Composition of Chondrules, Fragments and Matrix in the Unequilibrated Ordinary Chondrites Tieschitz and Sharps

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An electron microprobe study of the unequilibrated ordinary chondrites (UOC's) Tieschitz and Sharps shows that different populations of chondrules and fragments can be distinguished. Chondrules with clear glass (FeO 4.4%), spherical chondrules (FeO 7.1%), irregular chondrules (FeO 11.5%), and fragments (FeO 16.0%) form a sequence with increasing FeO content (all values from Tieschitz). Chondrules and fragments are coated by dark, fine-grained rims, the so-called black matrix. Its composition is not related to the enclosed particle; the mean is close to an average H-chondrite. The alkali-rich white matrix found in Tieschitz (50% albite, 25% nepheline in the norm) is a late deposit, perhaps formed by shock lithification. A genetic relation between chondrules and fragments is favored: chondrules were mechanically transformed into fragments and at the same time enriched in FeO. The FeO source could be the dark matrix material. This FeO distribution was established before agglomeration, because no *in situ* equilibration is found. Indications for this model are: an FeO-size relation, a radial increase in FeO in some fragments, and the constant average Fe/Mn ratio. The formation of chondrules from the fragment material by impact and reduction also seems possible. Secondary alterations have affected all components; they are mainly shown by the large variations in the Na/K ratio. Small, spherical Ca, Al, Ti-rich chondrules were also found. Besides olivine, they contain minerals not found in normal chondrules, namely spinel and Ti-augite. The average enrichment factors relative to Si and C1 are 12 for Al and Ti, and 4.7 for Ca.

1. INTRODUCTION

Unequilibrated ordinary chondrites (UOC's) are usually assigned to the H-, L-, or LL-group of uniform ordinary chondrites by their content of total iron. The meteorites Tieschitz (total Fe 24.6%; Hutchison *et al.*, 1981) and Sharps (total Fe 26.3%; Fredriksson *et al.*, 1969) were thus placed into the H-group, which has an average total iron content of 27.6% and a range of 24.5 to 30% (Mason, 1965), although their FeO contents of 13.5 and 13.6%, respectively, lie outside the H-group range (7–12% FeO, ave. 9.6%; Mason, 1965) and are more appropriate to the L-group (11.5–18% FeO, Mason, 1965; ave. 14.7%; Wlotzka and Jarosewich, 1977). The present study was undertaken in order to better understand this discrepancy and the relations of these "H"-group UOC's to the other, "equilibrated" (better called uniform), H-group chondrites. For this purpose a thin section study by electron microprobe was made. The broad-beam technique used for the bulk analysis of chondrules or fragments is not as accurate as chemical methods and does not yield trace elements. It is possible, however, to analyze *all* components in a given volume, including the matrix, which is difficult to achieve in the usual studies of separated chondrules or matrix material. It was hoped that this type of analysis would answer the following questions:

(1) Which constituent is responsible for the high mean FeO content of the meteorite and what is the contribution of the matrix to the bulk composition?

(2) Is there a uniform or "equilibrated" component corresponding in FeO to the H-, L-, or LL-group, or are there other populations of chondrules or fragments that can be distinguished by their composition?

Previous studies of chondrules from UOC's (Gooding *et al.*, 1980; Lux *et al.*, 1981) have not tried to compare the average composition of the chondrules to the bulk composition of the meteorite and discuss possible discrepancies. The reason was probably the limited number of analyzed chondrules, which did not allow significant conclusions. Therefore, we have attempted here to analyze a sufficiently large number of chondrules.

The meteorites studied are Tieschitz and Sharps. Tieschitz fell in 1878 in Czechoslovakia and was described in the same year by Tschermak (1878). Both are included in the survey of UOC's by Dodd *et al.* (1967). They give an unpublished analysis for Tieschitz by Wiik and determined the percent mean deviation (PMD) of the olivine composition as 45%. Several papers were published by Kurat (1969, 1970, 1971) with analyses of chondrule minerals, glasses, and the black matrix. Christophe Michel-Lévy (1976) described the black and the white matrix of Tieschitz. Hutchison *et al.* (1979, 1981) studied its petrography and mineral composition and gave a new chemical analysis. Sears *et al.* (1980) classified Tieschitz as a type 3.6 by the thermoluminescence sensitivity technique.

Sharps fell in Virginia, United States, in 1921. It was described by Watson (1923). A detailed petrographic description and analyses of its chondrules and lithic inclusions as well as a chemical analysis were given by Fredriksson *et al.* (1969). Dodd (1968, 1971) analyzed minerals and chondrules of Sharps. Dodd *et al.* (1967) give 37% for the PMD of the olivine composition. Sears *et al.* (1980) classified it as type 3.4.

2. RESULTS

a.) Chondrules and fragments

Figure 1 shows a thin section of Tieschitz at low magnification. Spherical chondrules can be distinguished from fragments, which have angular or square outlines. "Irregular chondrules" form a class in between "chondrules" and "fragments"; they show a rounded outline over more than half of their periphery. The rest may be irregular or straight, i.e., suggesting fragmentation or abrasion. Examples of these three types of particles are marked in Fig. 1. This definition is not the same as the distinction between "droplet" and "lithic" chondrules, which depends mainly on the internal structure of the particles (King and King, 1978). The internal structures of the fragments are the same as those known from chondrules, i.e., porphyritic, fine-grained, barred olivine, radiating pyroxene, etc. Also, all of them contain a glassy mesostasis as evidence for an igneous melt origin, the same as found in chondrules. The fragments are therefore most probably fragmented chondrules. In fact, these "fragments" fulfill the criteria for "chondrules" as defined by Dodd (1982).

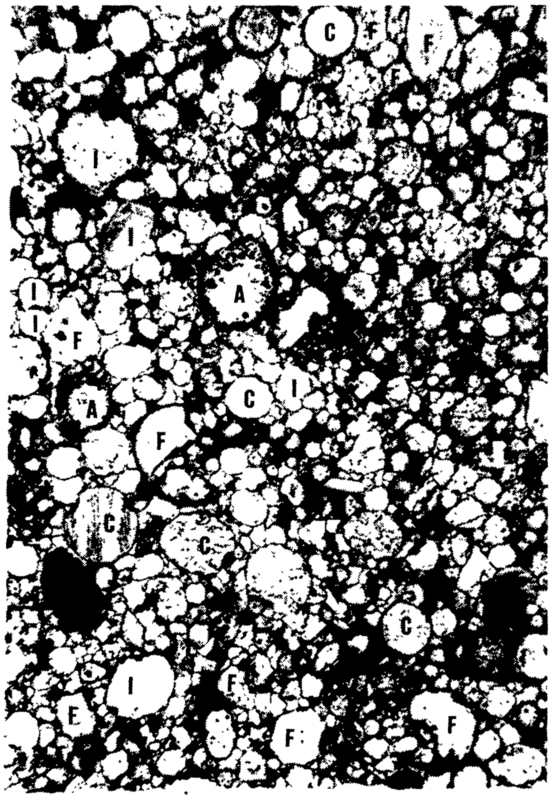

Fig. 1 Tieschitz, thin section in transmitted light. Length of section 16 mm. Examples of chondrules (C), irregular chondrules (I), and fragments (F) are marked. A = armoured chondrule.

In any case, the fragments described here from some UOC's should not be confused with the lithic fragments or clasts known from brecciated meteorites, especially the light-dark structured gas-rich chondrites (see, e.g., Wlotzka, 1963). These clasts have a chondritic texture in themselves and are usually larger in size than the chondrules of the host meteorite. The fragments found in Tieschitz and Sharps have the same size range as the chondrules in these meteorites and their internal texture is uniform in any given fragment. The reason for distinguishing fragments from chondrules in this paper lies mainly in the difference in composition as discussed below.

Chondrules and fragments were analyzed by electron microprobe with the broad-beam technique. The beam was placed on a cross-section as large as possible, avoiding metal and sulfide particles. In most cases, this was possible because metal and troilite occur outside the chondrules or at their periphery. Objects containing substantial amounts of metal or troilite throughout (which were very few) were not analyzed. Analyses showing sulfur were corrected by subtracting from the FeO value the amount of Fe to form FeS. The analysis was done by the energy dispersive method, using the correction procedures by Reed and Ware (1975). No further correction was applied for the fact that different element radiations come from different phases (e.g., McSween, 1977). This does not seem worthwhile here, because the analysis of random cross-sections instead of whole chondrules already introduces a certain error. The interpretation of the results will therefore be restricted to relatively large compositional differences.

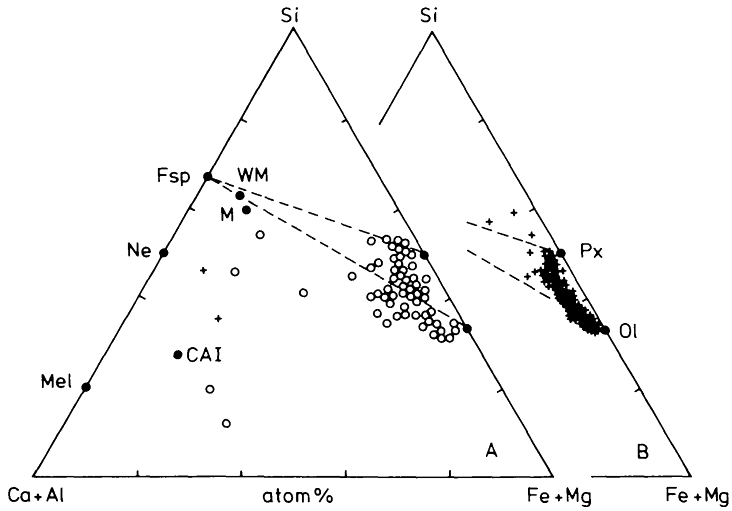

Fig. 2 **(a)** Composition of chondrules (o) and Ca,Al-rich fragments (+) in Tieschitz (atom.%). Px = pyroxene, Ol = olivine, Fsp = chondritic feldspar, Ne = nepheline, Mel = melilite, WM = white matrix, M = average of chondrule mesostases. CAI = Ca,Al-rich inclusion from Allende. **(b)** Composition of fragments in Tieschitz (atom.%). Note tighter clustering of points between Ol and Px.

The analyses plotted in Figs. 2 and 3 show that the compositions of chondrules and fragments are quite variable, in agreement with previous results (e.g., Gooding *et al.*, 1980; Grossman and Wasson, 1981; Lux *et al.*, 1981). Table 1 gives the mean compositions of chondrules and fragments. Chondrules with clear igneous glass, devitrified glass mesostases, irregular chondrules, and fragments form a sequence with increasing mean FeO content (Fig. 4). This holds for both Tieschitz and Sharps; the mean FeO contents and Fe/(Fe + Mg) ratios in these different groups are quite similar in these two meteorites (Table 2). MgO decreases with the increase of FeO. From the other elements, Al, Na, and K (i.e., the feldspar elements) are higher in the FeO-poor

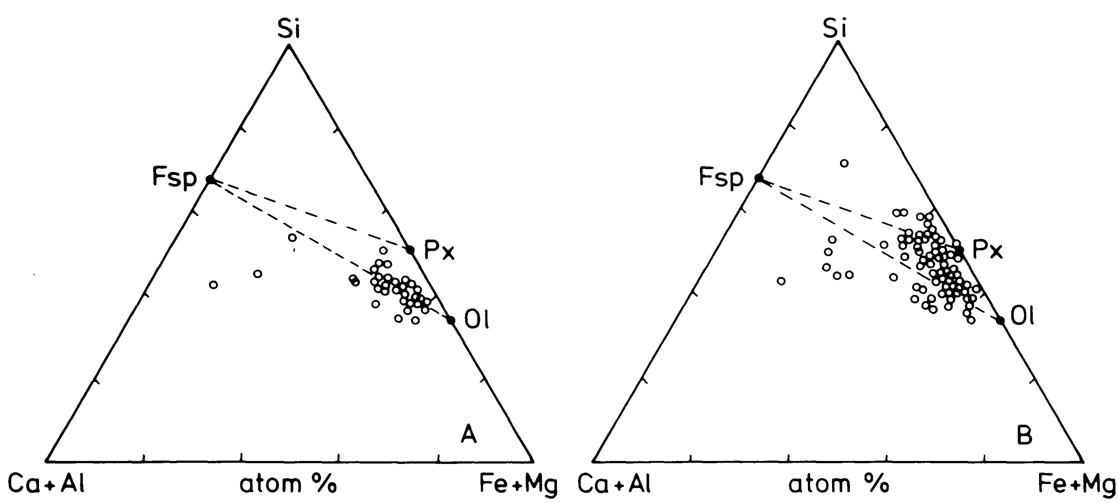

Fig. 3 Composition of chondrules with clear glass **(a)** and with devitrified glass **(b)**, in atom.%, from Sharps. Symbols as in Fig. 2. Fragments are not shown, because they plot very similar to normal chondrules.

Table 1. Mean composition of chondrules and fragments.

	Tieschitz				Sharps		
	Chondrules			Fragments	Chondrules		Fragments
	1	2	3		1	2,3	
	(10)*	(60)	(104)	(98)	(36)	(92)	(105)
SiO_2	43.9	47.1	46.7	44.9	46.3	51.1	49.0
Al_2O_3	7.66	5.20	4.13	3.26	5.38	3.67	2.96
Cr_2O_3	0.24	n.d.	n.d.	n.d.	0.41	0.59	n.d.
FeO	4.36	7.09	11.5	16.0	4.81	8.73	14.6
MnO	—	—	—	—	0.13	0.33	0.40
MgO	37.5	34.8	32.4	31.3	38.5	31.5	28.3
CaO	2.02	2.15	1.95	1.54	1.03	1.98	1.83
K_2O	—	—	—	—	0.50	0.26	0.16
Na_2O	3.39	1.88	1.42	1.02	2.71	1.45	1.29
Total	99.1	98.2	98.1	98.0	99.8	99.6	98.5

1. Chondrules with clear igneous glass.
2. Chondrules with devitrified glass.
3. Irregular chondrules, devitrified glass.

* Figures in parentheses give number analyzed.

n.d. Not determined.

— No average given, because many values are below detection limit.

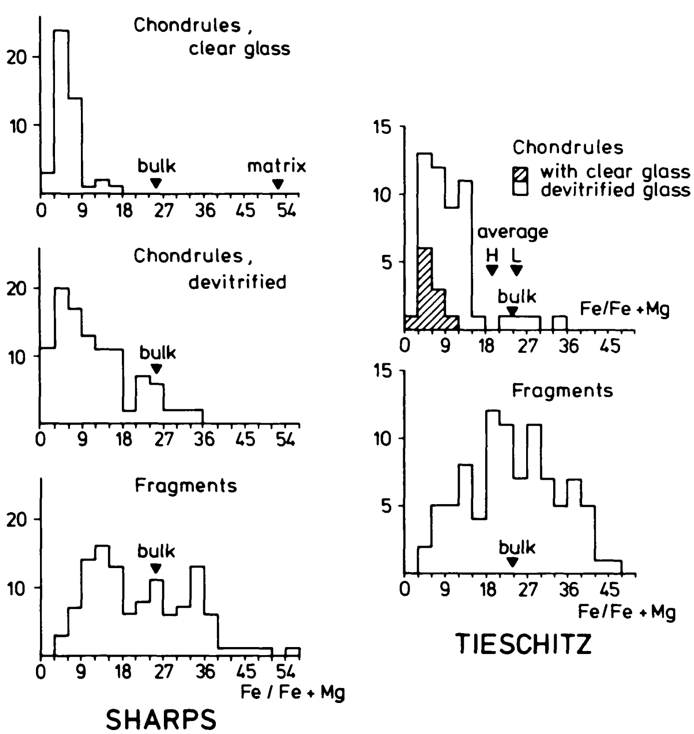

Fig. 4 Histogram of bulk Fe/(Fe + Mg) (mol.%) for chondrules and fragments from Tieschitz and Sharps.

Table 2. Mean FeO in chondrules and fragments.

		Chondrules with glass	Chondrules+	Irregular Chondrules+	Fragments	Bulk silicate
	Number analyzed	(10)	(60)	(104)	(98)	
Tieschitz	FeO%	4.4 ± 1	7.1 ± 4	11.5 ± 6	16.0 ± 7	16.5 (1)
	Fe/(Fe + Mg)(mol%)	6.1	10.3	16.6	22.3	23.8
	Number analyzed	(36)	(92)*		(105)	
Sharps	FeO%	4.8 ± 3	8.7 ± 6		14.6 ± 7	17.7 (2)
	Fe/(Fe + Mg)(mol.%)	6.6	13.5		22.4	25.6

(1) From Hutchison *et al.* (1981).
(2) From Fredriksson *et al.* (1969).
± Values are standard deviation.
+ With devitrified glass.
* For Sharps, no distinction between spherical and irregular chondrules was made.

chondrule types. Dodd (1971) has found from a more limited number of analyses on Sharps that olivines in irregular chondrules were on the average richer in FeO than in spherical ones. Fredriksson *et al.* (1969) noted that olivines in chondrules with clear glass in Sharps tend to be very low in FeO.

Other plots of FeO with chondrule types did not show such clear differences. Chondrules and fragments differ in their relative abundance of textural types; fragments have a higher percentage of fine-grained and granular types. But these variations are not responsible for the different Fe/(Fe +Mg) distributions as shown in Fig. 4.

Figure 5 is a plot of Na vs. K in the chondrule mesostases, which is the main carrier of these elements inside the chondrules. The values scatter widely and for Tieschitz, most K-contents are very low with K/Na ratio well below the bulk ratio. Sharps shows the same scatter, but many K-contents lie above the K/Na bulk ratio.

In Fig. 6 the apparent diameter of chondrules and fragments is plotted against the FeO/(FeO + MgO) ratio. The correlation is weak and is not a linear one, but it is the same in both plots: the upper right of these plots is empty; i.e., there are no large, Fe-rich chondrules or fragments. In other words, small ones occur in the whole FeO/(FeO + MgO) range, low to high, whereas large ones tend to be Fe-poor.

b.) Black rims and white matrix

The occurrence of a "black" and a "white" matrix is a peculiarity of Tieschitz, first described by Christophe Michel-Lévy (1976) and also by Hutchison *et al.* (1979) and Ashworth (1980). The black "matrix" should really be called black rims, as it coats *each* constituent of the meteorite as thin, black rims (width about 5–20 microns), i.e., chondrules, fragments of chondrules and silicate

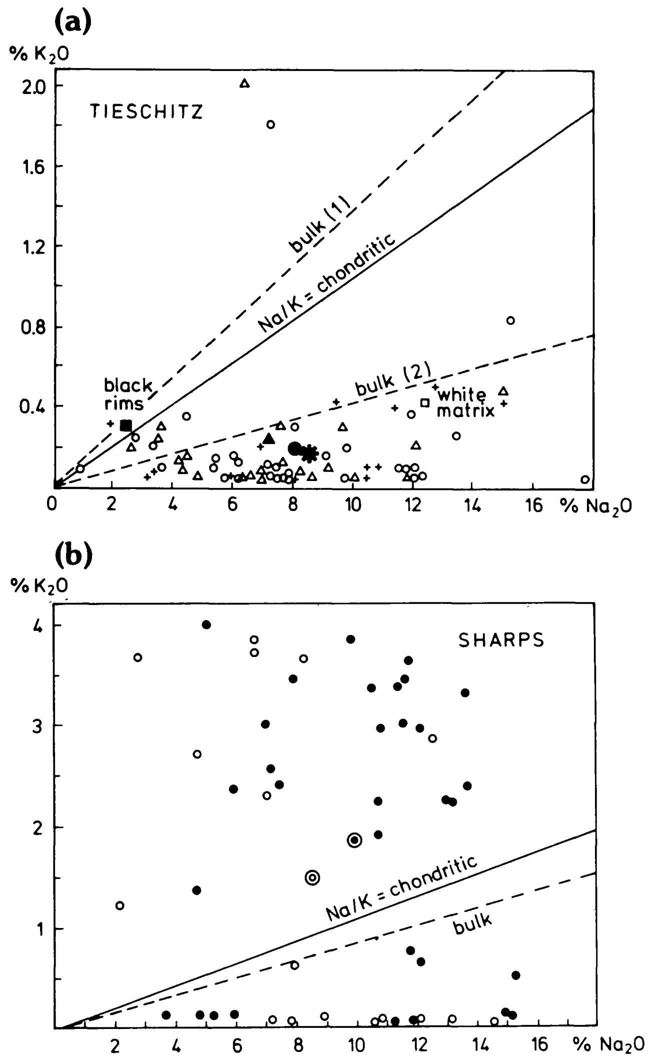

Fig. 5 Na_2O vs. K_2O (wt.%) in mesostases of chondrules and fragments. **(a)** Tieschitz, chondrules (open circles; average: filled circle), irregular chondrules (open triangles; average: filled triangle), fragments (crosses; average: star), black rims (filled square), white matrix (open square). Na/K bulk (1) from Hutchison *et al.* (1981), bulk (2) from Dodd *et al.* (1967). **(b)** Sharps, devitrified chondrules (open circles), chondrules with clear glass (filled circles). Encircled symbols are mean values. Bulk Na/K: Fredriksson *et al.* (1969). Note different scale for K_2O compared with the Tieschitz plot.

minerals, and also metal and troilite (Fig. 7). The outer surface of these rims is usually smooth, whereas the interior boundary is sharp and follows the shape of the enclosed particle, filling any indentations which might be present. Occasionally the black material is also found in a cavity completely inside a chondrule. This is probably not a real inclusion, however, but connected with the surface in the third dimension. In reflected light, the rims are medium grey, fine-grained, and occasionally contain resolvable specks of metal or troilite. Analyses by the broad-beam technique (Table 3) show the rims to be rich in iron. Rims are variable in composition, although not as variable as the chondrules themselves. No correlation was found between the composition of a given chondrule or fragment and the composition of its black rims. Thus rims around metal or troilite were not richer in Fe or Ni than others, and rims around Ca, Al-rich chondrules not enriched in Ca or Al.

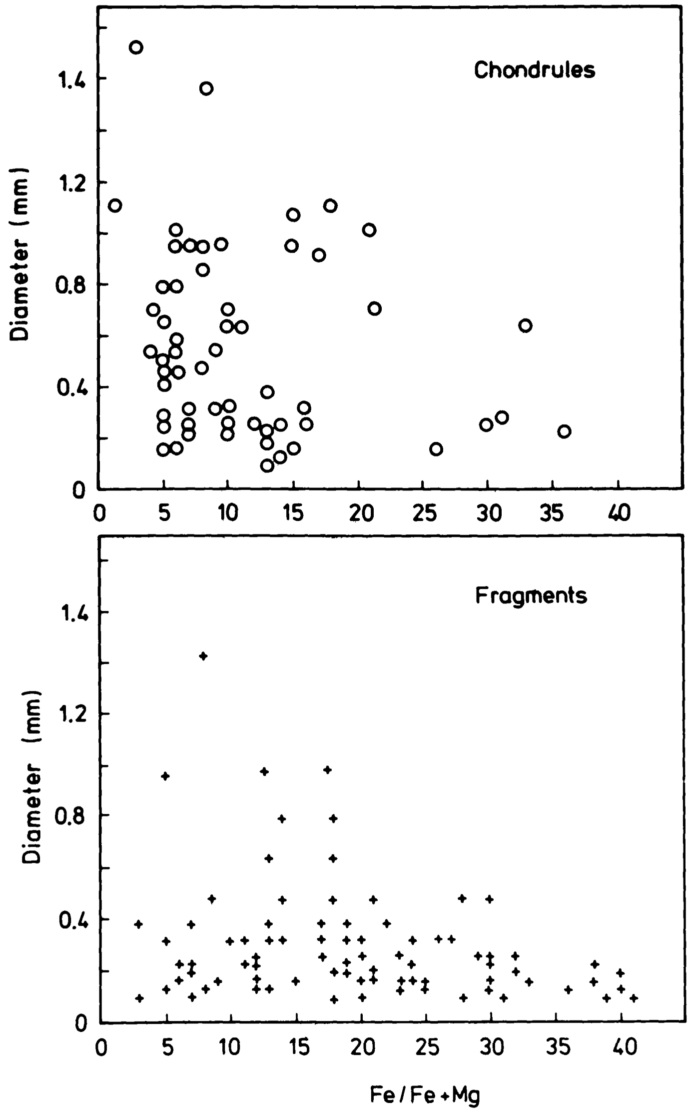

Fig. 6 Apparent diameter of chondrules and fragments from Tieschitz vs. Fe/(Fe + Mg) (mol.%).

The extensive study of chondrule rims by Allen *et al.* (1980) noted a greater variability in their composition, and often a high abundance of iron sulfides. In Tieschitz, this is not the case; no sulfide-rich rims were found, and sulfur averages were 0.37 ± 0.15% in the 20 analyses made. The reason for this discrepancy is probably a different definition of "rims." In this work on Tieschitz and Sharps, only "matrix rims" were analyzed, which are clearly separated from the chondrule bodies and appear to be secondary deposits. Metal and troilite-rich rims ("armoured chondrules") are different, usually more coarse-grained, and seem to be a part of the chondrule which they enclose. An example is shown in Fig. 1.

Chondrules and fragments in Tieschitz form a tightly fitting aggregate (Fig. 7). It seems remarkable that the black rims are preserved around all surfaces and that no clastic matrix is

Fig. 7 Tieschitz, thin section in transmitted light. All chondrules and fragments are surrounded by dark rims, the "black matrix." In the interstices between chondrules and fragments, the transparent "white matrix" occurs. Note close fit between all chondrules and fragments; no clastic matrix is present. Length of section 1.3 mm.

present. Instead, the interstices are filled with the white matrix, a transparent fine-grained intergrowth of crystals of low birefringence. Its average composition is given in Table 3. Of all constituents of Tieschitz, the white matrix has the least variable composition; broad-beam analyses give a standard deviation of 6% (relative) for Na_2O and 18% (relative) for K_2O.

In Sharps the relations are less clear (Fig. 8). Black rims can be distinguished only around some chondrules. Their average composition (Table 3) is similar to that of the black rims in Tieschitz. No white matrix is found.

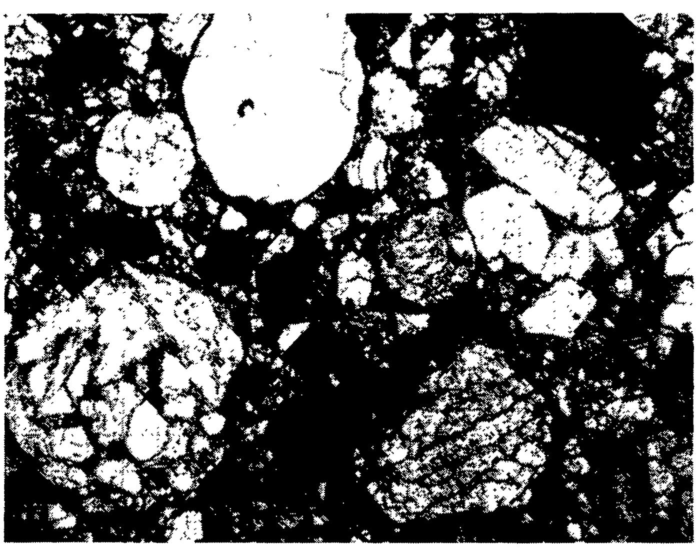

Fig. 8 Sharps, thin section in transmitted light, showing the gradation from spherical chondrules to irregular chondrules and fragments. Same magnification as Fig. 7.

Table 3. Composition of mesostases and matrices (in wt. %).

	Tieschitz			Sharps			White matrix	Black rims		Average H-chondrite*
	1 (33)	2 (22)	3 (15)	4 (34)	5 (17)	6 (13)	Tieschitz (18)	Tieschitz (20)	Sharps (5)	
P_2O_5	0.11	0.41	0.23	0.1	0.30	0.50	—	0.30	0.28	0.26
SiO_2	55.8	56.3	54.4	58.5	64.4	59.8	56.6	36.7	34.1	34.6
TiO_2	0.35	0.23	0.27	0.52	0.35	0.46	0.06	—	—	0.1
Al_2O_3	17.3	16.9	19.2	18.0	13.2	15.3	19.3	3.81	2.60	2.01
Cr_2O_3	0.32	0.32	0.30	0.57	0.26	0.16	—	0.28	0.42	0.49
FeO	4.01	3.54	4.22	2.24	4.16	5.58	4.93	35.1 ± 5	38.5 ± 4	33.6
NiO	—	—	—	—	—	—	—	0.24	1.16	2.08
MnO	0.25	0.20	0.14	0.1	0.12	0.1	—	0.53	0.53	0.29
MgO	5.96	5.84	6.13	5.52	3.86	3.32	3.12	17.6	20.0	22.1
CaO	6.93	7.92	5.36	2.67	2.64	4.03	2.69	1.32	0.92	1.65
K_2O	0.20	0.25	0.19	1.85	1.48	1.63	0.44	0.29	0.23	0.09
Na_2O	8.00	7.21	8.26	9.88	8.45	8.83	12.2	2.49	0.81	0.80
S	0.20	0.23	0.51	0.11	0.23	0.15	0.22	0.37	0.21	1.93
Cl	—	—	—	—	—	—	0.1	0.3	0.15	—
Total	99.7	99.7	100.0	100.0	99.5	99.8	99.7	100†	100†	100
Fe/(Fe + Mg)	27.4	25.4	27.9	18.6	37.7	48.5	46.2	51.3	51.9	(20.3)
Na/K	35.7	25.8	33.2	4.8	5.1	4.8	24.8	7.7	3.15	7.9

— Not detected

* From Wlotzka and Jarosewich (1977), with total Fe calculated as FeO. 1 through 6: Mesostases in spherical chondrules (1), irregular chondrules (2), and fragments (3) in Tieschitz; in glass-containing chondrules (4), devitrified chondrules (5), and fragments (6) in Sharps. Numbers in parentheses are number of analyzed chondrules, fragments or matrix areas.

† Analyses totaling 85–90% normalized to 100%.

c.) Calcium-aluminum rich chondrules

Figure 9 shows the large spread in CaO and Al_2O_3 contents of chondrules and fragments in Sharps. For Tieschitz the relations are similar. Calcium and Al correlate close to the meteoritic ratio of 1.1 (Ahrens *et al.*, 1969) in devitrified chondrules and fragments, but not in the

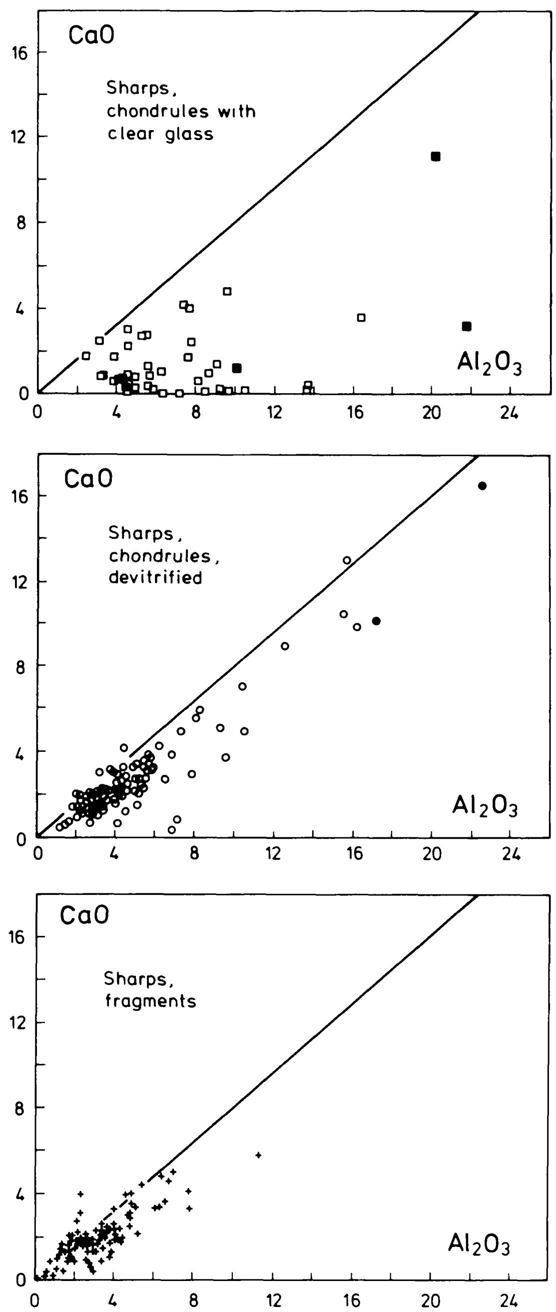

Fig. 9 CaO vs. Al_2O_3 (wt.%) for bulk chondrules and fragments from Sharps. The straight line gives the chondritic Ca/Al ratio (Ahrens *et al.*, 1969). Filled symbols are for Ca,Al-rich chondrules with Ti-augite and spinel.

glass-containing chondrules (see below). As the mesostasis is the main carrier of Ca and Al in the chondrules and fragments, the enrichment in these elements is often due to a high relative proportion of mesostasis in the analyzed cross-section. Sodium is often enriched together with Al, but because the Na content of the mesostases is rather variable (Fig. 5), Na and Al are not strongly correlated.

Besides these normal chondrules enriched in Ca and Al, special Ca, Al, Ti-rich chondrules also occur that are different in their mineralogy. They contain Ti-rich augite (fassaite), spinel, and olivine in an Al-rich mesostasis, usually a glass. Thus, they are similar to the Ca, Al-rich chondrules or inclusions found in carbonaceous chondrites, but they do not contain melilite. Eight such chondrules were found in Tieschitz, and several were found in Sharps; an example is shown in Fig. 10. They range in Al_2O_3 from 10 to 51% (ave. 26%), in CaO from 2.8 to 18.4% (ave. 9%), and in

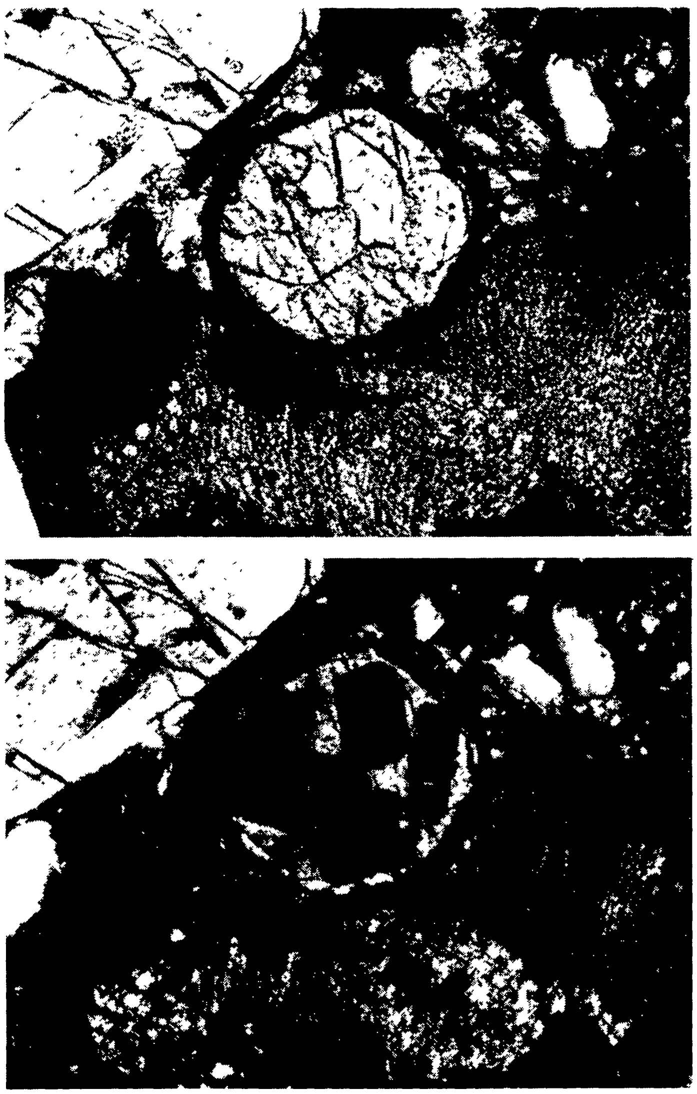

Fig. 10 Ca, Al-rich chondrule (apparent diameter 140 microns) in Tieschitz, in plain polarized light (top) and with crossed nicols (bottom). Isotropic grains (dark in bottom picture) are spinel. Dark rim around chondrule is "black matrix." Note concave contact surface of fine-grained fragment towards the chondrule.

TiO_2 from 0.24 to 6.6% (ave. 1.5%). The average enrichment factors (by weight) relative to C1 and Si are: for Al, 12; for Ca, 4.7; and for Ti, 12. These values are higher than the average refractory enrichment factor of 2.8 calculated by Grossman and Wasson (1981) for a refractory chondrule precursor component in Semarkona. Some of these chondrules are also enriched in Na (up to 14% Na_2O), as was already noted for some Ca, Al-rich inclusions in ordinary chondrites by Noonan *et al.* (1978).

Until now these Ca, Al-rich bodies were described in ordinary chondrites mainly as irregular inclusions (Noonan, 1975). Recently, Nagahara and Kushiro (1982) found chondrules similar to those described here in two Antarctic meteorites of type L3 and LL3. In Tieschitz all Ca,Al-rich chondrules are apparently rather small, 0.1 to 0.2 mm, i.e., at the lower end of the size range of normal chondrules. This is in contrast to their occurrence in the carbonaceous chondrite Allende, where they are much larger than the other chondrules (Mason and Taylor, 1982). A more detailed description of these special chondrules will be given elsewhere (Wlotzka, 1983).

3. INTERPRETATION

a.) Chondrules and fragments

Figures 2 and 3 show that the majority of chondrules and fragments plot inside the triangle defined by olivine, pyroxene, and feldspar. This agrees with an origin of chondrules from a granular precursor rock, which contained these three minerals (Suess, 1963), although it does not exclude other modes of origin. Fragments seem to be more "equilibrated" than chondrules, as they plot much closer together.

A main result is the lower mean FeO content and FeO/(FeO + MgO) ratio of chondrules compared to fragments (Table 2). The following interpretation will focus mainly on these relations and not on the origin of chondrules. It is important to note that the correlations found between FeO and chondrule shape and size are only statistical relations which refer to the *average* compositions and not to individual particles. There are chondrules rich in FeO and fragments poor in FeO. There are also small fragments in the Fe-rich black matrix that are very Fe-poor (Fig. 6). This excludes equilibration or diffusion process *in situ* after agglomeration of the meteoroid rock. Thus, the models all refer to pre-agglomeration processes that may have taken place either in the solar nebula or on the surface of a parent body:

Model 1: Chondrules and fragments have a separate origin and no genetic relation.

Model 2: Chondrules are the primary material; they are mechanically transformed into fragments and at the same time enriched in FeO.

Model 3: Chondrules are secondary, they are formed from FeO-rich rocks (now found as fragments); FeO is lost during chondrule formation by reduction to metal. The mechanism may be impact melting, as proposed by many authors (e.g., Urey, 1956; Fredriksson *et al.*, 1969; Dodd, 1971).

The following discussion will try to find arguments for or against one of these models:

In Model 1 chondrules and fragments could be formed by the same process, but at different times. Fragments should then be older than chondrules, thus having a higher chance of being fragmented before agglomeration or regolith consolidation. In most condensation scenarios (e.g., Wood, 1962; Grossman and Larimer, 1974), the opposite age sequence is produced, with Fe-free silicates condensing first.

Model 2 seems more appealing. The sequence—chondrules with clear glass–with devitrified glass–irregular chondrules–fragments—seems to be an evolutionary sequence; it agrees in the first two steps with the petrologic sequence by Van Schmus and Wood (1967). The envisioned sequence would be: (1) formation of chondrules from rapidly quenched melt droplets, resulting in silicate crystals in a supercooled residual melt, i.e., glass; (2) devitrification of the glass by mild thermal treatment; and (3) mechanical abrasion to form irregular chondrules and finally fragments. During all steps an enrichment with FeO takes place from the environment, be it a gas or a parent body surface. The fragmentation seems easier to achieve in a parent body regolith: the FeO source may be the Fe-rich fine-grained material, now present as the black matrix. Degree of alteration and FeO content will correlate, because both are acquired with time. This model would also satisfy the statistical nature of this correlation, as time can, but does not have to lead to fragmentation. This model has some similarity with the metamorphism model of Wood (1962); however, that model assumed an *in situ* equilibration between matrix and chondrules, whereas here the FeO enrichment takes place before agglomeration.

The first step in Model 2, namely the relation between chondrules with clear igneous glass and chondrules with devitrified glass, can be tested by a comparison of their bulk compositions. Figure 9 shows for Sharps that they are different in their Ca, Al-relations. Most of the glass-containing

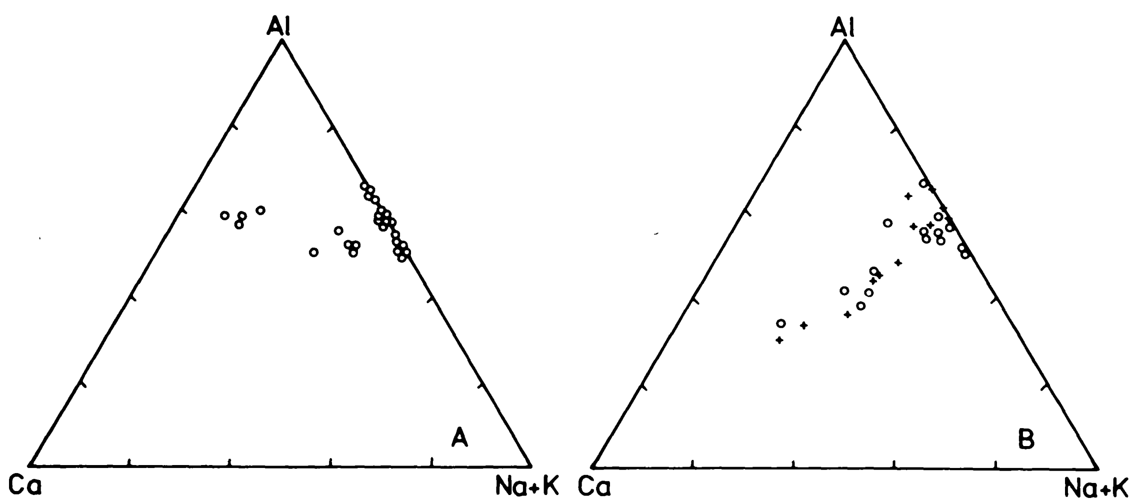

Fig. 11 Three-component plot for mesostases from Sharps (in wt.% of oxides). **(a)** clear glass; **(b)** devitrified glass in chondrules (o) and fragments (+).

chondrules are strongly depleted in Ca and their Ca/Al ratios are below the cosmic or primary ratio. Thus, they are probably not primitive in this sense, although they may be primitive in the petrologic sense.

This difference in bulk composition is also visible in the composition of the mesostases themselves. Figure 11 shows that in Sharps the glasses plot differently from the devitrified mesostases, and most of them are very Ca-poor. The higher Ca content of the devitrified glasses is probably due to the finely exsolved diopside, which is included in the analysis. The linear array of analysis points towards the Ca corner suggests this in Fig. 11, apparently a mixing line. A similar difference in composition between clear glasses and other mesostases was also noted for Tieschitz chondrules by Kurat (1971).

The compositional differences between chondrules with clear glass and chondrules with devitrified glass is the opposite of what one would expect from a condensation model. The more primitive, glass-containing chondrules should have cosmic Ca/Al ratios, whereas in the devitrified chondrules this ratio may have been changed by secondary processes during recrystallization. On the other hand, the low FeO content of the glass-containing chondrules could be in agreement with a primary origin, as the first condensing silicates should be Fe-poor (Wood, 1962; Grossman and Larimer, 1974).

An argument in favor of Model 2 is the reported radial increase in FeO toward the outside of several chondrules in Sharps (Dodd, 1971). Within several cases in this study, this increase was also found in Tieschitz chondrules and fragments. There is also the correlation between FeO content and size shown in Fig. 6. Both argue for a secondary FeO-enrichment from the outside. These observations are not clear and consistent enough, however, to make this argument very strong.

A difference in Ca-content of olivines from different chondrule types was reported by Dodd (1971) for Sharps and was used as an argument for different thermal histories. Such a difference could not be found here for chondrules and fragments in Tieschitz (Table 4). The data scatter too much for any firm conclusions to be drawn; better Ca measurements with a lower limit of detection may change this situation.

Table 4. Minor elements in Tieschitz olivine in wt.%.

		Chondrules		Fragments
CaO	(26)*	0.14 ± 0.07	(6)	0.16 ± 0.05
	(68)	<0.05	(30)	<0.05
MnO	(96)	0.22 ± 0.2	(36)	0.33 ± 0.2
FeO	(96)	13.0 ± 9	(36)	22.0 ± 9
Fe/Mn	ave.	59		68
Fe/Mn center of grains	(33)	48 ± 22	(17)	57 ± 27
Fe/Mn rim of grains	(21)	62 ± 28	(14)	80 ± 23

*Number of grains analyzed.

Model 3 implies the reduction of FeO during chondrule formation. The behavior of Mn may give a clue to this process. During reduction MnO would remain constant and the FeO/MnO ratio should decrease. An example of this is the relations in silicate inclusions of the Campo del Cielo iron meteorite. Here, reduction has caused the low FeO content of the olivines, e.g., 4.0% FeO in one inclusion, MnO has remained constant, 0.33%, resulting in the low Fe/Mn ratio of 12.1 (Wlotzka and Jarosewich, 1977). A normal chondritic Fe/Mn ratio is 42 as measured, for example, in olivines from the H5-chondrite Morro do Rocio (Wlotzka and Fredriksson, 1980 and unpublished data). No such difference is visible in Tieschitz chondrules compared to fragments. The average Fe/Mn ratios are similar and not far from the chondritic value mentioned above (Table 4). However, the individual Fe/Mn ratios vary widely; the range observed for olivines from chondrules is 9 to 125, from fragments 32 to 129. Often Mn varies in a crystal independently from Fe, but on the average crystal rims have a higher Fe/Mn ratio than the centers. Both values are slightly higher in the fragment than in the chondrule olivines (Table 4). The pyroxenes from Tieschitz have lower Fe/Mn than the olivines: the range is 1 to 27, and the average (10 values) is 14.6 ± 8. This olivine-pyroxene relation is the same as found for uniform chondrites (and terrestrial rocks); in Morro do Rocio the orthopyroxenes have an Fe/Mn of 23.6. Thus the Fe/Mn relations in Tieschitz do not seem to support a reduction model for chondrule formation, or at least not as a straightforward, simple mechanism.

b.) Black rims, white matrix, and Na,K-relations

The black rims are high in Fe: 27.3 ± 3.7% in Tieschitz, and 29.9 ± 3.1% in Sharps, which is remarkably close to the average total iron of H-chondrites (27.6%, see Table 3). The standard deviation of the mean for the 20 analyses for Tieschitz is small enough to allow a distinction from the average total iron of L-chondrites, 21.7% (Wlotzka and Jarosewich, 1977), although the field of the data points in Fig. 12 comes close to the L-chondrite composition point. This similarity, although not as close, also extends to other elements such as Si, P, Ca, Mn, and Cr; exceptions are Ni and S, which are depleted. The oxidation state of Fe in these rims is not known. Some of it may be metallic iron (minute metal particles being occasionally visible), but most of it is probably oxidized; Wood (1962) determined 30% magnetite in Tieschitz matrix. The actual microprobe analyses give totals of only 85 to 90%; the rest may be accounted for by porosity, water, and carbon. If all bulk C (0.1%, Hutchison *et al.*, 1981; 0.25%, Moore and Lewis, 1967) is assumed to reside in the black rims of Tieschitz (about 9 wt.% of the bulk, see below), a C-content of 1.1 to 2.8% can be calculated. This similarity in many elements agrees with the interpretation that the black rims may be a primary condensate, the low temperature matrix invoked by Wood (1962) and Anders (1964) as the carrier of volatile elements in ordinary chondrites.

In Tieschitz, the black rims are enriched in Al, Na, and K compared to H-chondrites. This can only partly be explained by infiltration by the alkali-rich white matrix (see Table 3) because the Na/K ratio of 7.7 in the rims is much lower than in the white matrix, 24.8, and close to the chondritic ratio of about 8. Furthermore, we find the same enrichment in the matrix of C1-chondrites (McSween and Richardson, 1977; also see Table 5). On the other hand, the black rims of Sharps, where no white matrix is found, are not enriched in Al and Na, only in K. The common feature of both meteorites is a higher K/Na ratio in the black rims than is found in the bulk meteorite (Tieschitz: 2.8 times; Sharps: 3.3 times), which would point to a K-enrichment process in these rims. It might be the formation of a K-rich sheet silicate, as it was found by Fredriksson *et al.* (1979) in the matrix of Bjurböle. A similar high K_2O content (0.28 K_2O, K/Na = 2.1 times chondritic) was found by Hoinkes *et al.* (1976) in black matrix rims in the L3-host of Dubrovnik.

As Fig. 5 shows, most chondrule and fragment mesostases in Tieschitz have very low K-contents and low K/Na ratios. Also, bulk Tieschitz seems to be inhomogeneous in Na and K, as the two analyses (Fig. 5 and Table 6) show. Minster and Allègre (1979) also noticed an inhomogeneity in Tieschitz with respect to Rb and Sr on a 0.5 g scale. The data obtained here for Na and K on a thin section agree better with the analysis by Wiik (see Fig. 5). The fractionation of Na from K cannot be a primary feature, as both condense at the same temperature (Fegley and Lewis, 1980). A redistribution of Na and K may have occurred through volatilization and recondensation during chondrule formation (see Kurat, 1971) or later high-temperature stages. Leaching may also have affected these elements (Kurat, 1969; Christophe Michel-Lévy, 1976). A similar K-depletion relative to Na was found in terrestrial impact "chondrules" from the Ries Crater (Graup, 1981). There is no systematic trend in the Na,K-contents and ratios between chondrules and fragments that would suggest different thermal histories. Tieschitz and Sharps behave in different ways: in the former, most mesostases are depleted in K and have high Na/K ratios, whereas in the latter, many are enriched in K (see Fig. 5) and the average Na/K ratios are low (Table 3).

This difference may be related to the occurrence of a white matrix in Tieschitz, but not in Sharps. This white matrix is rich in Al, Na, and K (Table 3) and its norm contains 50% albite and 25% nepheline. Christophe Michel-Lévy (1976) interpreted it as a hydrothermal deposit formed by leaching of the chondrules, whereas Hutchison *et al.* (1979) think of it as a liquid melt squeezed out of the chondrules during hot accretion. Its composition is indeed close to the average composition of the fragment and chondrule mesostases, as shown in Fig. 2.

A third possibility for the origin of the white matrix may be shock lithification, which may also have caused the tight-fitting texture of fragments and chondrules (Fig. 7). Allen *et al.* (1982)

Table 5. Element ratios (weight).

	Na/Si	K/Si	Al/Si	Ca/Si	Fe/Si
Tieschitz, black rims	0.106	0.015	0.116	0.047	1.56
Average H-chondrite (1)	0.036	0.005	0.065	0.073	1.61
C 1 matrix (2)	0.098	0.010	0.099	0.101	1.72

(1) See Wlotzka and Jarosewich (1977).
(2) See McSween and Richardson (1977).

have shown that rock powders shocked above 200 kbar develop an intergranular feldspar film, which transforms it into solid rock. According to Christophe Michel-Lévy (1976) and Ashworth (1980), however, no indications for post-accretionary shock were found in Tieschitz.

c.) Bulk composition and classification

Modal analysis of a thin section of Tieschitz (1750 points counted) gave the following composition: 74.8% silicates, 9.1% black rims, 2.5% white matrix, 9.5% metal, and 4.1% troilite (by weight). For this calculation the following densities were used: silicates 3.3, black rims 3, white matrix 2.6, metal 7.7, and troilite 4.7 (g/cm^3). The metal value confirms the low metal contents which were found by Wiik, 9.9% (see Dodd *et al.*, 1967), and by Hutchison *et al.* (1981), 12.6%, and which are below the range of equilibrated chondrites of the H-group: 16 to 20%, ave. 18.6% metal (Mason, 1965). Another integration gave the ratio 72% fragments to 28% chondrules by volume for Tieschitz, which was assumed to be the same ratio by weight. From these values the contribution of the different components to the bulk silicate composition of Tieschitz was calculated (Table 6). It shows that the black matrix contributes 24% of the total FeO. The summation to the bulk silicate composition agrees well with the two available chemical analyses, except that Al and Na are too high. This may result from sample inhomogeneity, as Na is also different in the two chemical analyses. But most of the discrepancy is probably due to the combined errors of the broad-beam microprobe technique and the point-counting.

It can be seen from Table 6 that chondrules plus fragments alone have an FeO/(FeO + MgO) ratio of 19.9 mol.%, which is near the average of the H-group [18.6 mol.% (Mason, 1965)],

Table 6. Bulk silicate composition of Tieschitz (in wt.%).

	(1) Chondrules + fragments	(2) Black matrix	(3) White matrix	(4) Bulk, 1 + 2 + 3	(5) Chemical analyses	(6)
SiO_2	40.0	4.16	1.72	45.9	47.4	44.3
Al_2O_3	3.19	0.43	0.59	4.21	3.11	2.89
FeO	12.2	3.98	0.15	16.3	16.7	21.1
MgO	28.1	2.00	0.09	30.2	30.1	28.6
CaO	1.47	0.15	0.08	1.70	2.20	1.94
Na_2O	1.07	0.28	0.37	1.72	0.43	1.14
Total	86.0	11.0	3.0	100	100	100
Fe/(Fe + Mg) mol. %	19.9	51.3	46.2	23.2	23.7	29.3

This table compares the bulk silicate composition (4) calculated from a summation of the components (1,2,3) with bulk chemical analyses (5,6 recalculated for the silicate portion). The abundance of the components was determined by point counting: 86 wt.% chondrules + fragments, 11 wt.% black matrix, 3 wt.% white matrix. It shows the large FeO contribution from the black matrix to total FeO. (5) is from Hutchison *et al.* (1981), (6) is from Dodd *et al.* (1967).

whereas the silicates plus matrix have FeO/(FeO + MgO) of 23.2 mol.% in the L-group range [ave. 25.0 mol.% (Wlotzka and Jarosewich, 1977)].

It was hoped to find a population of equilibrated chondrules or fragments in these chondrites that might correspond in their FeO/(FeO + MgO) ratio to either the H-, L-, or LL-group. A hint of such a component was found by Dodd (1968), who reported three equilibrated chondrules in Sharps (out of 25 analyzed) with homogeneous olivines of Fa 27–29, which would correspond to the LL-group. In this work no such component was found. Equilibrated chondrules and fragments with homogeneous olivines and/or pyroxenes of constant composition throughout do occur in both meteorites. But their Fe/(Fe + Mg) ratios range from 0 to 40 mol.% and no preferred compositions are present. Chondrule olivines again show lower mean Fa contents than fragment olivines.

A good argument for a relation of Tieschitz and Sharps to the H-group is the close similarity of the Fe-content of their black matrices to the average composition of H-chondrites, as discussed above. It would be interesting to see whether black matrix rims in L-group UOC's are also close to the average L-group composition and can be distinguished from the black matrix of Tieschitz and Sharps. The work of Huss *et al.* (1981) gives no indication for such a relation. However, Hoinkes *et al.* (1976) report black matrix rims around some chondrules in the L3-host of the L-chondrite Dubrovnik that have a bulk composition and Fe content (21.0% Fe) similar to the bulk composition and total iron of L-chondrites, 21.7% Fe (Wlotzka and Jarosewich, 1977). This relation between bulk and matrix composition would have consequences for determining the time of iron-silicate fractionation between the chondrite iron groups (see also Clayton *et al.*, 1981).

Thus the only clues found here for the classification of Tieschitz and Sharps into the H-group are their content of total iron and the composition of the black matrix. An additional argument for other type 3 chondrites was found in the content of siderophile trace elements by Sears (1982). However, for Tieschitz, the trace element content of the metal would place it in the L-group (see Rambaldi, 1977).

The two models proposed above for the genetic relations between chondrules, fragments, and matrix would lead to different results. If in Model 2 all chondrules were transformed into fragments and enriched in FeO (coming from the matrix), the resulting FeO/(FeO + MgO) ratio would be that of an L-chondrite. Some metal would then have to be lost from the system to bring total iron down into the L-group range. If in Model 3 chondrule formation with reduction moved the bulk composition towards lower FeO and higher metal contents, a normal H-chondrite composition may result. Because this H-chondrite classification is already inferred by total iron and matrix composition, Model 3 gets some support from this point of view. It is still not clear, however, whether such a genetic relationship between the unequilibrated chondrites and the higher petrologic types exists (see Wlotzka, 1981).

An oxidation-reduction relation between chondrules, fragments, and matrix is indicated by the FeO-SiO_2-MgO plots of Fig. 12 (these oxides account for more than 90% of the silicate portion of these meteorites). For both Tieschitz and Sharps, mixing lines can be drawn connecting the points of these three components, indicating addition or subtraction of iron. The direction of the

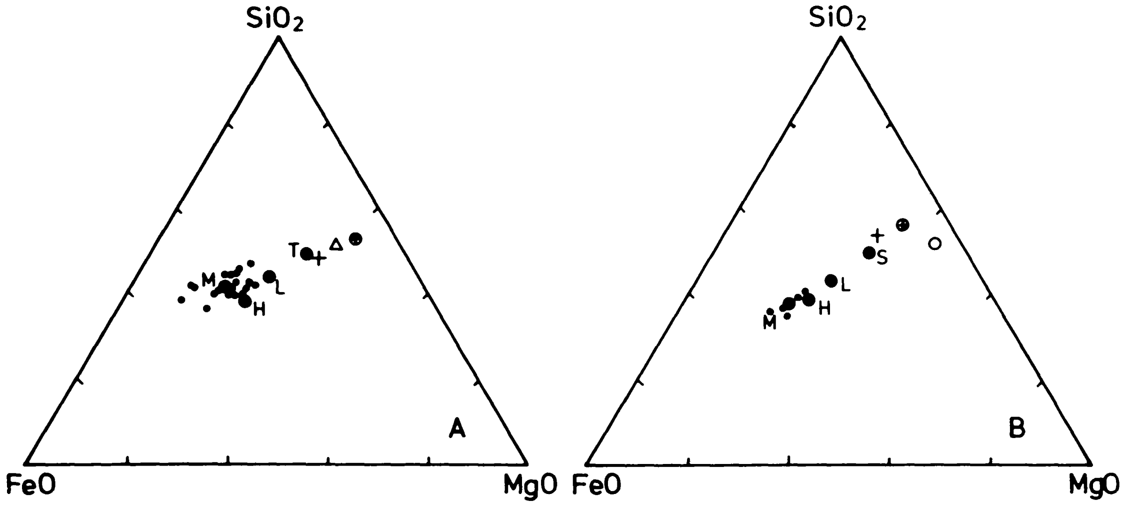

Fig. 12 Three-component plot (in wt.%) for mean compositions of chondrules with clear glass (o); chondrules with devitrified glass (⊕); irregular chondrules (Δ); and fragments (+), for Tieschitz **(a)** and Sharps **(b)**. M: black rims, average; small dots are single broad-beam analyses. H, L: average composition of H- and L-chondrites, respectively, with total iron as FeO (from Wlotzka and Jarosewich, 1977). T: bulk silicate of Tieschitz (from Hutchison *et al.*, 1981). S: bulk silicate of Sharps (from Fredriksson *et al.*, 1969).

iron movement is not known, of course. Figure 12 also shows that the average composition of the fragments is closer to the bulk composition of the meteorites than are the chondrules.

4. CONCLUSIONS

The results presented essentially confirm the findings by Dodd (1971) that shape and FeO-content of chondrules are correlated. Tieschitz and Sharps contain different populations of chondrules and fragments, which can be distinguished by their average FeO content and Fe/(Fe + Mg) ratios. There is also a small population of Ca, Al, Ti-rich chondrules, which are mineralogically distinct. The differences in average FeO among the various components were established before agglomeration of the meteorite. The most appealing model assumes a genetic relation between chondrules and fragments: Chondrules are the primary material; they are mechanically transformed into fragments and at the same time enriched in FeO. The FeO source may be the black matrix material. Indications for this relation are: the FeO-size relation, the radial enrichment of FeO in some chondrules and fragments, and the Fe/Mn relations.

The opposite relation, chondrules being formed from the fragment material by impact and reduction, also seems possible, although no direct indications for such a process were found. This process, however, may be able to transform UOC's like Tieschitz and Sharps into chondrites of normal H-group composition. A relation to the H-group is also indicated by the close similarity between the black matrix and the average H-group chondrite in bulk composition and, more importantly, total Fe content. If this black matrix is a primitive component, this would imply a metal-silicate fractionation between the H- and L-groups at a very early stage of chondrite evolution.

All components in Tieschitz and Sharps show secondary alterations, mainly visible in the Na,K-relations. These occurred either before or during the formation of the white matrix (in Tieschitz), which was deposited after accretion of the parent body.

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