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PETROLOGY AND CLASSIFICATION OF NEW ANTARCTIC CARBONACEOUS CHONDRITES PCA91082, TIL91722 AND WIS91600

Vladislav V. BIRJUKOV and Alexander A. ULYANOV

Division of Mineralogy, Geological Department of M.V. Lomonosov Moscow State University, Vorobievy Gory, Moscow, 119899, Russia

Abstract: Three Antarctic chondrites: Pecora Escarpment (PCA) 91082, Thiel Mountains (TIL) 91722 and Wisconsin Range (WIS) 91600 were studied by SEM-EDS methods and classified as CR2, CV3 and CM2, respectively. PCA91082 and TIL91722 contain rare fine-grained refractory inclusions and amoeboid olivine aggregates without any traces of secondary alteration processes. Chondrule pyroxene is enriched in Cr and Mn compared to pyroxenes from refractory inclusions. Presence of Cr^{2+} and Ti^{3+} with normal Cr^{3+} and Ti^{4+} in chondrule pyroxenes probably indicates reducing conditions during chondrule formation. Several unusual objects, such as a compound P-rich chondrule in PCA91082, and P and Cr enriched glasses in WIS91600, were studied. The metal fraction of PCA91082 shows a positive Ni *vs.* Co trend which can be produced by volatilization process. Bulk composition of inclusions and chondrules follows to condensation trend, but exsolution structures and glasses indicate crystallization from melts.

1. Introduction

Investigations of carbonaceous chondrites remain important today despite of considerable amount of data related them, because significant problems such as origin of chondrules, of different types of refractory inclusions, and of metal particles, are not resolved. Secondary alteration processes also have a large interest. In this connection, studying of a great number of Antarctic meteorites is unique possibility to solve many problems. We report here results of our petrological and mineralogical investigation of 3 Antarctic carbonaceous chondrites found in 1991 at Pecora Escarpment (PCA91082), Thiel Mountains (TIL91722) and Wisconsin Range (WIS91600) regions of Antarctica. Previously, described chondrites were classified as C2 (PCA91082 as CR2) meteorites (GROSSMAN, 1994).

2. Experimental Procedures

Polished thin sections (one from each meteorite) were received from NASA Johnson Space Center. They were studied optically by both transmitted and reflected light and electron microprobe methods. Chemical composition of minerals and areas were determined by scanning electron microscope CAMSCAN with energy-dispersive system (EDS) Link-10000. Some analyses were made using CAMEBAX SX-50 wavelength-dispersive system (WDS). Accelerating voltage was 15 keV with sample current 6 nA for EDS and 15 keV/20 nA for WDS.

Detection limits for EDS were (wt%): S > 0.1; K_2O > 0.12; SiO_2 > 0.15; TiO_2 and Al_2O_3 > 0.18; FeO, MnO, MgO, CaO, Cr_2O_3 and V_2O_3 > 0.2; ZnO > 0.3 and Na_2O > 0.5. All analyses with FIT-index > 2 (EDS) were excluded from further processing as analyses with unsatisfactory atomic proportions. Finally, bulk composition of areas which had been determined by defocused beam were normalized to 100% to compensate for loss of X-ray intensity in surface microrelief. Diameters of defocused beam for WDS analyses were less than 15 μm, linear sizes of scanning areas for EDS data were from 15 to 500 μm.

3. Results and Discussion

General view of polished thin sections are shown on Fig. 1a–c, average chondrule diameter and relative amounts of different petrologic fractions are given in Table 1.

3.1. Inclusions

High-temperature inclusions are represented by typical fine-grained inclusions (FGIs) and amoeboid olivine aggregates (AOAs). We observed 2 FGIs and 2 AOAs from TIL91722 and 1 FGI from PCA91082. FGIs from TIL91722 are aggregates of Al-diopside and Mg-spinel. FGI in PCA91082 consists of melilite (Ak21)–anorthite–Al-diopside clasts in fine-grained olivine matrix (Fa 3; 0.3 wt% Cr_2O_3). Main constituents of AOAs are forsteritic olivine (Fa 0.6; 0.3 wt% Cr_2O_3), Al-diopside and Mg-spinel. Diopside from CAIs does not contain Cr, in contrast to chondrule pyroxene. The absence of Fe-bearing spinel and feldspathoids is the good evidence of light nebular alteration for inclusions in PCA91082 and TIL91722.

(a)

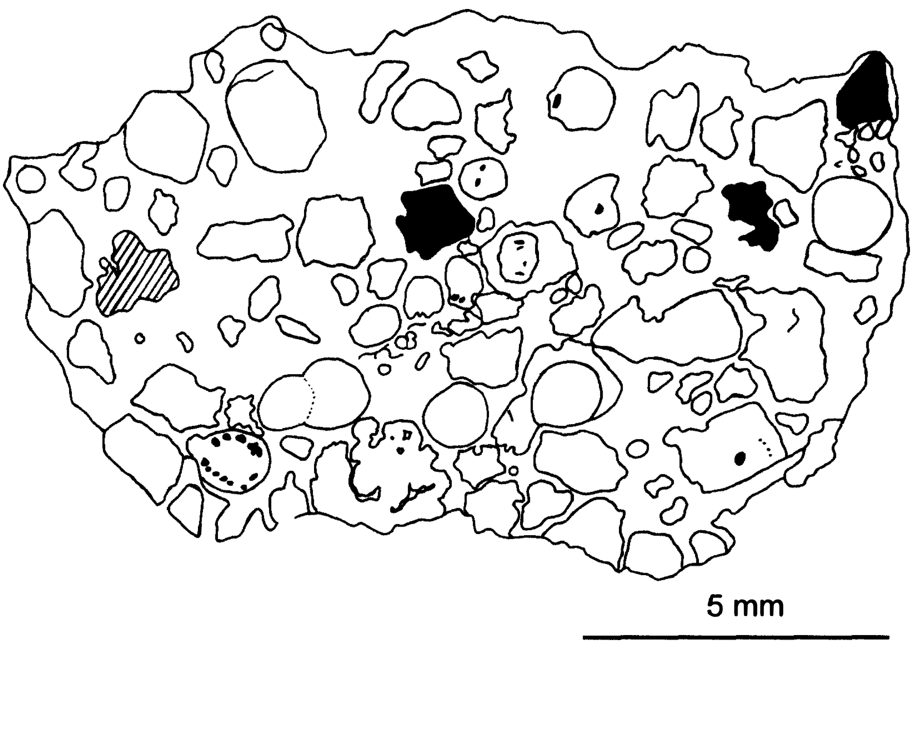
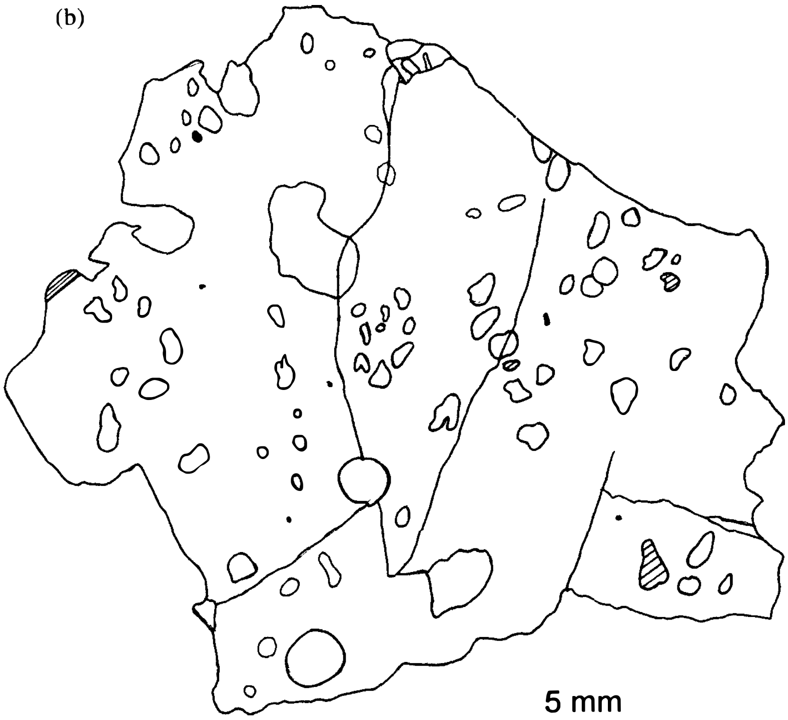


Fig. 1. General view of polished thin sections:
a) PCA91082.
▨ inclusions;
□ chondrules;
■ metal particles.

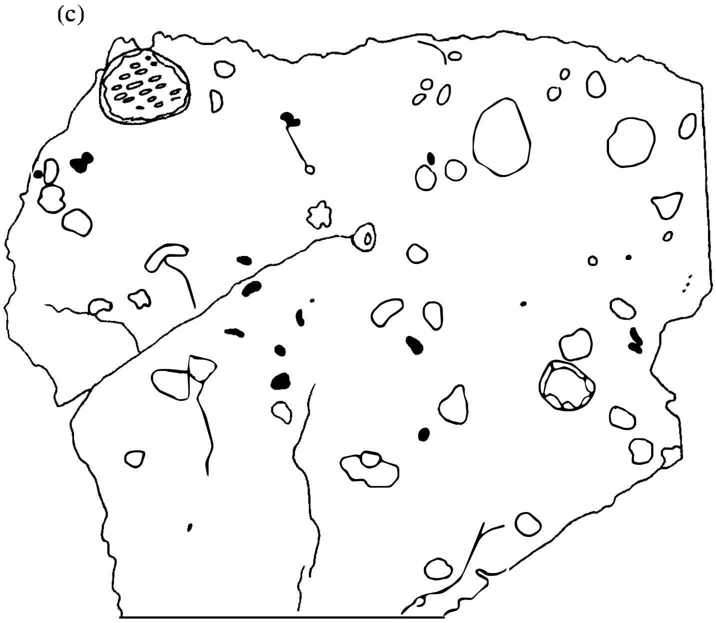
(b)



5 mm

Fig. 1. General view of polished thin sections:
b) TIL91722.
inclusions;
chondrules;
metal particles.

(c)



5 mm

Fig. 1. General view of polished thin sections:
c) WIS91600.
inclusions;
chondrules;
metal particles.

Table 1. Relative amounts and features of petrologic fractions.

Fraction	PCA91082	TIL91722	WIS91600
CAIs	rare	rare	none
Amounts of chondrules (vol%)	46.0	8.5	7.5
Average diameter of chondrules (mm)	0.74	0.51	0.37
Chondrules/mineral fragments ratio	<1	<1	~1
Metal	abundant	abundant	none
Sulfides	rare	abundant	abundant

3.2. Chondrules

As shown on Fig. 1, PCA91082 contains large chondrules with abundant metal particles; TIL91722 contains rare large chondrules and abundant small objects; WIS91600 consists mainly of matrix with rare chondrules and crystals. We studied 27 large chondrules in sample of PCA91082 (23 porphyritic-olivine (PO) and porphyritic-olivine-pyroxene (POP), 3 barred olivine (BO) and 1 radial (R) olivine); 19 in TIL91722 (18 PO and POP, 1 BO) and 12 in WIS91600 (8 PO, 1 BO, 1 R pyroxene and 2 glass (G)).

PO and POP chondrules consist of olivine grains with interstitial material which is mainly pyroxene for TIL91722, pyroxene and glass for PCA91082, and glass for WIS91600.

Olivines with increasing (Table 2, analysis No. 4, 5) and decreasing (Table 2, analysis No. 6, 7) of Fa contents from core to outer part of chondrule were studied. Forsteritic olivines are dominant (see Fig. 2). Olivines from all samples contain Cr_2O_3, MnO and CaO up to 1.0, 0.6 and 0.8 wt%. Positive correlation between Fe and Mn contents in olivine was detected for PCA91082 (see Fig. 3). We suggest that all Cr in olivine is trivalent because there is no deviation between real cation sum and its theoretical mean for Cr-rich olivines.

Pyroxenes in chondrules are mainly enstatite and Mg-augite; Mg-pigeonite and diopside are less abundant. Clinopyroxenes (but not orthopyroxenes) from TIL91722 and PCA91082 chondrules show negative correlation between cation sum and sum of

Table 2. Representative analyses (wt%) of olivine (1–8), pyroxene (9–11) and carbonate (12).

	PCA	TIL	PCA	PCA	PCA	TIL	TIL	PCA	PCA	TIL	WIS	WIS
No.	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	34.66	42.03	43.04	42.41	42.07	41.29	41.31	34.50	58.97	52.90	51.05	0.07
TiO_2	0	0	0	0	0	0	0	0	0.26	0	0	0
Al_2O_3	0	0	0	0	0	0	0	0	0.71	4.95	0	0.04
FeO	40.77	0.87	3.83	2.81	3.14	6.05	5.00	28.66	0.58	0	29.48	5.83
MnO	0.26	0.45	0	0.48	0.47	0.30	0.20	0.52	0.31	0	0.41	10.72
MgO	23.56	55.79	55.68	53.27	53.21	51.60	52.80	35.66	37.70	17.47	15.87	21.91
CaO	0.21	0.20	0.18	0	0	0	0	0	0.58	24.80	2.56	60.56
Cr_2O_3	0.30	0.64	0.67	1.20	0.72	0.69	0.50	0	0.66	0	0	0
P_2O_5	0	0	0	0	0	0	0	0.48	0	0	0	0
Sum	99.76	99.98	103.39	100.17	99.61	99.93	99.81	99.82	99.76	100.12	99.38	99.13

TIL: TIL91722; PCA: PCA91082; WIS: WIS91600.

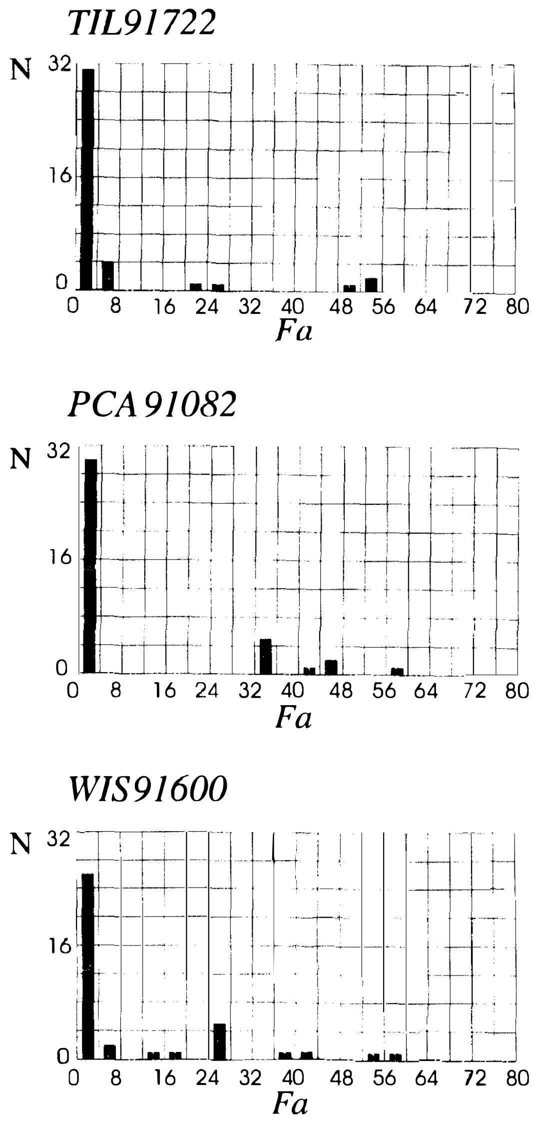


Fig. 2. Histograms of fayalit contents in olivine from chondrules.

contents of Ti^{4+} and Cr^{3+} (Fig. 4). Such effect is observed in some pyroxenes from CAIs, where it is interpreted as evidence of Ti^{3+} and Cr^{2+} presence (ULYANOV *et al.*, 1990). Line on Fig. 4 shows location of points of Ti^{3+} and Cr^{2+} pyroxenes if all Ti and Cr is calculated as Ti^{4+} and Cr^{3+} (maximum permissible deviation in the cation sum due to dissolution of $CaTi^{3+}AlSiO_6$ and $CaCr^{2+}Si_2O_6$ in pyroxenes). All analyses of pyroxenes from TIL91722 are placed within 1σ error interval near line on Fig. 4, most points of PCA91082 pyroxenes also lay within 1σ interval (Fig. 4, dotted lines). Three analyses above upper dotted line and with cation sum > 4 contain significant amount of FeO (2.17, 3.74 and 5.02 wt%). Probably excess of cation sum is connected with presence of Fe^{3+}. Points below inferior dotted line (only PCA91082) can be explained by the cation vacancies in pyroxene structure (ULYANOV *et al.*, 1990). Maximum concentrations of TiO_2 in pyroxenes are 1.3 wt%; Cr_2O_3 – 3.1 wt% and MnO – 0.9 wt% (see Fig. 5). Orthopyroxenes contain less Cr. All pyroxenes in WIS91600 chondrules probably are orthoenstatites.

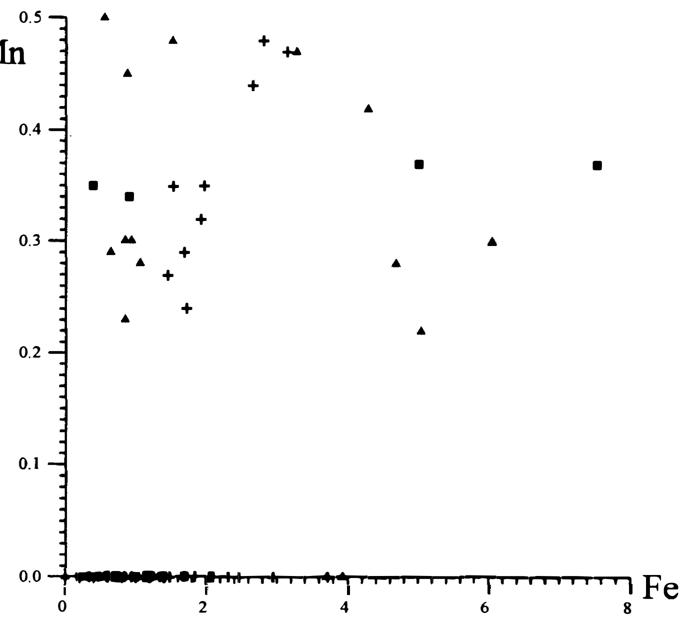


Fig. 3. FeO vs. MnO in olivines from chondrules (wt%).
+ PCA91082; ▲ TIL91722;
■ WIS91600.

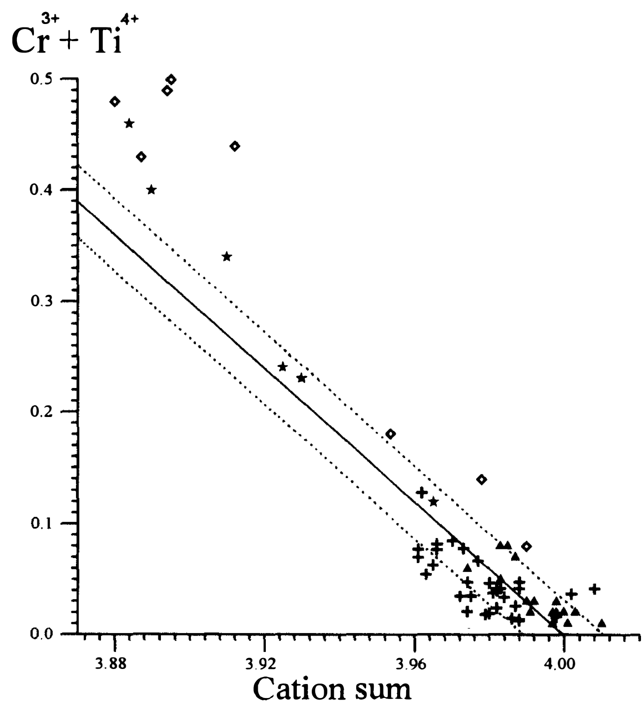


Fig. 4. Correlation between cation sum and content of Ti^{4+} and Cr^{3+} in pyroxenes.
+ chondrules; PCA91082;
▲ chondrules; TIL91722;
★ CAI E48; Efremovka CV3; (Ulyanov et al., 1993).
◇ CAI E50; Efremovka CV3; unpublished data of authors.
Solid line-maximum permissible deviation in the cation sum due to dissolution of $CaTi^{3+}AlSiO_6$ and $CaCr^{2+}Si_2O_6$ in pyroxenes (dotted lines mark 1σ intervals).

Glasses (without alteration and replacement structures) are major components of chondrules in PCA91082 and especially in WIS91600. They contain different amounts of clinopyroxene (and probably spinel) microlites which can be detected by positive correlation between Cr concentration and (Mg+Fe)/Si atomic ratio in glasses. Glass compositions of chondrules are shown on Fig. 6. They can be approximately described as a result of mixing of anorthite, diopside, spinel and enstatite in different proportions. PCA91082 contains Na-Fe-rich glasses which have also acmite and nepheline constitu-

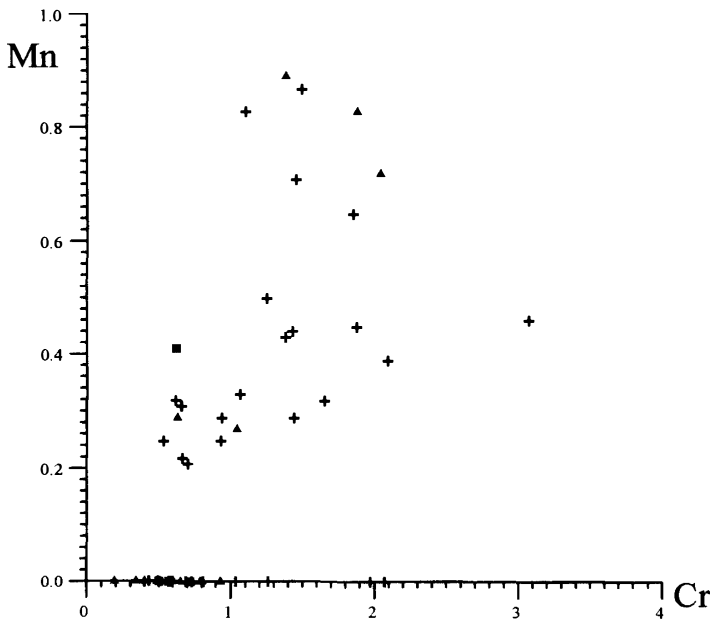


Fig. 5. Cr_2O_3 vs. MnO in pyroxenes from chondrules (wt%)
+ PCA91082;
▲ TIL91722;
■ WIS91600.

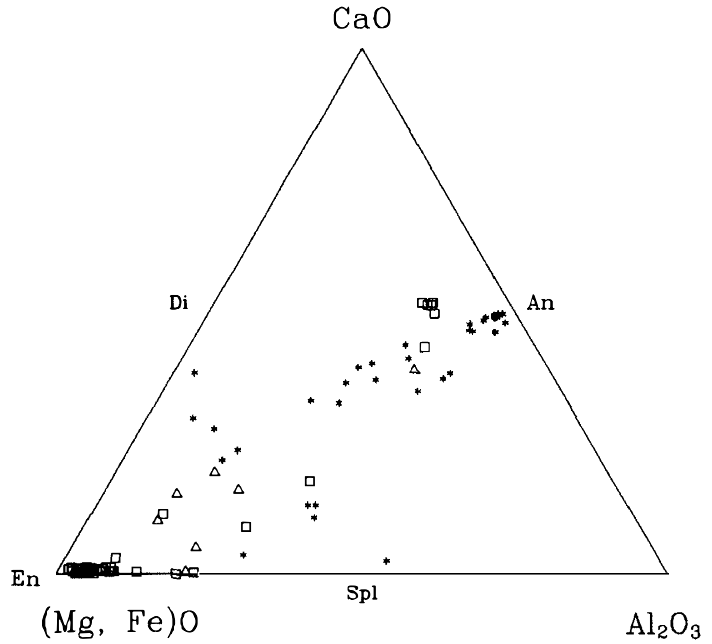


Fig. 6. Bulk composition of glasses (mol%)
★ PCA91082;
△ TIL91722;
□ WIS91600; An-anorthite, Di-diopside, En-enstatite, Spl-spinel.

ents (Table 3, analysis No. 6–7). Very unusual glasses were detected in WIS91600. They are dark-brown color, and occupy interstices between olivine grains and whole glass chondrules. Compositions of such glasses are similar with the meteorite matrix, but they are very enriched in Cr and sometimes in P (Table 3, analysis No. 8, 10, 11). Inclusions of chromite grains in these glasses were not detected. Ca-carbonate was found as interstitial mass in one chondrule in WIS91600. It contains up to 14.4 mol% MgO, 4.0% MnO and 2.1% FeO.

One unusual compound radial P-enriched chondrule of consorting type (NAKAMURA *et al.*, 1995) was described in PCA91082. It consists of a spherical object with 700 μm

Table 3 Bulk composition of glasses (1–14) and meteorite matrix (15–17); normalized to 100 wt%.

	TIL	PCA	PCA	PCA	PCA	PCA	PCA	WIS	WIS
No.	1	2	3	4	5	6	7	8	9
SiO_2	59.07	73.54	51.88	54.27	46.75	61.85	56.89	22.62	45.46
TiO_2	0.57	0.36	0.74	0.87	0	0.72	0.52	0.10	0.52
Al_2O_3	15.14	9.60	6.99	3.17	33.49	13.74	12.54	3.44	7.17
FeO	8.62	6.18	1.51	0.58	0	12.01	11.44	33.93	18.37
MnO	0	0	0	0	0	0	0.24	0.22	0
MgO	0.75	1.28	21.94	20.88	0.80	0.96	0.64	14.35	23.19
CaO	8.35	5.75	15.02	19.38	18.96	2.79	2.01	0.38	0.25
Na_2O	5.69	1.92	0	0	0	5.50	13.50	1.06	2.68
K_2O	0.74	0.29	0	0	0	1.18	1.15	0.16	1.13
Cr_2O_3	0	0.36	1.93	0.86	0	0	0	2.84	0.39
NiO	0	0	0	0	0	0	0	9.32	0
P_2O_5	0.94	0.61	0	0	0	0.89	0.89	3.02	0.30
S	0.13	0.10	0	0	0	0.37	0.18	8.57	0.55

	WIS	WIS	WIS	WIS	PCA	PCA	WIS	TIL
No.	10	11	12	13	14	15	16	17
SiO_2	21.72	39.95	45.38	23.47	61.18	38.21	39.46	32.53
TiO_2	2.32	0.15	0.92	0.22	0	0	0.12	0.07
Al_2O_3	1.83	4.09	27.32	10.22	1.71	1.80	3.59	2.74
FeO	42.56	21.48	0.74	41.03	13.78	34.04	22.06	34.62
MnO	0.68	0.31	0	0	0.30	0.37	0.21	0.35
MgO	19.81	24.31	3.52	3.60	11.28	18.02	23.20	19.70
CaO	0.57	0.13	21.52	5.50	2.05	0.88	1.53	1.07
Na_2O	0.80	0.58	0	1.78	7.61	1.80	0.61	0.77
K_2O	0.08	0.14	0	0.90	0.45	0.33	0.17	0.32
Cr_2O_3	2.53	7.69	0.29	1.10	0	0.47	0.49	0.46
NiO	1.93	0	0	4.32	0	1.71	2.44	2.86
P_2O_5	1.34	0.37	0.22	6.13	1.39	0.42	0.38	0.40
S	3.83	0.81	0.10	1.73	0.25	1.95	5.75	4.11

TIL: TIL91722; PCA: PCA91082; WIS: WIS91600.

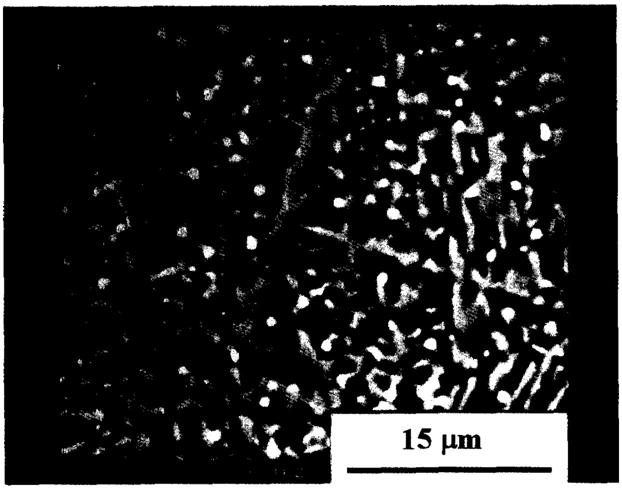


Fig. 7. Backscattered electron image of structure of P-enriched compound chondrule in PCA91082.

in diameter attached to larger (1 mm) one. Border between objects is traced by 5–30 μm-sized sulfide-metal blobs. Composition of both parts is the same: olivine (Table 2, analysis No. 8) and Na-Mg-Fe glass (Table 3, analysis No. 14) are formed dendritic intergrowth. Opaque minerals are presented by evenly distributed μm-sized chromite grains and rare metal particles. Structure of this chondrule is exsolution-like and uniform (Fig. 7), except one sector of the small part is more coarse-grained.

3.3. *Mineral fragments*

Isolated grains of olivine and orthopyroxene are relatively abundant in all samples. Large olivine crystals from WIS91600 contain elliptical inclusions of anorthite-pyroxene glass, sometimes with P_2O_5 impurity (up to 6.1 wt%; Table 3, analysis No. 13). High contents of Al_2O_3 and CaO (up to 0.4 and 0.6 wt% respectively) in host olivine suggest exsolution with the temperature decreasing. Olivine captured its maximum amount of Ca and Al, but excess of these elements and P crystallize in glass inclusions. Same resemblance of minor elements in chondrules and intercrystal glasses (high contents of P and Cr) indicates formation under the same condition, probably from one precursor.

3.4. *Opaque phases*

Opaque phases are also different among studied meteorites. TIL91722 contains mainly kamacite and pentlandite; taenite and troilite are rare. Some pentlandite grains contain P and Cr (up to 3.5 and 2.6 wt%). Kamacite is the main opaque phase in PCA91082, taenite is less abundant and troilite is rare (pentlandite is absent). Mineralogy of WIS91600 is unusual: this meteorite contains only sulfides (troilite and pentlandite in same proportions) and Fe-oxides. Absence of Fe-Ni metal can be connected with the terrestrial alteration process or aqueous alteration in parent body which is typical for CM meteorites.

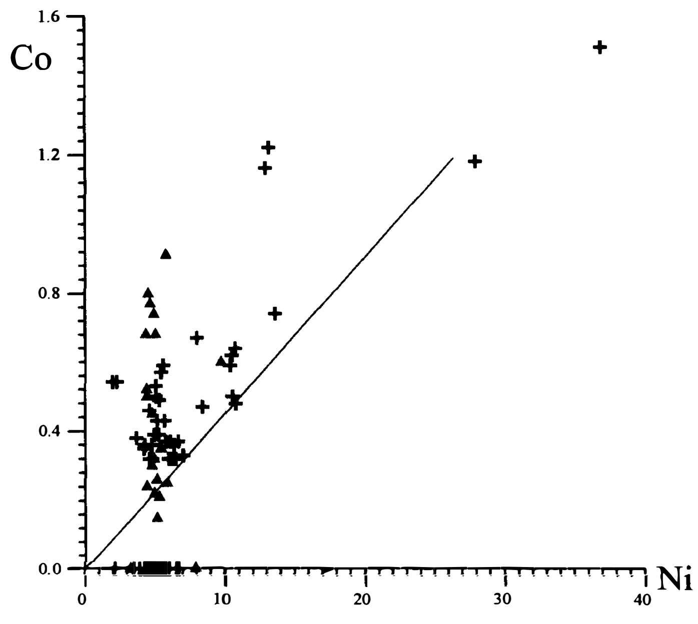


Fig. 8. Composition of Fe-Ni metal Ni vs. Co (at%)
+ PCA91082;
▲ TIL91722.
Solid line-Solar Co/Ni ratio (Anders and Grevesse, 1989).

The positive trend between Ni and Co contents in kamacite and taenite of PCA91082 (shown on Fig. 8) is typical for CR chondrites (WEISBERG *et al.*, 1993). According to experimental data (LAVRUHINA *et al.*, 1979), enrichment of Co and Ni in metal can be caused by partial volatilization of kamacite. Also enrichment both in Co and Ni can be produced by the process of sulfidization followed by reduction (LAVRUHINA *et al.*, 1989) and terrestrial weathering. Enrichment of metal in Co relative solar ratio (Fig. 8) confirm possibility of metal formation during volatilization process due to more refractory behaviour of Co than Ni (LAVRUHINA *et al.*, 1979). High concentrations of Cr and P in TIL91722 sulfides are probably explained by presence of chromite and phosphates, but these phases were not detected.

3.5. *Matrix*

Matrix compositions of described meteorites (Table 3, analysis No. 15–17) was not studied in detail. Mineral composition is usual: Fe-Mg-silicate with small grains of olivine, orthopyroxene and sulfides. Calcite also was detected in TIL91722 matrix.

3.6. *Classification*

Classification of studied meteorites is based on petrological data because of absence of enough representative samples for determining bulk meteorite composition. PCA91082 is classified as CR2 chondrite because it contains chondrules with average diameter more than 0.5 mm, and chondrule/matrix ratio >1 (DODD, 1981). Other attributes of CR chondrites such as specific matrix composition (NOGUCHI, 1994), abundant large metal grains (WEISBERG *et al.*, 1993) also are presented in PCA91082.

Problem of classification of TIL91722 is not so simple. Volume content and average diameter of chondrules (about 10% and 0.5 mm) is intermediate between CM and CV groups, but under a microscope it has image similar to a CV chondrite (porous chon-

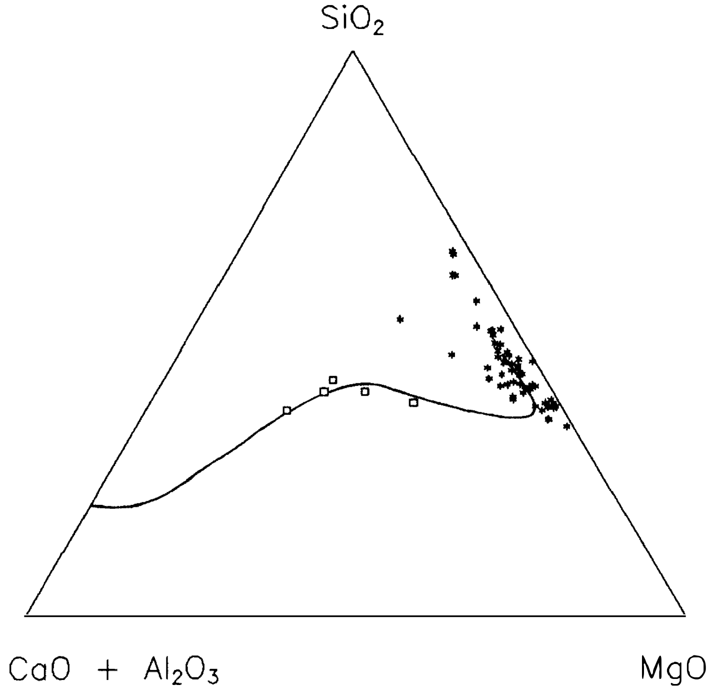


Fig. 9. Bulk composition of inclusions and chondrules (mol%)
□ inclusions;
★ chondrules;
Solid line-condensation trend.

drules with metal grains, etc.). TIL91722 contains small amount of isolated mineral grains, which is not usual for CM group (DODD, 1981) and has CAIs with typical composition of CV3 chondrites (BIRJUKOV and ULYANOV, 1995). Matrix of TIL91722 consists mainly of olivine, this is also attribute of C3 group. We suppose that this meteorite must be classified as anomalous CV3 chondrite according petrological features. TIL91722 probably is a member of reduced CV3 subgroup because of light alteration of CAIs, low concentrations of volatile elements (Na, K, Zn) and Fe in chondrule minerals and abundant Ni-rich sulfides (McSWEEN, 1977).

Classification of WIS91600 is based on usual for CM2 group low chondrule/matrix ratio, average size of chondrules less than 0.5 mm, abundant isolated mineral fragments and glass, absence of CAIs, and matrix composition.

Obviously all constituents of studied meteorites have complex history. Bulk compositions of inclusions and chondrules in TIL91722, PCA91082 and WIS91600 occur near the equilibrium condensation trend (Fig. 9), calculated using PHEQ program (WOOD and HASHIMOTO, 1993). Abundance of glasses and exsolution structures is evidence of a molten stage in the history of chondrule evolution. Ni-Co positive correlation in Fe-Ni metal probably is a result of vaporization effect or latest events.

4. Conclusions

Meteorites described in this paper are distinguished from other carbonaceous chondrites mostly in composition of middle-temperature fraction: chondrules and metal. Usually chondrule pyroxenes do not contain Ti^{3+} and Cr^{2+} (for example Allende) and presence of these valent forms indicates formation of chondrules under essentially reduction conditions. The second possible explanation is influence of secondary oxidation for series of meteorites like Allende (McSWEEN, 1977). Unusual enrichment of some minerals and glasses within chondrules in P and Cr can be produced by redistribution of these elements in crystallization stage of chondrules evolution, for example in formation of residual melt.

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