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MINERALOGY AND PETROLOGY OF THE CK CHONDRITES YAMATO-82104, YAMATO-693 AND A CARLISLE LAKES-TYPE CHONDRITE YAMATO-82002

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Abstract: We have studied the mineralogy and petrology of three metamorphosed chondrites, Yamato(Y)-82104, Y-693, and Y-82002, which were previously classified as C5, C4 and C5, respectively. The results indicate that Y-82104 and Y-693 should be included with the CK carbonaceous chondrites. Y-82104 and Y-693 are remarkably similar in mineralogy and texture (*e.g.*, virtually identical compositions of olivines, Fa 29.2±0.4 *vs.* Fa 29.4±0.7, respectively). Thus, they are probably paired. The compositional homogeneity of olivine and pyroxene and degree of recrystallization of olivine and plagioclase are consistent with Y-82104 and Y-693 being petrologic type 5. Y-82002 differs from most CK chondrites in mineralogy and petrology, but is similar to Carlisle Lakes-type chondrites which were recently proposed to be a new grouplet of chondrites (A. E. RUBIN and G. W. KALLEMEYN, Geochim. Cosmochim., **53**, 3035, 1989). We believe that Y-82002 is a member of this grouplet. Y-82002 was previously classified as petrologic type 5, but the relatively inhomogeneous compositions of olivine (*e.g.*, Fa 35.1±5.1 for chondrules) and low degree of recrystallization of olivine and plagioclase suggest that Y-82002 should be classified as petrologic type 3.8–3.9.

1. Introduction

In the process of parent-body evolution, chondrites are expected to have experienced diverse degrees of thermal and shock metamorphism. Such metamorphism has been extensively studied on ordinary chondrites, but less work has been done on other subgroup of chondrites. Metamorphosed (petrologic types 4–6) carbonaceous chondrites are recognized to have a close relationship to CO and CV chondrites (KALLEMEYN *et al.*, 1991) on the basis of their elemental abundance patterns (KALLEMEYN *et al.*, 1991; GEIGER and BISCHOFF 1991a) and oxygen isotope data (CLAYTON and MAYEDA, 1989; MAYEDA *et al.*, 1987). However, most of them have many mineralogical and compositional features which distinguish them from CO and CV chondrites, *e.g.*, abundant magnetite (SCOTT and TAYLOR, 1985; GEIGER and BISCHOFF, 1989a, 1990a), the presence of ilmenite and spinel lamellae in magnetite (GEIGER and BISCHOFF, 1990b) and Al/Mg and Zn/Mn ratios (KALLEMEYN *et al.*, 1991). Thus, GEIGER and BISCHOFF (1990a) recommended based on these features to group these metamorphosed carbonaceous chondrites in an own group and recently, KALLEMEYN *et al.* (1991) proposed a new group of carbonaceous chondrites (CK or Karoonda-type) for them.

Carlisle Lakes-type chondrites are also a newly defined chondrite grouplet (RUBIN and KALLEMEYN, 1989) which have petrologic and bulk compositional similarities to the ordinary chondrites, but are considerably more oxidized (*e.g.*, olivine Fa= 38–41 mol%) and have unusual oxygen isotopic compositions (WEISBERG *et al.*, 1991). Currently, five meteorites are known as members of this grouplet; Carlisle Lakes (BINNS and POOLEY, 1979; RUBIN and KALLEMEYN, 1989), Allan Hills (ALH) 85151 (RUBIN and KALLEMEYN, 1989), Yamato(Y)-75302 (YANAI and KOJIMA, 1987; RUBIN and KALLEMEYN, 1989), Y-793575 (YANAI, 1992) and Acfer 217 (WLOTZKA, 1992; GEIGER and BISCHOFF, 1992; BLAND *et al.*, 1992).

Here, we present the results of our petrographic and scanning electron microscope (SEM) studies of three metamorphosed chondrites from Antarctica, Y-82002, Y-82104 and Y-693. Y-82104 and Y-82002 were previously classified as C5, whereas Y-693 was classified as C4. A transmission electron microscope (TEM) was used to study microtextures of matrix minerals in Y-693 (a specimen for TEM study was available only from this meteorite). Although there are some early petrographic studies on Y-693 (OKADA, 1975; SCOTT and TAYLOR, 1985) and Y-82104 (GRAHAM and YANAI, 1986), details on mineralogy and petrology of these meteorites are still poorly known. Our primary goals are to provide detailed mineralogical and petrological study on these meteorites and to assign chondrite and petrologic types to them.

2. Samples and Methods

Polished thin sections of Y-82104, Y-82002 and Y-693 have been studied using an optical microscope, a scanning electron microscope (JEOL JSM 840) equipped with an energy-dispersive X-ray spectrometer (EDS), and an electron-microprobe analyzer (JEOL 8600 Superprobe) equipped with wave-length-dispersive X-ray spectrometers (WDS). EDS analyses were obtained at 15 kV and 3 nA with a focused beam $\sim 2\,\mu$m in diameter. WDS analyses were obtained at 15 kV and 12 nA with a focused beam $\sim 3\,\mu$m in diameter. After petrographic characterization, three areas of matrix of Y-693 were extracted from the thin section, mounted on TEM grids, and thinned by argon-ion bombardment for TEM study. Imaging and electron diffraction were performed with a JEOL JEM 100CX transmission electron microscope (TEM), operated at 100 kV and a Hitachi H-600 TEM, operated at 100 kV. Structural identification was based on high-resolution imaging and selected-area electron diffraction. Qualitative chemical analyses were obtained with an EDS on the Hitachi H-600 TEM. The electron beam was usually focused to 200 Å in diameter.

3. Results

3.1. General petrography

Y-82104, Y-693 and Y-82002 have similar overall textures; all meteorites contain blurred chondrules and mineral fragments set in semi-translucent recrystallized matrices (Figs. 1a, 1b and 1c). The matrices of Y-82104 and Y-693 exhibit pronounced silicate

(a)

(b)

(c)

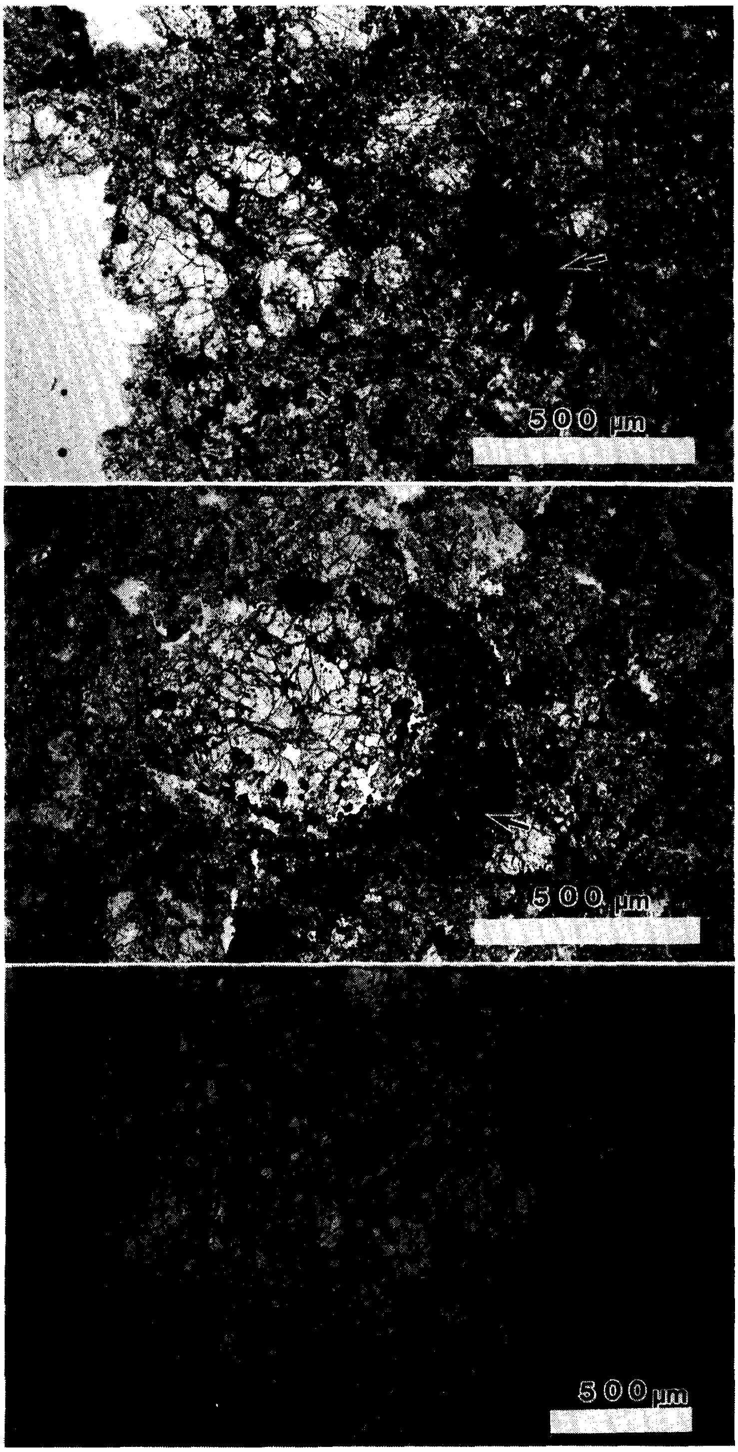

Fig. 1. Portions of thin sections of (a) Y-82104, (b) Y-693, and (c) Y-82002 in transmitted light. Chondrules in Y-82002 are smaller than those in Y-82104 and Y-693. Dark, glassy to microcrystalline material (indicated by arrows), probably a shock-induced melt, is seen in Y-82104 and Y-693.

blackening due to widely dispersed tiny (<1–5 μm) magnetite grains. No Ca- and Al-rich inclusion (CAI) was observed in any of our thin sections. Chondrules are blurred to various degrees, and it is often difficult to distinguish boundaries between chondrules and matrix. But it is obvious that Y-82002 contains more sharply defined chondrules than Y-82104 and Y-693. Modal abundances of recognizable chondrules and matrix in

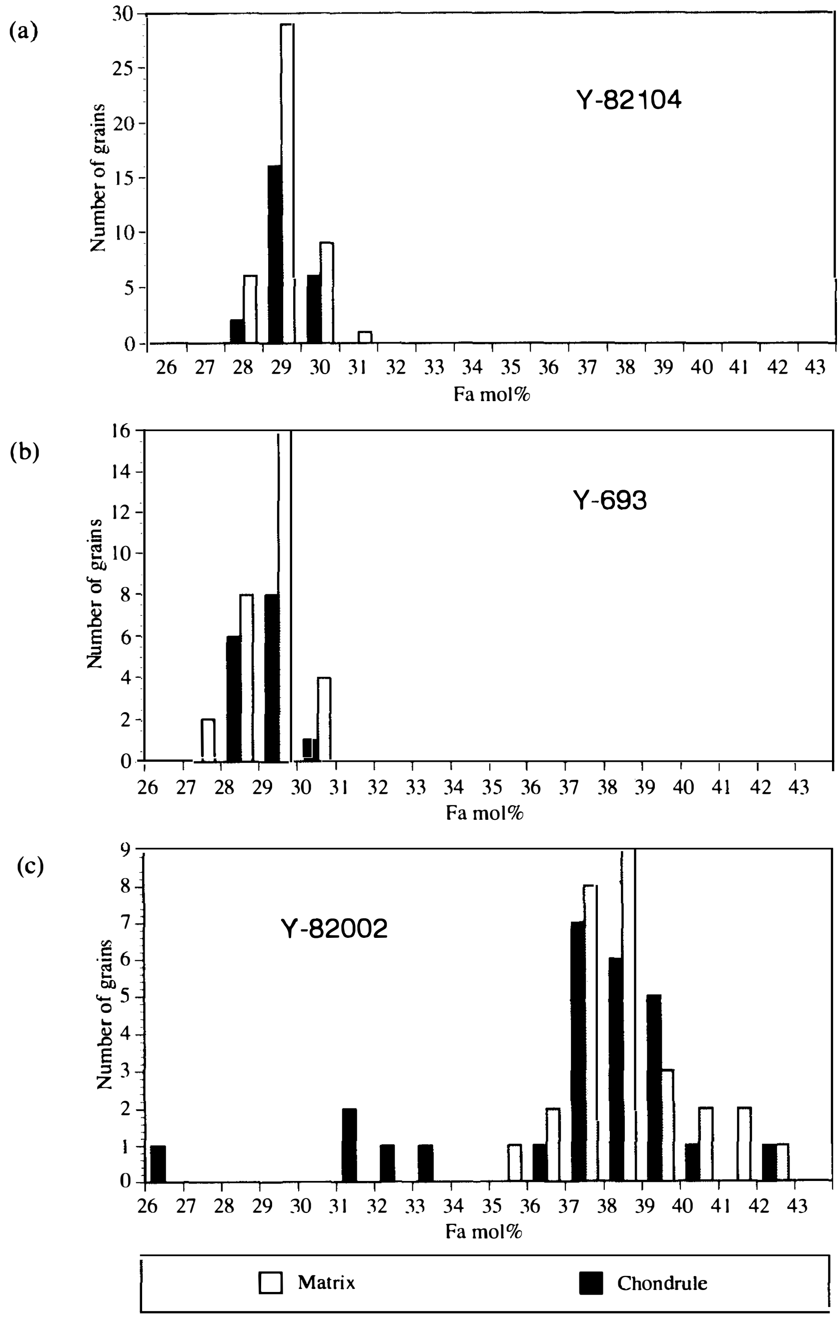

Fig. 2. Compositional distributions of olivine in (a) Y-82104, (b) Y-693, and (c) Y-82002. The distributions in Y-82104 and Y-693 are very similar and have narrower ranges than that in Y-82002. The distribution in Y-82002 has a peak at Fa 37–39, significantly beyond the range in Y-82104 and Y-693.

the thin sections were estimated from microphotographs by measuring areal ratios of chondrules and matrix. Y-82002 has highest abundance of chondrules (19 vol%), and Y-82104 (13 vol%) and Y-693 (11 vol%) have lower, but similar abundances of chondrules. Recognizable chondrules have apparent diameters of 300–800 μm for 17 chondrules in Y-82104, 200–800 μm for 15 chondrules in Y-693, and 200–500 μm for 22 chondrules in Y-82002; but two exceptionally large chondrules are observed, one 2 mm diameter porphyritic olivine chondrule in Y-82104 and the other 3 mm diameter barred olivine chondrule in Y-82002. Olivine in Y-82104 and Y-693 exhibits moderate to strong wavy extinction, whereas olivine in Y-82002 exhibits only weak wavy extinction. Dark, glassy to microcrystalline material, which is subrounded to elliptical in shape and 200–700 μm in diameter, occurs in some places in the matrices of Y-82104 and Y-693 (Figs. 1a and 1b); it is probably a localized shock-induced melt. No metallic phase was observed in any of our thin sections.

3.2. Y-82104

Chondrules are mostly porphyritic olivine type; granular olivine chondrules also occur in lesser amounts. Olivine in chondrules is very homogeneous (the mean Fa content is 29.5 ± 0.5 mol%) (Fig. 2a) and contains significant amounts of Ni ($\sim$0.48 wt% NiO) but trace amounts of Ca ($<$0.1 wt% CaO). Pyroxene is rare in chondrules; most are homogeneous low-Ca pyroxene with Fs 25.2 ± 1.8 (Fig. 3a).

Matrix consists largely of relatively coarsely recrystallized olivine (typically 50–200 μm occasionally up to 300 μm in diameter), plagioclase (10–50 μm occasionally up to 100 μm), magnetite ($<$1–5 μm occasionally up to 500 μm in diameter), and minor amounts of low-Ca pyroxene, pentlandite and pyrite (Fig. 4a). Olivine in matrix is very homogeneous (Fa 29.2 ± 0.4), and not only its Fa contents but also Ni and Ca contents are very close to those of olivine in chondrules ($\sim$0.37 wt% NiO and $<$0.1 wt% CaO). Low-Ca pyroxene is also homogeneous (Fs 25.8 ± 1.3) and has compositions similar to

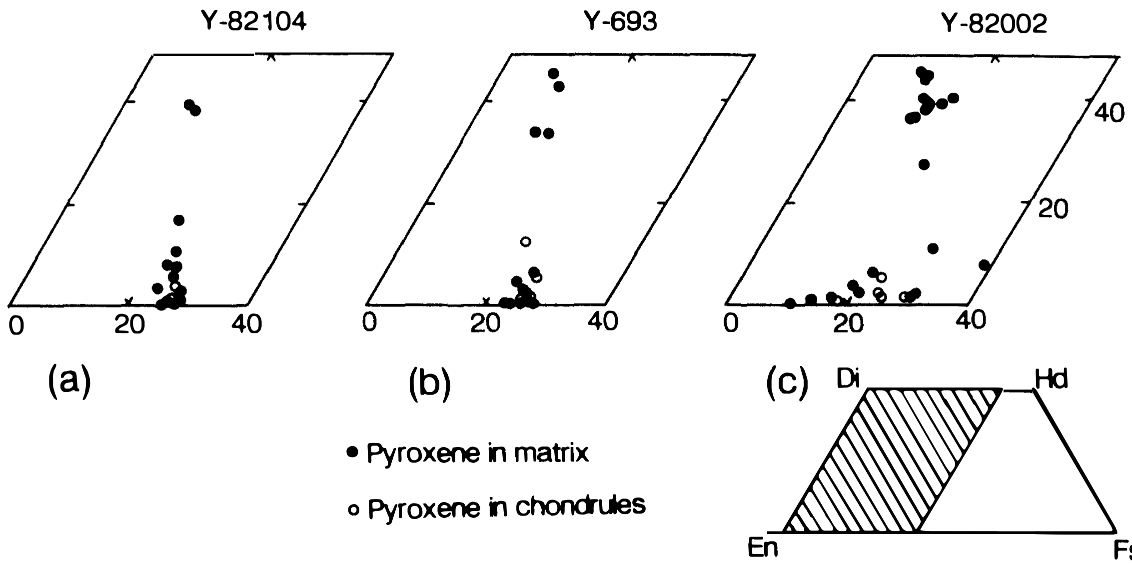

Fig. 3. Compositions of pyroxene in (a) Y-82104, (b) Y-693, and (c) Y-82002. Pyroxenes in Y-82104 and Y-693 are more equilibrated compared with those in Y-82002.

(a)
(b)
(c)

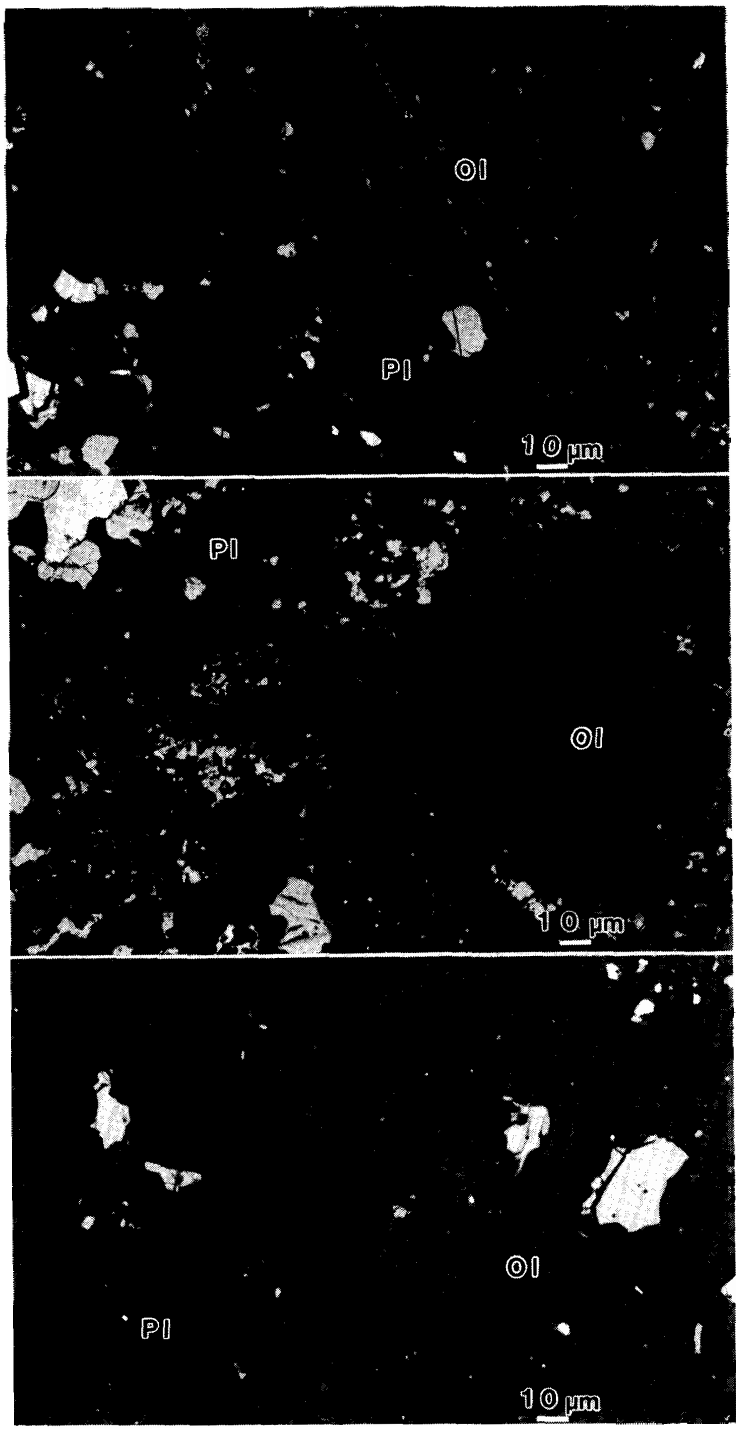

Fig. 4. Back-Scattered-Electron (BSE) images of matrices of (a) Y-82104, (b) Y-693, and (c) Y-82002. Olivine (Ol) and plagioclase (Pl) in the matrices of Y-82104 and Y-693 are coarser-grained than those in Y-82002. Many tiny (~3 μm) magnetite grains (bright grains) are dispersed in the matrices of Y-82104 and Y-693. In contrast, most bright grains in matrix of Y-82002 are pyrrhotite.

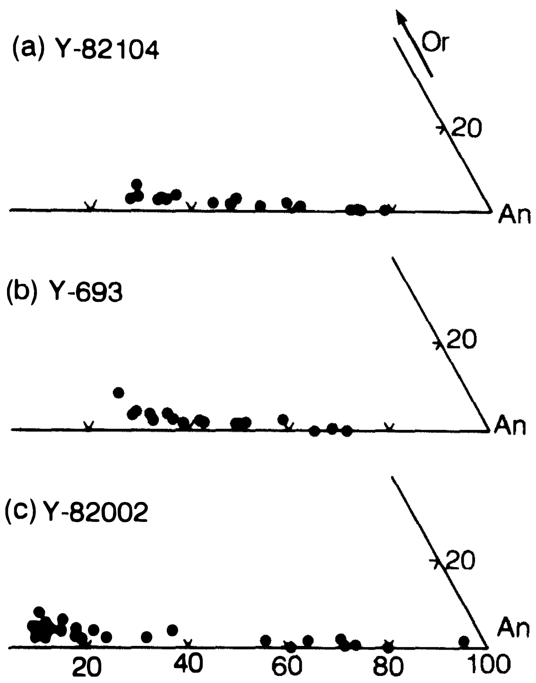

Fig. 5. Compositions of plagioclase in (a) Y-82104, (b) Y-693, and (c) Y-82002. Unlike olivine and pyroxene, plagioclase is heterogeneous in all of the meteorites. Plagioclase in Y-82002 has a wider range of compositions than those in Y-82104 and Y-693.

those in chondrules (Fig. 3a). In contrast, plagioclase in matrix is heterogeneous ranging from An28 to An79 (Fig. 5a). Low-Ca pyroxene in matrix commonly coexists with plagioclase and exhibits lath-like texture (Fig. 6a); such texture has not been reported from other metamorphosed carbonaceous chondrites except for Y-693 (OKADA, 1975).

Y-82104 contains a high abundance of magnetite; it occurs as micron-sized grains intermixed with olivine, pyroxene and plagioclase in both chondrules and matrix. Magnetite also occurs as relatively coarse grains (200–500 μm in diameter) which commonly contain lamellae of ilmenite and spinel that are typically 3–5 μm wide and 10–100 μm long (Fig. 7a). Some coarse magnetite grains coexist with pentlandite ($\sim$100 μm in diameter), minor pyrite ($\sim$50 μm) apatite ($\sim$30 μm) and chlorapatite ($\sim$30 μm). All magnetites contain appreciable Cr (up to about 4 wt% Cr_2O_3). Representative compositions of opaque minerals are shown in Tables 1 and 2.

3.3. Y-693

Most chondrules are porphyritic olivine type; granular olivine chondrules occur, but are rare. Olivine is the dominant silicate in chondrules and is very homogeneous (Fa 29.8 ± 1.4). The mean Fa content $\pm 1\delta$, and Ni and Ca contents in olivine in chondrules are very similar to those in Y-82104 chondrules ($\sim$0.50 wt% NiO and $<$0.1 wt% CaO). Low-Ca pyroxene in chondrules is also homogeneous (Fs 26.5 ± 1.7) and has a composition similar to that in Y-82104 chondrules.

The major constituents of matrix are olivine (typically 20–150 μm and occasionally up to 300 μm in diameter) and plagioclase (typically 10–40 μm and occasionally up to 70 μm), and the minor constituents include low-Ca pyroxene, magnetite and pentlandite

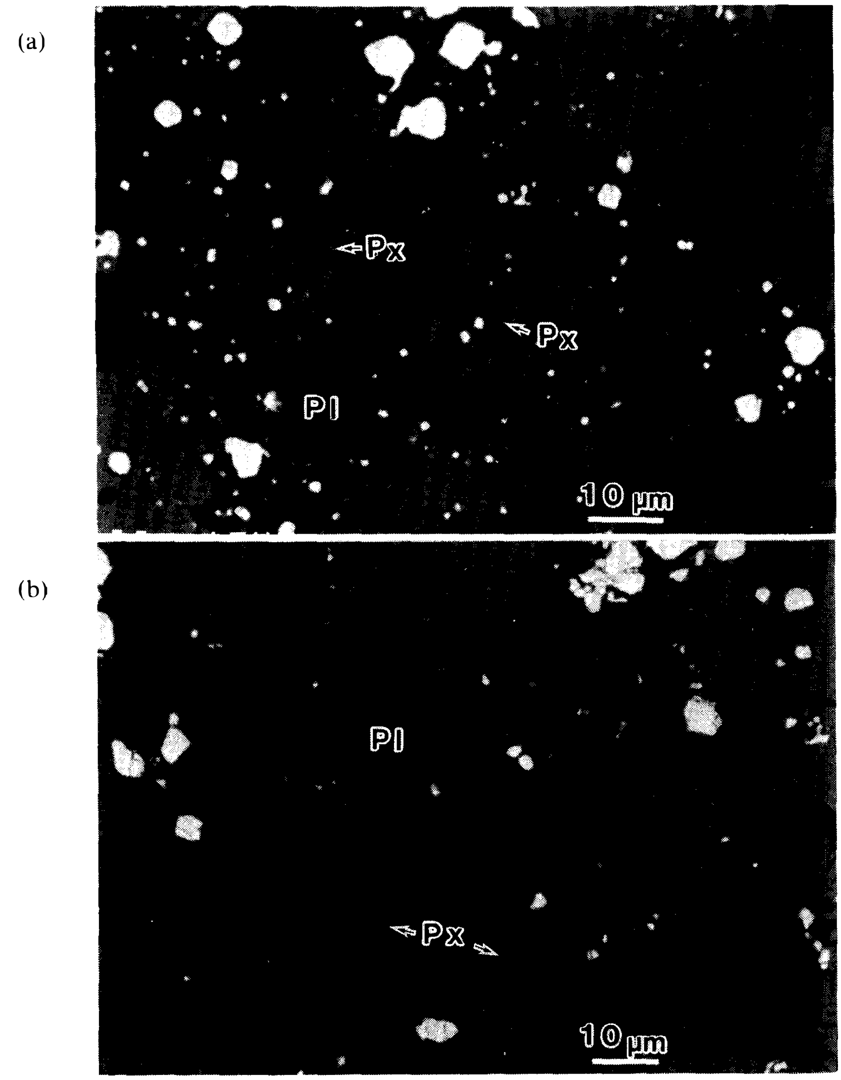

Fig. 6. BSE images of lath-like low-Ca pyroxene contained in plagioclase in the matrices of Y-82104 (a) and Y-693 (b).

(Fig. 4b). Olivine and low-Ca pyroxene in matrix are also very homogeneous (Fa 29.4 ± 0.7 and Fs 25.9 ± 1.5, respectively), and their compositions are close to those in the matrix of Y-82104 (Figs. 2b and 3b). Like within Y-82104, olivine and low-Ca pyroxene in matrix have compositions very similar to those in chondrules. Ni and Ca contents in olivine in matrix are almost equivalent to those in chondrules (~0.41 wt% NiO and <0.1 wt% CaO). Plagioclase is heterogeneous ranging from An 24 to An 71 (Fig. 5b). Low-Ca pyroxene shows lath-like texture (Fig. 6b) like the pyroxene in the matrix of Y-82104 (Fig. 6a).

Magnetite is abundant in both chondrules and matrix. The abundance and occurrence of magnetite resemble those of magnetite in Y-82104; micron-sized magnetite grains are dispersed in both chondrules and matrix, and coarse magnetite grains commonly contain lamellae of ilmenite and spinel as well as apatite and chlorapatite (Fig. 7b). In places, Os-, Ru-, and S-rich particles (<3 μm in diameter) occur in magnet-

(a)
(b)
(c)

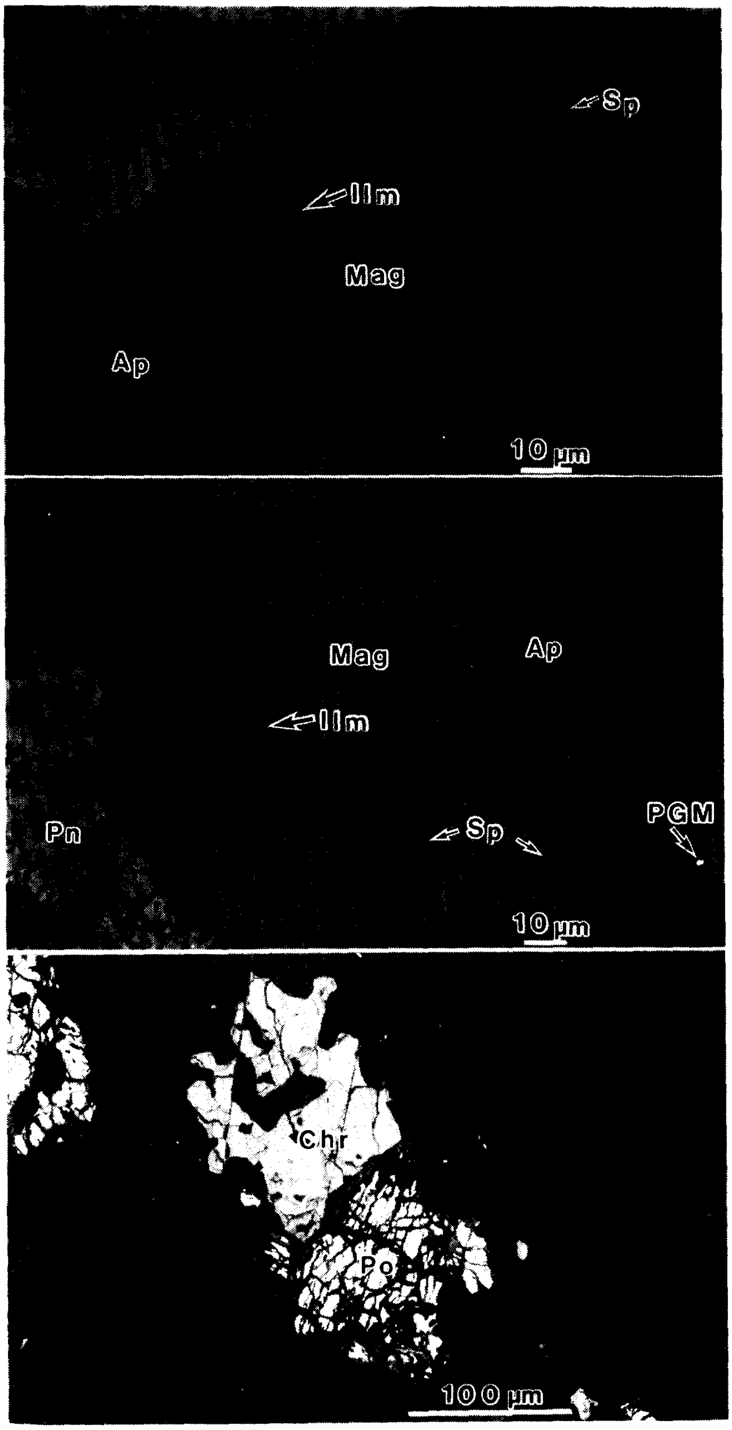

Fig. 7. (a) BSE image of a portion of a large aggregate (~500 μm in diameter) consisting mostly of magnetite (Mag) and pentlandite (Pn) in Y-82104. Magnetite contains lamellae of ilmenite (Ilm) and spinel (Sp), and apatite inclusions (Ap). (b) BSE image of a portion of a large aggregate (~350 μm in diameter) in Y-693. As well as Y-82104, lamellae of ilmenite (Ilm) and spinel (Sp), and apatite occur in magnetite. An Os-, Ru-, and S-rich particle (PGM) is present. (c) BSE image of an aggregate consisting of pyrrhotite (Po) and chromite (Chr) in Y-82002. A network of narrow veins of Fe-oxide occurs within the pyrrhotite.

Table 1. Representative compositions of sulfides.

	Y-82104		Y-693	Y-82002		
	pent.	pyrite	pent.	pent.	pyrr.	(wt%)
Fe	26.06	43.30	27.31	34.70	62.03	
Ni	39.39	0.96	38.55	28.58	0.54	
Co	0.86	1.12	0.81	1.78	0.16	
Cr	0.16	0.16	n.d.*	0.18	0.15	
S	33.70	49.77	32.13	33.08	36.58	
Total	100.17	95.31	98.80	98.36	99.46	

Abbreviations: pent., pentlandite; pyrr., pyrrhotite. * not detected.

Table 2. Representative compositions of magnetite and chromite.

	Magnetite		Chromite		
	Y-82104	Y-693	Y-82002		(wt%)
Na_2O	0.25	n.d.*	n.d.	n.d.	
MgO	n.d.	0.11	7.83	0.76	
Al_2O_3	n.d.	0.30	7.07	4.05	
SiO_2	n.d.	n.d.	0.27	n.d.	
K_2O	0.20	n.d.	n.d.	n.d.	
CaO	0.27	n.d.	n.d.	n.d.	
TiO_2	0.55	0.19	0.39	5.06	
Cr_2O_3	4.07	3.88	57.48	35.13	
MnO	0.07	0.02	0.20	0.38	
FeO	93.18#	94.79#	25.50	48.71	
NiO	1.13	0.25	0.05	0.08	
Total	99.71	99.54	94.16	98.81	

* not detected.
\# Total Fe is reported as Fe_3O_4.

ite. They might be a kind of platinum-group-minerals (PGM) previously reported by GEIGER and BISCHOFF (1989b, 1991b). Pentlandite is the major sulfide. These mineralogical and chemical features of both silicates and opaque phases are mostly consistent with those reported by OKADA (1975), SCOTT and TAYLOR (1985) and GEIGER and BISCHOFF (1990a).

TEM observations reveal that olivine in matrix contains screw dislocations with Burgers Vector b=[001]; dislocation densities range from 8×10^8 to 5×10^9 (Fig. 8a). Such high densities of dislocations are indicative of shock deformation (*e.g.*, ASHWORTH and BARBER, 1975). Low-Ca pyroxenes in matrix are predominantly orthopyroxene that is free of clinopyroxene lamellae and contains characteristic unit dislocations (Fig. 8b). These microtextures are commonly observed in olivine and pyroxene in shock-metamorphosed ordinary chondrites of type 4–6 (*e.g.*, ASHWORTH, 1985). Although

(a)

(b)

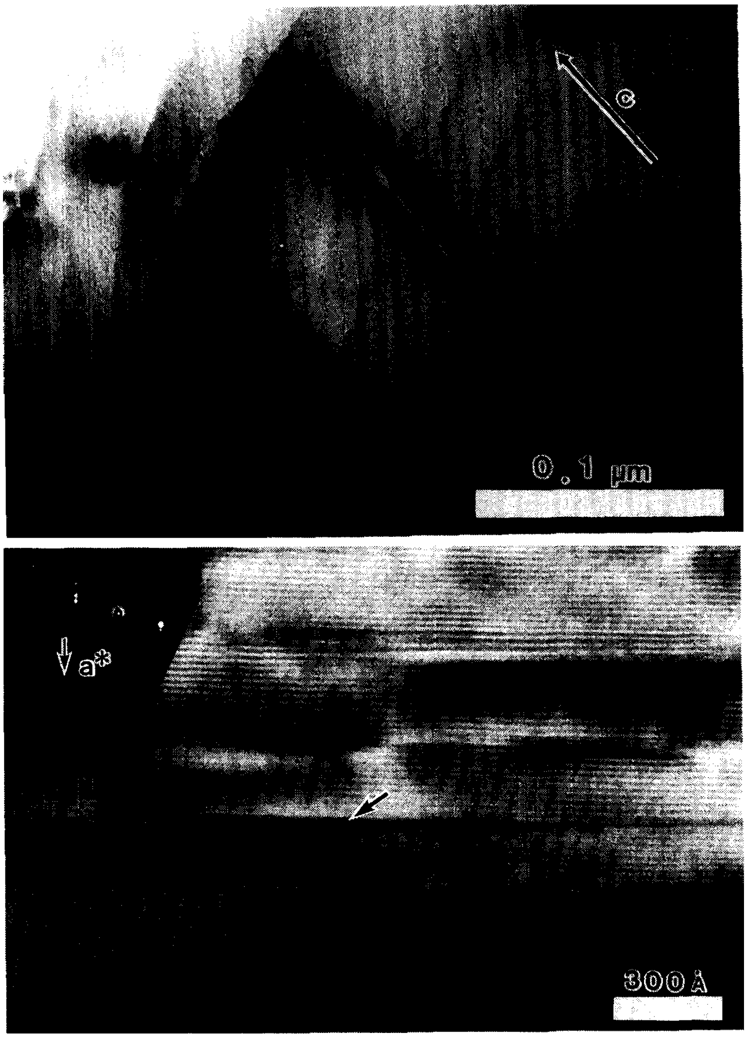

Fig. 8. (a) TEM image of a portion of an olivine grain in the matrix of Y-693 containing straight screw dislocations with Burgers vector b=[001]. (b) TEM image of a portion of a low-Ca pyroxene grain with its electron diffraction pattern (inset). The pyroxene exhibits only 18-Å fringes along (100) indicating it is orthopyroxene. Unit dislocations are present (the most pronounced one is indicated by an arrow).

these shock features are rare in carbonaceous chondrites, we have recently observed them in the CV3 chondrite, Leoville (NAKAMURA *et al.*, 1992).

3.4. Y-82002

Chondrules are mostly porphyritic olivine type; barred olivine chondrules occur, but are rare. Olivine in chondrules in this meteorite is less equilibrated (Fa 35.1 ± 5.1) than olivine in Y-82104 and Y-693 (Fig. 2c). The olivine in chondrules contains trace amounts of Ca (<0.1 wt% CaO). Ni concentrations are fairly low (~0.14 wt% NiO) compared with those of olivines in Y-82104 (~0.47 wt% NiO) and Y-693 (~0.50 wt% NiO). Low-Ca pyroxene in chondrules also has a much wider range in composition (Fs 23.7 ± 8.2) than that in Y-82104 and Y-693 (Fig. 3c).

Constituents of matrix are mostly similar to those in Y-82104 and Y-693, but they are smaller; olivine and plagioclase range in diameter from 10 to 50 μm (Fig. 4c). Like olivine in chondrules, olivine in matrix (Fa 37.3 ± 2.4) has much higher Fe concentrations and is less equilibrated than olivine in the matrices of Y-82104 and Y-693 (Fig. 2c). It should be also noted that unlike Y-82104 and Y-693, olivine in matrix has significantly higher Fa contents than olivine in chondrules (Fig. 2c). Olivine in matrix contains comparable Ca (<0.1 wt% CaO) and Ni (~0.14 wt% NiO) compared to olivine in chondrules. Pyroxene in matrix is heterogeneous and includes both high-Ca pyroxene (Fs 13.0–19.7 and Wo 27.8–46.3) and low-Ca pyroxene (Fs 9.7–39.8 and Wo 0.1–9.8) (Fig. 3c). Plagioclase has a wider compositional range (An 7–97 mol%) than those in Y-82104 and Y-693 with a large peak near 90 mol% Ab (Fig. 5c).

The opaque mineralogy of Y-82002 is distinctly different from that of Y-82104 and Y-693. Magnetite is absent in Y-82002, and instead pyrrhotite (10–200 μm in diameter) is the dominant opaque phase. Pyrrhotite contains minor amounts of Ni (<0.4 wt%). Minor pentlandite also occurs. Ni contents in pentlandite (~29 wt%) are lower than those in Y-693 and Y-82104 (both are ~40 wt%). An Fe-rich phase, presumably Fe hydroxide, forms network-like veins within the sulfides; it may have been formed from metal by terrestrial weathering (Fig. 7c). In many places of the matrix, subhedral to euhedral chromite grains (10–150 μm in diameter) occur commonly in coexistence with pyrrhotite (Fig. 7c). Chromite occurs in two compositionally different types; one is rich in Fe (~50 wt% FeO) and Ti (~5 wt% TiO_2), and the other is poor in Fe (~25 wt% FeO) and Ti (~0.5 wt% TiO_2). Representative compositions of pyrrhotite, pentlandite and chromite are listed in Tables 1 and 2.

4. Discussion

Our study reveals that Y-82104 and Y-693 are remarkably similar in mineralogy and texture in having the features: (1) virtually identical compositions of olivine (*e.g.*, Fa 29.2 ± 0.4 *vs.* Fa 29.4 ± 0.7 in matrix) and pyroxenes (Fs 25.8 ± 1.3 *vs.* Fs 25.9 ± 1.5 in matrix) (Figs. 2 and 3), (2) very similar chondrule sizes and degrees of coarsening of matrix minerals, (3) very similar abundances of chondrules (10–15 vol%), (4) high abundances of magnetite, some of which contain lamellae of ilmenite and spinel (Figs. 7a, b), (5) presence of characteristic dendritic texture of low-Ca pyroxene (Figs. 6a, b). Based on these features, we suggest that Y-82104 and Y-693 are probably paired. A minor but noticeable difference seen in these meteorites is that Y-82104 has coarser-grained matrix than Y-693; we believe the difference is probably due to sample inhomogeneity.

CK chondrites are known to have many distinct features in common (*e.g.*, SCOTT and TAYLOR, 1985; GEIGER and BISCHOFF, 1989a, 1990a, b, 1991b) such as: 1) homogeneous Fe-Mg silicates, 2) abundant magnetite, 3) heterogeneous plagioclase, 4) high NiO contents (0.33–0.72 wt%) and low CaO contents (<0.1 wt%) in olivine, 5) presence of ilmenite and spinel lamellae in magnetite and 6) occurrence of platinum-group-minerals. Almost all these features are observed in Y-82104 and Y-693, suggesting that They are classified as CK chondrites. KALLEMEYN *et al.* (1991) suggested that both Y-82104 and Y-693 are probably included with CK chondrites, although they did not study Y-82104. Oxygen isotope data for Y-82104 and Y-693 reported by MAYEDA *et al.* (1987) plot very close to each other within the cluster of CK chondrites in the three-oxygen-isotope diagram. These oxygen isotope data are consistent with our view that Y-82104 and Y-693 are paired CK chondrites.

Y-82104 was previously classified as petrologic type 5 (YANAI and KOJIMA, 1987), whereas Y-693 was classified as type 4 (OKADA, 1975; YANAI and KOJIMA, 1987; SCOTT and TAYLOR, 1985), although SCOTT (1985) once assigned Y-693 to type 5. Olivines and low-Ca pyroxenes in these meteorites show very small standard deviations in Fa and Fs contents, indicating that they are highly equilibrated. Both Y-82104 and Y-693 have relatively coarsely recrystallized olivines, 50–200 μm and 20–150 μm in diameter, respectively. On the basis of petrologic criteria of KALLEMEYN *et al.* (1991), the grain sizes of recrystallized olivines are consistent with a type 5 classification for Y-82104 and Y-693.

Y-82002 differs from CK chondrites in many respects. However, this meteorite has many features similar to Carlisle Lakes-type chondrites (RUBIN and KALLEMEYN, 1989; WEISBERG *et al.* 1991). Meteorites of this type are strongly characterized by Fe-rich silicates (Olivine Fa = 38–41 mol%) (RUBIN and KALLEMEYN, 1989). The most pronounced feature of Y-82002 is the high Fa contents of olivine (Fa 35–41) (Fig. 2c). Such high Fa values are not found in any type of chondrites. Other features indicating similarity to Carlisle Lakes-type chondrites include (1) high Ab contents (Ab 90) in plagioclase, (2) presence of high-Ca pyroxenes, (3) high abundance of pyrrhotite containing trace Ni, (4) presence of two compositionally different varieties of chromite. Based on these features, we suggest that Y-82002 should be included with the grouplet of Carlisle Lakes-type chondrites.

Y-82002 was previously classified as petrologic type 5, which is much higher than for other Carlisle Lakes-type chondrites (*e.g.*, Carlisle Lakes is type 3.8; ALH85151 is type 3.6; RUBIN and KALLEMEYN, 1989). Recrystallized olivine and plagioclase in Y-82002 are relatively smaller in size (10–50 μm). Chondrules in Y-82002 are more well-defined. Olivine and pyroxene in Y-82002 are not homogeneous. The coefficient of variations of olivine Fa $[(1\delta \pm /\text{mean Fa}) \times 100]$ is 14.5 for chondrules and 6.4 for matrix, suggesting that Y-82002 is assigned to petrologic type 3.8 or 3.9 (SEARS *et al.*, 1982).

Olivine in Y-82104 and Y-693 shows moderate to strong wavy extinction. Localized glassy material, probably a shock-induced melt, occurs in some places in the matrices of Y-82104 and Y-693 (Figs. 1a, b). TEM observations reveal that olivine in the matrix of Y-693 contains high densities of screw dislocations (Fig. 8a). All these observations are consistent with that Y-82104 and Y-693 experienced shock pressures of S3–S4 level (using the criteria of STÖFFLER *et al.*, 1991). On the other hand, olivine in Y-82002 shows only weak wavy extinction, suggesting that it has experienced milder shock pressures of probably S2 level (STÖFFLER *et al.*, 1991). TEM observations also reveal that low-Ca pyroxene in the matrix of Y-693 is predominantly orthopyroxene containing unit dislocations (Fig. 8b), suggesting that the low-Ca pyroxene initially contained clinopyroxene, but the clinopyroxene was transformed to orthopyroxene with unit dislocations by thermal annealing (ASHWORTH *et al.*, 1984).

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References

ASHWORTH, J. R. (1985): Transmission electron microscopy of L-group chondrites, 1. Natural shock effects. Earth Planet. Sci. Lett., **73**, 17–32.

ASHWORTH, J. R. and BARBER, D. J. (1975): Electron petrography of shock-deformed olivine in stony meteorites. Earth Planet. Sci. Lett., **27**, 43–50.

ASHWORTH, J. R., MALLINSON, L. G., HUTCHISON, R. and BIGGER, G. M. (1984): Chondrite thermal histories constrained by experimental annealing of Quenggouk orthopyroxene. Nature, **308**, 259–261.

BINNS, R. A. and POOLEY, G. D. (1979): Carlisle Lakes (a): A unique oxidized chondrite. Meteoritics, **14**, 349–350.

BLAND, P., HUTCHISON, R., PILINGER, C. T. and BISCHOFF, A. (1992): A unique type 4 chondrite from the Sahara-Acfer 217. Meteoritics, **27**, 204.

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

GEIGER, T. and BISCHOFF, A. (1989a): Mineralogy of the metamorphosed carbonaceous chondrites. Meteoritics, **24**, 269–270.

GEIGER, T. and BISCHOFF, A. (1989b): (Os, Ru, Ir)S_2 and other refractory siderophile element-rich particles in the metamorphosed carbonaceous chondrites Karoonda, Mulga (west), and PCA82500. Lunar and Planetary Science XX. Houston, Lunar Planet. Inst., 335–336.

GEIGER, T. and BISCHOFF, A. (1990a): The metamorphosed carbonaceous chondrites—A new meteorite group? Papers Presented to the 15th Symposium on Antarctic Meteorites, May 30–June 1, 1990. Tokyo, Natl Inst. Polar Res., 77-80.

GEIGER, T. and BISCHOFF, A. (1990b): Exsolution of spinel and ilmenite in magnetites from type 4–5 carbonaceous chondrites—Indications for metamorphic processes. Lunar and Planetary Science XXI. Houston, Lunar Planet. Inst., 409–410.

GEIGER, T. and BISCHOFF, A. (1991a): Maralinga—A new metamorphosed carbonaceous chondrite. Lunar and Planetary Science XXII. Houston, Lunar Planet. Inst., 433.

GEIGER, T. and BISCHOFF, A. (1991b): The CK chondrites—Conditions of parent body metamorphism. Meteoritics, **26**, 337.

GEIGER, T. and BISCHOFF, A. (1992): Mineralogy of carbonaceous chondrites and of Acfer 217 from the Sahara. Meteoritics, **27**, 223.

GRAHAM, A. L. and YANAI, K. (1986): A review of the Yamato-80, -81 and -82 meteorite collections. Mem. Natl Inst. Polar Res., Spec. Issue, **41**, 167–180.

KALLEMEYN, G. W., RUBIN, A. E. and WASSON, J. T. (1991): The compositional classification of chondrites: V. The Karoonda (CK) group of carbonaceous chondrites. Geochim. Cosmochim. Acta, **55**, 881–892.

MAYEDA, T. 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.

NAKAMURA, T., TOMEOKA, K. and TAKEDA, H. (1992): Shock effects of in the Leoville CV carbonaceous chondrite: A transmission electron microscope study. Earth Planet. Sci. Lett., **114**, 159–170.

OKADA, A. (1975): Petrological studies of Yamato meteorites, Part 1. Mineralogy of the Yamato meteorites. Mem. Natl Inst. Polar Res., Spec. Issue, **5**, 14–66.

RUBIN, A. E. and KALLEMEYN, G. W. (1989): Carlisle Lakes and Allan Hills 85151: Members of new chondrite grouplet. Geochim. Cosmochim. Acta, **53**, 3035–3044.

SCOTT, E. R. D. (1985): Further petrologic studies of metamorphosed carbonaceous chondrites. Lunar and Planetary Science XIV. Houston, Lunar Planet. Inst., 748.

SCOTT, E. R. D. and TAYLOR, G. J. (1985): Petrology of type 4-6 carbonaceous chondrites. J. Geophys. Res., **90**, 699–709.

SEARS, D. W., GROSSMAN, J. N. and MELCHER, C. L. (1982): Chemical and physical studies of type 3 chondrites—I: Metamorphism related studies of Antarctic and other type 3 ordinary chondrites. Geochim. Cosmochim. Acta, **46**, 2471–2481.

STÖFFLER, D., KEIL, K. and SCOTT, E. R. D. (1991): Shock metamorphism of ordinary chondrites. Geochim. Cosmochim. Acta, **55**, 3845–3867.

YANAI, K. (1992): Bulk composition of Yamato-793575 classified as Calisle Lakes-type chondrite. Lunar and Planetary Science XXIII. Houston, Lunar Planet. Inst., 1559.

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

WEISBERG, M. K., PRINZ, M., KOJIMA, H., YANAI, K., CLAYTON, R. N. and MAYEDA, T. K. (1991): The Carlisle Lakes-type chondrites: A new grouplet with high $\Delta^{17}O$ and evidence for nebular oxidation. Geochim. Cosmochim. Acta, **55**, 2657–2669.

WLOTZKA, F. (1992): The meteoritical bulletin, No. 73. Meteoritics, **27**, 477–483.

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