The Classification of Chondritic Meteorites

By Brian Mason[1]

INTRODUCTION

In 1862 Rose divided the stony meteorites into two classes, the chondrites and the achondrites, according to the presence or absence of the rounded aggregates of olivine or pyroxene, or both, known as chondrules. This division has been accepted ever since; the distinction is readily made, except for a few stones in which chondrules are few or poorly defined. In 1872 Tschermak extended Rose's classification by subdividing the chondrites into groups according to their color and structure, a subdivision later extended by Brezina, until in his final presentation (1904) no fewer than 31 groups were recognized. This classification, commonly known as the Rose-Tschermak-Brezina classification, was generally adopted and is still widely used.

Prior (1920) criticized this classification as complicated, over-elaborate, and based on the superficial characters of color and the presence or absence of brecciation or veining. He proposed a classification based on chemical composition, and recognized three groups, as follows:

1. Enstatite-chondrites: consisting essentially of crystalline, nearly pure, non-ferriferous enstatite, with nickel-iron in large amount up to 25 per cent and poor in nickel (Fe:Ni about 13), troilite, and some oligoclase.

2. Bronzite-chondrites or strictly olivine-bronzite chondrites: consisting essentially of bronzite and olivine in approximately equal amounts, with

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some oligoclase, nickel-iron, and troilite. The nickel-iron is less poor in nickel than in the enstatite-chondrites, and is less in amount, though this is generally over 10 per cent. The ratio of MgO to FeO in the ferromagnesian minerals in the type meteorite (Cronstad) is about 5.

3. Hypersthene-chondrites or strictly olivine-hypersthene chondrites: of similar composition and structure to the preceding group, except that the iron is richer in nickel (Fe:Ni varying from about 7 to 3) and generally in less amount, and the ferromagnesian minerals are correspondingly richer in ferrous oxide (MgO:FeO varying from about 4 to 2½).

In the development of his classification Prior established certain chemical and mineralogical regularities within the chondrites. These relationships, generally known as Prior's rules, can be stated as follows:

1. The smaller the amount of nickel-iron in a chondrite the higher is the Ni/Fe ratio in the nickel-iron.

2. The smaller the amount of nickel-iron in a chondrite, the higher the FeO/MgO ratio in the ferromagnesian silicate minerals. The validity of Prior's rules has been questioned by Urey and Craig (1953), but recent work by Ringwood (1961a) has amply confirmed them.

In spite of the use of mineralogical terms to describe the individual groups, Prior's classification is essentially a chemical one. He pointed out that the group to which a chondrite belonged could be established by any one of three criteria: (1) the MgO/FeO ratio in the bulk analysis; (2) the MgO/FeO ratio in the silicate material insoluble in HCl (essentially pyroxene with a little plagioclase); and (3) the amount and Fe/Ni ratio of the nickel-iron. The names enstatite, bronzite, and hypersthene chondrite imply the second criterion, with the divisions at the bronzite boundaries of MgO:FeO 9 and 4 ($FeSiO_3$ 10 to 20 mol per cent). However, the first criterion has been generally used, since a bulk analysis is more commonly available than a reliable analysis of the pyroxene. The two criteria give, on the whole, concordant results, since the MgO:FeO ratio in the bulk analysis is usually close to that in the pyroxene; this ratio is normally slightly higher in the pyroxene.

Prior's classification is logical and straightforward, but its application in the form outlined above leads to certain difficulties. It cannot be applied to the numerous chondrites that have not been analyzed. Many analyses of chondrites are incomplete, doubtful, or demonstrably inaccurate, especially the figure for FeO, essential to the classification (FeO in chondrite analyses is a calculated figure, determined from total iron after subtracting Fe as nickel-iron and Fe combined with total S as FeS; all the errors in the latter determinations accumulate in the FeO figure, which is especially serious where the true FeO figure is low). If

the chondrite is weathered (and most finds are weathered to some degree), the MgO/FeO figure will be influenced by the oxidation of nickel-iron and troilite and cannot be used for the classification of the meteorite. It will be shown that Prior's classification can be more readily and more generally applied by the determination of the composition of the olivine in chondrites by measurement of its refractive indices. Even in weathered chondrites, the olivine is usually unaltered.

It is proposed in this paper to modify Prior's classification by the addition of two groups, the olivine-pigeonite chondrites and the carbonaceous chondrites. Chondrites belonging to these two groups were included by Prior in the olivine-hypersthene chondrites. However, in the olivine-pigeonite chondrites pigeonite is the dominant pyroxene, and the carbonaceous chondrites contain little or no pyroxene. These two groups also show additional mineralogical and chemical differences which clearly differentiate them from the other groups of chondrites. The two groups are few in number; 11 olivine-pigeonite and 14 carbonaceous chondrites have been recognized, whereas the olivine-bronzite and olivine-hypersthene chondrites number many hundreds and are by far the commonest of all meteorites.

OLIVINE COMPOSITION IN CHONDRITES

Olivine is present in all chondrites except the enstatite chondrites and some of the carbonaceous chondrites. Traditionally the composition of the olivine in any chondrite has been calculated from an analysis of the acid-soluble material, on the assumption that all the Mg and Si is derived from olivine, and the addition of sufficient Fe to fill the stoichiometric requirements of the formula $(Mg,Fe)_2SiO_4$. Although this procedure is probably capable of reliable results when carefully applied, it is liable to serious errors. Under these circumstances, physical methods for determining olivine composition are preferable. The most generally applicable methods are the use of the spacing of a specific reflection in the X-ray diffraction pattern (Yoder and Sahama, 1957), and the measurement of refractive indices.

The measurement of refractive indices is a quick and reliable method and requires a minimum of expensive equipment. With a polarizing microscope and a calibrated set of immersion oils it is possible to make routine determinations of the refractive indices of olivine with an accuracy of ± 0.002. From one of the principal refractive indices the composition of the olivine in mol per cent of the Fe_2SiO_4(Fa) component can be read off from the determinative curve of Poldervaart (1950). An

increment of 0.002 in the gamma index corresponds to an increment of 1 per cent of the Fa component.

Ringwood (1961a) has measured and compiled from the literature the refractive indices of olivines from 34 chondrites. I have measured the gamma index of olivine for some 160 chondrites. The olivine compositions derived from these measurements are summarized in figure 1, which shows the frequency of occurrence of a particular olivine composition.
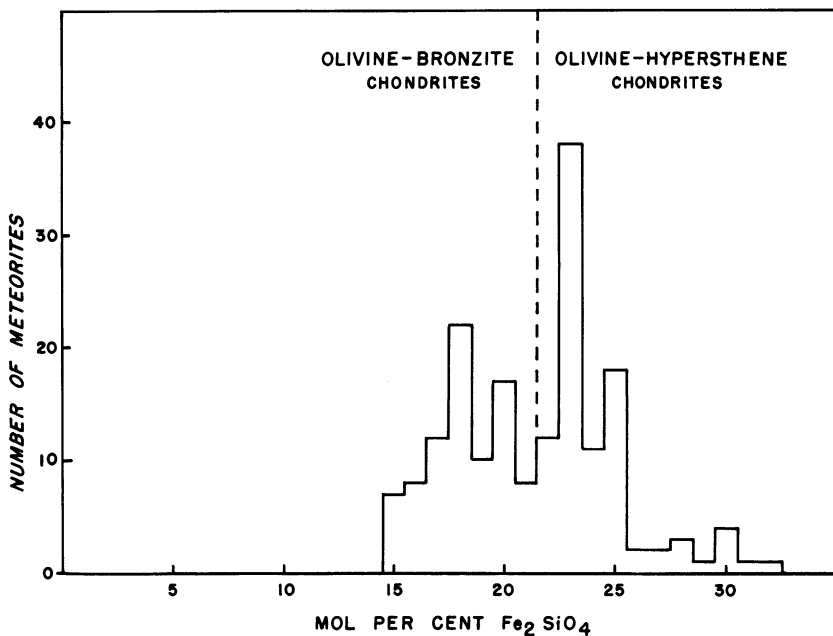

Fig. 1. Olivine composition in olivine-bronzite and olivine-hypersthene chondrites, determined from the measurement of refractive indices.

The meteorites represented in figure 1 are all olivine-bronzite and olivine-hypersthene chondrites. The boundary between the two groups is fixed at an olivine composition of Fa_{22}, for reasons that are discussed in a later section.

Significant features of figure 1 deserve consideration. It is clear that olivine in these two principal groups of chondrites has a limited composition, most falling between 15 and 25 mol per cent Fe_2SiO_4. There is a sharp cut-off at Fa_{15} and a tailing-off on the high-iron side to Fa_{32}. The distribution of compositions is not uniform over the whole range; the olivine-bronzite chondrites commonly have olivines in the Fa_{18-20} range,

the olivine-hypersthene chondrites in the Fa_{23-25} range. Between these two maxima there is a minimum which corresponds to the boundary between the two groups.

The olivine is somewhat richer in iron in the olivine-pigeonite chondrites than in the olivine-hypersthene chondrites. However, it is difficult to determine accurately the refractive indices of these olivines, because they usually are turbid to almost opaque with inclusions. Ringwood measured refractive indices of olivine in six olivine-pigeonite chondrites: Felix, Karoonda, Lance, Mokoia, Ornans, and Warrenton. For Karoonda he found a composition of Fa_{32}, for Warrenton Fa_{40}, and for the other four the refractive indices showed a wide spread of composition within each meteorite. From the chemical analyses of meteorites belonging to this group, the average composition of the olivines must be between 32 and 40 mol per cent Fe_2SiO_4.

RELATIONSHIP BETWEEN OLIVINE AND PYROXENE COMPOSITION

Pyroxene composition is not so readily determined by refractive index measurements as is olivine, owing to several factors. First, the compositional variation of pyroxene is inherently more complex than that of olivine. Whereas meteoritic olivine is essentially a two-component system Mg_2SiO_4–Fe_2SiO_4, with possibly slight substitution by Ca and Mn, in meteoritic orthopyroxene the system $MgSiO_3$–$FeSiO_3$ may be modified by the substitution of Al, Ca, Mn, Cr, and Ti, thereby causing complex variations in refractive indices. Second, the refractive index of orthopyroxene varies less rapidly with composition. Whereas an increase of 1 per cent in the Fe_2SiO_4 component in olivine results in an increment of 0.002 in the gamma refractive index, an increase of 1 per cent in the $FeSiO_3$ component (abbreviated as Fs) in orthopyroxene results in an increment of about 0.001 in its gamma index. Thus with the same precision of measurement of refractive index the accuracy in terms of composition is only half as great for the pyroxene. Third, in an immersion mount of crushed material from a chondrite, olivine grains are more readily and certainly recognized than pyroxene grains because of their high birefringence. All these factors combined make the use of olivine as a measure of chondrite composition much more advantageous.

However, a close and consistent relationship is normally present between olivine and orthopyroxene in the olivine-bronzite and olivine-hypersthene chondrites. This is illustrated in table 1, the data being taken partly from Ringwood (1961a) and partly from my own measurements.

TABLE 1

COMPOSITION OF COEXISTING OLIVINE AND ORTHOPYROXENE IN SOME CHONDRITES

Meteorite	Olivine (mol % Fe_2SiO_4)	Orthopyroxene (mol % $FeSiO_3$)	Difference
Chicora	32	28	4
Olivenza	30	25	5
Uden	28	25	3
Ottawa	28	24	4
Kyushu	26	22	4
Holbrook	26	24	2
Lake Labyrinth	25	23	2
Bjurbole	25	22	3
New Concord	24	21	3
Chateau-Renard	23	20	3
Middlesborough	23	20	3
Mocs	23	21	2
Homestead	22	20	2
Benoni	20	18	2
Forest City	19	16	3
Ochansk	19	17	2
Tomhannock Creek	19	17	2
Limerick	18	16	2
Miller	18	18	0
Yonozu[a]	17	16	1
Bur Gheluai	17	16	1

[a] The published optical data on Yonozu (Beck and Stevenson, 1951) are erroneous.

The precision of these measurements is probably about ± 1 for the olivine and $\pm 1\frac{1}{2}$ for the orthopyroxene. The figures show that the Fe/Mg ratio is slightly higher in the olivine than in the coexisting pyroxene, a relationship consistent with equilibrium conditions in the MgO-FeO-SiO_2 system, as established by Bowen and Schairer (1935). While the precision of the difference in composition is probably rather low, it does appear that the difference increases with increasing iron content, from about 1 at Fa_{15} to 4 at Fa_{30}. This indicates that olivine (Fa_{22}) coexists with orthopyroxene (Fs_{20}), so that the boundary between olivine-bronzite and olivine-hypersthene chondrites should be established at olivine of this composition, as was done on figure 1.

CHEMICAL COMPOSITION AND CHONDRITE GROUPS

Analyses of meteorites belonging to each of the five chondrite groups are set out in table 2. Within each group the range of composition is

TABLE 2

ANALYSES OF METEORITES BELONGING TO DIFFERENT CHONDRITE GROUPS

	1	2	3	4	5
Fe	23.70	15.15	6.27	4.02	0.00
Ni	1.78	1.88	1.34	1.43	0.00
Co	0.12	0.13	0.046	0.09	0.00
FeS	8.09	6.11	5.89	5.12	3.66(S)
SiO_2	38.47	36.55	39.93	34.82	27.81
TiO_2	0.12	0.14	0.14	0.15	0.08
Al_2O_3	1.78	1.91	1.86	2.18	2.15
MnO	0.02	0.32	0.33	0.20	0.21
FeO	0.23	10.21	15.44	24.34	27.34[a]
MgO	21.63	23.47	24.71	23.57	19.46
CaO	1.03	2.41	1.70	2.17	1.66
Na_2O	0.64	0.78	0.74	0.69	0.63
K_2O	0.15	0.20	0.13	0.23	0.05
P_2O_5	trace	0.30	0.31	0.20	0.30
H_2O	0.34	0.21	0.27	0.10	12.86
Cr_2O_3	0.23	0.52	0.54	0.58	0.36
NiO	0.11	—	—	0.00	1.53
CoO	—	—	—	0.00	0.07
C	0.32	—	0.03	0.19	2.48
	99.91[b]	100.29	99.67	100.08	101.01[a]

1 Enstatite chondrite (Daniel's Kuil; Prior, 1916, p. 14)
2 Olivine-bronzite chondrite (Oakley; Wiik, 1956, p. 280)
3 Olivine-hypersthene chondrite (Kyushu; Mason and Wiik, 1961, p. 274)
4 Olivine-pigeonite chondrite (Warrenton; Wiik, 1956, p. 280)
5 Carbonaceous chondrite (Mighei, Wiik, 1956, p. 280)

[a] Wiik reported all S as FeS, but it is given here as S, and the corresponding Fe is reported as FeO. Melikoff and Krschischanovsky (1898) found 3.69 per cent total S in Mighei, divided as follows: FeS, 0.46 per cent; S (free), 3.19 per cent; SO_3 (sulphate), 0.85 per cent; S_2O_2 (thiosulphate), 0.12 per cent. Wiik also reports 0.36 per cent loss on ignition, mainly organic matter.

[b] Includes CaS, 0.86; Cr_2S_3, 0.29.

comparatively small, so an analysis of one meteorite can be considered as fairly representative of all meteorites of that group.

When analyses from the different groups are compared, certain sequential relationships are clearly seen. There is a decline in free iron from the enstatite chondrites to the carbonaceous chondrites, coupled with an increase in combined iron (iron reported as FeO). The percentage of nickel alloyed with the free iron does not vary greatly, so that the metal phase is progressively richer in nickel in going from the enstatite chon-

TABLE 3

ANALYSES OF METEORITES BELONGING TO DIFFERENT CHONDRITE GROUPS, RECALCULATED
IN ATOM PERCENTAGES ON WATER, CARBON, OXYGEN, AND SULPHUR-FREE BASIS

	1	2	3	4	5
Fe	28.52	26.32	21.85	25.72	26.18
Ni	1.65	1.74	1.27	1.38	1.41
Co	0.11	0.12	0.04	0.08	0.06
Si	34.98	33.17	36.78	32.77	31.85
Ti	0.08	0.10	0.09	0.14	0.09
Al	1.91	2.04	2.01	2.42	2.90
Mn	0.02	0.25	0.26	0.16	0.19
Mg	29.43	31.72	33.92	33.03	33.19
Ca	1.67	2.34	1.67	2.19	2.04
Na	1.13	1.37	1.30	1.25	1.40
K	0.18	0.23	0.17	0.27	0.07
P	—	0.23	0.25	0.16	0.29
Cr	0.32	0.37	0.39	0.43	0.33
	100.00	100.00	100.00	100.00	100.00

1 Enstatite chondrite
2 Olivine-bronzite chondrite
3 Olivine-hypersthene chondrite
4 Olivine-pigeonite chondrite
5 Carbonaceous chondrite

drites to the olivine-pigeonite chondrites, as was first noted by Prior. The carbonaceous chondrites are clearly marked off from the other groups by the absence of free nickel-iron, the presence of carbon, a large amount of combined water, and sulphur as free sulphur and oxidized sulphur compounds. Nevertheless, the percentages of most of the major and minor components are quite similar in analyses of meteorites from the different groups; the primary difference is the difference in the state of oxidation of the iron. The close similarity in elemental composition between different chondrites was brought out by Wiik (1956) when he recalculated many analyses in atom per cent on a volatile-free (C, H, O, S) basis. When this is done the correspondence in composition is remarkably close, as can be seen from table 3.

Table 3, however, brings out one notable difference, which was first established by Urey and Craig (1953). The olivine-hypersthene chondrite has a markedly lower iron (and nickel) content than the other chondrites. Urey and Craig established this fact from a study of 94 selected analyses of chondrites. They plotted the Fe in metal and FeS against the Fe
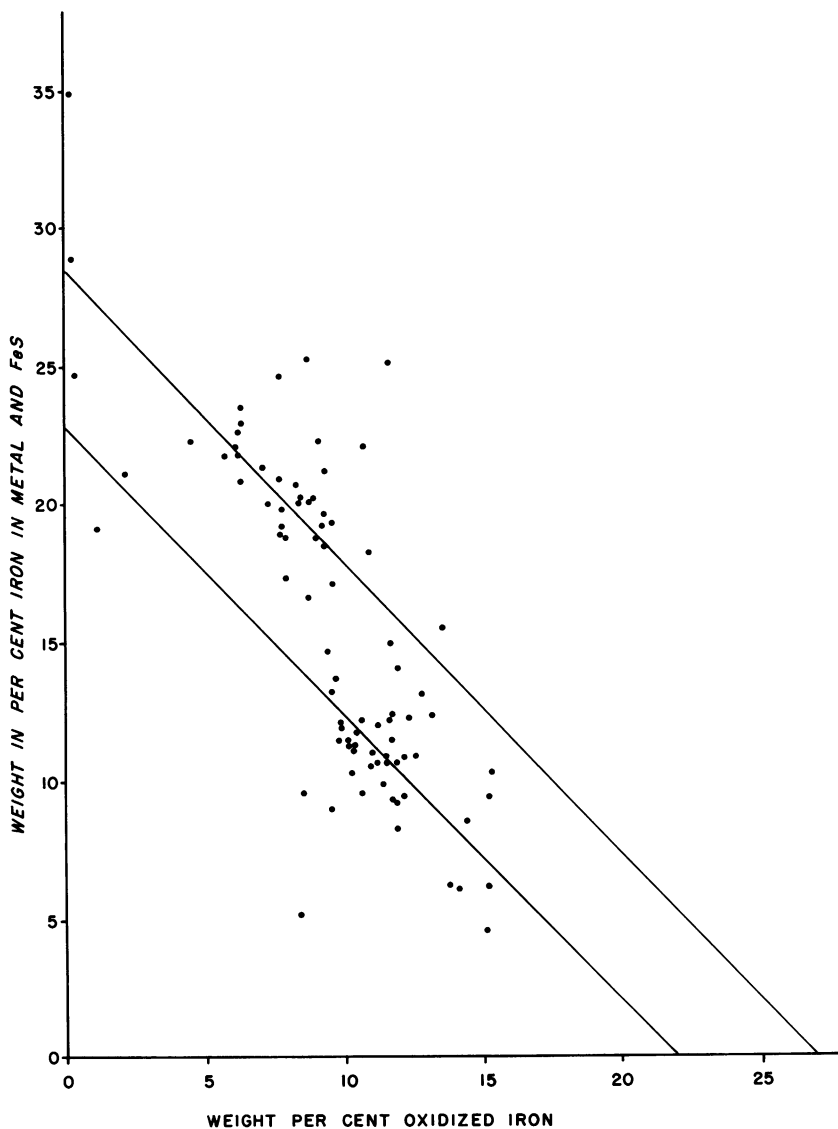
FIG. 2. The relationship between iron in metal and sulphide and oxidized iron in 94 selected analyses of chondrites (Urey and Craig, 1953, p. 57).

reported as FeO (fig. 2). The points representing the individual analyses cluster around two lines representing different total iron contents, one
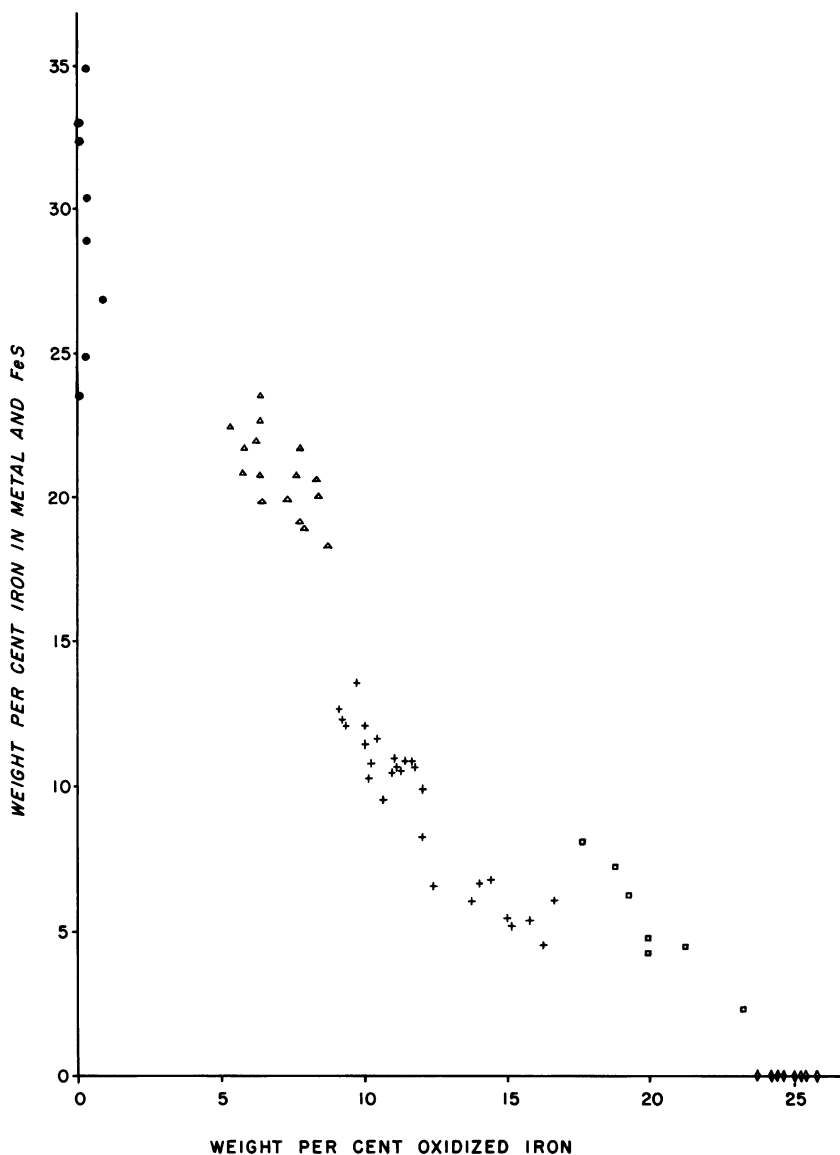
FIG. 3. A revised version of figure 2, with the use of analyses of observed falls that have been checked against the composition of the minerals. *Signs:* •, enstatite chondrites; △, olivine-bronzite chondrites; +, olivine-hypersthene chondrites; □, olivine-pigeonite chondrites; ◊, carbonaceous chondrites.

corresponding to about 28 per cent of total iron, the other about 22 per cent of total iron. On this basis Urey and Craig divided the chondrites into high-iron (H) and low-iron (L) groups (in the present paper referred to as H and L types, to avoid confusion with the five groups previously defined).

As can be seen from figure 2, the points representing the individual analyses show a considerable scatter and some overlap between the H and L types. The scatter and overlap are remarkably reduced if the analyses are selected according to the following criteria: (1) only falls are included, since finds may be weathered and oxidized and their analyses will not give a true picture of the relationship between metallic and oxidized iron in the meteorite; (2) the $FeO/FeO + MgO$ ratio in the olivine and pyroxene (determined from refractive indices) must be consistent (within $\pm 2\%$) with this ratio in the chemical analysis of the meteorite. The results of this procedure are shown in figure 3 [a similar diagram has recently been published by Ringwood (1961a)].

Figure 3 is very illuminating, in that it shows clearly that each of the five groups of chondrites occupies a specific composition field, and there is essentially no overlap of the different groups. The hiatus between the enstatite chondrites and the olivine-bronzite chondrites, noted and discussed by Ringwood (1961a), is very marked. Another remarkable feature is the coincidence of chondrites of L type with the olivine-hypersthene group; all olivine-hypersthene chondrites are L type, and none are H type. Carbonaceous chondrites, olivine-pigeonite chondrites, and olivine-bronzite chondrites are all H type. Enstatite chondrites show a considerable range of iron content. They may be included as H type, but Wiik (1956) has suggested that the more iron-rich ones should be considered as an HH type.

RELATIONSHIPS BETWEEN MINERALOGY AND CHEMICAL COMPOSITION

Prior's classification of the chondrites is based primarily on their chemical composition, but he showed that a close relationship existed between chemical composition and mineralogy, a relationship that has been emphasized by Mason (1960) and Ringwood (1961a). The major features of this relationship are presented in table 4 for the enstatite, olivine-bronzite, olivine-hypersthene, and olivine-pigeonite chondrites. The mineralogy of the carbonaceous chondrites is discussed separately, since it is basically different from that of the other groups.

TABLE 4

CHEMICAL AND MINERALOGICAL VARIATION WITHIN THE CHONDRITE GROUPS

(All figures are weight per cent, except FeO/FeO + MgO, which is in mol per cent.)

	Enstatite	Olivine-Bronzite	Olivine-Hypersthene	Olivine-Pigeonite
Pyroxene	50–60 (Fs_0)	20–35 (Fs_{14-20})	25–35 (Fs_{20-30})	~5
Olivine	None	25–40 (Fa_{15-22})	35–60 (Fa_{22-32})	65–70 (Fa_{32-40})
Nickel-iron	20–28	16–21	1–10	0–6
Oligoclase	5–10	5–10	5–10	5–10
Troilite	7–15	~5	~5	~5
Total Fe	23–35	27–30	20–23	24–26
FeO	<1	7–12	12–22	22–29
FeO/FeO+MgO	<1	15–22	22–32	32–40

ENSTATITE CHONDRITES

Chemically the enstatite chondrites are characterized by a high degree of reduction; essentially all the iron is present in the metal and sulphide phases (some analyses show a small amount of FeO, but this seems to be either analytical error or oxidation prior to or during analysis). Not only is iron totally reduced, but other elements are also. Calcium, manganese, and chromium may be present in the sulphide phases, and some silicon is present in the metal phase (Ringwood, 1961b). Total iron shows a much wider range than in other chondrite groups, from 23 to 35 per cent in the falls (the single find, Blithfield, has 20.7% total iron). Mineralogically they consist essentially of iron-free enstatite and nickel-iron, with some troilite and oligoclase and small amounts of accessory minerals.

TABLE 5

ENSTATITE CHONDRITES

	Date of Fall	Weight in Kilograms
Abee (Alberta, Canada)	6/10/1952	107.5
Blithfield (Ontario, Canada)	Found 1910	1.83
Daniel's Kuil (South Africa)	3/20/1868	1.20
Hvittis (Finland)	10/21/1901	14
Indarch (U.S.S.R.)	4/17/1891	27
Khairpur (India)	9/23/1873	14
Pillistfer (U.S.S.R.)	8/8/1863	23
St. Marks (South Africa)	1/3/1903	13.8
Saint-Sauveur (France)	7/10/1914	14

Olivine appears to be absent, and some of them contain a slight excess of SiO_2 in the form of quartz, tridymite, or cristobalite. The enstatite chondrites are rare meteorites; the Prior-Hey catalogue (1953) lists 19 of them, but some of those are wrongly classified (evidently because some investigators apply the name "enstatite" to all orthorhombic pyroxene in meteorites, without reference to iron content). Of the enstatite chondrites recorded in the Prior-Hey catalogue, Achiras, Aguada, Lake Labyrinth, Leonovka, Moorleah, Perpeti, Pervomaisky, and Sauguis are olivine-hypersthene chondrites; Cushing, Kunashak, and Miller (Arkansas) are olivine-bronzite chondrites. Only nine meteorites have been positively identified as enstatite chondrites, eight falls and one find; they are listed in table 5. Although few in number, they are of extraordinary interest as a group of very specific composition. They are separated by a complete hiatus from the olivine-bronzite chondrites, and they show some similarities with the carbonaceous chondrites in the presence of notable amounts (up to 0.5%) of carbon.

OLIVINE-BRONZITE CHONDRITES

Chemically this group is characterized by having the greater part of the iron in the free state. The FeO content ranges from 7 to 12 per cent; figures of less than 7 per cent have been recorded, but when checked against the composition of the minerals these figures prove to be erroneous, the analysis figure for FeO being especially liable to error when the true figure is low and the amount of free iron is high. In contrast to the enstatite chondrites, calcium, chromium, manganese, and silicon are present entirely as oxidic compounds. Mineralogically they consist of subequal amounts of olivine and bronzite, together with nickel-iron, oligoclase (or maskelynite), and troilite, with small amounts of accessory minerals. The olivine-bronzite and olivine-hypersthene chondrites together make up over 90 per cent of all chondrites; virtually all the unclassified chondrites belong to these two groups. Of the 177 chondrites included in figure 1, 84 belong to the olivine-bronzite group and 93 to the olivine-hypersthene group.

OLIVINE-HYPERSTHENE CHONDRITES

Chemically these meteorites are characterized by having a large part of their iron in the ferromagnesian silicates. The FeO content ranges from 12 to 22 per cent; figures above 22 per cent are erroneous or are of weathered meteorites containing free iron oxide formed from nickel-iron or troilite. As pointed out above, the olivine-hypersthene chondrites are distinguished from the other groups of chondrites by a lower total iron

TABLE 6

OLIVINE-PIGEONITE CHONDRITES

	Date of Fall	Weight in Kilograms	Notes
Felix (Alabama, U.S.A.)	5/15/1900	3	Carbonaceous
Grosnaja (U.S.S.R.)	6/28/1861	3.3	Carbonaceous
Kaba (Hungary)	4/15/1857	3	Carbonaceous
Karoonda (South Australia)	11/25/1930	42	—
Lance (France)	7/23/1872	52	Carbonaceous
Mokoia (New Zealand)	11/26/1908	4	Carbonaceous
Ngawi (Java)	10/3/1883	1.39	—
Ornans (France)	7/11/1868	6	—
Tieschitz (Czechoslovakia)	7/15/1878	28	—
Vigarano (Italy)	1/22/1910	16	Carbonaceous
Warrenton (Missouri, U.S.A.)	1/3/1877	1.6	—

content, averaging 22 per cent. Mineralogically they are very similar to the olivine-bronzite chondrites; olivine and hypersthene make up the greater part, olivine being somewhat in excess of hypersthene, with minor amounts of nickel-iron, troilite, and oligoclase (or maskelynite), and small quantities of accessory minerals. Those olivine-hypersthene chondrites that are relatively high in FeO may contain a minor amount of pigeonite as well as hypersthene.

OLIVINE-PIGEONITE CHONDRITES

When Prior drew up his classification of the chondritic meteorites he was not aware that in those with a high FeO content the pyroxene was pigeonite, not hypersthene, hence included these meteorites with the olivine-hypersthene chondrites. Nevertheless they form a distinct, if small, group (table 6). Some of them are black from the presence of carbonaceous compounds, although the carbon content does not exceed 0.5 per cent; these are the Type III carbonaceous chondrites of Wiik (1956).

Chemically the olivine-pigeonite chondrites are characterized by having most of their iron in the ferromagnesian silicates. Mineralogically they are characterized by the predominance of olivine (about 70%); other minerals are pigeonite, oligoclase, and troilite in small amounts, and accessory amounts of nickel-iron which is rich in nickel and entirely taenite. They commonly contain a small amount of magnetite. Pentlandite instead of troilite is the predominant sulphide mineral in one of them (Karoonda) and has also been recorded in Kaba (Sztrokay, 1960).

CARBONACEOUS CHONDRITES

The carbonaceous chondrites are here defined as a group with little or no iron as metal or sulphide, containing carbon and carbonaceous compounds in excess of 0.5 per cent, and considerable amounts of combined water [10–20%, according to Wiik's analyses (1956)]. Published analyses are misleading, since all S is reported as FeS, whereas these meteorites contain little or no troilite, the sulphur being present largely as free sulphur, sulphur in organic compounds, or oxidized sulphur compounds. If all iron is calculated as FeO, then the FeO/FeO+MgO mol per cent is 40–50. Total iron, if recalculated after the elimination of water from the analyses, is between 23 and 26 per cent. Wiik (1956) recalculated his analyses of carbonaceous chondrites on a volatile-free basis, and showed that they all belonged to the H type of Urey and Craig.

Wiik divided the carbonaceous chondrites into three subgroups, according to the mean values of certain constituents, as follows:

	SiO_2	MgO	C	H_2O	S
Type I	22.56	15.21	3.54	20.08	10.32
Type II	27.57	19.18	2.46	13.35	5.41
Type III	33.58	23.74	0.46	0.99	3.78

Type III carbonaceous chondrites are actually olivine-pigeonite chondrites and are here included in that group; Types I and II make up the carbonaceous chondrite group as defined above. Type I carbonaceous chondrites have notably low densities ($\sim$ 2.2), are made up largely of amorphous hydrated silicate, are strongly magnetic (apparently from the presence of an iron-nickel spinel), and have much of their sulphur as water-soluble sulphate. Type II carbonaceous chondrites have densities in the range 2.5–2.9, are made up largely of serpentine, are weakly or nonmagnetic, and have much of their sulphur in the free state. Type I carbonaceous chondrites contain no chondrules (an awkward contradiction in terms); those of Type II contain chondrules which vary from meteorite to meteorite in size, abundance, and perfection of form. These chondrules are olivine close to pure Mg_2SiO_4 in composition, and enstatite or clinoenstatite (possibly pigeonite). Trace amounts of nickel-iron occur in some of them.

The carbonaceous chondrites number comparatively few meteorites (table 7), but in spite of their low abundance they are highly significant because of the peculiarities in their chemical and mineralogical composition, especially the presence of hydrated minerals and carbonaceous compounds. All were seen to fall and were picked up shortly afterward;

TABLE 7

CARBONACEOUS CHONDRITES

	Date of Fall	Weight in Kilograms	Notes
Alais (France)	3/15/1806	6	Type I
Boriskino (U.S.S.R.)	4/20/1930	1.17	Type II
Cold Bokkeveld (South Africa)	10/13/1838	3	Type II
Crescent (Oklahoma, U.S.A.)	8/17/1936	0.08	Type II
Erakot (India)	6/22/1940	0.11	Type II
Haripura (India)	1/17/1921	0.32	Type II
Ivuna (Tanganyika)	12/16/1938	0.70	Type I
Mighei (U.S.S.R.)	6/18/1889	8	Type II
Murray (Kentucky, U.S.A.)	9/20/1950	12.6	Type II
Nawapali (India)	6/6/1890	0.06	Type II
Nogoya (Argentina)	6/30/1879	4	Type II
Orgueil (France)	5/14/1864	10	Type I
Santa Cruz (Mexico)	9/3/1939	0.05	Type II
Tonk (India)	1/22/1911	0.01	Type I

otherwise it is doubtful if they would survive for any length of time, because of their friability and the presence of water-soluble compounds.

DISCUSSION

The close relationships between the different chondrite groups demand explanation in any theory of the origin of these meteorites. The over-all uniformity of composition in terms of most of the elements, and the sequential chemical and mineralogical relationships between the individual groups, support the theory that the chondritic meteorites were all derived from a common parent material. Prior (1920) held this view and proposed that the different groups had been formed by the progressive oxidation of a highly reduced magma, the earliest stage being represented by the enstatite chondrites. Mason (1960) and Ringwood (1961a) have theorized that the parent material was highly oxidized, its original state being similar to that of the Type I carbonaceous chondrites, the other groups of chondrites having been produced from this material by dehydration and progressive reduction. Urey and Craig (1953), from the occurrence of H and L types of chondrites, have argued that these types must have been derived from at least two asteroids of different composition. Urey (1961) has recently criticized the theory that material similar to that of the carbonaceous chondrites could be the parent material of

all the chondritic meteorites, because of the differences in chemical composition between the different groups. Fish, Goles, and Anders (1960) favor an initial material similar in composition to the carbonaceous chondrites and the development of the other meteorite groups from this material in bodies of asteroidal size.

Nothing has been said so far regarding the characteristic chondritic structure, the origin of which is clearly part of the problem of the origin of these meteorites. Virtually all investigators have accepted the fact that chondrites were once molten drops, which requires a high temperature and a liquid state of the meteoritic material at one stage in its development. Ringwood suggests that the required temperature may have been reduced considerably (to below 1000° C.) by a high pressure of H_2O and CO_2. Mason (1960) has argued from the textural relations that the chondrites have never been molten, and that chondrules have been formed from serpentine or amorphous hydrated silicates by solid-state recrystallization at temperatures above 600° C. However, Bowen and Tuttle (1949) have shown that forsterite can be formed from serpentine below 400° C., so the formation of this mineral in Type II carbonaceous chondrites can have taken place at moderate temperatures.

I believe that the data set out in this paper support the concept of a common source material for the chondritic meteorites, despite the criticisms of Urey. The chemical differences that he emphasizes are of second-order magnitude in comparison to the over-all uniformity of composition. However, if we start from a uniform parent material of carbonaceous chondrite composition, it is clear that the formation of the different chondrite groups can hardly have been a simple sequential process. The processes of dehydration and reduction operated to produce two abundant groups, the olivine-bronzite and olivine-hypersthene chondrites, differing somewhat in degree of reduction and markedly in their total iron content. The olivine-pigeonite chondrites are closely related to the carbonaceous chondrites and represent dehydration, with comparatively little reduction or chemical differentiation. The enstatite chondrites are clearly marked off from all other groups by their high degree of reduction. These differences are not readily explained on the model of a single planet as expounded by Ringwood. The close chemical and mineralogical relationships between the different chondrite groups do not agree with the theory that these meteorites are chance aggregates of debris from collision between asteroids, as maintained by Urey and Craig. The theory of Fish, Goles, and Anders that meteorites formed in asteroidal bodies seems most in accordance with the available data.

SUMMARY AND CONCLUSIONS

Prior's classification of the chondritic meteorites into enstatite, olivine-bronzite, and olivine-hypersthene chondrites is extended by the recognition of two more groups, the olivine-pigeonite and the carbonaceous chondrites. These groups are defined by chemical composition, most readily by the $FeO/FeO + MgO$ mol per cent (in enstatite chondrites this is zero or near zero, olivine-bronzite chondrites 15–22, olivine-hypersthene chondrites 22–32, olivine-pigeonite chondrites 32–40, carbonaceous chondrites 40–50). However, the mineralogical composition is related to chemical composition, and the classification of an individual meteorite can be rapidly obtained by the presence or absence of olivine and its composition.

The boundaries between different groups of chondrites are marked by hiatuses and discontinuities in chemistry and mineralogy, rather than continuous transitions. Meteorites belonging to different groups are notably unequal in abundance. Of more than 800 chondrites, nine are enstatite chondrites; 11, olivine-pigeonite chondrites; 14, carbonaceous chondrites; and the remainder, olivine-bronzite and olivine-hypersthene chondrites in approximately equal numbers. The chondrites as a whole show a uniformity of composition in terms of the non-volatile elements, except that the olivine-hypersthene chondrites contain about 5 per cent less iron than the other groups; they comprise Urey and Craig's low-iron type, whereas the other groups of chondrites belong to their high-iron type. The significance of these facts is discussed, and it is concluded that all chondritic meteorites were derived by processes of dehydration and reduction from a primary material similar in composition to the carbonaceous chondrites. The hiatuses and discontinuities between the different groups are ascribed to differences in the intensity of these processes and to a limited amount of chemical and phase differentiation.

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