

THE MOORE COUNTY METEORITE: A FURTHER STUDY WITH COMMENT ON ITS PRIMORDIAL ENVIRONMENT

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ABSTRACT

The Moore County meteorite in bulk composition resembles a Sudbury norite. The pyroxenes present were initially probably a single phase, pigeonite. This has undergone a complicated series of changes from which it is deduced that the temperature of the original environment was approximately 1135° C. and that the meteorite left this environment with catastrophic suddenness. Investigation of the fabric of the meteorite indicates a dimensional orientation of the plagioclase and pyroxene. The plagioclase *b* and *c* crystallographic axes and the pyroxene *c* axis tend to lie in one plane. The fabric is considered to represent primary layering developed by crystal accumulation on the floor of a magma chamber. Thus crystallization differentiation must have occurred in the original environment.

INTRODUCTION

The Moore County, North Carolina, meteorite, a eucrite, was described in considerable detail by Henderson and Davis (1936). The comment was made that "there is very little bond between the component minerals. In fact the minerals can be easily separated by lightly rubbing the fingers over the surface . . ." "It was found to be almost impossible to make thin sections of this meteorite without causing the mineral grains to completely separate one from another." The present paper is occasioned by the fact that an excellent thin section has now been obtained as a result of which additional significant relations can be recorded and certain modifications of the original paper are in order. G. S. Rev made the thin section after impregnating the material with bakelite.

DESCRIPTION

The meteorite is unique in that it has very little native metal and in that it closely resembles in chemical composition, mineralogy, and texture a terrestrial plutonic igneous rock. The chemical analysis is given in Tables 1 and 2 along with a norite of similar composition from Sudbury, Ontario, for comparison.

The meteorite consists almost entirely of pyroxene and calcic plagioclase. A small amount of tridymite is present interstitial to the above minerals, and small grains of black opaque minerals may be seen in the section. The tridymite contains exceedingly minute colorless needles which appear to be apatite. Sporadic aggregations of equally minute opaque rounded blebs and specks are present in the plagioclase and pyroxene along fracture planes.

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TABLE 1

	Moore City* Eucrite	Sudbury† Norite
SiO ₂	48.16	46.69
Al ₂ O ₃	15.57	14.23
Fe ₂ O ₃	1.90	2.00
FeO	13.98	12.86
MgO	8.41	8.15
CaO	11.08	13.32
Na ₂ O	.45	.98
K ₂ O	.09	.00
H ₂ O+	—	.08
H ₂ O—	—	—
TiO ₂	.32	1.28
Cr ₂ O ₃	.44	—
P ₂ O ₅	—	.19
MnO	.31	.11
S	.30	.12
	101.01	100.01
—O for S	.15	
	100.86‡	

* Analyst E. P. Henderson.

† Washington's Tables p. 666.

‡ Fe₂O₃ was reported as determined, but a considerable part of this is metallic Fe. If all of it is calculated as Fe the summation becomes 100.28.

THE PYROXENE

The bulk of the pyroxene present is pigeonite. It has beautifully developed augite lamellae parallel to {001}. These can readily be seen in the photomicrograph Fig. 1. The augite lamellae are interpreted as having developed in an original homogeneous pigeonite by exsolution during cooling as elaborated further below. Thus the bulk chemical composition of the pyroxene given in Table 3 is believed to represent the composition of the original homogeneous pyroxene crystals which crystallized from a magma in the primordial environment of the meteorite. A further alteration of the pyroxene has taken place, namely the inversion of a small amount of the pigeonite to hypersthene. Small roughly quadrilateral areas bounded by cleavages and augite lamellae have inverted to hypersthene in a few of the pigeonite crystals. This hypersthene is identical to the orthopyroxenes of the Bushveld type described by Phillips and Hess (1938, 1940) and has within it the very fine exsolution lamellae of clinopyroxene parallel to the {100} plane of the orthopyroxene which is

characteristic of this mineral. Although the relationships between the pyroxene phases of the Moore County meteorite may seem to be complex from the above description, each step in the relations is clearly evident in the thin section and each is well known from terrestrial, igneous rock pyroxene relationships. Figure 2 portrays diagrammatically the sequence of changes which are assumed to have taken place in the pyroxene phases, Table 3 gives the bulk composition of the pyroxene as indicated by

TABLE 2. NORMS

	Moore County, Eucrite	Sudbury, Norite
Q	1.68	—
*Pc	$\left. \begin{array}{l} \text{Or} \\ \text{Ab} \\ \text{An} \end{array} \right\} \begin{array}{l} .56 \\ 3.67 \\ 40.31 \end{array} \right\} 44.54$	$\left. \begin{array}{l} .00 \\ 8.38 \\ 34.19 \end{array} \right\} 42.57$
Di	$\left. \begin{array}{l} \text{Wo} \\ \text{En} \\ \text{Fs} \end{array} \right\} \begin{array}{l} 6.03 \\ 2.90 \\ 3.04 \end{array} \right\} 11.97$	$\left. \begin{array}{l} 12.99 \\ 6.50 \\ 6.20 \end{array} \right\} 25.69$
Hy	$\left. \begin{array}{l} \text{En} \\ \text{Fs} \end{array} \right\} \begin{array}{l} 18.10 \\ 20.06 \end{array} \right\} 38.16$	$\left. \begin{array}{l} 10.40 \\ 10.30 \end{array} \right\} 20.70$
Ol	$\left. \begin{array}{l} \text{Fo} \\ \text{Fa} \end{array} \right\} \begin{array}{l} — \\ — \end{array} \right\} 50.13$	$\left. \begin{array}{l} 2.45 \\ 2.55 \end{array} \right\} 5.00$
†Mt	2.78	3.02
Il	.61	2.43
Cm	.67	—
Ap	—	.34
Py	.46	.24
H ₂ O	—	.08
	100.87 CIPW: 3,5,5,—	100.07

Mode †

Tridymite	1.5
Plagioclase	40.0 (Or ₁₅ Ab _{10.7} An _{88.8})
Pyroxene	56.0 (Ca ₁₀ Mg ₄₈ Fe ₄₄)
Opaque	2.5
Apatite	trace
	100.0

* Or₁Ab₉An₉₀

† Part of this is metallic iron.

‡ Only 3.5 sq. cm. available for traverse.

* Or₀Ab₂₀An₈₀

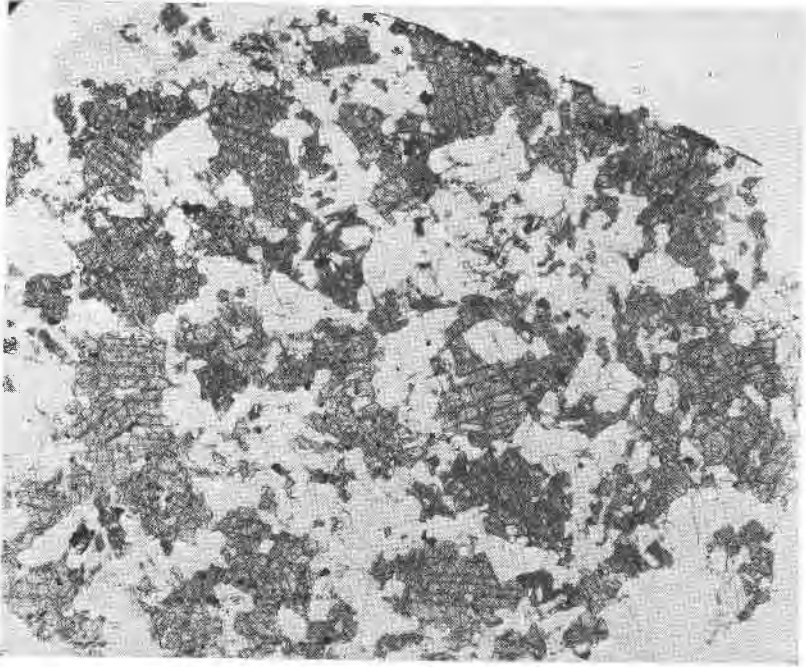


FIG. 1. Photomicrograph of thin section of Moore County, N. C. meteorite. Note augite lamellae in pigeonite are parallel to $\{100\}$ plane. Dark glass of the crust on meteorite is shown on upper right hand edge. This fused crust is about 0.2 mm. thick. It is crowded with small bubbles and passes abruptly into fresh silicates.

chemical analysis and Table 4 gives the optical properties and estimated compositions of the four pyroxene phases now observable.

Pigeonite in terrestrial rocks is only known from rapidly cooled lavas or small hypabyssal intrusives. It has commonly been suggested, because of its association with lavas, that pigeonite may be a metastable phase brought about by rapid chilling. This view however is not substantiated by the petrographic evidence (Hess, 1941, Edwards, 1942). Pigeonite occurs in some volcanic rocks as phenocrysts (Mull, Hallimond 1914 and Hakone, Kuno 1936) evidently of intratelluric crystallization. It has also been a common constituent of plutonic igneous rocks but has in these cases inverted upon slow cooling to the orthorhombic form, hypersthene. Such hypersthene contains exsolved plates of augite in a plane parallel to $\{001\}$ of the original pigeonite and are easily recognized thereby as inverted pigeonites (Hess, 1941, Edwards, 1942). In the case of the Moore County meteorite the crystallization of the original pigeonite was followed, upon cooling, by the exsolution of augite plates parallel to $\{001\}$

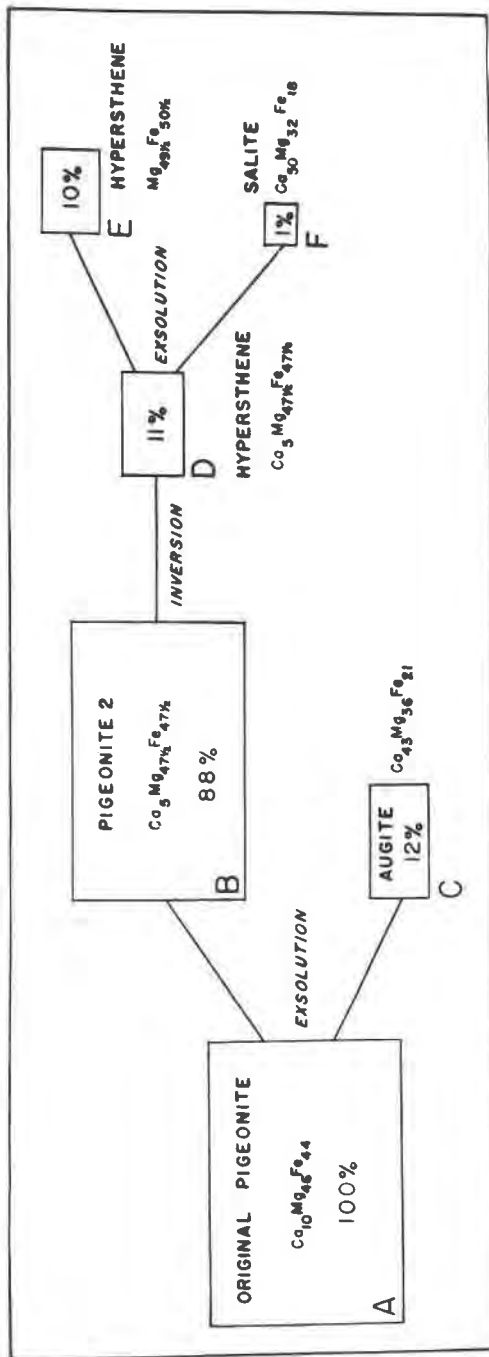


Fig. 2. Diagram to show relationships between the various pyroxene phases.

Solid Phase A Lacking; split into B and C by exsolution. (= chemical analysis)

Solid Phase B Present; approx. 77% of pyroxenic material remaining in the sample.

Solid Phase C Present; 12% of the pyroxenic material remaining.

Solid Phase D Lacking; split into E and F by exsolution.

Solid Phase E Present; approx. 10% of pyroxenic material remaining.

Solid Phase F Present; approx. 1% of pyroxenic material remaining.

TABLE 3. CHEMICAL COMPOSITION OF ORIGINAL PIGEONITE A

		Molec- ular Ratios	Ilmenite Magne- tite	Remain- der	Atomic Ratios		Cations to 6 O	
SiO ₂	49.37	8220		8220	Si ⁴⁺	822	} Z 843	
Al ₂ O ₃	1.55	152		152				
Fe ₂ O ₃	1.83	115	- 70	45				
FeO	26.44	3680	-130	3550	Al ⁺³	30		21*
MgO	15.54	3854		3854			9	} X+Y 847
CaO	4.60	820		820	Fe ⁺³	9		
TiO ₂	.62	77	- 60	17	Fe ⁺²	355		
MnO	.37	52		52	Mg ⁺²	385		
					Ca ⁺²	82		
	100.32				Ti ⁺⁴	2		
					Mn ⁺²	5		
					O ⁻²	2534		

Analyst E. P. Henderson.

Ca₁₀Mg₄₆Fe₄₄ (atomic %)

* Al divided between four fold and six fold positions in proportions necessary to balance the excess electrical charge of the Fe⁺³ and Ti⁺⁴ ions in X+Y group.

just as it is in terrestrial plutonics. But the cooling in its original environment did not proceed far enough to cause most of the pigeonite to invert to hypersthene though a small part of it, about 10 per cent, has inverted possibly after it became a meteorite.

Thus, to sum up, it is believed that six pyroxene solid phases were present at one time or another during the history of the meteorite, the relations between the four phases now visible can be explained, and their derivation from an original solid phase, pigeonite A, indicated.

PLAGIOCLASE

The plagioclase was analyzed by Henderson (Henderson and Davis, 1936) and found to be bytownite, Or_{.5}Ab_{10.7}An_{88.8}. It is clear, colorless

TABLE 4. OPTICAL PROPERTIES OF PYROXENE PHASES

	α	β	γ	Biref.	2V	Optic Plane	Dis- persion	Z Δc	Estimated Composition
Pigeonite B	1.7085	1.7095	1.736	.0275	+21°	\perp [010]	r > v	40°	Ca ₆ Mg _{17.4} Fe _{17.5}
Augite C	1.697	1.702	1.7255	.0285	+52°	[010]	r > v	44.5°	Ca ₁₃ Ng ₃₆ Fe ₂₁
Hypersthene E	1.710	1.713	1.7255	.0155	-52°	[010]	r < v strong	0°	Mg _{19.3} Fe _{10.5}
Salite F	1.688	approx.	1.715	—	—	—	—	—	Ca ₅₀ Mg ₅₂ Fe ₁₈

and glassy in the crushed sample. Zoning is not observable though rarely small portions of a crystal appear to have suffered some late stage alteration to slightly less calcic plagioclase.

A remarkable feature is the almost total absence of visible cleavage in the thin section. The plagioclase does commonly contain curved, apparently conchoidal, fracture planes; in many cases these are dotted by minute blebs and tiny spherical particles of a metallic mineral. In the few cases where cleavage was noted it was on $\{001\}$. The $\{010\}$ cleavage was not observed though a suggestion of $\{110\}$ and $\{1\bar{1}0\}$ parting was seen in one grain. The absence of cleavage will be commented on further in the consideration of the primordial environment.

The plagioclase has minute inclusions of a faintly pink, translucent mineral. It appears to be isotropic and has an index of refraction considerably lower than the feldspar but higher than the tridymite. Roughly it must be near 1.51. It has not been identified. The tiny opaque inclusions along fractures in the plagioclase (and to a lesser extent in the pyroxene) have already been mentioned. These range from distinctly visible blebs and tiny spherical masses to exceedingly minute specks. When viewed under the high power objective a transition can be seen from clearly identifiable specks to particles so small and closely spaced along the fracture surface that they trail out into a gray haze in which the individual particles are too small for the resolving power of the microscope. The fact that they have the form of droplets rather than crystals suggests that they may be metallic iron. Since they are in all cases found on fractures, they are clearly younger than the essential silicates.

The twinning observed in the plagioclase is rather unusual; pericline and albite twins predominate, with subordinate twinning on the manebach, ala A and ala B laws. Carlsbad twinning was not noted in any of the grains examined. For plagioclase of this composition some uncertainty exists in the identification of the twinning laws. At this composition it is very difficult to determine which is the plus and which the minus end of Z (N_z) optical direction. This is occasioned by the fact that the poles of $\{010\}$ and $\{001\}$ are almost symmetrically disposed on either side of the plane containing X and Y. Thus there is some doubt in many cases as to whether a given twin pair represent manebach or albite, ala A or ala B, and Carlsbad or pericline, etc. A positive determination can be made in those cases where pericline twinning has occurred and the $\{001\}$ cleavage, at a low angle to it, is observable. Table 5 below summarizes the observations made on the twinning but as pointed out above contains some uncertain determinations. Pericline twinning is more common in terrestrial bytownites and anorthites than in more sodic varieties,

but it seems to be even more common in this meteorite than in terrestrial bytownites.

The number of twin lamellae is small in a given crystal. In general the bulk of the area of a crystal in this section consists of a single member or simple pair of twins. Within this large area are found fine, widely spaced, twin lamellae.

TABLE 5

<i>No. of crystals</i>	<i>Twinning laws</i>
10	albite, pericline
2	albite, pericline, manebach
1	albite, manebach
1	manebach, ala A, ala B
1	albite, ala B
1	albite, ala A
1	pericline

There is an obvious crystallographic orientation of the plagioclase which is no doubt a dimensional orientation. More than three quarters of the crystals examined have the pole of {100} within 45° of the vertical. When considered in conjunction with the pyroxene *c* axis orientation, it may be concluded that the plagioclase crystals are tabular parallel to {100}, the *c* and *b* crystallographic axes are about of equal length but *a* is shorter.

TRIDYMIT

The tridymite occurs as anhedral grains interstitial to the pyroxene and plagioclase. It is evidently the last of the essential constituents to crystallize. It has very low birefringence and exhibits a patchy extinction under crossed nicols. The optical angle ranges from 45° to 50° and the indices of refraction are near 1.47. It is crowded with minute inclusions. These consist of sharp, well formed, acicular crystals, probably apatite, and the unidentified pinkish isotropic mineral, previously mentioned in the discussion of the plagioclase, and minute opaque specks.

OPAQUES

The opaque metallic grains were separated from the silicates magnetically and mounted in bakelite for study. Most of them are too small to make satisfactory determinations on them. The largest grains, about 0.15 mm., are of two varieties: one, an isotropic gray metallic mineral, occurring in equidimensional grains, probably chromite; two, a strongly anisotropic and pleochroic metallic having a purplish color which is probably an ilmenite-magnetite solid solution. Each grain consists of two or

three polygonal crystals with sharp straight boundaries between them. No trace of exsolution lamellae are to be seen in these grains such as are always present in comparable terrestrial ilmenites. A third metallic constituent which occurs as rounded blebs, is bright white in reflected light and may be metallic iron. There is a general tendency for the larger opaque grains to lie on or near plagioclase-pyroxene boundaries.

TEXTURE AND FABRIC

The pyroxenes generally range from 2 to $2\frac{1}{2}$ mm. in length along the c axis and are $1\frac{1}{2}$ to $2\frac{1}{2}$ times as long in this direction as at right angles to this direction. The plagioclases commonly are 0.5 to 1.5 mm. and are nearly equidimensional in the plane of the one thin section studied.

In general appearance the relations between crystals is similar to that found in crystal accumulates such as the rocks of the Stillwater Complex, Bushveld Complex, Skaergaard Intrusion, etc. Boundaries of original euhedral crystals which collected on the floor of a magma chamber have been added to form the interstitial liquid thus filling the remaining space and adding irregularities on a small scale to the former euhedral outlines of the settled crystals. Against late stage minerals which crystallize entirely from pore space liquid, the original settled crystals present well formed crystal faces. Such is the case in this meteorite at contacts of plagioclase or pyroxene with tridymite. Growth along the borders of large pyroxene grains has included smaller plagioclases so that locally small areas of ophitic to subophitic texture result. This is illustrated in the photomicrograph, Fig. 1, and in the drawing, Fig. 3.

Rough petrofabric diagrams were made by examining 24 pyroxene and 17 plagioclase crystals on the universal stage. These are adequate to show a well defined fabric. In the case of the pyroxenes, the c axes form a girdle almost parallel to the plane of the thin section, Fig. 4. An area representing a small circle on the stereographic projection with a diameter of 90° contains only one pyroxene c axis. The center of this circle is about 15 degrees from the center of the projection, or in other words the fabric pattern makes an angle of this amount with the plane of the thin section. The plagioclases in the plane of thin section examined are almost equidimensional and show no obvious fabric until compared to a stereographic plot of the poles of crystal faces (following somewhat the same procedure as used by van der Berg, 1947). The plot, Fig. 5, shows a strong tendency for the poles of $\{100\}$ faces to be nearly vertical to the plane of the section and for the poles of the zone $[100]$ to be horizontal. This indicates that the crystal habit of the feldspars probably was such that growth along the b and c axes was considerably greater than along

the a axis and the crystals therefore are tabular parallel roughly to $\{100\}$. They are so arranged in the fabric that the longer axes, b and c , lie in the same plane as the longest axis of the pyroxenes (the c axis). The conclusion which may be drawn from the whole fabric is that it is one of essentially planar dimensional orientation of the crystals. Secondly there is an indication of a tendency toward a weak linear orientation of the longest axis of the pyroxenes in the plane of layering. Such a fabric as

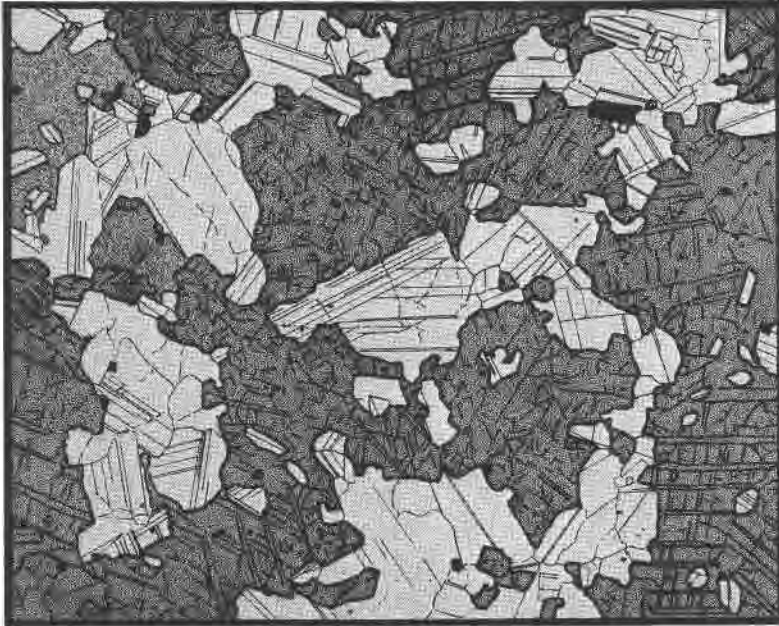


FIG. 3. Drawing of a portion of the thin section of the meteorite (traced from photograph). White=plagioclase; dotted=pyroxene, note augite lamellae parallel to $\{001\}$ of pigeonite; black=opaque minerals; gray (two areas in upper left-hand corner)=tridymite. Long dimension of figure equals 1.2 centimeters. Opaque grains tend to lie along boundaries between plagioclase and pyroxene.

this is characteristic of crystal accumulates formed by settling of crystals to the floor of a magma chamber and accumulation there in nearly horizontal layers and probably could not have developed in any other manner. Thus evidence is found to indicate magmatic differentiation by crystal settling in an extra-terrestrial body.

The tridymite plays a passive role in the fabric, having crystallized from pore space liquid after the fabric was formed.

PRIMORDIAL ENVIRONMENT AND EARLY HISTORY
OF THE METEORITE

The texture and grain size of the meteorite and the complete absence of zoning in the plagioclases indicates that it crystallized very slowly probably from a large body of magma. The orientation of the crystals with their longer axes tending to lie in one plane but without pronounced linear orientation of the longest axes in that plane indicates a primary layering of the igneous rock from which it was derived. This

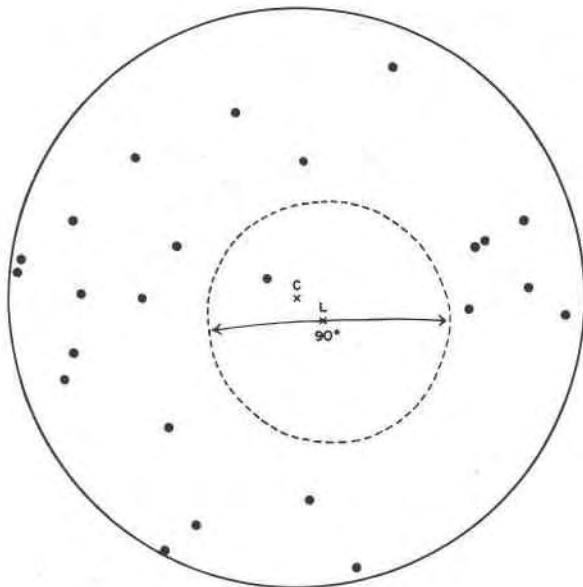


FIG. 4. Stereographic plot of the c axes of the pyroxenes with respect to the plane of the thin section. C is the center of the net and perpendicular to the thin section. L is the pole of the supposed plane of layering in the meteorite.

type of layering cannot be attributed to primary flow structure or to later orientation during metamorphism but almost unquestionably is the result of the sedimentation of crystals on the original floor of the magma chamber as set forth by Peoples (1934) in the case of the Stillwater Complex (also see Buddington, 1934, Wager and Deer, 1939). From this it is deduced that magmatic differentiation by crystal sorting has taken place in an extra-terrestrial body.

The temperature at which the meteorite crystallized must have been above the inversion temperature of the pyroxene (approximately 1065°C). Comparable rocks which have crystallized near the Earth's surface would have formed in the neighborhood of 1100°C . (Hess, 1941).

temperatures thought to obtain in the deeper part of the Earth's crust. The composition of the meteorite is similar to the composition at such a level in the Earth's crust according to the postulates of Buddington (1943). The temperature of the meteorite's primordial environment might be placed at $1135^{\circ}\text{C.} \pm 65^{\circ}$.

There is a suggestion that the body from which the meteorite was derived was of relatively large size, that is, it could not have been as small as an asteroid and could more appropriately be considered as coming from a body having a size of the order of magnitude of the Earth. The gravity field must have been sufficient to produce settling of 1 mm. plagioclase crystals with a density only 0.05 greater than the magma.

The slow crystallization and the temperature level also place a lower limit on the probable size of the original body. The usual reasoning from meteorites to speculation as to the composition of the interior of the Earth might in this case be reversed. If our concepts concerning the interior of the Earth are approximately correct, it probably would take a very large body of the bulk composition of the Earth to segregate from it a crust of basaltic composition. Judging from some of Jeffreys' recent papers there appears to be a fairly good correlation between diameter and composition of the inner planets and their satellites. Thus if the hypothetical parent of the meteorites did not have a diameter similar to the Earth it would probably not have had a crust of basaltic composition as does the Earth. In recent papers on meteorites Patterson and Brown (1948) conclude that exceedingly high pressures would be required to account for some of the observed phase relations in meteorites so that a parent body comparable to the Earth in size is suggested.

The event which produced the separation of the meteorite from its environment must have been of sudden and catastrophic nature. The tridymite did not invert to quartz nor did the bulk of the pigeonite invert to the orthorhombic form. To preserve these forms requires sudden chilling.

GENERAL CONCLUSIONS

The conclusions which are summarized below are deductions the writers made from rather limited data as represented in single thin section of one small specimen and accompanying chemical analyses of the meteorite as a whole and its component essential minerals. Admittedly these conclusions are speculative as by the very nature of the materials, they must be. Their validity may some day be capable of stronger proof when more such meteorites are found and studied.

The Moore County meteorite possibly came from the deeper part of the crust of a planet comparable in size to the Earth. It is a product of

crystallization of an intrusion of basaltic composition which appears to have differentiated by crystal settling to form a layered complex. The temperature conditions were in the neighborhood of 1135° C. The meteorite left this environment during catastrophic break up of the planet with great speed and consequent sudden cooling.

REFERENCES

- ADAMS, L. H., AND WILLIAMSON, E. D. (1923), *Jour. Wash. Acad. Sci.*, **13**, 413-428.
VAN DEN BERG, J. J. (1946), *Trans. Geol. Soc. S. Af.*, **XLIX**, 155-204.
BOWEN, N. L., AND SCHAIRER, J. F. (1935), *Am. Jour. Sci.*, **XXIX**, 151-215.
BROWN, H., AND PATTERSON, C. (1948), *Jour. Geol.*, **56**, 1-85.
BUDDINGTON, A. F. (1936), *16th Internat. Geol. Cong., Rept. 1*, 347-352.
———. (1943), *Am. Mineral.*, **28**, 119-140.
DALY, R. A. (1938), *Am. Geophys. Union Trans. 19th Ann. Mtg. Pt. 1*, 35-39.
EDWARDS, A. B. (1942), *Jour. Geol.*, **L**, 579-610.
HALLIMOND, A. F. (1914), *Mineral. Mag.*, **XVII**, 97-99.
HENDERSON, E. P., AND DAVIS, H. T. (1936), *Am. Mineral.* **21**, 215-229.
HESS, H. H., AND PHILLIPS, A. H. (1938), *Am. Mineral.* **23**, 450-456.
———. (1940), *Am. Mineral.* **25**, 271-285.
HESS, H. H. (1941), *Am. Mineral.*, **26**, 573-592.
JEFFREYS, H. (1936-1937), *Monthly Notices Roy. Astron. Soc. Geophys., Supp. 3, and 4*.
KUNO, H. (1936), *Jap. Jour. Geol. Geog.*, **XIII**, 109-140.
PEOPLES, J. W. (1934), *16th Internat. Geol. Cong. 1933, Rept. 1*, 353-360.
WAGER, L. R., AND DEER, W. A. (1939), *Medd. om Grøn.* **105**, No. 4, 352 pp.