

THE AMERICAN MINERALOGIST

JOURNAL OF THE MINERALOGICAL SOCIETY OF AMERICA

Vol. 52

MARCH-APRIL, 1967

Nos. 3 and 4

EXTRATERRESTRIAL MINERALOGY¹

BRIAN MASON, *U. S. National Museum, Washington, D. C.*

In looking over the list of my illustrious predecessors in the position of president of this society, I am intrigued to see that only two were museum curators (although some were university professors who were also curators of extensive collections). The last curator to stand in my present shoes was William F. Foshag in 1940, and his presidential address was entitled "Problems in the study of meteorites." Coming from the same institution, I feel it is not inappropriate to follow his good example, and to provide you with some account of the recent progress of meteorite mineralogy.

Although the obvious minerals of meteorites were recognized quite early, the study of the most abundant (and mineralogically complex) meteorites, the chondrites, was not possible until the introduction of the polarizing microscope about 100 years ago. The techniques of microscopic petrology were applied to stony meteorites originally by Sorby, who published a paper on this subject in 1863. The fortunate conjunction of a first-rate microscopist, Gustav Tschermak, and the outstanding meteorite collection of that day, the Vienna collection, resulted in a classic monograph on the mineralogy and petrology of meteorites, Tschermak's "Die mikroskopische Beschaffenheit der Meteoriten," published in 1885. This remarkable work, long unavailable except in a few libraries, was recently republished, in facsimile, with an English translation by Wood (1964). In it Tschermak recognized sixteen minerals occurring in meteorites. Table 1 traces the development of meteorite mineralogy over the following seventy years. It can be seen that the list grew very slowly. It is of interest to note that serpentine first appears in Krinov's 1955 list, although it is a major phase in some of the carbonaceous chondrites. Sulfur as a mineral is not recorded in any of the lists in Table 1, although Wöhler in 1860 extracted sulfur with alcohol from the Cold Bokkeveld meteorite, and later investigators extracted it from other carbonaceous

¹ Presidential Address, the Mineralogical Society of America. Delivered at the 47th Annual Meeting of the Society, November 15, 1966, San Francisco, California.

TABLE 1. THE MINERALS OF METEORITES, UP TO 1955

Mineral	Formula	Tschermak 1885	Farring- ton 1915	Heide 1934	Krinov 1955
Kamacite	(Fe, Ni)	x	x	x	x
Taenite	(Fe, Ni)	x	x	x	x
Copper	Cu				x
Diamond	C		x	x	x
Graphite	C	x	x	x	x
Moissanite	SiC		x	x	x
Cohenite	Fe ₃ C		x	x	x
*Schreibersite	(Fe, Ni) ₃ P	x	x	x	x
*Osbornite	TiN	x	x	x	x
Troilite	FeS	x	x	x	x
*Oldhamite	CaS	x	x	x	x
*Daubreelite	FeCr ₂ S ₄	x	x	x	x
*Lawrencite	(Fe, Ni)Cl ₂		x	x	x
Magnesite	(Mg, Fe)CO ₃	x	x		x
Calcite	CaCO ₃				x
Magnetite	Fe ₃ O ₄	x	x	x	x
Chromite	FeCr ₂ O ₄	x	x	x	x
Quartz	SiO ₂		x	x	x
Tridymite	SiO ₂	x	x	x	x
Chlorapatite	Ca ₅ (PO ₄) ₃ Cl		x	x	x
Merrillite (Whitlockite)	Ca ₃ (PO ₄) ₂			x	x
Olivine	(Mg, Fe) ₂ SiO ₄	x	x	x	x
Orthopyroxene	(Mg, Fe)SiO ₃	x	x	x	x
Clinopyroxene	(Ca, Mg, Fe)SiO ₃	x	x	x	x
Plagioclase	(Na, Ca)(Al, Si) ₄ O ₈	x	x	x	x
Serpentine	(Mg, Fe) ₆ Si ₄ O ₁₀ (O, OH) ₈				x

*(An asterisk indicates those not known to occur in terrestrial rocks.)

chondrites. Apparently these reports were discounted, or the sulfur ascribed to terrestrial weathering.

In 1955, therefore, to specialize in meteorite mineralogy might well have been considered the refuge of a lazy mineralogist—one could confine one's activities to less than thirty minerals out of the some 1500 species recognized! The situation has changed rather radically since then, as is illustrated in Table 2. The number of meteorite minerals has more than doubled in the last ten years. This remarkable upswing can be ascribed to two distinct factors: firstly, the greatly enhanced interest in outer space, and an appreciation of the significance of meteorites as the only extraterrestrial samples we yet have; and secondly, the application of

TABLE 2. MINERALS OF METEORITES DESCRIBED SINCE 1955

Mineral	Formula	Reference
Sulfur	S	DuFresne and Anders, 1962
*Perryite	Ni ₃ Si	Fredriksson and Henderson, 1965
Mackinawite	FeS	El Goresy, 1965
Pyrite	FeS ₂	Ramdohr, 1963
Sphalerite	ZnS	Ramdohr, 1963
Alabandite	(Mn, Fe)S	Dawson et al., 1960
*Niningerite	(Mg, Fe)S	Keil and Snetsinger, 1967
Pentlandite	(Fe, Ni) ₉ S ₈	Sztrokay, 1960
Cubanite	CuFe ₂ S ₃	Ramdohr, 1963
(Chalcopyrrhotite)		
Chalcopyrite	CuFeS ₂	Ramdohr, 1963
Valleriite	CuFeS ₂	Ramdohr, 1963
*Djerfisherite	K ₃ CuFe ₁₂ Si ₁₄	Fuchs, 1966
*Gentnerite	Cu ₃ Fe ₂ Cr ₁₁ Si ₈	El Goresy and Ottemann, 1966
Cristobalite	SiO ₂	Dawson et al., 1960
Rutile	TiO ₂	Buseck and Keil, 1966
Ilmenite	FeTiO ₃	Yudin, 1956
Spinel	MgAl ₂ O ₄	Sztrokay, 1960
*Sinoite	Si ₂ N ₂ O	Andersen et al., 1964
Dolomite	CaMg(CO ₃) ₂	DuFresne and Anders, 1962
Gypsum	CaSO ₄ ·2H ₂ O	DuFresne and Anders, 1962
Epsomite	MgSO ₄ ·7H ₂ O	DuFresne and Anders, 1961
Bloedite	Na ₂ Mg(SO ₄) ₂ ·4H ₂ O	DuFresne and Anders, 1962
*Farringtonite	Mg ₃ (PO ₄) ₂	DuFresne and Roy, 1961
Graftonite	(Fe, Mn) ₃ (PO ₄) ₂	Olsen and Fredriksson, 1966
Sarcopsidite	(Fe, Mn) ₃ (PO ₄) ₂	Olsen and Fredriksson, 1966
*Panethite	Na ₂ Mg ₂ (PO ₄) ₂	Fuchs et al., 1966
*Brianite	Na ₂ MgCa(PO ₄) ₂	Fuchs et al., 1966
*Stanfieldite	Mg ₃ Ca ₄ Fe ₂ (PO ₄) ₆	Fuchs, 1967
Zircon	ZrSiO ₄	Marvin and Klein, 1964
Ureyite	NaCrSi ₂ O ₆	Frondel and Klein, 1965
*Merrinucite	(K, Na) ₂ Fe ₅ Si ₁₂ O ₃₀	Dodd et al., 1965
*Roedderite	(K, Na) ₂ Mg ₅ Si ₁₂ O ₃₀	Fuchs et al., 1966
Richterite	Na ₂ CaMg ₅ Si ₈ O ₂₂ (OH, F) ₂	Olsen, 1967

* Not known to occur in terrestrial rocks.

new and improved instruments and techniques—the reflecting microscope, X-ray diffraction, and the electron-beam microprobe.

Most of the meteorite minerals recognized in the past ten years are trace constituents, present in amounts usually much less than 1 percent. For example, the abundance of zircon in the Vaca Muerta meteorite is estimated to be about 0.002 percent (Marvin & Klein, 1964). Nevertheless, the significance of a particular mineral is in no way determined by

TABLE 3. THE CLASSIFICATION OF METEORITES (FIGURES IN PARENTHESES ARE THE NUMBERS OF OBSERVED FALLS IN EACH CLASS)

Group	Class	Principal minerals
Chondrites	Enstatite (11)	Enstatite, nickel-iron
	Olivine-bronzite (227)	Olivine, bronzite, nickel-iron
	Olivine-hypersthene (303)	Olivine, hypersthene, nickel-iron
	Carbonaceous (31)	Serpentine, olivine
Achondrites	Aubrites (8)	Enstatite
	Diogenites (8)	Hypersthene
	Chassignite (1)	Olivine
	Ureilites (3)	Olivine, clinobronzite, nickel-iron
	Angrite (1)	Augite
	Nakhlite (1)	Diopside, olivine
	Eucrites and howardites (40)	Pyroxene, plagioclase
Stony-irons	Pallasites (2)	Olivine, nickel-iron
	Siderophyre (1)*	Orthopyroxene, nickel-iron
	Lodranite (1)	Orthopyroxene, olivine, nickel-iron
	Mesosiderites (6)	Pyroxene, plagioclase, nickel-iron
Irons	Hexahedrites (7)	Kamacite
	Octahedrites (32)	Kamacite, taenite
	Ni-rich ataxites (1)	Taenite

* Find.

its abundance. A mineral is abundant because the elements forming it are abundant, and the mineral itself has an extensive stability field. In practically all meteorites the elements Fe, Mg, Si, and O make up over 90 percent, both in weight and in number of atoms; hence the common minerals are metallic nickel-iron (as kamacite and taenite), olivine, orthopyroxene, and calcium-poor clinopyroxene. A rare mineral is rare either because it contains a rare element, or because it has a very limited stability field. A mineral reflecting the latter situation is of especial significance; it may enable us to deduce the conditions of origin of the meteorite far more precisely than could be established from the common minerals. Since one of the principal objectives of meteorite research is to determine the conditions under which these enigmatic bodies crystallized, the study of these rare minerals should be particularly rewarding.

For the benefit of those of you who have but a nodding acquaintance with meteorites, I will include at this point their current classification (Table 3). It is a mineralogical-structural classification similar in principle to that used for igneous rocks. I would direct your attention to the very uneven population of the different classes—some are represented by a single meteorite, others by several hundred.

This distribution suggests to me that, in attempting to establish a coherent picture of meteorite genesis, we are in effect working on a jigsaw puzzle with many pieces lacking. The octahedrites dominate among the irons, the olivine-bronzite and olivine-hypersthene chondrites (sometimes called jointly the common or ordinary chondrites) among the stones. Actually, in terms of observed falls, the chondrites are far more abundant than all other meteorites—chondrites, 84.6 percent; achondrites, 8.0 percent; stony-irons, 1.6 percent; irons, 5.8 percent. Few irons are seen to fall; most are found and recognized by the unique features distinguishing them from terrestrial rocks.

A few years ago (Mason, 1962) I wrote an account of the meteorite minerals known at that time. I intend to take the opportunity provided today to update this account. Not all the minerals listed in Tables 1 and 2 will be discussed, but only those for which significant new data are available, or additional information not included in the references given for the minerals in Table 2. I shall also give a brief account of those minerals formed in meteorites by interaction with the terrestrial environment. For convenience the material will be discussed under the following headings:

- The dominant silicate minerals
- Minor and accessory minerals
- Doubtful and incompletely described minerals
- Minerals produced by terrestrial effects

THE DOMINANT SILICATE MINERALS

The commonest silicate minerals in meteorites are olivine and pyroxene. Plagioclase is a minor constituent in most chondrites, and is an important constituent in the eucrites and howardites among the achondrites. Serpentine is found only in the carbonaceous chondrites, but it makes up the major part of many of these meteorites.

Olivine. The range in composition of meteoritic olivine is illustrated in Figure 1. Olivine is a dominant mineral in the olivine-bronzite and olivine-hypersthene chondrites; it is an important constituent in some of the carbonaceous chondrites, but is absent from the enstatite chondrites. In most of the olivine-bronzite and olivine-hypersthene chondrites the olivine is of uniform composition in any one meteorite, and the range of composition within each class is small (bronzite chondrites, Fa_{14-20} ; hypersthene chondrites, Fa_{22-31}). The narrow hiatus between olivine compositions in these two classes is remarkable, and the reasons for it are not fully understood. Recently, Dodd and Van Schumus (1965) have recognized a group of some twenty bronzite and hypersthene chondrites in which the olivine composition is highly variable (Fa_0 – Fa_{40}). Olivine

in the carbonaceous chondrites also shows this wide range of composition within a single meteorite.

The three meteorites with iron-rich olivine—Chassigny, Angra dos Reis, and Nakhla—are achondrites, each with a unique composition among meteorites. The stony-irons contain olivine in the Fa_{10-20} range, as do the ureilites. A few iron meteorites contain silicate inclusions, and in these the olivine is close to forsterite in composition, usually near Fa_5 . Pure Mg_2SiO_4 is found as an accessory mineral in a few aubrites (enstatite achondrites).

Pyroxene. A variety of pyroxenes occurs in meteorites, but as a first approximation they can all be considered as falling in the $MgSiO_3$ — $FeSiO_3$ — $CaMgSi_2O_6$ — $CaFeSi_2O_6$ system. Aluminum is uniformly low, the only occurrence of a true augite being in Angra dos Reis. Figure 2 illustrates the distribution of pyroxene compositions.

Prior (1920) divided meteoritic orthopyroxene into enstatite (less than 10 mole percent $FeSiO_3$), bronzite (10–20 mole percent $FeSiO_3$), and hypersthene (greater than 20 mole percent $FeSiO_3$), and used this division to classify the chondrites into enstatite, bronzite, and hypersthene chondrites. More recent work has confirmed this classification as dividing the large number of chondritic meteorites into well-defined groups separated by hiatuses in both chemical and mineralogical composition. This classification has been criticized on the specious grounds that current mineralogical usage defines bronzite as containing 10–30 mole percent $FeSiO_3$ and hence hypersthene chondrites should be called bronzite

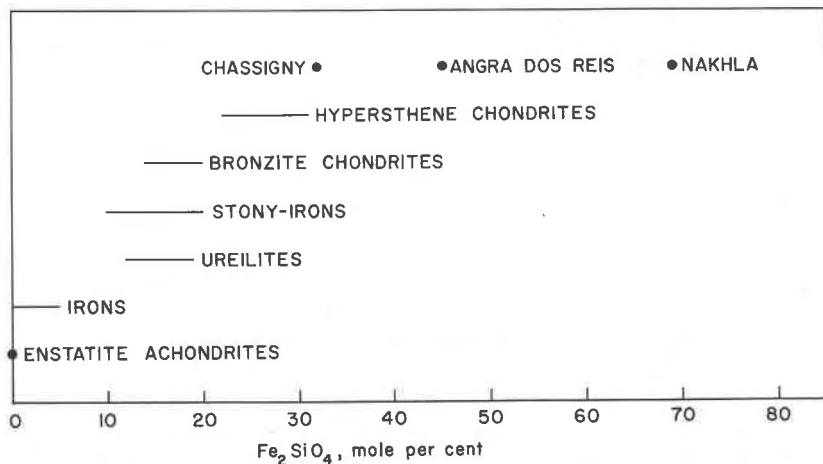


FIG. 1. Olivine composition in meteorites.

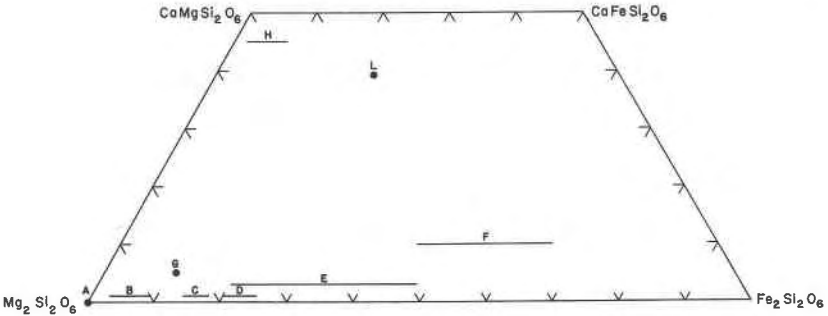


FIG. 2. Pyroxene composition in meteorites: A=enstatite chondrites and enstatite achondrites; B=orthopyroxene in silicate inclusions in irons; C=orthopyroxene in olivine-bronzite chondrites; D=orthopyroxene in olivine-hypersthene chondrites; E=orthopyroxene in achondrites and mesosiderites; F=pigeonite in achondrites and mesosiderites; H=diopside in chondrites and silicate inclusions in irons; L=diopside in Nakhla achondrite.

chondrites. Nevertheless, Prior's original definition and classification cannot be invalidated by the arbitrary redefinition of the composition limits of bronzite.

Along with the orthopyroxene, most chondrites contain some calcium-poor clinopyroxene referred to as clinoenstatite, clinobronzite, and clinohypersthene (with the same compositional ranges as the corresponding orthopyroxenes), and in some this clinopyroxene may be present to the exclusion of orthopyroxene. It is remarkable that these calcium-poor clinopyroxenes are common and abundant in many chondrites but are almost completely lacking from terrestrial rocks. This may have considerable significance for elucidating the mode of origin of these meteorites. From the present knowledge of crystallization in the $MgSiO_3$ system (Figure 3), it would appear that these low-calcium clinopyroxenes crystallized originally as the proto-form (the stable phase between about $1000^\circ C$ and the melting-point), and were then chilled so rapidly that they reached the clino-field without inverting into orthopyroxene. Under terrestrial conditions, even in volcanic rocks, orthopyroxene is formed in its stability field, and although it is eventually cooled into the clino-field it remains in the now-metastable ortho-form.

From this evidence the orthopyroxene in chondritic meteorites is probably the product of a thermal metamorphism in the parent chondrite bodies, a reheating of the material to temperatures within the orthopyroxene stability field. In some highly-recrystallized chondrites the low-calcium clinopyroxene (which has up to 5 atom percent Ca in $Ca+Mg+Fe$) has been completely converted into orthopyroxene (with

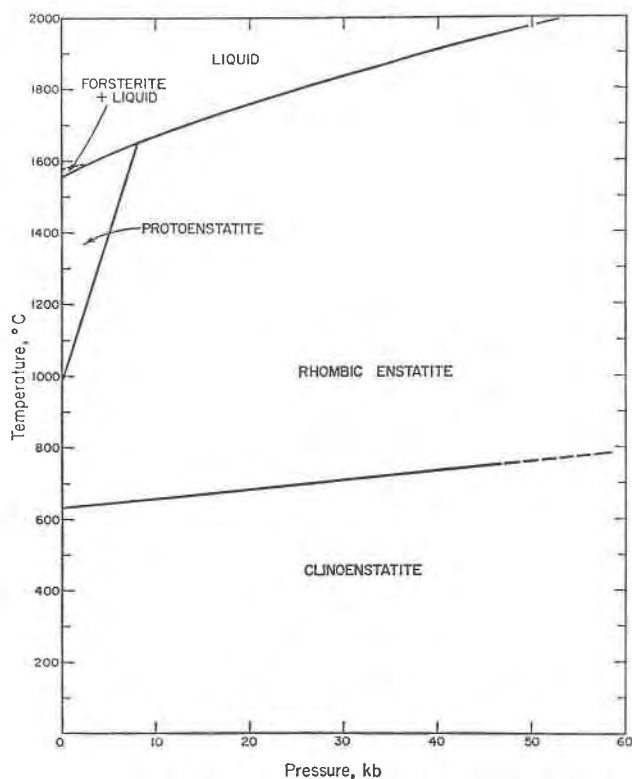


FIG. 3. Phase relations of enstatite, MgSiO₃ (Boyd and England, 1965).

about 1 percent Ca in Ca+Mg+Fe) and a small amount of diopside.

Some chondrites also contain a second generation of this low-calcium clinopyroxene. Highly shocked meteorites contain this form of pyroxene, and the textural relationships suggest that at least some of it may have been formed from orthopyroxene by mechanical deformation. Such an origin of clinoenstatite has been demonstrated experimentally by Turner *et al* (1960).

Some years ago (Mason, 1962) I suggested that those meteorites previously classified as Type III carbonaceous chondrites (those low in carbon and high in olivine) should be segregated as a specific class of olivine-pigeonite chondrites, since they all contain a calcium-poor clinopyroxene along with the major olivine. This clinopyroxene was identified as pigeonite on the basis of its X-ray diffraction pattern and its refractive indices. However, it is evidently a phase distinct from pigeonite, formed by the inversion of the proto-form, and not by direct crystallization from

a melt. In addition, this low-calcium clinopyroxene, while characteristic of the Type III carbonaceous chondrites, is not confined to them; it is present in many of the bronzite and hypersthene chondrites, especially the unequilibrated chondrites of Dodd and Van Schmus (1965). Under these circumstances I now believe that the term olivine-pigeonite chondrite should be abandoned, and these meteorites included with the carbonaceous chondrites; this I have done in Table 3.

The pyroxenes in chondrites ranges in composition from Fs_0 to Fs_{25} , with an extensive hiatus between the enstatite and bronzite chondrites and a small one between the bronzite and hypersthene chondrites. Pyroxenes richer in the $FeSiO_3$ component are known from the achondrites and the stony-irons. Up to about Fs_{45} they are orthorhombic and may be described as hypersthene (although some of this hypersthene is probably inverted pigeonite); beyond Fs_{45} they are monoclinic, more calcic, and are typical pigeonites, sometimes with exsolved calcium-rich clinopyroxene. Hess and Henderson (1949) have described the complex series of inversion and exsolutions shown by the pyroxene in the Moore County eucrite.

Plagioclase. One of the enigmatic features of meteorite mineralogy is the remarkable quantization of plagioclase composition. Whereas in terrestrial rocks we find all compositions from pure albite to pure anorthite, meteoritic plagioclase is practically limited to albite-oligoclase (in chondrites, enstatite achondrites, and silicate inclusions in irons) and bytownite-anorthite (in achondrites—except enstatite achondrites—and mesosiderites).

The presence of sodic plagioclase in "rocks" of ultrabasic composition may appear anomalous to petrologists conditioned by studying terrestrial rocks. This apparent anomaly, however, probably reflects a significant difference in bulk composition. Chondrites contain relatively high Na_2O (about 1 percent) compared to their nearest terrestrial analogs, the peridotite xenoliths in basalts, and are also rather low in Al_2O_3 (about 2 percent). Under these circumstances practically all the aluminum is taken up in forming the albite component, leaving little to combine with calcium as the anorthite component.

In a recent note (Mason, 1965) I suggested that the plagioclase in chondrites was produced during the inversion of clinopyroxene to orthopyroxene, the components of the plagioclase being in solid solution in the clinopyroxene but being unacceptable in the orthopyroxene structure. While this may account for some plagioclase, additional research has convinced me that most plagioclase in chondrites was originally glass; a brown transparent or turbid glass is a common constituent of plagio-

clase-free chondrites, and microprobe analysis has shown that this glass has a composition close to albite (Frederiksson and Reid, 1965). Devitrification of this glass produces disordered, so-called high-temperature plagioclase, and the plagioclase in chondrites shows a range of intermediate states, ordered plagioclase being present in the most recrystallized chondrites.

Serpentine. As long ago as 1860 Wöhler suggested from his analysis of the Cold Bokkeveld carbonaceous chondrite that this meteorite consisted largely of serpentine. This observation was overlooked or disbelieved for many years. Kvasha (1948) identified the groundmass of the Boris-kino carbonaceous chondrite as chlorite, and later recognized the same mineral in Mighei, another carbonaceous chondrite. Some years ago (Mason, 1962) I suggested this mineral was serpentine, rather than chlorite, on the following grounds: (a) X-ray powder photographs do not show the 14 Å reflection characteristic of chlorite; (b) the bulk composition of the meteorites in which it occurs is very low in Al_2O_3 (about 2 percent). Recently, however, Boström and Frederiksson (1966) have carefully studied this mineral in the Orgueil meteorite and their data indicate it is an iron-rich, aluminum-poor septechlorite, perhaps best described as a ferric chamosite.

The occurrence of this highly-hydrated ferromagnesium silicate as a major constituent of the carbonaceous chondrites, whereas all other classes of meteorites are essentially anhydrous, is a remarkable feature and highly significant in terms of the origin of these unique meteorites. Electron microscope studies indicate that the individual crystallites are very small, of the order of a few hundred Ångströms, and they are coated with the complex organic compounds characteristic of these meteorites. These features suggest that this material may be the condensate of a primordial "smoke" which formed in the outer cold part of an ancestral solar nebula.

MINOR AND ACCESSORY MINERALS

Some of the minor and accessory minerals listed in Tables 1 and 2 are common and widespread in meteorites. Troilite, for example, is probably present, at least in trace amounts, in all meteorites. Other widespread constituents are chromite (in practically all chondrites, achondrites, and stony-irons, and in many irons); native copper (rare grains have been found in many irons, stony-irons, and chondrites, although the average copper content in these meteorites is about 100 parts per million); merillite and chlorapatite, difficult to recognize under the microscope, are probably present in most stony meteorites. Other minerals are much

more restricted in their occurrence, being found only in a specific class of meteorites. Two classes of meteorites, the carbonaceous chondrites and the enstatite chondrites, are particularly noteworthy for their unique mineralogy.

The minerals unique to the carbonaceous chondrites include serpentine, calcite, dolomite, magnesite, gypsum, epsomite, bloedite, and sulfur. It will be noted that these include all the carbonates, sulfates, and hydrated minerals known from meteorites. This paragenesis shows that their original environment must have been cold, humid, and relatively oxidizing.

The enstatite chondrites and enstatite achondrites represent a completely contrasting paragenesis. The following minerals are known only from these classes: osbornite, oldhamite, niningerite, djerfisherite, cristobalite, sinoite, and roedderite. The enstatite chondrites and enstatite achondrites are highly reduced (the silicates are essentially iron-free, all iron being present as metal or sulfides) and show evidence of a high fugacity of sulfur in their original environment (in these meteorites calcium, manganese, chromium, titanium, magnesium, and even potassium—in djerfisherite—show chalcophilic behavior). These two classes also contain the only nitrides—osbornite and sinoite—known as minerals.

The following comments on a few of the minor and accessory minerals are intended to illustrate some of the problems of current interest in meteorite mineralogy.

Sulfur. The occurrence of sulfur as a constituent of the carbonaceous chondrites was first observed by Wöhler, who extracted it with alcohol from the Cold Bokkeveld meteorite. However, this report and other later ones have either been overlooked, or the sulfur considered a product of the terrestrial decomposition of troilite. Recently, DuFresne and Anders (1962) have clearly demonstrated that the sulfur in the Orgueil meteorite and other carbonaceous chondrites is an original constituent, and this has been confirmed by other investigators.

Cohenite. The significance of cohenite as a possible indicator of crystallization under high pressure was first propounded by Ringwood (1960), and has been the subject of considerable controversy. Brett (1966) has shown that the presence of cohenite indicates neither high nor low pressures in meteorites which contain it. However, the absence of cohenite in meteorites containing metal + graphite requires pressures below about 12 kb at temperatures below 600°C. Cohenite is found almost exclusively in iron meteorites containing from 6–8 percent nickel. Brett concludes from studies of the Fe-Ni-C system that cohenite which formed in meteorites with lower nickel content decomposed during cooling, and cohenite cannot form in meteorites with higher nickel.

Troilite. The characteristic and common sulfide of meteorites is troilite, stoichiometric FeS; its occurrence can be expected, in view of the almost universal presence of free iron as kamacite and taenite. The responding terrestrial mineral pyrrhotite, approximately Fe₇S₈, has also been recorded from meteorites. For many of these records the mineral was probably in fact troilite. Carpenter and Desborough (1964) record pyrrhotite intergrown with troilite in the Long Island chondrite; however, this meteorite is considerably weathered, and the pyrrhotite is probably the product of terrestrial weathering, e.g.,



However, in meteorites containing no free metal, such as some of the carbonaceous chondrites, it is probable that pyrrhotite of extraterrestrial origin is present.

The question as to the amount of nickel in solid solution in troilite is one of considerable geochemical interest, but one for which an unequivocal answer has not been available, because of the intimate association of troilite with nickel-iron. Wood (1967), on the basis of microprobe analyses, reports that the troilite of chondrites contains remarkably little nickel, commonly less than 0.2 percent. This is in agreement with equilibrium relations in the Fe-Ni-S system; Kullerud (1963) has shown that at 650° FeS in equilibrium with kamacite and taenite contains less than 0.2 percent Ni.

Cubanite. Ramdohr (1963) recorded "chalcopyrrhotite" as an accessory mineral in a number of stony meteorites. Yund and Kullerud (1966) have recently shown that this mineral is a quenched high-temperature form of the copper-iron sulfide cubanite.

Valleriite. This mineral was identified by Ramdohr (1963) as an abundant exsolution product in many "chalcopyrrhotites," and in some pentlandite. He commented that, from the geochemistry and phase relations of the meteorites containing it, valleriite should contain Fe as a major component and Cu as a minor component. This is consistent with the formula given for valleriite in Table 2. However, Evans *et al* (1964) have shown that much of what was previously identified as valleriite is actually a tetragonal polymorph of FeS which they named mackinawite. It is probable that some of the occurrences of valleriite recorded by Ramdohr are actually mackinawite. True mackinawite (composition checked by microprobe analysis) has been identified in the sulfide inclusions of a number of iron meteorites by El Goresy (1965).

Cristobalite. This mineral was first certainly identified in meteorites in the Abee enstatite chondrite (Dawson *et al.*, 1960), although Cohen (1903) had observed some clear isotropic grains in the Kendall County iron which he suggested might be cristobalite; this was shown to be tridymite by Marvin (1962). Cristobalite has since been identified in a number of enstatite chondrites, always in association with clinoenstatite (Mason, 1966). If this association was originally cristobalite-protoenstatite and represents an equilibrium crystallization, this puts narrow limits on the conditions of formation. At one atmosphere pressure cristobalite is stable above 1470°C, protoenstatite melts incongruently at 1557°C; both minerals are low-pressure phases, cristobalite being unstable above 5 kb, protoenstatite unstable above 8 kb.

Merrillite. This mineral was recognized, but not positively identified, in several chondrites by Tschermak (1883), who called it "Monticellit-ähnlich-Mineral." Merrill (1915) showed it was a phosphate, and Wherry (1917) named it merrillite in his honor. It was first positively characterized by Shannon and Larsen (1925), who succeeded in separating it from Allegan, Waconda, and New Concord chondrites after tedious and time-consuming effort. They described it as a calcium-sodium phosphate with the formula $3\text{CaO} \cdot \text{Na}_2\text{O} \cdot \text{P}_2\text{O}_5$ (based on an analysis of material from the New Concord meteorite); uniaxial, $\omega = 1.623$, $\epsilon = 1.620$; density 3.10.

In 1962 Fuchs, and later Christophe-Michel-Levy (1964) showed that merrillite is structurally identical with the terrestrial mineral whitlockite, described and named by Frondel (1941). Fuchs also showed that the meteoritic mineral contains much less sodium than is indicated by the formula given by Shannon and Larsen (which was based on the analysis of a 70-mg sample).

Whitlockite and merrillite are evidently identical. According to the rule of priority, the name merrillite has precedence over whitlockite. However, it can be argued that the original description of merrillite was inadequate to characterize the mineral. A ruling on which name should be used for the mineral in question might be sought from the International Mineralogical Association.

Spinel. This mineral was first recorded from meteorites by Sztrokay (1960), who identified it in Kaba, a carbonaceous chondrite. I have found it in Vigarano, also a carbonaceous chondrite, and Reid and Fredriksson (1967) have described it from the Sharps and Chainpur meteorites. In these meteorites the mineral occurs as crystals in glassy

chondrules, and microprobe analyses show that it is virtually pure $MgAl_2O_4$. Spinel crystallizes directly from melts in the olivine-plagioclase composition range at temperatures above $1400^\circ C$, but under equilibrium conditions of cooling it later reacts with the melt and is resorbed. The survival of spinel in these glassy chondrules is therefore evidence for the formation of the chondrules at high temperatures and their rapid chilling.

DOUBTFUL AND INCOMPLETELY DESCRIBED MINERALS

Moissanite. In 1962 I commented that the occurrence of silicon carbide as a meteoritic mineral rests solely on Moissan's (1904) identification of it in the insoluble residue from a 53 kg piece of the Canyon Diablo iron, and suggested that it might have been introduced as carborundum used for cutting the meteorite. Kunz (1905), who named the mineral in honor of Moissan, stated "No saws were used by Professor Moissan with the mass examined by him." However, in Moissan's original paper it is clearly stated that the 53 kg piece was cut from a 183 kg specimen using a steel band saw, although there is no mention of the abrasive used. (Carborundum was introduced as an abrasive in 1893.) If silicon carbide is a genuine meteorite mineral, it seems strange that it has not been noted by any of the numerous investigators of Canyon Diablo, nor has it been observed in any other meteorite.

Gold. Edwards (1953) identified as gold two small grains in a polished surface of the Wedderburn iron from Victoria, Australia. Ramdohr (1963) reported gold as tiny grains in the Atlanta enstatite chondrite; however he has since decided (personal communication) that the mineral is not gold, but is probably osbornite. This leaves Edwards' identification as the sole record of free gold in a meteorite. It seems very unlikely that free gold would exist in an iron meteorite, since the average gold content in meteoritic nickel-iron is 1.5 ppm, and the maximum recorded by Goldberg *et al* (1951) is 8.744 ppm. Two possibilities should be considered: (a) the gold was introduced into the Wedderburn meteorite (which was found in a gold-mining region) from a terrestrial source—Edwards mentioned this possibility, but considered it most unlikely; (b) the mineral was not gold, but osbornite. Unfortunately, a careful search has failed to locate the specimen investigated by Edwards.

Phosphorus. The occurrence of free (white) phosphorus in a meteorite has been recorded by Farrington (1903). He observed a white "smoke," with a pungent garlic-like odor similar to that of burning phosphorus, arising from a drillhole in the Saline meteorite, a bronzite chondrite. A luminous spot could be seen at the bottom of the drillhole; silver nitrate paper held in the fumes turned black in a few moments; and a phosphate

test was obtained from a nitric acid solution of some of the drillings. These observations have never been duplicated, and the occurrence of free phosphorus in a meteorite seems unlikely. Nevertheless, Farrington was an acute and experienced investigator of meteorites, and his statements must be taken seriously.

Orthoclase. Olsen and Mueller (1964) reported the occurrence of potassium feldspar, along with sodic plagioclase, in silicate inclusions in the Kodaikanal iron. The identification was based on X-ray diffraction patterns of the mixed feldspars. Bunch (oral communication, Meteoritical Society, 1966), has detected potassium-rich areas in sodic plagioclase inclusions in the Weekeroo iron. This suggests an antiperthitic intergrowth of orthoclase in sodic plagioclase.

Lonsdaleite. Strong *et al* (1966) have recently prepared this new high-pressure polymorph of carbon, with the wurtzite structure. They referred to it as "hexagonal diamond," but the name lonsdaleite has now been accepted for it. They identified it as a minor constituent of the carbonaceous material in the Canyon Diablo iron.

(Fe, Ni)₂P. Buseck (1966) has described a phase probably with this composition, associated with schreibersite and troilite in the Ollague pallasite.

Publications describing meteorites frequently mention unidentified minerals, some of which may be new species. For example, Ramdohr (1963) described the properties in polished sections of eleven new minerals of uncertain composition in stony meteorites, some of which have since been identified and named; and El Goresy (1965), in a study of sulfide inclusions in iron meteorites, has observed some probable new minerals. The utility of the electron-beam microprobe for determining the composition of minute grains has been of unique importance in identifying and characterizing these new minerals.

MINERALS PRODUCED BY TERRESTRIAL EFFECTS

Strictly speaking, this address should be confined to those minerals which existed in the meteorites before they entered the Earth's atmosphere. However, for the sake of completeness, I would like to add a few words about those minerals which exist in meteorites as a result of their interaction with the terrestrial environment.

The fiery passage of a meteorite through the atmosphere produces essentially no mineralogical changes within the meteorite itself. Ablation removes a considerable amount of material, and when the meteorite lands it is coated with a thin fusion crust. On stones the crust is glassy,

but it usually contains scattered crystals of magnetite produced by the oxidation of nickel-iron and ferromagnesian silicates. The crust on irons is largely magnetite, but may contain wüstite, (Fe, Ni)O, identified on the Bogou, Sikhote-Alin, Pitts, Rowton, Braunau, Keen Mountain, and Hex River Mountains irons by Marvin (1963).

A considerable number of minerals has been recorded as produced by the weathering of meteorites (Table 4). My own experience is that the common products of weathering are goethite and maghemite, the latter generally nickelian (up to 8.7 percent NiO in the weathered Wolf Creek meteorite), and that the silicates are unaffected. Hematite, although recorded by a number of investigators, seems to be quite rare. Ramdohr (1963) mentions that lepidocrocite is not uncommon. Akaganéite was

TABLE 4. MINERALS PRODUCED BY THE TERRESTRIAL WEATHERING OF METEORITES

Goethite	α -FeOOH	Chalcopyrite	CuFeS ₂
Akaganéite	β -FeOOH	Bornite	Cu ₅ FeS ₄
Lepidocrocite	γ -FeOOH	Unnamed	Ni(OH) ₂
Magnetite	Fe ₃ O ₄	Calcite	CaCO ₃
Hematite	α -Fe ₂ O ₃	Siderite	FeCO ₃
Maghemite	γ -Fe ₂ O ₃	Reevesite	Ni ₃ Fe ₂ (OH) ₁₆ (CO ₃) ₂ ·4H ₂ O
Copper	Cu	Gypsum	CaSO ₄ ·2H ₂ O
Sulfur	S	Jarosite	KFe ₃ (OH) ₆ (SO ₄) ₂
Pentlandite	(Fe, Ni) ₉ S ₈	Collinsite	Ca ₂ (Mg, Ni)(PO ₄) ₂ ·2H ₂ O
Heazlewoodite	Ni ₃ S ₂	Cassidyite	Ca ₂ (Ni, Mg)(PO ₄) ₂ ·2H ₂ O
Pyrite	FeS ₂	Lipscombite	Fe ₃ (OH) ₂ (PO ₄) ₂
Bravoite	(Fe, Ni) ₂ S ₂	Unnamed	Ni ₆ Si ₄ O ₁₀ (OH) ₈
Violarite	FeNi ₂ S ₄		

recognized in weathered irons by Marvin (1963), who suggested that it probably results from the oxidative decomposition of lawrencite.

Most of the other minerals in Table 4 have been recorded from only a few meteorites, and usually in trace amounts. It should be noted that some of them are also primary extraterrestrial phases, as indicated in Tables 1 and 2. Copper and the copper-iron sulfides are evidently produced by the dissolving of primary cubanite and the reaction of the copper-bearing solutions thus formed with other sulfides. Sulfur is formed by the oxidative decomposition of troilite. The nickel-bearing sulfides are largely the product of the reaction of nickeliferous solutions from nickel-iron with troilite. Calcite and gypsum are formed by the weathering of oldhamite, but are primary constituents in some of the carbonaceous chondrites.

Reevesite, jarosite, collinsite, cassidyite, lipscombite, and the unnamed nickel serpentine are recorded by White *et al* (1967) in the

weathered Wolf Creek meteorites; the phosphates are the products of the weathering of schreibersite. The green nickel-bearing crusts on weathered meteorites have frequently been identified as zaratite. However, the basis of the identification is not stated, and in view of the doubts regarding the nature and even the existence of zaratite (Issacs, 1963), this mineral is not included in the above list. "Zaratite" in the Wolf Creek meteorite proved to be a nickel serpentine, and green coatings on the South Dahna meteorite, a weathered iron from Saudi Arabia, (referred to as zaratite by Ramdohr, 1963) is a mixture of reevesite and $\text{Ni}(\text{OH})_2$, according to John S. White of the U. S. National Museum (pers. communication).

Buddhue (1957) has published an extensive monograph on the oxidation and weathering of meteorites. Besides the minerals recorded in Table 4, he reports the possible occurrence of the following: bunsenite, trevorite, melanterite, copiapite, and vivanite. While these minerals may well be formed by the weathering of meteorites, their occurrence therein has not yet been positively established.

ACKNOWLEDGEMENTS

Much of my own research work on meteorites has been supported by generous grants from the National Science Foundation (G-14567 and GP-1218) and the National Aeronautics and Space Administration (NsG-688), for which I should like to express my appreciation.

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