Farrington, 1915.

phenomenon, for the most observed meteorite falls have been in May and June, while the major meteor showers are in August and November (Farrington, 1915).

The hypothesis was early advanced that the meteorites, and probably also the asteroid belt, were debris from the shattering of one or more planets, which had at one time travelled in orbits between Mars and Jupiter. Conclusive proof of this idea has come in recent years with the laboratory investigation of the pressure-temperature stability field of diamond; for the presence of diamond in certain iron and stone meteorites was detected many years ago. It has been shown that these meteorites must have once occupied the deep portion of a body of roughly lunar dimensions or larger (Urey, 1956).

Thus meteorites furnish an opportunity to study in detail the interior of a planet. As such, they deserve far more attention than they have received from geophysicists and geologists, who could draw useful analogies with the earth, particularly in studies of its constitution at depth and its early history (the latter field is virtually untouched). Geochemists have concerned themselves with meteorites, but usually only for their estimates of the cosmic abundance of the elements.

In addition, some meteorites may still retain characteristics reflecting the processes by which the terrestrial planets accreted. If so, they would constitute observational

data relative to the formation of the solar system.

No satisfactory general theory relating the various types of meteorites to a parent meteorite planet has been proposed. The most significant study of this type has been made by Harold Urey, who has been interested principally in the implications of the chemistry of the meteorites.

The writer will attempt to relate the various types of meteorites to one or more parent meteorite planets, and to consider the processes involved in the evolution of the planet. This will be done on the basis of the petrography and chemistry of the meteorites.

#### B. BROAD CLASSES OF METEORITES

Some idea of the relative abundance of the different types of meteorites may be gained by considering the total number of witnessed falls of each type. Meteorites not seen to fall (i.e. finds) cannot be counted, for they are weighted strongly in favor of iron meteorites, which can be readily recognized as such when encountered. Stony meteorites are easily taken to be terrestrial boulders. The counting of falls is not completely unbiased either, because stones have a greater tendency than irons to disintegrate and be lost during passage through the atmosphere; on the other hand, the process of disintegration tends to advertise stone falls more effectively than iron falls.

The major classes of meteorites, and total number of falls of each as of 1952 (Prior and Hey, 1953) are as follows:

Stones	579 falls*
Chondrites	523
Achondrites	56
Stony-Irons	12
Irons	42

\* Plus 49 unclassified stones

Chondrites contain or are composed entirely of rounded, sometimes spherical silicate chondrules, usually  $\frac{1}{2}$  - 2 mm in diameter. These are absent in the achondrites, many of which are similar to terrestrial igneous rocks.

The writer will consider first the chondrites, the largest major class of meteorite; then the non-chondrites (achondrites, stony irons, and irons).

## II. CHONDRITES AND THE FORMATION OF THE SOLAR SYSTEM

### A. OBSERVATIONAL DATA ON

#### CHONDRITES

1. Classification. The classificational scheme of Prior, a modification of the more complex Rose-Tschermak-Brezina system, will be used. Chondrites are composed primarily of  $\text{SiO}_2$ ,  $\text{MgO}$ ,  $\text{FeO}$ , and  $\text{Fe}$ . They are classified according to bulk chemical analyses (not by observable mineralogy, as the



names imply) as in Table 1.

Table 1.  
Classification of Chondrites

Name	MgO/FeO	Metallic Fe/Ni
Enstatite-chondrite	9	13
Bronzite-olivine-chondrite	9-4	13-8
Hypersthene-olivine-chondrite	4-2	8-2

Content of metallic iron decreases downward in the table.

To these names are added modifying adjectives, as follows.

Color:

White

Intermediate

Gray

Black

Structure:

Crystalline (as terrestrial igneous rocks)

Spherical (containing many spherical chondrules, especially of the radiating enstatite type (described later), which do not break with the matrix)

Brecciated

Monomict (involving only one type of meteorite)

Polymict (compounded of several distinct types)

Veined

Composition:

Carbonaceous.

2. Textures and Mineralogy. Some chondrites consist entirely of rounded chondrules, either in direct contact with one another, or embedded in a black matrix. Examples of these may be seen in Plates I. through VI.\*

Petrographic study has shown chondrites to be essentially random mixtures of a few types of chondrules (Bullard, 1939; Foshag, 1941). These chondrules, and consequently the chondrites are composed almost exclusively of orthopyroxene, \*\* clivine ( $(\text{Mg,Fe})_2 \text{SiO}_4$ ), glass, and nickel-iron.

\* All plates are microphotographs of thin-sections from a collection kindly loaned to the writer by Dr. C. Frondel, Professor of Mineralogy and Curator of the Mineralogical Museum, Harvard Agassiz Museum. They were taken in plain polarized light. The enlargement is 46x, so that one inch equals about one-half millimeter.

\*\* Orthopyroxene:  $(\text{Mg}_{1-m}\text{Fe}_m)\text{SiO}_3$

enstatite  $m \leq .1$

bronzite  $.1 > m > .15$

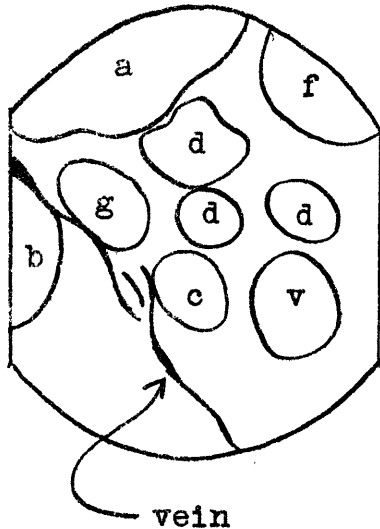
hypersthene  $m \geq .15$

## Plate I.

ALDSWORTH, England

Veined Gray Chondrite.

46x, plain polarized light.

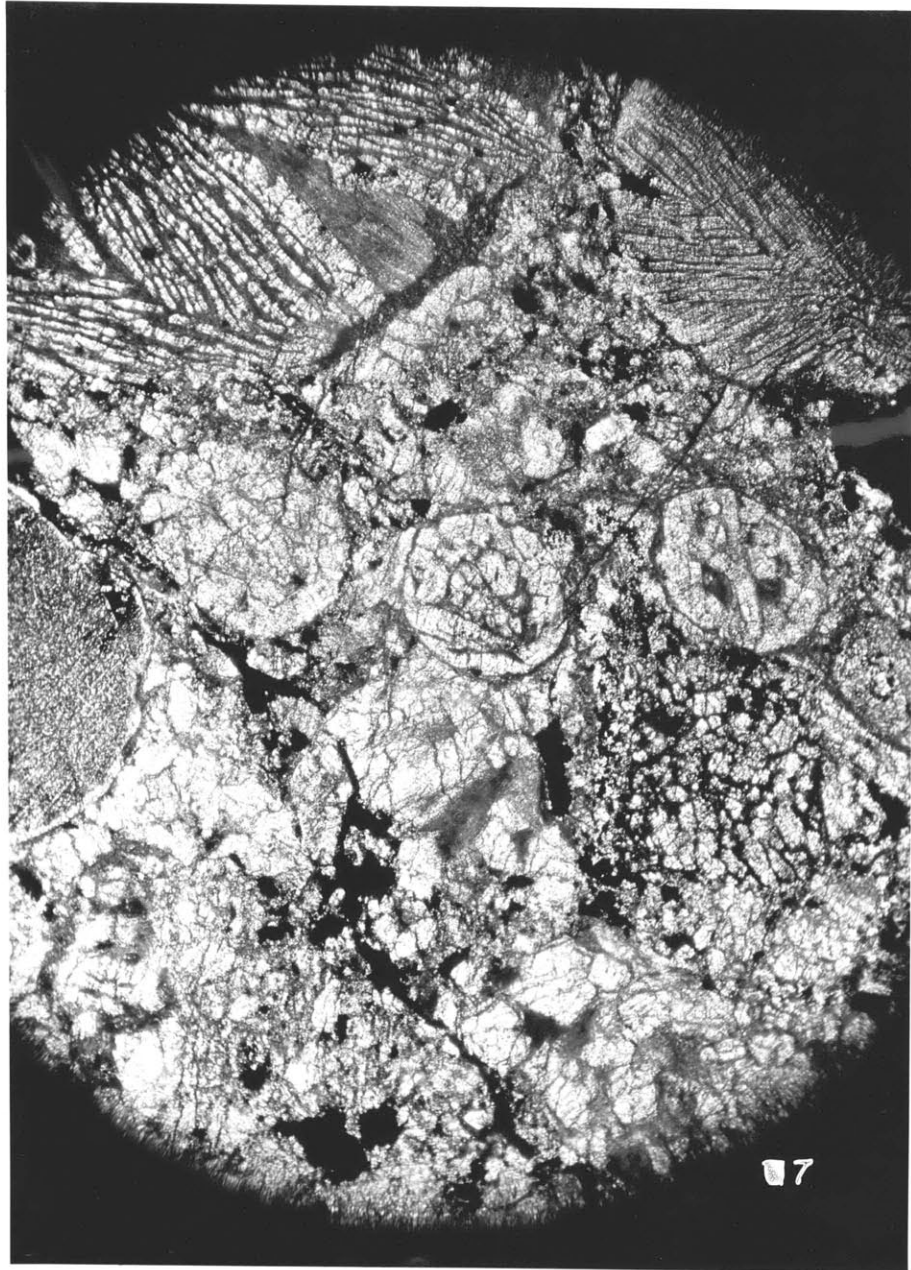


1 mm  
 ───────────  
 in photograph

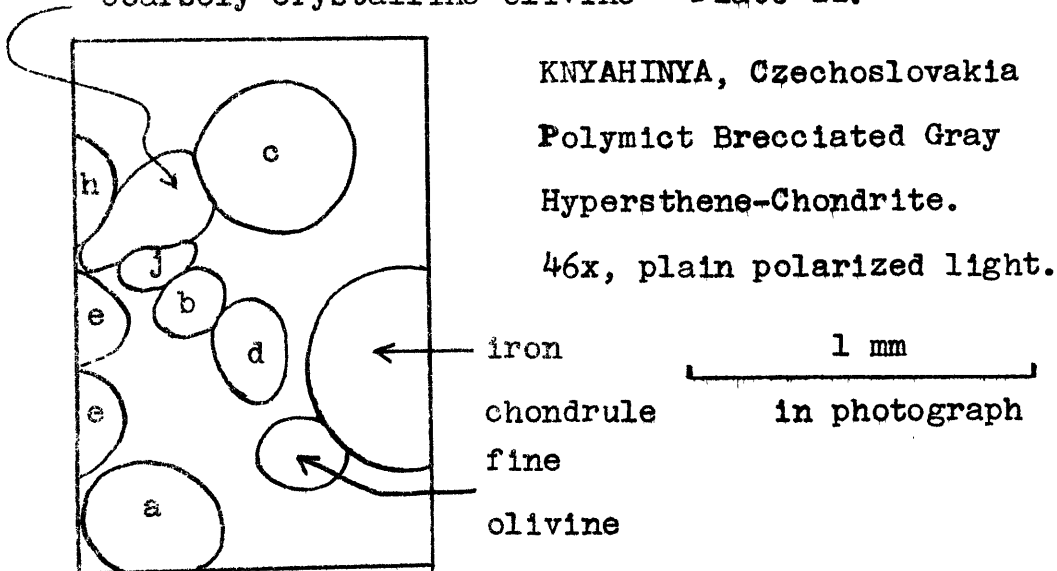
**Chondrules:**

- a. Barred olivine in dark glass matrix.
- b. Radiating orthopyroxene.
- c. Olivine phenocrysts in dark glass matrix.
- d. Olivine and Orthopyroxene phenocrysts in dark glass matrix.
- f. Orthopyroxene "sheafs"
- g. Orthopyroxene phenocrysts in fibrous orthopyroxene matrix.

The chondrules sometimes blend into one another or are hard to distinguish from the matrix. Others are quite distinct. Large opaque areas are nickel-iron, but smaller ones (i.e., constricted portions of the vein) do not reflect light.



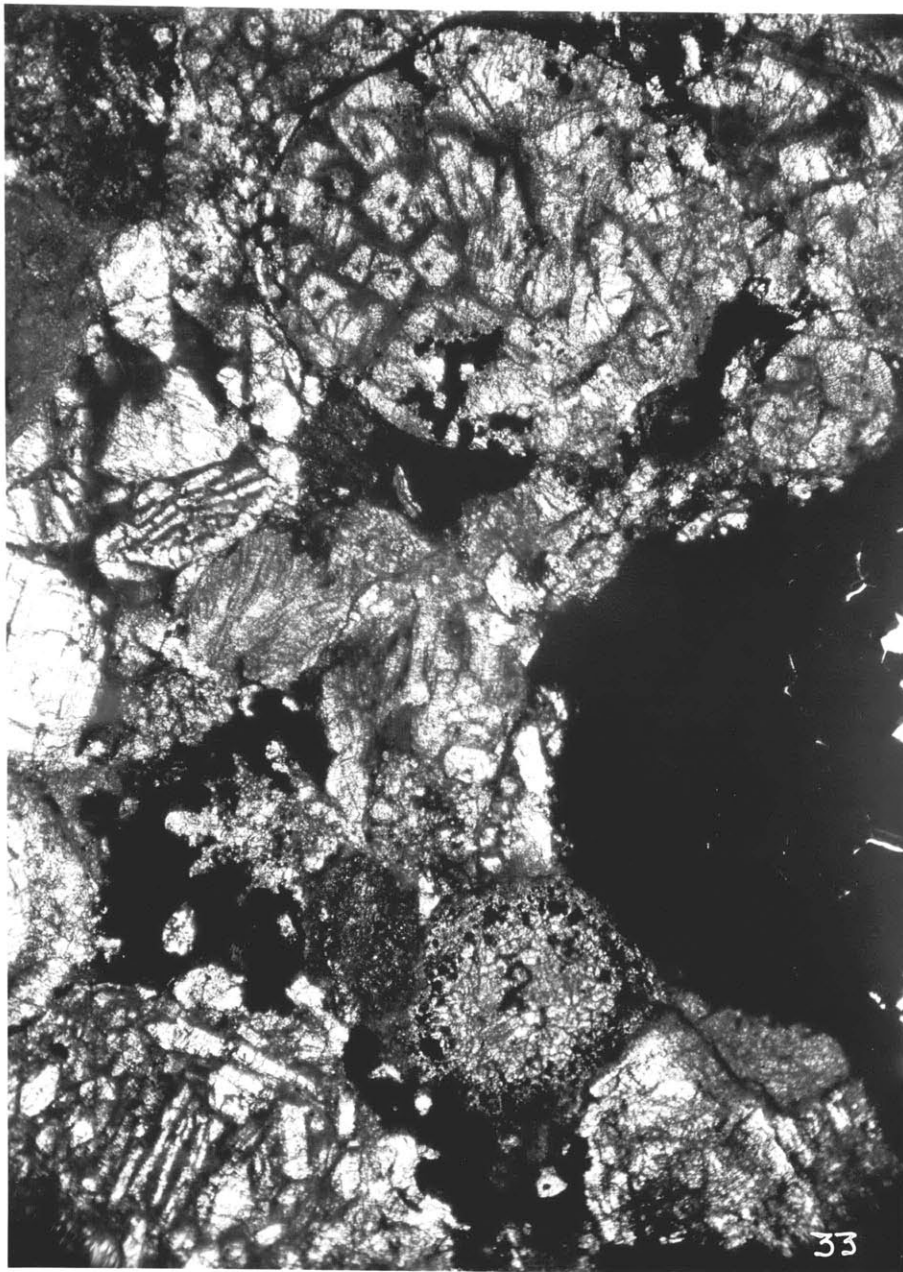
coarsely crystalline olivine Plate II.



**Chondrules:**

- a. Barred olivine in dark glass matrix.
- b. Radiating orthopyroxene.
- c. Olivine phenocrysts in dark glass matrix.
- d. Olivine and Orthopyroxene phenocrysts in dark glass matrix.
- e. Olivine single crystals.
- h. Devitrified glass.
- j. Barred olivine with optically continuous rim.

Large opaque areas are nickel-iron, but some of the opaque matrix does not reflect light. Chondrules can usually be easily distinguished. Other sections of Knyahinya (a polymict breccia) are different. All are chondritic, but some contain much less opaque material than this section.



## Plate III

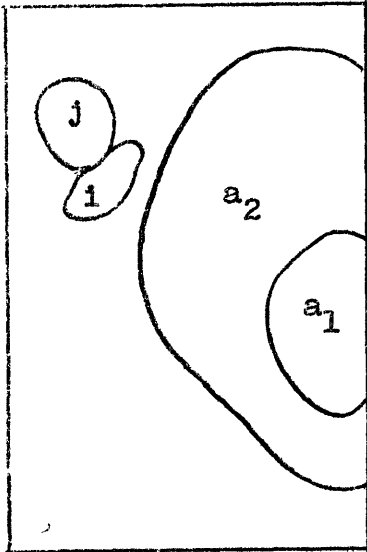
SERES, Greece

Gray Hypersthene - Chondrite.

46x, plain polarized light.

1 mm

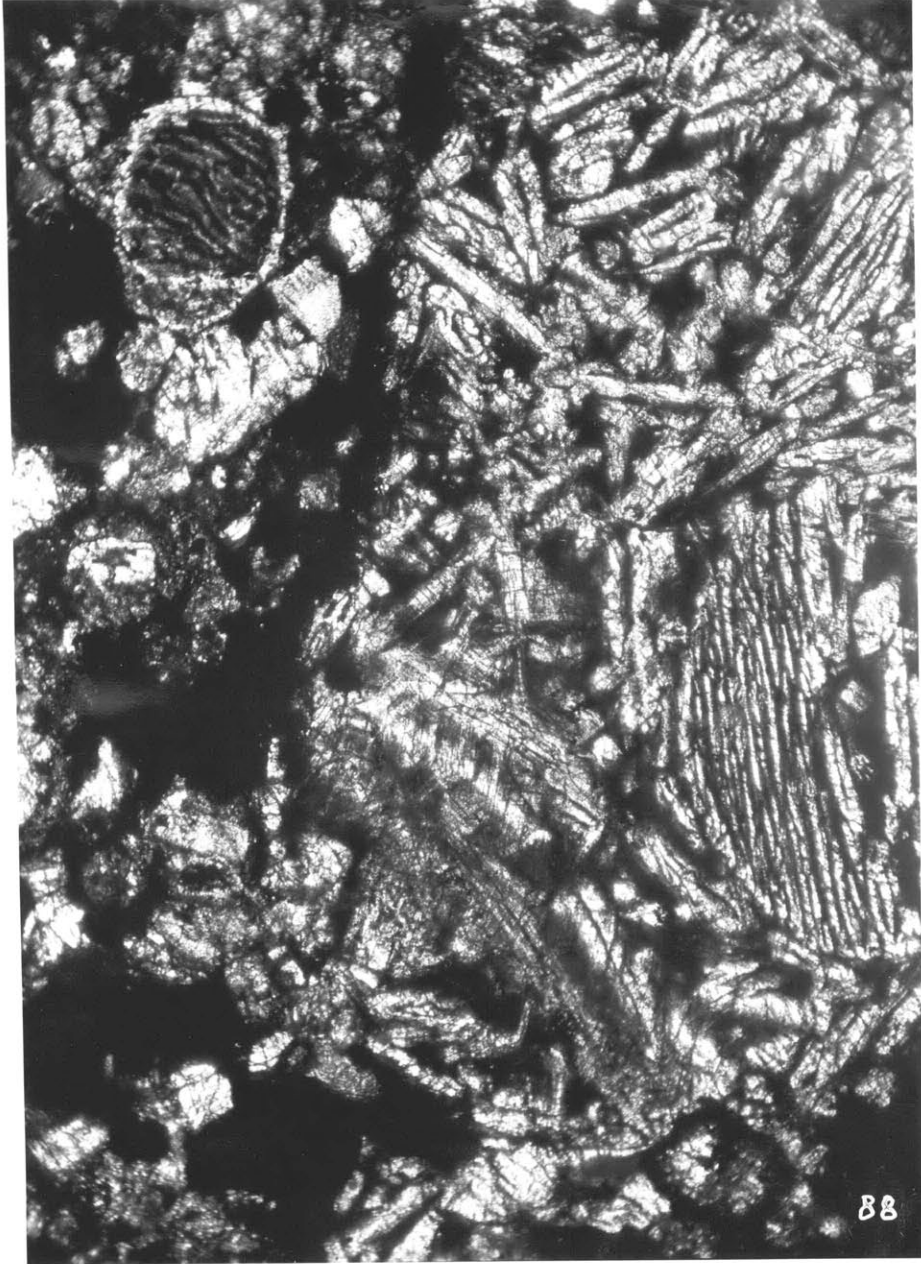
in photograph



## Chondrules:

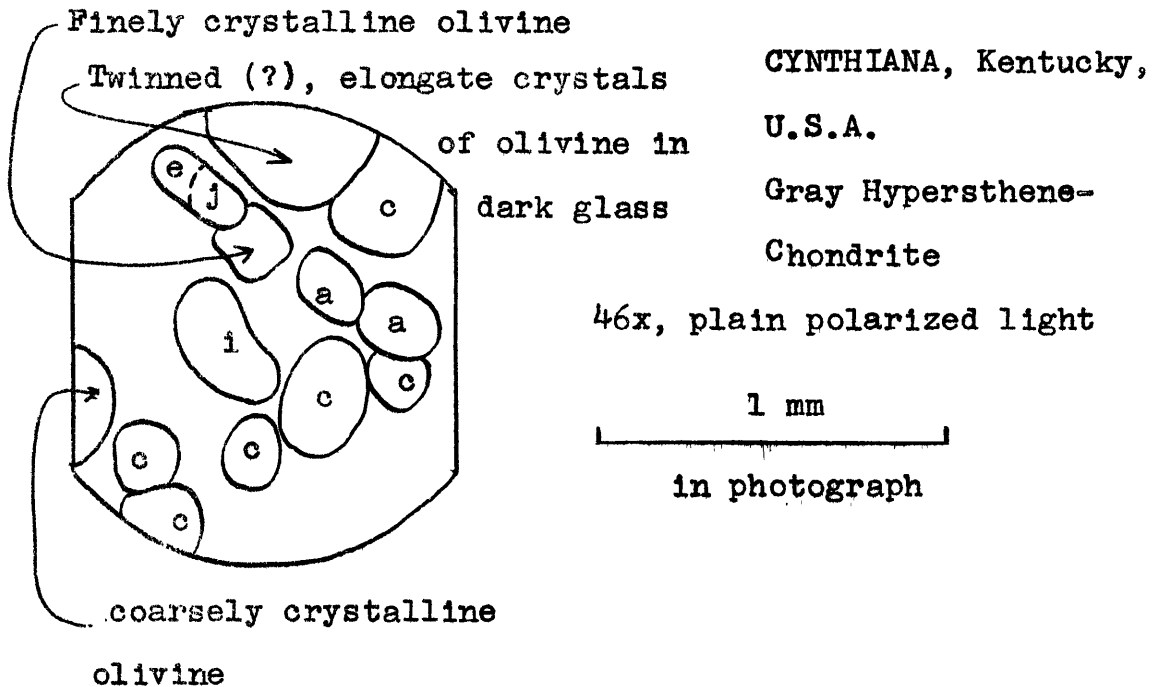
- a. Barred olivine in dark glass matrix.
- i. Coarsely crystalline orthopyroxene.
- j. Barred olivine with optically continuous rim.

$a_1$  indents  $a_2$  from the right. The olivine 'bars' in  $a_2$  retain a rough parallelism at the top of the chondrule -- perhaps  $a_2$  (still plastic) was developing into a normal, parallel barred olivine chondrule until  $a_1$  (completely solidified) collided with it. Major opaque areas are metal grains, minor ones do not reflect light.





## Plate IV

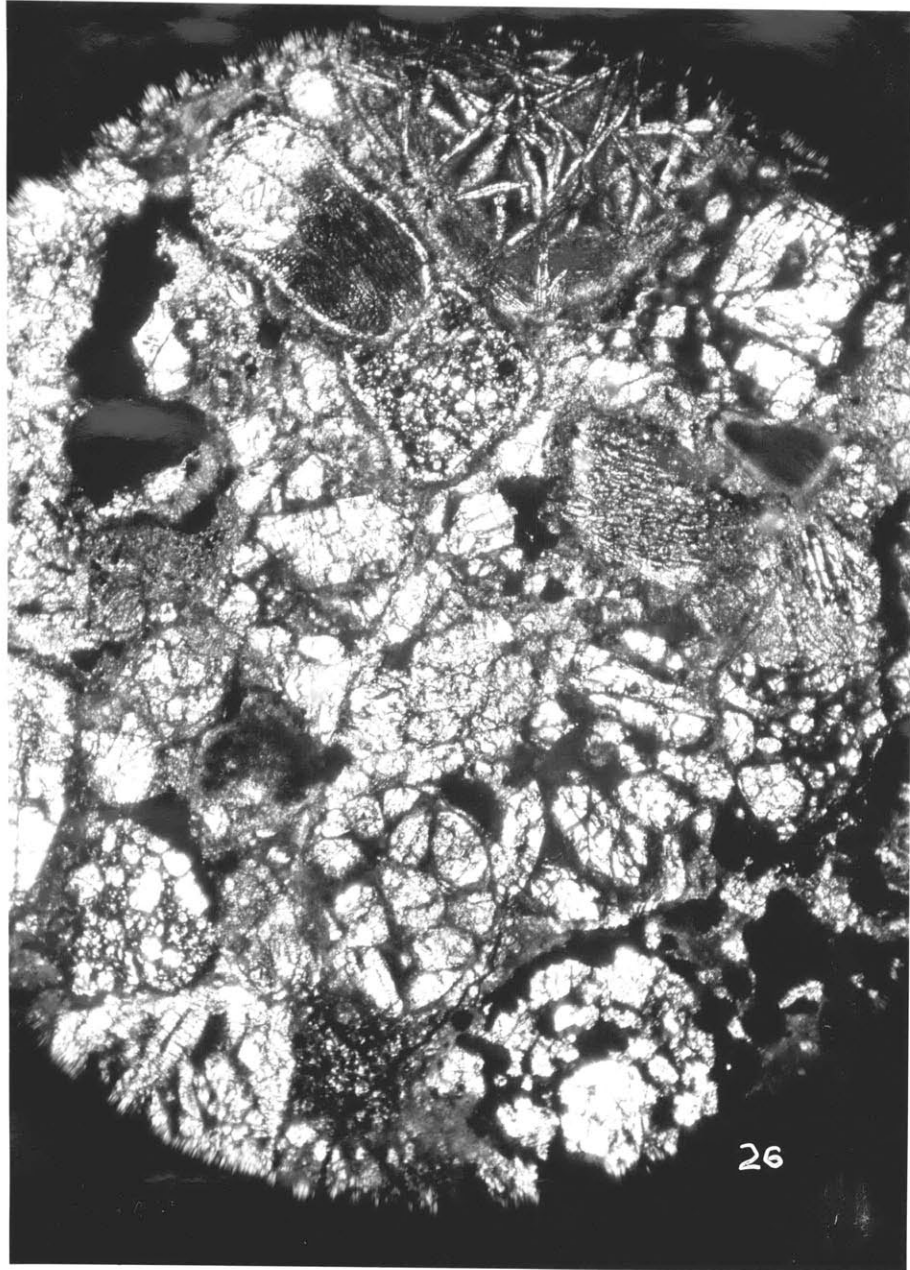


## Chondrules:

- a. Barred olivine in dark glass matrix.
- c. Olivine phenocrysts in dark glass matrix.
- e. (2) Olivine single crystals.
- i. Coarsely crystalline orthopyroxene.
- j. Barred olivine with optically continuous rim.

Chondrules are moderately distinct; one is clearly seen to indent another. Major opaque areas are nickel-iron.

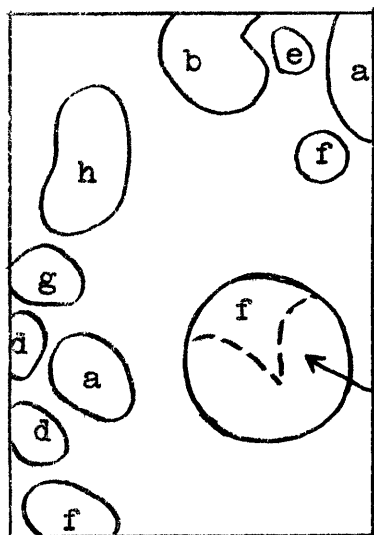
19



26

## Plate Va.

TIESCHITZ, Czechoslovakia  
Spherical Hypersthene-Chondrite.  
46x, plain polarized light.



1 mm

in photograph

olivine?

Chondrules:

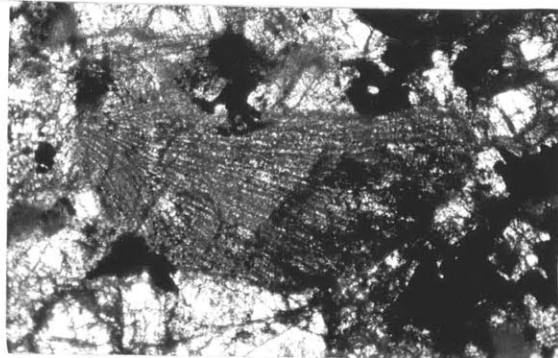
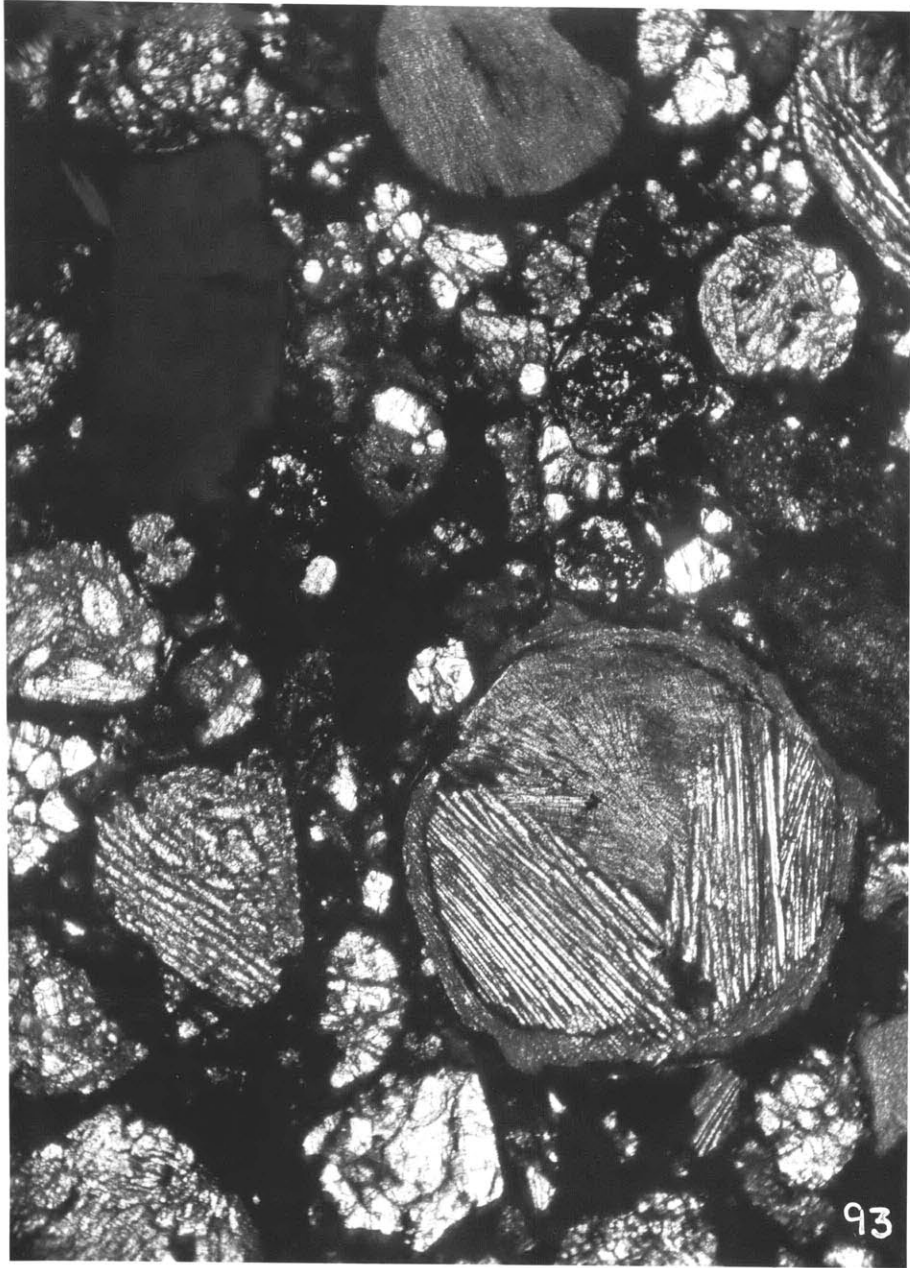
- a. Barred olivine in dark glass matrix,
- b. Very fine radiating orthopyroxene.
- d. Olivine and orthopyroxene phenocrysts in dark glass matrix.
- e. Olivine single crystal.
- f. Orthopyroxene "sheafs".
- g. Orthopyroxene phenocrysts in fibrous orthopyroxene matrix.
- h. Glass.

Chondrules form a very distinctly agglomeritic texture. The elongate crystals in the largest chondrule have the birefringence of olivine, but their crystal form is much more regular than any of the barred olivine crystals. Except for isolated grains of metal, opaque matrix does not reflect light.

## Plate Vb.

Fragment of radiating orthopyroxene chondrule.

PARNALLEE, India

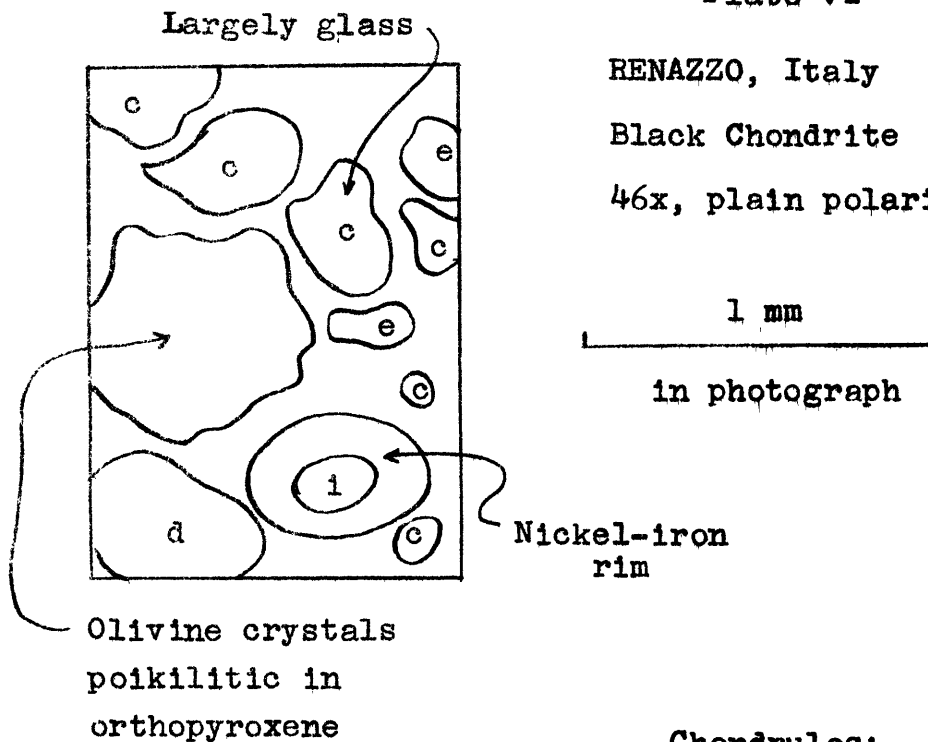


## Plate VI

RENAZZO, Italy

Black Chondrite

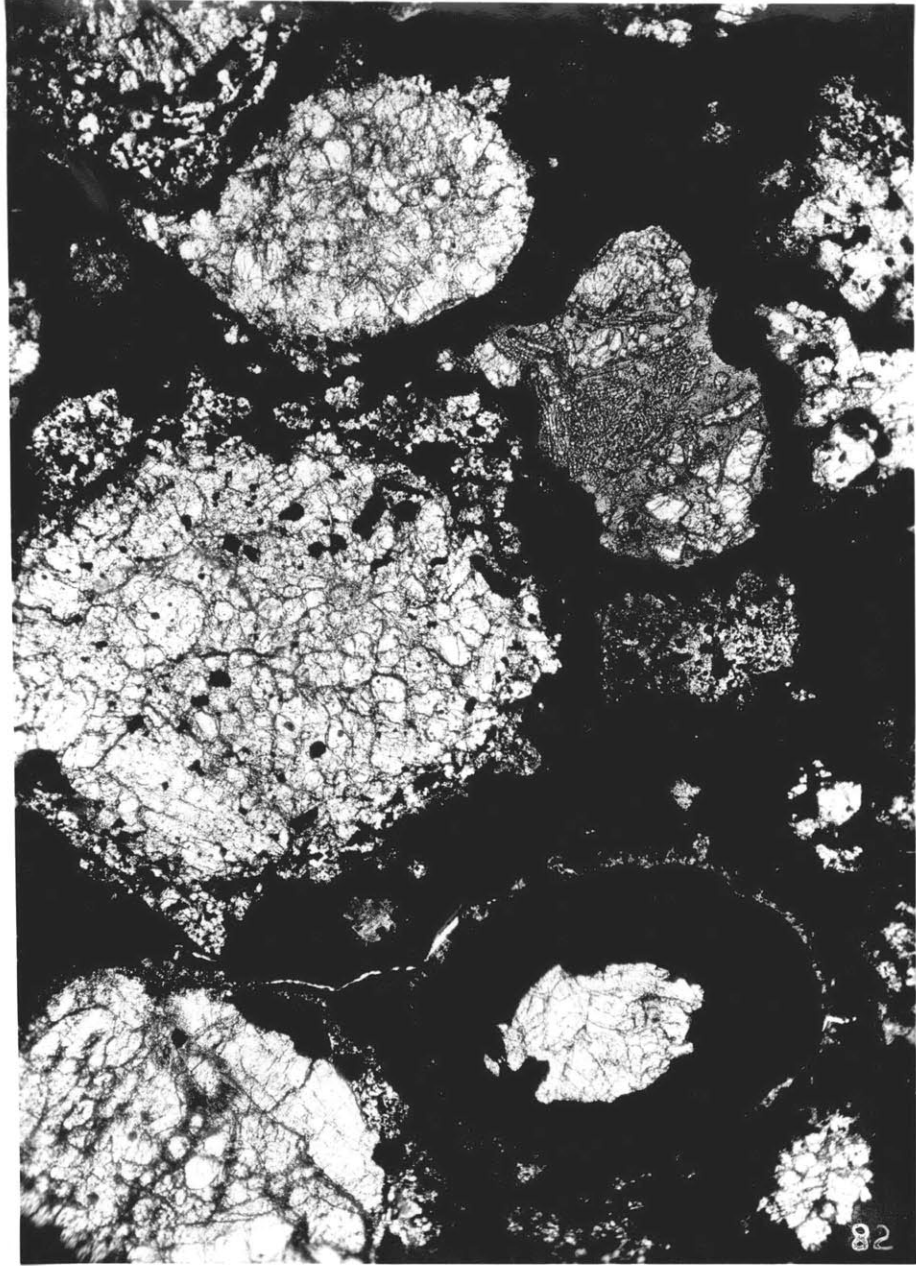
46x, plain polarized light



## Chondrules:

- c. Olivine phenocrysts in dark glass matrix.
- d. Olivine and orthopyroxene phenocrysts in dark glass matrix.
- e. Orthopyroxene single crystals.
- i. Coarsely crystalline orthopyroxene.

Chondrules form a very distinctly agglomeritic texture. They are unusually irregular in shape. Metal occurs as grains, and rimming silicate chondrules; otherwise, the opaque matrix is non-reflecting.



## TYPES OF CHONDRULES

(Most common; make up the bulk of chondrites)

- a. Barred olivine. Parallel elongated olivine crystals in a matrix of dark glass. Not necessarily optically continuous.
- b. Radiating orthopyroxene. Fibrous hypersthene, bronzite or enstatite radiating from a point usually at the edge of the chondrule. Extinction parallel to the fibers.
- c. Euhedral olivine phenocrysts in a matrix of dark glass.
- d. Olivine and orthopyroxene phenocrysts in a matrix of dark glass.

(Less common)

- e. Single crystals, usually of olivine.
- f. A collection of "sheafs" of orthopyroxene fibers, each "sheaf" being near optical continuity.
- g. Porphyritic orthopyroxene in a matrix of dark glass or fibrous orthopyroxene.
- h. Glass, sometimes devitrified.
- i. Entirely orthopyroxene, in several crystals.
- j. Barred olivine surrounded by a rim of olivine; the whole optically continuous. Dark glass between the bars.
- k. Olivine phenocrysts, fibrous orthopyroxene and glass.

Examples of these types of chondrules may be seen in Plates I. - VI. Key letters used in the captions refer to the preceding list of chondrule types.

In Plates III. and IV., instances are seen where one chondrule indented another while one or both were plastic. Vb. shows a broken chondrule; these are common, especially among the radiating orthopyroxene type. Chondrules have been reported (Farrington, 1915) which contained smaller chondrules.

Metallic iron, containing 6 to 20% Nickel, occurs in many forms in the chondrites. The black matrix in Plates Va. and VI. contains finely disseminated iron, but does not consist entirely of it. Plate VI. shows a large chondrule containing small grains of iron. In Plate I, a vein of metallic iron is seen. Iron also occurs as discrete chondrules (Plate II.), and as shells of varying thickness enclosing silicate chondrules (Plate VI.). Regular forms more or less resembling crystals are occasionally observed (Farrington, 1915).

Troilite (FeS) is present in chondrites in the form of small, scattered, irregular grains, bearing no relation to the structure of the chondrules.

Other minerals occur in small amounts in the chondrites. These are listed in Table 2.



Table 2.

## Minor Chondritic Minerals

Name	Composition	Crystal System	Occurrence
Clinopyroxenes esp. augite, hedenbergite	Mg, Fe, Ca, Al meta- silicates	monocl.	Accessory constituent in some chondrites.
Feldspar	Na, K, Ca aluminum silicates	tricl., monocl.	Crystalline anorthite sometimes seen; chon- drules entirely of anorthite have been reported. Other feld- spars are inferred from alkali content of bulk chemical analyses.
Tridymite	SiO <sub>2</sub>	hex.	Reported to occur in Fisher.
Apatite	Ca <sub>5</sub> (F, Cl)(PO <sub>4</sub> ) <sub>3</sub>	hex.	Rare; small grains.
Merrillite	Na <sub>2</sub> Ca <sub>3</sub> P <sub>2</sub> O <sub>9</sub>	hex?	More common; found only in stony mete- orites.

Name	Composition	Crystal System	Occurrence
Oldhamite	CaS	isom.	Small grains in some enstatite chondrites; has not been found on earth.
Schreibersite	$(\text{Fe}, \text{Ni}, \text{Co})_3\text{P}$	tetr.	In iron meteorites; thought to also be in stones, accounting for P in the analyses. Reacts with O to form phosphate; hence not known on earth.
Diamond	C	isom.	Observed in Carcote, a crystalline bronzite chondrite (von Sandberger, 1899).
Amorphous Carbon	C	--	Permeates the class of carbonaceous chondrites; forms 2-4.5% of their mass.
Graphite	C	hex.	In minute grains, especially in the

Name	Composition	Crystal System	Occurrence
Hydrocarbons	compounds of C,H,O,S; resemble terrestrial bitumens, petroleum, oxygenated hydrocarbons.	--	carbonaceous chondrites Principally in carbonaceous chondrites, but present in small amounts in some other chondrites.
Chlorite	$Mg_5(Al,Fe)(OH)_8(Al,Si)_4O_{10}$	monocl.	Recorded in Staroe Boriskino and Mighei, both carbonaceous chondrites (Zavaritzky, 1952).
Calcite	$CaCO_3$	hex.	Staroe Boriskino (Kvasha, 1948)
Water	$H_2O$	--	In carbonaceous chondrites; driven off by heating to 100°C. Probably partly in combination (e.g. $Fe(OH)_3$ ).

Relatively few of the chondrites have the distinct chondrules-and-fine-matrix texture referred to thus far, and illustrated best by Plates Va. and VI. Many more chondrites are of the type shown in Plate VII. Here a number of chondrules are plainly visible. But most of the chondrules, though recognizable as such, are indistinct, their boundaries blurred. Some of the crystalline matter in the photograph bears no obvious relation to chondrules.

Plates VIII. and IX. illustrate an equally abundant type of chondrite texture. Here the chondrules are extremely sparse, and their outlines even more indistinct. Except for such isolated chondrules, the textures of these chondrites are quite regular and homogeneous, resembling terrestrial crystalline rocks.

All gradations exist between the textures illustrated in these photographs, from the wholly chondritic texture of Tieschitz and Renazzo to stones completely devoid of chondrules, such as in the photograph of Khairpur (Plate X.).

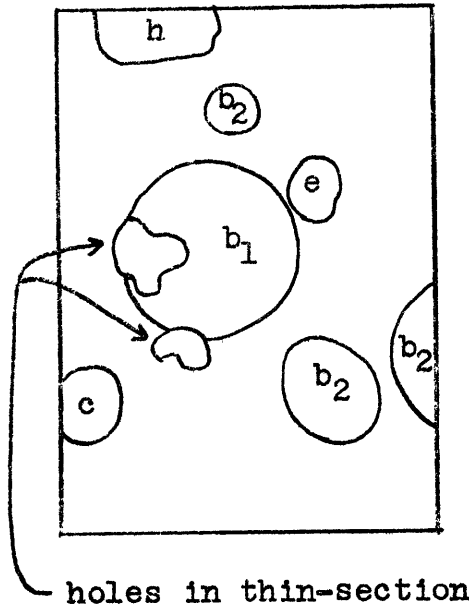
3. Chemical Compositions. The chondrites have long been known to be remarkably uniform in chemical composition. This can be seen in Fig. 2. A large number of chondrites have been analyzed, and the analyses have recently been critically evaluated by Urey and Craig (1953). Their average of the acceptable chondrite analyses is as follows.

## Plate VII

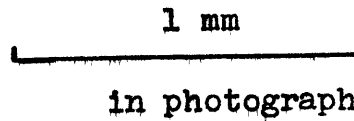
YATOOR, India

Spherical Chondrite.

46x, plain polarized light.



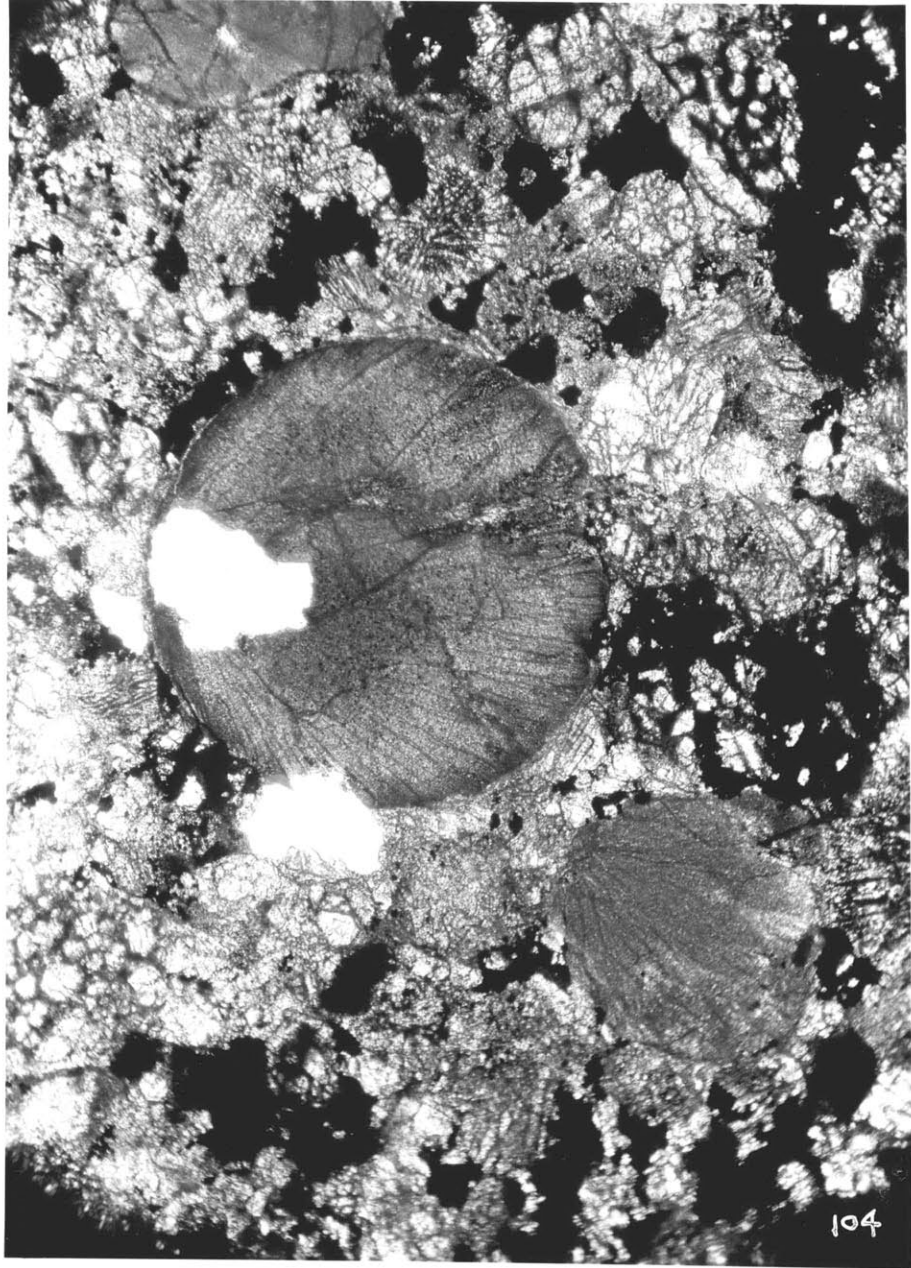
holes in thin-section



Chondrules:

- b<sub>1</sub>. Very fine radiating orthopyroxene.
- b<sub>2</sub>. Coarser radiating orthopyroxene.
- c. Olivine phenocrysts in dark glass matrix.
- e. Olivine single crystal.
- h. Devitrified glass.

Here distinct chondrules, demonstrating the perfect sphericity sometimes attained, are mingled with substantially recrystallized chondrules and matrix. Opaque areas are almost entirely nickel-iron grains.

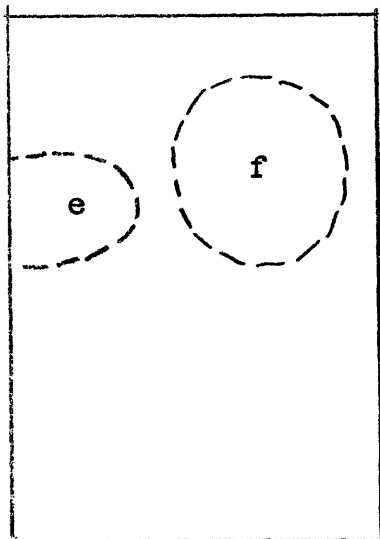


## Plate VIII

MILENA, Yugoslavia

White Chondrite

46x, plain polarized light.



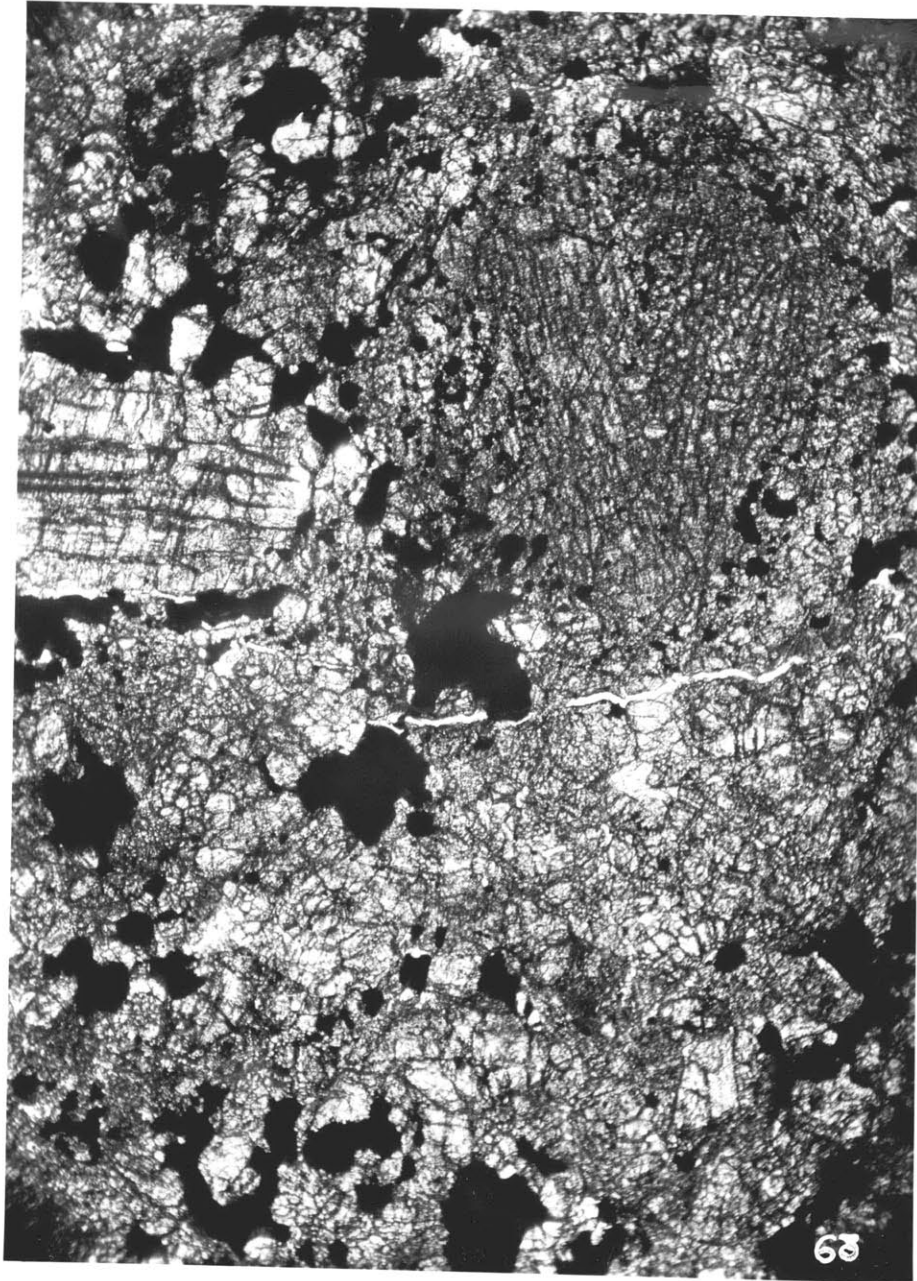
1 mm

in photograph

## Chondrules:

- e. Relict olivine single crystal chondrule. Note surrounding grains of metal.
- f. Relict orthopyroxene "sheafs" chondrule.

The chondrite is highly recrystallized. Most of the coarse grains comprising the granoblastic texture are olivine. Opaque areas all appear to be metal.



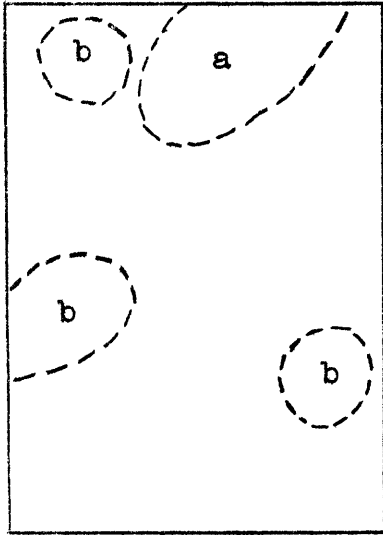


## Plate IX.

LISSA, Czechoslovakia

Veined White Hypersthene - Chondrite.

46x, plain polarized light



1 mm

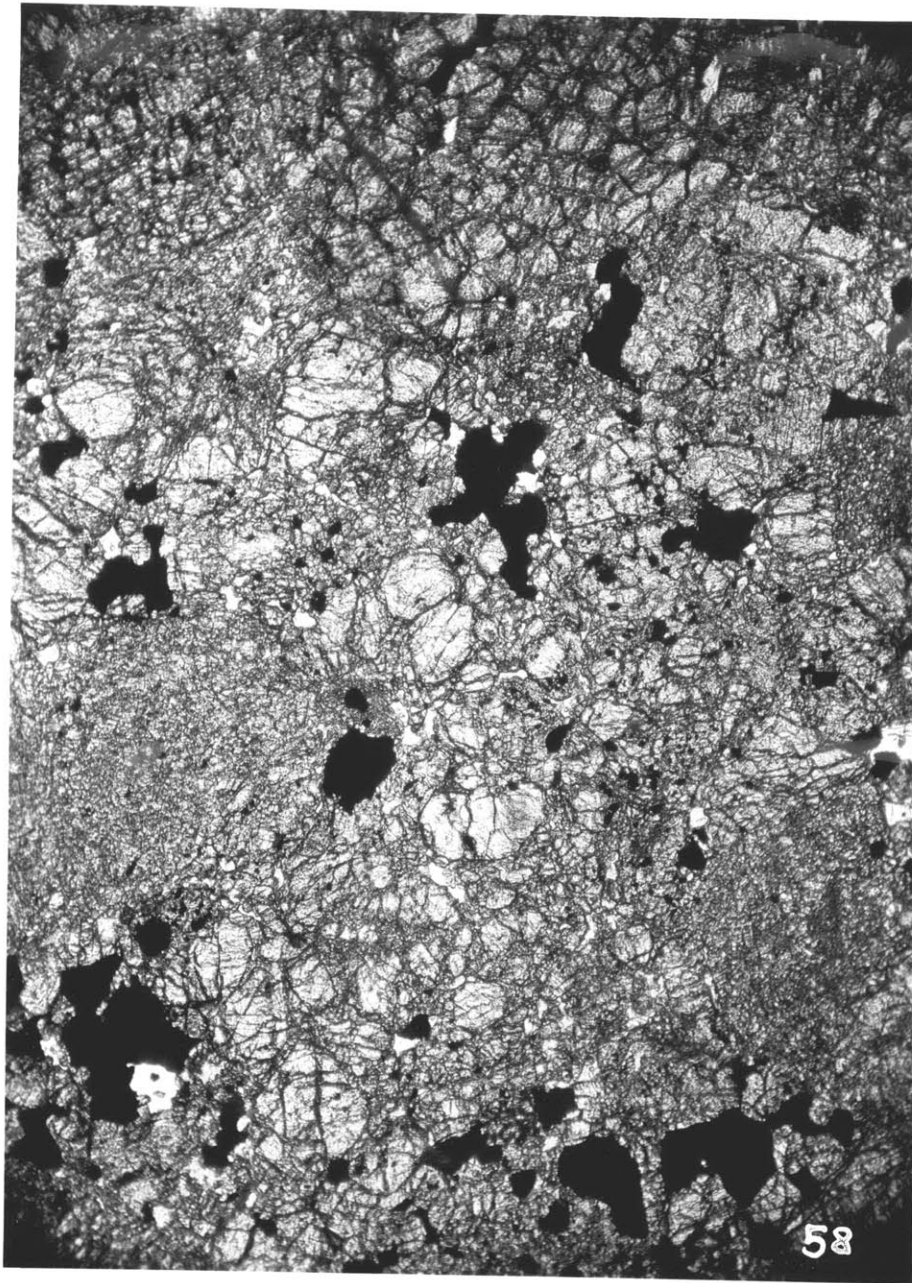
in photograph

## Chondrules:

- a. Relict barred olivine.
- b. Relict radiating orthopyroxene.

A highly recrystallized chondrite. Coarse grains in the matrix are mostly olivine. The opaque areas are usually metallic, but a few do not reflect light.

35



## Plate X.

KHAIRPUR, Pakistan

Crystalline enstatite-chondrite

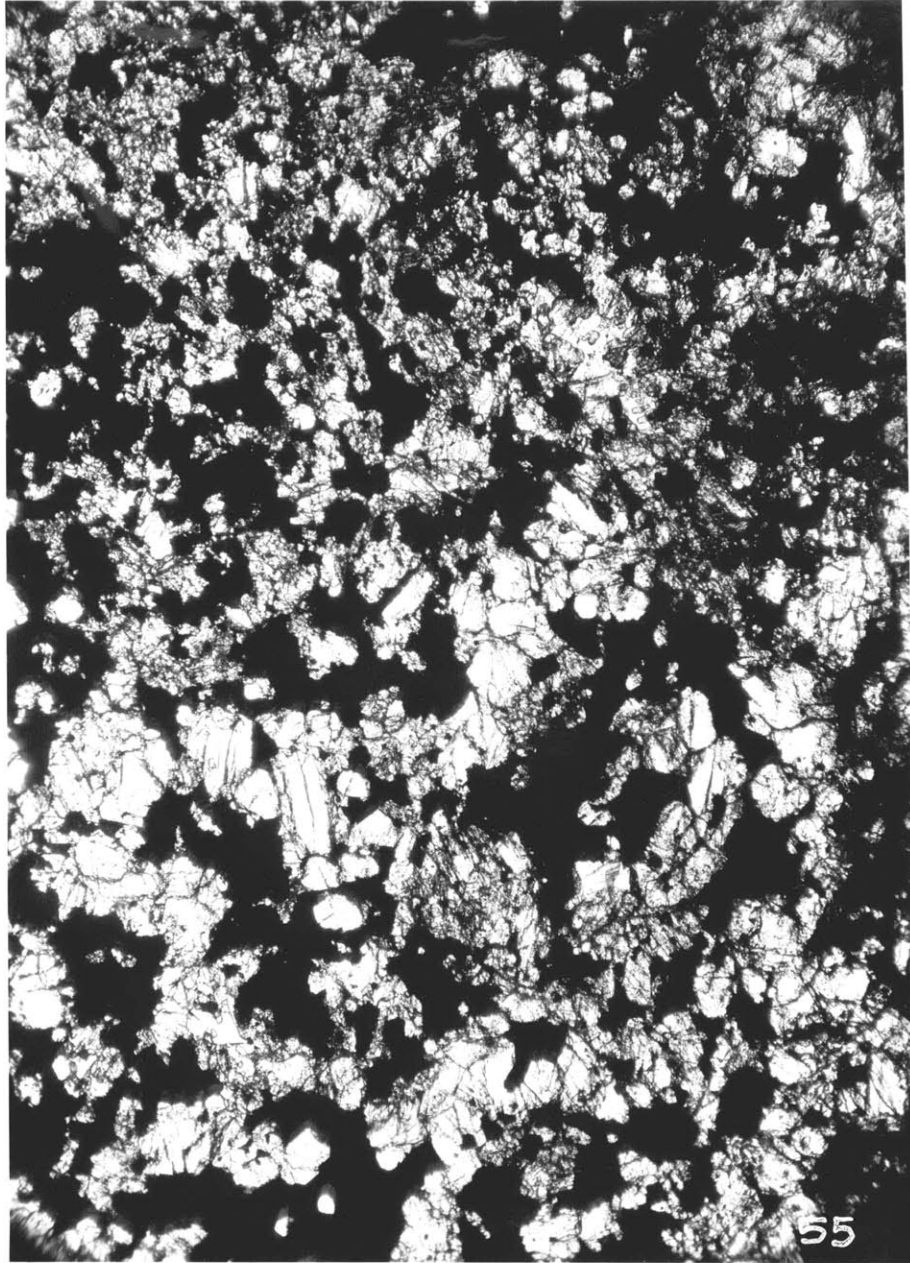
46x, Plain polarized light

1 mm.

---

in photograph

The silicate mineral is largely enstatite, with some forsterite. The texture is quite uniform. No chondrules can be seen in the section. About 50% of the section is opaque, but only about half of this reflects light.



	SiO <sub>2</sub>	38.04%
	MgO	23.84
	FeO	12.45
	Al <sub>2</sub> O <sub>3</sub>	2.50
	CaO	1.95
	Na <sub>2</sub> O	0.98
	K <sub>2</sub> O	0.17
	Cr <sub>2</sub> O <sub>3</sub>	0.36
	MnO	0.25
	TiO <sub>2</sub>	0.11
	P <sub>2</sub> O <sub>5</sub>	0.21
metallic	( Fe	11.75
	( Ni	1.34
	( Co	.08
sulfide	( Fe	3.64
	( S	2.09
	H <sub>2</sub> O	0.25

Except for its content of metallic iron and troilite, the average chondrite composition corresponds to a terrestrial peridotite (harzburgite). The average density of the chondrites is 3.58.

Little is known of the chemical compositions of individual phases in the chondrites (Smith, 1950). A detailed study of the compositions of discrete mineral grains from a

number of chondrites by x-ray, optical spectrographic or index of refraction by the immersion method, might reveal important relationships.

On comparing a number of bulk analyses of chondrites, it is seen that there are interesting systematic variations in the iron content. Iron occurs in three forms in chondrites: metallic iron, iron silicates (oxidized), and iron sulfide (troilite). Chondrites all have about the same content of sulfur, and approximately all of this is in the form of troilite.

But the (metallic plus silicate) iron varies, and in such a way that as total iron increases, silicate iron decreases (Prior's 'law'). This tendency was investigated by Urey and Craig (1953), who plotted (metallic plus sulfide) iron versus silicate iron. They found, not a continuous variation of iron content over a range, but two distinct concentrations of points, as in Fig. 1.

These two types of chondrites are referred to as the 'low' and 'high' (total) iron groups. They contain the following average weight percentages of elemental iron (Urey, 1957):

	Metal	Sulfide	Silicate	Total
Low iron group	7.04	3.66	11.63	22.33
High iron group	17.76	3.62	7.20	28.58

It has been suggested that chondrites contain more or less constant amounts of iron, which have been either oxidized or reduced to varying degrees. This may be checked by comput-

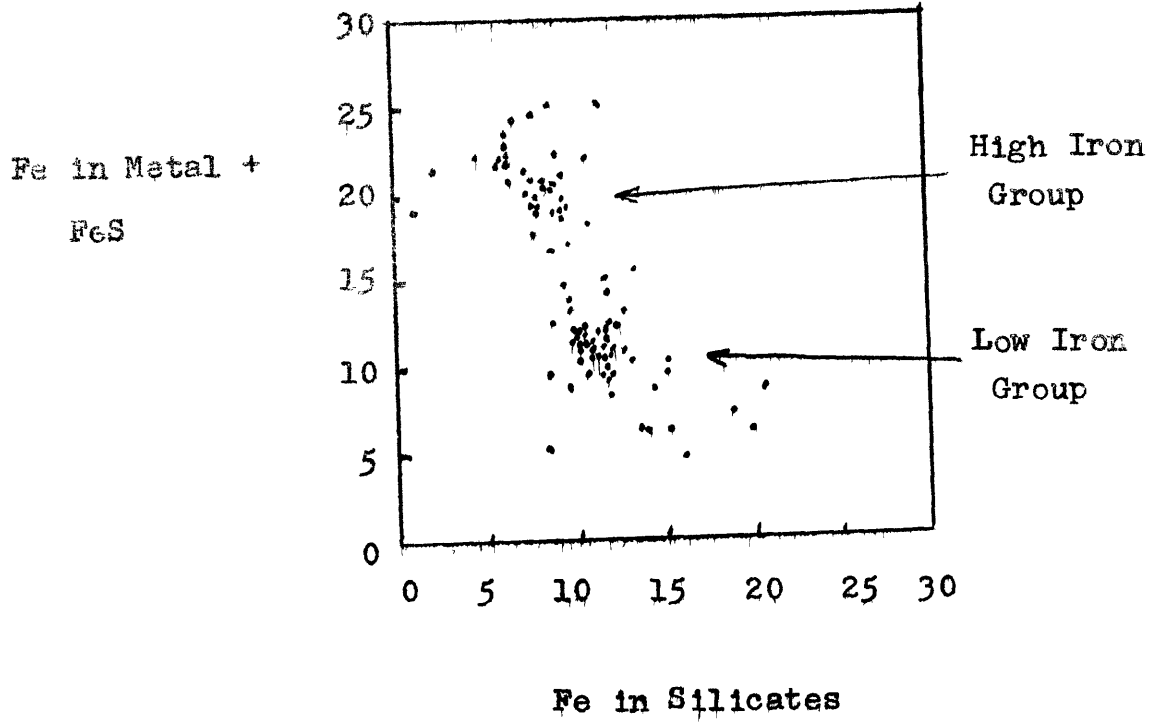


Figure 1. The Iron Groups (Urey and Craig, 1953)

ing the compositions of the two groups on the basis of atomic elemental abundance per Si atom; Fe/Si for the two groups should be nearly the same, the only substantial variation being in the ratios O/Si. In Table 3, this is seen not to be the case (Urey and Craig, 1953).

Table 3

## Average Atomic Abundances of the Elements in Chondrites\*

	Low Fe	High Fe	Average Chondrite
O	$3.48 \times 10^6$	$3.39 \times 10^6$	$3.44 \times 10^6$
Si	$1.00 \times 10^6$	$1.00 \times 10^6$	$1.00 \times 10^6$
Mg	$9.25 \times 10^5$	$9.46 \times 10^5$	$9.34 \times 10^5$
Fe	$6.06 \times 10^5$	$8.42 \times 10^5$	$7.12 \times 10^5$
Ni	$2.74 \times 10^4$	$4.76 \times 10^4$	$3.64 \times 10^4$
Co	$1.70 \times 10^3$	$2.84 \times 10^3$	$2.21 \times 10^3$
S	$1.00 \times 10^5$	$1.10 \times 10^5$	$1.04 \times 10^5$
Al	$7.92 \times 10^4$	$7.90 \times 10^4$	$7.91 \times 10^4$
Ca	$5.26 \times 10^4$	$5.84 \times 10^4$	$5.52 \times 10^4$
Na	$5.00 \times 10^4$	$4.87 \times 10^4$	$4.94 \times 10^4$
Cr	$8.59 \times 10^3$	$6.61 \times 10^3$	$7.70 \times 10^3$
K	$5.94 \times 10^3$	$5.95 \times 10^3$	$5.94 \times 10^3$
Mn	$5.66 \times 10^3$	$5.63 \times 10^3$	$5.64 \times 10^3$
P	$4.67 \times 10^3$	$4.39 \times 10^3$	$4.55 \times 10^3$
Ti	$2.20 \times 10^3$	$2.35 \times 10^3$	$2.27 \times 10^3$

\* Urey and Craig, 1953, (94 chondrites) and Wiik, 1956 (11 chondrites); except for oxygen, which is based only on Urey and Craig, 1953.



The only substantial variation is in the content of the transition metals -- Fe, Ni, Co.

#### B. IMPLICATIONS OF THE OBSERVATIONAL DATA

Some facts can be deduced or are, the writer feels, strongly implied by the preceding observational data.

1) Chondrites such as Tieschitz and Renazzo have the properties of terrestrial sedimentary rocks. They consist of small particles cemented by varying amounts of matrix material. The chondrules are mixed randomly with regard to mineralogy and internal structure, and are sorted in size to different degrees. The particles are nearly equidimensional, even round (but not generally as a result of mechanical abrasion; see 3) below). In these chondrites the matrix is relatively soft, so the chondrules would not break with the matrix. The writer, along with most others, will assume that these are sedimentary rocks (not necessarily water-laid).

2) Individually, the chondrules, or at least many of them, must have crystallized from a high-temperature silicate melt phase. Many chondrules contain unmistakable glass; others olivine and orthopyroxene in phenocrysts analogous to those in terrestrial lavas.

3) In order to obtain their spheroidal shapes, it seems necessary that the chondrules were suspended in some medium as droplets while they cooled. Occasionally the droplets collided and stuck while one or both was still plastic (as

seen in Seres, Cynthiana). Lacking any other possibility, the medium must have been either a gas, or free space.

The rounded shapes are not, in general, the result of mechanical wearing away, for the crystalline structure of some of the chondrules shows that they were spheroidal before they crystallized: those barred olivine chondrules surrounded by an optically continuous rim of olivine (see Seres), and many of the porphyritic chondrules, in which the phenocrysts nearest the surface tend to be oriented with their long axes parallel to the surface.

4) Those chondrites in which the chondritic structure is faint and obscure, such as Milena and Lissa bear close resemblance to terrestrial metamorphic rocks. By analogy with the process of metamorphism, we can predict the changes which would take place in a sedimentary chondrite (Tieschitz, Renazzo) if it were left for a long period of time in an environment of moderately high temperature and pressure. Phase changes would not be profound, since the olivine and orthopyroxene which constitute the bulk of the sediment are already high temperature phases. We would expect the glass, a metastable phase, to be rendered sufficiently mobile (through short range solid diffusion) by the heat to form stable crystalline minerals in time. If the olivine of chondrule A had a different MgO/FeO ratio than that of adjacent chondrule B, as might be expected in a sedimentary assemblage, metamorphism would

have the effect of destroying this difference. Equilibrium would be approached only when all the pyroxene in adjacent chondrules approached a uniform composition; similarly the olivine, and other phases.

Metamorphism would also have the effect of reducing textural inhomogeneity. Fibrous orthopyroxene, for example, because of its great surface to volume ratio, is a higher energy configuration than would be several large single crystals. In time, a chondrite, if its matter were made mobile enough by temperature, would seek a uniform texture, composed of relatively coarse, roughly equidimensional grains. The high-surface-energy chondrules would gradually fade away, leaving only the relict structures observed in Lissa and Milena, then perhaps disappearing altogether.

The changes described in the preceding two paragraphs are just what we observe in the more crystalline chondrites. It should be emphasized that they reflect slow recrystallization in the solid state, not remelting. They suggest, in fact, that a thermal gradient existed in the sedimentary sequence, just as it would if the sequence existed today on the earth or any other planet.

In summary, then, the textures and mineralogy of the chondrites strongly suggest the following sequence of events.

- a) The cooling of suspended molten silicate droplets
- b) Their deposition, along with finer matrix material, into a

thick sequence of sedimentary rock

- c) The imposition of a thermal gradient on the sequence, analogous to the geothermal gradient
- d) Recrystallization of the material low down in the sequence, and the attainment of mineralogical and textural equilibrium; consequently, partial erasure of the characteristic chondritic texture
- e) Ultimately, some form of catastrophic breakup of the sequence, leaving the debris (chondrites) in irregular orbits about the sun.

Two minor types of chondrites require additional consideration: the carbonaceous chondrites, and the enstatite chondrites. This will be deferred until part III.

Regarding the chemical observational data, the possibility should now be considered that the suggested sequence of chondrites was not homogeneous, but contained vertical variations in composition introduced either by the process of sedimentation, or by metamorphism. The latter involves shortrange chemical readjustments; the possibility of long-range chemical transport in a gravitational field should not be excluded. For example, Brown and Patterson (1948) assume that chondrites from the lower part of such a sequence would have higher contents of nickel-iron.

If the blurring and destruction of the chondrules is caused by geothermal gradient metamorphism; as the writer assumes,

then it should be possible to order roughly a group of chondrites as to the depth they once occupied, by making some measure of the degree to which the chondrules have been obliterated. This is not to say that absolute depths can be predicted, or that the function relating depth to obliteration is known; only that approximately, the less chondritic structure that can be seen, the more deeply buried was the chondrite.

With this in mind, the writer made integrating-stage measurements of thin sections\* of 34 chondrites for which reliable chemical analyses exist (Urey and Craig, 1953). The procedure was to scan the sections, recording on the integrating-stage the total distance traversed over chondrules, and the total distance over non-chondrules (crystalline silicate, opaque matrix). The "percentage chondritic structure" was then taken to be  $(\text{distance over chondrules}) / (\text{total distance})$ . Total traverse distance over each section was from 100 to 200 mm.

The technique is admittedly imperfect. A single thin section does not provide an adequate sampling of a chondrite.

\* The thin sections were from the Smithsonian Institution collection, and measurements were made in the U.S.N.M. laboratories. The writer is deeply indebted to Dr. E. P. Henderson for his help in this undertaking.

Table 4

## Percentage Chondritic Structure in 34 Measured Chondrites

Chondrite	Type*	Iron Group (Urey and Craig, 1953)	Percentage Chondritic Structure	Color**
Blithfield	Ce	-	0	s
Hvittis	Cek	(H)	0	s
Pillistfer	Cek	-	0	g
Oakley	Czk	H	2.8	s
Rich Mountain	Chia	L	5.0	g
Manbhoom	Amb	-	5.5	g
Djati-Pengilon	Czk	H	7.4	s
Lundsgård	Cgb	L	8.9	g
Mauerkirchen	Chw	(L)	11.2	w
Plantersville	Chwa	H	12.0	-
Cobija	Czk	H	12.4	s
Modoc	Chwa	L	12.4	w
Kernouvé	Czka	H	13.4	g
St. Michel	Chw	L	15.2	-
Chantonay	Chg	L	16.5	s
Coon Butte	Cgb	L	18.1	g
Crumlin	Chg	L	18.3	g
Mt. Browne	Czc	H	21.0	g
Hendersonville	Chc	(L)	27.3	-
Forksville	Chc	L	29.2	g

Chondrite	Type*	Iron Group (Urey and Craig, 1953)	Percentage Chondritic Structure	Color**
Kimble County	Chga	L	34.2	g
Olivenza	Chgc	(L)	35.0	i
Orgueil	K	-	36.4	s
Soko-Banja	Chcp	(L)	36.8	g
Beaver Creek	Czck	H	44.0	g
Forest City	Czcb	H	46.5	i
Indarch	Kc	-	56.6	s
Homestead	Czgp	L	57.8	g
Hessle	Czc	H	58.4	g
Felix	Khc	-	59.2	s
Mezö-Madaras	Chgp	L	64.0	g
McKinney	Chs	L	71.4	s
Shelburne	Chgap	L	74.5	-
Knyahinya	Chgp	H	84.7	g

\* According to Prior and Hey, 1953. Key:

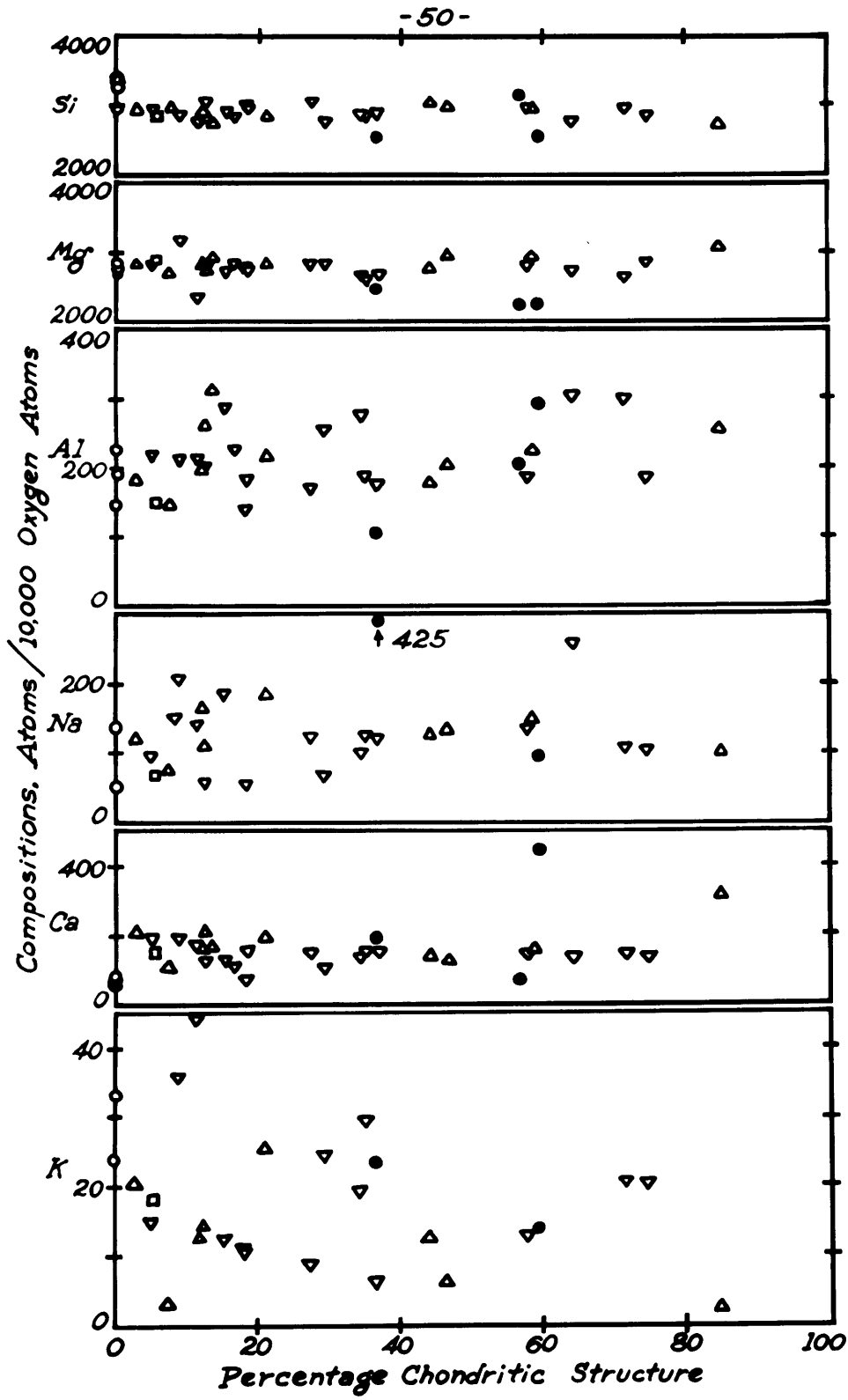
C - chondrite	w - white
K - carbonaceous chondrite	i - intermediate
Am - amphoterite (see Part II.)	g - gray
e - enstatite	s - black
h - hypersthene	a - veined
z - bronzite	b - monomict brecciated
c - spherical	p - polymict brecciated
k - crystalline	

\*\* By the writer. Same key.

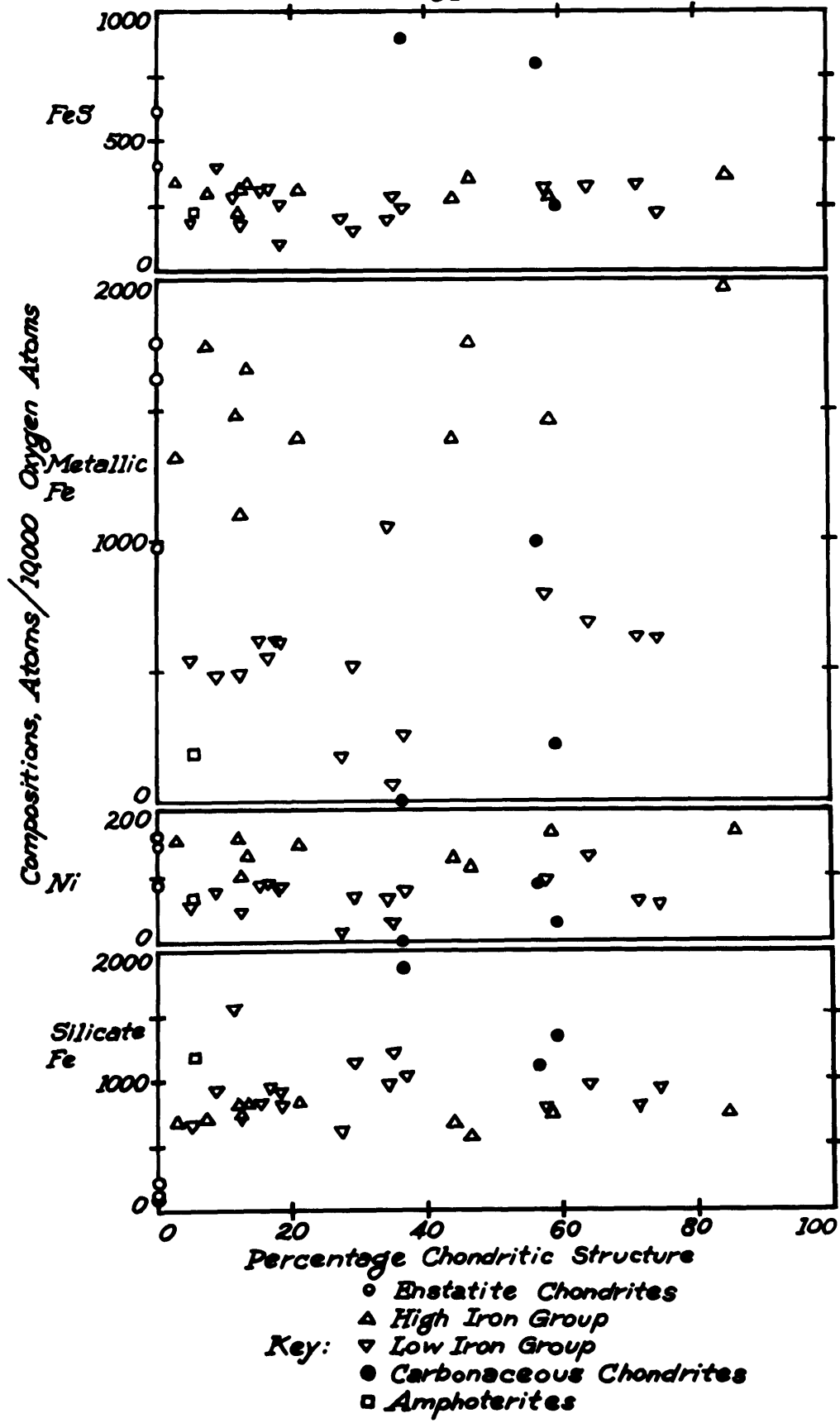
Chondrules show all stages of obliteration; deciding whether a particular area still exhibits relict chondrule structure becomes a somewhat subjective judgment. However, the measurements should serve to order the chondrites approximately; so that a plot of chemical composition versus percentage chondritic structure should indicate any gross, systematic variations in chemical composition, such as that assumed by Brown and Patterson. Results of the measurements are presented in Table 4.

Chemical compositions, in terms of atoms per 10,000 oxygen atoms, are plotted versus percentage chondritic structure in Fig. 2. The plots of Si, Mg, Al, and Na show small standard deviations and no apparent correlation between composition and inferred depth. The standard deviation is high for K (probably experimental error due to the small content of K), and again there is no correlation. Ca, FeS, and Fe<sup>++</sup> show systematic deviations from the mean for the three points representing the enstatite chondrites, but nowhere else. The standard deviation is small. The plot of metallic iron is wildly scattered. If any depth-composition correlations within the individual iron groups are present, a great many more points would be required to detect them. Clearly the iron group concept itself cannot be explained by different depth zones. Enstatite chondrites, carbonaceous chondrites, and amphoterites will be considered in Part III.





**Figure 2. Compositions Plotted  
Against Percentage Chondritic  
Structure**



It is of some interest to note the effect of depth and iron group on the classification of the chondrites. In Table 5. the qualifying adjectives used in classifying 28 of the chondrites are sorted into four boxes according to the two iron groups and "deep" or "shallow", for values of the percentage chondritic structure less or greater than 25 (the median) respectively.

No correlation was observed between veining or brecciation, depth, and iron group. Correlations are observed in the case of mineral, texture and color. The first two are trivial. By Prior's 'law' the high iron group chondrites have low iron silicate contents, hence are classed bronzite chondrites; for low iron group chondrites the reverse is true, making them hypersthene chondrites. The spherical chondrites are 'shallow' and the crystalline chondrites 'deep' because these were the properties measured in ordering the chondrites in the first place.

The colors plotted are those observed by the writer in examining hand specimens in the U.S.N.M. collection (Table 4), since the classifications in Prior and Hey neglect the color of about half of the chondrites. Blackness appears to be due to the metallic iron content of the meteorite, and to be brought out by recrystallization (except in the case of carbonaceous chondrites, not included in this plot). Perhaps this is because much of the metallic iron in 'shallow' chon-

PREDOMINATE NORMATIVE MINERAL

TEXTURE

Low Fe	High Fe
z hhhhhhh	zzz h
hhhhh	e zzzzz h

'Shallow'

'Deep'

Low Fe	High Fe
cccc	k ccc
	kkkkk c

COLOR

'Shallow'	1 ggggg s	1 ggg
'Deep'	ww gggg s	gg ssss

Table 5.

Chondrite Classification, Depth and Iron Group

drites is in the form of fine grains within the chondrules, hence is not brought to view on a broken surface when the chondrules do not break with the matrix. Recrystallization destroys the chondrules, and tends to expose more metallic iron on broken surfaces.

Returning to our original purpose, however, it seems that the chemical observational data (Prior's 'law', the iron groups) are not related to depth of burial, and their explanation must be sought elsewhere.

5) Granted that the chondrites are agglomerations of initially molten droplets which cooled while suspended in a gas or vacuum, how did they come to be in this situation?

One possibility is that two bodies collided and disrupted, the energy of collision being so high as to melt most of the solid matter in the process. This concept, or modifications of it, has been suggested several times. Certainly many of the chondrules (i.e., glass) have cooled very rapidly, and none have required very long, since the grain size even in single crystal chondrules is small. A rather tumultuous process, such as this, seems called for.

The production of chondrules by this mechanism would be analogous to the violent ejection of molten lava from active volcanoes, where the droplets cool in the atmosphere and fall to form pyroclastic deposits. But the ash so formed does not stand comparison to meteoritic chon-

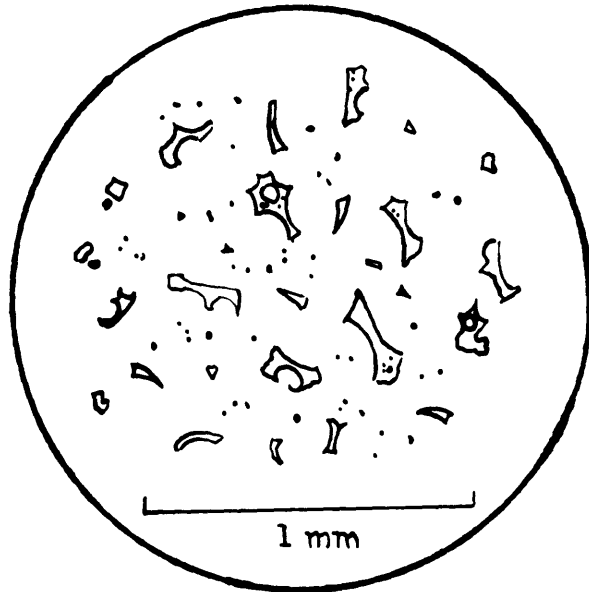
drules\*. Volcanic ejecta exhibit several properties not observed in chondrules.

Size distribution: active vulcanism produces ash ( $<4$  mm), lapilli (4 - 32 mm) and bombs ( $>32$  mm), all from molten lava hurled into the air. The largest chondrules are perhaps 30 mm, but these are very rare. A collision might have been expected to yield a wider range of particle sizes than those observed.

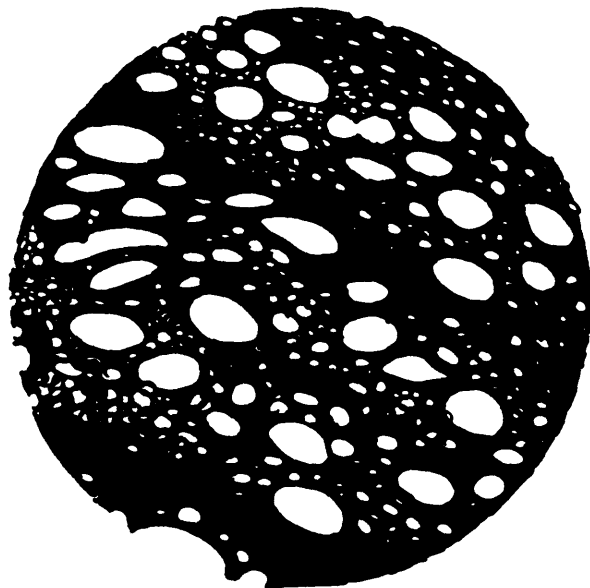
Shapes: the larger volcanic lapilli frequently are elongated and tortured in shape, like the filaments observed (along with drops) when a glass of water is thrown in the air. Basic volcanic ash sometimes takes the form of shards (Fig. 3a): angular glassy fragments with concave sides, from the shattering of vesicular pumice or scoria. These shapes are not observed among chondrules.

Vesiculation: This is perhaps the most striking discrepancy. Rock always contains a certain amount of occluded gas; the meteorites themselves contain sensible amounts. If a mass of rock is suddenly melted, the gas must be trapped in it, either in bubbles or in solution. When pressure is released suddenly, the gas in solution exsolves, and the melt becomes charged with bubbles. This produces the spongy, scoraceous consistency observed in volcanic ejecta. (Fig. 3b). Bubbles are never observed in chondrules.

\* In this connection, the writer considers only the type of chondrule composed entirely of glass, which should best be able to stand comparison.



a. Shards, produced by shattering of glass charged with gas bubbles



b. Scoraceous texture (section, to scale)

FIGURE 3. TERRESTRIAL VOLCANIC TEXTURES

Even if we assume the colliding planets were for some reason free of occluded gas, such a collision must have produced local superheating above the desired liquid state, so that in places boiling occurred. Again bubbles would be produced -- some few chondrules would surely still contain a bubble or two when they froze.

Without claiming that the above considerations completely rule out the possibility of chondrules formed by collision and melting, the writer would prefer to investigate the alternative possibility. This is that the chondruler condensed from a hot vapor into liquid droplets suspended in the vapor, then cooled into solid particles. Here we would not expect the droplets to have the properties of volcanic ejecta, and in particular we would not expect them to contain bubbles.

The writer proposes that the hot vapor was the material of the gaseous nebula from which the sun formed; that the condensation of chondrules, and ultimately their agglomeration into planets, is a normal by-product of the condensation of main-sequence stars; and therefore that in the chondrules we see surviving 'planetesimals', members of the whirling disk pictured in the planetesimal hypothesis for the origin of the terrestrial planets.

To investigate this proposal, we must know something of the mechanics of stellar condensation, including the temperatures and pressures during the process; and the phase relations



applicable to meteoritic matter under these conditions.

C. SOLAR SYSTEM EVOLUTION AND THE CONDENSATION  
OF THE CHONDRULES

1. Currently considered hypotheses for the formation of the solar system.

a) H. Alfvén (1954) postulates that electrodynamic forces are at least as important as mechanical forces. He gives close attention to the satellite systems, and feels that their mode of origin is precisely analogous to that of the planetary system.

Alfvén's hypothesis is as follows: The solar system came into existence either after the formation of the sun, or during the terminal stages of the sun's formation. The presence of a massive, rotating central body, possessing a magnetic field above a certain minimal value, is essential.

Initially, the sun is surrounded by a vast cloud of ionized gas (radius of  $10^{17}$  cm). This ionization tends to prevent the fall of the gas toward the sun. As the gas gradually becomes deionized, the various elements, in order of decreasing ionization potential, are no longer retarded from gravitational infall. Three or four groups of elements may be so distinguished and form discrete clouds when they collapse. Each cloud will be stopped from further infall when it becomes heated by compression sufficiently to re-ionize. For the B-cloud, this is at a radius corresponding to the terrestrial

Table 6

Infalling clouds of matter which  
may be distinguished (Alfvén).

Cloud	Composition	Approximate Ionization Potential (ev)	Ultimately forms:
A (doubtful)	He, Ne	23	
B	H,O,N (He,Ne)	15	Terrestrial Planets
C	C,S	11	Major Planets
D	Fe, Si, Mg	8	Pluto and outward

planets; for the C-cloud, to the major planets.

After the fall of each cloud is so arrested, it begins to be rotationally accelerated by the magnetic field of the sun (at the expense of the initially high angular momentum of the sun). This causes the ionized clouds to be concentrated into rings in the plane of the ecliptic.

From the rings small droplets or grains condense, moving in Kepler orbits. These small bodies usually then aggregate into planets; an exception being the asteroid belt. Alfvén's detailed consideration of the acceleration and condensation processes provides explanations for the sizes and orbital radii of the planets and satellites.

The hypothesis requires that the sun possess a very high magnetic dipole moment. Zeeman effect measurements on the sun indicate that the dipole moment is not nearly this high, but Alfvén feels that a systematic error may exist which causes a much smaller Zeeman effect than that corresponding to the real field.

It is also required that the initial cloud be ionized, either by a high kinetic temperature, or by radiation from the already-formed sun.

The several clouds would not have the ideal compositions given in Table 1., but would be to some degree contaminated. The faster the initial cloud deionized, the greater would be the contamination. Still, the basic compositions of the clouds (Table 1.) are not in very good accord with what we know of the compositions of their respective planets.

b) In 1952, Harold Urey published The Planets, a long-overdue treatment of the physical chemistry of planetary formation.

His present hypothesis (1957) for the formation of the solar system is as follows: 'Primary objects', bodies of lunar size or greater, accumulated in a cold dust cloud. By some means melting occurred in the bodies, producing silicate and iron fractions; in the latter, diamond was later able to form. It is suggested that the heat required for melting might have been made available by the inclusion of free radicals (e.g. NH,

CH, OH), uncombined atoms, and certain molecules (e.g.  $H_2O_2$ ,  $N_2H_2$ ,  $C_2H_2$ ) in the accreting primary objects (Urey and Donn, 1956). Periodically, this material within the freshly accumulated layer of a body would react, releasing enough heat to melt part of the layer.

With formation of the sun and a solar nebula, collisions occurred among the primary objects, reducing them to fine (1 cm or less) debris. These collisions could have been brought about in two ways. If the primary objects already existed when the solar nebula was formed, the increasing gravitational field of the latter would attract them in (in eccentric orbits), and collisions would be frequent in the vicinity of the sun. On the other hand, if the primary objects accumulated in the already existing solar nebula, orbits would not be eccentric, nor collisions frequent. In this case, Urey postulates that Jupiter began to grow near the sun; its orbital velocity was accelerated by tidal friction with the sun (slowing the rotation of the latter). Consequently, Jupiter's mean distance increased to its present value; as the giant planet passed among the circling primary objects, it perturbed them into more eccentric orbits, promoting extensive collisions.

Thereafter, the planets and asteroids (secondary objects) as we know them accreted from the debris. Remaining dust and gas would be removed from the nebula by solar light pressure, and coarser material by the Poynting-Robertson effect. The

chondritic meteorites are fragments of several disrupted asteroids, still bearing an agglomeritic texture.

Urey's thought has been heavily influenced by meteoritic data. He has considered the chemical compositions of meteorites, thermodynamic equilibria of certain of the observed phases, some aspects of their textures, and the time-schedule imposed by recent isotopic dating. To meet all of these conditions, it was necessary to propose the rather involved mechanism of primary and secondary objects.

c) The hypothesis of C. F. von Weizsäcker is based on astronomical and gas dynamic observations and theory. The following summary and discussion are from Struve (1950).

All the stars have formed between 2 and  $6 \times 10^9$  years ago. Before this, there was only gas, in turbulent motion, and having a composition nearly the same as cosmic matter today. Small concentrations within the gas initiated condensations.

These condensing masses of gas each inherited some net angular momentum, and this is conserved as the masses shrank. Thus the angular velocity of a potential star increased with time, causing it to take on a nebular form.

At the outer rim of the nebula, gas was whirling at very nearly orbital velocity. In the dense core, material was spinning rapidly, the angular velocity being kept independent of radius by viscous friction. But between these two regions,

with their great difference in angular velocity, the gas was in turbulent motion, and tended to transfer angular momentum from the core to the rim. There, material was accelerated beyond escape velocity.

In time, the core shrank and heated up sufficiently to initiate nuclear energy generation. The central body still possessed too much angular momentum for secular stability, and continued to shed matter and momentum until a stable state (such as that of the sun) was reached.

Spectra thought to be caused by nebulae are actually observed, for example about the stars Pleione and 48 Librae. Further, the nebulae appear to be in turbulent motion. However, they are thought to have only about  $10^{-7}$  the mass assumed by von Weizsäcker.

Ter Haar has shown that if the central star rotated with an equatorial velocity of 100 km/sec, the drag of the gaseous nebula could dissipate only a small amount of its angular momentum. He suggests that interaction of the sun's magnetic field with interstellar ionized hydrogen might have braked an initially rapidly rotating sun to its present slow rate of rotation (about 2 km/sec), in the manner proposed by Alfvén.

Observational data relative to this process are presented in Table 7.

Table 7.

Stellar Rotational Velocities vs.  
Spectral Class (Struve, 1950)

Spectrum	<u>Equatorial Velocity (km/sec)</u>		Shell Spectra
	Average	Maximum	
Oe - Be	350	500	
O - B	94	250	always seen
A	112	250	sometimes seen
FO - F2	51	250	) ) ) ) ) never seen
F5 - F8	20	50	
dG(incl. Sun)	0	0	
dK	0	0	
dM	0	0	

The average age of the members of each spectral class increase downward in the table, according to current theories of stellar evolution. The shell spectra imply the existence of nebulae. It is seen that the young stars possess nebulae; possibly these cause slowing of rotational velocities between classes Oe - Be and O - B, as von Weizsäcker suggests. But it is also seen that rotational velocities continue to be braked after the stars have lost their nebulae (after class A).

As already noted, this braking may be the effect of magnetic interaction between the sun and interstellar hydrogen. Removing angular momentum from the sun has always been a stumbling block of solar system hypotheses. The process is

not of immediate consequence to the condensation of chondrules, however, since it occurs after the nebula has been removed, hence presumably after the chondrules have formed.

We will assume that the general concept of interstellar gas clouds condensing into stars is correct, and go on to investigate the conditions within the contracting cloud. Nothing will be said of the question of once initiating such a condensation. It will also be assumed that electrodynamic effects during the condensation are subordinate to mechanical forces.

2. Stellar Temperatures and Pressures. We will at first assume that the star is not rotating, and consists of a spherically symmetrical mass of gas in hydrostatic equilibrium. The temperature within such a mass will adjust itself so that pressure just balances gravitational attraction. The sphere shrinks and becomes hotter with time, transforming potential energy into heat and radiating it off.

Under such circumstances, if radiation pressure can be neglected, pressure and density are related by the adiabatic gas law

$$P = K\rho^\gamma . \quad (1)$$

If heat transfer in the body is solely by gas convection, we say it is in convective or adiabatic equilibrium; then

$$\gamma = \frac{C_p}{C_v} = \frac{5}{3}$$



for a sphere composed of an ideal monatomic gas. If heat transfer is entirely by radiation, the pressure-density relationship takes the (polytropic) form of (1) only if we assume the Eddington stellar model. In this case,  $\gamma = \frac{4}{3}$ .

Emden's equation (1907) expresses the relationship between temperature and radius in the sphere:

$$\frac{1}{x^2} \frac{d}{dx} \left( x^2 \frac{dy}{dx} \right) + y^n = 0, \quad \text{where}$$

$$x = \frac{x_0}{a} r \quad (a = \text{total radius; } x_0 = x_{T=0})$$

$$y = \frac{T}{T_c} \quad (T_c = \text{central temperature})$$

$$n = \frac{1}{\gamma - 1}$$

The British Association for the Advancement of Science (1932) has solved the equation by numerical integration for several values of  $n$ . Suffice it to say that for adiabatic equilibrium,  $T$ ,  $P$  and  $\rho$  decrease roughly linearly between the center and boundary of the sphere; for radiative equilibrium (the Eddington model), mass becomes highly concentrated in the center. The shape of the  $T$  curve does not change greatly. The latter configuration approaches that thought to exist in the sun.

We will consider only average pressure and temperature in the sphere (Aller, 1954). If we define average pressure by

$$\bar{P} = \frac{1}{M} \int_0^a P \, dMr ,$$

where  $Mr$  is the mass beneath radius  $r$ , it turns out that

$$\bar{P} > \frac{GM^2}{12\pi a^4} . \quad (2)$$

Similarly, if we define average temperature by

$$\bar{T} = \frac{1}{M} \int_0^a T \, dMr ,$$

and if we assume the perfect gas equation,

$$\bar{T} > \frac{GM\mu\beta}{6Ra} \quad (3)$$

where  $\mu$  is molecular weight,  $R$  the gas constant, and

$$P_{\text{radiation}} = (1 - \beta)P .$$

These equations give minimum temperatures and pressures. A more precise knowledge of these quantities requires that we know the relative effectiveness of radiation and convection in transferring heat, laws of energy generation, and applicable gas laws. The mode of energy transport, at least, will be changing during the stage of condensation in which we are interested.

If we assume conductive equilibrium, for example, we find that  $\bar{P}$  according to (2) is too small by a factor of about 3,  $\bar{T}$  by less than 1.5. These discrepancies are not excessive for our purpose, so (2) and (3) will be used to approximate the

properties of the condensing sun.

Taking

$$M = 2 \times 10^{33} \text{ grams (present solar system mass)}$$

$$\mu \approx 0.7 \text{ for completely ionized solar material}$$

$$\beta \approx 1 \text{ for all but the most massive stars, the}$$

approximate temperature-pressure curve of a condensing sun is plotted in Fig. 4.

3. Effect of rotation. Jeans (1929) has considered analytically the effect of rotation on various types of fluid bodies whose integrity depend on their own gravitational fields. He finds that as angular velocity increases, instability and disruption will come in either of two ways. If  $\gamma > 2.2$  (e.g. 'liquid' planets), the body will tend to become irregularly elongate perpendicular to the rotation axis, and at the critical velocity will separate into two bodies. If  $\gamma < 2.2$  (e.g. stars), however, acceleration of rotation will cause the body to become increasingly oblate, finally assuming a lenticular shape. At the critical velocity material begins to be shed from its equator.

In particular, Jeans treats the case of gaseous bodies in polytropic equilibrium. Here, the critical velocity is reached when

$$0.36 > \frac{\omega^2}{2\pi G \rho} > 0.31 \quad (4)$$

(for  $\gamma=1.2$ )                      (for  $\gamma=2.2$ )

(assuming that Boyle's law holds).

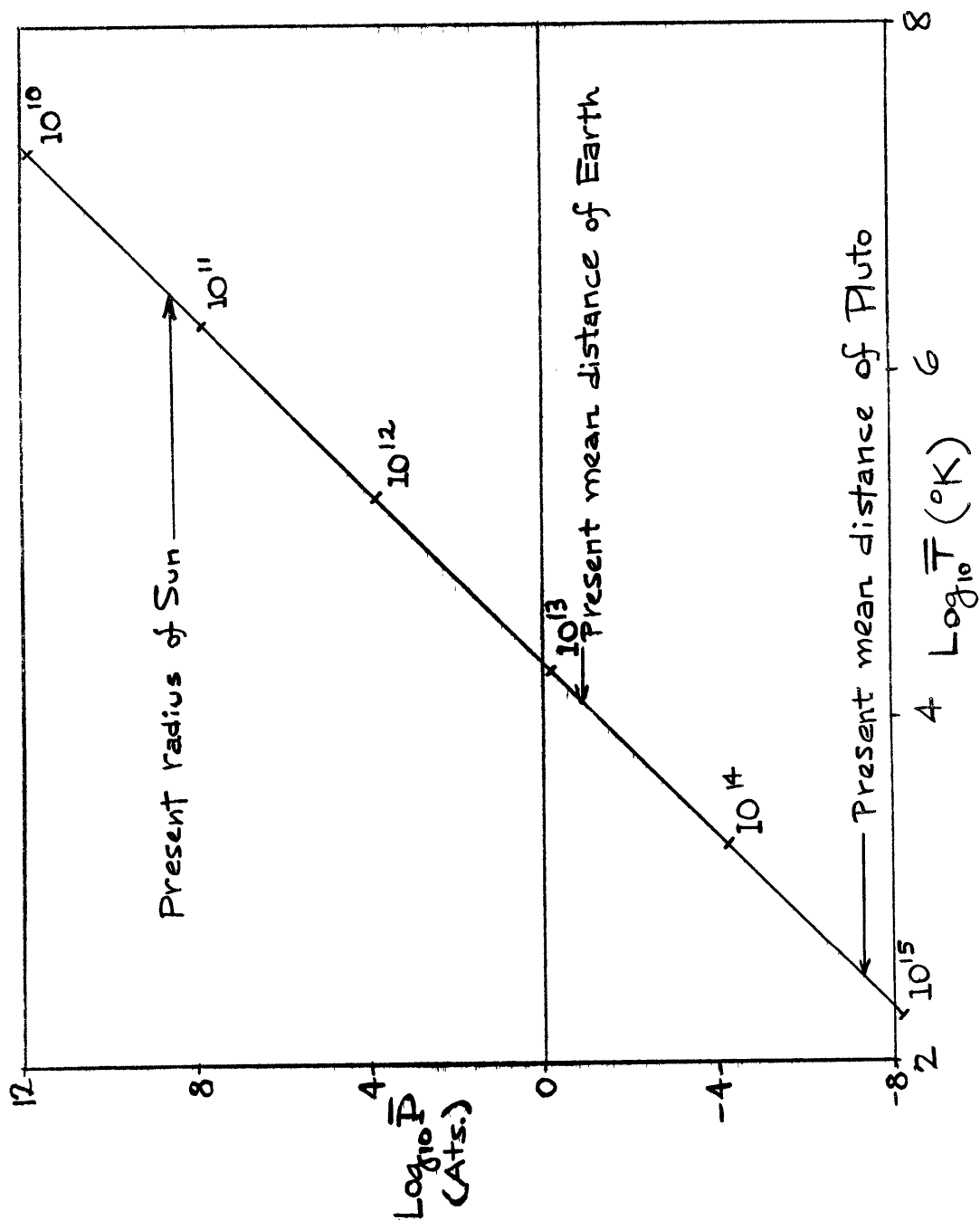


Figure 4. Average Pressure and Temperature in Contracting Gas Cloud, as a function of Radius (in cm.).

$$\gamma = \frac{5}{3}$$

To predict when the shrinking sun, accelerating because its angular momentum is conserved, began to shed matter around its equator, we need to know  $\omega(a)$  (angular velocity). Since

$$h = I_z \omega , \quad (5)$$

we require two quantities: the moment of inertia ( $I_z$ ) of a body in radiative equilibrium (anticipating that shedding did not begin until the sun became small and very hot), and the angular momentum ( $h$ ) of the system at that time.

The density distribution in an Eddington model star is shown in Fig. 5. Using the piecewise linear approximation also shown,

$$I_z = \frac{8}{3} \pi a^5 \int_0^1 \rho \left(\frac{r}{a}\right)^4 d \left(\frac{r}{a}\right) = 5.11 \times 10^{-3} \rho_c a^5 ,$$

( $\rho_c$  = central density), and

$$M = 4\pi a^3 \int_0^1 \rho \left(\frac{r}{a}\right)^2 d \left(\frac{r}{a}\right) = .084 a^3 \rho_c ,$$

from which

$$I_z = .069 M a^2 . \quad (6)$$

Table 7. indicates that stars have equatorial velocities of about 100 km/sec at the time their nebulae disappear. We will assume the sun to have once rotated at that rate, and that it has subsequently dissipated most of its angular momentum by some process not influencing the planets or planetesi-

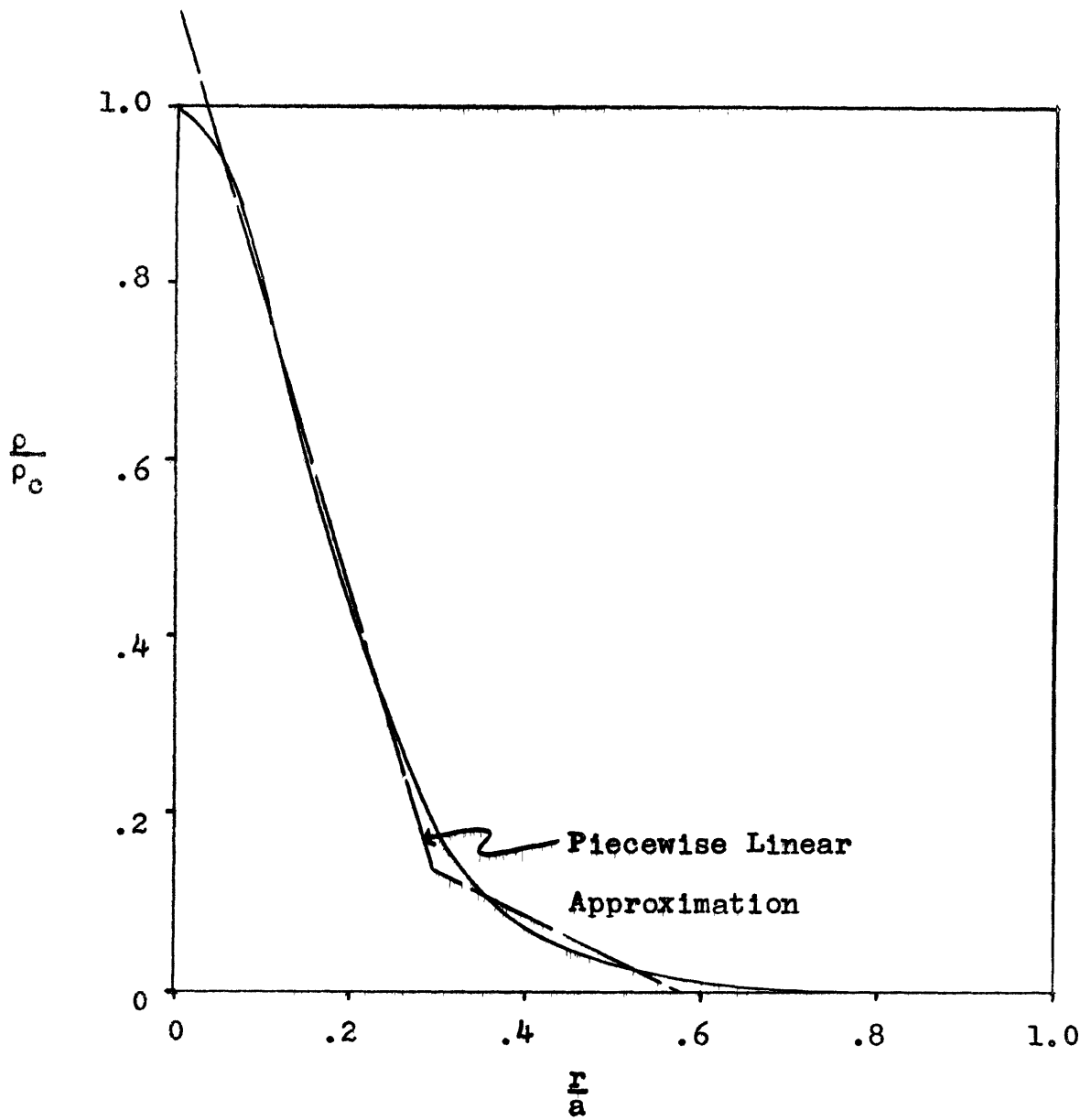


Figure 5. Solar Density, according to Eddington Model

mals (e.g., magnetic interaction with interstellar hydrogen).

For 100 km/sec,  $\omega = 1.43 \times 10^{-4}$ /sec, and  $h_{\text{sun}} =$

$I_z \omega \approx 10^{50}$  gm-cm<sup>2</sup>/sec. We assume the present day planets to contain virtually all the mass and angular momentum possessed by the nebula ( $3.24 \times 10^{50}$  gm-cm<sup>2</sup>/sec). Thus, we take the total angular momentum of the sun during its condensation to have been about  $4.24 \times 10^{50}$  gm-cm<sup>2</sup>/sec.

Approximating the moment of inertia of the rotating, lenticular star by that of a sphere of equal mass and equatorial radius (6), and using (4) and (5),

$$a_{\text{critical}} \approx 452 \frac{h^2}{GM^3} = 1.5 \times 10^{11} \text{ cm.}$$

Thus, we might expect that by the time the condensing sun reached approximately twice its present radius, it became rotationally unstable and began to shed matter around its equator. The shedding continued as long as the sun continued to decrease in size and increase in temperature. When nuclear energy generation, which is a sensitive function of temperature, became equal to net radiative heat loss, the shrinking and shedding ceased.

If the preceding assumption as to mass distribution in the nebula is correct, the sun would have spun off only 0.13% of its mass (i.e., the mass of the planets). The shedding probably also rid it of only a small fraction of its angu-

lar momentum. The shed material, now in the form of a nebula, presumably had braked the sun by friction to an equatorial velocity of 100 km/sec by the time it condensed into planets.

The material shed at the equator would initially be travelling at orbital velocity. Turbulence in the nebula (as proposed by von Weizsäcker) would tend to reduce differences in angular velocity, however. The effect of this would be to accelerate the outermost portion of the disk, causing it to increase in radius. At the same time the inner part of the disk would be decelerated below orbital velocity, tending to crowd in on the central sun.

Thus a substantial amount of the mass of the disk would remain concentrated around the sun. Probably pressure, temperature, density and angular velocity would be gradational over a considerable radial distance, rather than there being a sharp discontinuity between the sun and nebula.

If this were the case, we might expect that the motion of mass shed from the sun to the disk, and its consequent expansion and cooling would proceed at a finite rate, rather than instantaneously. Conceivably it might have proceeded slowly enough for chondrule-sized liquid droplets to be able to condense, if the cooling curve passed through the liquid field in the appropriate phase diagram.

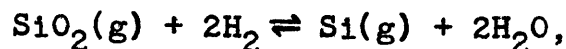
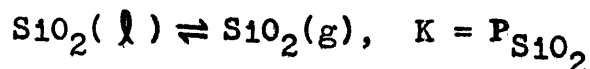
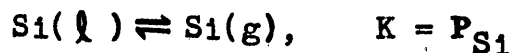
This mass-concentration in the vicinity of the sun would continue to brake the sun after shedding halted. The angular



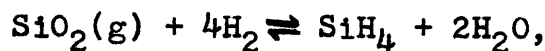
momentum removed from the sun would be transmitted outward by turbulence, continuing to increase the radius of the nebula, presumably until it corresponded to the size of the present solar system.

4. Phase Equilibria. Urey (1952) treats the question of phase equilibria in a gas of stellar composition in detail. The reactions and equilibrium constant expressions considered below are taken from his treatment.

The condensation of silicates will be approximated by considering the vapor-condensed phase curve of pure  $\text{SiO}_2$ . The following reactions need to be considered:



$$K_2 = \frac{P_{\text{Si}} P_{\text{H}_2\text{O}}^2}{P_{\text{SiO}_2} P_{\text{H}_2}^2}$$



$$K_1 = \frac{P_{\text{SiH}_4} P_{\text{H}_2\text{O}}^2}{P_{\text{SiO}_2} P_{\text{H}_2}^4} .$$

Urey finds the equations for the equilibrium constants (from admittedly inadequate thermochemical data) to be

$$\begin{aligned} \log_{10} P_{\text{Si}} &= -\frac{17100}{T} - 1.02 \log_{10} T + 9.43 \\ \log_{10} P_{\text{SiO}_2} &= -\frac{22200}{T} + 7.65 \\ \log_{10} K_1 &= \frac{8050}{T} - 10.0 \\ \log_{10} K_2 &= -\frac{15150}{T} - 1.02 \log_{10} T + 5.87 . \end{aligned} \tag{7}$$

The condition at which Si is just completely volatilized is

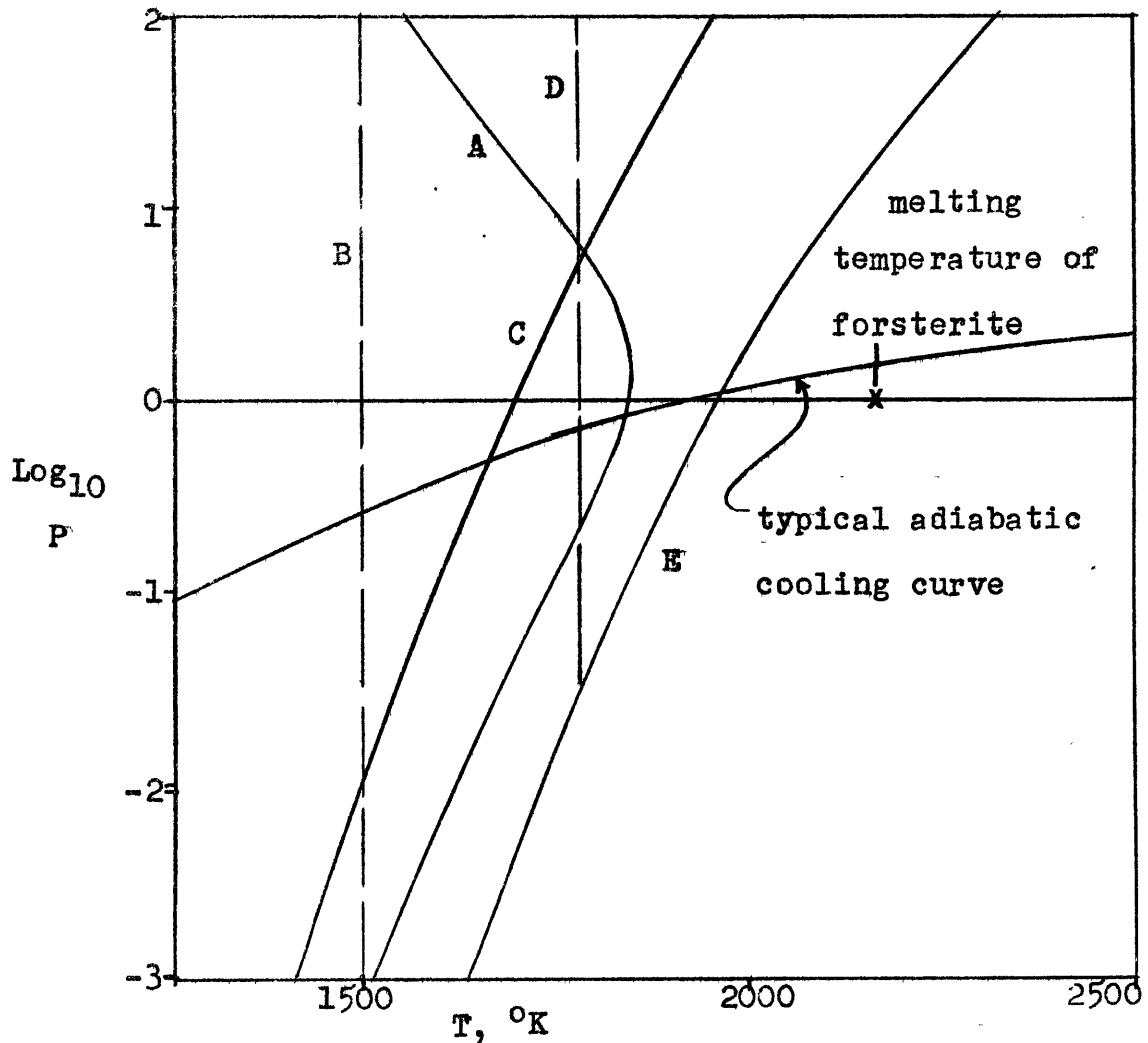
$$P_{\text{SiH}_4} + P_{\text{Si}} + P_{\text{SiO}_2} = R_{\text{Si}} P,$$

where  $R_{\text{Si}}$  is the ratio Si/H<sub>2</sub> in solar matter. Eliminating  $P_{\text{SiH}_4}$  and  $P_{\text{Si}}$  from this equation, Urey finds

$$P = \frac{R_{\text{Si}} R_{\text{H}_2\text{O}}^2}{sK_1 P_{\text{SiO}_2}} \pm \sqrt{\left(\frac{R_{\text{Si}} R_{\text{H}_2\text{O}}^2}{2K_1 P_{\text{SiO}_2}}\right)^2 - \frac{K_2}{K_1} - \frac{R_{\text{H}_2\text{O}}^2}{K_1}}, \tag{8}$$

where  $R_{\text{H}_2\text{O}} = \text{H}_2\text{O}/\text{H}_2$  in solar matter,  $\approx \text{O}/\text{H}_2$ . The assumption is made that most hydrogen is in the form of diatomic molecules by the time silica condensation begins ( $T < 1850^\circ\text{K}$ ). (8) is plotted in Fig. 6. Condensation begins at a maximum temperature at a pressure of about one atmosphere. At greater pressures, volatilization as SiH<sub>4</sub> becomes increasingly effective. At lower pressures, the silica exists in the vapor phase largely as Si(g) and SiO<sub>2</sub>(g).

Figure 6. Phase Relations in a Gas of Solar Composition (Urey, 1952)

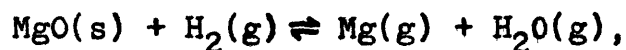


- A. Vaporization curve for pure  $\text{SiO}_2$  (approximate)
- B. Eutectic melting temperature, system  
 $\text{SiO}_2 - \text{Mg}_2\text{SiO}_4 - \text{CaAl}_2\text{Si}_2\text{O}_8$
- C. Vaporization curve for pure  $\text{MgO}$
- D. Temperature at which 10% Ni-Fe begins to melt
- E. Vaporization curve for pure Fe

Spectrographic determinations of elemental abundances in the solar photosphere (Aller, 1958) are employed in finding  $R_{Si}$  and  $R_{H_2O}$ :

element	relative abundance
H	1,000,000
He	380,000
O	1,000
C	363
N	95
Si	40
Mg	19
S	15
Fe	5.7

For the equation



Urey finds

$$\log_{10} K = - \frac{25150}{T} + 7.7.$$

This curve is also plotted in Fig. 6.

The melting points of  $SiO_2$  and  $MgO$  are  $1996^\circ K$  and  $3073^\circ K$  respectively, so the pure condensed phases will be solid everywhere in Fig. 6. Even the eutectic temperature of the system  $MgO - SiO_2$  ( $1816^\circ K$ ) is just too high to allow melting in a mixed condensed phase.

We must also consider the effect of  $Al_2O_3$  and  $CaO$  in

the condensed phase, however; Urey shows that both will be present. The eutectic temperature in the system  $\text{SiO}_2 - \text{Mg}_2\text{SiO}_4 - \text{CaAl}_2\text{Si}_2\text{O}_8$  (Anderson, 1915) is  $1495^\circ\text{K}$ , within the range of the condensed phase field of Fig. 6. The condensed phase can not become completely fluid unless  $2163^\circ\text{K}$  (the melting point of forsterite) is attainable. The fact that we are dealing not with  $\text{SiO}_2$ , but with a mixture of  $\text{SiO}_2$ , and several other oxides will probably act to increase the boiling point of the liquid above that of pure  $\text{SiO}_2$ , expanding the liquid field in Fig. 6. some unknown amount to the right.

In such a severely reducing hydrogen atmosphere, iron oxides cannot survive above about  $400^\circ\text{K}$ , fayalite ( $\text{Fe}_2\text{SiO}_4$ ) about  $500^\circ\text{K}$ . Thus the condensing silicate can contain no iron. The situation is analogous to that encountered in blast furnaces. There the silicate slag, in contact with molten iron, itself contains only trace amounts of iron.

Metallic iron has the experimentally determined (Brewer, 1946) vapor pressure curve shown in Fig. 6. The triple points of nickel and cobalt are close to that of iron. The melting point shown ( $1773^\circ\text{K}$ ) is for a 10% Ni-Fe alloy.

Urey shows that the reaction



acts to prevent formation of any troilite above about  $600^\circ\text{K}$ .

The alkali metals will not oxidize until lower temperatures than those in Fig. 6 are reached.

5. Adiabatic Cooling. If we assume the gas to cool adiabatically as it moves from the rotating sun into the nebula,

$$\frac{P}{P_0} = \left(\frac{T}{T_0}\right)^{\frac{5}{2}} \quad (9)$$

for an ideal monatomic gas in which  $C_p = \frac{5}{2} nR$ .

In Fig. 7. are reproduced the  $\bar{P} - \bar{T}$  curve for the condensation of the sun, from Fig. 4; the critical radius at which shedding begins; and the liquid silicate field from Fig. 6. On plotting (9) for limiting values of  $\bar{P}_0$ ,  $\bar{T}_0$  representing the onset and cessation of rotational shedding, it is seen that all the material shed from the equator will pass through the liquid silicate field. Thus, if the process proceeds slowly enough, we may expect droplets of (at least partly) liquid silicate and iron to condense.

6. The condensation process. The writer proposes that the chondrules were formed in this way. In order to attempt to explain the chemical and mineralogical data on chondrites, we need to consider in detail what type of solid material would be circulating about in the nebula.

The path of adiabatic cooling may be followed in Fig. 6. First, nickel-iron would condense in liquid droplets. Much or most of the metal would not have a chance to join macroscopically.

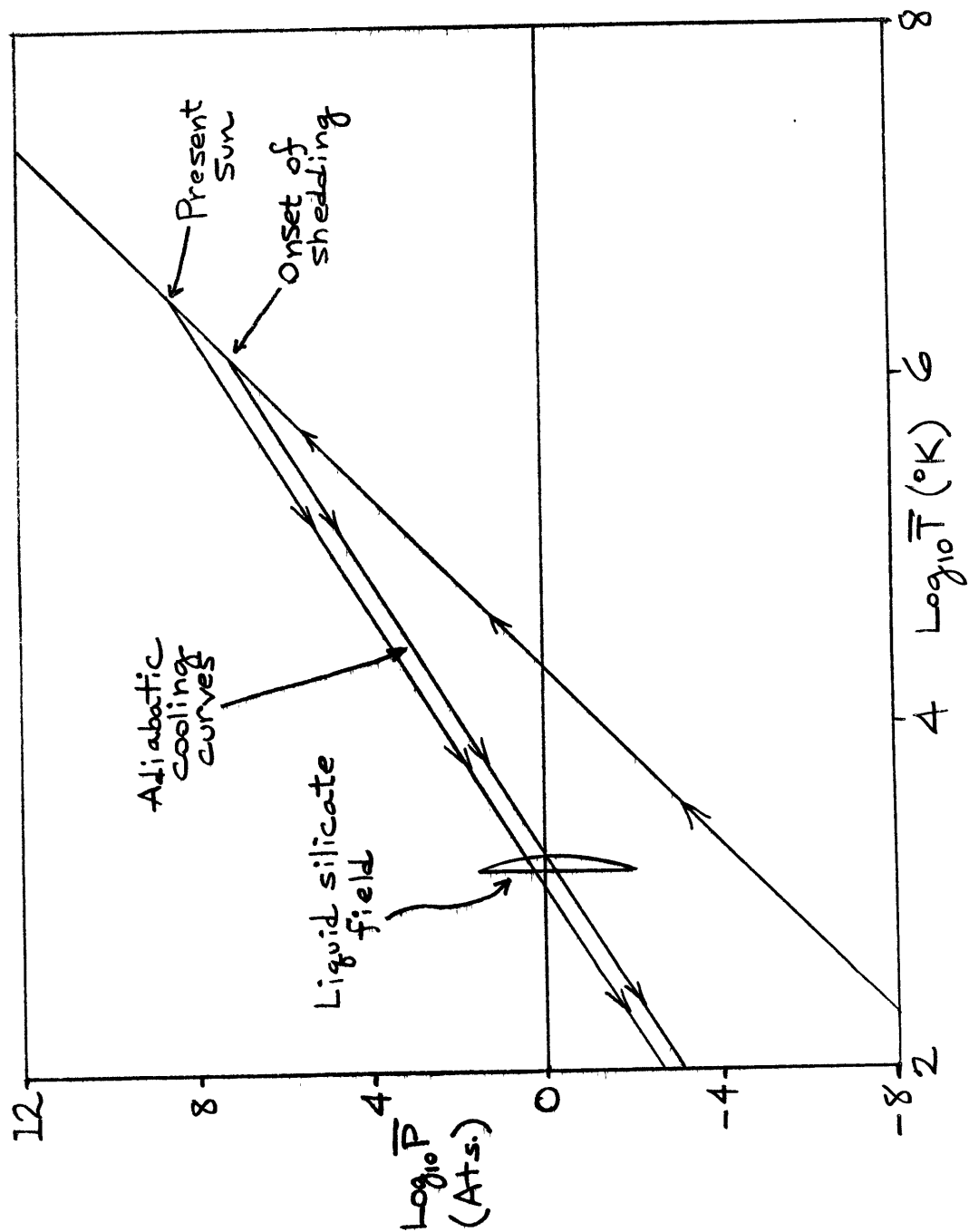


Figure 7. Adiabatic Cooling of Solar Material

pic chondrules, but would freeze as a colloidal dust.

Then liquid silicate droplets would begin to condense. Increase in boiling point due to  $MgO$ ,  $Al_2O_3$  and  $CaO$  content, and/or more accurate thermochemical data might expand the liquid field far enough to the right to produce the observed all-glass chondrules. If so, silicate and iron would exist in the liquid state simultaneously, explaining iron-clad chondrules such as seen in Renazzo. Also, the condensing glass would nucleate around or capture pre-existing smaller bits of iron, such as the grains observed in chondrules.

Again, much of the condensing silicate would have frozen as a colloidal dust rather than joining chondrules, not necessarily in the same proportion as did the iron. The motion of turbulent gas would have sped some chondrules to the surface of the nebula, there to chill into glass. Others would remain longer in the interior of the nebula, and have the chance to crystallize.

At much lower temperatures,  $H_2S$  and  $H_2O$  would react with the metallic iron, especially the fine iron dust, with its great surface area, to form  $FeS$ , iron oxides, and perhaps silicates. The alkali and other volatile metals would condense in some form. The solid particles, particularly the colloidal dust, would tend to adsorb on their surfaces some or all of the types of gas present in



the nebula. The situation is reviewed in Table 8.

Table 8.

Solid Constituents of the Solar Nebula

Fraction	Major Constituents	Minor Constituents
Iron chondrules	Fe	Ni, Co FeO
Silicate Chondrules	Mg <sub>2</sub> SiO <sub>4</sub> MgSiO <sub>3</sub> Glass (incl. Ca, Al)	Fe
Colloidal-microscopic dust	Fe, Fe oxide, silicates FeS	Na, K compounds Hg, Zn, Cd, Bi, As, etc. Adsorbed NH <sub>3</sub> , H <sub>2</sub> O, CH <sub>4</sub> , H <sub>2</sub> ; He, A, Ne

7. Chondrule-Dust Fractionation. Because a radial pressure gradient existed in the nebula, mass elements of the gas would have circled the sun with net velocities slightly less than orbital. Thus, a solid body moving in the nebula would not describe a stable orbit, but would continually dissipate its energy by drag in the more slowly moving gas, gradually spiralling in to the sun.

All the condensed particles would fall back into the sun, except for the action of gas turbulence. This would tend to keep the particles 'suspended', just as turbulence in streams keeps silt and sand in suspension. The effectiveness of this suspending process would differ for the three fractions of solid particles (Table 8), being more effective the greater the surface area/mass ratio of the particles. Its effectiveness would decrease for all particles with increasing nebular radius, because of decreasing gas density. Fig. 8 is a diagrammatic sketch of the expected material density variations.

A relationship such as this might provide the silicate-metallic phase fractionation proposed by Urey (1951) to account for the planetary densities (Table 9). Although these are subject to error (observational: planetary masses and diameters; theoretical: estimating degree of compression), they appear to indicate an increase in specific gravity of planetary matter inward in the system.

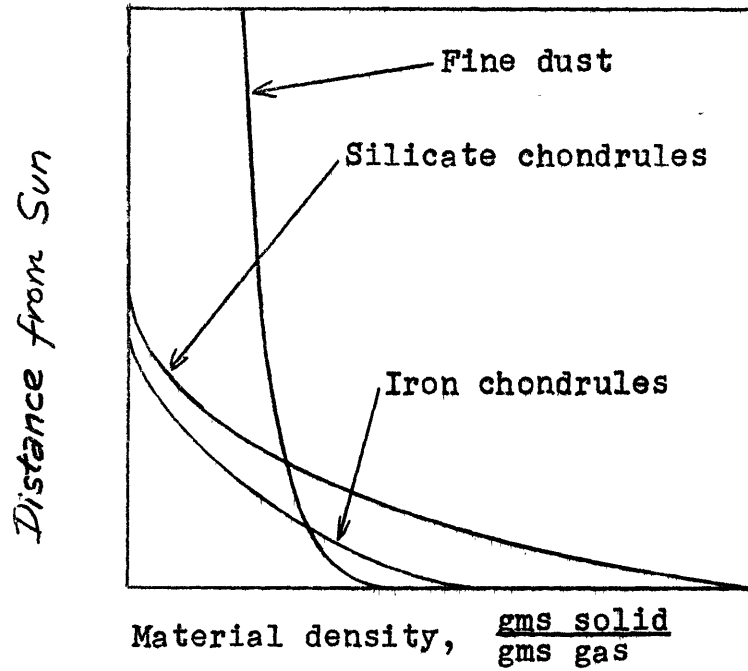


Figure 8. Diagrammatic sketch of proposed differential variations in ability of turbulent gas to suspend solid particles

Table 9

## Densities of Terrestrial Planets (Urey, 1952)

	Uncompressed density	Inferred content of metal phase
Mercury (Dollfus, 1954)	6.1	71
Venus	4.4	45 (?)
Earth	4.4	45
Mars	4.02	30
(Meteorites:		
High iron group	3.66	19.5
Low iron group	3.51	8.2)

The average specific gravity of the suspended solid material (Table 8) would increase inward in the nebula, as the relative content of iron chondrules increased and that of fine dust (highly oxidized, hence light) decreased.

It is possible that this fractionating effect can also account for Prior's law and the Iron groups. Urey (1953) has suggested that the iron groups might have been derived from two parent meteorite planets. Plotting Urey's inferred metal phase content against mean distance in Fig. 9 and extrapolating the former to approach zero in the vicinity of Jupiter, it is seen that the two iron groups correspond to distances of very roughly 2.6 A.U. (high

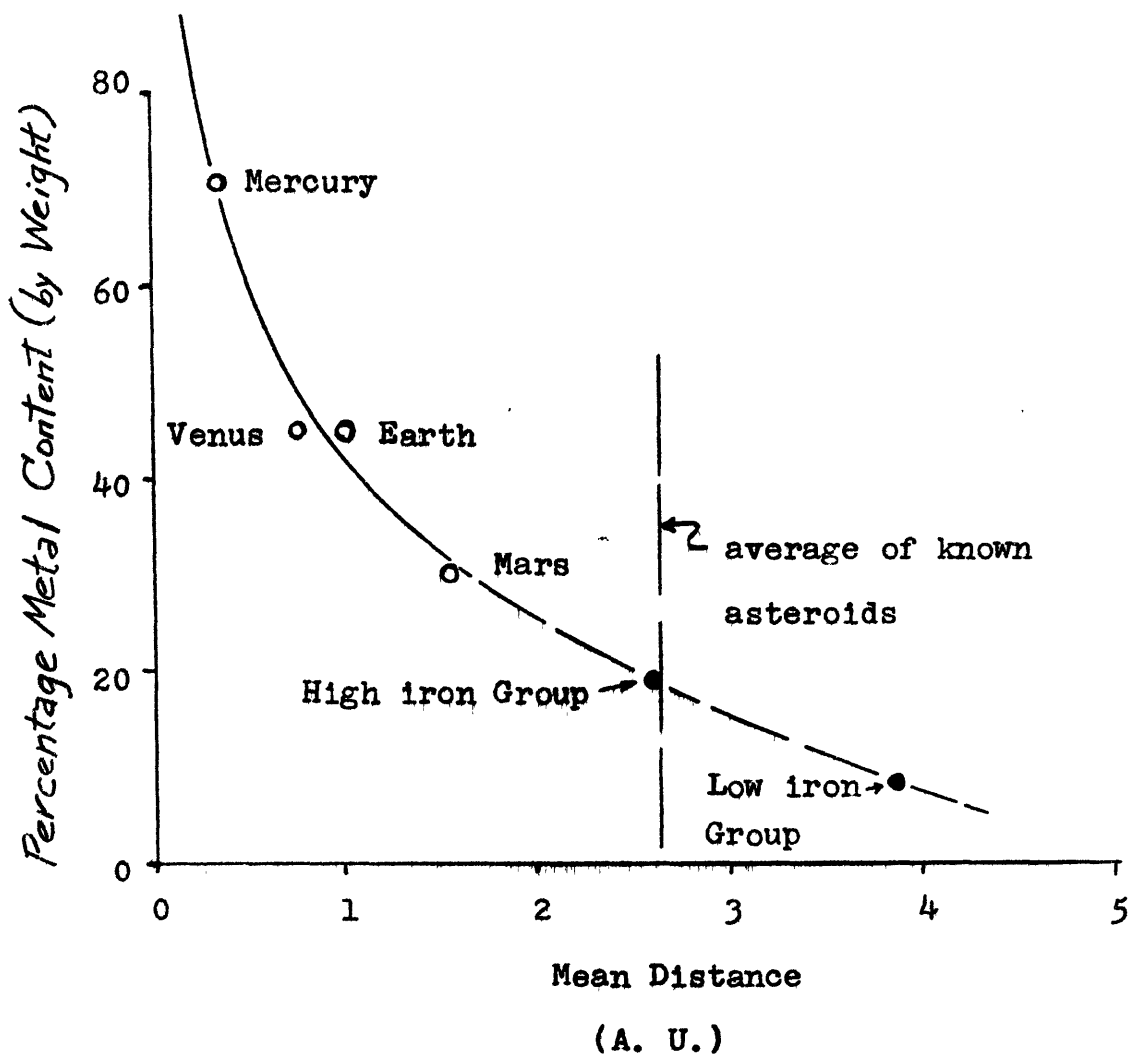


Figure 9. Inferred Metal Phase Content of the Terrestrial Planets (Urey, 1952)

iron group) and 3.9 A.U. (low iron group), both in the asteroid belt.

Then, if the iron groups do represent two bodies formed at different mean distances, we would expect the inner one to contain more chondrules and less dust than the outer. If, for example, the composition of the suspended solid matter were

	Chondrules (Iron and silicate)	Dust
High Iron Group (Inner)	80%	20%
Low Iron Group (Outer)	50%	50%

from Table 3 we see that these two fractions would have to have the following contents (atoms per  $10^6$  Si atoms) to account for the iron groups:

	Chondrules	Dust
Fe	$9.98 \times 10^5$	$2.13 \times 10^5$
O	$3.33 \times 10^6$	$3.62 \times 10^6$
S	$1.17 \times 10^5$	$0.83 \times 10^5$ .

How does this compare with the compositions predicted in Table 8? We were not able to say which of the fractions had the higher content of iron. Now we see that the iron groups are compatible with chondrule-dust fractionation only if the chondrules contain a high percentage of the iron in the system. This would require that the molten chondrules were quite effective in "sweeping up" and ab-

sorbing earlier formed iron particles, large and small. The photograph of Lumpkin (Plate XV, page 143) indicates such a process. Here a radiating orthopyroxene chondrule has undergone partial recrystallization. In recrystallizing, the iron grains have attained visible dimensions, revealing that the seemingly all-silicate chondrule contained quite a large amount of sub-microscopic metallic iron.

Table 8 does predict that the low iron group will have the higher oxygen content, because such iron as is present in the fine dust will be available for oxidation when the temperature falls below  $\sim 500^{\circ}\text{K}$ , while that in the chondrules will be largely shielded from reaction by enclosing solid silicate chondrules. It is interesting to note that the difference in oxygen content between the chondrule and dust fractions ( $2.9 \times 10^5$  O atoms/ $10^6$  Si atoms) in the example cited above is of the same order as the iron content of the dust ( $2.13 \times 10^5$ ). In other words, the oxygen content of the fractions could be accounted for if all the iron in the chondrules were in the metallic state, and all in the dust were oxidized to the ferrous state.

The content of sulfur calculated for the two fractions is in disagreement with that predicted in Table 8, where it was expected that sulfur, like oxygen,

would react largely with the iron in the dust fraction.

8. Optical Measurements of Iron Content of Olivine in Chondrites. A test of the concepts of condensation from a (reducing) gas of solar composition, and of the chondrule-dust fractionation, would be to separate and analyse the fractions from a chondrite. A beginning was made in this direction by the writer by making optical determinations of the compositions of olivine crystals in fifteen chondrite thin-sections.

In each section, ten measurements of the axial angle (2V) were made on different grains, and averaged (it was assumed that some variation in composition from grain to grain existed in at least some of the sections). Measurement was made of one axis, by the direct method, on a universal-stage polarizing microscope. Results are presented in Table 10, and Fig. 10.

Table 10.

Average Fayalite ( $\text{Fe}_2\text{SiO}_4$ ) Content of Olivine in 15 Chondrites

Chondrite	Average Mole % $\text{Fe}_2\text{SiO}_4$	% Chondritic Structure
Agen	24	25
Aldsworth (Plate I)	29	43
Alfianello	28	9
Aumières	48	2



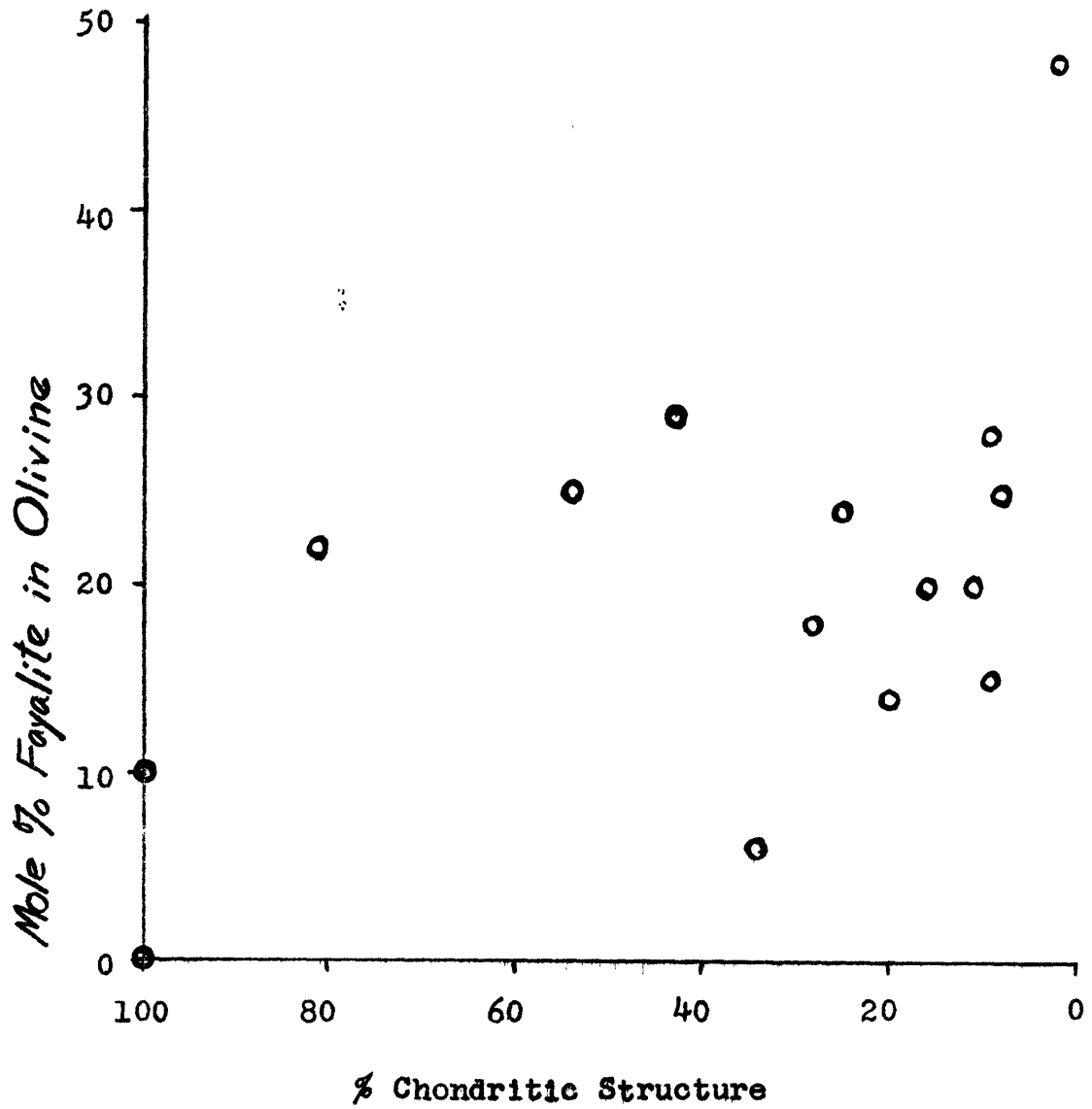


Figure 10. Compositions of Olivine in Fifteen Chondrites

Chondrite	Average Mole % $\text{Fe}_2\text{SiO}_4$	% Chondritic Structure
Cynthiana (Plate IV)	22	81
Lissa (Plate IX)	25	8
Marion	15	9
Mauerkirchen	20	11
Milena (Plate VIII)	20	16
Renazzo (Plate VI)	0	100
Searsmont	18	28
Seres (Plate III)	6	34
Soko-Banja	23	54
Tieschitz (Plate Va)	10	100
Zatoor (Plate VII)	14	20

If the olivine in the chondrules was initially pure forsterite ( $\text{Mg}_2\text{SiO}_4$ ), as it must have been if the chondrules formed in a reducing atmosphere; and if they were deposited in a matrix containing oxidized iron, we would expect the system to attain chemical equilibrium (i.e., oxidized iron and magnesium silicates would disappear in favor of more ferrous silicates, unless the system were deficient in  $\text{SiO}_2$ ) if it were subjected to metamorphic temperatures (> about  $500^\circ\text{C}$ ) for any length of time. Thus, we could expect only the uppermost (un-metamorphosed) layers of the proposed sequence of chon-

drites to contain iron-free olivine.

The two points representing Renazzo and Tieschitz in Fig. 10. appear to indicate this sort of relationship. Not enough sections of high percentage chondritic structure were measured to yield a conclusive answer. Since the attainment of coherence in a sedimentary chondrite would necessarily involve some small amount of recrystallization, the more interesting chondrites (those composed of unreacted chondrules and dust, hence extremely friable) would rarely survive passage through the earth's atmosphere.

A more definitive experiment would be to obtain several friable, unrecrystallized, non-carbonaceous chondrites, such as Renazzo, separate the chondrule and dust fractions, and analyse them chemically. The more purely sedimentary the chondrites, the more meaningful the results would be.

A significant observation with respect to the above was made by Prendel (1893). In examining the chondrite Grossliebenthal, he found orthopyroxenes of varying composition in coexistence. Specifically, the chondrules contained relatively iron-free enstatite, the matrix hypersthene. This could be interpreted in several ways. It is just what we observe in igneous rocks, where the larger, earlyformed crystals are magnesian, the later ones increasingly ferrous. If the chondrites have been correctly

interpreted as sediments which have undergone varying degrees of metamorphism, however, Prendel's observation is in agreement with the postulated chondrule and dust fractions.

These two fractions could not account for the denser inner planets, since the pure chondrule fraction considered would contain only about 30% metal phase. However, with the three-fraction model originally outlined in Table 8, an increase in the content of iron chondrules could achieve the 71% metal phase content for Mercury inferred in Table 9.

8. Accretion. Little will be said about the process of dust and chondrules accreting into planets. One point is worth mentioning, however. It has been pointed out by Urey (1952) that a "sticking agent" is required to make the colliding planetesimals cohere until large enough bodies accumulate to possess perceptible gravitational fields. Urey postulates that water and ammonia just below their freezing points act as the "sticking agent". Hoyle (1955) suggests oxygenated hydrocarbons (i.e. pitch).

One other possible "sticking agent" might be considered. The writer has postulated a system containing a sizeable fraction of colloidal silicate dust, perhaps with various gases adsorbed on it. Conceivably, conditions might have allowed this dust to coagulate, to cohere by

virtue of its high surface energy. In Renazzo (Plate VI), the manner in which chondrules are separated from one another by the matrix suggests that each had accumulated a layer of the black matrix material before they were brought together. Possibly the chondrules in general did gather such coatings, of various thicknesses, which then caused them to cohere to one another on colliding.

Briefly, then, the following history of the terrestrial planets is suggested.

a) The existence of a turbulent gaseous nebula, containing chondrules and fine dust in suspension.

b) The gradual flocculation of the solid material into bodies with palpable gravitational fields. Only six attained significant size - the present terrestrial planets, and two bodies in orbits outside of Mars.\* All their orbits would have low eccentricity, and collisions would be improbable or impossible.

c) Simultaneously, the accretion of the major planets from water and ammonia, at distances from the sun where these can exist as condensed phases.

d) Finally, the capture of virtually all the nebular gases (mainly  $H_2$  and He) by Jupiter and Saturn, after these planets gained sufficiently massive gravitational fields.

\* Admittedly contradictory to Bode's 'law'.

e) After removal of the suspending gaseous medium, the "cleaning up" of most residual chondrules and dust by planetary capture, solar light pressure, and the Poynting-Robertson effect.

f) With the growth of Jupiter and its gravitational field, the perturbation of the outermost terrestrial planet into a more eccentric orbit.

g) After many years, the collision of the outermost planet with the next inner one, disrupting both, and forming the present asteroid belt.

### III. NON-CHONDRITES AND THE PARENT

#### METEORITE PLANET

##### A. OBSERVATIONAL DATA ON NON-CHONDRITES

1. Classification, Mineralogy, Textures. Achondrites, stony-iron and iron meteorites are embraced by the term "non-chondrites". These have coarser textures and more varied mineralogies than did the chondrites. Hence they are generally classed according to observable mineralogy and texture, rather than by bulk chemistry and texture, as were the chondrites. Again Prior's (1953) classification is employed. The different types of non-chondrites, with their mineralogies and observed frequency of falls are presented in Table 11.

A number of minerals are cited in Table 11 which were not described previously (Table 2); characteristics of these new minerals may be found in Table 12.

Table II.  
Properties of Non-chondrites (Prior, 1953; Smith,

Type	Principal Minerals ( $m = \text{MgO}/\text{FeO}$ ; $f =$ content of Nickel-Iron; $n =$ $\text{Fe}/\text{Ni}$ in metal)	Accessory Minerals
	ACHONDRITES Ca - poor or	
Aubrite	Enstatite, clinoenstatite	Oldhamite nodules, containing osbornite octahedra (Bustee); Ni-poor nickel-iron, troilite, forsterite, plagioclase (oligo- clase)
Ureilite	Olivine, $m=4-5$ ; clinobronzite, $m=8-12$	Nickel-iron, 5.5-8.5% diamond (microscopic)



1950; Farrington, 1915; Leonard, 1956; Foshag, 1941)

No. of falls	Terrestrial Igneous Equivalent	Remarks
--------------	--------------------------------------	---------

"Chondritic" Achondrites

6	Enstatolite	<p>Bladed enstatite crystals up to 4.5 cm (Shallowater). Usually intensely brecciated.</p> <p>See Bustee, Plate XIII</p>
2	---	<p>Novo Urei: grains of olivine and pyroxene in a fine matrix consisting of nickel-iron, graphite, and containing diamond. Goalpara (see Plate XIX) consists of 1-2 mm aggregates of extremely fine silicate grains. These aggregates are in turn aggregated in an opaque black matrix.</p>

Type	Principal Minerals	Accessory Minerals
Amphoterite	Olivine, $m \approx 2$ ; hypersthene, $m=2-3$	Plagioclase (labradorite)
Diogenite	Hypersthene, $m=2-4$	Plagioclase (bytownite), nickel-iron, tridymite
Chassignite	Olivine, $m \approx 2$	Rare maskelynite - like substance in interstices.

## Ca - rich or

Angrite	Augite (purple, pleochroic, lime- rich, aluminous; $m=2.5$ ; contains 2% $TiO_2$ )	
Nakhlite	Diopside, $m=1.5$ ; minor olivine, $m = 0.5$	Plagioclase (oligo- clase-andesine),
Eucrite	Plagioclase (bytownite- anorthite),	Tridymite, augite, hypersthene (Moore County);

No. of falls	Terrestrial Igneous Equivalent	Remarks
9	--	See Manbhoom, Plate XVI.
5	Hypersthenite	Usually brecciated
2	Dunite	Uniformly granular structure. Friable.

## "Basaltic" Achondrites

1	Augitite	Fine grained, friable
1	Lherzolite	
14	Diabase	Has the same ophitic texture (idio- morphic laths of plagioclase, in-

Type	Principal Minerals	Accessory Minerals
Eucrite (cont.)	clinohypersthene, ) or hedenbergite ) pigeonite, m(bulk analysis)=0.5-1	Olivine
Sherghottite	Maskelynite (andesine glass), diopside, ) or clinohypersthene ) pigeonite	Magnetite
Howardite	Anorthite, Hypersthene, clinohypersthene m(bulk analysis)=.7-2.5	Olivine

No. of falls	Terrestrial Igneous Equivalent	Remarks
		<p>terstitial pyroxene) and mineralogy as terrestrial diabase. Uniform chemical composition, near that of Sudbury norite. Usually brecciated. Moore County lacks ophitic texture; fabric analysis indicates mineral layering, interpreted as settling on the floor of a magma chamber (Hess and Henderson, 1949). Plagioclase often shows the effect of mechanical strain. See Stannern, Plate XIV,</p>
1	---	<p>Ophitic texture, as above; the maskelynite is pseudomorphous after idiomorphic plagioclase.</p>
14	---	<p>Not a distinct type of "achondrite"; actually a polymict breccia, consisting mostly of fragmented eucrite.</p> <p>See Frankfort, Plate XVII</p>

Type	Principal Minerals	Accessory Minerals
------	--------------------	--------------------

## STONY -

Pallasite	Olivine, m=4-9, average 6.1; nickel-iron, (kamacite, taenite, plessite) f=11-80, average 43; n= 5-19, average 10	(see octahedrites, below)
Siderophyre	Bronzite, m = 4 - 5; tridymite, nickel-iron, f=51, n=9	
Lodranite	Bronzite, m=5; olivine, m=7; nickel-iron, f=30, n=11.5	
Mesosiderite	Hypersthene, ) )m=2-3.3; clinohypersthene) olivine, m=4.1-10, average 7.4;	Albite (plagio- clase in Pinnaroo is Ab <sub>10</sub> An <sub>90</sub> ),

No. of falls	Remarks
--------------	---------

## IRONS

2	Olivine crystals, up to 1 cm, are held in a matrix of nickel-iron bearing Widmanstätten figures (see octahedrites, below). Brenham consists partly of pallasite, partly of all-metal octahedrite. Olivine often displays crystal faces, but has edges rounded off. Grains usually surrounded by a layer of kamacite, showing iron crystallized subsequently to silicate.
0 (1 find)	See Steinbach, Plate XI
1	Consists of euhedral grains in a matrix of iron.
7	Olivine crystals reported as large as 10 cm. Structure variable. Iron usually in the form of grains, rather than matrix.

Type	Principal Minerals	Accessory Minerals
Meso- side- rites (cont.)	anorthite, nickel-iron, f=42-69, average 50; n=9-15, average 12	magnetite, ilmenite, lawrencite, oldhamite, tridymite

## IRONS

Hexahed- rite	Nickel-iron (kamacite), Ni $\approx$ 7%	Schreibersite need- les (called rhab- dite), troilite, daubréelite, graphite, quartz, chromite
------------------	---	--



No. of falls	Remarks
	See Mincy, Plate XII.

6	Contain Neumann lines: faint traces of a series of surfaces related to the cubic $\gamma$ iron lattice, thus the name 'hexahedrite'. The metal otherwise appears to be homogeneous.
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Type	Principal Minerals	Accessory Minerals
Octahed- rite	Nickel-iron (kamacite, taenite, plessite), Ni = 7-14%	Schreibersite and Troi- lite, in nodules, or plates parallel to la- mellæ; graphite nodules. Inclusions sometimes bor- dered by kamacite. Cohen- ite; diamond, up to 1/2mm, in Canon Diablo; daubrè- elite; moissanite in Canon Diablo, lawrencite, quartz, chromite, olivine
Nickel- poor Ataxite	Nickel-iron, Ni < 6%	Schreibersite (rhabdite) and others
Ataxite	Nickel-iron, Ni 7 - 14%	
Nickel- rich Ataxite	Nickel-iron, Ni > 14%	

No. of falls	Remarks
29	<p>Characterized by Widmanstätten figures: Kamacite lamellae intergrown parallel to 111 planes of <math>\gamma</math> iron lattice, hence the term 'octahedrite'. Kamacite bounded by thin layers of taenite; interstices between lamellae occupied by plessite or additional finer lamellae. Total nickel content decreases as coarseness of the structure increases.</p>
1	Fine, granular structure.
2	<p>Fine, granular structure. Thought to be altered octahedrites.</p>
0 (33 finds)	Fine, granular structure.

## Plate XII.

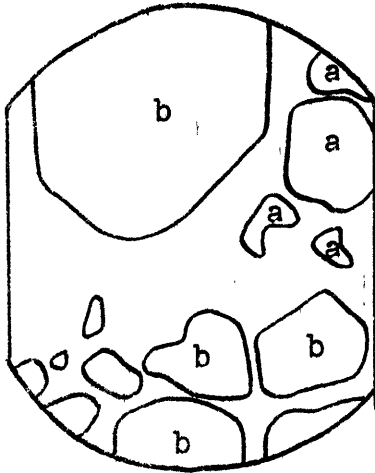
STEINBACH, Germany

Siderophyre

46x, Plain polarized light

1 mm.

in photograph



The opaque matrix is nickel-iron. Grains of bronzite ( $MgO/FeO = 4-5$ ) are labelled b; one shows euhedral outlines. Interference colors are high (up to fourth order) because of abnormal section thickness.

The grains labelled a are unidentified: they have very low birefringence ( $\sim .0015$ ); maximum interference color of first order yellow, in spite of section thickness. Some of them display peculiar checkerboard twinning. The mineral is abundant, comprising about 20% of the transparent matter in the section. It is biaxial  $+$ ,  $2V \sim 75^\circ$ . Tridymite, which is reported to be a major constituent of Steinbach, has a  $2V$  of  $35^\circ$ ; none was found in the section.




## Plate XII.

MINCY, Missouri, U.S.A.

Mesosiderite

46x, Plain polarized light

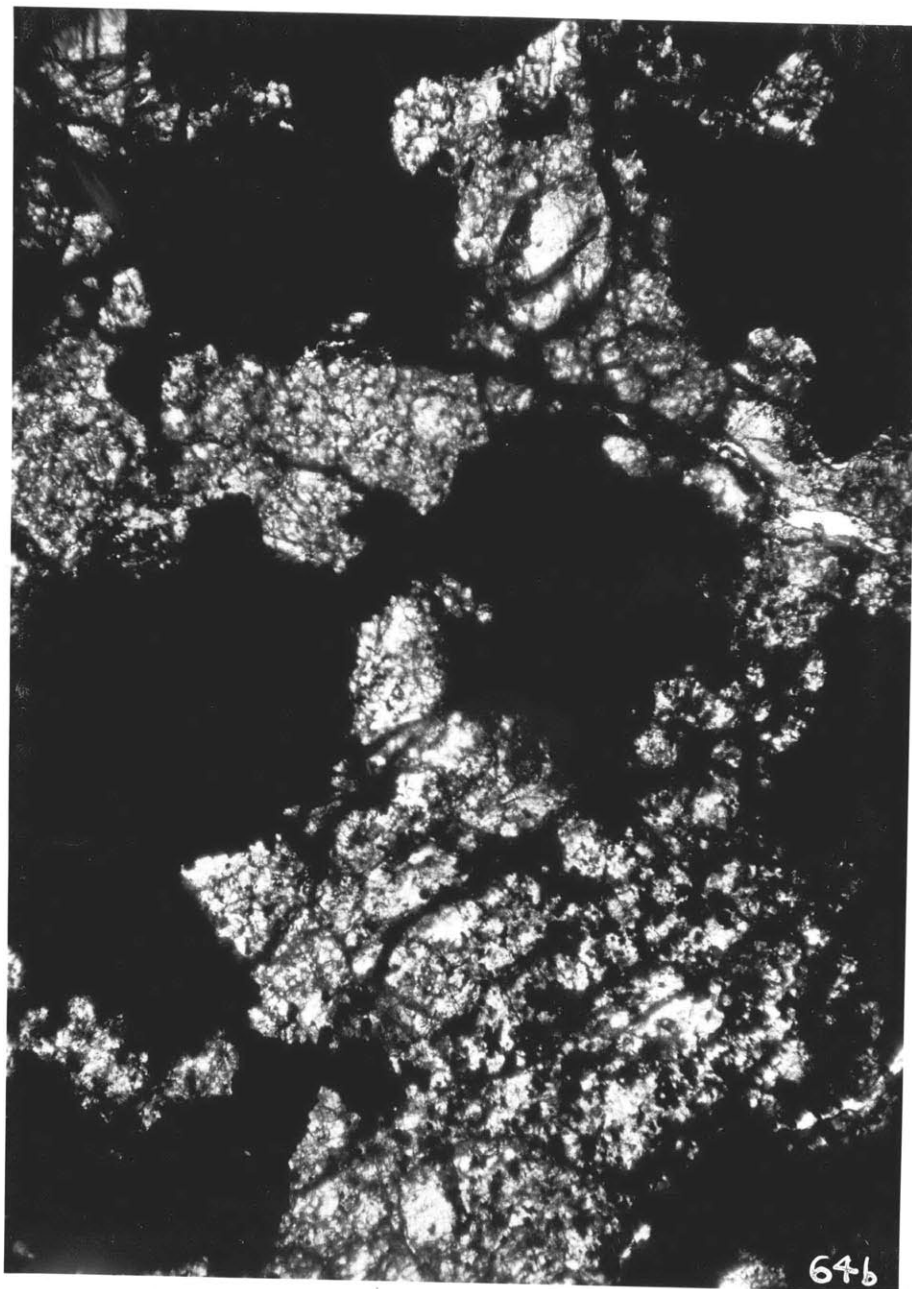
1 mm.

  
in photograph

The areas of silicate are mostly aggregates of very fine, randomly oriented grains (very much like those seen in Goalpara, Plate XIX, a ureilite). Among these are included occasional larger ( $< \frac{1}{2}$ mm.) grains of highly magnesian olivine.

Metal, making up about 50% of the section, occurs in grains, as seen in the photograph. This distinguishes mesosiderites from the other stony-irons. The silicates are charged with fine metal grains.

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## Plate XIII.

BUSTEE, India

Polymict brecciated aubrite

46x, Plain polarized light

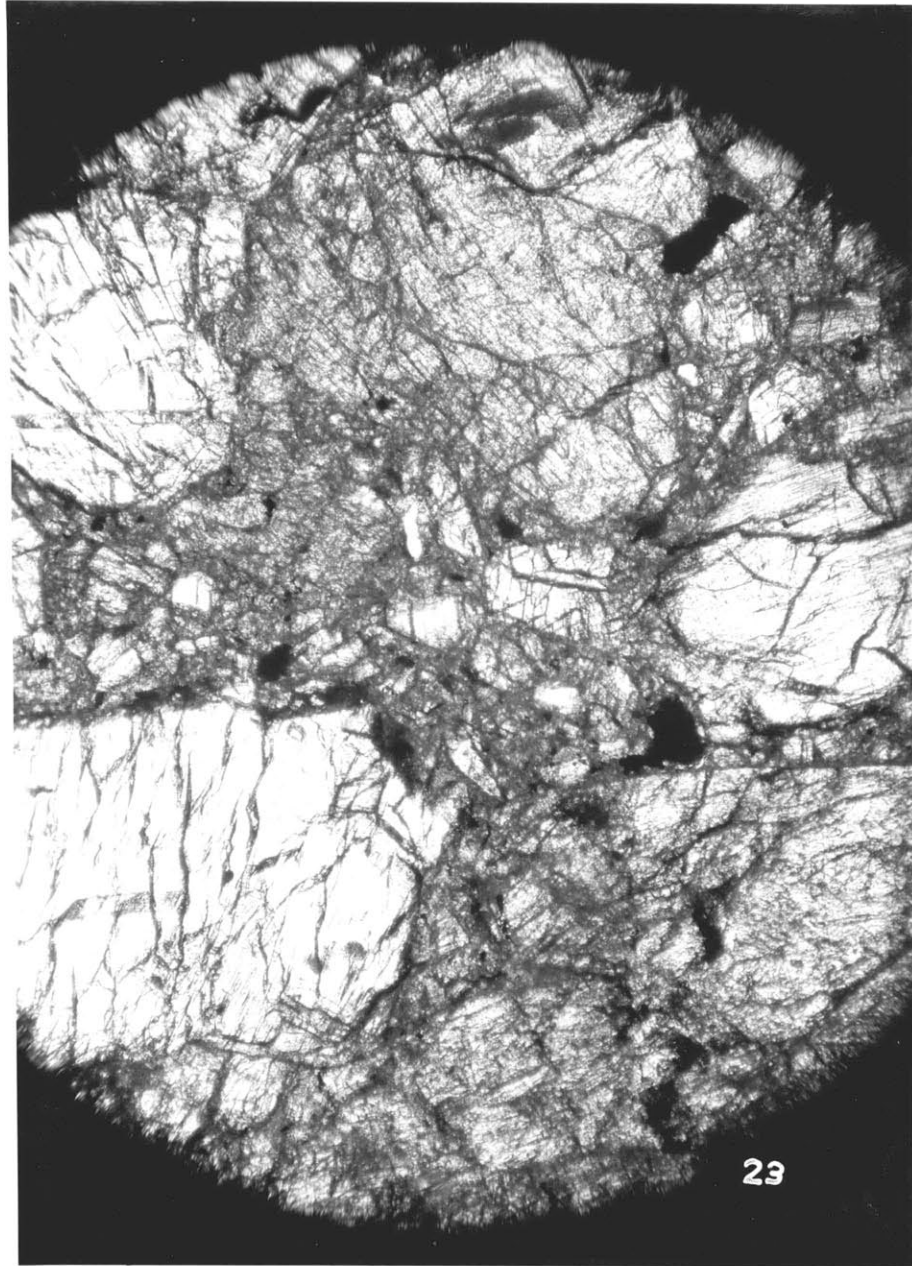
1 mm.

  
in photograph

Bustee consists of crystal fragments up to 5 mm, mostly of enstatite. Some forsterite crystals are present, and a very small amount of metal. The brecciated texture is obvious.



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## Plate XIV

STANNERN, Czechoslovakia

Monomict brecciated eucrite

46x, Plain polarized light

1 mm.

  
in photograph

Stannern displays the ophitic texture characteristic of terrestrial diabases. The light-colored grains are plagioclase (bytownite) laths. Some are polysynthetically twinned. Darker grains are pyroxene, densely charged with very fine opaque matter. Some grains of hypersthene are recognizable, but most of them (probably clinopyroxene) are not transparent enough to permit optical inspection.

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Table 12.

## Meteoritic Minerals not Included in Table 2.

Mineral	Composition	Crystal system	Remarks
Kamacite	Fe-Ni, about 6% Ni	isom.	$\alpha$ phase in the system Fe-Ni
Taenite	Fe-Ni, 13-50% Ni	isom.	$\gamma$ phase
Plessite	Fe-Ni	--	Fine intergrowth of kamacite and taenite (above)
Plagioclase (feldspar)	Solid solution of albite ( $\text{NaAlSi}_3\text{O}_8$ ) and anorthite ( $\text{CaAl}_2\text{Si}_2\text{O}_8$ )	tricl.	Ab <sub>100</sub> Albite Ab <sub>90</sub> An <sub>10</sub> Oligoclase Ab <sub>70</sub> An <sub>30</sub> Andesine Ab <sub>50</sub> An <sub>50</sub> Labradorite Ab <sub>30</sub> An <sub>70</sub> Bytownite Ab <sub>10</sub> An <sub>90</sub> Anorthite An <sub>100</sub>
Maskelynite	(see plagioclase)	--	Fused plagioclase

Mineral	Composition	Crystal system	Remarks
Chromite	$\text{FeCr}_2\text{O}_4$	isom.	
Magnetite	$\text{Fe}_3\text{O}_4$	isom.	
Ilmenite	$\text{FeTiO}_3$	hex.	
Moissanite	$\text{SiC}$	hex.	Natural carborundum
Cohenite	$(\text{Fe}, \text{Ni}, \text{Co})_3\text{C}$	orth.	
Osbornite	$\text{TiN}$	isom.	Occurs in blast furnace slag
Daubr�eelite	$\text{FeCr}_2\text{S}_4$	isom.	
Quartz	$\text{SiO}_2$	hex.	Occurs in insoluble residue of iron meteorites; may have inverted from some other primary polymorph.

2. Chemical Compositions. The achondrites vary as widely in chemistry as they do in mineralogy. Systematic chemical variations are similar to those encountered in studies of terrestrial basic and ultrabasic igneous rocks. Analyses of representatives of the different types of

achondrites may be found in Urey and Craig (1953). From this source, the average of analyses of the Ca-poor and Ca-rich achondrites respectively are presented in Table 13, together with the average chondrite and terrestrial basalt, for comparison.

Table 13.

## Achondrite Analyses (Urey and Craig, 1953)

	Average of Chondrite Analyses	Average of Ca-poor (chondritic) Achondrite Analyses	Average of Ca-rich (basaltic) Achondrite Analyses	Average Terrestrial Effusive Basalt (Daly, 1933)
SiO <sub>2</sub>	38.04	52.56	48.65	49.06
MgO	23.84	30.47	9.87	6.17
FeO	12.45	11.45	16.31	6.37
Fe <sub>2</sub> O <sub>3</sub>	0.00	0.00	1.14	5.38
Al <sub>2</sub> O <sub>3</sub>	2.50	1.09	11.71	15.70
CaO	1.95	1.20	10.39	8.95
Na <sub>2</sub> O	0.98	0.36	0.83	3.11
K <sub>2</sub> O	0.17	0.11	0.27	1.52
TiO <sub>2</sub>	0.11	0.12	0.50	1.36

	Average of Chondrite Analyses	Average of Ca-poor (chondritic) Achondrite Analyses	Average of Ca-rich (basaltic) Achondrite Analyses	Average Terrestrial Effusive Basalt (Daly, 1933)
$P_2O_5$	0.21	0.10	0.10	0.45
$H_2O$	0.25	0.89	0.40	1.62
Fe	11.75	2.68	(very little)	0.00
Mg	1.34	0.17		--
FeS	5.73	0.96	0.57	--

There are important differences in the compositions of chondritic achondrites and chondrites. The differences are lessened by considering only the silicate fraction of the average chondrite, but even in this case the chondrite has about three times the content of  $Al_2O_3$ , CaO and alkalis (i.e., feldspar) found in the average chondritic achondrite.

Nor does the composition of the basaltic achondrites perfectly match that of the terrestrial basalt - the latter has a higher content of iron, in a less oxidized state; its content of alkalis is only about 1/4 that of a terrestrial basalt.

## B. QUESTIONS RAISED BY THE OBSERVATIONAL DATA

1. The relation of non-chondrites to chondrites. We must consider three possibilities: that the chondrites and non-chondrites formed independently; that there existed primary objects composed of non-chondritic material, part of which by some process of disruption and re-agglomeration came to form the chondrites; and the reverse of this, that the primary objects were composed of chondritic material, part of which somehow segregated into the non-chondritic meteorite types.

The first possibility is not often proposed. The observations of Wahl (1952) on polymict breccias constitute one objection to it: fragments of both chondritic and achondritic matter occur in the same polymict breccias.

The hypothesis advanced by Urey (see II C. 1.b. earlier) comes under the second possibility. The writer feels it does not fully account for the observed textures of chondrites (II. B. 5).

If we accept the mechanism advanced in part II for the formation of the chondrites, or some variation of it, then the non-chondrites must be viewed from the standpoint of the third possibility, that they were derived from chondritic matter. This course will be followed in the present treatment. Some support is lent the concept by the results of potassium-argon dating by Geiss and Hess (1958),



who found four achondrites to average about a half billion years younger than seven chondrites.

The achondrites, with a few exceptions, are similar both in texture and mineralogy to the various rock types in terrestrial basic igneous stratiform sheets. The comparison has been made in detail by Buddington (1943); Table 14 is condensed from this source. If the achondrites were, then, derived from the chondrites, it must have been by some process of heating and re-melting after the accretion of the parent meteorite planets.

2. The Question of Heat. We must inquire into the source of the heat required to melt a portion of the planet. Four possibilities present themselves:

a) That the kinetic energy of infalling matter during the accretion process, transformed into heat, is retained in amounts large enough to produce local melting. Consider an object falling from infinity to the surface of a body as large as the moon. Its kinetic energy before impact is

$$\text{K.E.} = -\text{P.E.} = \frac{GMm}{r} = 2,110 \text{ joules/gm}$$

$$= (\text{for clinoenstatite}) 50,500 \text{ cal/mole};$$

the increase in temperature would be  $\Delta T$  (for clinoenstatite)  $\approx 2580^\circ\text{C}$ , if all the kinetic energy were converted to heat and confined to the impacting particle. For the entire

Table 14

## Comparative Vertical Sequences in Four

	Duluth, Minnesota	Stillwater, Montana
Top	Granophyre	Unknown
Upper part	Olivine gabbro	Gabbroic zone
Above central part	Olivine gabbro (anorthosite, ilmenite-mag- netite layers)	Anorthosite zone
Below central part	Olivine gabbro	Noritic layered zone
Lower part	Olivine gabbro (peridotite layers)	Ultramafic zone
Chilled facies	Olivine gabbro	Norite

## Stratiform Sheets (Buddington, 1943)

Skaergaard, Greenland	Bushveld, Africa	Similar Achondrites
Granophyre, ferrogabbros	Granite	Tektites ?
Hypersthene- olivine gabbros	Gabbro	Pigeonite eucrites
	Norite (anorthosite, ilmenite- magnetite layers)	Hypersthene eucrites
	Norite	
	Bronzitite (peridotite, anorthosite, norite, dunite minor Chromite layers)	Diogenites, ureilites
Olivine gabbro	Norite	Olivine eucrite

process of accretion of the moon,

$$\text{-P.E. of assembly} = \frac{3}{5} \frac{GM^2}{R} \text{ (assuming } \rho = \text{const.)};$$

$$\overline{\Delta T} = \frac{3}{5}(2580^\circ\text{C}) \approx 1550^\circ\text{C}$$

for the whole moon, if all energy were retained as heat. Heating would occur at the surface, where it would be largely radiated off. But if the accretion occurred over a short period of time, and involved the gathering in of sizeable aggregations of matter, rather than just loose dust and chondrules, the collisional shock waves would transmit part of the kinetic energy into the interior of the body. There attenuation of the shock waves would ultimately transform it into heat. Such a process might make a major contribution to the temperature needed to cause melting.

b) Urey and Donn (1956) suggest that the solid matter from which the primary objects condensed might have included condensed NH, CH, OH, and similar unstable compounds. After the accumulation of a layer of this mixture, reaction would have somehow been initiated, releasing enough heat to melt a substantial fraction of the primary body. These free radicals condense only at temperatures below the boiling point of nitrogen, however, so could not have condensed unless the sun at that time were

much cooler than at present. Even in this case, it would seem that the kinetic energy of impact (a, above) would be too great to allow the accumulation of condensed free radicals.

c) Urey (1952) has also suggested that the sun increased in temperature at some early time, melting and even distilling the surface of bodies then occupying the asteroid belt. He has since discarded the possibility of surface melting, because the metallurgical analysis of iron meteorites by Uhlig (1954) and the presence of diamonds in them both point to cooling at depth.

d) Perhaps the most conventional process of heat generation is by radioactive disintegration. Hamaguchi, Reed and Turkevich (1957) have measured the uranium content of four chondrites by the thermal neutron activation method, and find an average value of  $1.1 \times 10^{-8}$  grams U/gram. Allan and Jacobs (1956) treat the problem of radioactive heating and melting within asteroid-sized bodies. Apparently it is possible that radioactivity could have generated sufficient heat to cause melting in the parent meteorite planets. A conclusive answer would require knowledge of the time of accretion of the body. Dating methods used thus far on meteorites have been a measure only of the last period of extensive heating undergone by the parent meteorite planet (i.e., the time of melting). On the time of accretion

would depend two critical factors: the initial content of fissionable material of the planet ( $U^{235}$  and  $K^{40}$  have half-lives of about  $10^9$  years), and the time available in which the heating and melting must have occurred. This may have been as long as  $10^9$  years, since datings of the high-temperature period in the meteorites' history have consistently given ages of  $\sim 4.5 \times 10^9$  years<sup>\*</sup>; an upper limit of  $5.6 \times 10^9$  years is imposed on the accretion by assuming that all  $Pb^{207}$  is derived from  $U^{235}$  decay.

Enough heat to cause extensive melting might have been provided by a combination of impact energy and radioactive heating, the central temperature reaching a maximum value at some early date in the history of the planet, and falling off thereafter.

If radioactivity was a significant factor in the heating, and bearing in mind that some meteorites contain diamonds, we conclude that the melting occurred in the central portion of the parent meteorite body. This model

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\* Geiss and Hess (1958) find the argon-potassium ages for seven chondrites to range from 4.0 to  $4.4 \times 10^9$  years; for 4 achondrites (excluding a shergotite), 3.2 to  $4.0 \times 10^9$  years. Wasserburg and Hayden (1955) found, by the same method, three chondrites to lie between 4.1 and  $4.4 \times 10^9$  years. Patterson (1955) finds that the  $Pb^{207}/Pb^{206}$  method gives ages of  $4.5 \pm 0.1 \times 10^9$  years for two chondrites and a howardite.

has been considered previously (e.g., Lovering, 1957a, 1957b). Melted chondritic material would have consisted of three immiscible phases, silicate, iron sulfide, and iron: the latter two would, of course, sink to the center of the planet.

Four factors would have operated to bring about the subsequent cooling and crystallization of the liquid phases:

- a) Loss of the initial heat of impact
- b) The decrease in content of fissionable material (hence in heat generation) by radioactive decay
- c) The removal of fissionable material from the center, and concentration nearer the surface of the body by the sinking of the iron phase, and by subsequent fractional crystallization of the silicates
- d) The increase in conductivity of the overlying unmelted layers by as much as an order of magnitude, by the recrystallization of most of it from unconsolidated dust and chondrules to massive rock (discussed in part II).

A consideration of the process of crystallization of the molten silicate raises interesting questions.

3. The Question of Crystal Fractionation. Extensive study of basic igneous intrusive bodies on the earth has led to recognition, if not complete understanding, of

the processes involved.

If we melted a mass of chondritic meteorite, first two immiscible phases, metal and troilite, would sink to the bottom of the crucible. Then, if we very gradually cooled the melt, crystals of olivine and pyroxene, rich in magnesium, would form and sink. With time, the residual liquid would be enriched in iron, aluminum, and the alkali metals. At a late stage, the remaining liquid would correspond in composition to a eucrite. The various layerings of earlier-formed crystals would be similar to aubrites, diogenites, chassignites, nakhlites, possible angrites. The iron, which would have crystallized while the silicate was still about half liquid, would of course correspond to the iron meteorites. The troilite layer, which corresponds to no known meteorite type, would crystallize last of all.

Great discrepancies in the comparison appear when we compute the quantities of the various rock types involved. In Table 15, the compositions of the average of chondrite analyses, and of Stannern, a eucrite, are given (Urey and Craig, 1953). As an approximation to the fractionation process, we subtract from the parent chondritic melt (column 1) enough of the final liquid (eucritic; column 2) to use all the CaO in the parent melt. The residue (column 3) corresponds to the magnesian pyroxenes and



Table 15.

Chemistry of Fractional Crystallization  
of a Melt of Meteoritic Composition

	1	2	3
	Average Chondrite  (Urey and Craig, 1953)	Stannern (Eucrite)	Residue, after deriving 2 from 1  (100% silicate basis)
SiO <sub>2</sub>	38.04	47.94	47.0
MgO	23.84	7.14	36.6
FeO	12.45	20.05	14.1
Al <sub>2</sub> O <sub>3</sub>	2.50	11.19	0.6
CaO	1.95	10.36	0.0
Na <sub>2</sub> O	0.98	0.75	1.4
K <sub>2</sub> O	0.17	0.13	0.2
Fe+Ni	13.09	--	--
FeS	5.73	0.86	--

olivines removed during the early and intermediate stages of cooling, except for the anomalous content of alkali metals.

Then the various rock types formed from the melt would have appeared in the following proportions:

	Weight %	Volume %
Eucrite (Col. 2)	18.8	21.8
Ultrabasics (Col. 3)	63.2	68.0
Troilite	5.7	4.4
Metal	12.3	5.8

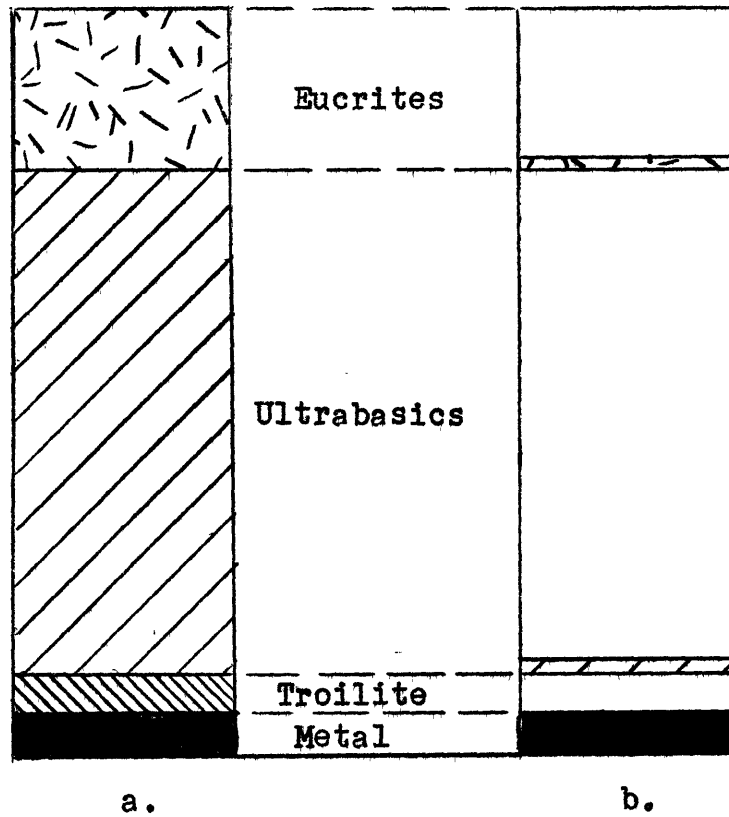
The volume percentages appear graphically in Figure 11a. Now consider the number of falls, from Table 11, of the various types of non-chondrites; these should be proportional to the volume occupied by the respective types in the parent meteorite planet:

	Falls	Percentage, on basis of Metal = 5.8
Eucrites	14	1.9
Ultrabasics (aubrites, diogenites, chassignites, nakhlites, angrites)	15	2.0
Troilite	0	0.0
Metal (irons, pallasites, ureilites*, siderophyres, lodranites**)	43	5.8

\* Assumed to be related to the iron core because of their content of diamonds.

\*\* Mesosiderites will be considered separately.

Figure 11. Proportions of Non-chondrites



Derived from chondrite by melting and frac- tional crystallization	On the basis of falls (calculated so metal phase equals that in a.)
--	---

The number of falls is plotted in Fig. 11b. The proportions of meteorite types encountered in the two cases bear no resemblance to each other. From this we conclude that either

a) The model under consideration, that of the non-chondrites having been formed by melting chondritic rock, is completely wrong, or

b) the proportions of meteorite types based on falls are enormously biased; that, relative to the number of irons which are seen to fall,

100% of troilite meteorites

97% of ultrabasic igneous achondrites

91% of eucrites

are for some reason missing from the record. Before this second alternative is dismissed, it will be interesting to consider perhaps the most puzzling aspect of the meteorites as we know them.

4. The Question of Pressure. In Fig. 12, the equilibrium curve along which diamond and graphite can coexist, on the basis of thermochemical data (Rossini and Jessup, 1938) is plotted. The diamond-bearing octahedrites and ureilites must have occupied pressures and temperatures above this curve until the disruption of the parent meteorite planet. Why were they at such high pressures? Presumably because they were at the center of a planet, and

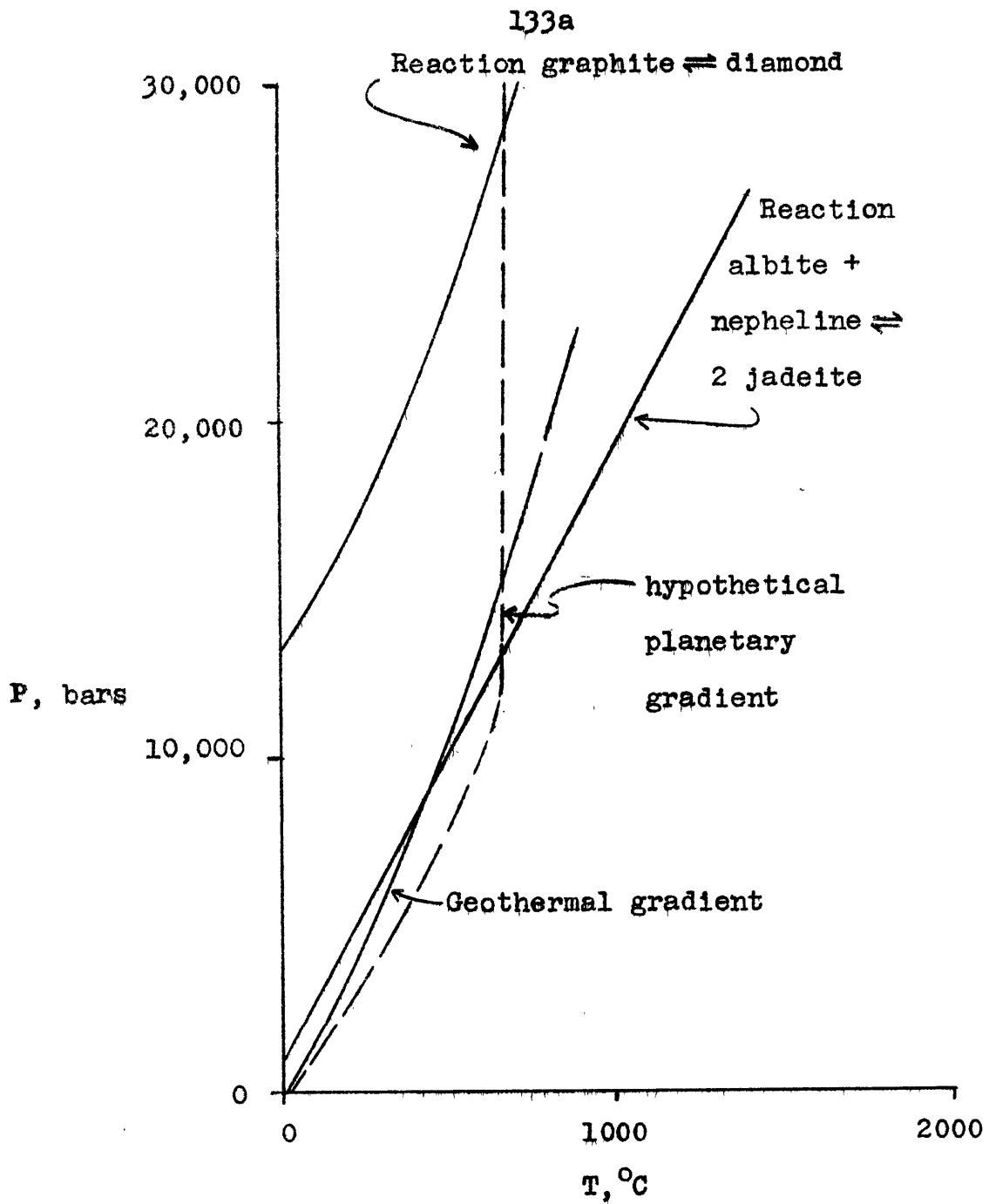


Figure 12. Graphite-Diamond (Rossini and Jessup, 1938) and Albite-Nepheline-Jadeite (Robertson, Birch and MacDonald, 1957) Equilibria.

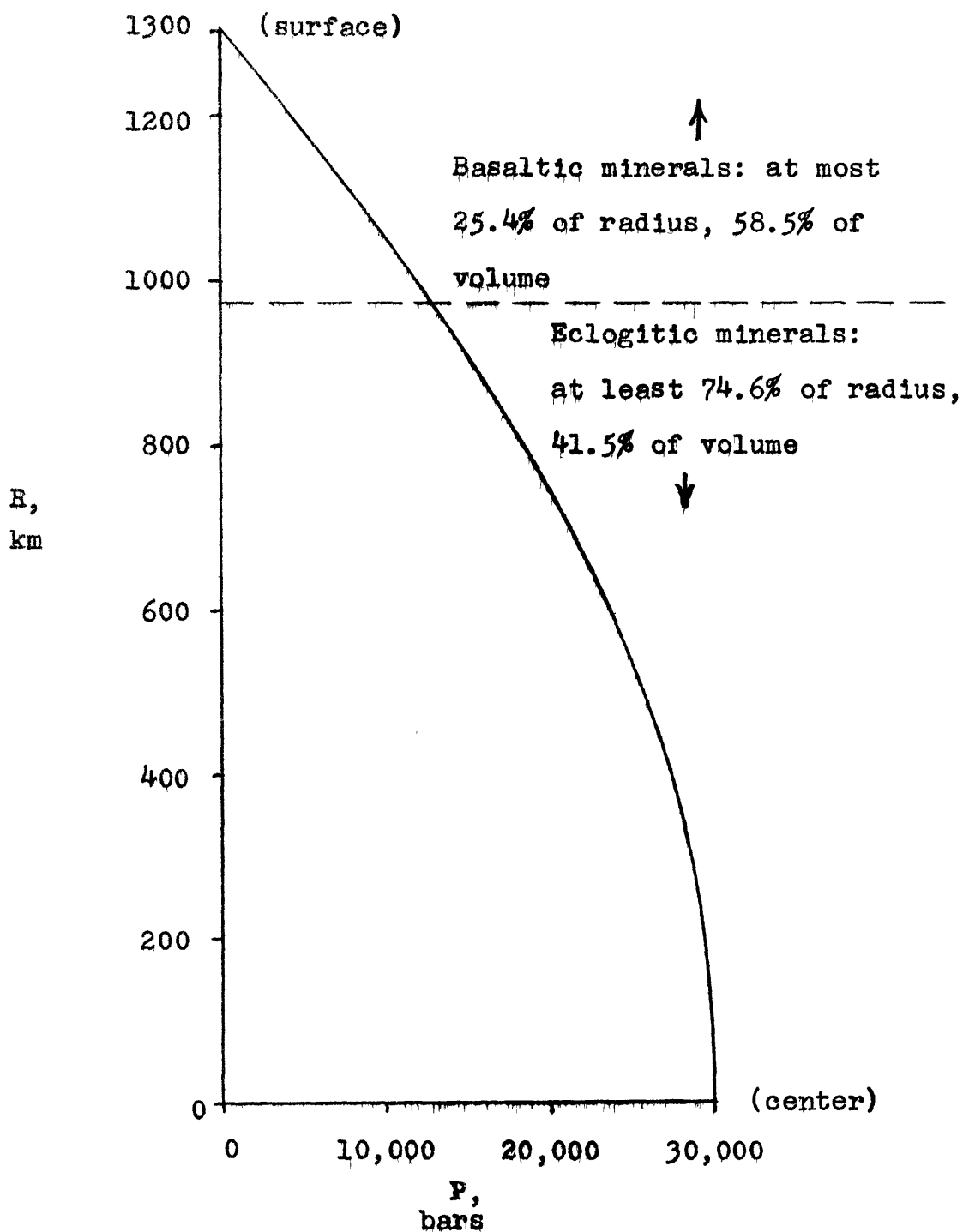


Figure 13. Mineral Stability in the Hypothetical Parent Meteorite Planet



the plot above this curve.

Let us consider a hypothetical parent meteorite planet, just large enough for diamond to be stable at its center. We will assume a thermal gradient in the planet, at the time of disruption, as shown in Fig. 12. This gradient\* requires that all heat generation take place in the outer layers of the planet; and along with the total size of the planet, was contrived to minimize the percentage of planetary matter which would have been subjected to conditions where the eclogite assemblage was the stable configuration.

In Fig. 13, pressures are converted to depth (making the approximation that  $\rho = \text{const.}$  in the body), and we are able to see that no matter what planetary model we assume, in order for diamond to be stable in the center of a planet, roughly half the volume of the planet (at least) must have

\*The central temperature and pressure ( $675^{\circ}\text{C}$  and  $3 \times 10^4$  bars) assumed is in disagreement with that ( $< 400^{\circ}\text{C}$ ,  $10^5$  bars) which Uhlig (1954) finds on the basis of metallographic study of the iron meteorites. Two factors, which were not taken into account in his study, might significantly alter the inferred temperature and pressure. 1) Diffusion rates in solids are decreased by the application of pressure. 2) Besides the  $dT/dP$  effect considered by Uhlig, the application of pressures as high as  $10^5$  bars might be expected to affect a phase diagram by causing phase boundaries to change in slope, stability fields to shrink, etc.



been within the stability field of the eclogite minerals.

The embarrassing fact is that no meteorites are known to contain eclogite minerals. And of all the classified meteorite falls, aggregating 633, only 46:

- 2 Ureilites
- 2 Chassignites
- 1 Angrite
- 2 Pallasites
- 1 Lodranite
- 38 Irons

are free of plagioclase feldspar, hence could exist unchanged in the eclogite stability field.

So we see that at least 93% of the meteorite falls must have come from the outer half of the volume of the parent planet -- only 7% could have existed in the interior half. Of this 7%, 6% are irons, hence presumably were at the core --- there is an almost complete deficit of meteorite types which could have occupied the 50% of volume overlying the core!

This lends credibility to the alternative conclusion considered in the last section, that the meteorite falls are not representative of the abundances of meteorite types in the parent body.

What factors would tend to bias the proportions of meteorite falls? For one thing, the behavior of the

different types of rock during disruption of the parent planet; for another, their behavior during passage through the earth's atmosphere. Neither process can be discussed in any detail, but both will depend on the strength and coherence of the meteorites. We can make some statements about relative strengths of meteorite types derived from sudden disruption of the planet model discussed thus far.

a) The ultrabasic achondrites would be inherently more weakly aggregated than the iron and stony-iron meteorites, the troilite meteorites, and the recrystallized chondrites. The crystals comprising the ultrabasic achondrites froze in the body of the silicate melt, then sank to the floor, forming 'sedimentary' layers, bonded by the small amount of residual melt in their interstices. The crystals of the other meteorite types grew in place, forming stronger interlocking fabrics.

The eucrites grew not by crystal settling, but by freezing in place. The textures of eucrites (see Stannern, Plate XIV) corresponds closely to terrestrial diabases, which are always found in shallow dikes and sills. Presumably, during the late stages of cooling, some of the late residual liquid was intruded into joints and faults in the overlying solid chondritic 'mantle'; the remainder cooled in place. We have only one sample of this latter meteorite type, the Moore County eucrite (Henderson and Davis, 1936;

Hess and Henderson, 1949), which has a eucritic mineralogy, but a coarser texture, and an oriented, non-ophitic fabric which suggests crystal settling. Its grains are very weakly bonded.

b) The crystals which grew under high pressure must expand instantaneously at the moment of disruption. If they expand anisotropically, as all crystals except those in the isometric (cubic) system will, and if they are randomly oriented in the meteorite, the sudden expansion will exert a weakening, disrupting influence on the aggregation\*. The irons would not suffer from this effect, for they are composed of kamacite and taenite, which have cubic symmetry; nor would the stony-irons, where the anisotropically expanding grains of olivine, etc. are encased in iron, which because of its malleability can adjust to the differential expansion. In the deeper igneous achondrites, this expansion might consistently shatter their in-

---

\*For quartz, at 75°C,

$$\Delta L/L_0 \approx .0119 \text{ parallel to } c$$

$$\approx .0171 \text{ perpendicular to } c$$

for  $\Delta P = -20,000$  bars (Bridgman, 1928). The effect is of the same order as heating a rock to 1000°C and quenching it instantaneously, except that the analogue involves both expansion and contraction.

initially weak bonding. Chassigny, one of the two chassignite falls (which should have been one of the most abundant types, according to the crystal fractionation model) "scratches glass, but with difficulty, because of its tendency to crack and be crushed beneath a weak pressure" (Damour, 1862).

c) The troilite meteorites would suffer from two effects: anisotropic decompression, and passage through the earth's atmosphere (troilite melts at  $1193^{\circ}\text{C}$ , the lowest temperature of any important meteoritic mineral). It is, of course, questionable whether these would serve to completely eliminate the troilite meteorites from the record, both of falls and finds.

d) Recrystallized chondrites would be relatively durable, having come from lesser pressures than the ultrabasic chondrites, and having more close-knit metamorphic textures. Shallow intrusive eucrites also satisfy these conditions. Shallower chondrites, only partly recrystallized, could not as frequently make their way intact to the earth's surface.

### C. THE PARENT METEORITE PLANET

The preceding consideration of relative integrity of the meteorite types seems in accordance with the postulated bias in numbers of types seen to fall. After a brief

review of the central-melting model, several hitherto neglected meteorite types will be considered in the light of this model.

1. Review of Central-Melting Model.

- a) Homogeneous sphere,  $R \sim 1000 - 2000$  km (somewhat smaller than the moon), composed of chondrules and dust; at a uniform, (moderately high?) temperature from impacts sustained during accretion.
- b) Cooling at shallow depths, heating in interior from radioactive disintegration; melting of the interior ( $\sim 50\%$ ) of the body.
- c) Separation of a liquid iron phase, which sinks to the center, a liquid troilite phase which overlies it\*, and a liquid silicate phase between the troilite and overlying unmelted chondritic material.
- d) Beginning of cooling; settling of early-formed mag-

---

\* The concept of a sulfide zone between the iron core and silicate mantle in the earth was introduced by Goldschmidt (1922), who pointed out the analogy between the earth and metallurgical smelting processes.

nesian olivine on top of troilite layer.

- e) Crystallization and settling of the bulk of the silicate magma as olivines and pyroxenes, leaving great thicknesses of chassignite and later diogenite; residual liquid becomes eucritic in composition. Crystallization of iron core. Recrystallization of deeper portions of the unmelted chondritic material.
- f) Faulting and jointing in the unmelted chondritic layers; intrusion of eucritic dikes. Cooling in place of the remaining silicate melt. Crystallization of the troilite layer.
- g) Collision and breakup, involving almost complete destruction of the deep-seated igneous rocks.

2. Enstatite Chondrites and Aubrites. The enstatite chondrites (see Khairpur, Plate X) are puzzling. Their silicate fractions do, indeed, consist almost wholly of enstatite. From the almost complete eradication of chondritic structure in them, we infer that they occupied positions low in the unmelted sequence. Possibly they might have comprised the "ceiling" of the magma chamber.

If so, the enstatite chondrites might have gained their mineral composition by reacting with the melt at a time when enstatite was the solid phase in equilibrium with it. That the melt was once in this state is attested by the

## Plate XV.

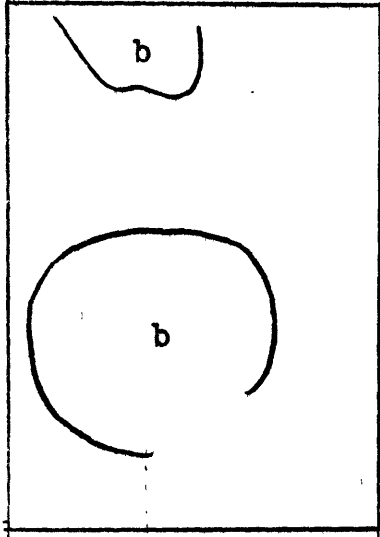
LUMPKIN, Georgia, U.S.A.

Crystalline spherical hypersthen-  
chondrite

46x, Plain polarized light

1 mm.

in photograph

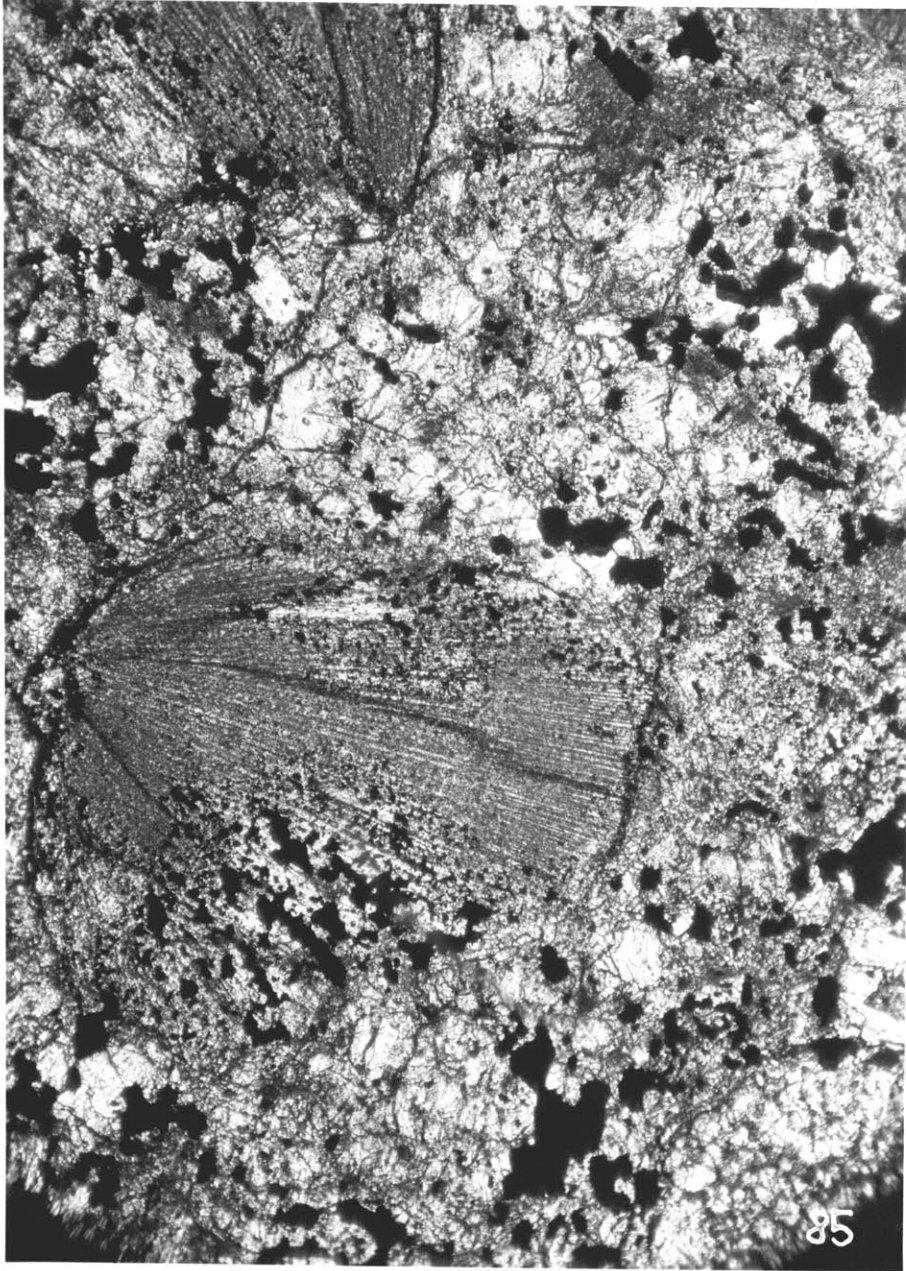


An excellent illustration of  
recrystallization in chondrites.

Two radiating orthopyroxene chondrules (b) are seen in all stages of recrystallization, from fine, uniformly fibrous to coarsely granular orthopyroxene. Recrystallization makes apparant the amount of finely disseminated iron which was contained in the chondrules.

Larger matrix grains are usually olivine; the opaque areas are nickel-iron.

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## Plate XVI.

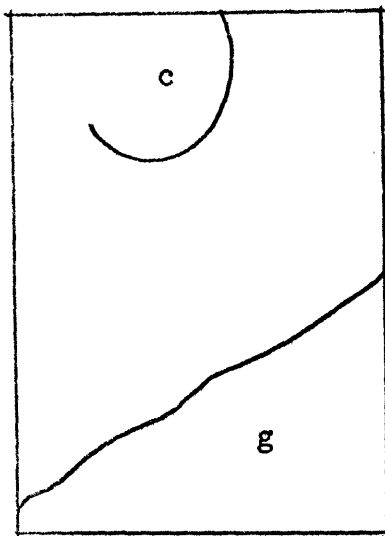
MANBHOOM, India

Monomict Brecciated Amphoterite

46x, Plain polarized light

1 mm.

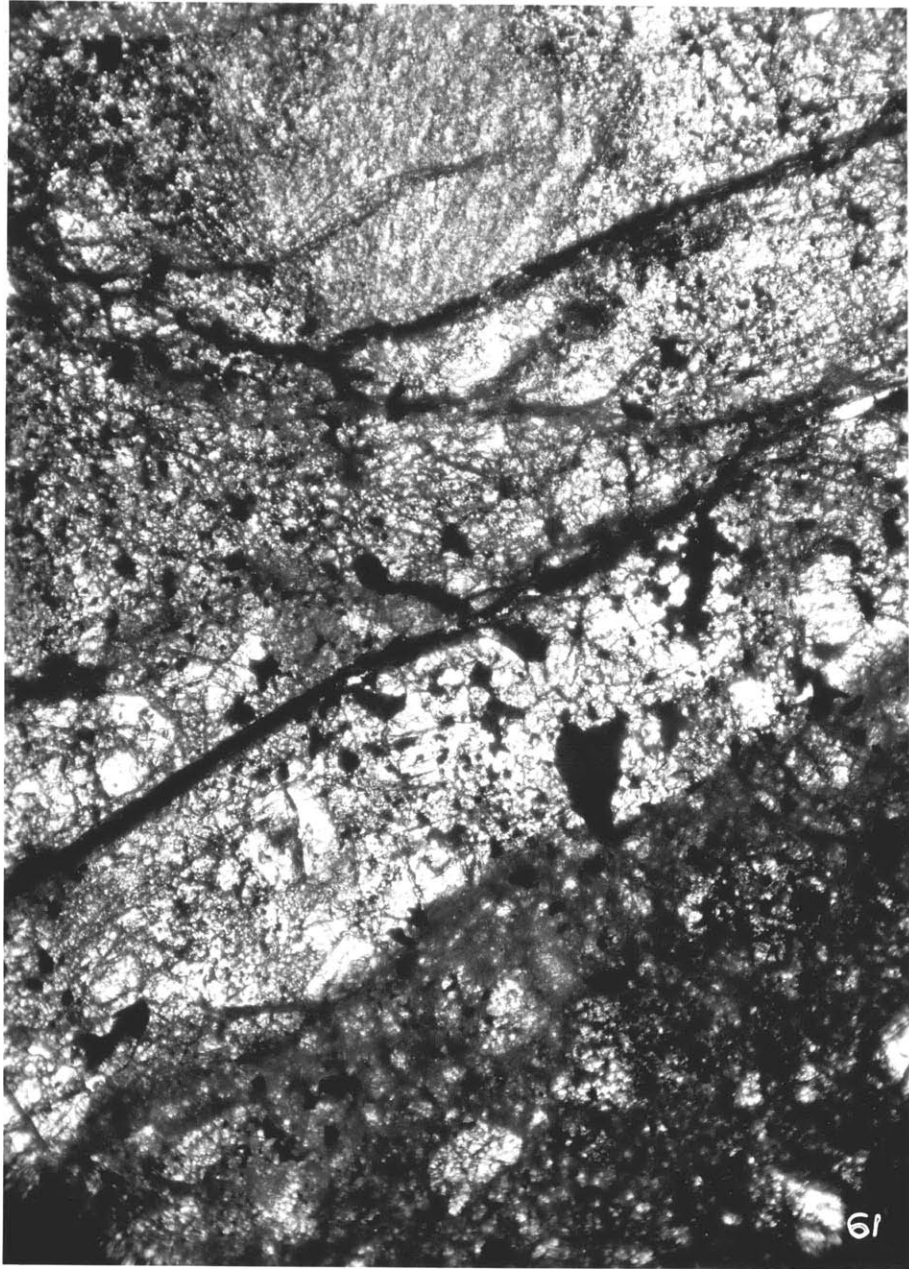
in photograph



Manbhoom consists of an aggregation of extremely fine grains of silicate ( $< .02\text{mm}$ ), much like those that comprise Goalpara and

Mincy, ureilite and mesosiderite respectively. Occasional coarser grains of olivine and orthopyroxene may be recognized. Several relict chondrules are to be seen in this unusual matrix, faded, but unmistakable. One may be seen at c in the photograph. The area g is a finely pulverized gouge, containing some larger angular particles. Metal occurs in grains as large as 1 mm, but most of it is in fine particles, disseminated through the silicate.

~~144~~ 145



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## Plate XVII.

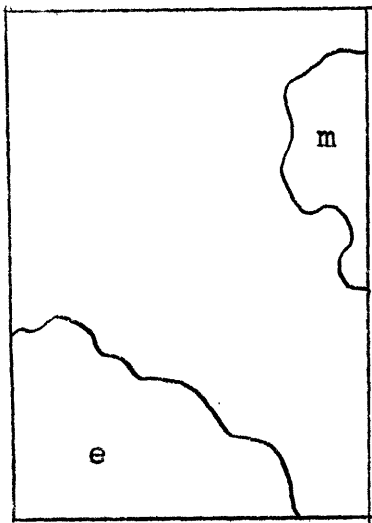
FRANKFORT, Alabama, U.S.A.

Howardite

46x, Plain polarized light

1 mm.

in photograph

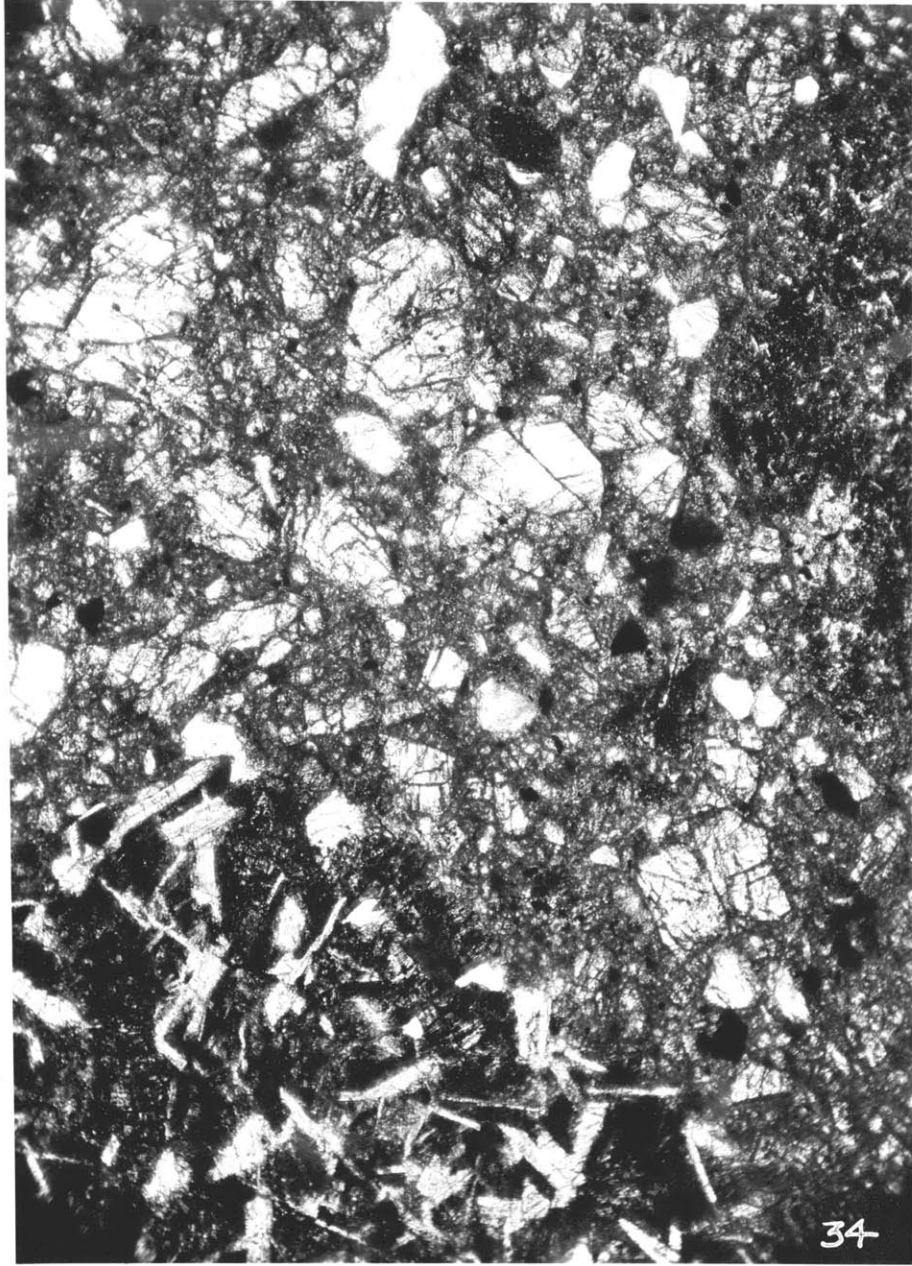


A good example of a polymict breccia. Most of the field in the photograph is a fine gouge, containing broken crystals, up to 1mm,

of orthopyroxene and olivine (largely the former).

e is an area of eucritic composition, displaying the characteristic ophitic texture. Sharp boundaries against the surrounding gouge indicate that e had completely crystallized at the time of brecciation. m, however, is separated from the gouge by an indistinct, re-entrant outline, and is extremely fine grained (plagioclase laths are recognizable). Apparently it was liquid during brecciation. No fragments of chondrites, or grains of metal, can be seen in the section.

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## Plate XVIII.

ST. MESMIM, France

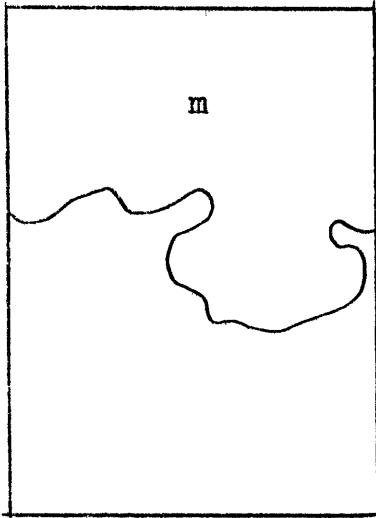
Polymict brecciated intermediate  
hypersthene-chondrite

46x, Plain polarized light

1mm,



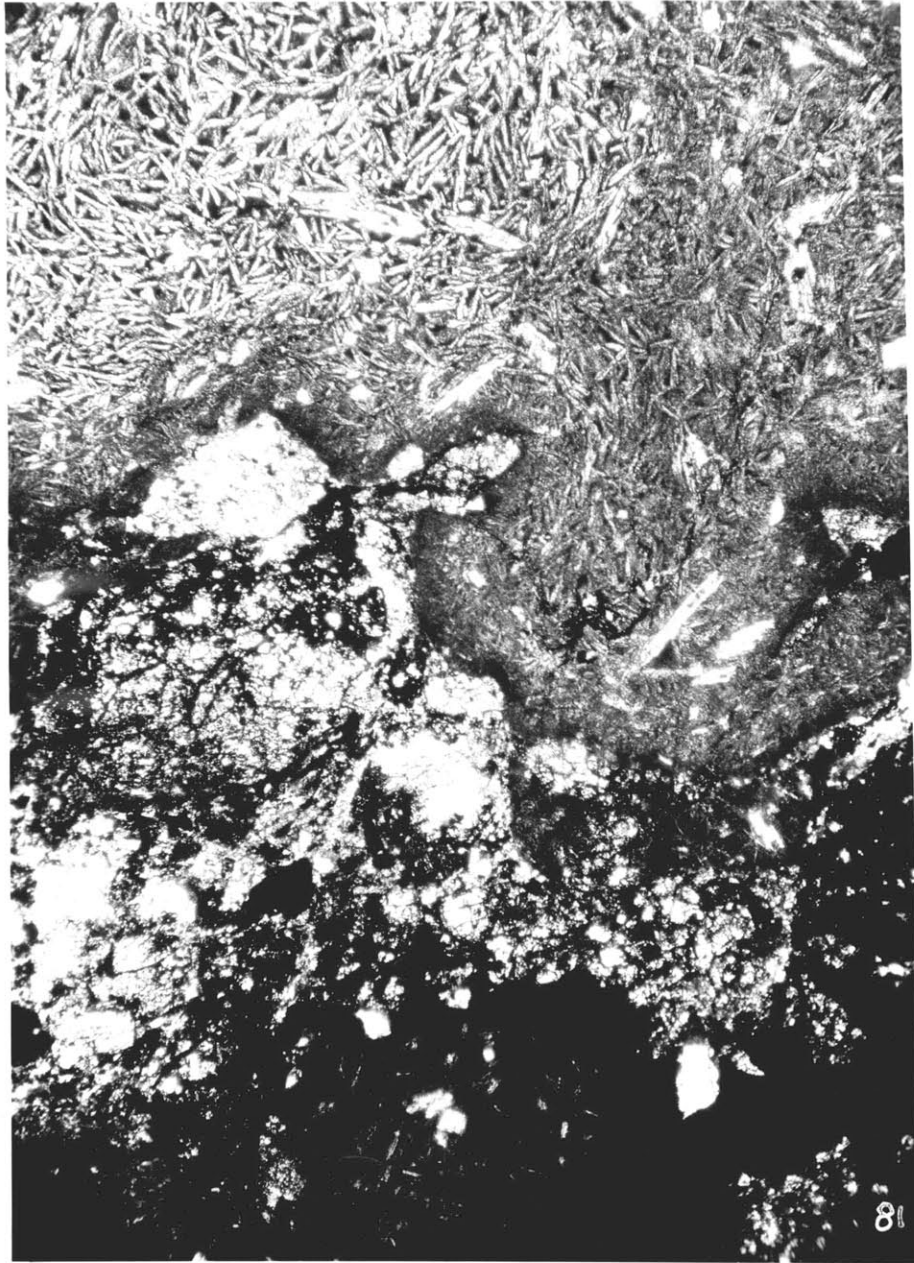
in photograph



Part of the section (not  
visible in photograph) is an  
orthodox chondrite, little re-

crystallized. m was clearly molten silicate at the time of brecciation-- note the re-entrant contact, and chilled border. The laths are not feldspar, but appear (from birefringence) to be olivine, such as that seen in the uppermost chondrule in Plate IV. Hence the melt was not eucritic, but of a composition having a higher melting-point than eucrite. The opaque area at the bottom of the photograph is part of a 3 mm metal grain, whose shape indicates that it too was liquid during brecciation.

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## Plate XIX

GOALPARA, India

Ureilite

46x, Plain polarized light

1 mm.

  
in photograph

Goalpara is a collection of particles, 1 - 2 mm, with rounded edges, of two types: 1) consisting of an agglomeration of extremely fine silicate crystals, as the transparent areas in the photograph; and 2) single crystals of olivine and orthopyroxene, densely charged with fine iron grains. The extensive opaque matrix joining the major particles contains much finely disseminated iron, but consists largely of some other, non-reflecting opaque substance.

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existence of aubrites. We might surmise that this was the terminal stage of cooling, since the enstatite chondrite ceiling (?) has not undergone further reaction, and since the aubrites contain oligoclase, a feldspar much more sodic (hence later) than the bytownite-anorthite of the eucrites. On the other hand, Mg rich minerals always crystallize early, becoming progressively more ferrous during crystal fractionation. It is unthinkable that the final liquid in the crystallization of a basic magma should have the composition of enstatite (although enstatite pyroxenite veins are frequently observed to cut earlier, more ferrous peridotites). No reasonable explanation for the existence of enstatite chondrites suggests itself.

3. The Stony-Irons, Ureilites. The existence of silicate crystals suspended in (still liquid) nickel iron is very difficult to explain. It seems unlikely that crystals settling to the floor of the magma chamber would submerge themselves to any degree in liquid iron; in addition, the model considered interposes a troilite layer at the interface.

The stony-irons might be more understandable if it could be shown that the silicates crystallized within the iron melt, rather than without. The presence of finely dispersed particles of solid oxides (e.g.,  $\text{SiO}_2$ ) in liquid

steel is a familiar (and unwelcome) phenomenon. The particles are too small for gravity to effectively remove over economic periods of time (Schenk, 1945, p. 531). During the melting and differentiation of the interior of a planet, the metal phase would certainly have the opportunity to become charged with such impurities. A much longer period of time would be available for gravity to remove them, but the force of gravity near the center of the planet would be very small.

Metallurgical practice is to act to increase the FeO content of the steel, thereby causing the  $\text{SiO}_2$  to melt as ferrous silicates; in liquid form, the particles soon coalesce into droplets large enough for gravity to effectively remove.

It is possible that the complex process of crystallization of the core might have given rise to conditions which favored such a "purging" of the iron of finely disseminated, highly magnesian silicates, in the form of liquid globules of somewhat more ferrous silicate. Crystallization of these globules could account for the rounded-off form of the olivine crystals in pallasites.

Ureilites are described in Table 11. Their finely polycrystalline textures could have been produced by some type of agglomeration of the dispersed silicates, not in-

involving melting.

4. Howardites, breccias. These are presumably produced during faulting of the solid rock in the planet, in the case of the howardites involving the introduction of eucritic magma along the fault plane. Wahl (1952) interprets the polymict breccias as sediments, but thin sections of Petersburg and Frankfort (see Plate XVII) (howardites) bear closer resemblance to fault gouges. Petersburg contains one particle of a distinctive type which has been broken and the fragments somewhat separated, all in a matrix of finely pulverized silicate.

St. Mesmin, classified as a chondrite, contains also several irregular blobs of rapidly chilled lava (see Plate XVIII). This might have been associated with igneous activity, or it may have been due to local heating by mechanical energy during the breakup.

5. Sherghottites are eucritic dike rocks, in which plagioclase glass is pseudomorphous after ophitic plagioclase. Here an interesting tale is recorded. The rock must have been reheated, since the plagioclase has obviously once been crystalline. It must have been heated impulsively, as by a mechanical shock, or (effectively) by the release of pressure from a eucrite barely below its melting point, because slower heating would have caused eutectic melting at the grain boundaries, rather than

complete melting of one of the mineral phases. And it must have cooled rapidly, in order to prevent crystallization of the molten plagioclase. The process may very likely have been associated with the breakup of the planet, but a satisfactory explanation is not immediately obvious.

6. Mesosiderites. These, comprising the majority of the stony-iron falls, have not been considered with the other stony-irons. The mesosiderites differ fundamentally from the pallasites, siderophyres and lodranites:

a) In their major minerals; the mesosiderites have mineralogies corresponding closely to the chondrites. They contain feldspar, hence would not have been stable in the lower 50% of the proposed planet, where the diamond-bearing octahedrites and ureilites must have occurred, and where it is inferred that the other irons and stony-irons occurred.

b) In accessory minerals (see Table 11).

c) In texture - the mesosiderites usually consist of a uniform granular aggregate of silicates and iron (see Mincy, Plate XII), rather than the euhedral-silicates-in-iron-matrix fabric seen in the other stony-irons.

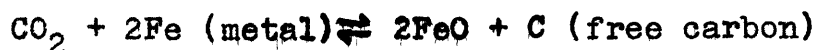
One possible explanation is that the mesosiderites represent the core of the second, smaller parent meteorite planet (supposedly the outer, low iron group planet).

Because of its smaller size, melting might have taken place only at the center, and there only incompletely. Just enough mobility might have been obtained to allow a concentration of iron toward the center, the final product being a rock such as Mincy. •

7. Occluded Gases and the Carbonaceous Chondrites.

Wright (1876) found that chondrites, on being heated to redness, emitted about twice their own volumes of gas (Cold Bokkeveld, a carbonaceous chondrite, over twenty times its volume). Spectroscopic examination of the gases indicated that they consisted mainly of CO<sub>2</sub> and CO, and also contained H<sub>2</sub>, N<sub>2</sub> and CH<sub>4</sub>.

These gases may be identified with those postulated to be adsorbed on the dust fraction before accretion (part II). The central melting, and strong thermal gradient imposed on the unmelted chondrite sequence would cause an outward diffusion of these gases. On more massive planets, they would be retained and modified as atmospheres. In the parent meteorite planet, since the surface is at very low temperature, the upward-diffusing CO<sub>2</sub> must eventually reach a depth at which the temperature allows the reaction



to proceed to the right. Representatives of this depth

would be the carbonaceous chondrites, with their high content of carbon and oxidized iron, and low content of metallic iron. The high percentage chondritic structure and friability of this class of chondrites attests to the shallow depth at which the reaction occurred.

8. Amphoterites. These often show relict chondrules; the thin-section of Manbhoom contains several, one of which appears in Plate XVI. The mineralogy and chemistry of amphoterites correspond to those of chondrites, except for a low content of metallic iron. It would appear that these are a special case of the (re-crystallized) chondrites, and should not be grouped with the achondrites.

IV. SUMMARY

Unless we have completely misinterpreted the meaning of meteorites, we have in them a valuable key to studies of the origin and evolution of the earth, and possibly to the formation of the solar system.

The writer has been guided by the convictions that 1) the ever-increasing amounts of valuable chemical and isotopic research on meteorites should be supplemented by a good, hard look (i.e., petrographic) at the subjects of the study; 2) that, since the meteorites are rocks, petrology should be one of the most important disciplines involved in their study; and 3) that petrography and petrology are helpful only when considered in the context of the whole, complex problem of planetary genesis. This last conviction has unfortunately led to consideration of such a diversity of phenomena that none are covered in adequate detail.

The petrography of the meteorites poses several questions; possible answers, a few suggested by the writer, were considered:

Are the chondrites, with their unique type of texture, analogous to terrestrial rocks? The possibility is explored that they correspond to sedimentary and metamorphic rocks.

Where did the chondrules come from? It is postulated that they were primary objects which condensed during the

formation of the solar system, and this complex process investigated. It seems possible that the proposed model can account for the densities of the terrestrial planets.

If the achondrites are indeed analogous to terrestrial differentiated basic igneous rocks, why do they not fall in numbers proportionate to the expected volumes of the various rock types?

If the center of the parent meteorite planet is at high enough pressure to produce diamonds, where are the eclogitic mineral assemblages which should have occupied the interior of the planet? It is suggested that much of the interior of the planet was composed of chassignites and diogenites, which were more effectively pulverized during disruption of the planet than were the overlying chondrites.

Fig. 14 is a cross-section of the parent meteorite planet, according to the various proposals advanced.

#### ACKNOWLEDGMENTS

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labor in reproducing it in thesis form, and under a severe time limit. The research was conducted under the employment of the Smithsonian Astrophysical Observatory, which will issue it as a report, and which has permitted it to be submitted as a thesis.

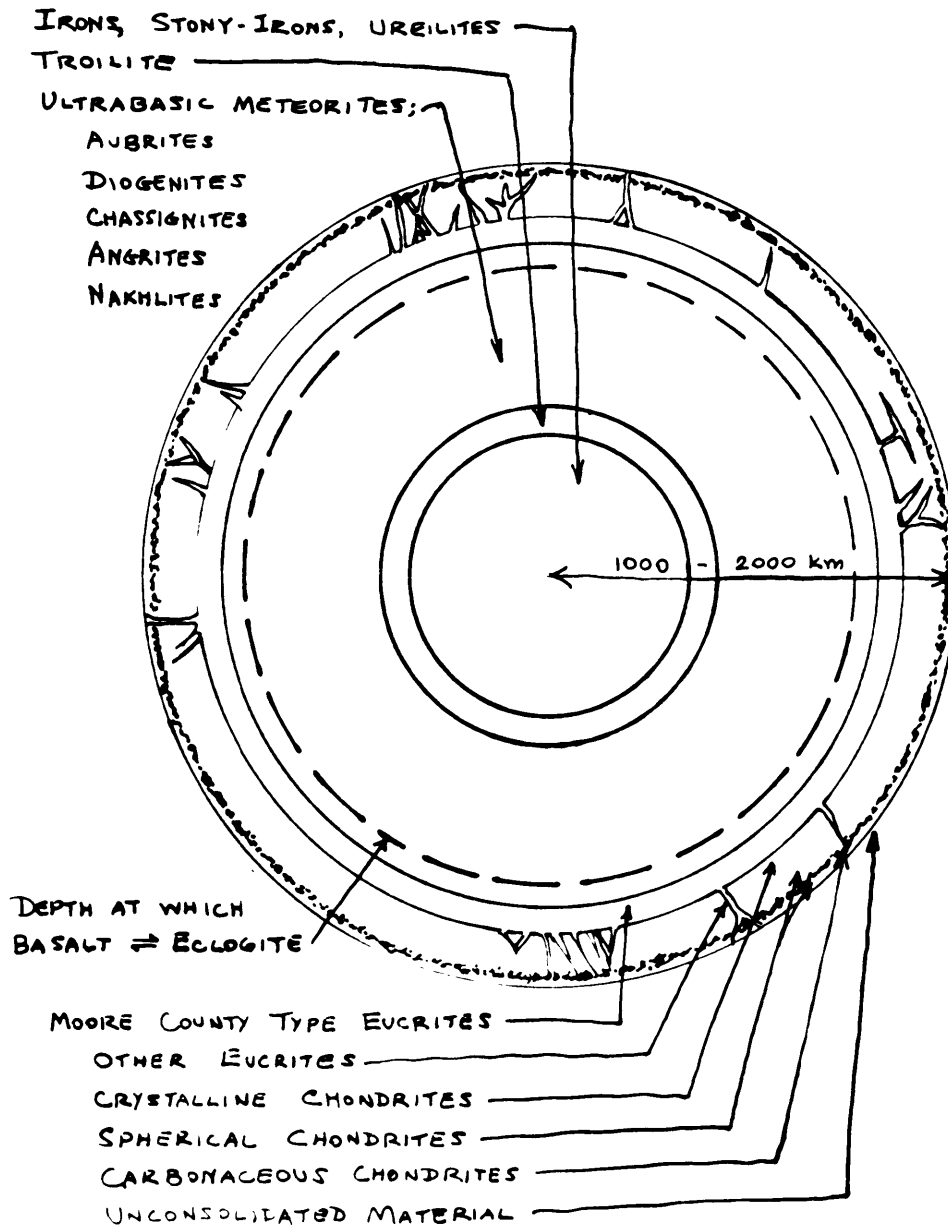


FIGURE 14. THE PROPOSED PARENT METEORITE  
PLANET

## BIBLIOGRAPHY

- Alfven, H., 1954, On the Origin of the Solar System, Clarendon Press, Oxford.
- Allan, D. W., and Jacobs, J. A., 1956, The Melting of Asteroids and the Origin of Meteorites, Geochim. et Cosmochim. Acta, 2, 256.
- Aller, L. H., 1954, Astrophysics: Nuclear Transformations, Stellar Interiors, and Nebulae, Ronald Press, N. Y.
- Aller, L. H., 1958, The Abundances of the Elements in the Sun and Stars, Handbuch der Physik, Chap. 9c, Part X, Vol. 2.
- Anderson, O., 1915, The System Anorthite - Forsterite - Silica, Am. Jour. of Sci., 4th Ser., 39, 440.
- Brewer, L., 1946, Report for the Manhattan Project MDDC - 438c.
- Bridgman, P. W., 1928, The Linear Compressibility of Thirteen Natural Crystals, Am. Jour. Sci., 15, 287.
- British Association for the Advancement of Science, 1932, Mathematical Tables, Vol. II, London.
- Buddington, A. F., 1943, Some Petrological Concepts and the Interior of the Earth, Am. Mineral., 28, 119.
- Bullard, F. M., 1939, The Rosebud Meteorite, Am. Mineral. 24, 242.
- Daly, R. A., 1933, Igneous Rocks and the Depths of the Earth, McGraw-Hill Inc., N. Y.

- Damour, M. A., 1862, Note sur la pierre meteorique de Chassigny, Comptes Rendus Acad. Sci. Paris, 55, 591.
- Dollfus, A., 1954, L'Astronomie, 68, 337.
- Emden, R., 1907, Gaskugeln, Leipzig, Berlin.
- Farrington, O. C., 1915, Meteorites, (Publ. by the author), Chicago.
- Foshag, W. F., 1941, Problems in the Study of Meteorites, Am. Mineral., 26, 137.
- Geiss, J., and Hess, D. C., 1958, Argon-Potassium Ages and the Isotopic Composition of Argon from Meteorites, Ap. J., 127, 224.
- Goldschmidt, V. M., 1922, Der Stoffwechsel der Erde. Norsk. Videnskapsselskapets Skrifter, 1. Mat. - Naturv. Klasse No. 11.
- Henderson, E. P., and Davis, H. T., 1936, Moore County, N.C., Meteorite - a New Eucrite, Am. Mineral., 21, 215.
- Hess, H. H., and Henderson, E. P., 1949, The Moore County Meteorite: a further study with Comment on its Primordial Environment, Am. Mineral., 34, 494.
- Hoyle, F., 1955, Frontiers of Astronomy, Harper and Bros., New York.
- J Jeans, Sir J. H., 1929, Astronomy and Cosmology, Cambridge U.P.

- Kvasha, L. G., 1948, Investigation of the Stony Meteorite Staroye Boriskino, Meteoritica, Acad. Sci. USSR, 4, 83.
- Leonard, F. C., 1956, A Classificational Catalogue of the Meteoritic Falls of the World, U. of Cal. Press, Los Angeles.
- Lovering, J. F., 1957a, Differentiation in the Iron-Nickel core of a Parent Meteorite Body, Geochim. et Cosmochim. Acta, 12, 238.
- Lovering, J. F., 1957b, Pressures and Temperatures within a Typical Parent Meteorite Body, Geochim. et Cosmochim. Acta, 12, 253.
- Patterson, C., 1955, The  $Pb^{206}/Pb^{207}$  Ages of some stone Meteorites, Geochim. et Cosmochim. Acta, 7, 151.
- Prenzel, 1893,  
Mem. Soc. Nat. Russie, Odessa, p. 18.
- Prior, G. T., and Hey, M. H., 1953, Catalogue of Meteorites, British Museum, London.
- Robertson, E. C., Birch, F., MacDonald, G. J. F., 1957, Experimental Determination of Jadeite Stability relations to 25,000 bars, Am. Jour. Sci., 255, 115.
- Rossini, F. D., and Jessup, R. S., 1938, Heat and Free Energy of Formation of Carbon Dioxide, and of the Transition between Graphite and Diamond, J. Research Nat'l. Bur. Standards, 21, 491, (Research Paper No. 1141).
- Sandberger, F. von, 1899,  
Neues Jb. Min. Geol. Paläont., 2, 173.

- Schenk, H. G., 1945, Introduction to the Physical Chemistry of Steelmaking, The British Iron & Steel Research Association, London.
- Smith, W. Campbell, 1950, Stony Meteorites, The Advancement of Science, No. 26.
- Struve, O., 1950, Stellar Evolution, Princeton, U.P.
- Turner, F. J., and Verhoogen, J., 1951, Igneous and Metamorphic Petrology, McGraw-Hill, Inc., N. Y.
- Uhlig, H. H., 1954, Contribution of Metallurgy to the Origin of Meteorites, part I - Structure of Metallic Meteorites, their Composition and the Effect of Pressure, Geochim. et Cosmochim. Acta, 6, 282.
- Urey, H. C., 1951, The Origin and Development of the Earth and Other Terrestrial Planets, Geochim. et Cosmochim. Acta, 1, 207.
- Urey, H. C., 1952, The Planets, Yale University Press, New Haven.
- Urey, H. C., 1956, Diamonds, Meteorites and the Origin of the Solar System, Ap. J., 124, 623.
- Urey, H. C., 1957, Meteorites and the Origin of the Solar System, Year Book of the Physical Society, 14.
- Urey, H. C. and Cragin, H., 1953, The Composition of the stone meteorites and the origin of the meteorites, Geochim. et Cosmochim. Acta, 4, 36.
- Urey, H. C. and Donn, B., 1956, Chemical Heating for Meteorites, Ap. J. 124, 307.

- Wahl, W., 1952, The Brecciated Stony Meteorites and Meteorites containing Foreign Fragments, Geochim. et Cosmochim. Acta 2, 91.
- Wasserburg, G. J. and Hayden, R. J., 1955,  $A^{40} - K^{40}$  Dating, Geochim. et Cosmochim. Acta 2, 51.
- Wiik, H. B., 1956, Chemical Composition of some stony Meteorites, Geochim. et Cosmochim. Acta 2, 279.
- Wright, A. W., 1876, On the Gases Contained in Meteorites, Am. Jour. Sci. 11, 235.
- Zavaritzky, A. N., 1952, The Meteorites of USSR, Moscow (Acad. Sci. USSR).

## BIOGRAPHY

John Wood was born in Roanoke, Virginia, on 28 July 1932. He attended senior high school in Jacksonville, Florida, graduating in 1950. In 1954, he received the B.S. degree in Geology from Virginia Polytechnic Institute. While there, he was initiated into Sigma Gamma Epsilon (earth sciences) and Phi Kappa Phi (scholarship) honorary fraternities, and received the Geology Department's Holden Prize for scholarship among geology majors.

He enrolled at M.I.T. in the Department of Geology and Geophysics as a doctoral candidate in 1954, and completed the requirements for the degree in June, 1958. During his first two years at M.I.T. he was a third-time teaching assistant, instructing laboratory sections in optical crystallography and petrography. His third year he held a National Science Foundation Fellowship. During his fourth year, he was employed half-time by the Smithsonian Astrophysical Observatory to make a petrographic study of stony meteorites, which was also submitted as a doctoral thesis to the Department of Geology and Geophysics. Petrology and Theoretical Geology were his principal fields of study at M.I.T. He was initiated into Sigma Xi (research honorary fraternity in 1954).

His professional summer field experience has been as follows: 1954- Junior Assistant, Blue Ridge Province of Virginia, Virginia Engineering Experiment Station; 1955- Senior Assistant, Canadian Shield (Western Quebec), Geological Survey of Canada; 1956- Mapping in White Mountains, N.H., for proposed thesis; 1957- Geologist, central New Brunswick, the Anaconda Co. (Canada) Ltd.