

## YAMATO-82042: AN UNUSUAL CARBONACEOUS CHONDRITE WITH CM AFFINITIES

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**Abstract:** The Yamato-82042 carbonaceous chondrite has been the subject of a consortium study, designed to determine its properties and hence attempt a more precise classification of the meteorite. Major and minor elemental abundance and oxygen isotope data indicate that the specimen is a CM chondrite, but on textural and petrologic grounds the meteorite is more akin to CI stones. It is possible that Y-82042 is the first CM1 chondrite recognized.

### 1. Introduction

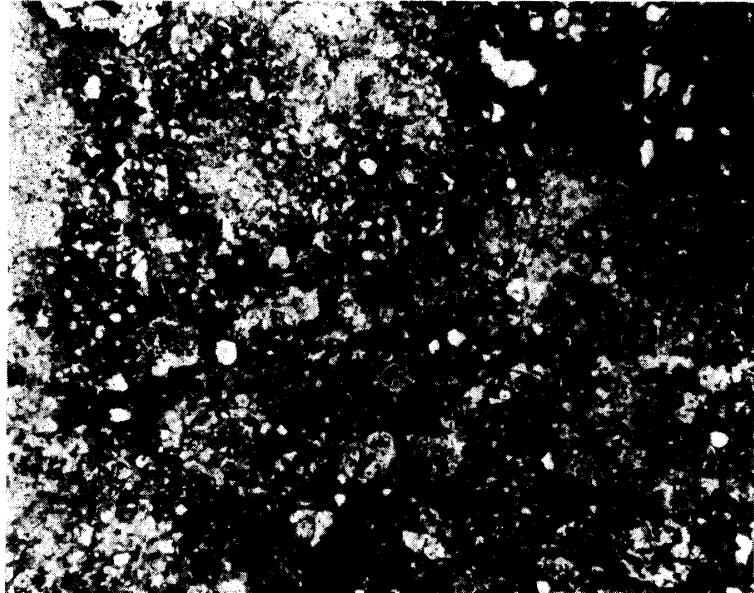
The 1982–1983 Japanese exploration of the Yamato Mountains in Antarctica yielded over two hundred meteorites (YANAI and KOJIMA, 1985), even though part of the area explored overlapped with regions covered in the 1974 and 1979 seasons. Of the samples returned, ten proved to be carbonaceous chondrites, including the unusual meteorite Yamato-82042. This specimen, an angular fragment weighing 37.08 g, was found to be almost totally covered by black fusion crust, and had apparently suffered little terrestrial oxidation. Only on one face of the stone had the fusion crust been partially weathered away, leaving a pale surface coated with sulphates and clay minerals. The relatively unaltered appearance of Y-82042 is unusual for Antarctic carbonaceous chondrites, which, being of a friable nature, are usually heavily weathered. One implication of this observation is that Y-82042 possibly has a very short terrestrial age. The interior of the specimen is dull dark grey and apparently chondrule-free with few visible individual crystals or mineral fragments. Also, unusually for a carbonaceous chondrite, there are no cross-cutting veins of sulphate and carbonate minerals.

The above observations, coupled with a preliminary thin-section description and probe data for individual olivines led to the suggestion that Y-82042 was possibly a CI chondrite (GRAHAM *et al.*, 1985), and therefore worthy of much more detailed examination. A consortium study was initiated to prepare a complete description of the meteorite in terms of mineralogy, petrology and chemistry. This paper attempts to draw together the principal results of the consortium, and is presented in several sections,

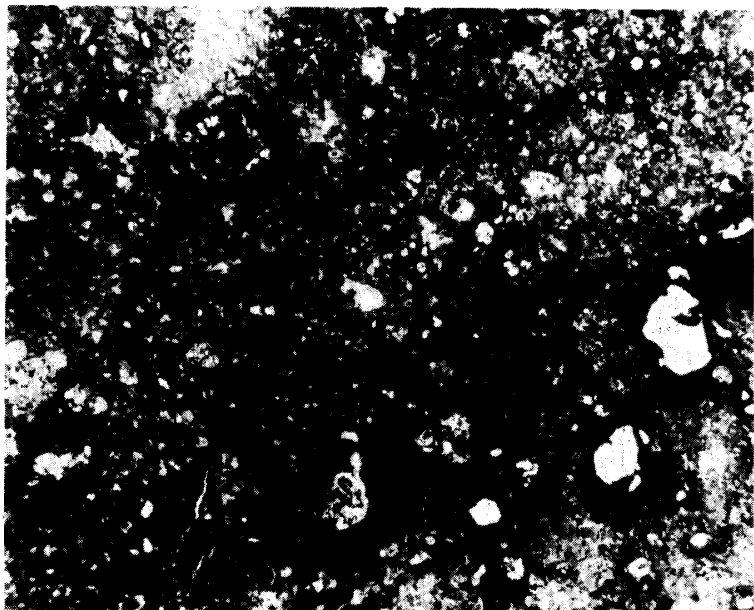
reflecting each aspect of the study.

## 2. Mineralogy and Petrology

The mineralogy is dominated by the abundant, fine-grained phyllosilicate matrix. This has been examined by transmission electron microscopy (TEM) and is discussed in the next section. The non-phyllosilicate mineralogy is principally olivine, carbonates and very minor sulphides. Pyroxene has not been observed in this stone. The olivines and carbonates occur as single crystals and also as crystal aggregates irregularly dispersed throughout the matrix (Fig. 1). Chondrules are very rare, though there are rounded carbonate and phyllosilicate aggregates (Fig. 2). Olivines are *ca.* 30  $\mu\text{m}$  in diameter, though a few range up to 100  $\mu\text{m}$ . The modal proportion is low when compared with other CM2 chondrites, but higher than that of CI stones. The composition



*Fig. 1. Thin section micrograph of Y-82042. The field consists mainly of phyllosilicates with minor olivine and carbonate. Field width = 2 mm, plane polarized illumination.*



*Fig. 2. Thin section micrograph showing phyllosilicate matrix with olivine phenocrysts surrounded by dark phyllosilicate coronas and a round carbonate-rich object (chondrule?). Field width = 2 mm, plane polarized illumination.*

ranges from Fa<sub>0</sub> to Fa<sub>36</sub>, but the large majority of the olivines are more magnesian than Fa<sub>1</sub>. Most forsterites are surrounded by a corona of dark brown phyllosilicates, with a gradational boundary between this and the lighter brown matrix phyllosilicates (Fig. 2). Some olivines are zoned, becoming more iron-rich towards the rim. Occasionally this iron-enrichment is very slight, but there is a marked change in the minor element contents. One grain was examined which showed two distinct zones differing markedly in their minor element contents with no gradation between them (Table 1, columns 2 and 3). This olvine shows minor element trends similar to those described by STEELE (1986) which are characteristic of crystals with a two-stage history. Included within this crystal are rounded blebs of low-Ni metal and Ca-Al-rich glass. A few olivines contain metal grains up to 10  $\mu\text{m}$  across, but there is no metal visible in the matrix of the stone. The composition of these metal grains averages 6.3–7.6% Ni, 0.4% Si, 0.5% P and 0.4% Co. Although most of the olivines show little serpentinization, there are a few subhedral crystals of altered olvine, which tend to be more Fe-rich than the fresher grains, and are not surrounded by the brown phyllosilicate corona.

Table 1. Electron microprobe analyses of olivines and carbonates in Y-82042.

Analysis	1	2	3	4	5	6	7	8
SiO <sub>2</sub>	42.3	43.4	42.8	39.7	38.5	0.40	0.15	0.12
TiO <sub>2</sub>	—	—	—	—	—	—	—	—
Al <sub>2</sub> O <sub>3</sub>	0.25	0.21	0.03	0.03	0.05	—	—	—
Cr <sub>2</sub> O <sub>3</sub>	—	0.05	0.19	0.29	0.44	—	—	—
FeO	1.27	0.26	0.56	16.7	21.9	3.94	6.00	0.39
MnO	0.07	0.01	0.02	0.17	0.22	2.68	2.33	0.29
MgO	55.9	56.5	57.3	43.3	37.7	16.9	16.7	0.10
CaO	0.54	0.54	0.05	0.16	0.17	29.5	28.6	56.0
CO <sub>2</sub> *	—	—	—	—	—	45.7	45.8	44.0
Total	100.33	100.97	100.95	100.35	98.98	99.12	99.58	100.90
Fa	1.3	0.3	0.5	17.8	24.6			

1. Isolated olvine crystal. 2. Interior of olvine phenocryst. 3. Exterior zone of 2. 4, 5. Isolated olvine crystals. 6, 7. Twinned dolomite. 8. Calcite.

\* CO<sub>2</sub> by stoichiometry.

In contrast to the olvine, carbonate minerals are present in higher proportion in Y-82042 than in other groups of carbonaceous chondrites. They occur either as discrete crystals within the matrix or as chondrule-like objects. Matrix carbonates are twinned calcite, dolomite and ankeritic (*i.e.* iron-rich, up to 9 wt% FeO) dolomite, all ranging up to 30  $\mu\text{m}$  in size; some of the dolomites also contain up to 4 wt% MnO. These minerals do not show distinct boundaries with the matrix (Fig. 3), but rather their outer edges grade into porous phyllosilicates and hydrous calcium sulphates.

Rounded, chondrule-like carbonate objects, containing Mg-Cr spinel, are less common than the matrix carbonates. Irregular, carbonate-rich aggregates have also been observed, containing Mg-Al spinel and Al-rich phyllosilicate, enveloped by dolomite.

In addition to olivines and carbonates, minor opaque minerals are scattered throughout the matrix: sulphides, metal oxides and metal. Sulphides are mainly troilite (containing up to 1.6% Ni) and pentlandite, the latter occurring with two distinct compositions:

Fig. 3. TEM micrograph of the boundary region between a carbonate grain (Mn-rich dolomite) and the phyllosilicate ground-mass (upper left). Arrows indicate the contact. The apparent sharp "edge" is a cleavage plane in the dolomite, which had composition MgO 36.7, CaO 54.0, MnO 3.2, FeO 6.1 wt%.



- (1) 49% Fe, 13% Ni; 0.22% Co,
- (2) 29% Fe; 34% Ni; 3.2% Co.

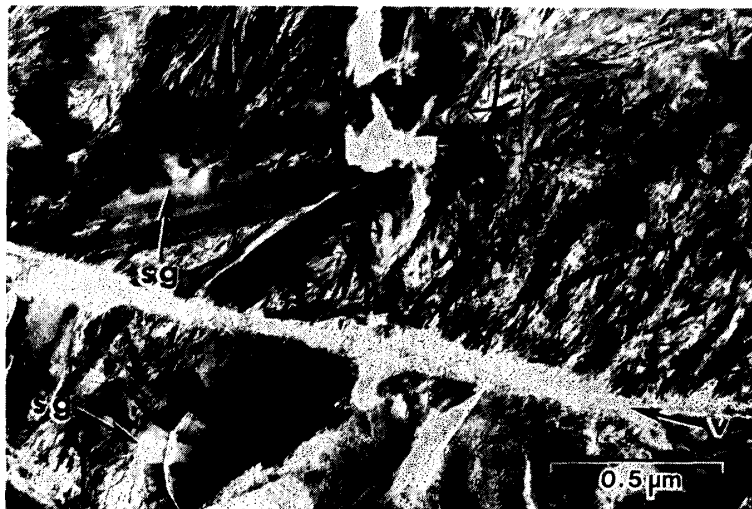
There are also two dominant metal oxide compositions, one with chondritic Ni/Co ratio (*ca.* 22), the other (produced by oxidation of metal) with Ni/Co *ca.* 10. Metal is rare in the matrix, and mostly occurs as rounded grains within olivines, as discussed above.

Neither pyroxenes nor high temperature calcium-aluminium inclusions (CAI's) have been found within the matrix, but the irregular aggregates surrounded by dolomite are similar in form to the CAI's rimmed by diopside which occur in CM2 chondrites.

### 3. Matrix

The matrix of Y-82042 consists of abundant sub-rounded aggregates of phyllosilicates embedded in a groundmass of very fine-grained and, occasionally, amorphous material. In thin section, the matrix is similar in appearance to that of Orgueil and Cold Bokkeveld, but is distinct from other CM chondrites (BARBER, 1981) and is not cut by optically-visible alteration veins. Part of the matrix is altered olivine-like

Fig. 4. TEM micrograph showing various phyllosilicate growth morphologies within a chondrule-like object, which exhibits a thin vein (arrow v) filled with amorphous material. Chrysotile grains with sectored growth morphologies (arrows Sg) are common, but acicular forms predominate, here in very fine-grained form.



crystals, with Fe/(Fe+Mg) ranging from 0.22 to 0.58. Carbonates are also important matrix constituents and representative compositions are given in Table 1.

Study of the matrix using TEM/EDS methods indicates that most of the phyllosilicates are serpentine-type minerals, with basal spacings in the range 7.17 to 7.30 Å. These phyllosilicates exhibit a variety of growth forms in both the groundmass and the chondrule-like objects, from which an interior microstructure is illustrated in Fig. 4. Electron diffraction data show that one of the more common phyllosilicates is an orthorhombic type with typical interplanar spacings:  $d(001)=7.17$  Å,  $d(020)=4.60$  Å,  $d(200)=2.67$  Å and  $d(201)=2.52$  Å. The phyllosilicate composition is usually in the ranges MgO: 25–39 wt%, SiO<sub>2</sub>: 37–41 wt%, FeO: 17–30 wt%, Al<sub>2</sub>O<sub>3</sub>: 1–3 wt%, with minor Cr<sub>2</sub>O<sub>3</sub> and MnO. Acicular and platy forms of this material occur, and where it is coarse-grained and has intercrystalline porosity, there are significant concentrations of dispersed Fe/Ni sulphides. Sulphides are even more highly concentrated in the coarse-grained phyllosilicates which characterize the matrix regions rimming chondrule-like objects.

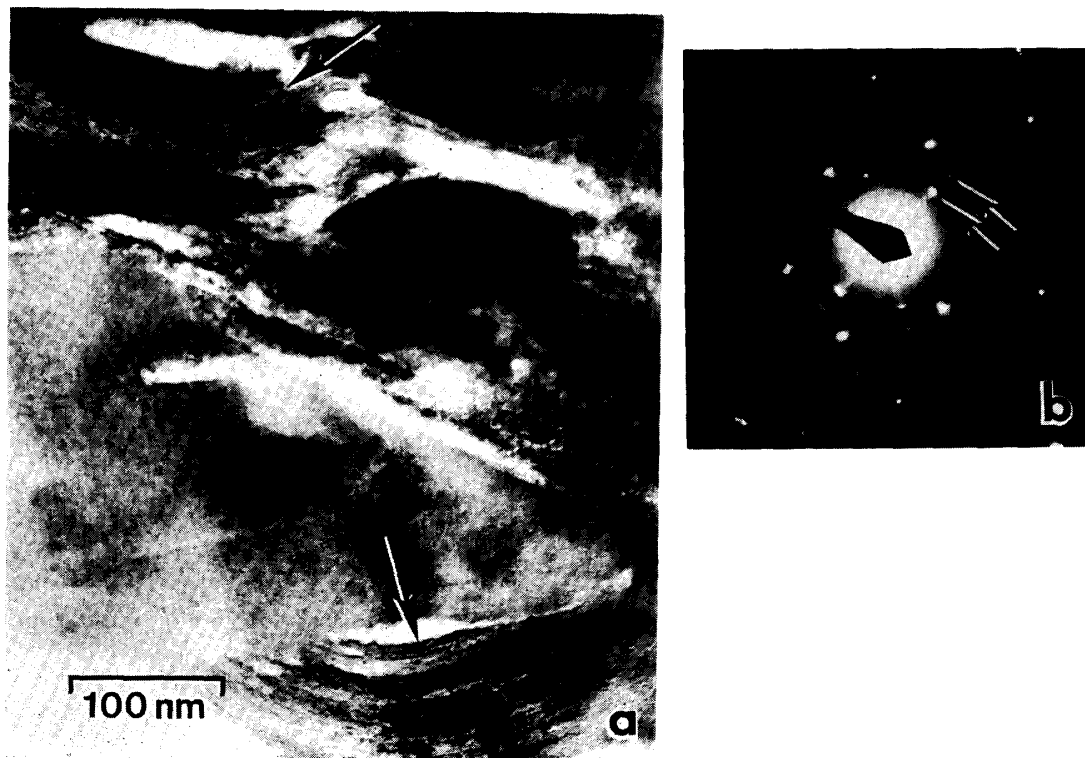


Fig. 5. (a) TEM micrograph showing poorly characterized phases (PCP) in matrix of Y-82042. Lattice fringes in the arrowed fibres correspond to 10.8 and 17.9 Å. (b) Electron diffraction from PCP giving a strong systematic row of reflections corresponding to 17.9 Å (arrows give reciprocal spacing).

Minor amounts of chlorite-montmorillonite have also been identified in the groundmass matrix, but the Fe-rich serpentine (cronstedtite) common in many CM's (MÜLLER *et al.*, 1979; BUNCH and CHANG, 1980; BARBER, 1981) is absent. Intimately dispersed within the groundmass are very minor amounts of poorly characterized phases, PCP (FUCHS *et al.*, 1973), now believed to consist mostly of tochilinite (MACKINNON and

ZOLENSKY, 1984). In Y-82042, fibres and sheets of PCP giving the 10.8 Å tochilinite basal spacing (BARBER *et al.*, 1983) are not well-developed. However interlayered fibres showing 17.9 Å lattice fringes (AKAI, 1980) have also been found, as shown in Fig. 5a, and in some regions the interlayering is sufficiently extensive to give diffraction spacings corresponding to 17.9 Å, as shown in Fig. 5b. Such basal spacings have been explained in terms of a tochilinite interlayer model by MACKINNON and ZOLENSKY (1984).

Carbonates in the groundmass of Y-82042 are also often intimately intergrown with phyllosilicates. Analysis by TEM/EDS has further revealed the presence of the unusual minerals carbonate fluorapatite ( $\text{Ca}_5(\text{PO}_4, \text{CO}_3, \text{OH})_3(\text{F}, \text{OH})?$ ) and calcium silicate sulphate hydrate ( $\text{Ca}(\text{SiO}_4, \text{SO}_4) \cdot n\text{H}_2\text{O}?$ , which has an apatite structure).

#### 4. Major and Minor Element Composition

Wet chemical analysis of Y-82042 is given in Table 2 (from GRAHAM and YANAI, 1986); data for most major elements were close to those of other CM chondrites. Major and minor elements were determined by instrumental neutron activation analysis (INAA) on two pieces of the meteorite (137.7 mg and 72.86 mg). The results

Table 2. Bulk chemical analysis of Y-82042 (GRAHAM and YANAI, 1986).

SiO <sub>2</sub>	25.52	K <sub>2</sub> O	0.03
TiO <sub>2</sub>	0.15	H <sub>2</sub> O (–)	6.77
Al <sub>2</sub> O <sub>3</sub>	1.58	H <sub>2</sub> O (+)	14.57
Fe <sub>2</sub> O <sub>3</sub>	15.14	P <sub>2</sub> O <sub>5</sub>	0.25
FeO	6.69	Cr <sub>2</sub> O <sub>3</sub>	0.43
MnO	0.26	FeS	6.90
MgO	18.79	Ni	0.53
CaO	1.69	Co	<0.03
Na <sub>2</sub> O	0.48	Total	99.78

Analyst: H. HARAMURA. Note: H<sub>2</sub>O (+) represents all the volatiles lost up to 1100°C and includes 1.1% C.

are given in Table 3 and Fig. 6. For comparison, data on the two CM2 chondrites Murchison and Murray, obtained using the same technique, are given. The close agreement between the Y-82042 and the Murchison and Murray analyses (Fig. 6) is remarkable and leaves no doubt with respect to the classification of Y-82042 as a CM meteorite. The Fe/Mn (Fig. 7) ratio is a suitable discriminator for classifying carbonaceous chondrites, and Y-82042 falls into the cluster of CM's. The same is true for the volatile elements Se and Zn (Fig. 8). Their abundances significantly decrease from CI to CO and CV. Again, Y-82042 plots in the field of CM meteorites.

Na, K and Br are the only elements listed in Table 3 with large differences in concentration between Y-82042 and Murray and Murchison respectively. As pointed out by SPETTEL *et al.* (1978), Na, K, Cl and Br are the elements with the largest, unsystematic variations among carbonaceous chondrites. In particular, there is a spread in the Na contents of CM meteorites from 1400 ppm to about 4600 ppm (unpublished data, MPI-Mainz). KALLEMEYN and WASSON (1981) found even lower Na contents in

Table 3. Bulk major and trace element contents of Y-82042.

Element	Y-82042		Murray (1)	Murchison (1)	Standard deviation %
	A 137.7 mg	B 72.86 mg			
Mg	11.07	1.70	11.90	11.48	3
Al	1.10	1.06	1.17	1.16	3
Ca	1.0*	0.80*	0.94	1.39	10
Ti	0.030*	0.052*	—	0.050	10
Fe	19.48	21.91	21.38	21.21	3
Na	3540	3570	1920	1420	3
K	365	365	300	250	5
Cr	2730	3030	3100	3100	3
Mn	1625	1690	1720	1740	3
Ni	12800	15200	12500	13700	4
Sc	7.76	9.14	8.62	8.75	3
V	64.4	68.4	—	—	5
Co	534	648	589	589	3
Cu	110*	103*	320*	141	10
Zn	200	176	235	176	10
Ga	7.99	7.85	8.80	7.44	8
As	1.84	1.74	1.86	1.86	5
Se	12.4	14.3	12.2	12.7	6
Br	7.31	7.28	1.33	0.50*	6
Mo	0.91	1.10	—	1.24	15
Ru	0.90	0.99	0.60	0.94	25
Sb	0.11*	0.12*	0.18*	0.10	7
La	0.30*	0.29*	0.44*	0.36*	5
Sm	0.20	0.20	0.215	0.21	5
Eu	0.065*	0.069*	0.090*	0.084	5
Dy	0.34*	0.33*	—	0.36	5
Yb	0.20*	0.22*	0.26*	0.26	7
Lu	0.030*	0.030*	0.032*	0.038	7
Hf	0.14	0.16	—	0.18	20
Re	0.046*	0.058*	—	0.051	7
Os	0.68*	0.75*	0.65*	0.87	5
Ir	0.563	0.684	0.593	0.660	4
Pt	1.1*	1.2*	—	1.29	10
Au	0.160	0.162	0.159	0.150	4

\* Accuracy reduced by a factor of two. (1) Unpublished results, MPI, Mainz. Major elements in wt%, minor and trace elements in ppm.

Murray, and variable concentrations in Murchison. The reason for these variations is not really known. The K concentrations follow this trend to a smaller extent. Although the Cl and Br concentrations also appear to vary with the alkali metals (SPETTEL *et al.*, 1978), the >7 ppm Br in Y-82042 is far too high for a carbonaceous chondrite. It is possible that Br was introduced during weathering in the Antarctic.

Taken together, these data once more demonstrate the tight compositional clustering of carbonaceous chondrites, despite large differences in mineralogy. Any alteration must have been isochemical, since even samples of tenth of milligrams have the same

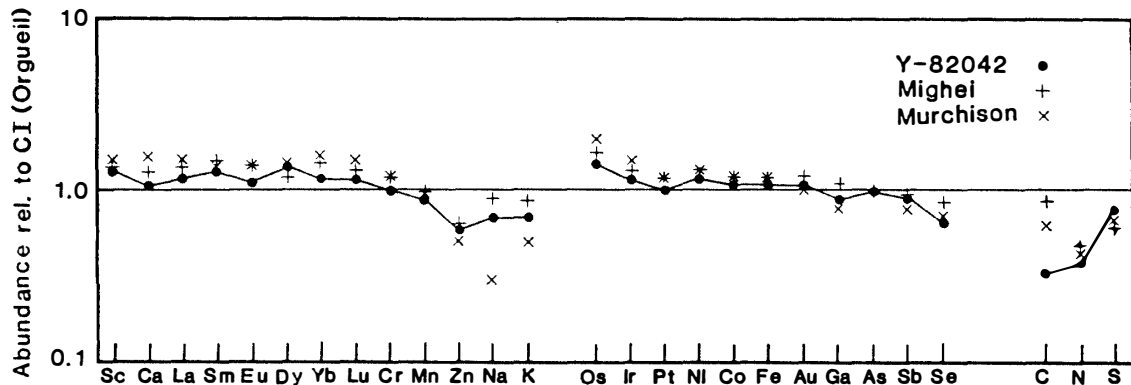


Fig. 6. Major and minor element abundance data from Y-82042, compared to those of Murchison and Mighei. Normalized to abundances in Orgueil C11 chondrite.

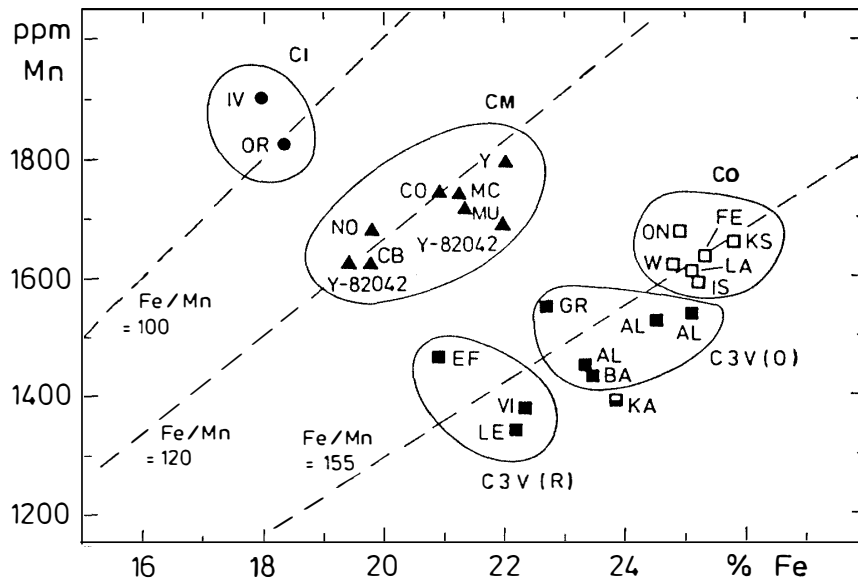


Fig. 7. Fe vs. Mn in carbonaceous chondrites. Two Y-82042 samples fall into the cluster of CM meteorites. Unpublished data MPI (Cosmochemistry), Mainz. Abbreviations: IV-Ivuna; OR-Orgueil; CB-Cold Bokkeveld; CO-Cochabamba; MC-Murchison; MU-Murray; NO-Nogoya; Y-Y-74662; FE-Felix; IS-Isna; KS-Kainsaz; LA-Lancé; ON-Ornans; W-Warrenton; AL-Allende; BA-Bali; GR-Grosnaja; EF-Efremovka; LE-Leoville; VI-Vigarano; KA-Karoonda. C3(V)O-oxidized and C3(V) R-reduced type C3(V) chondrites, respectively.

chemical composition.

## 5. Light Element Stable Isotopes

### 5.1. Oxygen

Whole-rock analysis of Y-82042 for oxygen yields an isotopic composition which plots within the CM range. As may be seen from Fig. 9, the point for Y-82042 ( $\delta^{18}\text{O} = +8.46\%$  relative to SMOW;  $\delta^{17}\text{O} = +2.35\%$ ) falls along the CM matrix line (CLAYTON *et al.*, 1976). Acid dissolution (see below) also allows measurement of the  $\delta^{18}\text{O}$  of the



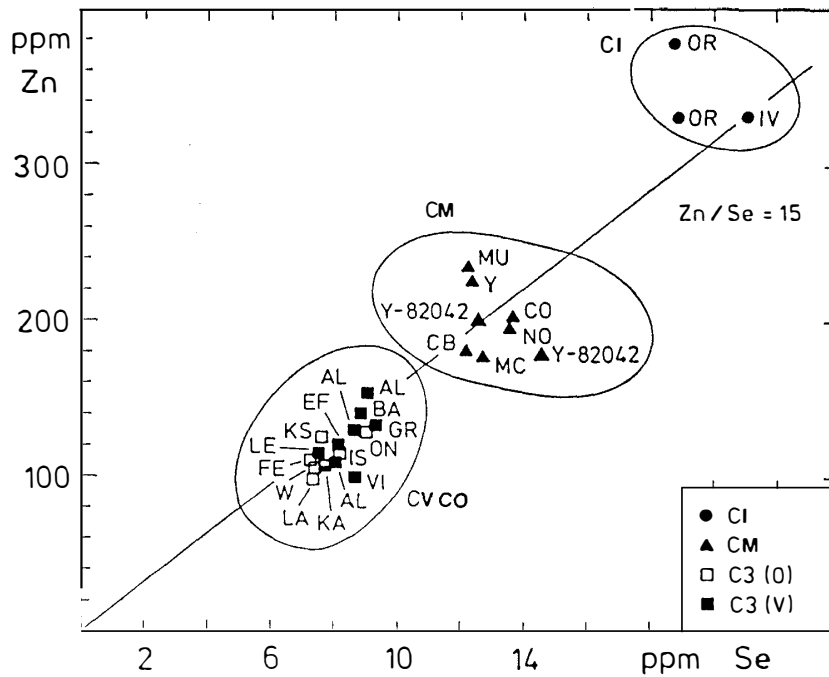


Fig. 8. *Se vs. Zn in carbonaceous chondrites. Unpublished data MPI (Cosmochemistry), Mainz. Abbreviations as for Fig. 7.*

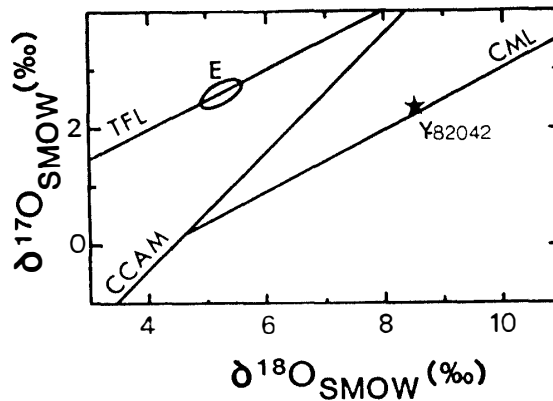


Fig. 9. *Oxygen isotopic composition of Y-82042. Abbreviations: CCAM—carbonaceous chondrite anhydrous minerals; CML—carbonaceous chondrite matrix line; E—Earth; TFL—terrestrial fractionation line. Data from CLAYTON *et al.* (1976), CLAYTON and MAYEDA (1984).*

carbonate minerals. These parameters are +34.3‰ for calcite and +32.1‰ for dolomite, again similar to other values quoted for CM chondrites (CLAYTON and MAYEDA, 1984).

## 5.2. Carbon

Analysis of carbon in Y-82042 was carried out on carbon dioxide derived from the meteorite by two different processes:

- (1) dissolution in acid to obtain a measurement of the amount and  $\delta^{13}\text{C}$  of the

carbonate minerals present (MCCREA, 1950);

(2) stepped combustion to determine the total carbon content, its distribution between different components and the  $\delta^{13}\text{C}$  values of these components (SWART *et al.*, 1983a).

Reaction of Y-82042 with orthophosphoric acid yielded 1884 ppm  $\text{CO}_2$  with  $\delta^{13}\text{C}$  of +36.6‰ relative to PDB. This gas was mainly derived from calcite. After an extended reaction time, a second extraction gave a further 878 ppm, presumably after dissolution of the less reactive dolomite and ankerite, enriched in  $^{13}\text{C}$  relative to that from calcite, with  $\delta^{13}\text{C} = +50.1\text{‰}$ . Carbon isotopic composition such as these are typical of carbonates from CM chondrites, and are lower in  $\delta^{13}\text{C}$  than corresponding CII values (CLAYTON, 1963; KROUSE and MODZELESKI, 1970; GRADY, 1983).

Stepped combustion of the meteorite resulted in a value for the total carbon abundance of the sample of 1.05 wt%. A similar figure has been obtained by other investigators (1.69%, SHIMOYAMA *et al.*, 1986). The summed  $\delta^{13}\text{C}$  was +9.8‰. This sum may be divided into several different components, with distinct isotopic signatures (see Fig. 10):

- (1) organic, macromolecular material: *ca.* 5450 ppm with weighted  $\delta^{13}\text{C}$  of  $-9.4\text{‰}$ ;
- (2) carbonates: 4470 ppm carbon with  $\delta^{13}\text{C} = +33.4\text{‰}$  combusts in the temperature range associated with decrepitation of carbonate minerals. The apparent concentration is higher and isotopic composition lighter than the corresponding values determined by acid dissolution, possibly due to simultaneous combustion of a small quantity of organic material;

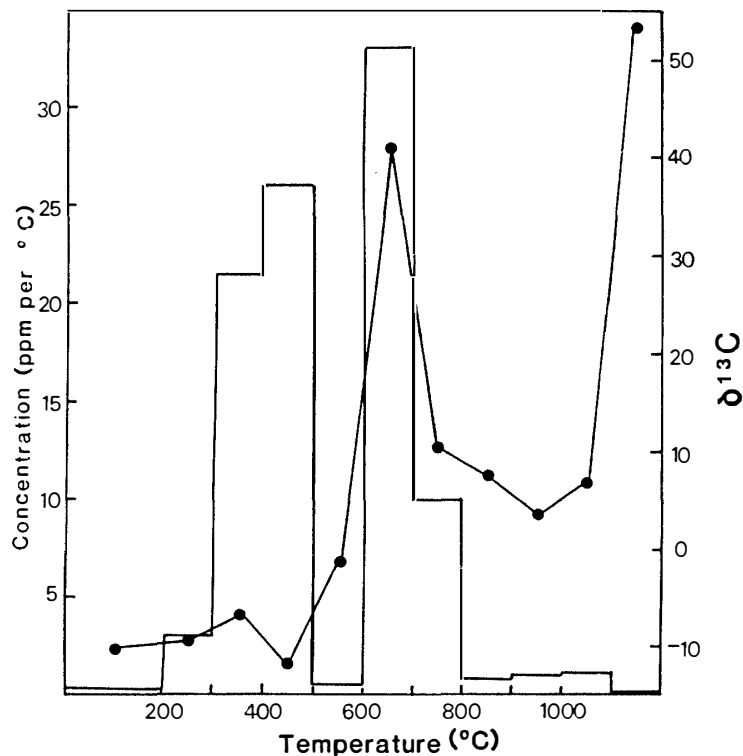


Fig. 10. The abundance (—) and isotopic composition (—●—) of carbon in Y-82042 as determined by stepped combustion.

(3) minor carbonaceous components which combust at high temperatures ( $>800^{\circ}\text{C}$ ). Carbon locked inside other mineral grains starts to combust as the silicate structure breaks down. The isotopic signature of this carbon is enriched in  $^{13}\text{C}$ , and may be from carbonate inside olivine crystals, or from high temperature inclusions (FREDRIKSSON *et al.*, 1981; ARMSTRONG *et al.*, 1982). At the highest temperature attained, 21 ppm carbon with  $\delta^{13}\text{C}$  of  $+53.4\text{‰}$  combusts. Analogy with Orgueil and CM chondrites implies that such carbon is "exotic", probably interstellar, and formed by a different mechanism from those which are responsible for the production and incorporation of the rest of the carbon (SWART *et al.*, 1983b).

The total carbon abundance in Y-82042 is much lower than that in both CI and CM2 meteorites, whilst whole-rock  $\delta^{13}\text{C}$  is more positive (see Table 4). This is partly a reflection of a lower concentration of organic material in this sample, allowing the

Table 4. Carbon, nitrogen and sulphur in Y-82042, as compared to other carbonaceous chondrite groups.

Meteorite group	Carbon		Nitrogen		Sulphur	
	wt%	$\delta^{13}\text{C}$	ppm	$\delta^{15}\text{N}$	wt%	$\delta^{34}\text{S}$
Y-82042	1.1	+9.8	534	+3.0	2.9	+0.4
CI1	2.7-4.8	-16 to -7	1300-1900	+30 to +52	4.5-6.7	+0.4 to +0.8
CM2	1.6-5.2	-22 to 0	500-1150	+13 to +47	2.8-5.4	0 to +1.3
CO, CV	0.1-1.0	-24 to -13	10-170	-45 to +24	1.3-2.7	-0.2 to +0.5

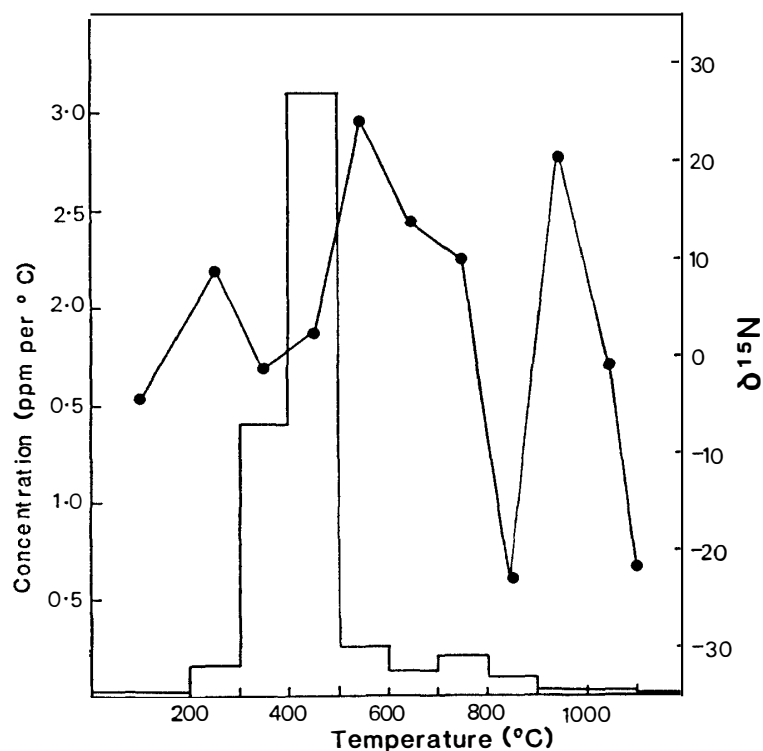


Fig. 11. The abundance (—) and isotopic composition (—●—) of nitrogen in Y-82042 as determined by stepped combustion.

$^{13}\text{C}$ -enriched signature of the carbonate minerals to dominate the whole-rock value. However, not only are the organics depleted relative to other CI and CM meteorites, they are also isotopically heavier (SMITH and KAPLAN, 1970), indicating that a specific component of the macromolecule is missing, allowing constituents more enriched in  $^{13}\text{C}$  to dominate (BECKER and EPSTEIN, 1982; GILMOUR *et al.*, 1985).

### 5.3. Nitrogen

The nitrogen content of Y-82042 was determined by stepped combustion in a manner similar to that used to measure carbon abundance. A whole-rock sample yielded some 540 ppm nitrogen, with a weighted  $\delta^{15}\text{N}$  value of +3.0‰ (see Fig. 11). Nitrogen concentration is just within the range for all CM chondrites, but the summed  $\delta^{15}\text{N}$  value is lower than all other quoted CI and CM meteorites (KUNG and CLAYTON, 1978; ROBERT and EPSTEIN, 1982; KERRIDGE, 1985, and see Table 4). Nitrogen associated with macromolecular material is known to be  $^{15}\text{N}$ -enriched (ROBERT and EPSTEIN, 1982; KERRIDGE, 1983), and it is likely that it is the relative absence of this component which leads to the observed results. The nitrogen isotopic composition varied with temperature, from -22.7‰ to +24.3‰, reflecting the presence of several nitrogen-bearing components. Most of the nitrogen (*ca.* 470 ppm) is from organic material, implying a C/N atomic ratio for the macromolecular material of *ca.* 12, and has a combined  $\delta^{15}\text{N}$  of +1.7‰. Small quantities of nitrogen are liberated at higher temperatures, presumably from gas trapped within carbonate and silicate structures. Isotopic composition varies widely, possibly from nitrogen released from different sites within the mineral structures.

### 5.4. Sulphur

Sulphur, like carbon, is known to be present in carbonaceous chondrites in elemental form, and also as oxidized (*e.g.* sulphates) and reduced (*e.g.* sulphides) compounds. Stepped combustion of a whole-rock sample of Y-82042 showed total sulphur abundance of 2.9 wt% with  $\delta^{34}\text{S} = +0.4\%$ , resolved into several different sulphur-bearing components (see Fig. 12):

(1) elemental and organic sulphur, combusting from room temperature up to 300°C, accounts for *ca.* 0.44 wt% sulphur, with variable isotopic composition from +0.7 to +6.7‰, a mean value of +2.5‰.

(2) At least two major sulphides (troilite and pentlandite) and one minor reduced sulphur-bearing compound (PCP) are known to be present in Y-82042. They combust at 300–500°C, but the combustion experiment does not distinguish between the different types, simply indicating a mean reduced sulphur abundance of 0.39 wt% with  $\delta^{34}\text{S} = +1.1\%$ .

(3) Most of the sulphur in Y-82042 occurs as the sulphates gypsum and epsomite, as well as unusual minor constituents in the matrix. These components combust at high temperatures, from 600–1200°C. Sulphates account for slightly over 2.0 wt% of the total sulphur abundance, with variable  $\delta^{34}\text{S}$  from -3.0 to +3.0‰.

Compared to other carbonaceous chondrites (KAPLAN and HULSTON, 1966), Y-82042 seems most closely allied to the CM group in terms of abundance (see Table 4). The sulphur isotopic signature is less diagnostic, since the entire range of  $\delta^{34}\text{S}$  values spans -0.2 to +1.3‰ in all carbonaceous chondrite groups.

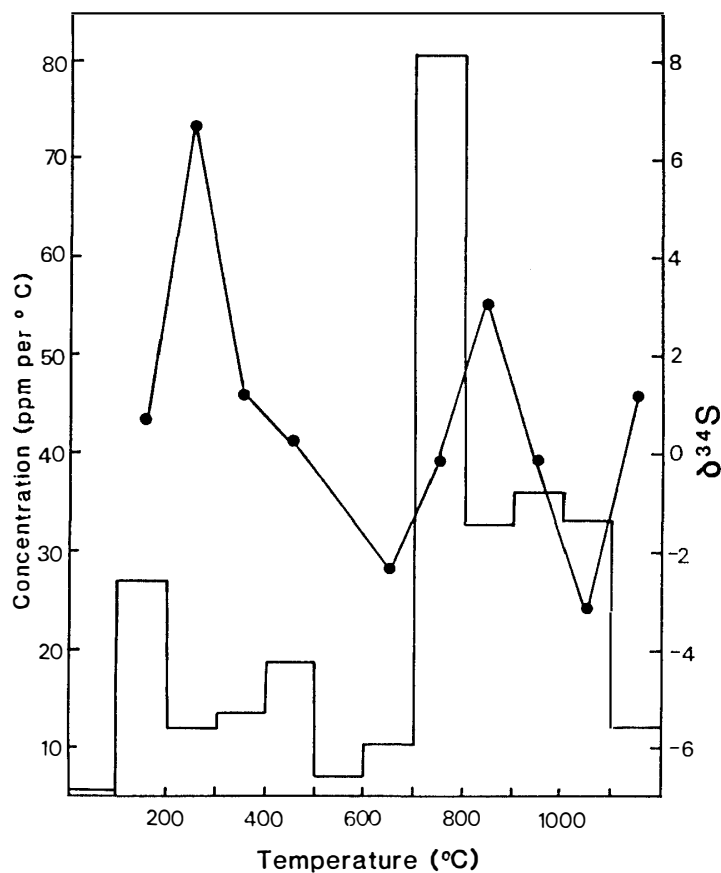


Fig. 12. The abundance (—) and isotopic composition (—●—) of sulphur in Y-82042 as determined by stepped combustion.

Table 5. Noble gas abundances in Y-82042 ( $\times 10^{-8} \text{ cm}^3 \text{ STP g}^{-1}$ ).

Isotope	Abundance in sample	
	A (29 mg)	B (22 mg)
<sup>3</sup> He	1.61	1.92
<sup>4</sup> He	3182	3101
<sup>20</sup> Ne	12.2	12.4
<sup>21</sup> Ne	0.328	0.276
<sup>22</sup> Ne	1.85	1.76
<sup>36</sup> Ar	45.3*	55.0 (46.9) <sup>†</sup>
<sup>38</sup> Ar	8.53*	10.5 (8.92) <sup>†</sup>
<sup>40</sup> Ar	99.7*	534 (173) <sup>†</sup>
<sup>64</sup> Kr	0.450*	0.759 (0.497) <sup>†</sup>
<sup>132</sup> Xe	0.630*	1.33 (0.789) <sup>†</sup>

\* Ar and Kr from the first release ( $T=800^\circ\text{C}$ ) were lost for sample A. Only the amounts of Ar, Kr and Xe released at higher temperatures are reported for this sample.

<sup>†</sup> Xe (and hence likely Kr) released at  $T \leq 800^\circ\text{C}$  from both samples was dominated by absorbed air, as indicated by the isotopic composition. Numbers in parentheses are for the Ar, Kr and Xe released above this temperature. The fraction of indigenous xenon released at  $T \leq 800^\circ\text{C}$  is estimated to be  $<15\%$  (based on isotopic composition).

### 5.5. Noble gases

The noble gas content of Y-82042 was determined by vacuum pyrolysis. The resulting gas concentrations are given in Table 5. The noble gas inventory is dominated by planetary-type gases with a similar abundance pattern to those of other carbonaceous chondrites (OZIMA and PODOSEK, 1983). Both the  $^{36}\text{Ar}/^{84}\text{Kr}$  (=100) and  $^{36}\text{Ar}/^{132}\text{Xe}$  (=70) are within the ranges given for other carbonaceous chondrites (MAZOR *et al.*, 1970), implying that Y-82042 belongs to this group. The K-Ar age based on the  $^{40}\text{Ar}$  abundance (Table 5) and the K abundance of 365 ppm (Table 3) is only  $2.03 \pm 0.09$  by, which indicates loss of a major fraction of radiogenic Ar. This is not unusual, however, for carbonaceous chondrites (*cf.* MAZOR *et al.*, 1970). The  $^{21}\text{Ne}$  concentration is also used as an indicator of the cosmic ray exposure age of the specimen. Using the mean production rates for CI and CM chondrites given by CRESSY and BOGARD (1976), but modified according to NISHIZUMI *et al.* (1980), this age is *ca.* 1.2 Ma.

## 6. Cosmogenic Nuclides

Accelerator mass spectrometry was used to measure the  $^{10}\text{Be}$  ( $t_{1/2}=1.6$  Ma) and  $^{26}\text{Al}$  ( $t_{1/2}=0.72$  Ma) contents of Y-82042; resulting concentrations were:

- (1)  $^{10}\text{Be} = 16.9 \pm 1.0$  dpm  $\text{kg}^{-1}$ ;
- (2)  $^{26}\text{Al} = 34.4 \pm 2.0$  dpm  $\text{kg}^{-1}$ .

Application of the analytical data (Table 3) to standard relationships (HAMPEL *et al.*, 1980; PAL *et al.*, 1983) allows a theoretical value for the production rates ( $P$ ) or radionuclide contents to be calculated (assuming a body of average meteoroid dimensions irradiated in space for several million years). The values so derived, namely  $P_{10}=22$  dpm  $\text{kg}^{-1}$  and  $P_{26}=45.8$  dpm  $\text{kg}^{-1}$  are higher than the experimental values. A possible explanation for this discrepancy is that Y-82042 spent *ca.* 4.8 Ma in space as a typical small body, and then landed on Earth *ca.* 0.29 Ma ago, since which time the  $^{10}\text{Be}$  and  $^{26}\text{Al}$  decayed from values near  $P_{10}$  and  $P_{26}$  to the observed levels. A terrestrial age of 0.29 Ma is somewhat long for a Yamato meteorite (NISHIZUMI and ELMORE, 1985). A shorter terrestrial age would be permitted if Y-82042 came from the centre of a large stone where production rates would have been lower. The  $^{10}\text{Be}$  and  $^{26}\text{Al}$  chronology cannot readily be reconciled with the  $^{21}\text{Ne}$  age. The observed  $^{10}\text{Be}$  and  $^{26}\text{Al}$  contents are higher than would be expected from the  $^{21}\text{Ne}$  content. It is worth noting here that the activities actually measured in CI and CM chondrites by PAL *et al.* (1983) are all higher than the calculated production rate (23.5, 26.6, 25.1 *vs.* 22; the exception being Orgueil, with its short exposure age). It is also possible that Y-82042 lost some  $^{21}\text{Ne}$ , even though such loss may not be indicated by He content. Other possible explanations involve unusual chemistries or irradiation conditions.

## 7. Conclusions

Major and minor elemental abundances in Y-82042 indicate that this apparently unusual meteorite is a CM chondrite. Diagnostic oxygen isotopic signatures confirm such a classification. Light element stable isotope values are less characteristic: sulphur is well within the range of CM compositions, but carbon and nitrogen data are

more enigmatic. Conclusions drawn from analysis of these data are that Y-82042 is a CM chondrite which is depleted in a C- and N-bearing organic component. Noble gas isotope ratios may also be used for classification purposes, and again confirm Y-82042 as a member of the CM group. However, the petrology and texture of the meteorite are unlike those of other CM chondrites: no chondrules have been found; the modal abundance of phyllosilicates is closer to that of CI meteorites, as is the abundance of olivine. It is possible that the Y-82042 chondrite is the first CM1 chondrite to be recognized.

Since delicate structures within the matrix have been preserved, it follows that there has been little or no post-accretional loading or reheating of the stone. The corona of phyllosilicates which surrounds most olivine and carbonate crystals grades into the matrix, implying that formation of the phyllosilicates occurred prior to assembly of the stone, and that the olivines accreted with their "skin" already in place. Although carbonates are common, intense hydrothermal activity is unlikely, as the olivines are only rarely serpentinized and there are apparently no veins cross-cutting the sample.

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