Proc. NIPR Symp. Antarct. Meteorites, **4**, 226–246, 1991

MINERALOGY AND PETROGRAPHY OF THE ANOMALOUS CARBONACEOUS CHONDRITES YAMATO-86720, YAMATO-82162, AND BELGICA-7904

A. BISCHOFF and K. METZLER

Institute of Planetology, University of Münster, Wilhelm-Klemm-Str. 10, 4400 Münster, F. R. of Germany

Abstract: As a part of the consortium study on antarctic meteorites with affinities to CI-chondrites we studied the samples of Yamato (Y)-86720, Y-82162, and Belgica (B)-7904. These carbonaceous chondrites are unique samples and do not perfectly fit in the traditional classification schemes. Therefore, they have to be considered as very important samples to carry distinct information about processes in the early solar system.

Y-82162 is a very fine-grained carbonaceous chondrite. Based on the occurrence of abundant clasts (up to several mm in size) we suggest that this sample is a chondritic breccia. The dominating phases are phyllosilicates; abundant sulfide grains are scattered throughout the entire sample. However, the abundances of sulfides vary from clast to clast. Y-86720 contains about 13 vol% of light objects embedded in a fine-grained, phyllosilicate-rich groundmass. Some of these objects appear to be relict chondrules; however, they essentially consist of phyllosilicates. Most light, round to irregularly-shaped components exhibit well-preserved accretionary dust mantles ("dark rims") similar to those found in CM-chondrites. Y-86720 is mineralogically more closely related to the CI-chondrites than to any other chondrite group; texturally, however, it appears to be an intermediate chondrite between CI and CM as also suggested by bulk chemical criteria (G. W. KALLEMEYN; Papers Presented to the 13th symposium on Antarctic Meteorites, June 7–9, 1988, Tokyo, NIPR, 132, 1988). B-7904 contains 18 vol% of objects larger than about 70 μm in size. 42 vol% of these components are chondrules or chondrule fragments. The most abundant constituents are, however, olivine-bearing, fragment-like objects (45.9 vol%) unknown from other chondrites. The olivines within these components are embedded in a fine-grained brownish-grey matrix. Other constituents include fine-grained CAIs, olivine aggregates, and mineral fragments. B-7904 is a new kind of carbonaceous chondrite and we do not like to classify this meteorite as a CM-type chondrite because of the following reasons: a) A great number of chondrules in B-7904 is much larger (0.5–3 mm) than measured for the mean size of chondrules in CM-chondrites (0.3 mm). b) Many components (olivine-bearing, fragment-like objects, Cr, Al-rich fine-grained particles) are unknown from CM-chondrites. c) The oxygen isotope composition and the low H_2O-contents are untypical for CM-chondrites.

1. Introduction

Carbonaceous chondrites are the most important source of information about processes in the early solar system. Many carbonaceous chondrites are, however, regarded as having been affected by secondary alteration processes. This is especially the case for the CI- and CM-chondrites. The carbonaceous chondrites Yamato

(Y)-86720, Y-82162 and Belgica (B)-7904 are unique samples that do not fit in the traditional classification schemes (*e.g.* ZOLENSKY *et al.*, 1989a; SKIRIUS *et al.*, 1986; KALLEMEYN, 1988; TOMEOKA *et al.*, 1988a, b; TOMEOKA, 1989; STEELE *et al.*, 1984). Based on the oxygen isotopic composition all three meteorites were classified as CI-chondrites (MAYEDA *et al.*, 1987; CLAYTON and MAYEDA, 1989; MAYEDA and CLAYTON, 1990). B-7904, however, is chemically and petrologically a CM (C2)-chondrite (*e.g.* SKIRIUS *et al.*, 1986; YANAI and KOJIMA, 1987; AKAI, 1988; KALLEMEYN, 1988). Based on the petrology, mineralogy, and chemistry Y-86720 has been classified as a CM or an intermediate chondrite between CI and CM (*e.g.* KALLEMEYN, 1988; TOMEOKA *et al.*, 1988b; EBIHARA and SHINONAGA, 1989). Y-82162 is classified by most authors as a CI-chondrite (*e.g.* KALLEMEYN, 1988; TOMEOKA *et al.*, 1988a; WATANABE *et al.*, 1988; YAMAMOTO and NAKAMURA, 1989; ZOLENSKY *et al.*, 1989a).

Several authors suggested that these three chondrites experienced significant thermal metamorphism (*e.g.* AKAI, 1988, 1989, 1990; TOMEOKA, 1989; PAUL and LIPSCHUTZ, 1989). These circumstances make it even more difficult to classify the three meteorites using the traditional classification schemes.

In this study we present detailed mineralogical and chemical data on B-7904 and limited, but interesting data on Y-82162 and Y-86720. Our main aim was to determine the abundances of individual components of these meteorites and to characterize these constituents chemically and mineralogically.

2. Analytical Techniques

We have studied polished thin sections of the three carbonaceous chondrites in transmitted and reflected light with a Zeiss polarizing microscope in combination with a Zeiss Mop Videoplan.

The fine-grained textures of these chondrites were resolved with a Jeol 840 A scanning electron microscope (SEM) equipped with an LZ-5 detector for energy dispersive analysis (EDS). Quantitative analyses were obtained by the EDS (Link AN10000). Appropriate mineral standards were taken at an excitation voltage of 20 kV and the beam current constancy was always controlled by a Faraday cup. Usual ZAF-corrections were applied.

Most bulk compositions of the accretionary dust mantles were obtained with an ARL-SEMQ-51 electron microprobe operating at 15 kV and a sample current of about 20 nA. The compositions were measured using a broad (15–60 μm) electron beam. Matrix corrections were made according to BENCE and ALBEE (1968).

3. Mineralogy and Petrography

3.1. Yamato-82162

Y-82162 is a very fine-grained carbonaceous chondrite. However, the sample is not homogeneous. Large, mm-sized, fragment-like objects are visible (Fig. 1). It appears that many of these clasts are poorer in Fe than the surroundings; however, also some sulfide-rich fragments were observed. Y-82162 contains abundant small objects (usually <300 μm in size) that were described as coarse-grained phyllosilicate-

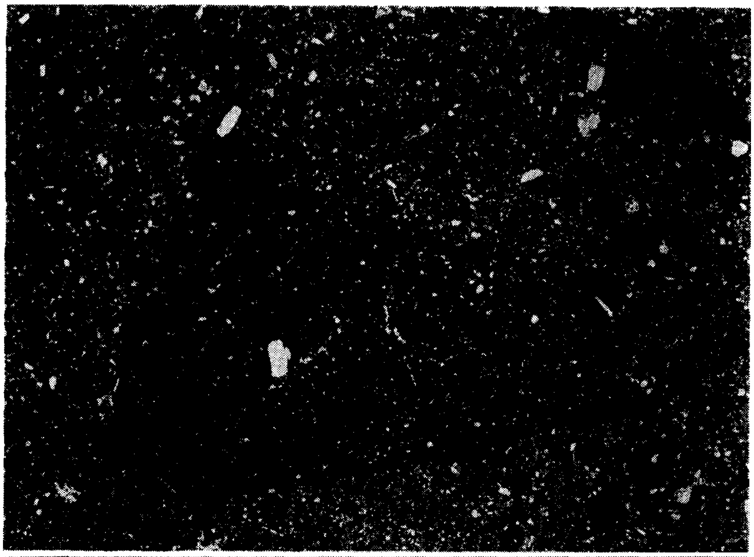


Fig. 1. Large, 1 mm-sized fragment-like object containing a large sulfide grain (white) within Y-82162. Based on the dark appearence it seems to be poorer in Fe than the surroundings. Back-scattered electron photomicrograph.

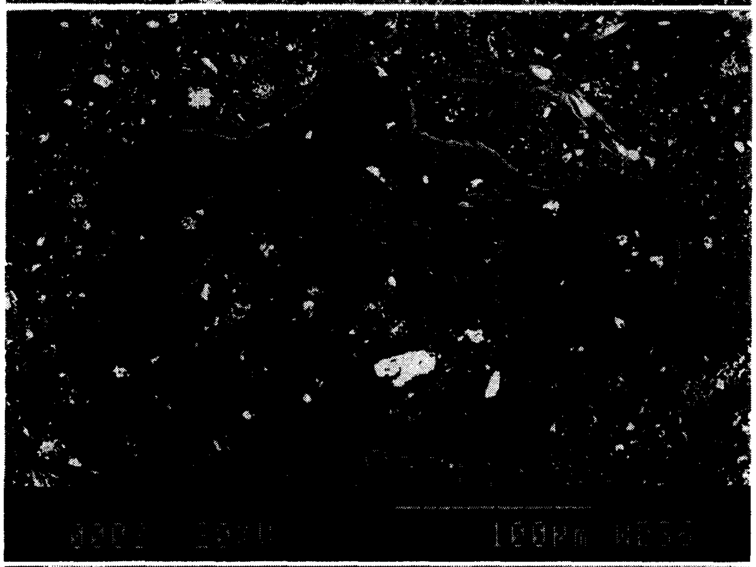


Fig. 2. Coarse-grained, phyllosilicate-rich cluster containing some sulfides within Y-82162; back-scattered electron photomicrograph.

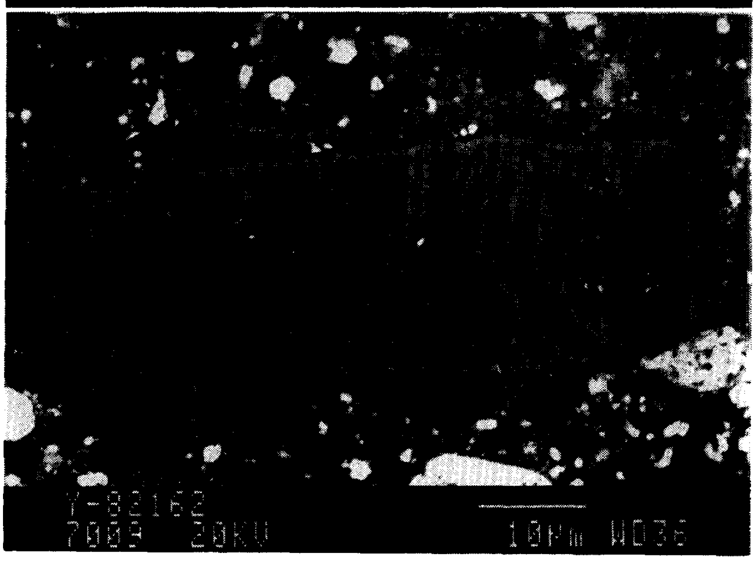


Fig. 3. Phyllosilicate-rich fragment-like object within Y-82162 (see Table 1 for the bulk composition); back-scattered electron photomicrograph.

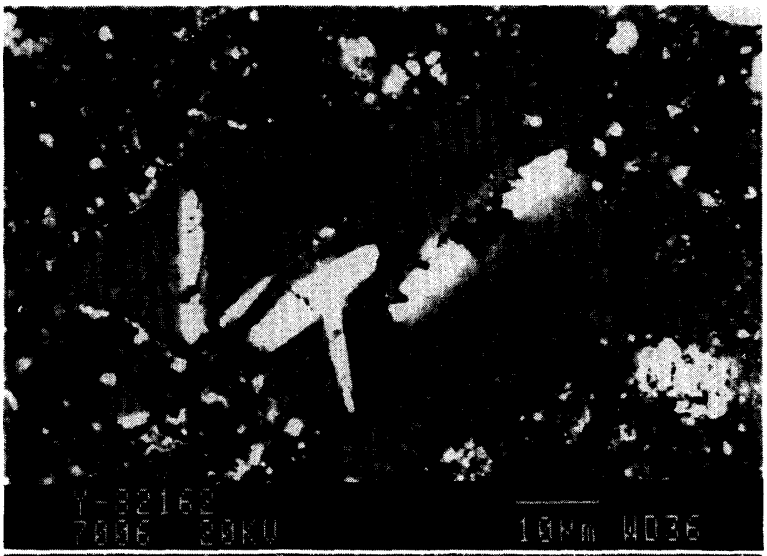


Fig. 4. Intergrowth of sulfides within a phyllosilicate-rich cluster (Y-82162). The intergrowths appears to be a relic of a primary igneous texture. Back-scattered electron photomicrograph.

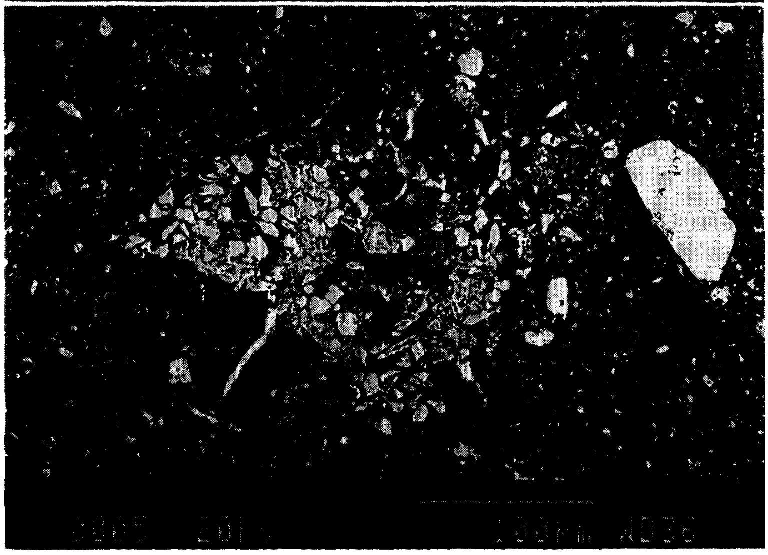


Fig. 5. Fragment-like aggregate basically consisting of magnetites (white) and phosphates (grey). Note, that magnetites with different morphologies occur within this aggregate (Y-82162). A large sulfide grain is visible on the right-hand side. Electron photomicrograph (SE).

clusters with irregular shapes (WATANABE *et al.*, 1988). Two of these constituents are shown in Figs. 2 and 3. In some of these phyllosilicate-rich objects intergrowths of sulfides exist, that could be relics of a primary igneous texture (Fig. 4). Other fragment-like objects include aggregates of phosphates and magnetites (Fig. 5), relics of chondrule-like and CAI-like components and various minerals (see below). Based on similar observations ZOLENSKY *et al.* (1989a) stated that Y-82162 is a breccia. The abundant fractures within the sample are usually free of secondary products.

The most abundant phases in Y-82162 are phyllosilicates. As reported earlier, two principal phyllosilicates are present, serpentine and saponite (TOMEOKA *et al.*, 1988a; ZOLENSKY *et al.*, 1989a). The bulk composition of a phyllosilicate-rich cluster is listed in Table 1 (compare Fig. 3). Abundant sulfide grains are scattered throughout the entire sample. However, the abundance of sulfides varies from clast to clast. Two different varieties of sulfides exist. Most of the larger grains (up to $\sim$300 μm in length) are euhedral, whereas the majority of the small sulfides are anhedral in morphology. ZOLENSKY *et al.* (1989a) have identified both pyrrhotite

Table 1. Compositions of various constituents from the Y-82162 carbonaceous chondrite.

	1	2	3	4	5	6	7
Na_2O	1.53	2.28	—	—	—	—	—
MgO	22.2	19.7	5.1	—	—	—	—
Al_2O_3	2.92	3.7	14.2	—	—	—	—
SiO_2	31.2	40.7	<0.22	—	—	—	—
S	10.6	0.61	<0.09	34.7	37.1	36.4	—
K_2O	<0.11	0.28	n. d.	—	—	—	—
CaO	<0.21	<0.16	<0.02	—	—	—	—
TiO_2	n. d.	<0.16	0.76	—	n. d.	n. d.	n. d.
Cr_2O_3	0.79	0.28	49.9	n. d.	n. d.	<0.26	<0.02
MnO	n. d.	n. d.	0.50	<0.09	n. d.	n. d.	<0.06
Fe	23.5	10.4*	28.4*	56.4	64.4	62.0	34.4
Co	—	—	—	0.35	<0.06	<0.05	2.42
Ni	<0.18	<0.05	<0.20	9.2	<0.12	<0.25	63.2
Total	93.24	78.32	99.39	100.74	101.68	98.96	100.10

1: Bulk composition of a phyllosilicate-rich cluster containing an intergrowth of sulfides; 2: Bulk composition of the phyllosilicate-rich cluster shown in Fig. 3; 3: Cr-spinel; 4–6: Sulfides; 7: a tiny metal grain (≈ 3 μm).
Data in wt%.
*All Fe as FeO.
n. d.: not detected.
—: not analysed.

and troilite. One single pentlandite-grain was found within Y-82162. Based on a study of TOMEOKA *et al.* (1988a), the sulfides constitute ~10 vol% of the meteorite and are much more abundant than magnetite (~0.5 vol%). Some typical analyses are listed in Table 1. All metals analysed are rich in Ni (~63–66 wt%; compare Table 1) and occur occasionally intergrown with sulfides. As reported earlier (TOMEOKA *et al.*, 1988a; ZOLENSKY *et al.*, 1989a), magnetite is a common component that occurs as isolated grains within the matrix and as aggregates of euhedral to subhedral crystals. They are sometimes intergrown with phosphates (Fig. 5). Most of the magnetites are smaller than 25 μm. As shown in Fig. 5 magnetites with different morphologies are visible within the same aggregate (compare ZOLENSKY *et al.*, 1989a). The phosphates are usually < 10 μm in size; however, some large fragment-like grains of about 30 μm were found in the matrix. Olivines exist as a minor component of the matrix. KOJIMA and YANAI (1987) and ZOLENSKY *et al.* (1989a) also reported the occurrence of small olivines (Fo_{74}, on average) within Y-82162. The presence of orthopyroxene was pointed out by WATANABE *et al.* (1988). In our study we identified a Cr-spinel (Table 1). Carbonates have been observed within carbonate-rich clusters.

3.2. *Yamato-86720*

Based on an optical investigation with a polarizing microscope, Y-86720 contains abundant light-coloured objects embedded in a fine-grained, phyllosilicate-rich groundmass. In reflected light a great number of large (~400 μm in size) sulfide laths is obvious. We have determined the frequency distribution of various com-

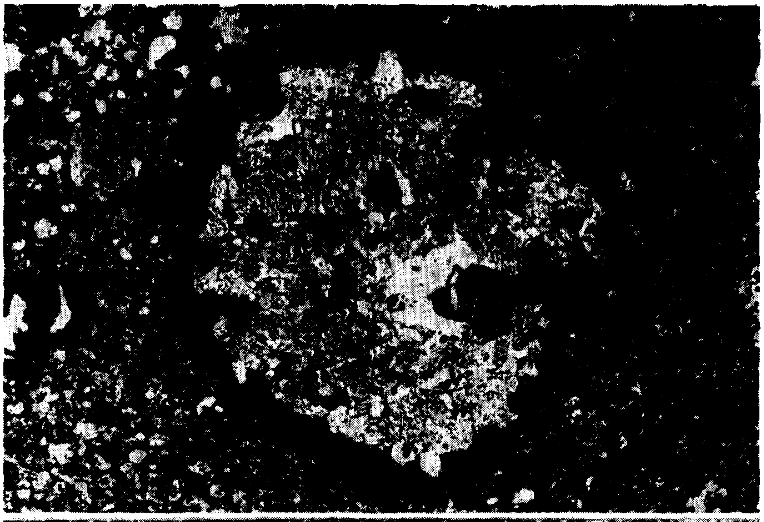


Fig. 6. Almost spherical phyllosilicate-rich object (~1 mm in apparent diameter) within Y-86720; note the well-preserved, dark accretionary dust mantle; photograph in transmitted light.

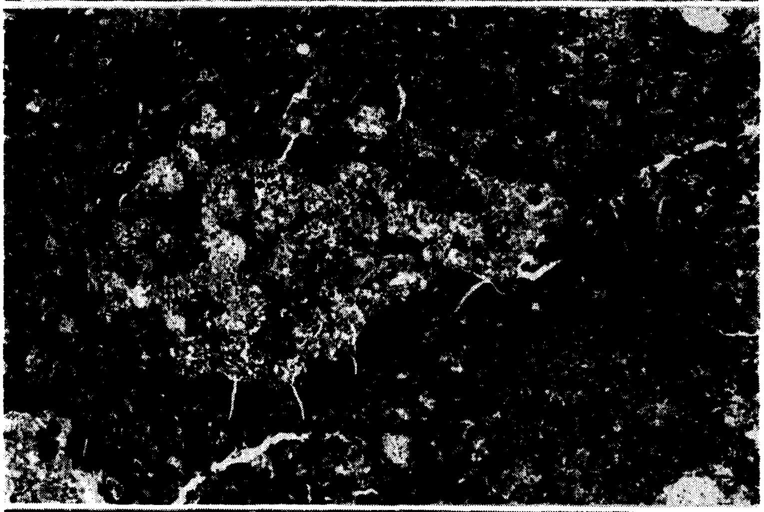


Fig. 7. Irregularly-shaped, phyllosilicate-rich object (~1.5 mm in largest dimension) with a dark dust mantle in Y-86720. On the right-hand side a large sulfide lath is visible; photograph in transmitted light.

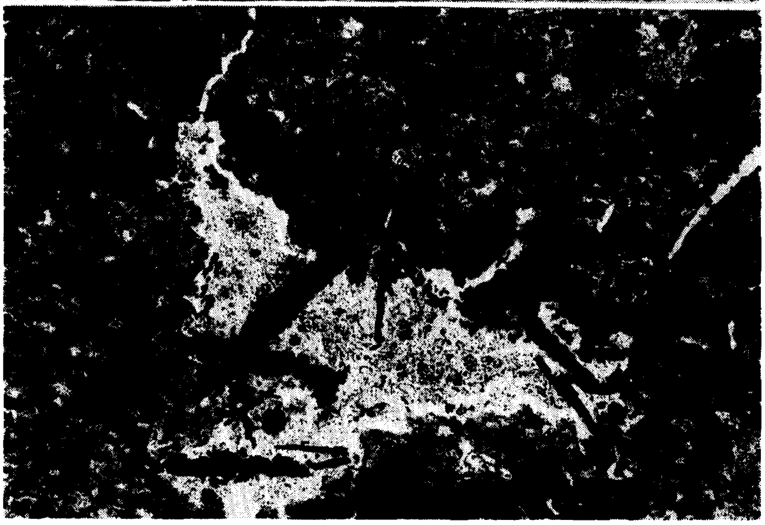


Fig. 8. Fragment-like, phyllosilicate-rich component in Y-86720 containing an intergrowth of sulfide-laths (black); the object is about 500 μm in the largest dimension; photograph in transmitted light.

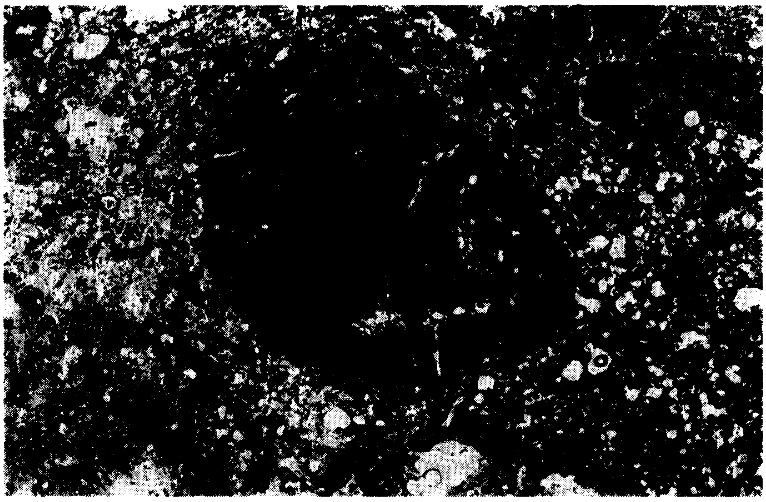


Fig. 9. Millimeter-sized, sulfide-rich almost opaque object with an accretionary dust mantle within Y-86720; photograph in transmitted light.

Table 2. Composition of unknown phases or components within phyllosilicate-rich clusters of Y-86720.

Na_2O	1.22	0.71	2.89	3.1	1.11	1.17	1.66	1.05
MgO	22.0	22.1	21.2	20.3	32.1	33.4	26.0	25.6
Al_2O_3	3.0	3.1	19.8	20.7	3.2	3.6	5.3	5.2
SiO_2	33.5	34.2	35.2	35.8	48.8	48.9	40.0	38.4
P_2O_5	—	—	<0.13	<0.04	—	—	—	—
SO_3	2.04	2.23	0.57	0.70	<0.08	0.34	0.54	0.28
K_2O	<0.02	<0.02	<0.15	0.20	<0.03	<0.11	0.35	0.25
CaO	29.0	28.3	—	<0.02	0.28	<0.06	2.51	2.55
TiO_2	—	—	<0.12	0.31	<0.04	—	<0.15	<0.12
Cr_2O_3	0.23	0.49	0.58	0.63	1.61	1.88	2.61	2.72
MnO	1.79	1.50	<0.09	<0.13	<0.10	<0.19	0.36	0.22
FeO	5.6	5.5	16.4	16.8	11.2	10.8	18.5	18.8
NiO	—	0.40	<0.09	<0.02	<0.03	—	<0.17	0.25
Total	98.40	98.55	97.22	98.75	98.58	100.45	98.15	95.44

All data in wt%.
—: not detected.

ponents larger than about 100 μm in size. 528 mineral and lithic objects from an area of about 134 mm^2 were analysed (BISCHOFF and METZLER, 1990a). The chondrite contains 14.35 vol% of components larger than ~100 μm. Most abundant are rounded (Fig. 6) to irregularly-shaped (Fig. 7), phyllosilicate-rich objects (9.42 vol%). The round components appear to be relic chondrules (see also ZOLENSKY *et al.*, 1989b). Many phyllosilicate-rich objects also contain sulfide laths (3.55 vol%; Fig. 8). Sulfide-rich, almost opaque aggregates (Fig. 9) and sulfide mineral grains constitute 0.57 and 0.81 vol%, respectively. ZOLENSKY *et al.* (1989b) reported that relic chondrules and most lithic fragments are composed predominantly of phyllosilicates.

We have analysed various phases within these light-coloured, phyllosilicate-rich objects that appeared homogeneous in the back-scattered electron image. Based on the oxide totals of about 100 wt%, some grains cannot contain significant contents of H_2O. The compositions of several unknown phases are listed in Table 2: All

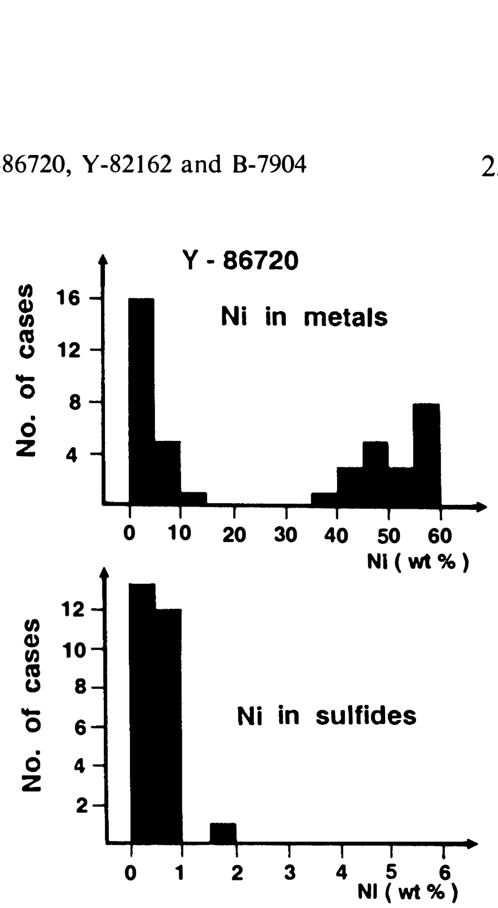


Fig. 10. Concentration of Ni in metals and sulfides from Y-86720; data in wt%.

grains contain a considerable amount of Al_2O_3 (>3.0 wt%), some are rich in CaO (up to 29 wt%), and others have a high SiO_2-concentration (~50 wt%). Most light objects exhibit well-preserved accretionary dust mantles ("dark rims"; compare Figs. 6 and 7) similar to those found in CM-chondrites (METZLER and BISCHOFF, 1987, 1989, 1990; METZLER *et al.*, 1988).

Y-86720 contains abundant large (up to ~500 μm) sulfide grains (compare Fig. 7). They are similar in composition to the abundant small sulfides within the fine-grained, phyllosilicate-rich groundmass (Fig. 10). The composition is close to stoichiometric FeS. ZOLENSKY *et al.* (1989b) stated that these grains are pyrrhotite ($Fe_{0.99}$ S). We also analysed small grains of magnetite and metal. The Ni-contents of metals are shown in Fig. 10.

3.3. *Belgica-7904*

Texturally B-7904 is somehow similar to CM-chondrites; however, this meteorite has very low H_2O-content (~2.60 wt%; HARAMURA *et al.*, 1983), large chondrules (up to 3 mm in size), and contains abundant components that have not been described in CM-chondrites (see below). Chondrules, CAIs, various kinds of irregularly-shaped olivine-bearing components, and lithic and mineral fragments are embedded in a brownish-grey to dark-grey, fine-grained groundmass. By comparing the two thin sections of B-7904 (—92,1 and —92,2) we found that the size of individual constituents in B-7904 is quite variable: On average, the size of chondrules in B-7904–92,2 is much smaller than within the other sample. In B-7904–92,1 inclusions and fragments are usually smaller than ~1 mm in size; however, several chondrules are in the order of 1 mm or greater in size. The coarse-grained objects are usually surrounded by very dark fine-grained, accretionary dust mantles (compare METZLER and BISCHOFF, 1987, 1989, 1990; METZLER *et al.*, 1988). In order to obtain detailed

Fig. 11. Olivine-rich chondrule (~600 μm in apparent diameter) within B-7904. The olivines are very fresh and contain abundant small opaque grains; photograph in transmitted light (crossed polarizers).

Fig. 12. Al-rich inclusion in B-7904; ilmenites (white) are embedded within an Al-rich groundmass. The inclusion is partly surrounded by a dark layer, which appears to consist of a fine-grained intergrowth of different phases. Backscattered electron photomicrograph.

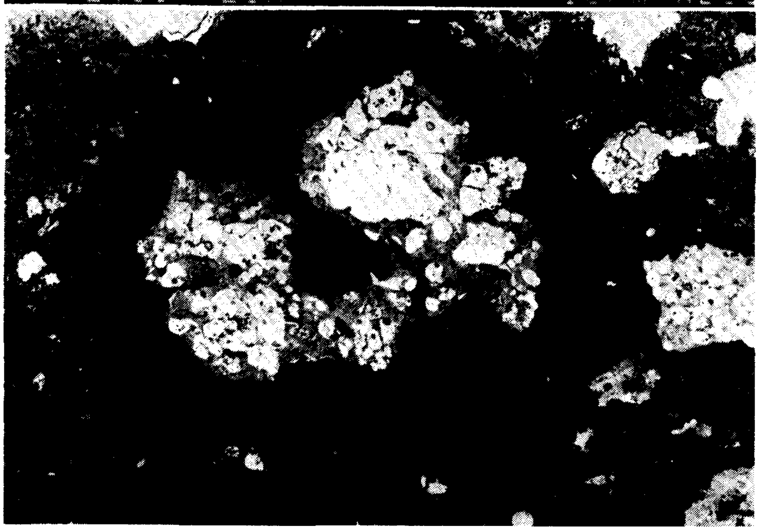


Fig. 13. Unusual irregularly-shaped, fragment-like object (~1 mm in size) in B-7904 that consists of olivines (white) embedded in a brownish-grey, fine-grained matrix. Note the well-preserved dark accretionary dust mantle. Photograph in transmitted light.

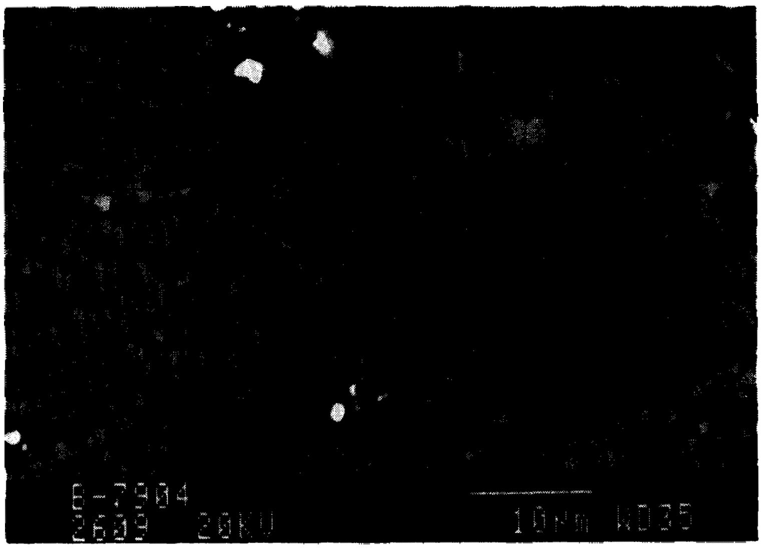


Fig. 14. Typical texture of a fine-grained olivine aggregate within B-7904; white spots are sulfides and metals. Back-scattered electron photomicrograph.

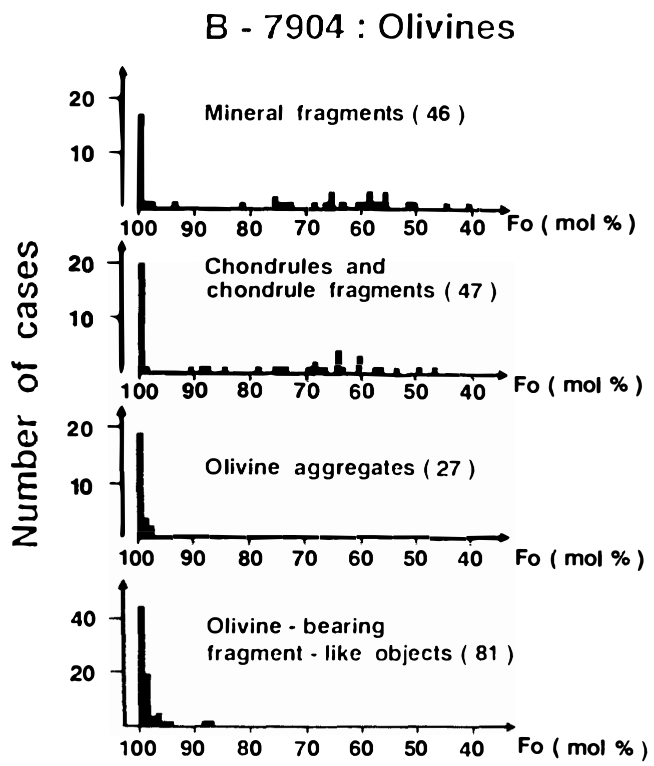


Fig. 15. Composition of olivines in various components of B-7904. On average, the compositions of olivines from different constituents are different.

information about the various kinds of constituents within this meteorite, we have determined the frequency distribution of all objects larger than about 70 μm in size. 435 lithic and mineral components were counted on a surface area of about 61 mm^2 (BISCHOFF and METZLER, 1990a). B-7904 contains ~18 vol% of objects larger than about 70 μm. 42 vol% of these components are chondrules or chondrule fragments (Fig. 11). Most of these chondrules and chondrule fragments are rich in porphyritic olivines; only a small number of porphyritic olivine-pyroxene and barred-olivine chondrules exist. The olivines in many chondrules are very fresh and show neither detectable shock effects nor indications of significant aqueous alteration (Fig. 11). The abundance of CAIs is far below 1 vol%. Two small (<200 μm) refractory inclusions were found (Fig. 12). Most abundant components are olivine-bearing, fragment-like objects (45.9 vol%); the olivines are embedded in a fine-grained brownish-grey matrix (Fig. 13). These objects might be the irregular chondrules described by PRINZ *et al.* (1989). In our view these objects cannot be counted as chondrules and are based on their appearance and quantity unknown from CM-chondrites (compare Fig. 13). About 9.4 vol% and 3.1 vol% of the components within B-7904 are olivine aggregates and olivine mineral fragments, respectively. Some of the olivine aggregates are very fine-grained. A typical example is given in Fig. 14.

Distinct olivine compositions for the various components have been measured (Fig. 15). More than 200 olivines from different constituents (mineral and chondrule fragments, chondrules, aggregates and olivine-bearing, fragment-like objects) were analysed. About 50% of the olivines that occur within chondrules and chondrule fragments or as mineral fragments are Fo-rich ($Fo_{>99.0}$); however, others can be very Fa-rich ($Fo_{\sim 40}$; Fig. 15). Olivines within other constituents of B-7904 are on average Fo-richer than those within chondrules and chondrule fragments. More than 97% of the crystals analysed in olivine aggregates or within the olivine-bearing, fragment-like objects are Fo-rich ($Fo_{>95}$; Fig. 15). Only a small number of olivines contain up to ~15 mol% Fa. Thus, the composition of olivine within different components of this carbonaceous chondrite is different. AKAI (1990) and PAUL and LIPSCHUTZ (1989) estimated the temperature of metamorphism for B-7904 in excess of 700°C. It is difficult to imagine, why the olivines of various components in B-7904 have different compositions (compare Fig. 15). In the case of a metamorphism at temperatures above 700°C the duration of heating must have been very short.

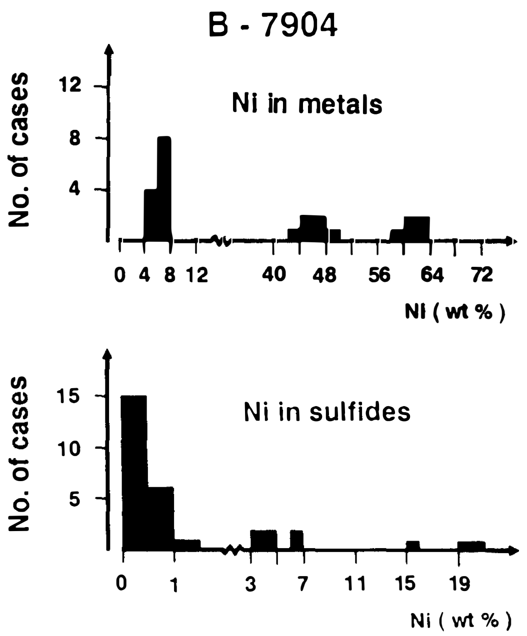


Fig. 16. Concentration of Ni in metals and sulfides from B-7904; data in wt%.

Small metal grains were found in all constituents of B-7904. In general, those within chondrules and olivine-bearing, fragment-like objects are poorer in Ni (Ni <7 wt%, kamacite; Fig. 16) than those analysed in sulfide-metal-assemblages (~ 47 wt% Ni) and within olivine aggregates (~ 60 wt% Ni). On average metals within these sulfide-metal-assemblages are richer in Co (>2 wt%) than metals in other components. Most sulfides are Ni-poor (Fig. 16). Based on our analyses these sulfides are stoichiometric FeS (troilite) with traces of Ni, as also stated by KOJIMA *et al.* (1984) and TOMEOKA (1989). ZOLENSKY *et al.* (1989b) suggested that pyrrhotite ($Fe_{0.98}$ S) is the major sulfide mineral. Pentlandite is rare in B-7904. Only some grains with variable Ni-contents were analysed. Further opaque minerals include Cr-spinel, magnetite and ilmenite. The Cr-spinels were found within chondrules and as euhedral crystals within the matrix, whereas all ilmenites occur in an Al-rich inclusion (Fig. 12; see below).

The ilmenite-bearing Al-rich inclusion ($\sim 120 \times 50$ μm in size; Fig. 12) consists of about 20 ilmenite grains embedded in a fine-grained Al- and Fe-rich groundmass (Table 3). The inclusion is partly surrounded by an Al-rich layer, which appears to be itself a fine-grained intergrowth of several phases (Table 3). We suggest that primary perovskite grains were altered to ilmenites. Such reactions are known from the study of Ca,Al-rich inclusions in ordinary chondrites (BISCHOFF and KEIL, 1984). Within these inclusions small grains are often completely transformed to ilmenites, whereas larger ones have still a core of perovskite and a rim of ilmenite. The second Al-rich inclusion contains abundant spinels. Although the inclusion is rimmed by an Fe-rich, fine-grained porous layer, the spinels are poor in FeO (Table 3).

Most chondrules, chondrule fragments, and olivine-bearing, fragment-like objects

Table 3. Compositions of constituents within Al-rich inclusions from B-7904.

	1	2	3	4	5	6	7	8	9
Na_2O	n. a.	n. a.	2.22	0.85	1.85	<0.15	—	<0.16	2.59
MgO	3.9	4.9	20.1	20.9	20.4	28.3	28.5	27.8	23.5
Al_2O_3	0.47	0.66	19.9	17.9	18.5	70.9	70.4	71.1	11.9
SiO_2	1.11	1.00	27.8	28.8	32.4	—	—	—	40.1
P_2O_5	—	—	1.72	1.17	1.61	—	—	—	0.67
SO_3	<0.10	<0.06	0.26	0.49	0.69	—	—	<0.04	1.50
K_2O	<0.02	<0.04	—	<0.01	0.23	<0.05	<0.09	<0.06	0.46
CaO	<0.11	<0.13	2.92	2.58	2.35	—	—	—	0.41
TiO_2	52.4	51.3	0.67	0.47	0.32	<0.12	<0.15	0.32	0.28
Cr_2O_3	<0.09	<0.06	<0.02	—	<0.14	0.40	0.31	0.22	<0.07
MnO	0.42	0.49	0.22	0.23	0.20	—	—	—	<0.15
FeO	40.3	39.3	23.8	24.0	17.3	<0.08	0.32	0.24	9.2
NiO	<0.12	<0.17	—	—	0.24	—	<0.14	—	0.29
Total	99.04	98.11	99.63	97.40	96.23	100.00	99.91	99.94	91.12

1, 2: ilmenite (<5 μm); 3, 4: fine-grained groundmass; 5: fine-grained, dark material (see Fig. 12), partly surrounding the inclusion; 6–8: spinels; 9: fine-grained porous material surrounding the spinel-rich inclusion.

All data in wt%.

n. a.: not analysed.

—: not detected.

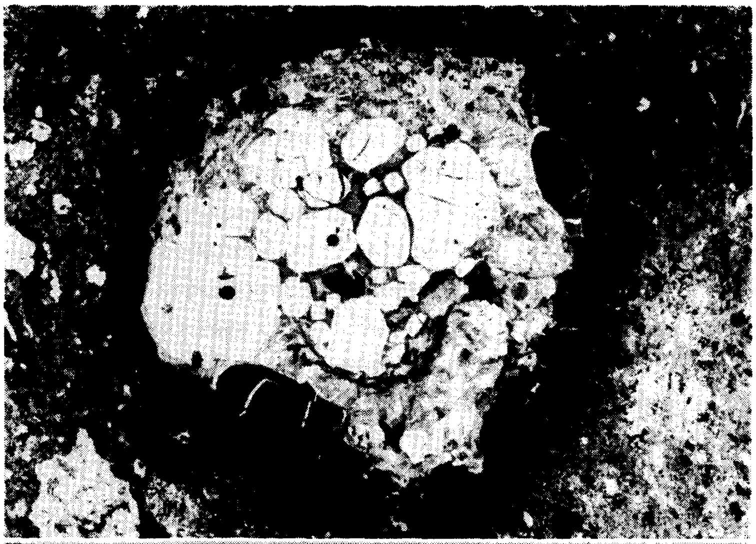


Fig. 17. Chondrule-like object ($\approx$ 1.2 mm in apparent diameter), rimmed by fine-grained accretionary dust, that contains abundant olivine (white) and some round or egg-shaped, Cr-rich inclusions (dark, compare Fig. 18); photograph in transmitted light.

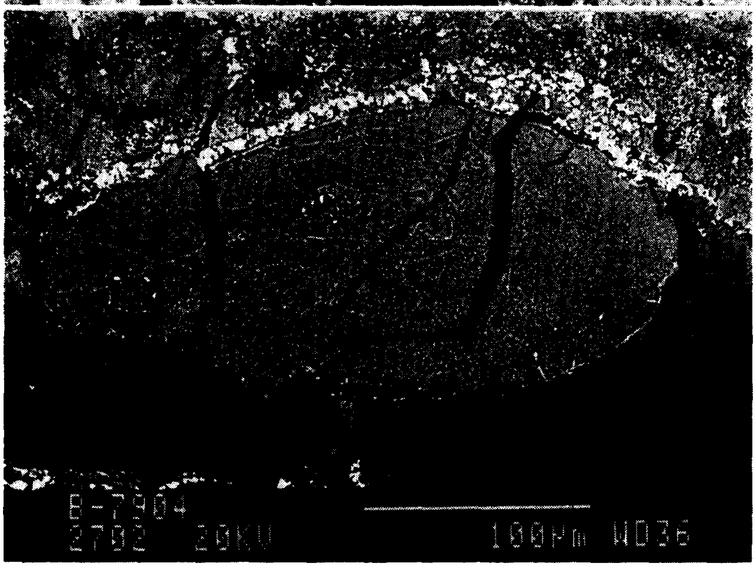


Fig. 18. Typical texture of a fine-grained, Cr- and Al-rich particle (compare Fig. 17 and Table 4); the light grains appear to be tiny Cr-spinel grains. Back-scattered electron photomicrograph.

Table 4. Bulk composition of the Cr-rich, spherical to egg-shaped fine-grained particles from B-7904 (compare Figs. 17 and 18).

Na_2O	1.58	1.80	1.90	1.74	1.52	1.92	1.60	1.75
MgO	18.9	20.5	22.4	20.6	20.5	20.4	20.8	20.9
Al_2O_3	5.9	4.7	5.4	4.7	4.3	6.0	6.8	5.5
SiO_2	37.5	40.0	42.3	39.9	40.3	39.5	40.6	39.9
SO_3	0.70	0.63	0.70	0.53	0.90	1.06	1.10	0.70
K_2O	0.49	0.50	0.40	0.45	0.48	0.49	0.51	0.45
CaO	0.45	n. a.	n. a.	0.21	<0.13	0.22	n. a.	<0.12
TiO_2	—	n. a.	n. a.	<0.20	<0.17	<0.02	n. a.	<0.18
Cr_2O_3	3.2	4.0	3.8	4.5	4.0	2.00	2.10	2.70
MnO	<0.07	n. a.	n. a.	<0.18	<0.18	<0.09	n. a.	<0.15
FeO	16.8	18.7	19.4	18.8	19.6	15.3	16.0	19.5
NiO	<0.19	n. a.	n. a.	<0.08	<0.18	0.40	n. a.	0.22
Total	85.78	90.83	96.30	91.89	92.26	87.40	89.51	92.07

All data in wt%.
n. a.: not analysed.
—: not detected.

contain spherical to egg-shaped fine-grained particles (Figs. 17 and 18). SKIRIUS *et al.* (1986) describe these objects as "isotropic grains". The particles are rich in Cr_2O_3 (2–5 wt%) and Al_2O_3 (4–7 wt%) (Table 4). Based on an electron microscopic study they appear to contain tiny Cr-spinel grains. The oxide totals of the bulk analyses are always far below 100% suggesting the presence of light element-bearing componets (*e.g.* H_2O, CO_2 (?)). Such Cr-rich objects have never been observed before in other carbonaceous chondrites.

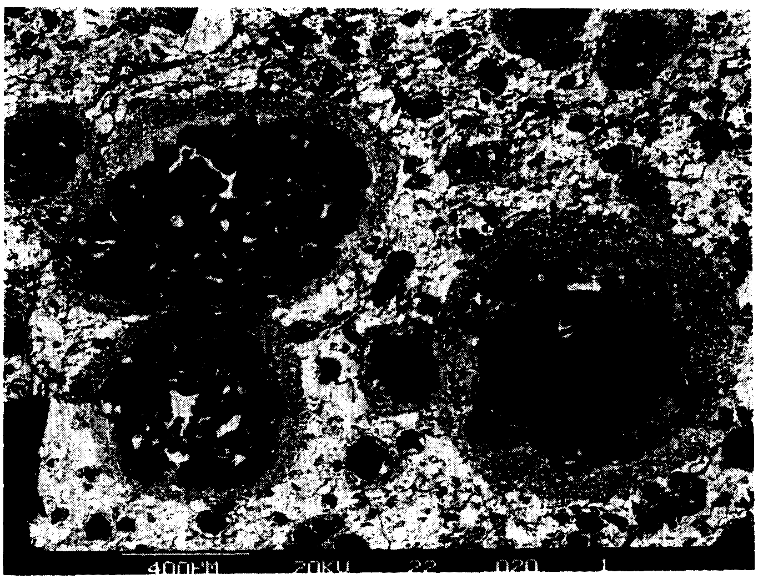
4. Discussion

4.1. Accretionary dust mantles as indicators for nebula processes

Most CM-chondrites are breccias containing pristine rock fragments and a fine-grained clastic matrix (*e.g.* METZLER and BISCHOFF, 1989, 1990; METZLER, 1990). The most characteristic features of such pristine fragments are the fine-grained accretionary dust mantles surrounding all coarse-grained components (*e.g.* chondrules, fragments, CAIs, PCP-rich objects; compare Fig. 19; METZLER and BISCHOFF, 1990).

Most components of B-7904 (chondrules, inclusions, fragments) are surrounded by accretionary dust mantles similar to those observed in CM-chondrites (METZLER and BISCHOFF, 1987, 1989, 1990; METZLER *et al.*, 1988). SKIRIUS *et al.* (1986) and PRINZ *et al.* (1989) also state that these "matrix shells" or "dark, fine-grained rims" are distinct from the general meteorite matrix and tend to give a rounder outline to each enclosed component by filling recesses. We studied several of these accretionary dust mantles from B-7904 in order to obtain information about their chemical characteristics in comparison to the bulk composition of B-7904 and to the composition of accretionary dust mantles in CM-chondrites (METZLER, 1990). The dark accretionary dust mantles in B-7904 are on average richer in Fe and S than those in the CM-chondrites Y-74662, Y-791198, and Mighei (Fig. 20; Table 5; compare also METZLER and BISCHOFF, 1990). The dust mantles in B-7904 contain abundant sulfides, whereas most S in dust mantles within the other chondrites listed above is present

Fig. 19. Y-791198 (CM); chondrules, fragments, and other meteorite components are surrounded by accretionary dust mantles: note that the light PCP-rich objects are also rimmed by thin dust mantles. Back-scattered electron photomicrograph.



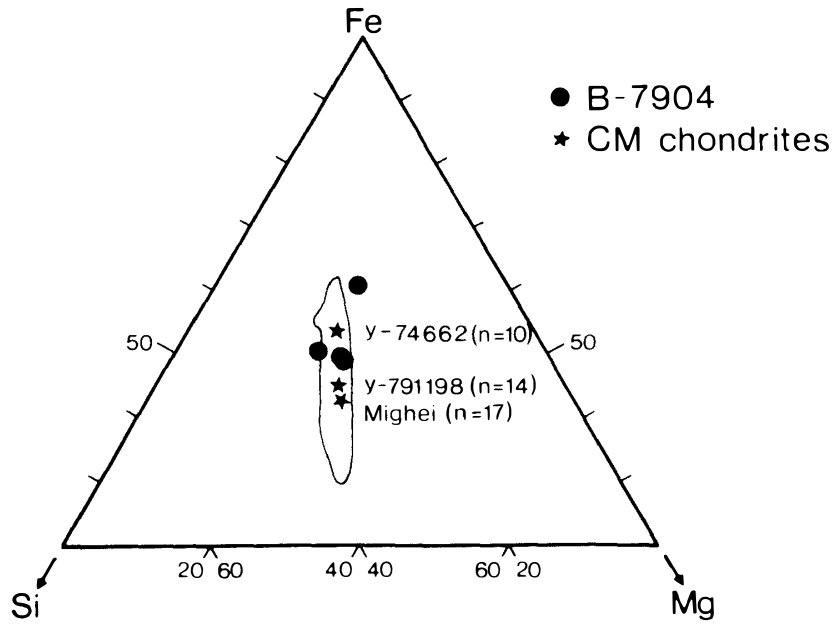


Fig. 20. Chemical composition (wt%) of individual accretionary dust mantles in B-7904. The field represents the chemical variations of 86 individual dust mantles in 14 different CM-chondrites. For comparison the mean values for dust mantles in the three CM-chondrites Y-74662, Y-791198, and Mighei are plotted (n = number of dust mantles analyzed; METZLER, *1990).*

Table 5. Chemical composition of accretionary dust mantles (b) in B-7904, Y-791198, Y-74662, and Mighei compared with the bulk chemical composition (a) of these chondrites.

	B-7904		Y-791198		Y-74662		Mighei	
	a	b	a	b	a	b	a	b
n:		4		14		10		17
Na_2O	0.66	0.95	0.15	0.20	0.28	0.27	0.63	0.92
MgO	23.7	16.5	19.5	16.5	19.3	15.3	19.5	15.6
Al_2O_3	3.3	3.1	2.62	2.05	2.38	2.41	2.23	1.81
SiO_2	31.5	26.4	28.4	28.3	29.2	27.3	27.8	24.8
S	4.2	5.0	2.93	3.6	2.69	2.57	3.7	3.1
K_2O	0.04	<0.13	0.03	<0.08	0.04	<0.04	0.05	<0.05
CaO	2.22	0.68	1.65	0.49	1.70	0.60	1.65	0.77
TiO_2	0.16	<0.22	0.12	<0.06	0.22	<0.09	0.08	<0.14
Cr_2O_3	0.50	0.45	0.42	0.50	0.52	0.56	0.35	0.51
MnO	0.25	<0.19	0.27	0.27	0.22	0.25	0.21	<0.17
FeO	31.3	31.6	27.2	26.1	28.6	33.0	27.3	21.1
Ni	0.95	1.55	0.72	1.81	0.67	1.63	1.20	1.27
Total	98.78	86.77	84.01	79.96	85.82	84.02	84.70	70.24
Mg/Fe	0.59	0.41	0.56	0.49	0.52	0.36	0.55	0.57
Ca/Na	3.25	0.69	10.73	2.37	5.84	2.15	2.51	0.81

n: Number of dust mantles analysed.
All data in wt%.
The bulk compositions are taken from HARAMURA *et al.* (1983) and WIIK (1969).

in tochilinites. In general the accretionary dust mantles in B-7904 contain lower Mg/Fe- and Ca/Na-ratios compared to the bulk composition. The very strong discrepancy in the Ca/Na-ratios between the composition of the dust mantles and the bulk composition is very surprising. The same effect has been found by comparing the compositions of accretionary dust mantles from Y-74662, Y-791198, and Mighei with the bulk composition of these meteorites (METZLER and BISCHOFF, 1990).

Based on textural and chemical investigations we suggest that the dark rims surrounding coarse-grained components in B-7904 and Y-86720 cannot be explained by parent body processes (compare METZLER and BISCHOFF, 1987, 1989, 1990; BISCHOFF and METZLER, 1990b). It appears that the formation of fine-grained ("dusty") mantles surrounding various components within these and other chondrites (CM, CV, CO, ordinary and enstatite chondrites; METZLER, 1990) can only be explained by accretionary processes in the solar nebula. In CM-chondrites PCP-rich objects and calcites are also rimmed by these fine-grained materials (METZLER and BISCHOFF, 1990), suggesting that these components had to be present in the nebula prior to the aggregation of dusty matter and prior to parent body formation. The coexistence of unaltered Fe,Ni-metals, Fe,Ni-metals with magnetite rims, magnetites, sulfides, unaltered ("fresh") olivines of various composition and abundant H_2O-bearing phases within the accretionary dust mantles of CM-chondrites indicates that significant aqueous alteration on the parent body can be ruled out (BISCHOFF and METZLER, 1990b; METZLER and BISCHOFF, 1990). The coexistence of olivine (Fo_{99}), sulfides, Fe,Ni-metals, and phyllosilcates was also found in an accretionary rim within B-7904.

In the following we will prove what has been stated above by describing the relationship between a chondrule fragment and the accretionary dust mantle in the CM-chondrite Murray. The chondrule fragment from Murray (Fig. 21) consists of zoned olivine crystals and areas where small skeletal pyroxene crystals are embedded in an optically clear isotropic glass. This fragment is surrounded by a fine-grained, phyllosilicate-rich accretionary dust mantle. From the optical observation it is

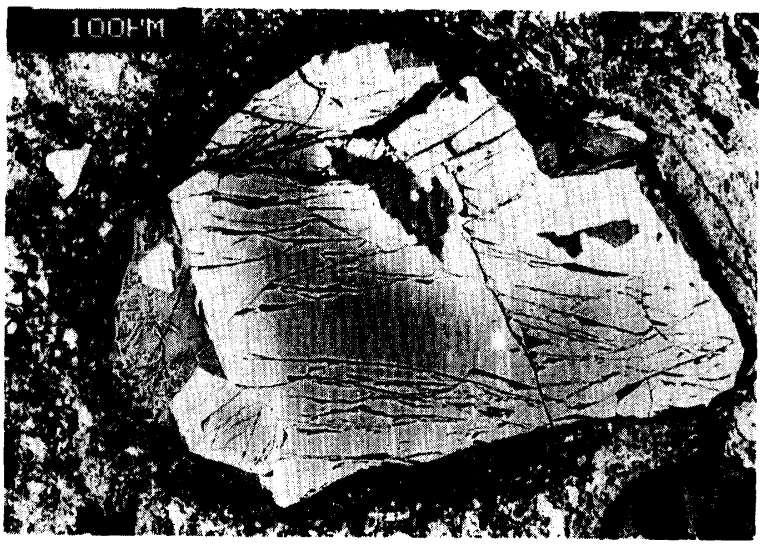


Fig. 21. Chondrule fragment surrounded by an accretionary dust mantle within the CM-chondrite Murray. The chondrule fragment consists of zoned olivine crystals and a clear isotropic glass, in which some skeletal pyroxene crystals are embedded. The accretionary dust mantle mainly contains water-bearing phases. Note the sharp boundary between the chondrule glass (left side) and the phyllosilicate-rich dust mantle: No reaction zone is visible. Backscattered electron photomicrograph.

known that the mesostasis glass in chondrules usually reacts very fast with water to form water-bearing phases (*e.g.* TOMEOKA and BUSECK, 1985; ZOLENSKY and MCSWEEN, 1988). In this case, however, we do not see any indication for the replacement of the chondrule glass by water-bearing phases due to aqueous alteration processes: a sharp boundary exists between the glassy chondrule mesostasis and the phyllosilicate-rich accretionary dust mantle. We do not see any reason, why the phyllosilicates within the accretionary dust mantle should have been formed by aqueous alteration processes in the parent body without affecting the coexisting mesostasis glass. Thus, H_2O-bearing phases had to be present prior to the formation of the dust mantle. As stated above we suggest that this chondrule fragment—like other coarse-grained components (chondrules, inclusions, fragments, PCP-rich objects; compare Fig. 19) within B-7904, Y-86720 and within the CM-chondrites—was enclosed by accretionary dust in the solar nebula prior to the formation of the *last* meteorite parent body, where these rocks come from. We cannot rule out that the water-bearing phases were formed on preexisting small parent bodies. After the formation of water-bearing phases these bodies had to be destroyed by impact resulting in a mixture of various of components (chondrules, CAIs, PCP-rich objects, fragments, and dusty materials). The adhesion process which formed the dust mantles was followed by reaccretion to establish the last chondrite parent body(ies). In our view the evolutionary processes on the CI-meteorite parent bodies are different. The existence of veins filled with carbonates, sulfates, and phyllosilicates (*e.g.* TOMEOKA and BUSECK, 1988; TOMEOKA, 1990a) clearly indicates that alteration processes were involved in the evolution of the parent body.

4.2. *The difficulties in the classification of B-7904, Y-82162, and Y-86720*

As pointed out earlier, these chondrites do not fit in the traditional classification schemes. Based on the oxygen isotopic composition they can be classified as CI-chondrites, although the values of $\delta^{18}O$ and $\delta^{17}O$ are much higher than those of all other meteorites (MAYEDA and CLAYTON, 1990), but ambiguities arise in the classification based on mineralogical and chemical (major elements, volatile elements) criteria. MAYEDA and CLAYTON (1990) suggested that the high $\delta^{18}O$- and $\delta^{17}O$-values are the result of an *extensive* aqueous alteration on the parent body at low temperature. We have some difficulties to understand, why B-7904 contains abundant chondrules and other coarse-grained components that show only minor effects of alteration (compare Fig. 11), if aqueous alteration on the parent body was such an extensive process.

In this study we cannot offer a satisfying suggestion, how to classify these chondrites. However, we can present some information and ideas for future discussions. Based on the mineralogy Y-82162 is closely related to CI-chondrites; however, it shows many unusual mineralogical and chemical features that will not be discussed here, again (*e.g.* TOMEOKA *et al.*, 1988a; ZOLENSKY *et al.*, 1989b; TOMEOKA, 1990b). The occurrence of abundant clasts indicates that this meteorite is a breccia. So far, no data on noble gases have been published to decide wether Y-82162 is a regolith or a fragmental breccia.

Y-86720 is mineralogically more closely related to the CI-chondrites than to any other chondrite group. Compared to CM-chondrites like Murchison or Mighei no olivine- or pyroxene-bearing chondrules or fragments are present. Some round light-coloured objects appear to be relict chondrules, but they contain essentially no anhydrous silicates. Texturally, Y-86720 appears to be an intermediate chondrite between CI and CM, as also suggested by KALLEMEYN (1988) based on bulk chemical criteria.

The bulk analysis of B-7904 shows that the contents of the volatile components are similar to typical C3-chondrite values (KOJIMA *et al.*, 1984). These and other authors (*e.g.* AKAI, 1988, 1989, 1990; TOMEOKA, 1989; PAUL and LIPSCHUTZ, 1989) state that the recrystallized olivines within the matrix are the result of intense heating (above 700°C) on or in the parent body. As pointed out earlier, we have difficulties to understand, why the thermal metamorphism at such a high temperature did not cause equilibration of olivines (compare Fig. 15). The recrystallization of olivine can only be the result of a very short heating process. The planetary environment, where such a process could have been taken place, is difficult to decipher. Short heating processes can be caused by impact events, but the constituents of B-7904 do not appear to have been significantly shocked (compare STÖFFLER *et al.*, 1988).

B-7904 is a new kind of carbonaceous chondrite. Based on reasons given below, we do not like to classify this meteorite as a CM-type chondrite (compare PRINZ *et al.*, 1989):

a) The mean diameter of chondrules from CM-chondrites is in the order of 0.3 mm (*e.g.* GROSSMAN *et al.*, 1988). A great number of chondrules in B-7904 is much larger (0.5–2 mm).

b) The most abundant component (olivine-bearing, fragment-like objects with a brownish-grey, fine-grained groundmass; Fig. 13) is unknown from CM-chondrites.

c) The Cr- and Al-rich spherical to egg-shaped, fine-grained particles (Fig. 18), that are present in most of the coarse-grained constituents of B-7904 have not been observed before in CM-chondrites.

d) Several other aspects indicate that this meteorite is not a CM-chondrite including, for example, the oxygen isotopes (MAYEDA *et al.*, 1987), the low H_2O-contents (HARAMURA *et al.*, 1983), and the high abundances of dehydrated phases (ZOLENSKY *et al.*, 1988b).

Since the values of $\delta^{18}O$ and $\delta^{17}O$ of these chondrites are much higher than those of all other meteorites (MAYEDA and CLAYTON, 1990), one might speculate, if all three meteorites could derive from a parent body, which is distinct from the CI-chondrite parent body (ies).

Acknowledgments

We very much appreciate the generosity of the National Institute of Polar Research for making available thin sections from these interesting carbonaceous chondrites. We thank Prof. Y. IKEDA for organizing the CI-consortium and for a helpful review of this paper. We also thank two anonymous reviewers for their constructive reviews and M. ENDREß and F. BARTSCHAT for the analytical and technical help.

References

AKAI, J. (1988): Incompletely transformed serpentine-type phyllosilicates in the matrix of Antarctic CM chondrites. Geochim. Cosmochim. Acta, **52**, 1593–1599.

AKAI, J. (1989): Mineralogical evidence of heating events in carbonaceous chondrites, Y-82162 and Y-86720. Papers Presented to the 14th Symposium on Antarctic Meteorites, June 6–9, 1989. Tokyo, Natl Inst. Polar Res., 22–23.

AKAI, J. (1990): Thermal metamorphism in four Antarctic carbonaceous chondrites and its temperature scale estimated by T-T-T diagram. Papers Presented to the 15th Symposium on Antarctic Meteorites, May 30–June 1, 1990. Tokyo, Natl Inst. Polar Res., 86–87.

BENCE, A. E. and ALBEE, A. L. (1968): Empirical correction factors for the electron microanalysis of silicates and oxides. J. Geol., **76**, 382–403.

BISCHOFF, A. and KEIL, K. (1984): Al-rich objects in ordinary chondrites: Related origin of carbonaceous and ordinary chondrites and their constituents. Geochim. Cosmochim. Acta, **48**, 693–709.

BISCHOFF, A. and METZLER, K. (1990a): Petrography and chemistry of the three carbonaceous chondrites Y-86720, Y-82162, and B-7904. Papers Presented to the 15th Symposium on Antarctic Meteorites, May 30–June 1, 1990. Tokyo, Natl Inst. Polar Res., 185–187.

BISCHOFF, A. and METZLER, K. (1990b): Shock metamorphism and formation of accretionary dust mantels as fundamental nebula processes. Meteoritics, **25**, 350.

CLAYTON, R. N. and MAYEDA, T. K. (1989): Oxygen isotope classification of carbonaceous chondrites. Lunar and Planetary Science XX. Houston, Lunar Planet. Inst., 169–170.

EBIHARA, M. and SHINONAGA, T. (1989): Chemical composition of some primitive carbonaceous chondrites from Antarctica. Papers Presented to the 14th Symposium on Antarctic Meteorites, June 6–9, 1989. Tokyo, Natl Inst. Polar Res., 35–36.

GROSSMAN, J. N., RUBIN, A. E., NAGAHARA, H. and KING, E. A. (1988): Properties of chondrules. Meteorites and the Early Solar System, ed. by J. F. KERRIDGE and M. S. MATTHEWS. Tucson, Univ. Arizona Press, 619–659.

HARAMURA, H., KUSHIRO, I. and YANAI, K. (1983): Chemical compositions of Antarctic meteorites I. Mem. Natl Inst. Polar Res., Spec. Issue, **30**, 109–121.

KALLEMEYN, G. W. (1988): Compositional study of carbonaceous chondrites with CI-CM affinities. Papers Presented to the 13th Symposium on Antarctic Meteorites, June 7–9, 1988. Tokyo, Natl Inst. Polar Res., 132–134.

KOJIMA, H. and YANAI, K. (1987): Yamato-82162; Possible first C1 carbonaceous chondrite from Antarctica. Papers Presented to the 12th Symposium on Antarctic Meteorites, June 8–10, 1987. Tokyo, Natl Inst. Polar Res., 15.

KOJIMA, H., IKEDA, Y. and YANAI, K. (1984): The alteration of chondrules and matrices in new Antarctic carbonaceous chondrites. Mem. Natl Inst. Polar Res., Spec. Issue, **35**, 184–199.

MAYEDA, T. K. and CLAYTON, R. N. (1990): Oxygen isotopic compositions of B-7904, Y-82162, and Y-86720. Papers Presented to the 15th Symposium on Antarctic Meteorites, May 30–June 1, 1990. Tokyo, Natl Inst. Polar Res., 196–197.

MAYEDA, K., CLAYTON, R. N. and YANAI, K. (1987): Oxygen isotopic compositions of several Antarctic meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **46**, 144–150.

METZLER, K. (1990): Petrographische und mikrochemische Untersuchungen zur Akkretionsgeschichte chondritischer Mutterkörper am Beispiel der CM-Chondrite. Ph. D. thesis, Universität Münster, 185 p.

METZLER, K. and BISCHOFF, A. (1987): Accretionary dark rims in CM-chondrites. Meteoritics, **22**, 458–459.

METZLER, K. and BISCHOFF, A. (1989): Accretionary dust mantles in CM-chondrites as indicators for processes prior to parent body formation. Lunar and Planetary Science XX. Houston, Lunar Planet. Inst., 689–690.

METZLER, K. and BISCHOFF, A. (1990): Petrography and chemistry of accretionary dust mantles in the CM-chondrites Y-791198, Y-793321, Y-74662 and ALHA83100—Indications for nebula processes. Papers Presented to the 15th Symposium on Antarctic Meteorites, May 30–June 1, 1990. Tokyo, Natl Inst. Polar Res., 198–200.

METZLER, K., BISCHOFF, A. and STÖFFLER, D. (1988): Characteristics of accretionary dark rims in carbonaceous chondrites. Lunar and Planetary Science XIX. Lunar Planet. Inst., 772–773.

PAUL, R. L. and LIPSCHUTZ, M. E. (1989): Consortium report on carbonaceous chondrites from Queen Maud Land, Antarctica: Glimpses of new parents. Papers Presented to the 14th Symposium on Antarctic Meteorites, June 6–9, 1989. Tokyo, Natl Inst. Polar Res., 32–33.

PRINZ, M., WEISBERG, M. K., HAN, R. and ZOLENSKY, M. E. (1989): Type I and II chondrules in the B7904 carbonaceous chondrite. Meteoritics, **24**, 317–318.

SKIRIUS, C., STEELE, I. M. and SMITH, J. V. (1986): Belgica-7904: A new carbonaceous chondrite from Antarctica; Minor-element chemistry of olivine. Mem. Natl Inst. Polar Res., Spec. Issue, **41**, 243–258.

STEELE, I. M., COX, R. T., JR. and SMITH, J. V. (1984): Belgica-7904, an extreme C2 from Antarctica; Petrology and mineral chemistry. Lunar and Planetary Science XV. Houston, Lunar Planet. Inst., 820–821.

STÖFFLER, D., BISCHOFF, A., BUCHWALD, V. and RUBIN, A. E. (1988): Shock effects in meteorites. Meteorites and the Early Solar System, ed. by J. F. KERRIDGE and M. S. MATTHEWS. Tucson, Univ. Arizona Press, 165–202.

TOMEOKA, K. (1989): Belgica-7904: A new kind of carbonaceous chondrite from Antarctica; mineralogy and petrology. Papers Presented to the 14th Symposium on Antarctic Meteorites, June 6–9, 1989. Tokyo, Natl Inst. Polar Res., 18–20.

TOMEOKA, K. (1990a): Phyllosilicate veins in the Yamato-82162 CI carbonaceous chondrite: Evidence for post-accretionary aqueous alteration. Meteoritics, **25**, 415.

TOMEOKA, K. (1990b): The origin of phyllosilicates in the Yamato-82162 CI carbonaceous chondrite. Papers Presented to the 15th Symposium on Antarctic Meteorites, May 30–June 1, 1990. Tokyo, Natl Inst. Polar Res., 83–85.

TOMEOKA, K. and BUSECK, P. R. (1985): Indicators of aqueous alteration in CM carbonaceous chondrites: Microtextures of a layered mineral containing Fe, S, O, and Ni. Geochim. Cosmochim. Acta, **49**, 2149–2163.

TOMEOKA, K. and BUSECK, P. R. (1988): Matrix mineralogy of the Orgueil CI carbonaceous chondrite. Geochim. Cosmochim. Acta, **52**, 1627–1640.

TOMEOKA, K., KOJIMA, H. and YANAI, K. (1988a): Yamato-82162: A new kind of CI carbonaceous chondrite found in Antarctica. Papers Presented to the 13th Symposium on Antarctic Meteorites, June 7–9, 1988. Tokyo, Natl Inst. Polar Res., 126–127.

TOMEOKA, K., KOJIMA, H. and YANAI, K. (1988b): Yamato-86720: An extensively altered and thermally metamorphosed CM carbonaceous chondrite? Papers Presented to the 13th Symposium on Antarctic Meteorites, June 7–9, 1988. Tokyo, Natl Inst. Polar Res., 130–131.

WATANABE, S., TSUCHIYAMA, A. and KITAMURA, M. (1988): A preliminary report of mineralogy of Y-82162 (CI). Papers Presented to the 13th Symposium on Antarctic Meteorites, June 7–9, 1988. Tokyo, Natl Inst. Polar Res., 128–129.

WIIK, H. B. (1969): On the regular discontinuities in the composition of meteorites. Commentat. Phys.-Math., Soc. Sci. Fenn., **34**, 135–145.

YAMAMOTO, K. and NAKAMURA, N. (1989): Chemical characteristics and their inference to classification of Yamato-82162 and -86720 meteorites. Papers Presented to the 14th Symposium on Antarctic Meteorites, June 6–8, 1989. Tokyo, Natl Inst. Polar Res., 27–29.

YANAI, K. and KOJIMA, H., comp. (1987): Photographic Catalog of the Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 298 p.

ZOLENSKY, M. E. and MCSWEEN, H. Y., JR. (1988): Aqueous alteration. Meteorites and the Early Solar System, ed. by J. F. KERRIDGE and M. S. MATTHEWS. Tucson, Univ. Arizona Press. 114–143.

ZOLENSKY, M. E., BARRETT, R. A. and PRINZ, M. (1989a): Petrography, mineralogy and matrix composition of Yamato-82162, a new CI2 chondrite. Lunar and Planetary Science XX. Houston, Lunar Planet. Inst., 1253–1254.

ZOLENSKY, M. E., BARRETT, R. A. and PRINZ, M. (1989b): Mineralogy and petrology of Yamato-86720 and Belgica-7904. Papers Presented to the 14th Symposium on Antarctic Meteorites, June 6–9, 1989. Tokyo, Natl Inst. Polar Res., 24–26.

(Received July 23, 1990; Revised manuscript received October 9, 1990)