
Ferromagnesian Chondrules in Carbonaceous Chondrites

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Carbonaceous chondrites (groups CO and CV) contain three types of ferromagnesian chondrules that can be distinguished on the basis of mineralogy and texture. Statistical analysis of the bulk chemical compositions of these chondrule types suggests that two of the three types are genetically related. The chondrules in carbonaceous chondrites can thus be separated into two populations. These populations are also apparently distinct in terms of redox state and oxygen isotopic composition. The more abundant population (I) is clearly different from chondrules in unequilibrated ordinary chondrites, but the minor population (II) is similar to them in many respects. These chondrule populations may have formed by melting of solid, locally homogeneous precursor materials in different regions of the nebula, and were mixed after solidification was complete.

INTRODUCTION

Within the past few years, there has been a resurgence of interest in meteoritic chondrules. This research has focused almost exclusively on chondrules in ordinary chondrites, but ferromagnesian chondrules are the most abundant compositional types in both ordinary and carbonaceous chondrites. Although the chondrules in carbonaceous chondrites have many similarities to those in ordinary chondrites, they differ in some important respects. The only recent systematic studies of ferromagnesian chondrules in carbonaceous chondrites were published by McSween (1977a) and Simon and Haggerty (1980). This paper will reevaluate the same chemical data set utilized in McSween's previous study. This data set was previously treated only in graphical form; the application of statistical methods in this paper has resulted in some new insights into chondrule populations in carbonaceous chondrites, as well as new conclusions about chondrule origin at variance with the previous work.

ANALYTICAL METHODS

Some carbonaceous chondrites have experienced aqueous alteration, as in the case of all CM chondrites, or thermal metamorphism, as in the case of a few CO and CV chondrites (McSween, 1979). Such meteorites have been excluded from the present study. Only chondrule analyses from the following relatively unaltered type 3 carbonaceous chondrites (with respective numbers of chondrules in parentheses) are included in this compilation: CV [Allende (14), Arch (8), Bali (17), Efremovka (17), Grosnaja (16), Kaba (14), Leoville (13), Mokoia (6), Vigarano (12)], and CO [Felix (30), Kainsaz (48), Lancé (43), Ormans (29)]. A tabulation of individual analyses may be requested from the senior author.

Chondrule analyses were obtained using an electron microprobe defocused beam procedure described by McSween (1977a). The compositions of glass chondrules were determined from simple averages of random spot analyses covering the chondrules. A modified data reduction procedure (Bower *et al.*, 1977) was employed for coarse-grained chondrules. After each iteration, a provisional norm for the target material was calculated, providing estimates of the compositions of the mineral phases in which each element was cited; in succeeding iterations, corrections were calculated for each element on the basis of this heterogeneous mixture of hypothetical minerals. This procedure is not rigorously correct, but for heterogeneous targets it yields accurate analyses if the normative and modal mineralogies are similar (Albee *et al.*, 1977). The only significant difference between normative and modal phases in ferromagnesian chondrules is that normative feldspar components are actually cited in interstitial glass. However, because these glass compositions are generally similar to feldspars (McSween, 1977b), this is not a significant source of error. Lux *et al.* (1980) tested the accuracy of this procedure against chondrules analyzed by INAA and found good agreement.

Chondrule bulk compositions (361 chondrules in 13 meteorites) obtained by the procedure above were previously presented only in graphical form (McSween, 1977a). In this paper various statistical methods have been employed. Programs by Barr *et al.* (1976) and Jennrich and Sampson (1981) were utilized for factor analysis and stepwise discriminant analysis, respectively.

PETROGRAPHIC FEATURES OF CHONDRULES IN THIS STUDY

Chondrule types

The chondrules considered here are distinct from inclusions and mineral fragments in that all are polyminerally and have internal textures that testify to solidification of molten material, but some are drop-formed and others have irregular shapes. McSween (1977a) devised a working classification for chondrules in carbonaceous chondrites, based on texture and mineralogy. A slight modification of this classification, summarized in Table 1, is adopted here. More detailed

Table 1. Petrologic classification of ferromagnesian chondrules in carbonaceous chondrites.

	Texture	Mineralogy	Modal Abundance Ranges*	
			CO	CV
Type I	Granular	Olivine (Fo ₉₀₋₁₀₀) ± pyroxene (En ₉₀₋₁₀₀) ± spinel ± metal or magnetite with colorless interstitial glass	25-39	35-51
Type II	Microporphyritic or barred	Olivine (strongly zoned from Fo ₈₅₋₅₀) + Cr-rich hercynite with dark brown interstitial glass	< 3	< 1
Type III	Excentroradial or glassy	Pyroxene (En ₉₀₋₁₀₀) + light brown to yellow glass	< 2	Trace

* Modal data in vol.% of the meteorite, determined from point counts on polished thin sections.

descriptions of the chondrule types were published by McSween (1977c, d). The textural and mineralogical properties of each chondrules type provide sufficient differences to allow petrographic classification. The type I chondrules were previously subdivided into those that contained opaque minerals (metal or magnetite) and those that did not. Chemical data cannot differentiate between these groups, and because this study deals with chondrule chemistry, the distinction between opaque-bearing and opaque-absent type I chondrules has not been continued. We also note in Table 1 that type II chondrules have two very different textures: microporphyritic or barred. It is possible that these may represent two distinct types, but their mineralogies and bulk compositions are indistinguishable. Microporphyritic chondrules occur more commonly in CO and barred occur more commonly in CV chondrites. McSween (1977a) also recognized type IV chondrules, which have refractory compositions similar to Ca, Al-rich inclusions and probably represent their melted equivalents; this paper will focus only on ferromagnesian chondrules.

Chondrule abundances

The modal abundance ranges for various chondrule types are presented in Table 1. Abundance data for nine CV chondrites are from McSween (1977c). The ranges for nine CO meteorites include new data for the ALHA 77003, 77029, and 77307 chondrites (McSween, unpublished data), newly discovered Antarctic representatives of this group (Scott *et al.*, 1981), as well as previously published CO data (McSween, 1977d). There are significant differences between the relative abundances of the three chondrule types in carbonaceous chondrites. However, the relative abundances may have been changed prior to or during accretion, as chondrules in these meteorites show clear evidence of sorting by size (King and King, 1978).

Additional petrographic observations

Some double and even triple chondrules have been observed in carbonaceous chondrites (McSween, 1977a). These were welded together while still hot or in some cases partially molten, as the join may serve as a point of crystal nucleation for both droplets. When multiple chondrules occur, they are almost invariably of the same type. Similar relationships have been observed among chondrules in ordinary chondrites (Lux *et al.*, 1981), although a few exceptions have been noted (Gooding and Keil, 1981).

Relict grains of olivine, or less commonly orthopyroxene, that survived the chondrule formation process without melting have been described in chondrules of ordinary chondrites (Nagahara, 1981; Rambaldi, 1981). These grains typically are dusted with metal inclusions and exhibit reverse Mg-Fe zonation. Kracher *et al.* (1983) described several similar grains in chondrules of the Vigarano CV chondrite. However, relict grains in the chondrules of carbonaceous chondrites must be much less common than in ordinary chondrites or most must have a different appearance.

CHONDRULE COMPOSITIONS

Chemical and normative compositions

Average chemical compositions and standard deviations for each chondrule type are presented in Table 2. The various types of chondrules in carbonaceous chondrites appear to have distinctive compositional ranges, as illustrated by variations in MgO, FeO, and SiO₂ (Fig. 1). However, some overlap occurs among the three groups, particularly between types I and III. These data include some multiple chondrules, which are always of the same type and composition.

Figure 2 shows analyses of chondrules for Ni, Mn, and Fe (calculated as oxides). These three elements can exist in several oxidation states and thus respond differently to changes in redox conditions. Nickel contents of type I chondrules are highest, as expected for chondrules that contain metal, and type II chondrules lie off the NiO/FeO trend of the other two types. The MnO/FeO pattern for type II chondrules is also distinct, but type I and III chondrules overlap. These differences are interpreted as fractionations that occurred under different redox conditions. [These elements also have different condensation temperatures, and therefore could be fractionated during condensation. However, separation of Fe and Ni (Fig. 2) in different chondrule types

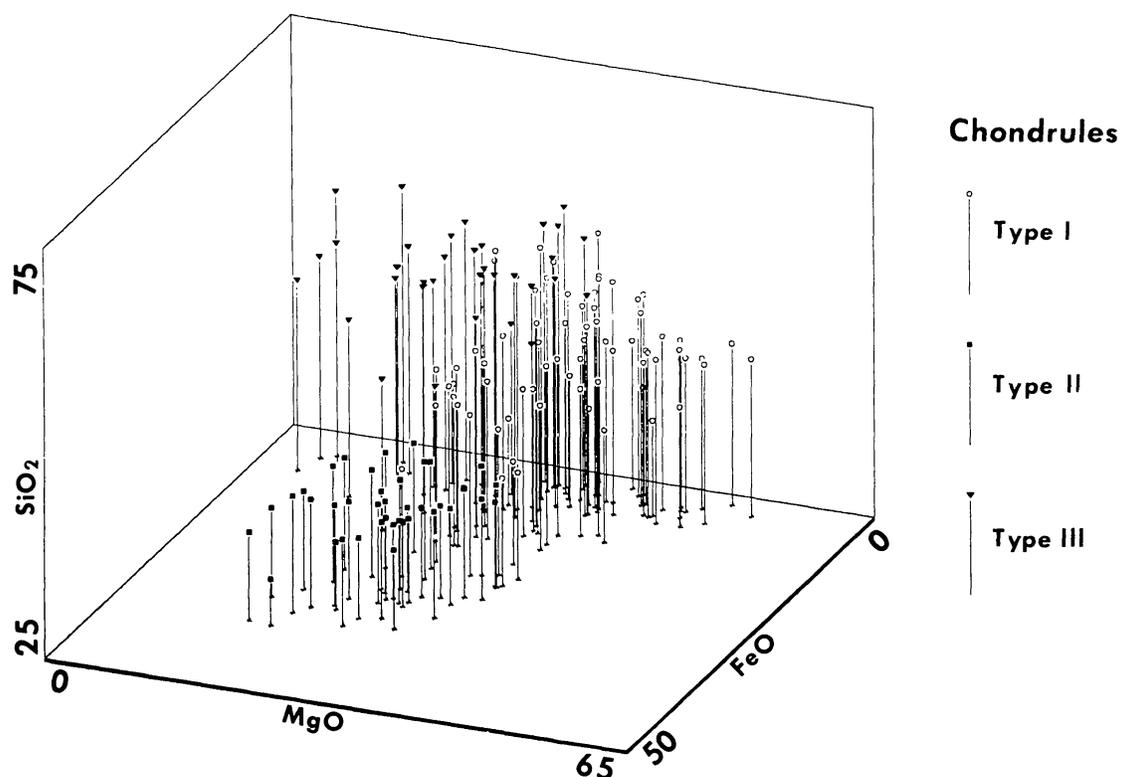


Fig. 1 FeO vs. MgO vs. SiO₂ (wt.%) for chondrules in carbonaceous chondrites.

may require condensation under different redox conditions.] Variations in oxidation state are also reflected in the mineralogy of type I and II chondrules (McSween, 1977b). Metal is absent, and olivines and spinels contain distinctly more Fe^{2+} in type II chondrules, reflecting their higher

Table 2. Average chondrule compositions in carbonaceous chondrites.

Wt. % oxides	Type I	Type II	Type III
SiO_2	44.3 (47) [†]	36.8 (21)	52.4 (41)
TiO_2	0.18 (10)	0.12 (7)	0.28 (17)
Al_2O_3	4.24 (261)	3.29 (183)	7.65 (493)
Cr_2O_3	0.42 (20)	0.39 (23)	0.54 (24)
FeO^*	9.25 (594)	27.8 (61)	7.45 (377)
MnO	0.14 (10)	0.24 (7)	0.29 (17)
MgO	38.2 (74)	27.0 (69)	23.0 (91)
CaO	2.89 (172)	1.91 (143)	7.26 (380)
Na_2O	0.60 (54)	1.35 (98)	1.81 (150)
K_2O	0.05 (5)	0.06 (5)	0.08 (11)
Ni	0.32 (35)	0.12 (12)	0.09 (12)
S	0.48 (95)	0.19 (22)	0.14 (19)
$\text{Mg}/(\text{Mg} + \text{Fe})^\ddagger$	0.88	0.63	0.85
No. analyses	282	42	37
<i>Norms</i> [§]			
or	0.29	—	0.47
ab	5.05	—	15.17
an	8.68	2.78	12.39
ne	—	6.28	—
lc	—	0.28	—
di	4.41	1.96	18.53
hy	10.49	—	29.31
ol	69.22	87.52	22.55
ilm	0.34	0.23	0.53
chr	0.62	0.59	0.79
py	0.89	0.36	0.26
<i>Normative Mineral Compositions</i>			
plag	$\text{Or}_2\text{Ab}_{36}$	An_{100}	$\text{Or}_2\text{Ab}_{54}$
di	$\text{Wo}_{53}\text{En}_{41}$	$\text{Wo}_{51}\text{En}_{28}$	$\text{Wo}_{52}\text{En}_{37}$
hy	En_{86}	—	En_{82}
ol	Fo_{85}	Fo_{54}	Fo_{80}

* Total Fe as FeO.

† Numbers in parentheses represent one standard deviation in terms of least unit given, i.e., 44.3 (47) is ± 4.7 .

‡ Molar ratios.

§ CIPW norms in wt.%.

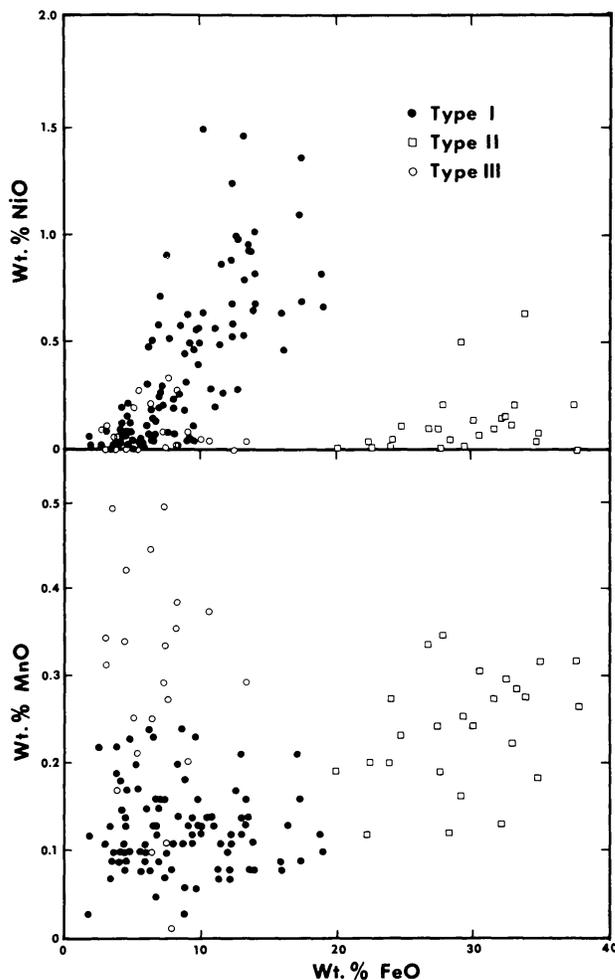


Fig. 2 NiO and MnO vs. FeO (wt.%) for chondrules in carbonaceous chondrites.

oxidation state. Differences in redox conditions established during droplet crystallization might produce different mineral compositions, but it is difficult to see how this could alter bulk compositions. Thus fractionations under different redox conditions must have occurred in the chondrule precursor materials prior to the chondrule-forming event. Type II chondrules must have formed from more highly oxidized material than types I or III.

Another way of emphasizing the differences between the compositions of chondrule types is by comparison of calculated CIPW norms (Table 2). It should be noted that these are "oxidized" norms, as a portion of Fe has not been allotted to metal in type I chondrules. This was not done because the proportion of Fe in metal is unknown, and because we wish to compare the compositions of these chondrules on equal bases. The entire chondrule population in carbonaceous chondrites varies in normative olivine/pyroxene ratio at roughly constant feldspar plus feldspathoid content (Fig. 3). However, there are significant differences between types I, II, and III. Type I chondrules show a much wider range of normative mineralogy than other types. This is consistent with their highly variable modal proportions of olivine and pyroxene. Relative to type I,

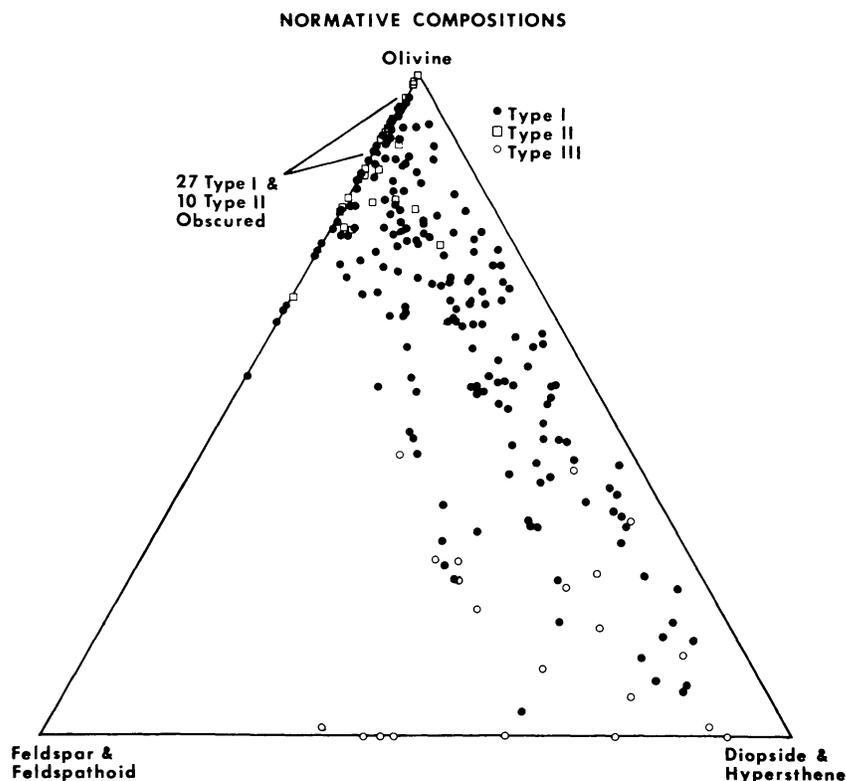


Fig. 3 CIPW normative components for chondrules in carbonaceous chondrites.

most type II chondrules contain almost no pyroxene component and appreciable amounts of feldspathoid, reflecting their low silica contents. These chondrules contain no modal pyroxene, and normative feldspathoid and plagioclase are represented modally by interstitial glass. Type III chondrules contain the highest proportions of pyroxene component, but have some similarities to type I. These chondrules contain abundant modal pyroxene, but no modal olivine.

Statistical analysis

In order to assess the significance of differences in all the analyzed elements in types I, II, and III chondrules, both factor analysis and stepwise discriminant analysis were employed. Factor analysis attempts to reduce the number of variables needed to define a population. This is accomplished by combining the most highly correlated variables into simple linear equations, or factors. No initial judgement is made about whether a specific chondrule belongs to one type or another, and chondrules of the same type should have similar factor scores. Factor analysis is deemed successful if a large number of variables can be reduced to a few factors, and each individual variable is associated with a minimum number of factors. Discriminant analysis, on the other hand, maximizes the difference between pre-defined populations by developing linear equations for each population. Thus, each chondrule type is defined by a discriminant function, and an assessment is made of how well these functions classify each chondrule. Discriminant

analysis is judged successful if only a few samples are incorrectly classified by their respective discriminant functions.

Prior to applying these multivariate analysis techniques, we ascertained that no systematic increase in coefficient of variance occurred with increasing arithmetic mean for each oxide. For this reason, arithmetic (unnormalized) rather than geometric (normalized) means were calculated for average chondrule compositions (Table 2). Because our results of factor and discriminant tests using unnormalized data were successful, additional analyses employing normalized data were judged unnecessary.

The results of R-mode factor analysis are shown in Table 3. The twelve analyzed elements are reduced to four rotated factors with eigenvectors greater than 1.0, and there are noticeable variations among element loadings for the different factors. F1 is dominated by MgO, TiO₂, and feldspar components (Na₂O, CaO, and Al₂O₃); F2 is controlled by FeO and SiO₂; F3 is most affected by MnO and Cr₂O₃; and F4 is controlled by S and Ni. These four factors account for 73.7% of the total variance (Table 3). A plot of factor scores for F1 vs. F2 is presented in Fig. 4. F1 partially discriminates between the fields of chondrule types I and III, and F2 differentiates the field of type II chondrules from I and III. Plots involving F3 and F4 provide less resolution than F1 or F2.

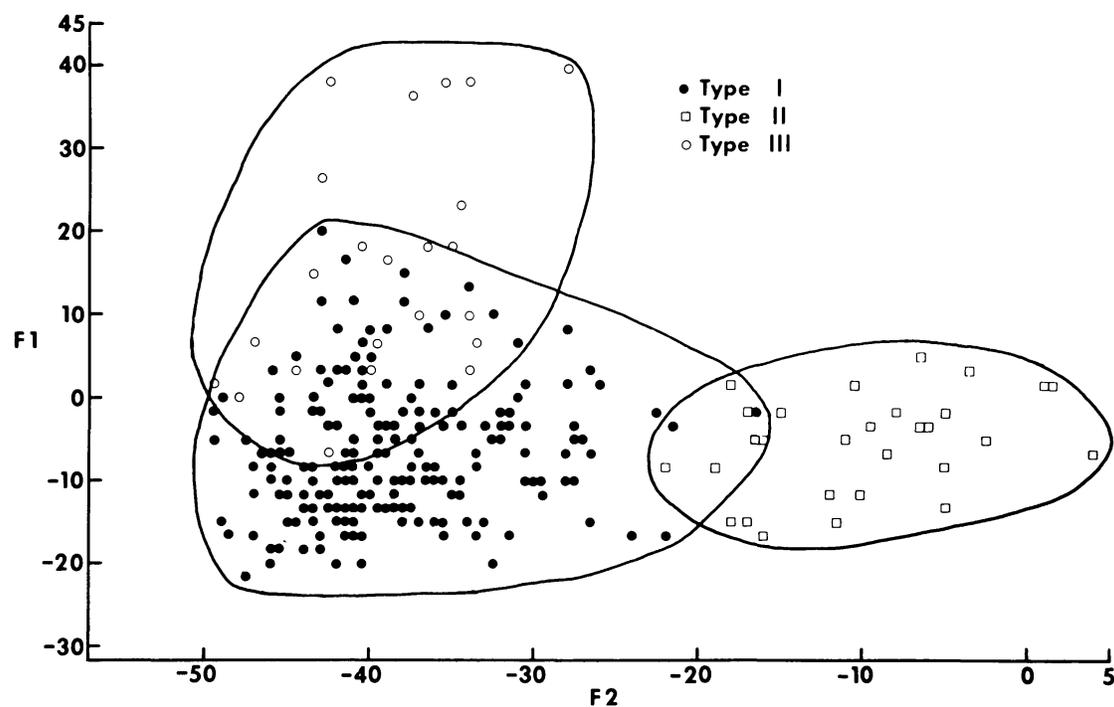


Fig. 4 An example of factor analysis for chondrules. The coefficients for factors F1 and F2 are defined in Table 3.

Table 3. Factor and discriminant analyses for chondrules.

	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	S	K ₂ O	CaO	TiO ₂	Cr ₂ O ₃	MnO	FeO	Ni	%Total Variance Explained	
<i>Factor Analysis for Chondrules*</i>														
F1	0.6452	-0.6211	0.9156	0.2860	0.0608	0.5099	0.8695	0.8390	-0.0455	0.0499	-0.1977	-0.0308	31.9	
F2	0.4681	-0.3433	-0.0315	-0.6928	0.0996	0.5161	-0.1707	-0.1891	-0.1071	0.1196	0.8359	0.0401	17.1	
F3	0.2637	-0.5897	-0.0023	0.3839	0.0140	-0.0602	0.2326	0.0008	0.7273	0.8149	0.3055	-0.0077	13.3	
F4	-0.1812	-0.0108	-0.0149	-0.2105	0.8132	-0.0053	-0.0070	0.0520	0.2640	-0.2490	0.1079	0.8218	11.4	
<i>Discriminant Analysis for Chondrules†</i>														
	<u>Constant</u>													
D1	-148.39	5.02						11.13	92.35	27.65	69.70	3.65	- 2.06	
D2	-165.85	4.97						10.70	100.71	17.88	77.40	5.00	-13.24	
D3	-140.79	4.70						11.92	77.98	25.18	89.93	3.41	- 4.50	
<i>Canonical Equation Coefficients</i>														
C1	1.123	0.005						0.086	-1.674	1.717	-1.128	-0.244	1.968	
C2	-3.609	0.088						-0.231	4.165	0.592	-5.650	-0.081	0.567	

* Equimax rotated principal axis factor method, analysis program by Barr *et al.* (1976).

† Stepwise discriminant analysis program by Jenrich and Sampson (1981).

There are some inherent difficulties in the interpretation of factor analyses. Because chemical analyses theoretically add to 100%, any one of the oxides in an analysis is a dependent variable of the others. Koch and Link (1971) showed that this “constant sum” problem does not appreciably affect factor analysis because the method, by its very nature, is searching for independent linear combinations of variables. Le Maitre (1982) discussed problems in making petrogenetic interpretations of R-mode factors. As there is no unique solution to the initial factor matrix, an indeterminate set of factor scores and loadings can be generated. Factor analysis is a valuable tool, however, in that it examines the degree of correlation among the variables, identifying the minimum number of independent variables needed to characterize the data. For these reasons, we have not attempted to assign mineralogic or petrologic significance to the individual factors, but have used two-dimensional plots of factor scores only to separate the data into chondrule types.

Stepwise discriminant analysis results are also shown in Table 3. The order in which oxides are admitted into the discriminant functions is predicated on their ability to differentiate between the three chondrule types. This order of entrance was limited by a cutoff value for each element which we arbitrarily set so as to provide a confidence level of > 98% for the last element admitted. The components meeting this screen were FeO, MgO, Ni, MnO, Cr₂O₃, TiO₂, and CaO; the remaining oxides were not used in the analysis. The discriminant functions were effective in classifying each individual chondrule as to type I, II, or III. Assignment of chondrules to type I was correct in 95% of all cases, to type II in 93%, and to type III in 88%. Most of the incorrect classifications were between chondrules of types I and III. An F-matrix was also generated, as another means of testing the confidence level at which the discriminant functions classified the chondrule types. These data indicated that all three types were discriminated above the 99% confidence level. The F-matrix scores were greatest for types I vs. II or II vs. III, indicating that type II chondrules are most clearly resolved from types I and III.

Two canonical functions (Table 3) that maximized the differences between chondrule types in two-dimensional space were calculated from the discriminant function data. In a plot of these functions (Fig. 5), type I and III chondrules define a continuous, slightly overlapping population, whereas type II chondrules are clearly resolved. Even though the canonical variables do not completely separate types I and III, the discriminant functions accurately differentiate between them in most cases.

Chondrule populations

Factor analysis and discriminant analysis both lead to the same conclusion: that carbonaceous chondrites contain three recognizable types. However, these three types can probably be grouped into two independent *populations* of chondrules, as the two types have many similarities. One population, consisting only of type II chondrules and thus called population (II), is clearly resolved by both statistical methods (Figs. 4 and 5). The other consists of poorly resolved types I and III chondrules (Figs. 4 and 5) and henceforth will be called population (I). Types I and III, i.e., population (I), chondrules also appear to be related in terms of the redox state of their precursor

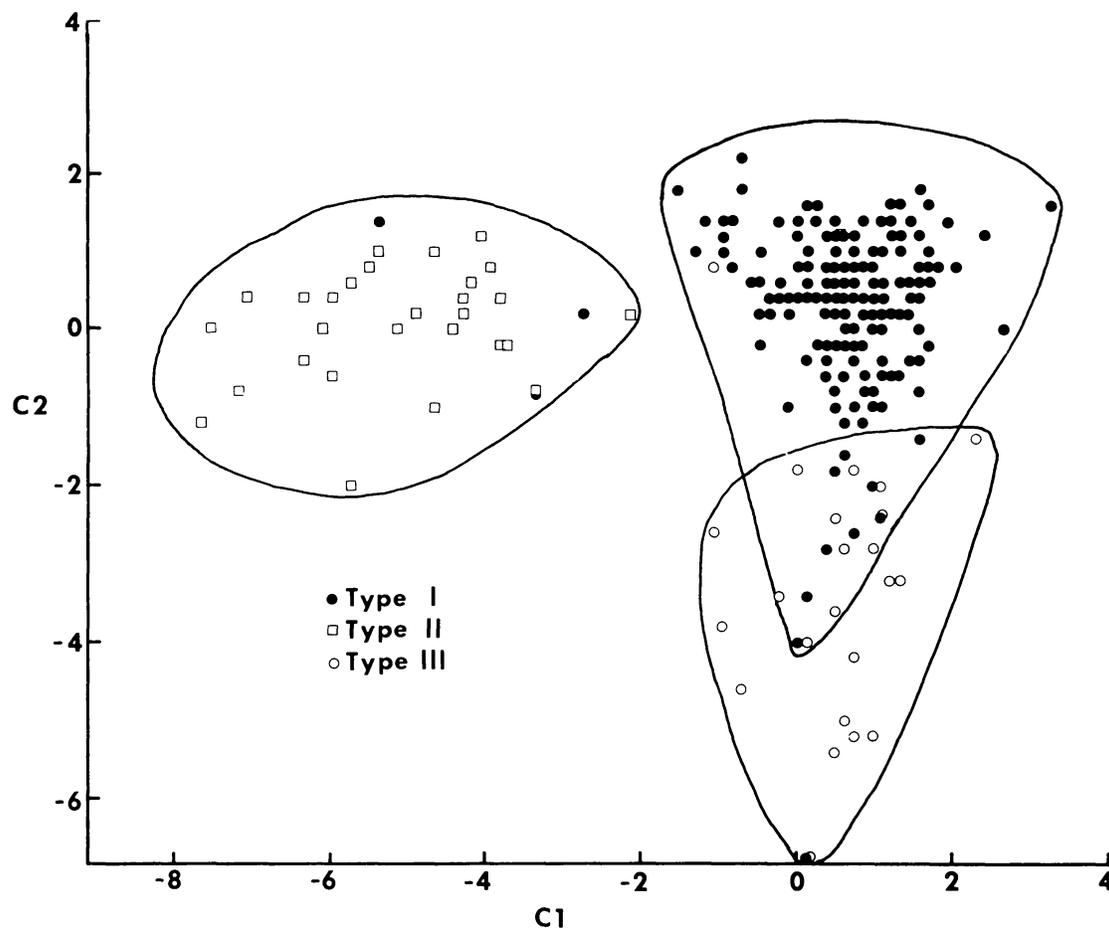


Fig. 5 Results of discriminant analysis for chondrules. The canonical variables C1 and C2 are calculated as the sum of the constants and oxide-coefficient products given in Table 3.

materials, and these are clearly distinct from the more oxidized population (II). The petrographic distinction between types I and III is primarily textural, but a textural change from excentroradial to granular may occur within a continuous compositional sequence of chondrules. Comparison of the normative mineralogy of types I and III chondrules (Table 2) suggests that type III chondrules could have formed from more highly differentiated but related protolithic material relative to type I.

COMPARISON OF CHONDRULES IN CARBONACEOUS AND ORDINARY CHONDRITES

The weighted average compositions for the two chondrule populations in thirteen carbonaceous chondrites are compared to the average chondrule compositions for unequilibrated ordinary chondrites in Table 4. The latter represent data from three H3 chondrites by Lux *et al.*

Table 4. Comparison of chondrule populations in carbonaceous and ordinary chondrites.

Wt. % Oxides	Carbonaceous Population (I)*	Carbonaceous Population (II)	H3 Chondrites†	L3 chondrites ‡
SiO ₂	45.2	36.8	50.3	46.0
TiO ₂	0.19	0.12	0.14	0.13
Al ₂ O ₃	4.64	3.29	3.23	3.35
Cr ₂ O ₃	0.43	0.39	0.54	0.60
FeO [§]	9.04	27.8	8.82	16.4
MnO	0.16	0.24	0.33	0.41
MgO	36.4	27.0	29.7	28.0
CaO	3.40	1.91	2.18	2.05
Na ₂ O	0.74	1.35	1.40	1.07
K ₂ O	0.05	0.06	0.18	0.22
No. analyses	319	42	87	23

* Weighted average of type I and III chondrules in Table 2.

† Data from the Sharps, Tieschitz, and Bremervörde chondrites by Lux *et al.* (1981).

‡ Data from the Manych chondrite by Dodd (1978).

§ Total Fe as FeO.

(1981) and one L3 chondrite by Dodd (1978). These two data sets were chosen for comparison because they included most of the same elements analyzed in chondrules of carbonaceous chondrites. Both data sets were also obtained by microprobe defocused beam analysis, though Dodd (1978) did not apply corrections for heterogeneous targets to his data. Both H3 and L3 chondrule data sets are very similar, in agreement with the conclusion of Gooding *et al.* (1980) that unequilibrated ordinary chondrites of different chemical groups (H, L, LL) contain indistinguishable chondrule populations. The only noticeable differences in the data for H and L chondrites is in FeO content (Table 4). Gooding *et al.* (1980) reported a mean FeO content of 13.9 wt.% for chondrules from four H, L, LL3 chondrites, intermediate between that of Lux *et al.* (1981) and Dodd (1978), and their reported standard deviations were higher for iron than for any other major element. Neither of these data sets was obtained using random sets of chondrules, and this may account for the difference in FeO values. Within each ordinary chondrite, there may also exist two distinct chondrule populations, one porphyritic and one non-porphyritic (Gooding *et al.*, 1980); however, the chemical differences between these are mainly in refractory and siderophile elements, many of which are in trace quantities. Since corresponding data are not available for chondrules in carbonaceous chondrites, we have not considered these possible groups in ordinary chondrites separately.

Scott *et al.* (1982) have emphasized the similarities between the components (including chondrules) of carbonaceous and unequilibrated ordinary chondrites. However, some important differences are apparent in Table 4. A comparison of the compositions of population (I) chondrules in carbonaceous vs. ordinary chondrites indicates the following: both have equivalent amounts of feldspar components, but CaO contents in carbonaceous chondrite population (I) are higher and

alkalis are lower; and chondrules in population (I) have much higher MgO/FeO ratios than those in ordinary chondrites.

A comparison of population (II) chondrules with those in ordinary chondrites indicates some strong similarities (Table 4). Most oxide concentrations are very similar, except for lower FeO and higher SiO₂ in ordinary chondrites. The difference in FeO contents could be explained if chondrules in ordinary chondrites and population (II) formed from similar materials, but chondrules in ordinary chondrites experienced reduction during melting and subsequent fractionation of metal. Grossman (1982) suggested that reduced Fe metal beads have been lost from chondrules in ordinary chondrites, and a general depletion of siderophile elements in chondrules relative to cosmic values (Gooding *et al.*, 1980) is consistent with this idea. Loss of Fe would also possibly explain the higher contents of oxides other than FeO (especially SiO₂ and MgO) in the chondrules of ordinary chondrites. Reduction and loss of FeO from population (II) to ordinary chondrite levels (assumed 13.9 wt.%, Gooding *et al.*, 1980) would cause increases of 5.9% in SiO₂, 4.4% in MgO, and only modest increases in other oxides to approximate the values in the chondrules of ordinary chondrites.

Gooding *et al.* (1982) reported oxygen isotopic compositions of individual chondrules in unequilibrated ordinary chondrites. They found that such chondrules scatter about a line with slope ~ 1 on a three-isotope diagram, and that the isotopic compositions bear no relationship to the chemical group of the parent meteorite. Clayton *et al.* (1983) reported new isotopic data for chondrules in the Allende carbonaceous chondrite. Chondrules whose textural and mineralogical descriptions suggest they are of population (I) (one type III and numerous type I chondrules) also define a line of slope ~ 1 , but it is significantly displaced from the regression line for chondrules in ordinary chondrites. Barred olivine, i.e., type II or population (II), chondrules in Allende define a distinct grouping that plots between the two previously described populations. These trends might be explained by partial equilibration of solid chondrule precursor materials rich in ¹⁶O with two different gaseous reservoirs depleted in ¹⁶O. One of these reservoirs would plot between the chondrules in ordinary chondrites and population (II), and the other on an extension of the population (I) trend. Thus population (II) and chondrules in ordinary chondrites, which also share some chemical similarities, may have equilibrated with the same isotopic reservoir and thus formed in similar environments. In this regard, population (II) chondrules may be considered as interlopers that were transported into the carbonaceous chondrite accretion zone, within which the more abundant population (I) chondrules were typical.

CONSTRAINTS ON CHONDRULE ORIGIN

In carbonaceous chondrites, there appear to be two distinct populations of chondrules, differing in chemical and mineralogical composition. Variations in Fe, Ni, and Mn contents may reflect fractionations at different oxidation states that were established in the precursor materials before chondrule formation. These differences are difficult to reconcile with a condensation origin (e.g., McSween, 1977a), though condensation of metastable liquids (Blander and Katz, 1967)

might be possible. Chondrules were more likely produced by melting solid precursor materials that in some cases had been processed from their presumed nebular starting compositions.

The present populations of chondrules in carbonaceous chondrites experienced mechanical sorting prior to assembly (King and King, 1978). Such sorting is unlikely to have occurred during accretion, as fine-grained matrix was accreted along with coarser chondrules. No genetic significance can be attached to the limited size range or relative abundances of chondrule types, because these were probably affected by the sorting process. The distinction between droplet and lithic chondrules in these meteorites may also be meaningless because lithic chondrules may have been larger droplet chondrules that were broken to meet size-sorting requirements.

Multiple chondrules that obviously formed in close proximity are almost always of the same type and composition (McSween, 1977a). Thus, the chondrule-forming process probably did not sample a coarse-grained, heterogeneous protolith on a small (non-representative) scale (e.g., Dodd, 1978). Such a process would produce chondrules of varying compositions, but these would form together and thus occasionally be attached as multiple chondrules. Another argument against this process is the observation that differences in chondrule compositions within a population cannot be explained by differences in the proportions of melted phases of fixed composition. For example, type I and III chondrules within population (I) differ not only in the proportions of normative feldspar, pyroxene, and olivine components, but also in the normative compositions of these minerals (Table 2). These arguments mitigate against formation of chondrules by impacts into regoliths, unless these were chemically and isotopically homogeneous on a small scale but heterogeneous on a large scale. More likely, chondrules probably formed by melting of locally homogeneous (i.e., fine-grained) material in the nebula, before being mixed with other populations during accretion. This interpretation may conflict with the observation of coarse relict grains in chondrules, but such large grains may have been unusual in this material (possibly explaining their survival during melting). Rubin *et al.* (1982) have argued from the observation of matrix lumps in chondrules that fine-grained matrix was the chondrule precursor. Although it seems possible that many of these lumps are of secondary origin, having filled chondrule surface irregularities and interior voids connected to the surface, something like matrix would have been a suitable precursor material.

Population (I) chondrules are apparently chemically and isotopically distinct from population (II) and the chondrules in ordinary chondrites. The latter two chondrule groups may have formed in proximity to each other in a heterogeneous nebula, as they can be interpreted as having partially equilibrated with the same gaseous reservoir. An alternative is that both formed at similar times in a homogeneous nebular gas with an evolving isotopic composition. Clayton *et al.* (1983) suggested that the porphyritic (population I) chondrules may have been only partially molten and the barred (population II) chondrules were completely molten, allowing the latter to experience more complete isotopic exchange with the same gas. The high FeO/MgO contents of population (II) chondrules would lower their solidus temperatures and facilitate melting. However, it is not known whether such partial equilibration took place with the solid precursor materials or while the chondrules were molten. It is difficult to envision how chondrule melts suspended in reasonable

nebula gas compositions could become so oxidized as population (II), or even remain so oxidized during melting of an oxidized solid precursor. It is clear, however, that the nebula in which chondrules formed was a complex place, containing solids of different chemical composition and redox state and possibly gases of different isotopic composition. The many similarities between all of these chondrule populations suggest that all formed by a similar process, but different solid precursor materials were clearly involved.

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