

A survey of the unequilibrated ordinary chondrites

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Abstract—The iron contents of olivines and low-calcium pyroxenes in thirty-one ordinary (H-, L- and LL-group) chondrites were determined by microprobe analysis. Twenty-five of these contain inhomogeneous silicates and are, in this respect, unequilibrated.

Petrographic study of these chondrites reveals that those of each chemical group whose silicates are most heterogeneous possess many characteristics which suggest that they are nearly unmetamorphosed. These are textural (absence of chondrule-chondrule and chondrule-matrix intergrowth; presence of a fine-grained, dark matrix; presence in some chondrules of silicic glass), mineralogical (near-absence of visible plagioclase; predominance of monoclinic low calcium pyroxenes), and chemical (high abundances of water, carbon, argon, and other volatile constituents). A complete gradation of properties exists between these meteorites and the equilibrated ordinary chondrites. We believe the least-metamorphosed chondrites of each chemical group closely approximate the unmetamorphosed precursors of the equilibrated ordinary chondrites.

That the three chemical groups were distinct at the earliest stages of metamorphism indicates that their different contents of the siderophile elements were established during or before agglomeration of the parent materials. Close similarities in the mean compositions and proportions of olivines and pyroxenes in the least metamorphosed members of the three groups suggest that the siderophile fractionation among these groups may have resulted from mechanical mixture of a common silicate fraction with different proportions of metal rich material. There appears to be no comparably simple chemical or genetic relationship between the ordinary chondrites and the carbonaceous or enstatite chondrites.

The origin of chondrules and chondrites remains, in the light of this study, an open question, for our results are consistent with any disequilibrium process entailing the production of chondrules through rapid cooling of molten and semi-molten droplets.

INTRODUCTION

A PERSISTENT problem in the study of chondrites is the selection of material which represents the premetamorphic character of the ordinary chondrites. DODD and VAN SCHMUS (1965) discussed this problem and showed that existing theories for the origin of chondrites are largely outgrowths of different choices of starting material. They drew attention to a small group of ordinary chondrites (their "unequilibrated ordinary chondrites") in which freedom from petrographic evidence of recrystallization is accompanied by the presence of heterogeneous olivines, and they suggested that some of these meteorites may closely resemble the unmetamorphosed parent material of the equilibrated chondrites. SCHMITT and SMITH (1964) and SCHMITT, GOLES and SMITH (1966) reached a similar conclusion

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on the basis of chemical data from some of the meteorites studied by DODD and VAN SCHMUS and from other chondrites of similar character.

The purposes of the work reported in this paper were (1) to identify other unequilibrated ordinary chondrites; (2) to determine the petrographic and chemical characteristics of such meteorites, and (3) to consider the bearing of these data on the genetic relationships among, and the origin of, the ordinary chondrites.

METHODS OF STUDY

Sample selection

The choice of samples for this study was based on several criteria:

1. Chondrites were chosen which were already known to contain heterogeneous olivines and pyroxenes, either through earlier microprobe analyses (KEIL, MASON, WILK and FREDRIKSSON, 1964; KEIL and FREDRIKSSON, 1964; DODD and VAN SCHMUS, 1965) or from X-ray diffraction data (MASON, 1963 and personal communication).

2. Other chondrites were selected on the basis of hand specimen or petrographic evidence suggesting relative freedom from recrystallization. Such evidence includes the presence of glass in chondrules (DODD and VAN SCHMUS, 1965) and distinctness of chondrules and matrix. The selection of these chondrites was made after examination of all available chondrites in several major meteorite collections.*

3. Finally, we included chondrites brought to our attention by other workers who had found them to resemble the meteorites discussed by DODD and VAN SCHMUS (1965).

The samples thus chosen certainly do not include all unequilibrated ordinary chondrites; others will doubtless be found in American and foreign collections. However, the chondrites assembled for this study do, we believe, represent the majority of such meteorites.

Microprobe analyses

The principal analytical effort of this study was the determination, by microprobe analysis, of the iron contents of olivines and pyroxenes in the unequilibrated ordinary chondrites. Sample preparation, instrumentation, data collection and reduction, and precision and accuracy are considered in this section. The results are summarized in Table 3 and given in detail in the Appendix (Table 8).

Samples. The samples used were in the form of one-inch diameter, circular, polished thin sections of standard thickness (0.03 mm). These samples were coated with carbon to make them electrically conductive, and Aquadag was applied to insure contact with the brass sample holder.

Instrument and operating conditions. The microprobe measurements were made on a two-channel instrument designed, built and operated by the Advanced Metals Research Corporation of Burlington, Massachusetts. This instrument is very similar in design and operation to the Philips AMR/3 instrument for which

* The collections studied are those at the American Museum of Natural History, Harvard University, the Nininger Collection of Arizona State University, the U.S. National Museum, and Yale University.

it was a prototype. For this study, the spectrometers were set for FeK α and SiK α radiation.

At the outset, data were taken at an accelerating voltage of 30 kV; this was later reduced to 20 kV. Specimen currents used were approximately 0.2 microamp. Sample points were counted for either 16 or 32 sec, the choice dictated by counting rates for each sample. Tests for stability showed that both olivine and pyroxene are stable under these operating conditions.

During the analytical runs, one and sometimes two olivine standards were analyzed every 30 to 60 min both to provide compositional references for the analyses and to check on instrument stability. The point and standard measurements were corrected for dead-time, drift and background, and the iron intensity for each analyzed point was converted to an intensity ratio by dividing by the iron intensity of our prime standard (olivine from the Springwater pallasite). This intensity ratio was then converted to the iron concentration (wt.%) using an empirical calibration curve constructed from microprobe measurements on chemically analyzed olivines and pyroxenes. (Table 9 in the Appendix lists the standards used for this curve and their iron contents.) This curve was found to be linear for iron concentrations of 0–20 wt.%. The same curve was found for both olivines and pyroxenes, and for accelerating voltages of 20 and 30 kV; it also agrees closely with theoretical calibration curves prepared using several accepted procedures.

Point selection and measurements. Points were selected in most samples by traversing in 500 μ steps along traverses 1000 μ apart. Smaller intervals were used for small samples, in order to obtain about 100 olivine measurements and a comparable number of pyroxene measurements in each sample.

A single measurement for Si and Fe was made at each grid point. If there was no silicate grain at a point, or if there was a visible imperfection (inclusion, crack, or grain boundary) at the point, the sample was moved as much as 20 μ to reach a silicate grain. Where this was necessary, the sample was repositioned randomly to avoid biasing the data in favor of grain margins or centers. If there was no silicate grain within 20 μ of a grid point, the point was omitted.

Although the samples were viewed in transmitted light, identification of olivine and pyroxene was based principally on the silicon content, which is roughly half again as great in low-calcium pyroxene as in olivine. Grains with silicon contents outside the olivine or pyroxene range were interpreted as glass or another mineral phase and were rejected. In cases where the silicon data were ambiguous, and where an iron measurement was unusually high or low for the sample under study, the questionable points were relocated and analyzed for Mg and Ca. Any point whose Fe, Si, Mg and Ca contents were inappropriate to either olivine or pyroxene was then discarded. (In our experience, most such points would have been identified as pyroxene on the basis of silicon data alone. This is because the microcrystalline material in many of the chondrules has about the same silicon content as pyroxene.)

After the data were screened for spurious measurements, the iron data were used to calculate weight per cent iron in the olivine or pyroxene at each grid point, using the empirical calibration curve. Mean iron concentrations were calculated

for the olivines and pyroxenes in each sample, and the deviations of individual measurements from the mean, and the mean deviation were determined. The last value for each mineral was then converted to the "per cent mean deviation" by dividing the mean deviation by the average iron content (both in weight per cent) and multiplying by 100. This "per cent mean deviation" is the parameter used in this paper as an index of olivine or pyroxene heterogeneity.

Precision. The precision of the mean iron concentrations (expressed as per cent mean deviation) reported in Tables 3 and 8 is the result of several factors: counting statistics, variations of mineral composition, sample preparation, and instrument design. The effect of each of these must be understood in order to interpret the significance of the per cent mean deviations which are our index of mineral homogeneity.

On the basis of repeated analyses of our fayalite standard, run in alternation with chondrite points (Table 8), we estimate the precision of measurements of homogeneous minerals to be $\pm 2\%$ of their iron concentrations. This precision would also apply to repeated measurements of the same grain, and, in the absence of sample and instrumental effects, to analyses of many grains of the same composition in a chondrite.

In practice, the combined effects of sample preparation and instrumental design reduce the precision of measurements of homogeneous minerals below the ideal figures. The fine-grained matrices of many of the chondrites are difficult to polish, with the result that their surfaces are not ideally (or uniformly) smooth. Surface irregularities reduce analytical precision, especially where the microprobe used has a low X-ray take off angle. (in this case 15°) (ADLER, 1964). Because much of the pyroxene in these chondrites is very fine-grained, the influence of these factors is greater on pyroxene than on olivine. We estimate the overall precision, taking into account counting statistics and errors due to surface effects, to be $\pm 2\frac{1}{2}\%$ for olivine and $\pm 5\%$ for pyroxene.

Chondrites for which per cent mean deviations fall below these values are considered to possess homogeneous olivines and pyroxenes and are regarded as mineralogically equilibrated. That Bjurböle falls near these limits* and Modoc falls well below is probably due to their different textures: Bjurböle possesses a fine-grained matrix, but Modoc, which is more strongly recrystallized, lacks such a matrix. Both chondrites are, by our criteria, equilibrated.

Per cent mean deviations significantly greater than these limits are real and reflect inhomogeneities in the minerals.

Accuracy. Accuracy has two meanings in the present context: (1) the degree to which the data for a thin section represent that thin section; and (2) the degree to which those data represent the entire chondrite. Inasmuch as about 100 olivine measurements and a comparable number of pyroxene measurements were made for each section, the accuracy for each section is thought to be very good. The principal uncertainty is due to the possibility that the data favor the larger grains, especially those of pyroxene.

* FREDRIKSSON (1963) reports slightly smaller variations in iron content for Bjurböle silicates than those reported here.

The small size of each thin section (approximately 1 cm²) makes it necessary to use caution in extrapolating from sample to chondrite. The nature of variations among thin sections of the same chondrite can be seen in Table 8, where results are reported for different sections of the same chondrite. In most cases, the different sections give similar results; in some, notably Mezö-Madaras, there are large discrepancies. In the case of Mezö-Madaras, the difference is clearly due to the polymict (WAHL, 1952) nature of the meteorite (VAN SCHMUS, 1966)*. In the others it may have the same cause, or it may represent real variations within the chondrites.

Regardless of the cause, the effect of sample variability makes it necessary to interpret Table 3 judiciously. The general position of a chondrite in this table is significant; its specific location relative to others with similar per cent mean deviations may not be.

The absolute accuracy of the iron concentrations reported in this work is limited primarily by the errors in the analyses of the minerals used to determine our empirical calibration curve. We estimate the errors inherent in our calibration curve to be $\pm 2\%$ of the amount of iron present. Our results for Bjurböle (OL = 18.6% Fe, PX = 10.8% Fe; Table 8) compare very favorably with those given by FREDRIKSSON (1963, OL = 17.8% Fe, PX = 10.8% Fe). Part of the difference is undoubtedly due to the choice of standards used and the compositions assigned to them (e.g. Marjalahti and Susimaki olivines, Table 9).

Petrography and mineralogy

In addition to the preliminary examination made during sample selection, each sample used in this study was examined in both reflected and transmitted light to determine its texture and mineralogy. The mineralogical observations are not detailed, as they were intended solely to record the presence (or absence) and modes of occurrence of the major minerals.

Chemical data

In order to classify the chondrites used in this study, and to permit a comparison of the chemical compositions of unequilibrated and equilibrated chondrites of each class, we collected the available major and trace element data for unequilibrated chondrites. The bulk chemical compositions of the meteorites studied are given in Table 1; other chemical data are presented in the text and in subsequent tables as needed.

RESULTS

Classification of unequilibrated ordinary chondrites

Five major groups of chondritic meteorites are recognized by most workers: Enstatite chondrites, carbonaceous chondrites, H-Group chondrites, L-Group

* VAN SCHMUS (1966) has shown that olivines in the included fragments are less heterogeneous than those of the meteorite as a whole, suggesting more advanced recrystallization of the inclusions. In this case and in others where discrepant results are obtained, the higher per cent mean deviations probably best represent the chondrite.

Table 1. Chemical composition of samples studied

Chondrite	SiO ₂	MgO	FeO	Al ₂ O ₃	CaO	Na ₂ O	K ₂ O	Cr ₂ O ₃	MnO	TiO ₂	P ₂ O ₅	Fe	Ni	Co	FeS	H ₂ O ⁺	H ₂ O ⁻	C ^a	Total Fe	Reference
1. Baratta	40-61	25-32	15-63	2-63	1-56	0-95	0-11	0-46	0-33	0-12	0-26	4-89	1-20	0-08	6-25	0-20	0-10	0-09	21-07	1
2. *Bishampur	40-54	25-06	11-89	2-23	1-83	0-95	0-10	0-51	0-32	0-15	0-30	6-62	1-05	0-06	6-47	1-10	0-27	0-53	19-98	2
3. *Bjurböle	41-06	25-75	13-17	2-55	1-82	1-24	0-32	0-59	0-12	0-32	0-32	6-87	0-78	0-04	5-44			0-05	20-55	3
4. *Bremervörde	37-64	23-80	12-86	2-23	1-42	0-97	0-09	0-50	0-31	0-10	0-27	12-65	1-52	0-10	5-95	0-23	0-10	0-22	26-52	1
5. Carraweena	40-39	26-15	14-32	1-59	3-15	0-67	0-09	0-35	0-35	0-10	0-22	4-55	1-10	0-06	6-52	0-98	0-17	0-09	19-83	1
6. *Castalia	36-25	23-70	12-59	1-94	2-73	0-90	0-14	0-43	0-30	0-08	0-29	12-28	1-78	0-10	5-92	0-43	0-17	0-27	25-83	1
7. *Chainpur	40-63	25-14	16-29	2-63	1-55	0-75	0-12	0-70	0-32	0-09	0-36	3-02	0-96	0-04	6-44	1-00	0-10	0-44	19-78	4
8. Clovis No. 1	35-40	22-28	17-70 ^b	2-06	1-64	0-64	0-07	0-46	0-31	0-10	0-35	5-09	1-56	0-06	6-36	2-53	0-97	0-22	(22-91) ^c	2
9. *Cynthiana	41-61	25-74	14-89	2-36	1-96	1-02	0-10	0-58	0-35	0-13	0-25	3-80	1-01	0-03	6-05	0-24	0-02	0-10		12
10. *Geidam	36-62	24-04	11-04	2-62	1-75	0-91	0-07	0-51	0-32	0-13	0-31	15-68	1-69	0-13	4-63	0-57	0-00		27-20	5
11. Goodland	39-67	24-67	14-61	2-27	1-86	0-77	0-08	0-52	0-33	0-15	0-32	5-91	1-25	0-05	6-64	0-53	0-26	0-07	21-49	6
12. *Hallingsberg	39-20	23-97	14-01	2-24	2-26	0-91	0-12	0-53	0-34	0-11	0-16	6-86	1-29	0-06	6-64	0-95	0-36	0-26	21-98	2
13. *Hamlet	41-05	25-25	17-43	2-64	2-12	1-02	0-07	0-56	0-28	0-14	0-28	2-86	0-90	0-06	5-81	0-04	0-00	0-16	20-10	1
14. Ioka	38-90	24-13	16-57 ^c	2-11	1-83	0-88	0-11	0-43	0-33	0-15	0-31	3-70	1-24	0-05	6-61	1-47	0-35	0-12	20-77	2
15. *Khotar	39-40	24-72	14-20	2-28	1-78	0-89	0-10	0-52	0-35	0-11	0-27	6-61	1-25	0-05	6-14	1-16	0-09	0-32	21-56	2
16. *Krynka	40-10	25-01	14-29	2-93	1-88	0-84	0-07	0-52	0-34	0-14	0-20	4-71	1-15		6-05			0-27	19-67	7
17. *Lusa	40-76	25-97	13-34	2-96	2-24	1-50	0-22	0-75	0-22	0-23	0-22	5-88	1-14		6-57			0-11	20-43	8
18. *Manyeh	39-58	24-61	14-46	1-94	2-01	0-99	0-11	0-52	0-36	0-13	0-27	6-54	1-24	0-06	6-01	0-79	0-13	0-45	21-60	6
19. *Mezö-Madaras	39-29	24-77	14-96	2-49	2-74	0-93	0-11	0-56	0-34	0-12	0-30	6-68	1-30		6-47			0-16	22-42	
20. *Modoc	40-36	25-60	18-14	2-57	1-83	0-99	0-09	0-62	0-36	0-10	0-18	0-60	1-06	0-05	6-08	1-40	0-38	0-39	18-57	1
21. *Ngawi	41-03	26-34	15-78	2-64	1-58	0-91	0-11	0-59	0-35	0-21	0-23	2-54	0-88	0-03	5-48	(0-14)		0-19	18-29	9
22. *Parnallee	d																	0-35		
23. Prairie Dog Creek	40-16	24-86	17-57	2-23	2-04	0-96	0-10	0-49	0-35	0-10	0-24	2-05	1-16	0-05	5-32	1-22	0-40	0-57	19-09	2
24. *Semarkona	35-39	22-24	13-04	1-90	1-71	0-82	0-07	0-45	0-30	0-12	0-29	12-02	1-70	0-09	5-77	2-03	0-33	0-95	26-26	6
25. *Sharps	d																			
26. *Sindhri	40-13	24-77	10-85	2-37	2-00	1-08	0-07	0-54	0-31	0-15	0-40	9-24	1-13	0-06	6-33	0-51	0-03	0-10	21-69	5
27. *Tonnasilm	36-84	23-79	17-54	2-40	1-61	0-95	0-04	0-73	0-34	0-08	0-21	8-10	1-71	0-10	5-34	0-88	0-07	0-25	25-13	1
28. *Tieschitz	35-59	22-84	11-14	2-23	1-78	0-95	0-14	0-52	0-32	0-13	0-32	14-87	1-54	0-11	5-31	0-98	0-10	0-28	26-90	5
29. *Weston																				
Average H-Group	36-52	23-48	8-87	2-43	1-82	0-85	0-14	0-36	0-25	0-13	0-23	17-23	1-58	0-09	5-35	(0-33)		0-07	27-52	10
Average L-Group	39-88	24-98	13-12	2-31	1-90	0-88	0-14	0-44	0-27	0-15	0-26	7-70	1-12	0-06	6-17	(0-34)		0-03	21-82	10
Average LL-Group	40-20	25-32	19-42	2-39	1-77	0-80	0-16	0-44	0-30	0-14	0-26	1-65	0-96	0-06	6-04				20-58	11

* Observed fall.

a. Except for the chondrites Clovis and Sharps, the carbon

abundances are from Moore and Lewis (1967).

b. 10-20% Fe₂O₃ recalculated as FeO (oxidized find).

c. Badly oxidized find. The total Fe is probably too low;

(Clovis is an H-Group chondrite).

d. No reliable analysis of this chondrite available.

e. 5-49% Fe₂O₃ recalculated as FeO (oxidized find).

References:

1. H. B. WILK, unpublished analyses.
2. JAROSIEWICZ (1966).
3. RAMSAY and BORGSTROM (1902) [in UREY and CRAIG (1953)].
4. KEIL *et al.* (1964); H. B. WILK analyst.
5. MASON and WILK (1965); H. B. WILK analyst.
6. E. JAROSIEWICZ, unpublished analyses.
7. D'YAKONOVA and KHARITONOVA (1960).
8. D'YAKONOVA (1964).
9. WILK (1966).
10. CRAIG (1964).
11. MASON and WILK (1964); average derived from their Table 1.
12. A. D. MAYNES, unpublished analysis.

chondrites, and LL-Group chondrites. The samples considered in this paper are from the latter three groups, which are commonly grouped as the "ordinary chondrites."

Many of the unequilibrated chondrites discussed in this paper are somewhat difficult to classify solely on petrographic or mineralogical grounds. This is particularly true of those meteorites which contain extremely heterogeneous olivines and pyroxenes. They resemble the olivine-pigeonite chondrites (MASON, 1963b) in containing predominantly monoclinic pyroxenes, and the Type III carbonaceous chondrites in containing variable but generally high abundances of carbon (up to 1 wt. %—MOORE and LEWIS, 1965, 1967) and water (up to 2% in observed falls; Table 5). Their olivine and pyroxene compositions vary and hence cannot be used for classification according to the techniques and criteria of MASON (1963a) or KEIL and FREDRIKSSON (1964).^{*} KEIL *et al.* (1964, p. 23) expressed the problem well with reference to Chainpur: "In brief, Chainpur is an olivine-hypersthene chondrite in chemical composition and an olivine-pigeonite *chondrite* in mineralogy (and structure)."

Our designation of the chondrites listed in Table 1 as "ordinary" chondrites (as distinct from carbonaceous or enstatite chondrites) is based primarily on the silicon-magnesium relationships among the chondrite groups. It has been shown (UREY, 1961; DUFRESNE and ANDERS, 1962; AHRENS, 1964, 1965; MASON, 1966) that the SiO_2/MgO ratios in the ordinary chondrites (H, L, LL-Groups) are different from those in the carbonaceous chondrites and enstatite chondrites. The carbonaceous chondrites have SiO_2/MgO values (wt. %) ranging from 1.33 to 1.51 with a strong mode (and mean) at 1.42; the ordinary chondrites range from 1.50 to 1.70 with a strong mode (and mean) at 1.58; the enstatite chondrites have SiO_2/MgO values from 1.70 to 2.15. Table 2 lists the SiO_2/MgO ratios for the samples studied, based on the bulk analyses in Table 1. It is obvious that all of the samples listed in Table 2 resemble the ordinary chondrites in their silicon-magnesium relationships and differ from both carbonaceous and enstatite chondrites in this respect.

As SCHMITT and SMITH (1965) and SCHMITT, GOLES and SMITH (1966) have observed, there are other chemical distinctions between the Type III carbonaceous chondrites (their Type IIIA) and the mineralogically similar unequilibrated ordinary chondrites. The former have lower sodium and manganese abundances than the latter.

The meteorites listed in Table 1 are also texturally distinct from the Type III carbonaceous chondrites, in that: (1) they contain higher ratios of chondrules to matrix materials,[†] and (2) most of their chondrules lack the profuse metal inclusions which are common in chondrules of carbonaceous chondrites (WOOD,

^{*} Samples in which compositional variations are small can be assigned to the three ordinary chondrite groups on the basis of modal olivine composition and metal content (See histograms, Figs. 2 and 3).

[†] Bjurböle is the sole exception known to the writers. Its silicate particles have a size distribution which is closely similar to the distributions found in Type III carbonaceous chondrites (DODD, in preparation).

Table 2. Summary of classification of samples

Chondrite	Total Fe	Fe°/Fe	SiO ₂ /MgO	Fa	Fa	Classification		
	(%)	(a)	(wt. ratio)	(b)	(c)	Total Fe	Group (d)	Type (e)
Barratta	21.1		1.61	25	23	low	L	4
Bishunpur	20.0	0.33	1.62			low	(L)	3
Bjurböle	20.6	0.33	1.59	26	26	low	L	4
Bremervörde	26.5	0.48	1.58			high	H	3
Carraweena	19.8		1.54	24	24	low	L	3
Castalia	25.8	0.48	1.53	19	20	high	H	5
Chainpur	19.8	0.15	1.62			low	(LL)	3
Clovis No. 1	(22.9) ^f		1.59	19	18		H	3
Cynthiana				25	25		L	4
Geidam	27.2	0.58	1.52	19	18	high	H	4
Goodland	21.5		1.61	25	25	low	L	4
Hallingeberg	22.0	0.31	1.64			low	(L)	3
Hamlet	20.1	0.14	1.63	27	29	low	LL	4
Ioka	20.8		1.62	23	24	low	L	3
Khohar	21.6	0.31	1.59			low	(L)	3
Krymka	19.7	0.24	1.60			low	(L)	3
Lua				24	25		L	4
Manych	20.4	0.29	1.57			low	(L)	3
Mező-Madaras	21.6	0.28	1.61			low	(L)	3
Modoc	22.4	0.30	1.59	23	25	low	L	6
Ngawi	18.6	0.03	1.58			low	(LL)	3
Parnallee	18.3	0.14	1.56			low	(LL)	3
Prairie Dog Creek				19	19		H	3
Semarkona	19.1	0.11	1.62			low	(LL)	3
Sharps	26.3	0.46	1.59			high	H	3
Sindhri				19	19		H	5
Tennasilm	21.7	0.43	1.62	23	23	low	L	4
Tieschitz	25.1	0.32	1.55			high	H	3
Weston	26.9	0.55	1.60	19	18	high	H	4
Average H-Group	27.5	0.63	1.56	18				
Average L-Group	21.8	0.35	1.60	24				
Average LL-Group	20.6	0.08	1.59	29				

(a) Fe°/Fe is the ratio of metallic iron to total iron; values included for falls only.

(b) FeO/(FeO + MgO) in olivine; Data from MASON (1963a). Only values for chondrites with a defined olivine composition are given.

(c) As in (b); Data from this study.

(d) Parentheses indicate a lesser degree of confidence for highly unequilibrated samples.

(e) According to VAN SCHMUS and WOOD (1967).

(f) Questionable because of intense weathering.

1967). Neither of these criteria is as strong as the chemical criteria, but they serve where chemical data are unavailable.*

Both total iron content and, for equilibrated or nearly equilibrated samples, the olivine composition, are conclusive criteria for the distinction of H-group

* Two chondrites—Coolidge and Efremovka—which were initially selected for this study, were regarded with suspicion because of high proportions of matrix and abundant metal-bearing chondrules. Chemical data (E. JAROSEWICH, pers. comm.) proved both to be carbonaceous chondrites.

ordinary chondrites from those of either the L- or the LL-group (Table 2).

Many authors, most recently KEIL and FREDRIKSSON (1964), have proposed that the low-iron chondrites are in fact two groups. KEIL and FREDRIKSSON called these the L- and LL-groups, terms which we have used in this paper. The reality of these two divisions has been questioned by some workers (MASON, 1965a; RINGWOOD, 1966a), but the distinction seems valid in the light of recent work by FREDRIKSSON (1966) and VAN SCHMUS and WOOD (1967).

The L- and LL-group chondrites are, however, not always readily distinguished; this is particularly true for unequilibrated examples. There is no distinct hiatus of total iron content between the two groups such as that which sets apart the H- and L-groups; total iron is therefore an imperfect criterion. Olivine and pyroxene compositions are diagnostic for equilibrated samples (FREDRIKSSON, 1966) but not for unequilibrated samples. The most generally useful criterion is the ratio of metallic to total iron (VAN SCHMUS and WOOD, 1967), but even this can be misleading for finds. Furthermore, this ratio may not be entirely stable during metamorphism.

Our distinctions between L- and LL-group chondrites in Table 2 are based, wherever possible, on the abundance of metallic iron, which is expressed in Table 2 as Fe^0/Fe . Where this parameter is unsupported by other data (e.g. the olivine and pyroxene compositions in equilibrated or nearly equilibrated meteorites), we have enclosed the classification in brackets to indicate our reservations. It should be noted that the possibility of misclassification of meteorites which lie on the border between these two groups does not influence any of the conclusions of this paper.

A column in Table 2 gives the classification of each chondrite studied according to the scheme proposed recently by VAN SCHMUS and WOOD (1967), which is essentially a subdivision of the various chemical groups on the basis of mineralogical and petrological variations. This classification has the considerable advantage of highlighting the chemical distinction between the unequilibrated ordinary chondrites and the mineralogically similar Type III carbonaceous chondrites, a distinction which is lost if the two groups are joined in the olivine-pigeonite chondrites (MASON, 1963b; WOOD, 1967) or merely separated into Types III-A and III-B carbonaceous chondrites after the fashion of SCHMITT *et al.* (1966).

In summary, we conclude that all of the chondrites listed in Tables 1 and 2 are ordinary chondrites and that they include representatives of all three chemical divisions of these meteorites. To emphasize their chemical kinship with other ordinary chondrites, we propose that examples which contain heterogeneous silicate minerals be called, simply, "unequilibrated H- (or L-, or LL-) group chondrites," or further divided, where this is possible, along the lines of VAN SCHMUS and WOOD (1967).

MICROPROBE DATA ON OLIVINE AND PYROXENE

The results of microprobe analytical surveys on all the samples studied are presented in Table 3. Data for some samples are also presented graphically in Figs. 1-3. The samples are ranked within each chemical class according to decreasing values of per cent mean deviation (hereafter abbreviated "%m.d.") of

Table 3. Mineralogical and textural data on samples studied

Chondrites	Olivine ^(a)			Pyroxene ^(a)			Integration	Glass
	%MD	$\overline{\text{Fe}}$	$\overline{\text{Fa}}$	%MD	$\overline{\text{Fe}}$	$\overline{\text{Fs}}$		
<i>H-Group</i>								
Tieschitz ^(b)	45	14.5	19.9	56	6.0	11.2	Minor	Present
Sharps	37	14.0	19.2	54	7.4	13.9	Minor	Very Abundant
Bremervörde	15	11.7	15.8	46	6.7	12.5	Minor	Present
“Sindhri” ^(c)	8.3	14.3	19.6	15	8.8	16.7	Moderate	Present
Prairie Dog Creek	6.9	14.3	19.6	34	7.7	14.5	Minor	Abundant
Clovis No. 1	5.6	13.4	18.3	29	6.7	12.5	Minor	Abundant
Castalia	3.6	15.0	20.6	5.3	9.0	17.1	Moderate	Rare, Turbid
Geidam	* ^(d)	13.3	18.1	*	8.3	15.7	Extensive	Absent
Sindhri	*	14.2	19.4	*	9.0	17.1	Extensive	Absent
Weston	*	13.4	18.3	*	8.4	15.9	Extensive	Absent
<i>L-Group</i>								
Krymka ^(b)	45	11.5	15.5	52	6.4	12.0	Minor	Abundant
Bishunpur ^(b)	39	12.3	16.6	56	7.0	13.1	Minor	Abundant
Hallingeberg	38	14.4	19.8	57	5.7	10.6	Minor	Very Abundant
Mező-Madaras ^(e)	28	15.7	21.7	44	7.5	14.1	Minor	Very Abundant
Manyeh	26	17.8	24.9	40	7.6	14.3	Minor	Abundant
Khohar ^(b)	18	17.2	24.0	36	8.2	15.5	Minor	Abundant
Carraweena	6.0	17.8	24.9	20	10.4	19.9	Minor	Abundant
Ioka	5.8	17.5	24.5	31	8.1	17.3	Moderate	Present
Barratta	4.2	17.0	23.7	23	8.8	16.7	Moderate	Abundant, Turbid
Goodland	2.6	17.9	25.1	14	10.0	19.1	Moderate	Present, Turbid
Cynthiana	*	18.2	25.6	6.1	10.8	20.7	Moderate	Rare, Turbid
Tennasilim	*	16.9	23.5	6.9	10.1	19.3	Moderate	Rare, Turbid
Bjurböle	*	18.6	26.2	*	10.8	20.7	Moderate	Absent
Lua	*	17.9	25.1	*	10.8	20.7	Moderate	Absent
Modoc	*	18.2	25.6	*	11.0	21.1	Advanced	Absent
<i>LL-Group</i>								
Ngawi	40	15.6	21.6	53	8.1	15.3	Minor	Abundant
Semarkona	37	12.1	16.3	50	6.5	12.2	Minor	Present
Chainpur	32	15.0	20.6	44	7.7	14.5	Minor	Present
Parnallee	19	18.6	26.2	37	8.3	15.7	Minor	Present
“Ngawi” ^(f)	15	19.9	28.2	30	10.7	20.5	Moderate	Present
Hamlet	3.5	20.6	29.4	8.9	11.7	22.5	Moderate	Present, Turbid

(a) %MD = per cent mean deviation (see text); $\overline{\text{Fe}}$ is the average iron content of the olivine or pyroxene; $\overline{\text{Fa}}$ is the average fayalite content (Fe_2SiO_4) of the olivine, based on $\overline{\text{Fe}}(01)$ and assuming stoichiometry; $\overline{\text{Fs}}$ is the average ferrosilite content (FeSiO_3) of the pyroxene, based on $\overline{\text{Fe}}(\text{Px})$ and assuming stoichiometry.

(b) Average of two analyses. See appendix for individual analyses.

(c) This sample was borrowed from K. FREDRIKSSON and is the "Sindhri" reported by KEIL and FREDRIKSSON (1964) and DODD and VAN SCHMUS (1965). However, it is apparently from a mis-labeled specimen; Sindhri obtained from other collections is definitely equilibrated (Table 3). In addition, "Sindhri" obtained from the Chicago Natural History Museum is an L-group chondrite (VAN SCHMUS, unpublished).

(d) The samples with an asterisk (*) substituted for %MD are considered to be equilibrated with respect to their olivine or pyroxene compositions. Further discussion in text.

(e) Second of two analyses (separate samples). First analysis excluded because of the presence of an inclusion (VAN SCHMUS, 1966).

(f) Apparently a mis-labeled specimen (MASON, pers. communication). The true Ngawi is distinctly more unequilibrated. Both specimens from the U.S. National Museum.

the olivine composition in the particular sample.* Because, as discussed above, this parameter may be subject to relatively large uncertainties caused by the analysis of small portions of each chondrite, no importance should be attached to exact order of samples with similar values of %m.d.; attention should be focused instead on the general relationships. Where more than one analysis was made on a chondrite (see Appendix), an average is reported in Table 3.

Several significant features emerge from Table 3 and the histograms in Figs. 1-3:

1. The chondrites of each chemical group which show the largest %m.d. values (greater than about 30%) yield histograms (Fig. 1) which lack modes (a weak mode at low Fe values can sometimes be detected for pyroxene†). The iron contents of their olivines and pyroxenes are irregularly distributed from zero to as much as 30 wt.% for olivines or 20 wt.% for pyroxenes, concentrations which exceed those found in equilibrated ordinary chondrites. The mean iron concentrations in the olivines and pyroxenes of these chondrites are quite similar for members of all three chemical groups; all fall in the ranges found in equilibrated H-group chondrites.

2. Histograms for chondrites which show smaller %m.d.'s for the silicates (Figs. 2 and 3) show distinct modes in the olivine and pyroxene distributions. These modes occur at iron concentrations appropriate to the equilibrated H-, L- and LL-group chondrites (MASON, 1963a; KEIL and FREDRIKSSON, 1964; FREDRIKSSON, 1966). As the %m.d. diminishes among the L- and LL-group chondrites, the mean iron contents of olivine and pyroxene increase toward their modal compositions. Only among the H-group chondrites are the mean and modal compositions similar regardless of the dispersion of individual grain compositions.

3. In a given unequilibrated chondrite, the dispersion of pyroxene compositions is greater than that of olivine compositions. That is, pyroxene appears to lag behind olivine as the two minerals approach homogeneity.

4. The mean and modal olivine compositions become equal at %m.d. values of approximately 2.5 and 5% for olivine and pyroxene respectively. Deviations of this order are to be expected from the vagaries of measurement, and they thus indicate homogeneity. Chondrites which show deviations this small or smaller (e.g., Modoc, Fig. 3) are regarded as equilibrated with respect to their ferromagnesian silicates. Their names are italicized in Table 3.

All of these observations will be discussed further in a later section of this paper, in connection with other data from these chondrites.

* See "Methods of Study" for a definition of this parameter. Because random selection of any practical number of olivine grains does not establish the extremes of the distribution, the observed range of iron contents, which was used by DODD and VAN SCHMUS (1965) in their reconnaissance study, is a poor measure of the spread of the frequency distribution. Mezö-Madaras, for example, contains exceptionally iron-rich olivines which were not encountered in the random survey of this meteorite (DODD, VAN SCHMUS and MARVIN, 1965, 1966).

† The analyses reported in Table 3 and Figs. 1-3 are restricted to low-Ca pyroxenes. Where these are chemically very heterogeneous, they are chiefly monoclinic (polysynthetically twinned, with inclined extinction); where they are essentially homogeneous, they are chiefly or wholly orthorhombic. Calcium-rich pyroxenes are rare or absent in samples near the top of each group in Table 3, but are present in some of the nearly equilibrated chondrites.

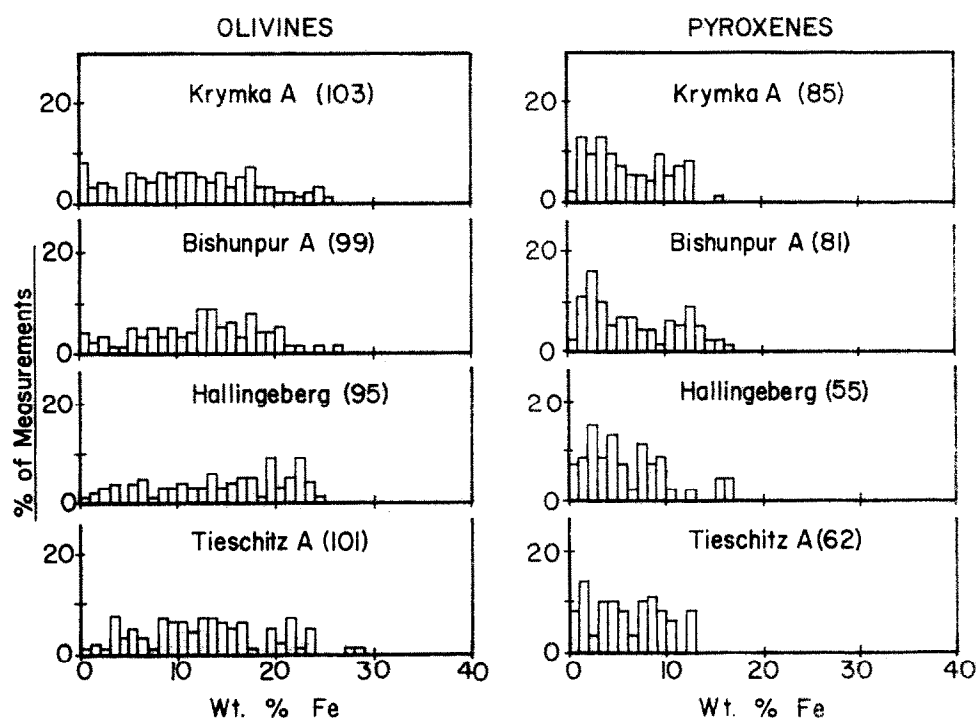


Fig. 1. Iron contents of olivines and low-calcium pyroxenes in four unmetamorphosed or slightly metamorphosed ordinary chondrites. The number of measurements for each sample is in brackets following the name.

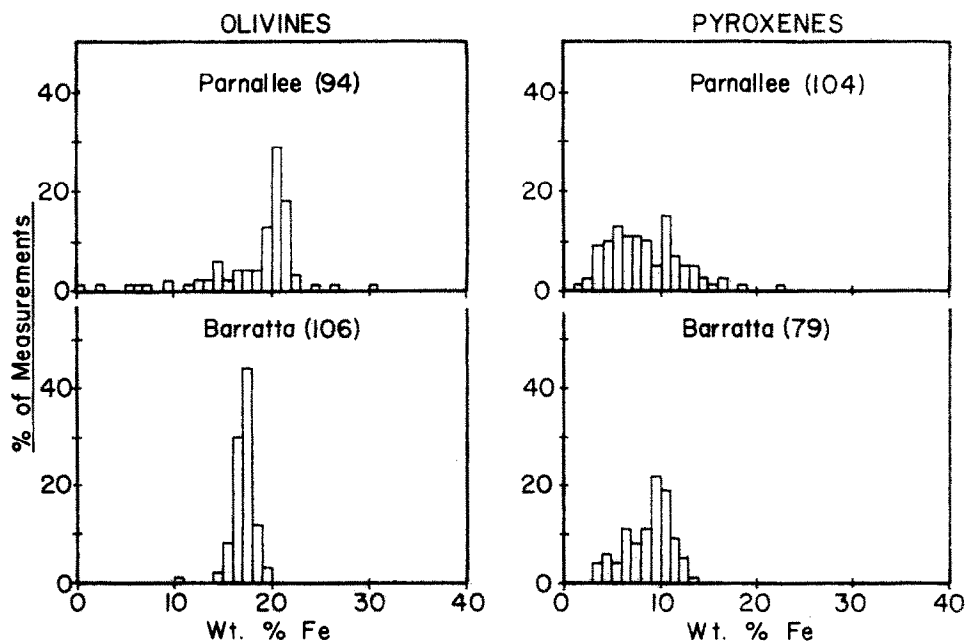


Fig. 2. Iron contents of olivines and low-calcium pyroxenes in two moderately unequilibrated ordinary chondrites. The number of measurements per sample is in brackets following the name.

Texture

Petrographic examination of a larger number of chondrites than were studied by DODD and VAN SCHMUS (1965) supports their conclusions: (1) that heterogeneous ferromagnesian silicates are found only in those chondrites which show textural evidence of slight or negligible recrystallization, and (2) that the degree of heterogeneity of these silicates varies inversely with the degree of recrystallization and is greatest in chondrites which are nearly unrecrystallized.

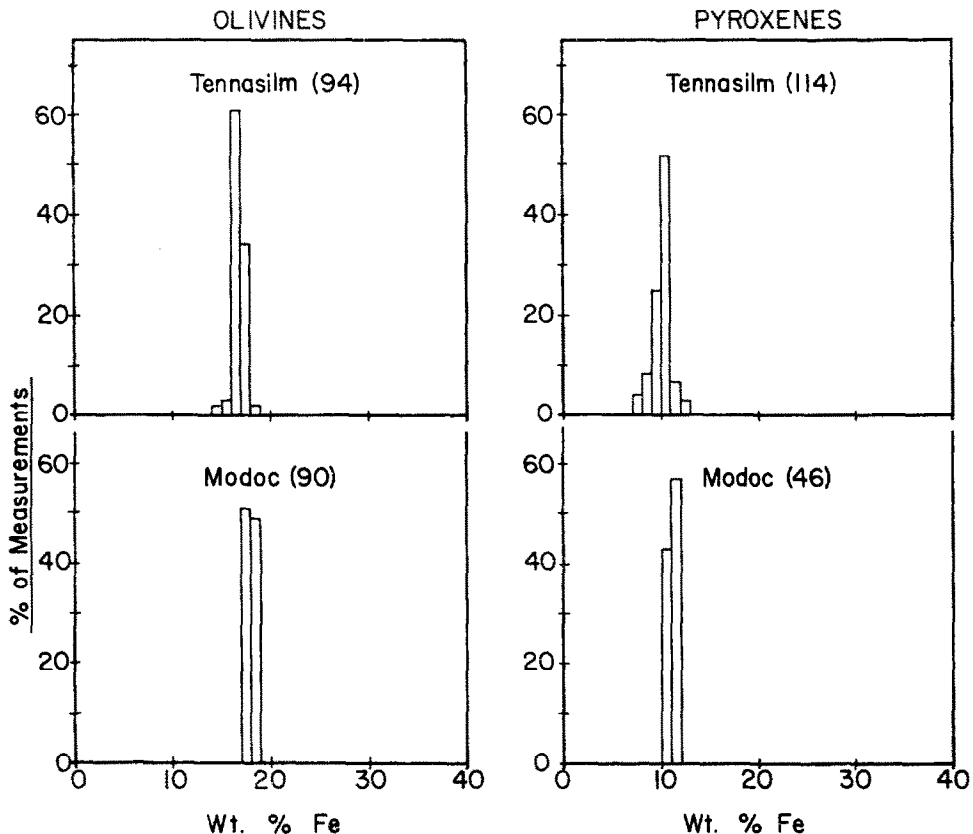


Fig. 3. Iron contents of olivines and low-calcium pyroxenes in a nearly equilibrated chondrite (Tenna-silm) and a completely equilibrated chondrite (Modoc). The number of measurements per sample is in brackets following the name.

Table 3 includes data on the textures of the samples examined in this study. Inasmuch as it is difficult to establish quantitative criteria for comparing the textures of two chondrites (see discussion by DODD and VAN SCHMUS, 1965), it is necessary to set forth in detail, and to illustrate, the criteria we used for this purpose. A further justification for an extended discussion of textural variations is the fact that texture has been widely used in chondrite classifications in the past and will be so used in the future (VAN SCHMUS and WOOD, 1967).

Each of the groups of chondrites in Table 3 shows systematic changes of texture with increasing homogeneity of olivines and pyroxenes. These are (1) changes in the articulation of chondrules, metal grains and matrix; and (2)

changes in the internal textures of chondrules, including the disappearance of glass. Because the first type of variation leads to greater *integration* of the samples at the bottom of each group of samples in Table 3, this seems a suitable term under which to summarize the inter-particle relationships in the chondrites.

Integration. The textural properties included in integration are: (1) degree of intergrowth between adjacent chondrules; (2) grain size of the matrix; (3) degree of intergrowth between chondrules and matrix; and (4) form of metal and troilite particles. The first of these parameters is most readily determined microscopically. In chondrites which possess highly heterogeneous olivines and pyroxenes, adjacent chondrules are distinct, with only rare development of minute silicate grains which are shared between chondrules.* As heterogeneity of mineral composition decreases in each group of Table 3, more pairs of chondrules are involved in a sample, and each pair is joined at several points. Ultimately, the boundaries between adjacent chondrules become completely indistinct, a condition which is realized in many equilibrated chondrites (e.g. Modoc) but not in the unequilibrated chondrites.

The character of the matrix also changes as mineral variation decreases. These changes are rather difficult to follow because all of the meteorites studied (except Bjurböle), possess little matrix and some have practically none. At the top of each group in Table 3, the matrix consists chiefly of unresolvable, non-metallic opaque material with a small content of minute metallic (magnetite?) and transparent grains. The grain size of this material increases as mineral heterogeneity decreases and its color changes, first to pale brown and then to grey. In the equilibrated samples of each group, the matrix material is distinctly crystalline, though fine-grained.

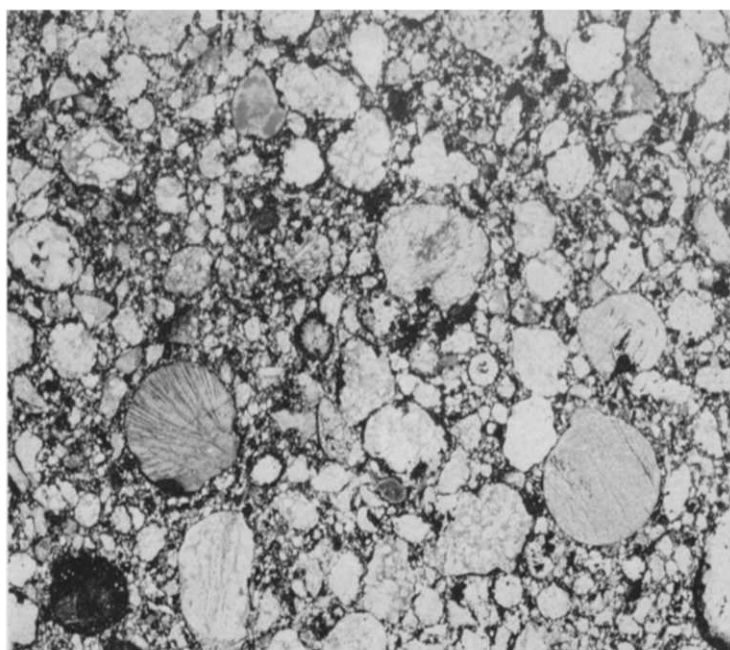
An increasing degree of intergrowth between chondrules and matrix parallels the changes described above. Such intergrowth is not evident in samples which contain very heterogeneous silicates, but becomes apparent as heterogeneity decreases. It appears that chondrule-matrix intergrowth proceeded more slowly than chondrule-chondrule intergrowth during recrystallization, for even the equilibrated samples (except Modoc) at the bottom of each group in Table 3 have quite distinct chondrules and matrices.

Although it is impossible to measure or express integration quantitatively, it is desirable to attempt a rough classification and we have done this in Table 3. The textural terms used therein are defined as follows:

1. *Minor*—Few chondrules pairs in the sample show any intergrowth and in those pairs which do share grains, such grains are few in number. The matrix consists mainly of very fine-grained, dull, opaque material with sparse metallic and transparent grains. Bishunpur exemplifies this degree of integration (Fig. 4).

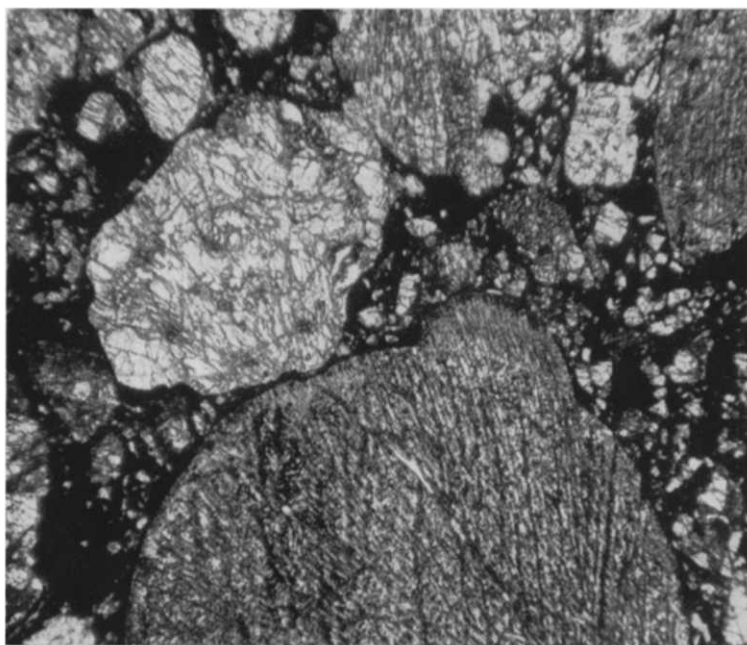
2. *Moderate*—Most or all pairs of adjacent chondrules share grains. Shared

* It should be noted that all of the chondrites examined contain some compound chondrules which indent each other and are completely intergrown. WOOD (1963a, plate 6c) shows such a chondrule pair. In the samples at the top of each chemical group in Table 3, there is no gradation between these and the chondrule pairs with sparse shared grains, and we interpret the compound chondrules as due to preagglomeration impact of plastic and solid chondrules, in agreement with TSCHERMAK (1885, p. 12) and later workers.



(a)

Fig. 4a. Photomicrograph (plane light) of the Bishunpur chondrite, illustrating minor textural integration. Long dimension of photograph = 10 mm.



(b)

Fig. 4b. Enlargement of part of Fig. 4a. Most chondrules show no intergrowth with each other or with the opaque, fine-grained groundmass. An exception appears in the middle-right portion of the Fig. Long dimension = 2 mm.

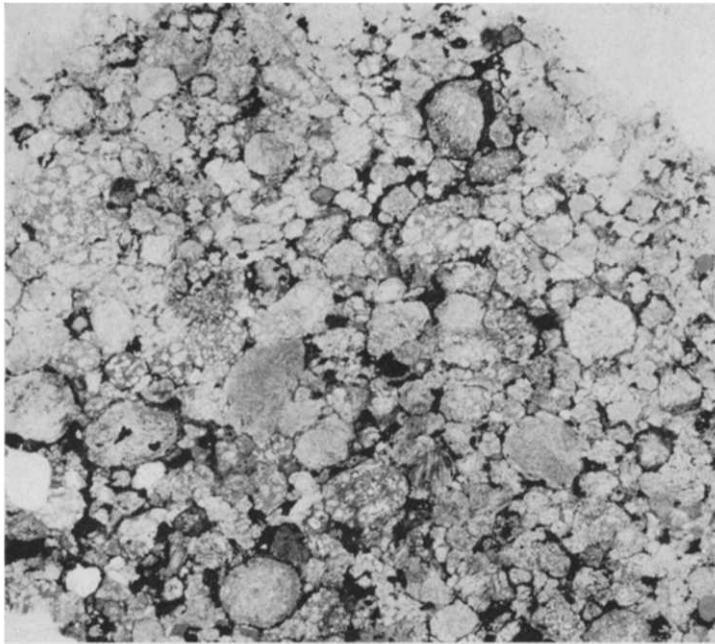


Fig. 5a. Photomicrograph (plane light) of the Barratta chondrite, illustrating moderate textural integration. Long dimension of picture = 10 mm.

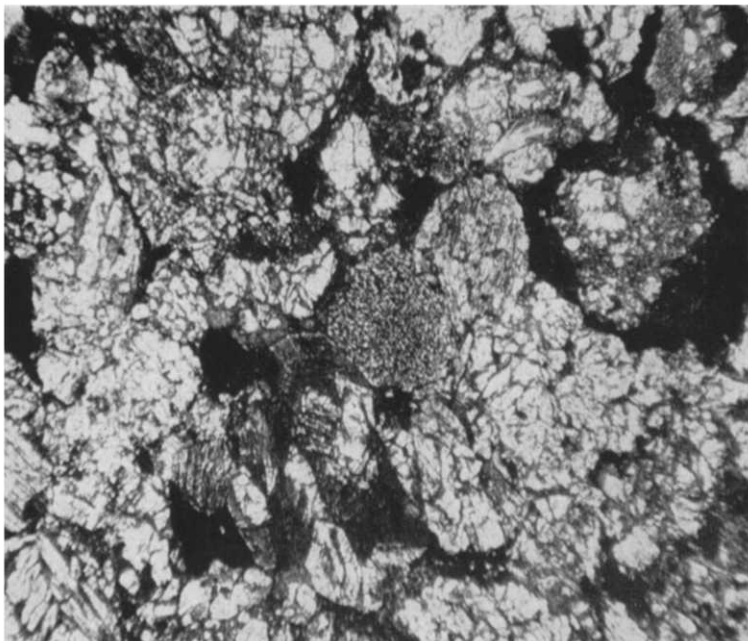


Fig. 5b. Enlargement of part of Fig. 5a. Note that most adjacent chondrules are intergrown to some degree but that their boundaries remain distinct. Inter-growth between chondrules and the sparse, dark matrix is inconspicuous. Long dimension of photograph = 2 mm.

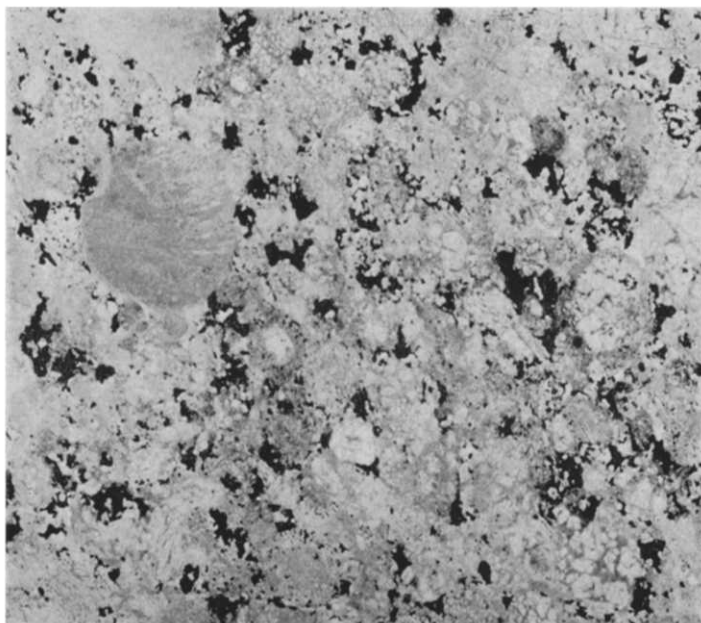


Fig. 6a. Photomicrograph (plane light) of the Shelburne chondrite, illustrating extensive textural integration. Long dimension of photograph = 10 mm.

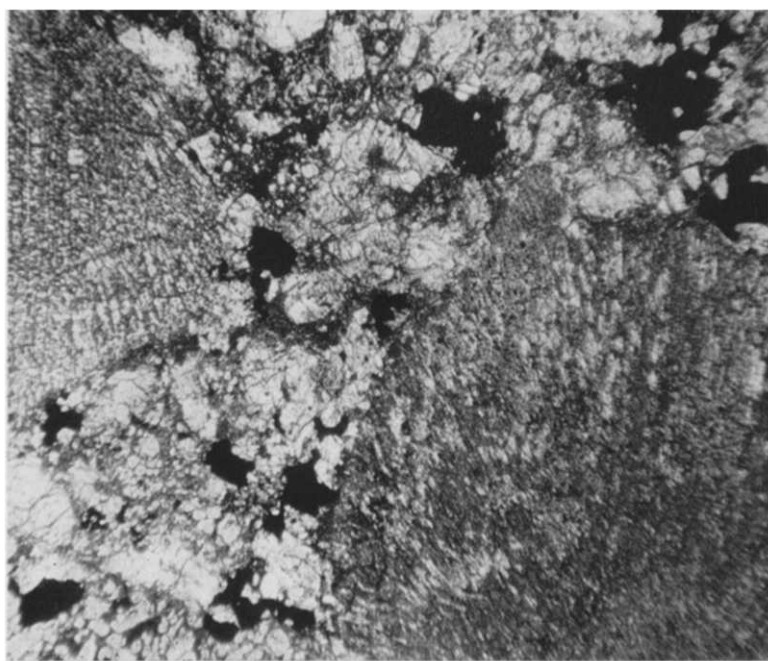


Fig. 6b. Enlargement of part of Fig. 6a. Note that at this stage of recrystallization most chondrules pairs are strongly intergrown, and chondrules are intergrown with the pale, crystalline matrix. Metal particles (black) are typically of very irregular form. Long dimension of photograph = 2 mm.

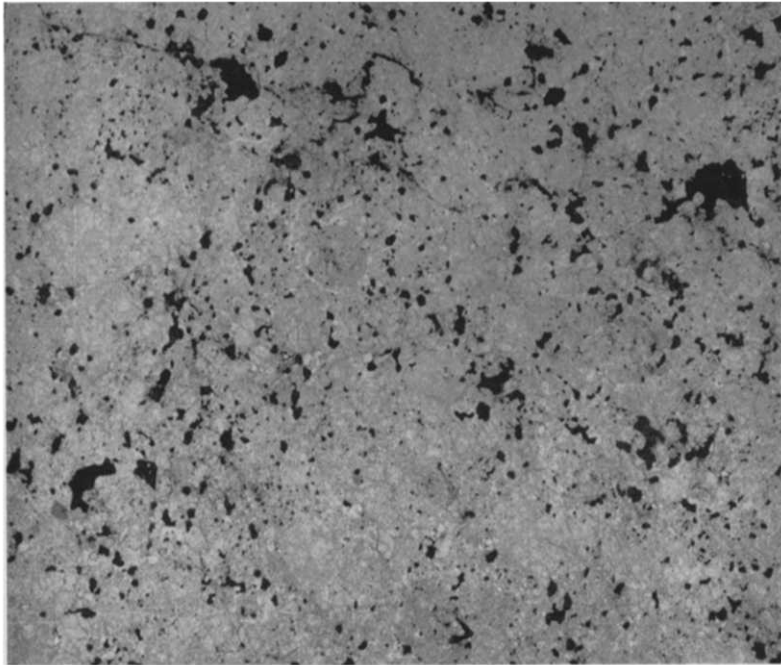


Fig. 7a. Photomicrograph (plane light) of the Modoc chondrite, illustrating advanced textural integration. Long dimension of photograph = 10 mm.

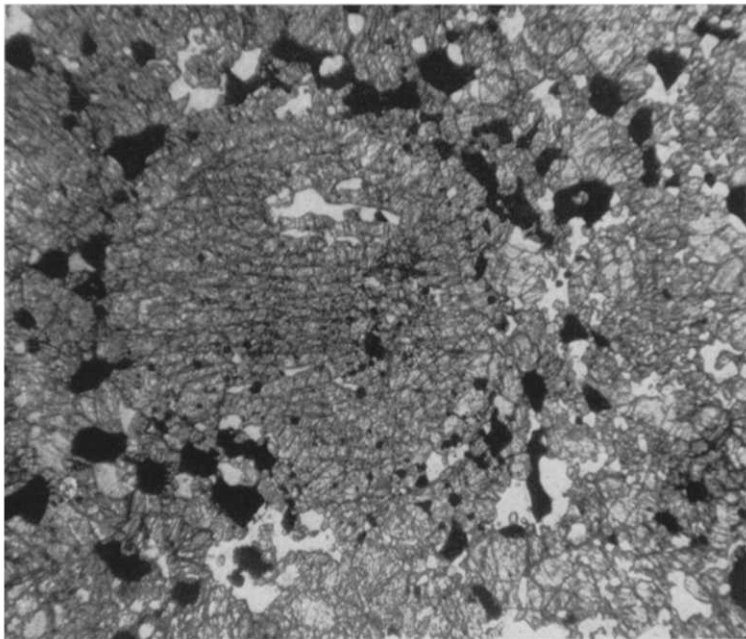


Fig. 7b. Enlargement of part of Fig. 7a. Chondrules and matrix are strongly intergrown and cannot be distinguished on the basis of grain size. Feldspar (white) is conspicuous at this stage. Long dimension of photograph = 2 mm.

grains are numerous, but chondrule-chondrule boundaries are still typically distinct. Matrix material is still fine-grained and dark. Barratta affords an example of moderate integration (Fig. 5).

3. *Extensive*—Most or all chondrule pairs share grains. Cases of obliteration of boundaries are common, but in most chondrule pairs the individuals are still distinct. The matrix is less distinct than in (2) and gray rather than opaque. An example of extensive integration is Shelburne (Fig. 6).

4. *Advanced*—Most chondrule-chondrule boundaries are indistinct or wholly obliterated. The matrix is granular and chondrule-matrix intergrowth is common. An example is Modoc (Fig. 7).

5. *Complete*—Chondrule-chondrule boundaries are no longer visible and there is no distinction of grain size between chondrules and matrix. Where chondrules can be identified, it is chiefly because of relict internal textures (e.g. olivine bars). The Shaw chondrite and many of the amphoterites (= LL-group chondrites) show complete integration (MASON and WILK, 1964).

As Table 3 indicates, most of the mineralogically unequilibrated chondrites show either minor or moderate integration. A few, whose olivines and pyroxenes are nearly homogeneous, show extensive integration, but none shows advanced or complete textural integration.

It is also evident from Table 3 that the relationship between mineralogy and integration is not perfect. One occasionally finds extensive integration in samples whose silicate compositions lead one to expect moderate integration, and vice versa. These apparent anomalies are at least partly due to primary textural differences, e.g. in the proportions of chondrules and matrix; they are considered further in a later section.

Internal textures of chondrules

DODD and VAN SCHMUS (1965) observed that the presence of isotropic, apparently glassy,* material in chondrules is typical of the unequilibrated ordinary chondrites. This observation is supported by the present study. All of the samples near the top of each group in Table 3 possess brown, red-brown, or mauve, water-clear, isotropic glass. In samples near the bottom of each group, glass is either absent or, if present, somewhat turbid. Devitrified glass is present in all samples.

The abundance of glass in the unequilibrated chondrites appears to vary widely in a way unrelated to either classification (H-, L-, or LL-group), degree of mineral variation, or extent of textural integration. These variations may be due wholly or in part to the small samples used in this study. One thin section of Semarkona revealed no glass; another contained five glass-bearing chondrules.

* This material is glass in a petrographic sense: The presence of some degree of ordering cannot be ruled out on the basis of optical appearance. It should be noted that we have previously called this material "mafic" (DODD and VAN SCHMUS, 1965). According to the data of FREDRIKSSON and REID (1965) and VAN SCHMUS (1966), it is in fact siliceous and commonly albitic. FREDRIKSSON and REID (1965) note that glass is usually encountered in chondrules which contain iron-poor silicates, and DODD (in preparation) has observed a strong correlation between the presence of glass and the presence of droplike metal inclusions in porphyritic chondrules.

For this reason, glass-bearing chondrules must be sought with some care and in as many thin sections of a meteorite as possible.

Other mineralogical trends

Petrographic examination of the chondrites in Table 3 revealed other mineralogical variations which are correlated with the degree of heterogeneity of olivine and pyroxene. In most cases, these observations corroborate and extend the findings of other workers.

Feldspar. Feldspar was not encountered with the microprobe, and was rarely seen under the microscope, in the unequilibrated chondrites listed in Table 3. This observation agrees with MASON's (1965b) conclusion that the chondrites with little or no feldspar always contain distinct chondrules and matrix.

It appears that most of the plagioclase found in equilibrated ordinary chondrites is a product of devitrification of glass and recrystallization of microcrystalline material.* The evidence for this is the great abundance of normative albite in glasses from chondrules (FREDRIKSSON and REID, 1965; VAN SCHMUS, 1966) and the presence of feldspar in the devitrified glass present in strongly metamorphosed chondrites. As MASON (1965b) notes, some "potential" feldspar may also be present in the pyroxenes of unmetamorphosed chondrites.

Nickel-iron. Our observations of the opaque phases in these meteorites were limited to a study of their modes of occurrence and forms. WOOD (1966) has studied metal particles in some of these chondrites both metallographically and with the microprobe. The reader is referred to his paper for details.

Most of the nickel-iron in the ordinary chondrites occurs as distinct grains outside the chondrules. Chondrules which contain droplike metal grains occur in all samples studied, but are much less abundant than in the carbonaceous chondrites (WOOD, 1966). In the chondrites which contain very heterogeneous olivines and pyroxenes most metal grains have simple shapes (typically subequant; oval and, in some instances, spherical). Highly irregular grains whose shapes conform with those of the surrounding silicates are the exception in those meteorites. By contrast, the chondrites which contain homogeneous or nearly homogeneous silicates contain irregularly shaped masses of metal which are commonly molded around the silicate grains. KVASHA (1961) made similar observations.

Although we did not determine metal compositions in this study, WOOD (1967) gives the compositions of metal grains in six of the chondrites listed in Table 3. The data in Table 4 are drawn from WOOD's Figs. 9, 18 and 19. It shows that the chondrites of each chemical group which contain the most heterogeneous olivines and pyroxenes typically contain kamacite which is poorer in nickel and taenite which is richer in nickel than are present in equilibrated chondrites. It is interesting to note that Bjurböle contains taenite which is richer in Ni, on the average, than that found by WOOD in other equilibrated ordinary chondrites. This is understandable because, although Bjurböle is equilibrated, it is texturally similar to the

* Primary feldspar is not entirely absent from ordinary chondrites, however; one of us (RTD) has observed twinned plagioclase in a chondrule in the Hallingeborg chondrite, and the equilibrated Leedey chondrite contains subhedral grains of plagioclase which very probably predate the metamorphism of this chondrite. (MOORE, DODD and WILK, in preparation.)

unequilibrated samples near it in Table 3 and has probably undergone only slightly more recrystallization.

It is also noteworthy that all of the meteorites in Table 4, except Bjurböle, contain closely similar abundances of Ni in kamacite (i.e. 3–7 wt.%). Their taenite compositions, though more variable, are also similar. The proportions of kamacite and taenite in each meteorite, and hence the average nickel content of the metal, is unknown. Thus it is impossible to determine from available data whether the metal phases in meteorites of the three chemical groups are of the same or different mean compositions, a question relevant to the possibility of a mixing relationship among the three groups (see discussion below).

Troilite. Troilite occurs as irregular grains and masses in all of the meteorites studied, and is commonly intergrown with metal. In the most unequilibrated

Table 4. Approximate ranges of nickel abundances in taenite and kamacite grains from five unequilibrated ordinary chondrites*

Chondrite	Kamacite (Wt. % Ni)	Taenite (Wt. % Ni)
Krymka (L)	3–5	42–50
Bishunpur (L)	3–6	45–53
Tieschitz (H)	3–7	37–43
Chainpur (L)	3–6	37–44
Mezö-Madaras (L)	3–6	33–45
Bjurböle (L)†	6–6 1/2	32–39

* Data from figures in WOOD (1967).

† Bjurböle is equilibrated.

samples (e.g. Krymka, Bishunpur) it occurs both as distinct grains and as very fine material dispersed throughout the opaque matrix. In the equilibrated samples listed in Table 3, the troilite grains are fewer, larger and of more irregular form. Some of them show complex exsolution textures in polarized reflected light.

The troilite in these chondrites is very poor in nickel. WOOD (1967) analyzed thirty-eight troilite grains in "pigeonite chondrites" and found all of them to contain less than 2 wt.% Ni. Of the thirty-eight grains, those from the unequilibrated ordinary chondrites he studied (Bishunpur, Chainpur, Krymka, Mezö-Madaras, Tieschitz; the other chondrites studied were Type III carbonaceous) contained less than 0.2% Ni (WOOD, personal communication). More extensive data by one of us (WRV) on five chondrites from Table 3 (Bishunpur, Krymka, Mezö-Madaras, Sharps, Tieschitz) confirmed this result.* Therefore we can say that nickel is a minor or trace element ($\leq 0.1\%$) in the sulfide of even the most heterogeneous samples listed in Table 3. This fact and the interstitial texture of troilite suggest that sufficient metamorphism has taken place to rework the troilite in all of the samples studied.

Chromite. Most of the chondrites in Table 3 contain very little or no chromite. Minor chromite was found in Tennasilm (equilibrated), and the mineral is an ubiquitous and abundant accessory in the more recrystallized ordinary chondrites. These observations agree with data given by KEIL (1962), who found much less

* Dr. VAN SCHMUS wishes to thank W. G. ERNST of the Department of Geology, University of California at Los Angeles, for the use of the UCLA microprobe for these analyses.

chromite in Barratta, Mezö-Madaras, and Parnallee than in other ordinary chondrites. It appears that most of the chromium in the unequilibrated ordinary chondrites occurs in some phase other than chromite.*

DISCUSSION

Metamorphism of chondrites

The sequence of correlated textural and mineralogical variations observed in each of the three groups of samples listed in Table 3 is most readily interpreted as due to progressive metamorphism of three types of starting material. Many workers, most recently WOOD (1962, 1963b) have reached similar conclusions on the basis of less extensive evidence. This interpretation is not universally accepted, however, and it is thus necessary to consider arguments against metamorphic homogenization of the chondritic silicates.

The focus of these arguments is a small group of chondrites, exemplified by Bjurböle and Allegan, which contain homogeneous silicates but retain distinct chondrules and matrices and high porosity (FREDRIKSSON, 1963; KEIL and FREDRIKSSON, 1964; REID and FREDRIKSSON, 1967). It is argued that the primary fabric could not survive heating sufficient to homogenize the silicates and that, therefore, the present silicate compositions are of primary (i.e. igneous) origin.

The validity of this argument depends strongly on the conditions under which metamorphism took place and, in particular, on temperature. CRAIG (1963) infers temperatures of equilibration in excess of 1200°C for the equilibrated ordinary chondrites, on the basis of the distribution of iron between olivine and orthopyroxene. At such temperatures, most petrologists—the authors included—would expect much more extensive recrystallization than is observed in Bjurböle. However, recent work by VAN SCHMUS and KOFFMAN (1967) casts doubt on the validity of the high temperatures inferred from the olivine–orthopyroxene partition. Using the distribution of iron between orthopyroxene and diopside in equilibrated chondrites, they infer temperatures of 800–850°C, and they suggest that the maximum metamorphic temperatures attained by these chondrites were of the order of 1000–1100°C. These lower temperatures, though still very high by comparison with those inferred for terrestrial metamorphites, might effect little visible recrystallization if the system were dry (WOOD, 1967). In the absence of a pore fluid, ionic migration would take place chiefly across grain contacts and over short distances. The effects of recrystallization would be least conspicuous in chondrites with abundant matrix, for, as was observed above, intergrowth appears to have proceeded most rapidly between adjacent chondrules rather than between chondrules and matrix. There is a clear need for more careful study of the temperature relationships in the chondrites and for experimental study of dry metamorphism. However, we see no justification for rejecting the metamorphic model on the basis of the data from Bjurböle and Allegan.

* Note added in proof: RAMDOHR (personal communication) reports chromite in normal amounts in several unequilibrated chondrites, and finds abnormally low amounts only in Tieschitz. He suggests plucking during polishing as a possible cause for an apparent deficiency in our samples. In the absence of knowledge of which chondrites RAMDOHR examined, we can offer no explanation of our differing results.

The strong textural difference between Bjurböle and other mineralogically similar chondrites in Table 3 raises an important point. Although the chondrites in each group are chemically similar, they differ somewhat in texture even at comparable degrees of equilibration. The chondrites which contain the most heterogeneous silicates and which show the least textural integration show small but distinct differences in the size distributions of silicate and metal particles (DODD, in preparation). It is reasonable to expect such differences to be reflected in the more recrystallized samples up to the point of complete obliteration of the primary texture. That we find no exact textural analogue of Bjurböle among the least-equilibrated chondrites is not surprising, for the few such meteorites which are known cannot be expected to represent all possible textural variations in the original material. It is clearly impossible to produce a matrix-rich chondrite like Bjurböle by recrystallizing a matrix-poor chondrite like Hallingeborg. On the other hand, the mineralogy of the former can be produced by metamorphosing the latter, and it is in this sense that we regard each of the three groups of chondrites in Table 3 as a metamorphic series.

That the glass which occurs in some chondrules of the unequilibrated chondrites is siliceous rather than mafic as was previously supposed (e.g. by DODD and VAN SCHMUS, 1965) makes its survival during mild recrystallization easy to understand. Siliceous glasses in dry experimental systems recrystallize very slowly, even at temperatures near the liquidus (TUTTLE and BOWEN, 1958, pp. 5 and 39). The retention of glass in chondrites such as Carraweena is thus no longer an embarrassment to the metamorphic model (see WOOD's discussion of this problem (1967)).

We conclude that each of the groups of chondrites in Table 3 represents thermal metamorphism of chemically homogeneous but texturally variable parent material. In the early stages of metamorphism, the most pronounced change in this material was the homogenization of the ferromagnesian silicate minerals; textural changes accompanied this process, but were not sufficient to obliterate the primary chondritic texture. The conditions of metamorphism represented by chondrites are poorly known, but the maximum temperatures probably did not exceed 1100°C and the system was probably dry.

These conclusions are essentially the same as those expressed by DODD and VAN SCHMUS (1965). The balance of this discussion rests on them.

Unmetamorphosed ordinary chondrites

DODD and VAN SCHMUS (1965) and SCHMITT, GOLES and SMITH (1966) have proposed that the unmetamorphosed precursors of the ordinary chondrites resembled the Chainpur chondrite (KEIL *et al.*, 1964) in containing very heterogeneous olivines and pyroxenes. They expressed doubt that such heterogeneous silicates could have arisen through metamorphism of homogeneous magnesian silicates, as WOOD (1962, 1963b) suggests, without more textural change than is observed. An examination of extremely iron-rich olivines shows that at least some of these olivines pre-date metamorphism (DODD, VAN SCHMUS and MARVIN, 1966).

On the basis of mineral heterogeneity (Table 3), texture, and the abundance of volatile constituents, several other ordinary chondrites of all three chemical groups come at least as close to unmetamorphosed material as does Chainpur. These are Ngawi and Semarkona (LL-group), Krymka, Bishunpur, and Hallingeborg (L-group), and Sharps and Tieschitz (H-group). It is extremely important to determine whether any of these meteorites is completely free of metamorphic effects or, if not, how great the metamorphic effects in these meteorites are.

As was noted in a previous section of this paper, the interstitial texture and low nickel content of troilite in these meteorites suggest that all of them have experienced mild reheating and, perhaps, equilibration of the troilite with the associated metal phases (KULLERUD, 1963). It thus appears that none of the chondrites which we have studied has completely escaped metamorphism.

That some of these meteorites have undergone but slight reheating is indicated by the metal data of WOOD (1967). WOOD examined and analyzed with the microprobe the metal phases of a large number of ordinary chondrites. He found that the majority, including Mezö-Madaras, Chainpur and Tieschitz among the unequilibrated chondrites, contain taenite particles whose central nickel contents are systematically related to particle size, and whose compositions and textures can be quantitatively explained by low-temperature diffusion of nickel and iron through the chondrites. It is clear from this that these chondrites, one of which (Tieschitz) is nearly free of textural evidence of recrystallization, have been heated sufficiently since agglomeration to redistribute their iron and nickel among the metal and sulfide phases.

Krymka and Bishunpur do not show this orderly relationship between the composition and size of taenite grains (WOOD did not examine Semarkona, Ngawi, Hallingeborg or Sharps). Furthermore, WOOD (1967) found as much nickel in the matrix of Krymka, and nearly as much in that of Bishunpur, as is present in the matrices of carbonaceous chondrites. These facts, plus the presence of abundant carbon (MOORE and LEWIS, 1967), Ar^{36} (HEYMANN, quoted in WOOD, 1967) and combined water (analysis, Table 1 of this paper) in these meteorites testify to little heating of these chondrites since they accumulated. The close similarity of Tieschitz, Semarkona, Hallingeborg and Sharps to these two chondrites, with respect to texture, mineralogy and volatile contents, leads us to conclude that they have experienced only slightly more metamorphism than Krymka and Bishunpur. In our opinion, all of these meteorites—certainly Krymka and Bishunpur and probably the others—are only slightly removed from unmetamorphosed material.

This conclusion has many implications. The most obvious is that these chondrites best preserve the primary characteristics of chondritic material which must be accounted for by genetic models. As DODD and VAN SCHMUS (1965) observed, some of these characteristics (e.g. heterogeneous silicates, glass and monoclinic low-Ca pyroxenes) remove many of the difficulties inherent in models which require primary crystallization of homogeneous silicates (e.g. KEIL and FREDRIKSSON, 1964) and orthorhombic pyroxenes (RINGWOOD, 1961).

Another implication is that these meteorites may afford a better picture of the chemical composition of ordinary chondrites at the time of agglomeration than do

equilibrated samples. This in turn bears on the question of fractionations among meteorite groups. In the following sections, we briefly discuss such fractionations.

It is perhaps wise to emphasize at this point that the search for unmetamorphosed ordinary chondrites is not over: A continuing effort must be made to find other candidates for this distinction and to evaluate the effects of metamorphism, however slight, on such chondrites as Krymka. Such work is absolutely essential to correct identification of the primary attributes of chondrites and to an accurate interpretation of the origin of chondrites.

Chemical fractionations correlated with metamorphism

Although the chondrites listed in Table 1 are similar in composition to equilibrated ordinary chondrites, they also show some consistent differences, most notable of which are larger abundances of the volatile constituents water, carbon and argon (Table 5). There is fragmentary evidence that other volatiles (e.g. indium and chlorine) are similarly enriched in unequilibrated ordinary chondrites (SCHMITT *et al.*, 1966), and it thus appears likely that at least part of the depletion of volatiles which is characteristic of ordinary chondrites (REED *et al.*, 1960; ANDERS, 1964) is due to metamorphism as various authors have suggested. More trace element data for the unequilibrated ordinary chondrites are badly needed to define the primary (i.e. pre-metamorphic) differences between ordinary and carbonaceous chondrites with respect to the volatile elements.*

It is also important to establish whether metamorphism of the ordinary chondrites has altered the proportions of the major elements, however subtly. A comparison of the individual analyses in Table 1 with the average compositions of the H-, L- and LL-group chondrites (also in Table 1) reveals no obvious differences between the unequilibrated and equilibrated ordinary chondrites.† Therefore we conclude that the metamorphism represented by our samples was isochemical with respect to the major elements but entailed a loss of the volatile constituents, carbon, argon, water and probably others as well.

One significant chemical change which did take place during recrystallization was in the mode of occurrence of iron in the chondrites. The mean Fe^{++} contents of olivines and pyroxenes in the L- and LL-group chondrites increase with increasing metamorphism. These changes were noted above and are presented graphically in Fig. 8, where the mean iron contents of olivines in the chondrites listed in Table 3 are plotted against per cent mean deviation. This figure suggests the following conclusions:

1. Three distinct series are represented.
2. The average olivine compositions in the most unequilibrated ordinary chondrites do not differ greatly from group to group.

* ANDERS (private communication) has raised the possibility that the material which formed the equilibrated ordinary chondrites may have agglomerated with a smaller proportion of volatiles than the material of the unequilibrated ordinary chondrites. That is, there may be both primary and metamorphic differences in the trace element suites of the two types of ordinary chondrites.

† The unequilibrated chondrites appear to contain slightly more sulfur (expressed as FeS) than their metamorphosed equivalents, but the differences (5–10% relative) are not great enough for certainty.

Table 5. Water, carbon and primordial argon in unequilibrated ordinary chondrites

Chondrite	Olivine ^a (%MD)	H ₂ O ^b (wt. %)	C ^c (wt. %)	(Ar ³⁶) primordial ^d (10 ⁻⁸ cc)	Ref.
<i>H-Group</i>					
Tieschitz	45	0.88	0.25	22	1
Sharps	37	2.03	0.95		
Bremervörde	15	0.23	0.22		
Prairie Dog Creek	6.9		0.35		
Clovis No. 1	5.6		0.22		
Castalia	3.6	0.43	0.27		
Geidam	*	0.57			
Sindhri	*				
Weston	*	0.98	0.28		
<i>L-Group</i>					
Krymka	45		0.27	52	2
Bishunpur	39	1.10	0.53	55	2
Hallingeberg	38	0.95	0.26		
Manych	26			12	3
Mezö-Madaras	21		0.45	51	1
Khohar	18	1.16	0.32		
Carraweena	6.0		0.09	3.0	4
Ioka	5.8		0.12		
Barratta	4.2		0.09	5.6	2
Goodland	2.6		0.07	6.7	2
Cynthiana	*		0.10		
Tennasilm	*	0.51	0.10		
Bjurböle	*			2.5	5
Lua	*		0.11		
Modoc	*		0.16		
<i>LL-Group</i>					
Ngawi	40	1.40	0.39		
Semarkona	37	1.22	0.57		
Chainpur	32	1.00	0.44	59	2
Parnallee	19		0.19	13	3
Hamlet	3.5	0.04	0.16	9.5	5

^a From Table 3.^b From Table 1; Data represents H₂O⁺ and is not reported for finds.^c From Table 1.^d Excludes cosmogenic Ar³⁶ and "solar component" Ar³⁶.

References:

1. EBERHARDT *et al.* (1966).
2. D. HEYMANN, personal communication.
3. VINOGRADOV and ZADOROZHNYI (1964).
4. HEYMANN (1965).
5. ZAHNINGER (1962).

3. The average iron content of the olivine in the L- and LL-groups increases during equilibration while the average iron content of the olivine in H-group chondrites remains essentially unchanged.

It is uncertain at this time what other changes in iron distribution occurred (i.e. oxidation of metallic Fe, reduction of Fe₂O₃, loss of another phase containing FeO) in order to provide additional FeO for the olivine and pyroxene in low-iron

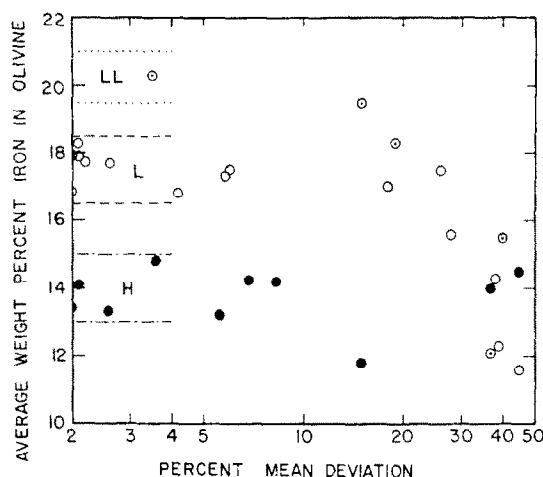


Fig. 8. Plot of average iron content of olivine versus percent mean deviation for chondrites listed in Table 3. Note the trend toward lower iron contents for the olivine in the most unequilibrated LL-Group chondrites (Open circles with dot) and L-Group chondrites (Open circles). Olivine from the H-Group chondrites (Solid circles) shows little change. The dashed line pairs above and below "LL", "L" and "H" denote the approximate range in compositions of olivine from equilibrated samples.

Table 6. Mean iron contents and proportions of olivines and pyroxenes in least-metamorphosed ordinary chondrites

Chondrite	Olivine		Pyroxene	
	Fa ^a	Vol. % ^b	Fs ^c	Vol. % ^b
<i>Low-iron group</i>				
Krymka ^d	15.5	46	11.5	54
Bishunpur ^d	16.7	40	12.8	60
Semarkona	16.3	43	12.0	57
Hallingeberg	19.7	37	10.5	63
Mean of low-iron	17.1	42	11.7	58
<i>High-iron group</i>				
Sharps ^d	19.2	41	14.0	59
Tieschitz ^d	19.7	45	11.0	55
Mean of high-iron	19.5	43	12.5	57

^a Mean mol % of Fayalite in olivine (Fa).

^b Vol. % of total olivine + pyroxene. Based on number of olivine and pyroxene grains measured during surveys (Table 8). May not be representative because of unanalyzed microcrystalline phases.

^c Mean mol % of ferrosilite in pyroxene (Fs).

^d Means of two analyzed samples.

chondrites. The observation that Tieschitz contains magnetite (WOOD, 1962; MASON, personal communication) suggests that reduction of Fe^{+++} to Fe^{++} and/or Fe (metal) is the dominant process, but no conclusive statement can be made on the basis of data now available.

Chemical and genetic relationships among chondrite groups

The results of the present study bear significantly on the relationships among the groups of ordinary chondrites and, to a lesser degree, on relationships between ordinary and carbonaceous and enstatite chondrites.

Genetic relationships among the ordinary chondrites. Several workers (UREY and CRAIG, 1953; MASON, 1965a; GREENLAND and LOVERING, 1965) have shown that the H-, L- and LL-group chondrites differ principally in their contents of iron, nickel and cobalt. These and other authors (e.g. ANDERS, 1964) have suggested derivation of the three groups from one another, or from a common parent material, through a transfer of metal.

Because the three groups were distinct at the earliest stages of metamorphism, such metal transfer must have occurred either during or before the agglomeration phase of chondrite evolution. Our data for the silicates and WOOD's results for metal (1967) suggest that the three chondrite groups may represent mechanical mixtures, in different proportions, of metal-poor and metal-rich fractions which were common to all three types of ordinary chondrites.

In a previous section, we noted that the least-metamorphosed chondrites of the three chemical groups contain olivines and pyroxenes of similar mean compositions (Fig. 8). The proportions of olivine and pyroxene in these chondrites are also similar (Table 6), suggesting that the three groups contained a common silicate fraction at the time of agglomeration. The data for metal are less complete. Although WOOD's work (1967) suggests that kamacite and taenite have similar mean compositions in the least-metamorphosed representatives of the three groups, the relative proportions of these phases (and hence the bulk composition of metal) are unknown. Data on the mean compositions of metal phases in the least-metamorphosed chondrites would provide a good test of the feasibility of a mixing model for siderophile differentiation.

Other petrological arguments support the mixing hypothesis. Studies of the grain size distributions of silicate and metal particles in chondrites (DODD, in preparation) show that these distributions are closely similar for the three ordinary chondrite groups. The only clear petrographic distinction among the groups is that metal and metal-bearing chondrules are more abundant in high-iron chondrites than in low-iron chondrites. Matrix material, which might contribute iron in the form of magnetite (WOOD, 1962), is of similar (and small) abundance in all three groups; hence differences in matrix abundance cannot account for the siderophile fractionation.

It must be stressed that a mixture of metal-rich and metal-poor fractions does not imply either that the metal and silicates were physically distinct at the time of agglomeration or that they came from different sources. The presence of metal in chondrules is well-established, and KEIL and FREDRIKSSON (1964) have reviewed

substantial evidence that the silicates and metal were cogenetic. It is entirely possible that a single process formed silicate droplets (chondrules), metal droplets and metal-silicate droplets (metal-bearing chondrules), and that these were incompletely segregated by gravity or magnetic fields before they accumulated to form the chondrites. In this sense, the term "fractions" may be imprecise: The chondrites may represent non-random sampling of a continuum extending from metal to silicate material.

Regardless of the specific process of siderophile fractionation, it appears that the ordinary chondrites are closely and simply related chemically, and, probably, in history.

Relationships among ordinary, enstatite, and carbonaceous chondrites

Although it is possible to account for the chemical difference between the high- and low-iron groups of ordinary chondrites with a simple mixing model, there

Table 7. Comparison of ratios of major elements in ordinary, enstatite and carbonaceous chondrites*

Group	Si/Mg ^a	Na ^b	K ^b	Al ^b	Ca ^b	Cr ^b	P ^b	Mn ^b	Na/K ^a
Enstatite chondrites	1.26	464	35	610	350	79	69	53	13.3
Ordinary chondrites	1.05	460	35	720	513	91	58	75	13.3
Carbonaceous chondrites: Type III	0.94	345	37	943	743	125	76	53	9.3
Type II	0.96	411	28	908	719	120	90	63	14.7
Type I	0.94	647	35	842	681	120	122	84	18.5

* Data from MASON (1965a, b).

^a Atomic ratio.

^b Si = 10,000 atoms.

seems to be no analogous simple chemical relationship among ordinary, carbonaceous, and enstatite chondrites. The differences which separate these groups involve both volatile minor elements (REED *et al.*, 1960; ANDERS, 1964) and major elements (UREY, 1961; DuFRESNE and ANDERS, 1962; AHRENS, 1964, 1965).

We have already noted that trace element data for the unequilibrated ordinary chondrites are few but that the available data indicate an enrichment of volatile constituents in the least-metamorphosed ordinary chondrites relative to metamorphosed chondrites. Whether there are also primary (i.e. premetamorphic) differences in the volatile contents of the major chondrite groups (ordinary, carbonaceous and enstatite) remains to be determined.

There are pre-metamorphic differences among these groups with respect to the more abundant elements. AHRENS' (1964, 1965) observation that the carbonaceous, enstatite and ordinary chondrites differ with respect to their SiO₂/MgO ratios was noted previously in reference to the classification of unequilibrated chondrites. Other differences are shown in Table 7, the data for which are from MASON (1965a and 1966). All of the major divisions are closely similar with respect to K/Si. Beyond this correlation, there is a bewildering assortment of agreements and disagreements, which suggest that the three basic types of chondrites—carbonaceous, enstatite and ordinary—are related by chemically complex processes, if they are related at all.

The data for carbonaceous chondrites in Table 7 favor the suggestion made by DUFRESNE and ANDERS (1962) and ANDERS (1964) that the three groups of carbonaceous chondrites differ chemically because they consist of different proportions of a high-temperature component (chondrules, chondrule fragments and individual olivine and pyroxene grains) and a low-temperature component (matrix). If it is assumed that the silicon content (volatile-free) of the three carbonaceous groups is the same, then it appears from Table 7 that the chondrules are depleted in Na and enriched in Al, Ca (and perhaps Cr) relative to the matrix, while the abundances of Mg and K are nearly identical in the two fractions. Comparisons of elemental abundances in separated chondrules and whole samples of Types II and III carbonaceous chondrites (SCHMITT *et al.*, 1965) support this conclusion for Na, Cr and Fe, but are equivocal for Mn. No data are available for the abundances of Mg, K, and Ti in chondrules and matrices.

If an effort is made to extend Anders' mixing hypothesis to the ordinary chondrites, in which matrix material is still less abundant, the model fails. Although Al/Si, Ca/Si and Cr/Si vary inversely with matrix abundance in the carbonaceous chondrites we find lower values for these ratios in the matrix-poor ordinary chondrites than in Type III carbonaceous chondrites. Conversely, Na/Si, Na/K and Mn/Si, all of which decrease with matrix abundance from Type I to Type III carbonaceous chondrites, increase from Type III to ordinary chondrites. Thus although the carbonaceous chondrites can be plausibly interpreted as mixtures, in different proportions, of the same type of chondrules and the same type of matrix, it does not seem possible to produce the ordinary chondrites by mixing together the components used in the carbonaceous chondrite model in any proportions. If the ordinary chondrites arose from the carbonaceous chondrites, the processes by which they are related are not simple and cannot now be described.

Until such time as the major elemental differences which distinguish carbonaceous, ordinary and enstatite chondrites can be explained, we prefer the view that these three major groups developed from separate batches of material, but that the subtypes within each group (H-, L- and LL-group ordinary chondrites; Types I, II and III carbonaceous chondrites) formed through mechanical and/or chemical fractionation of a single batch of material.

Origin of chondrites

The work reported here does not change the conclusions expressed by DODD and VAN SCHMUS (1965) concerning the origin of chondrules and chondrites. The presence of non-equilibrium high-temperature mineral assemblages in chondrules is an expected result of the rapid solidification of these chondrules which is indicated by their internal textures. Whether the molten droplets formed separately in space, as is required by the nebular condensation model of WOOD (1958, *et seq.*) or represent samples from an extended body of magma, as is implied by the volcanic models of FISH, GOLES and ANDERS (1960), RINGWOOD (1961) and others, is uncertain.

It is clear, however, that the origin of chondrules and chondrites must be sought in the most unmetamorphosed material available. We believe the chondrites at the top of each group in Table 3 to be such material.

CONCLUSIONS

Petrographic and microprobe analysis of twenty-five unequilibrated ordinary chondrites, and a review of the available chemical data for these meteorites lead us to the following conclusions:

1. Those chondrites in each chemical group which show the greatest variations in olivine and pyroxene composition most nearly approach freedom from metamorphism, though it is unlikely that any of the samples we have examined is completely unmetamorphosed.

2. Each group of ordinary chondrites constitutes a separate metamorphic series. Metamorphism was in each case nearly isochemical with respect to the major elements but entailed losses of volatile minor and trace constituents. The conditions of metamorphism (temperature, abundance of water vapor) were such that most of the redistribution of iron took place before the primary textures of the chondrites were effaced, but minor textural changes are correlated with an approach to equilibrium in the mafic silicates.

3. The three groups of ordinary chondrites were distinct at the earliest stages of metamorphism. Hence siderophile fractionation among them took place during or before agglomeration and may be due to a mechanical mixture, in different proportions, of metal-rich and metal-poor materials.

4. Although the chemical (and perhaps genetic) relationships among the ordinary chondrites appear to be simple, no simple relationship is apparent between these chondrites and the carbonaceous and enstatite chondrites.

5. The origin of chondrules and chondrites remains an open question, for the properties of those chondrites which are most nearly unmetamorphosed are consistent with any disequilibrium mechanism which includes the formation and rapid cooling of molten and semi-molten droplets to produce chondrules.

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APPENDIX—MICROPROBE DATA FOR SAMPLES AND STANDARDS

Table 8. Analytical data from microprobe analyses on samples studied

	No. ^a	Olivine		No. ^a	Pyroxene		k ^v c	I(Fe) ^d I(Sp)		Sample Source
		Fe ^b	%md ^b		Fe ^b	%md		Fe ^b	k ^v c	
Barratta	106	17.0	4.2	81	8.8	23	30	16.7	30	Arizona State University (Nininger Collection)
Bishunpur Af	99	12.5	39	82	6.8	58	30	12.7	30	Arizona State University
Bishunpur Bf	101	12.1	40	78	7.1	54	20	13.3	20	U.S. National Museum*
Bjurböle	101	18.6	2.1	37	10.8	4.2	20	20.7	20	Arizona State University
Brennervörde	101	11.7	15	55	6.7	46	20	12.5	20	American Museum of Natural History
Carraveena	103	17.8	6.0	93	10.4	20	30	19.9	30	South Australian Museum
Castalia	100	15.0	3.6	78	9.0	5.3	20	17.1	20	Arizona State University
Chalnupur	98	15.0	32	91	7.7	44	20	14.5	20	Arizona State University
Clavis No. 1	99	13.4	5.6	50	6.7	29	20	12.5	20	U.S. National Museum*
Cynthiana	98	18.2	2.1	90	10.8	6.1	20	20.7	20	American Museum of Natural History
Cesdam	86	13.3	2.6	49	8.3	3.7	30	15.7	30	American Museum of Natural History
Goodland	102	17.9	2.6	75	10.0	14	20	19.1	20	Dieter Heymann
Hallingeberg	95	14.4	38	54	5.7	57	30	10.6	30	U.S. National Museum*
Hamlet	100	20.6	3.5	33	11.7	8.9	20	22.5	20	U.S. National Museum*
Ioka	99	17.5	5.8	80	8.1	31	20	17.3	20	U.S. National Museum*
Khochar Af	100	17.3	17	66	7.9	42	20	14.9	20	Arizona State University
Khochar Bf	99	17.0	19	59	8.4	30	20	15.9	20	Arizona State University
Krymka Af	103	11.4	49	15.3	6.1	54	20	11.4	20	Academy of Sciences, U.S.S.R.*
Krymka Bf	98	11.6	41	15.6	6.0	6.7	20	12.5	20	Academy of Sciences, U.S.S.R.*
Lua	102	17.9	2.2	57	10.8	3.5	20	20.7	20	Arizona State University
Manych	83	17.8	26	67	7.6	40	20	14.3	20	Academy of Sciences, U.S.S.R.*
Mezö-Madaras Af ^g	97	17.5	15	70	8.6	26	30	16.3	30	Academy of Sciences, U.S.S.R.*
Mezö-Madaras Bf	99	15.7	28	21.7	7.5	44	20	14.1	20	Academy of Sciences, U.S.S.R.*
Modoc Af	90	18.0	1.3	25.2	46	10.9	30	20.9	30	Arizona State University
Modoc Bf	102	18.3	1.2	25.7	55	11.0	20	21.1	20	Arizona State University
"Ngawi"	82	18.9	15	28.2	70	10.7	20	20.5	20	(Same section as Modoc A)
Ngawi	102	15.6	40	21.6	70	8.1	20	15.3	20	U.S. National Museum*
Pernallee	94	18.6	19	26.2	104	8.3	30	15.7	30	U.S. National Museum*
Prairie Dog Creek	98	14.3	6.9	19.6	82	7.7	30	14.5	30	Yale University
Semarakona	109	12.1	37	16.3	47	6.5	20	12.2	20	Arizona State University
Sharps	100	14.0	37	19.2	61	7.4	20	13.9	20	U.S. National Museum*
"Sindhri"	102	14.3	8.3	19.6	43	8.8	20	16.7	20	U.S. National Museum
Sindhri	100	14.2	2.1	19.4	87	9.0	30	17.1	30	Kurt Fredrikson*
Tennasilin	97	16.9	2.0	23.5	114	10.1	30	19.3	30	Arizona State University
Tieschitz Af	101	12.9	43	17.5	62	5.7	20	10.6	20	American Museum of Natural History
Tieschitz Bf	102	16.1	47	22.3	79	6.4	20	12.0	20	U.S. National Museum*
Weston	90	13.4	1.9	18.3	100	8.4	20	15.9	20	U.S. National Museum*

* Sample borrowed as prepared microprobe section.

^a Number of grains in average (1 point analyzed per grain).^b See Table 3.^c Accelerating voltage of electron beam during analysis.^d Intensity ratio of FeK α X-rays (after corrections) for fayalite-olivine standard relative to Springwater olivine standard.^e "A" and "B" denote analyses on separate thin sections of the same meteorite except for Modoc, in which case "A" and "B" denote repeat analyses on the same thin section.^g This analysis was performed on a polymict sample and is therefore non-representative (VAN SCHMUS, 1966).

Table 9. Standards used for microprobe calibration curves

Mineral ^a	Fe (wt. %)	Reference
Enstatite, Bushveld (Orthopyroxene 7666)	6.2	HESS (1960)
Enstatite (E-1), Bamle, Norway	7.0	RIEKER and SEIFEIT (1964)
Olivine, Ichinomegata, Japan	8.2	SMITH (1966) ^b
Olivine, Marjalahti Meteorite	8.9	SMITH (1966) ^b
Olivine, Springwater Meteorite	13.3	MASON (1963c)
Olivine, Susimaki, Finland	31.2	SMITH (1966) ^b
Olivine (fayalite), Rockport, Mass.	53.4	VAN SCHMUS, unpublished (based on probe analysis for Mg, Mn, Ca and assumed stoichiometry).

^a Samples provided by C. FRONDEL (Rockport fayalite), H. HESS (Bushveld orthopyroxene), K. KEIL (Susimaki olivine), B. MASON (Marjalahti and Springwater olivine), K. SEIFEIT (Bamle enstatite), and H. YODER (Ichinomegata olivine).

^b The data by SMITH (1966) are superior to the original analyses for these minerals tabulated by YODER and SAHAMA (1957), except for Marjalahti, in which case they are comparable. KEIL and FREDRIKSSON (1964) used Susimaki = 29.9% Fe and Marjalahti = 8.5% Fe.

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