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The Songyuan ordinary chondrite (China) — rich in alien rock fragments and its reclassification

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The Songyuan chondrite is composed mostly of minerals and chondrule types common in equilibrated ordinary chondrites. More distinctively, the Songyuan material includes numerous sintered cryptocrystalline rock lumps, possible chondrule precursors, and less frequent fragments of olivine-pyroxene basalt. The moderate porosity (estimated under the polarizing microscope at a few percent by volume) and uncompacted metal grains, suggest that the meteorite came from very shallow horizons of the regolith. The shallow original position of the Songyuan fragment on its parent body is consistent also with the abundance of numerous euhedral crystals of the main meteoritic components present in the interstitial pores. They crystallized most probably from fluids migrating through the superficial horizons from the inner parts of the Songyuan parent body. The structural characteristics and slight differentiation in olivine composition suggests a high degree of homogenization and, together with the median value of the fayalite content (26.2 ±0.24 wt.%), corresponds to the L5 chemical-petrologic group of equilibrated ordinary chondrites. Moreover, the homogenous extinction in the olivine crystals and the absence of multiple planar fractures indicate the lowest level of the shock metamorphism (S1), whereas the lack of any oxide rims around kamacite and troilite grains points to the lowest level of weathering (W_0).

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INTRODUCTION

The fall of a small shower of meteorites was observed on the early afternoon of August 15, 1993, in Jilin Province, China. Four stones, weighing in total 36.9 kg, were recovered within a 10 km^2 area shortly after landing in the countryside of Fuyu in Songyuan city. The largest fragment, weighing 28 kg, was embedded in the ground to a depth of 60 centimetres. Unfortunately, the finders cleaned the stone and removed the thin, fragile crust.

The main mass of the meteorite is exposed in Songyuan City Museum, whereas the other stone of 6.4 kg was purchased by the USA five years later. Then, cuts of the stone were studied at UCLA (University of California Los Angeles) and the Songyuan meteorite (the original name “Fuyu” was finally changed to “Songyuan”) was classified by A. Rubin as an ordinary chondrite L6, S2, W_1 (Grossman, 2000). The cut surface revealed a greenish-gray matrix with scattered dark chondrules. M. Morgan (Mile High Meteorites, Lakewood CO, USA), who donated the samples of Songyuan and initiated the present study, has stated that its cut surfaces are apparently similar to those of Mt. Tazerzait and Baszkówka (Morgan, 2002).

METHODS

Two kind of the analytical tools were used in the study:

— optical polarizing microscopes (*Ernst Leitz*, *Wetzlar*, Germany and *MIN-8*, USSR);

— electron microscopes (*JEOL 35*, *JEOL 840A* and *LEO 1430*) with energy dispersive X-ray spectrometers.

Improved sets of standard samples were composed of mineral and/or artificial materials for quantitative measurements.

Uncovered thin sections, prepared using standard procedures, were used in microscopic examinations and in chemical microanalysis. Firstly, over one hundred selected objects were studied under the polarizing microscope and then, selected structures were analysed in two laboratories by X-ray spectrometry. Samples labelled A–F were analysed at the Polish Geological Institute, Warsaw, whereas samples labelled S were analysed at the Institute of Geological Sciences Polish Academy of Sciences, Warsaw.

In general the following notations are used here: OL — olivine, OPX — orthopyroxene, CPX — clinopyroxene, PLG — plagioclase, FeNi — meteoritic iron, TR — troilite, CR — chromite, WTH — withlockite, CHA — chlorapatite, PO — porphyritic olivine chondrule, PP — porphyritic pyroxene chondrule, RO — radial olivine chondrule, RP — radial pyroxene chondrule, BO — barred olivine chondrule, FNB — phenocryst in PO, KLS — subhedral, clastic olivine crystal, MEZ — mesostasis of PO, MTR — inclusions in FeNi-TR aggregates, MTX — small, anhedral grains in matrix, RCK — rock fragments, RIM — rim of PO, FRC — secondary minerals, OPP — cryptocrystalline lumps of OL–PX–PLG.

RESULTS AND DISCUSSION

THE STRUCTURE AND MINERALOGY OF THE SONGYUAN METEORITE

The granular structure of Songyuan chondrite is easily visible on flat, unpolished surfaces of samples: dark gray spherical, oval or shapeless grains, most of them chondrules, are enclosed in an abundant dark brown matrix. Almost half of the chondrules, examined in thin section, (Fig. 1) are only slightly damaged or undamaged and rimless. More or less one quarter are partly fragmented, and about one quarter are fragmented. The apparent diameters of the undamaged chondrules, measured under the microscope, fall within the range 0.4–3.6 mm, with a statistical distribution similar to a lognormal one and a median value of 1.13 mm. Numerous small holes and fissures are visible on the flat surfaces of Songyuan, and the porosity of the chondrite was estimated under the microscope to be about vol. 5–10%. The interstitial nature of the pore spaces is evident. Inside the voids, numerous euhedral crystals of the main meteoritic minerals were found: olivine, pyroxene, feldspar, FeNi-metal and chromite (Fig. 3A–E successively) but also melanterite — the product of secondary alteration (Fig. 3F). By analogy with previous observations (Wlotzka and Otto, 2001; Borucki and Stępniewski, 2001) it may be supposed that they crystallized from a vapor phase migrating through the loosely compacted rock. As an effect of the variability of the chemical composition of the migrating phases, faces of the euhedral olivine and pyroxene show growth steps and chromite faces display etch figures.

Thin layers of iron-nickel oxide/hydroxide — possible products of oxidation in the terrestrial environment — are present in some of the fissures or other voids. Melanterite aggregate found in a void of Songyuan most probably is the product of a similar weathering process. But it is worth noting that there is no oxidation rim around grains of meteoritic iron and troilite, that excludes the oxidation stage W_1 of Wlotzka's (1993) scale, indicating rather to the W_0 stage.

OLIVINE IN THE MATRIX

Small olivine grains (MTX: 0.01–0.2 mm) form nearly 70 vol.% of the Songyuan matrix, whereas the large grains (KLS: ~0.08–0.7 mm) are present in the matrix as rare subhedral crystals. Olivine is present also as principal component in many of the chondrules (e.g., RO and BO chondrules), but above all as phenocrysts (FNB) of the porphyritic olivine chondrules (PO), and as the main component of most of the rock fragments (RCK) as well. A pelitic olivine fraction MTX is composed of numerous, anhedral, frequently turbid olivine grains, whereas crystals of the fraction KLS are characterized by well-developed pinacoid and pyramid faces, multiphase inclusions and corrosion fractures. However, there is no gap in the continuity of grain dimensions. Characteristic features of the KLS are preserved only in large grains, whereas the pelitic grains MTX are to small to preserve them.

Although the chemical composition of the olivine (see Table 1) is generally uniform (e.g., the span of the calculated fayalite content is small: 25.6–27.0 wt.%), this does not indicate the equal origin of all the mineralogical fractions of olivine, since the material of Songyuan has been homogenized during the equilibration of the parent body. The median value of 26.2 wt.% Fa (somewhat higher than that estimated by Rubin) indicates the L5 group of ordinary chondrites. However, some significant differences are present in the distribution of SiO_2, and particularly in the distribution of MnO, where the content in the small matrix grain fraction of olivine (0.64–0.87 wt.% MnO) is clearly higher than in remaining structural groups in total (FNB + KLS + RCK = 0.22–0.64 wt.%). It is impossible to conclude whether the present distribution of Mn reflects primary differences in the olivine mineral fractions or was produced by a secondary process.

PORPHYRITIC OLIVINE CHONDRULES (PO CHONDRULE) AND CLASTIC OLIVINE GRAINS (KLS)

Most of the phenocrysts in the Songyuan PO chondrules are limpid and homogeneous. They have well-developed crystal faces and rounded corners. Only exceptional chondrules display subhedral or anhedral phenocrysts. Similar optical features show clastic olivine grains dispersed in the matrix of the meteorite. In almost in all observed cases, both the phenocrysts and the clastic grains exhibit homogeneous extinction in cross-polarized light (shock level S1 according to the scale of Stöffler *et al*. (1991). Undulose, irregular fractures, frequently with surfaces covered by a thin film of limonite are generally rare in both kinds of the olivine crystals (planar fractures are absent). Mosaic extinction was observed exceptionally at the borders of some of the fractures.

Short, greenish or reddish (~1 to ~40 μm) crystals as well as anhedral metal or sulfide grains (<1 to ~5 μm) are moderately abundant in the olivine phenocrysts and clastic olivine grains. However, specific to both kinds of olivine crystals are multi-phase inclusions and long coves (Fig. 1A), that both could be supposed to be the remnants of primary solid-liquid-gas inclusions. The inclusions (a few tens to a few hundreds of μm long and a few tens of μm in diameter) are oval

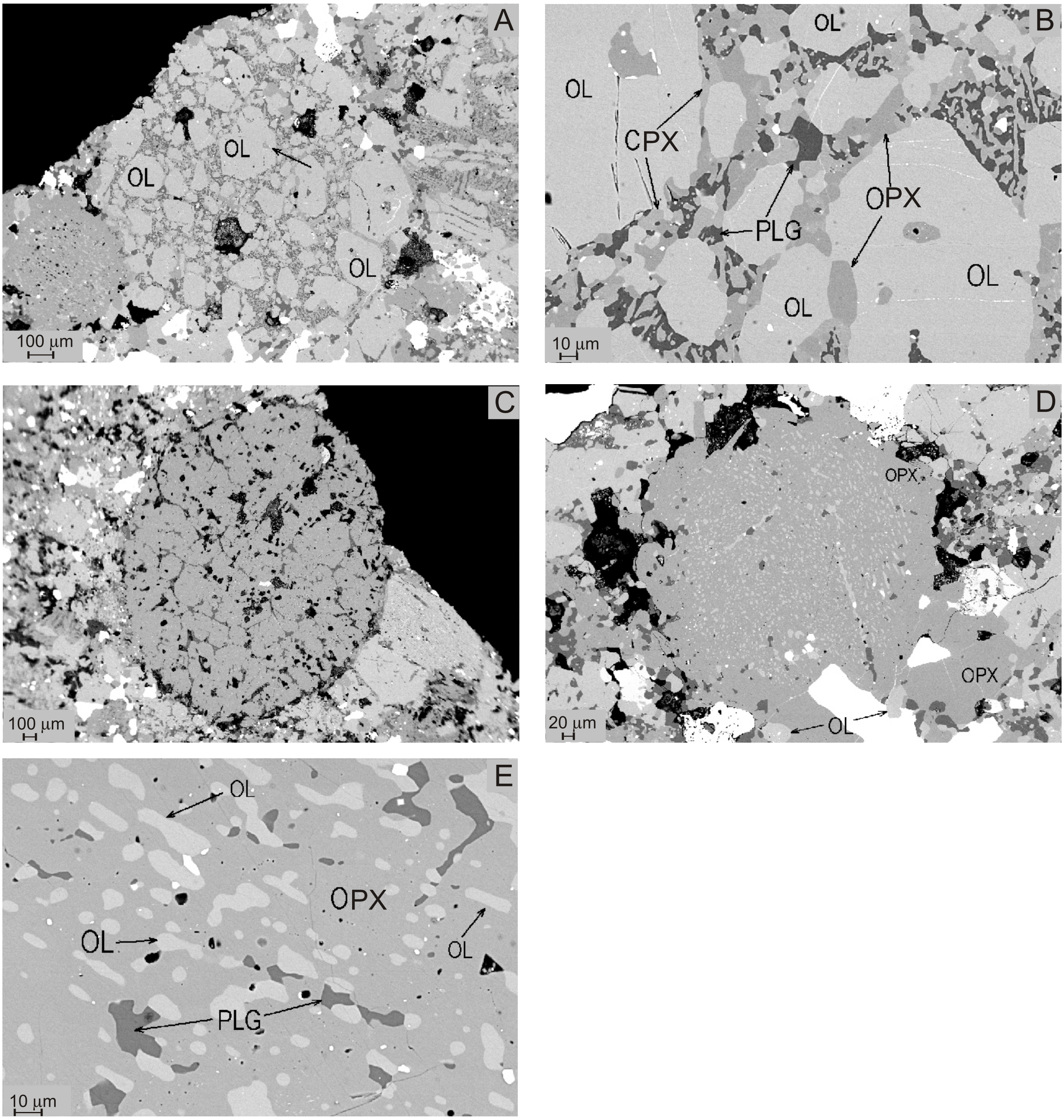
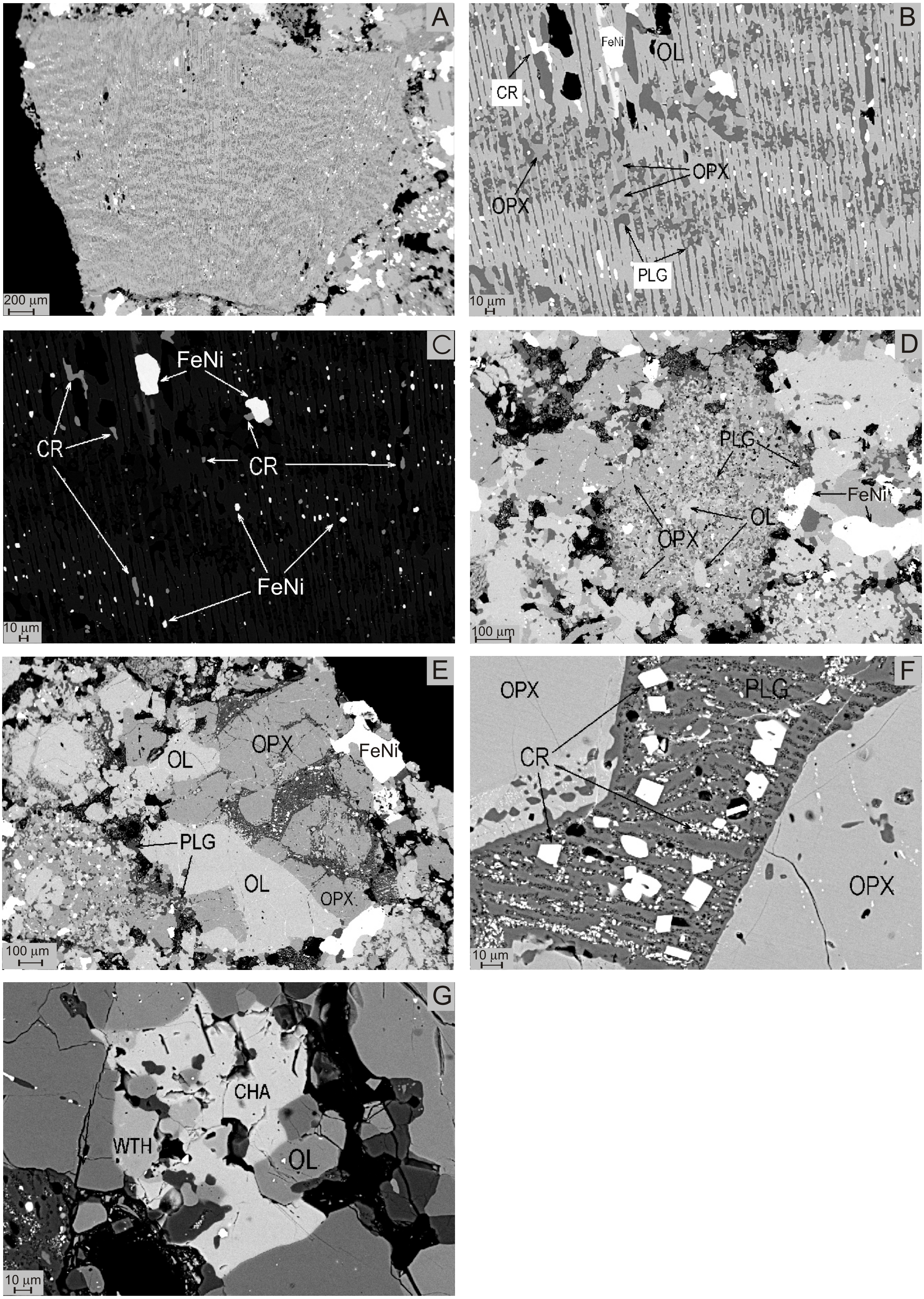


Fig. 1. BSE (back-scattered electrons) pictures of chondrules in the Songyuan meteorite

A — porphyritic olivine chondrule in a OPX–CPX–PLG groundmass. Rare multiphase inclusions (see text) are visible in some of the olivine phenocrysts. The holes in the mesostasis are the products of crumbling out of the grains during thin section preparation. The chondrule, that was accreted in the regolith sediment as a crystallized hard object, is separated from the remaining components of the regolith by a chain of pores making the irregular bordering fissure. Note the rarity of the metal and of other opaque's (much rarer than in the matrix of the chondrite) indicating different formation environments. **B** — a segment of the same PO chondrule as in Figure 1A illustrates a sequence of accelerating crystallization: a — large, euhedral or subhedral olivine phenocrysts had crystallized relatively slowly from unconstrained silicate melt; b — anhedral OPX and CPX grains, filling the spaces between the phenocrysts, crystallized rapidly in a confined environment full of suspended crystals; c — small, dendritic, ghost crystals of OPX and CPX crystals crystallized instantly in d — the amorphous PLG mass. **C** — porphyritic (granular ?) pyroxene chondrule (PP): the ellipsoidal shape shows that the floppy chondrule was rotating in space before hardening, but the almost complete bordering fissure shows that it accreted to the regolith already after crystallization (hardening). Small intergranular spaces between the subhedral OPX phenocrysts are partly filled with a porous, shapeless, plagioclase (albite) mesostasis with rare nanometric grains of metal dust. Grains of chlorapatite and a grain of troilite are present, whereas the total absence of the metal is striking. **D** — a small cryptocrystalline chondrule with a notched surface suggesting moderate erosion (in nebular space) preceding sedimentation onto the secondary parent body. The chondrule is partly separated from the chondrite matrix by bordering voids (though a few of these could, however, have been created during preparation of the thin section). The chondrule has an OPX shell, and the core is composed of the OPX groundmass with an numerous, olivine prisms in it. **E** — a part of the core of the other similar chondrule. OPX groundmass with oriented oval olivine prism in it. Plagioclase fills the free spaces between OPX and olivine grains. Metal grains and small holes are rare.


A
200 µm
B
FeNi
OL
CR
OPX
OPX
PLG
10 µm
C
FeNi
CR
CR
FeNi
10 µm
D
PLG
FeNi
OL
OPX
100 µm
E
OL
OPX
FeNi
PLG
OL
OPX
100 µm
F
OPX
PLG
CR
OPX
10 µm
G
CHA
WTH
OL
10 µm

and rounded or locally vermiform. Some of the inclusions are empty, others are filled or partly filled with light gray amorphous plagioclase sediment. A few of the inclusions contain scarce grains of orthopyroxene and/or metal, that have crystallized on the surface of the sediment. By contrast to the inclusions, the coves, particularly those in the clastic olivine grains, are filled with a mosaic aggregate of olivine and orthopyroxene similar to that of the mesostasis of the PO chondrules.

Mesostasis of the predominant PO chondrules in the Songyuan meteorite is built of a dark gray, partly translucent plagioclase groundmass in which abundant clinopyroxene dendrites are present. Other, rather uncommon PO chondrules contain an olivine aggregate mezostasis, where crystals up to 50–60 µm in size display a mosaic structure.

Most of the PO chondrules are devoid of rims and probably they never were rimmed. Some of the chondrules have notched surfaces as an effect of moderate corrosion. A few of the PO chondrules preserve small fragments of their original accretion rim (effectively up to ~50 µm large), that is composed of mosaic olivine crystal (up to ~20–40 µm) aggregates. Some exceptional rim fragments border the clastic olivine grains. When present, they are composed of an olivine micro-mosaic, or of a micro-grained aggregate of OPX, small crystals of olivine and nanometric opaque dust.

The median fayalite content in the olivine phenocrysts (26.2 wt.%) and in the clastic olivine grains (26.8 wt.%) are similar, showing the almost perfect equilibration of the Songyuan chondrite. Only the contents of MnO shows heterogeneity, whereas the small heterogeneity in the SiO_2 distribution seems insignificant. On the other hand, the mineralogical similarities between the clastic olivine grains and the phenocrysts in the PO chondrules show that the clastic olivine grains may have formed as a result of crumbling of PO chondrules having a diameter of ~1 to ~1.5 mm. In the process of crushing, the brittle chondrule matrix would be destroyed, whereas the resistant phenocrysts were extracted and preserved as clastic grains.

PORPHYRITIC PYROXENE CHONDRULES (PP) AND CLASTIC OPX GRAINS

Clastic orthopyroxene grains are particularly scarce in the Songyuan chondrite; in general they represent the principal component (~5% vol.), although being much less abundant than olivine. The chemical composition (Table 2) of the orthopyroxene grains and crystals is very close, as shown by the small standard deviation of calculated forsterite content (Fs): $s = 0.8025$ wt.% Fs. In the matrix of Songyuan, orthopyroxene exists in two distinct morphological forms:

— a fine fraction of grains that are colourless, shapeless and often "bruised", having dimensions of 0.5 to 0.9 mm, typical "pyroxene" cleavage and zoned structure. Symptoms of secondary alteration (turbidity, opacity and mosaic structure) are common in most of the grains, whereas only a few contain small (2–40 µm) inclusions of FeNi-metal. "Dinted" surfaces of grains (on which some sparse grains of olivine, FeNi-metal or porous troilite are stuck) have been primarily shaped by some kind of mild corrosion;

— a fraction of large, subhedral crystals, elongated (1:5) and up to 200 µm long, having euhedral pinacoid faces, and frequently enclosing oval inclusions of olivine.

Very few porphyritic pyroxene chondrules were noticed in the thin sections of the Songyuan meteorite. They have ellipsoidal, slightly oblate contours with the long axis from ~0.5 to ~3 mm long. The orthopyroxene phenocryst prisms are the principal component of the PP chondrules (Fig. 1C). They are 0.04–0.6 mm long and have a ~2:1 elongation. Pale gray orthopyroxene crystals display strong relief, distinct cleavage, and a few undulose fractures. The extinction, mostly homogeneous, rarely shows a mosaic or undulose pattern. Typical of the orthopyroxene crystals are vermicular or shapeless inclusions, representing some kind of micro-channels (many micrometers long and a few micrometers in cross-section), particularly common at the borders of crystals. In general, they generally resemble the inclusions described above in the olivine clastic crystals and olivine phenocrysts. As in the olivine grains and crystals, a thin layer of a clear or dark gray, mostly opaque, rarely transparent, plagioclase sediment, and small, crystalline

Fig. 2. BSE pictures of alien rock fragments and other structural objects in the Songyuan meteorite

A — a sharp-edged fragment of a metamorphic rock. The fragment is separated from the chondrite matrix by an irregular bordering chain of voids. No trace of similar metamorphic change is present in the neighbouring matrix grains. **B** — part of the fragment shown in Figure 2A. Metamorphic changes appear as a replacement of the primary structure of olivine lamellae interleaved with plagioclase by a more irregular pattern with the frequent presence of the anhedral OPX grains. This structure was formed by a relatively long, complicated process on the primary parent body. **C** — the same fragment as in Figure 2A. Example of the presence of unusually numerous micrometric chromite grains contrasting with the relatively small number of metal grains. **D** — a fragment of a hetero-granoblastic rock showing a mosaic structure and composed mainly of olivine, OPX and PLG (albite), with rare metal grains and nanometric metal dust. Porosity very low. The fragment is mostly separated from the chondrite matrix by a chain of large voids, but two metal grains are deeply squezzed into the fragment, showing that the plastic nature of the rock was greater than that of the metal. Probably a fragment of solidified crust of the primary parent body. **E** — an angular fragment of basalt shows porphyritic texture with subhedral OPX and anhedral olivine phenocrysts. Orthopyroxene displays numerous curvilinear fractures, and epitaxial outgrowths of mixed orthopyroxene-plagioclase fringes. Intensive magmatic corrosion is present. Olivine is more homogeneous and less affected by the magmatic corrosion. Small crystals of chromite are abundant in the mesostasis of the basalt. A single grain of metal is present as well as a complex aggregate of phosphates. The fragment is almost entirely separated from the chondrite matrix by a train of voids. **F** — a part of Figure 2E displaying the oriented, nematoblastic texture of the plagioclase mesostasis. Numerous, euhedral chromite crystals and nanometric chromite dust are abundant in the central parts of the mesostasis, whereas they are entirely absent at the orthopyroxene phenocryst borders. **G** — a part of Figure 2E showing the secondary withlockite–chloroapatite–olivine aggregate situated in a void at the edge of the basalt fragment (probably alteration products).

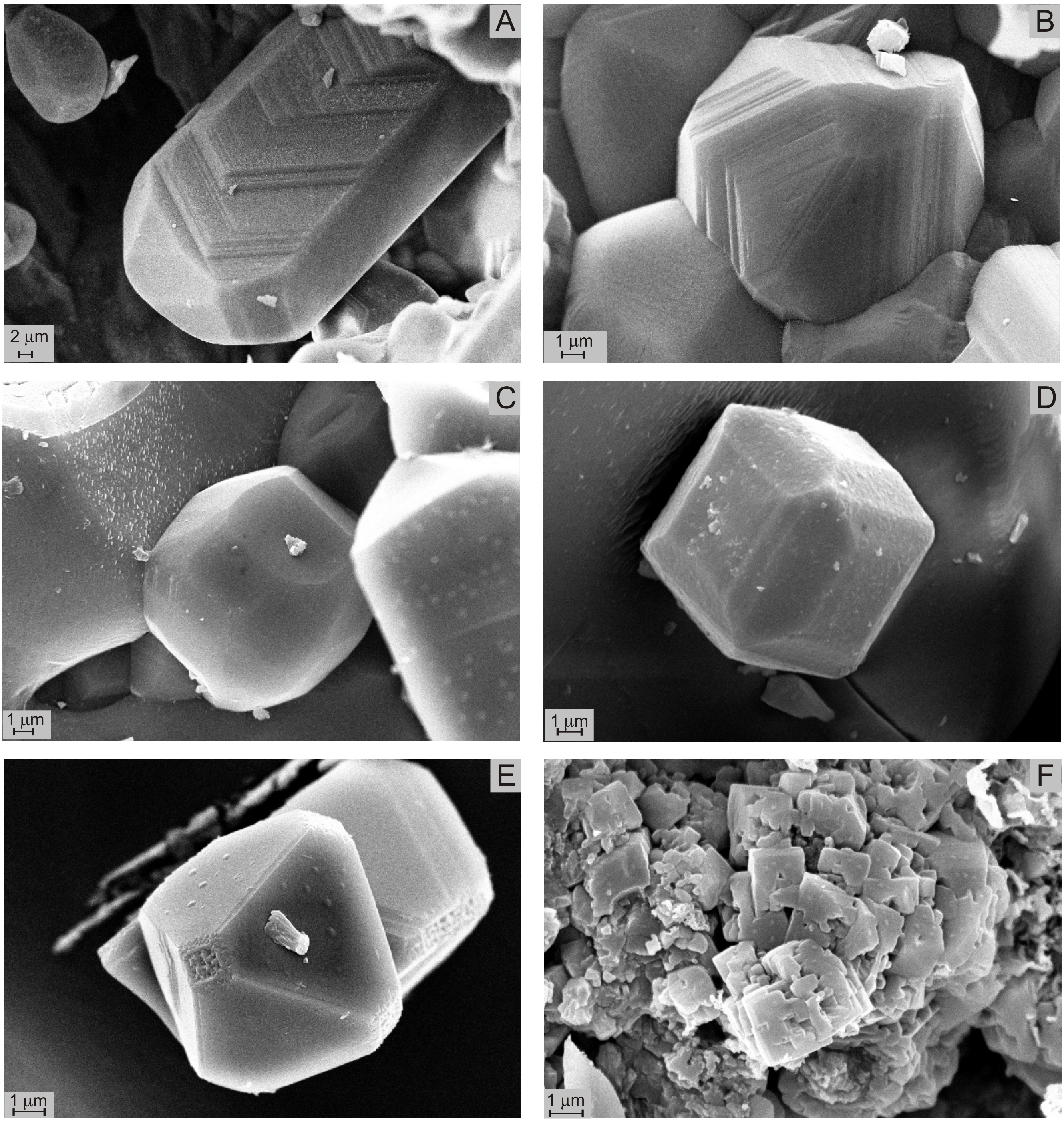


Fig. 3. SEM (scanning electron microscope) pictures of crystals of the main meteorite-forming minerals in interstitial pore spaces of the Songyuan meteorite

A — an elongated olivine crystal with straight growth steps. Very similar decorated crystals were found in the Baszkówka meteorite (Wlotzka and Otto, 2001; Borucki and Stępniewski, 2001); **B** — growth steps on the pyroxene crystal faces. They show that the chemical composition of vapors varied during crystallization; **C** — pore crystal of feldspar; **D** — FeNi crystal stuck on olivine grain in a pore of Songyuan. Intensities of Fe and Ni lines on ED X-ray spectrum suggest tetrataenite; **E** — characteristic octahedral chromite crystal with etch figures. Similar figures were observed in Baszkówka (Borucki and Stępniewski, 2001); **F** — tabulate aggregate of melanterite, probably terrestrial post-troilite product of oxidation.

micro-druses of olivine and orthopyroxene decorate the walls of the channels. Beyond the described inclusions, micrometric crystals are moderately abundant, disposed in swarms or series conforming to the main growth directions of the orthopyroxene crystals. Inclusions of metal and chromite are very rare. Scant mesostasis is present as an isotropic, semitransparent, dark gray-brown substance. It forms thin layers on the surfaces of the phenocrysts and fills up the small spaces between them.

The optical characteristics of both groups orthopyroxene (clastic and chondrules PP) are distinctly different, so the origin

Table 1

Results of chemical microanalysis of olivine grains from different structural elements (STR) in the Songyuan meteorite

MIC	STR	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total
A001	FNB	37.41	ND	ND	ND	23.50	0.59	36.51	0.13	ND	ND	98.15
A002	FNB	37.77	ND	ND	ND	23.36	0.47	37.64	0.01	ND	ND	99.23
A003	FNB	37.80	ND	ND	ND	23.30	0.62	37.17	0.04	ND	ND	98.85
S315	KLS	39.13	0.00	0.00	0.00	22.56	0.64	37.78	0.00	0.00	0.02	100.14
S316	KLS	38.19	0.00	0.10	0.00	22.73	0.54	37.30	0.06	0.23	0.03	99.19
S322	KLS	38.36	0.00	0.02	0.00	22.98	0.59	37.25	0.11	0.10	0.00	99.40
S323	KLS	38.65	0.00	0.00	0.00	23.52	0.62	37.47	0.09	0.26	0.05	100.66
S324	KLS	38.69	0.11	0.08	0.08	23.38	0.57	36.80	0.14	0.48	0.00	100.32
S325	KLS	38.06	0.00	0.00	0.09	23.37	0.56	37.72	0.19	0.24	0.00	100.23
S134	MTX	38.38	0.00	0.04	0.11	22.62	0.74	37.12	0.20	0.00	0.04	99.24
S135	MTX	38.21	0.00	0.00	0.19	22.54	0.86	37.22	0.00	0.14	0.01	99.16
S310	MTX	38.31	0.00	0.00	0.00	22.14	0.83	37.44	0.08	0.10	0.00	98.90
S313	MTX	38.71	0.11	0.03	0.00	23.17	0.66	37.46	0.11	0.10	0.00	100.35
S314	MTX	38.21	0.01	0.00	0.00	22.29	0.64	37.06	0.11	0.23	0.00	98.55
S318	MTX	38.47	0.00	0.14	0.00	22.95	0.87	36.85	0.12	0.37	0.00	99.78
S326	MTX	38.39	0.00	0.00	0.13	22.85	0.72	37.81	0.09	0.06	0.00	100.05
S205	RCK	37.95	0.00	0.13	0.00	23.11	0.55	37.23	0.06	0.32	0.05	99.40
S206	RCK	38.01	0.00	0.14	0.24	22.89	0.22	36.92	0.11	0.35	0.05	98.92

The calculated median value of the fayalite contents for 18 analyses (26.2 ±0.24 wt.%) corresponds to the L5 group of equilibrated ordinary chondrites; ND — not determined; MIC — number of chemical microanalysis; see text for other explanations

of clastic orthopyroxene as remnants of the crushing of PP chondrules is unlikely, and unfortunately, the present chemical data being insufficient to enable any further comparisons.

RADIAL CHONDRULES (RP, ROP CHONDRULES)

Pyroxene radial chondrules (RP) are not very frequent in the Songyuan chondrite, whereas olivine-pyroxene (ROP) radial chondrules seems to be quite exceptional; only one such chondrule was noticed in the thin sections studied. Most of the radial chondrules show a single fan, the crystallization of which was initiated at the circumference by small grains of metal or troilite, that, in many instances, still remain stuck to the surface. The laths of the RP fans are apparently about 5 to 30 μm across and are composed of the non pleochroic orthopyroxene aggregate displaying a mosaic extinction in cross polarized light. Numerous planar fractures are roughly vertical to the elongation of the laths, while magnification higher than 1000x reveals the hatched contours of the orthopyroxene, typical of skeletal crystals. Numerous, very small metal dust grains, having nanometric dimensions (<1 μm) are evenly dispersed in the chondrules, whereas by contrast, some bigger (few tens of μm large) metal grains are gathered mostly at the obtuse fringes of fans. Such spacing may be caused by diffusion migration of Fe atoms during crystallization of the pyroxene. Small spaces between the laths are filled by dark gray, partly opaque matrix mainly composed of plagioclase. Accretion rims are mostly absent, and the bare surfaces of RP and ROP chondrules are strongly indented much more than in other kinds of chondrules in the Songyuan matter.

PYROXENE METAMORPHIC ROCK

Some angular fragments, present in the material of the Songyuan chondrite, have a radial structure resembling that of radial chondrules (Fig. 2E, F). They may be the result of crushing of large- a few millimetres across- RP or ROP chondrules. Moreover, the widths of laths and also their composition (olivine and/or low Fe bronzite), are quite alike in both kinds of the chondrite components. However, symptoms of evident alteration (Fig. 2F), common in the “angular fragments”, are totally absent in the radial chondrules. The alteration is manifested by an abundance of relatively large, undulose laminae oblique to the directions of non-metamorphosed laths. The altered, granoblastic laminae are intercalated with unaffected ones, in which the original lamellae are preserved. The composition of both is generally similar, with orthopyroxene as the main component, and olivine, feldspar and FeNi as accessory ones (Fig. 2G). The quantity of feldspar in metamorphosed laminae is somewhat higher, and the quantity of metal is slightly reduced in comparison to the unaffected laminae.

A few olivine, porous troilite and FeNi grains stick to the surfaces of the angular fragments. They make accretion rims on the fragments of surfaces previously formed by intensive corrasion. Summing up, the fragments (or original chondrules)

Table 2

Results of chemical analysis of the orthopyroxene and diopside grains in different structural objects of the Songyuan meteorite

MIC	STR	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total
ORTOPYROXENE												
S137	MEZ	55.92	0.22	0.25	0.19	13.39	0.58	27.82	0.82	0.42	0.00	99.61
S139	MEZ	55.35	0.00	0.27	0.00	13.37	0.67	28.29	0.85	0.18	0.03	98.99
S140	MEZ	54.85	0.22	0.00	0.25	14.30	0.70	27.81	0.81	0.14	0.00	99.08
S132	MTX	54.75	0.11	0.10	0.21	15.42	0.29	27.58	0.58	0.31	0.00	99.35
S133	MTX	55.26	0.21	0.14	0.00	14.27	0.74	27.84	0.81	0.34	0.19	99.73
S312	MTX	55.85	0.13	0.00	0.00	13.76	0.74	28.02	0.86	0.12	0.04	99.53
S427	MTX	55.52	0.22	0.11	0.06	13.93	0.43	27.47	0.95	0.36	0.01	99.04
S428	MTX	54.96	0.15	0.21	0.02	13.91	0.64	27.57	0.70	0.27	0.00	98.43
A005	MTX	55.22	0.41	ND	0.08	13.95	0.39	27.51	0.83	0.81	0.05	99.15
A006	MTX	54.33	0.42	ND	0.04	13.71	0.33	27.79	0.91	0.58	0.12	98.23
A007	MTX	55.33	0.09	ND	0.11	14.07	0.57	27.31	0.93	0.66	0.06	98.94
A008	MTX	54.58	0.18	ND	0.19	14.34	0.74	27.47	0.63	0.84	0.03	98.93
D003	MTX	56.34	0.19	ND	0.23	13.98	0.50	27.87	0.81	0.74	0.09	100.75
S203	RCK	55.50	0.32	0.30	0.50	13.73	0.35	28.33	0.80	0.33	0.07	100.24
S204	RCK	55.54	0.14	0.18	0.39	13.74	0.83	28.24	0.54	0.22	0.01	99.84
DIOPSIDE												
F001	–	54.61	0.34	0.03	0.94	5.52	0.28	16.86	22.56	0.08	0.08	101.30
F002	–	55.07	0.24	0.11	1.39	5.01	0.18	15.81	22.52	0.92	0.06	101.31
F003	–	55.34	0.59	0.04	1.06	4.44	0.24	14.97	22.37	1.04	0.03	100.12
F004	–	53.96	0.38	0.28	1.11	4.58	0.57	15.40	22.32	0.77	0.10	99.47

For explanations see Table 1

have been metamorphosed and corroded before they were settled as the components of the Songyuan regolith.

PLAGIOCLASE IN THE MATRIX, CHONDRULES AND ROCK FRAGMENTS

High potassium oligoclase, an accessory mineral in the Songyuan material, contains from 10 to over 13 vol.% of calculated anorthite (An) and from 2.8 to 7.7 vol.% of calculated orthoclase (Or). It appears in the matrix, chondrules and rock fragments of the meteorite, filling small voids, intergranular spaces and fractures or in places forming independent, anhedral grains. Together with pyroxenes (orthopyroxene and clinopyroxene), plagioclase forms the matrix of the PO, BO and radial chondrules. In kinds of chondrule, plagioclase is present as anhedral, isometric grains rarely reaching a few tens of micrometers. Eight grains of oligoclase analysed from different structural objects have a large dispersion, characterized here by the standard deviations of the calculated albite, anorthite and orthoclase molecules. The standard deviation of Ab, An and Or is respectively 2.22, 1.04 and 1.44 wt.%, considerably higher than for those of Fa in olivine or Fs in orthopyroxene (0.24 and 0.80 wt.% respectively). The divergence in the plagioclase chemical composition is so significant, that it is evident that the grains analysed belong to different populations, and the chemical constitution of the plagioclase has not equilibrated. Therefore, the present composition of plagioclase was, most probably, established after equilibration of the chondrite, maybe during some undefined, secondary processes. For chemical composition of the plagioclases see Table 3.

BARRED OLIVINE CHONDRULES (BO CHONDRULES)

Well-developed, barred olivine chondrules are certainly sparse in the Songyuan chondrite, much more frequent are their fragments, that are, often difficult to identify. In a few observed examples the bars (40–70 µm large), consisting of the cylindrical, limpid olivine crystals, display vertical dendrite-like notches and homogeneous or more rarely speckled extinction. Only a few FeNi cubes and ill-shaped chromite grains (dimensions: ~30–40 µm) appear in the olivine crystals, whereas metal dust (grains ≤1 µm) is ubiquitous. The spaces between the bars are filled with a mezostasis composed of a limpid aggregate of bronzite and feldspar. Clear gray bronzite crystals, with strong relief and low interference colours, and gray, low relief, amorphous feldspar grains (≤ 15 µm), compose a micro-granoblastic pattern. Most of the chondrule rims are destroyed, and the exposed chondrule surfaces are mildly "dinted". Most of the crystallization rims (in the rare cases present) display a poikilitic structure, with orthopyroxene oiko-crystals enclosing a few oval olivine chada-crystals. By contrast, a granoblastic olivine-orthopyroxene aggregate is present in non-poikilitic accretion rims. Very rare, small opaque grains are dispersed in both kinds of rim.

Table 3

Chemical compositions of plagioclase grains in the Songyuan chondrite

MIC	STR	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total
S136	MTX	65.10	0.00	21.28	0.03	1.24	0.14	0.09	2.37	9.04	1.32	100.61
S136	MTX	65.08	0.00	20.94	0.03	0.26	0.00	0.06	2.18	9.64	0.79	98.98
S311	MTX	64.53	0.14	20.46	0.11	0.94	0.00	0.00	2.44	9.01	1.03	98.67
S317	MTX	64.09	0.15	20.54	0.06	1.12	0.00	0.00	2.07	10.03	0.51	98.57
D002	MTX	64.99	0.07	21.03	ND	0.49	0.14	ND	2.74	9.55	0.91	99.64
A018	RIM	65.04	0.29	21.62	ND	0.65	0.08	ND	2.17	9.02	0.76	99.63
A019	RIM	65.23	0.13	20.97	ND	0.55	0.15	ND	2.36	9.67	0.96	99.73
A020	MEZ	63.35	0.14	21.08	ND	1.11	0.27	ND	2.63	9.25	1.13	99.45

For explanations see Table 1

Table 4

Chemical compositions of withlockite and Cl-apatite grains in the Songyuan meteorite

MIC	Na_2O	MgO	P_2O_5	Cl	CaO	TiO_2	Cr_2O_3	MnO	FeO	Total
WITHLOCKITE										
C004	2.44	3.58	45.50	0.01	46.54	ND	ND	0.05	1.36	99.48
C007	2.14	3.72	46.30	0.01	47.11	ND	ND	0.07	1.14	100.49
C008	2.24	3.44	46.61	0.07	47.12	ND	ND	0.24	0.47	100.19
C009	2.66	3.97	46.29	0.09	46.96	ND	ND	0.03	1.58	101.58
F006	2.89	3.68	46.12	0.12	46.31	0.11	0.76	ND	1.51	101.50
F007	2.61	2.86	46.20	0.02	46.18	0.25	0.87	ND	1.12	100.11
F008	2.28	2.97	45.56	0.07	46.75	0.09	0.71	ND	1.38	99.81
F009	2.17	2.58	47.05	0.01	47.61	0.13	0.06	ND	0.79	100.40
F010	2.65	3.37	45.91	0.15	46.30	0.11	0.72	ND	0.90	100.11
Cl-APATITE										
C002	0.41	0.09	40.45	4.84	54.23	–	–	0.39	0.92	101.33
C003	0.35	0.08	41.11	4.77	54.70	–	–	0.14	0.62	101.77
C005	0.96	0.20	41.33	4.13	53.92	–	–	0.20	0.47	101.21
C006	0.48	0.55	42.78	3.57	52.85	–	–	0.26	1.12	101.61

For explanations see Table 1

CRYPTOCRYSTALLINE CHONDRULES (C CHONDRULES)

Only a few cryptocrystalline chondrules were found in the thin sections examined, yet it was possible to define some of their significant features (Fig. 1D, E). The C chondrules are mostly separated from other components of the chondrite matrix by sets of contact voids and/or holes. The "bare" surfaces of the chondrules display roughly notched contours, whereas the rather short sections tightly joined to the other clastic components of the chondrite matrix have barely visible, smoothed contacts. The C chondrules have cores composed of the abundant cryptocrystalline orthopyroxene groundmass with numerous oval, smoothed grains of olivine chadacrystals. By contrast, plagioclase mezostasis fills the rare irregular voids between the olivine and orthopyroxene grains. The arrangment of the olivine grains is evidently directional. Significant also is the striking rarity of metal grains and the presence of some micro-pores. In general the structure of the core may be interpreted as a result of eutectic crystallization. The cores of the C chondrules are surrounded by cryptocrystalline orthopyroxene shells. Probably melted drops fell into the relatively cooler regolith sediment, where their surface layers crystallized rapidly, forming the rims and enclosing the eutectic cores.

CRYPTO-CRYSTALLINE OLIVINE-PYROXENE LUMPS

Cryptocrystalline lumps, sometimes difficult to distinguish against the background of the chondrite matrix, are quite numerous in the Songyuan material. Their observed dimensions

Table 5

Results of chemical analysis of the massive and porous troilites in the Songyuan meteorite

MIC	STR	MgO	Al_2O_3	SiO_2	CaO	TiO_2	Cr_2O_3	MnO	FeO	NiO	ZnO	Total
A013	RIM	2.39	4.97	0.30	0.18	3.34	56.90	ND	30.99	0.38	ND	99.45
A014	RIM	2.29	5.29	0.81	0.13	3.50	57.51	ND	29.77	0.20	ND	99.12
C001	MTR	2.36	5.22	0.72	0.02	3.52	57.91	0.05	30.37	0.19	ND	100.36
D001	MTX	3.13	5.86	0.67	0.13	3.39	57.43	0.08	30.12	0.02	ND	100.79
S201	RCK	3.27	5.47	0.19	0.17	3.48	56.83	0.71	28.54	0.40	0.01	99.07
S202	RCK	3.20	5.14	0.28	0.15	3.64	56.57	0.74	28.54	0.12	0.62	99.00

For explanations see Table 1

Table 6

Results of chemical analysis of chromites from different structural objects in the Songyuan meteorite

MIC	STR	Si	S	Ti	Cr	Fe	Co	Ni	Cu	Zn	Total
S320	MTX/mass.	ND	35.18	ND	ND	62.86	0.00	0.00	0.00	0.31	98.35
S321	MTX/mass.	ND	35.35	ND	ND	61.74	0.00	0.00	0.00	0.12	97.21
S431	MYX/por.	ND	35.85	ND	ND	63.00	0.02	0.10	0.05	0.00	99.02
BO06	ALT/por.	0.17	36.53	0.02	0.05	63.79	ND	0.10	ND	ND	100.46
A015	RIM/por.	0.35	36.73	0.13	0.04	64.53	ND	0.12	ND	ND	101.56
A016	MTX/por.	0.25	35.69	0.11	0.03	64.80	ND	0.21	ND	ND	100.82
A017	MTX/por.	0.12	36.42	0.05	0.12	64.39	ND	0.18	ND	ND	101.18

mass. — massive, por. — porous; for other explanations see Table 1

vary from a few tens of micrometers to some millimetres. Sharp-edged fragments are entirely absent, whereas rare, smoothed and rounded, grains are abundant. Some lumps are well-fitted to the enclosing silicates, metal, and/or sulfide. But most of them display “bare” surfaces, separated from the chondrite matrix by bordering voids. The presence of small metal and sulfide grains squeezing deeply into the lumps seems particularly significant. It may be supposed that during accretion of the Songyuan regolith the material of the lumps was more plastic than brittle, while its plastic character was even greater than that of the metal. Probably the lumps were composed of fluffy, relatively cold clots of matter kept together only by cohesion (Fig. 2A–C).

The lumps are characterized by the presence of numerous domains with blurred contours, a slightly diversified structure (granoblastic, porphyroblastic or laminated) and an almost uniform mineral composition. Short subhedral, clear-gray, semitransparent prisms of bronzite (Δ ~0.013 nm) are the dominant principal component in all the domains, whereas anhedral, limpid and clear-olive olivine grains are much less abundant (Δ ≥0.030 nm). Both olivine grains and orthopyroxene prisms have dimensions from a few micrometers to a few tens of micrometer. In the domains with a porphyroblastic structure the phenoblasts of olivine are set in an orthopyroxene groundmass. Plagioclase — a transparent, translucent, white and shapeless substance with a low birefringence (Δ ~0.005–0.006 nm) — fills the small spaces between the olivine and orthopyroxene grains. The hypothetical cristobalite (limpid, sub-euhedral octahedrons ~5–15 μm large, having a heavy negative relief and very low birefringence <0.005 nm), observed only using a polarizing microscope and not confirmed by X-Ray microscope, was found in two large lumps (a few millimetres across). Nanometric dust of metal (and possibly sulfide) is very abudant, probably accreted onto the Songyuan parent body together with silicates. In spite of the dust, micrometric, rounded grains of the FeNi and troilite (and exceptional chromite) are rather rare, and seem to have mixed with the silicate matter much later — during accretion of the Songyuan regolith.

The mineral composition and structures of the lumps suggest that they were built of sintered and not molten matter. We suppose that the lumps represent crumbled matter of the surface layer covering the Songyuan parent body.

OPAQUE MINERALS

Native metal (taenite and kamacite), troilite (massive and porous variety) and chromite are the principal opaque minerals in the Songyuan material, making together several percent by volume.

Native metal is present in two distinct grain fractions:
— very fine, sub-micrometric metallic dust particles,
— larger, sub-millimetric metal grains.

Table 7

Results of chemical analysis of metallic iron from the Songyuan meteorite

MIC	Si	S	Ca	Ti	Al	Cr	Fe	Mn	Mg	Ni	Zn	Co	Cu
A009	0.14	0.05	ND	0.01	ND	0.07	81.54	ND	ND	17.07	ND	ND	ND
A010	0.25	0.21	ND	0.11	ND	0.00	84.09	ND	ND	14.36	ND	ND	ND
A011	0.21	0.09	ND	0.01	ND	0.03	87.91	ND	ND	11.02	ND	ND	ND
A012	0.15	0.07	ND	0.07	ND	0.07	85.60	ND	ND	13.28	ND	ND	ND
E001	0.49	ND	ND	0.03	ND	0.00	75.02	ND	ND	25.58	ND	ND	ND
E002	0.37	ND	ND	0.06	ND	0.03	74.39	ND	ND	25.86	ND	ND	ND
S207	0.10	ND	0.11	0.00	0.00	0.05	82.56	0.00	0.11	14.63	0.73	0.20	0.00
S208	0.13	ND	0.06	0.00	0.02	0.06	83.69	0.17	0.15	13.74	0.00	0.21	0.28
S209	0.19	ND	0.03	0.00	0.04	0.02	91.74	0.00	0.00	7.28	0.28	0.27	0.01
S319	0.21	ND	0.12	0.00	0.03	0.18	77.49	0.00	0.20	20.72	0.00	0.16	0.00
S429	0.11	ND	0.02	0.05	0.00	0.00	52.79	0.24	0.00	45.98	0.00	0.32	0.56
S430	0.06	ND	0.00	0.01	0.00	0.00	80.08	0.00	0.12	17.01	0.50	1.03	0.11

S208 and S209 — the same iron object (125 × 500 μm) from a fine-grained rock fragment, S429 and S430 — the same iron grain (73 × 95 μm) in a weathering fissure; for other explanations see Table 1

Table 8

Chemical compositions of weathered iron minerals from the Songyuan meteorite showing the sequence of oxidation

MIC	O	Si	S	Ti	V	Cr	Mn	Fe	Ni	Total
wt.% of the elements										
E001	ND	0.49	ND	0.03	ND	0.00	0	75.02	25.58	101.12
E002	ND	0.37	ND	0.06	ND	0.03	0	74.39	25.86	100.71
E003	29.56	0.28	0.85	0.02	0.15	0.04	0.03	69.93	0.14	101.00
E004	37.86	0.33	0.78	0.05	0.13	0.21	0.12	55.24	3.15	97.87

atomic contents in wt.% calculated to 100 [%]										
MIC	MC	O	Si	S	Ti	V	Cr	Mn	Fe	Ni
E001	taenite	ND	0.98	0.10	0.04	ND	0.00	ND	74.66	24.22
E002	taenite	ND	0.73	0.07	0.07	ND	0.04	ND	74.52	24.64
E003	magnetite	58.79	0.32	0.85	0.01	0.09	0.02	0.02	39.85	0.08
E004	limonite	68.70	0.34	0.71	0.03	0.07	0.12	0.07	28.71	1.56

MC — main components; for other explanations see Table 1

It appears in chondrules as well as in the matrix of the meteorite. The metal grains are clearly allotriomorphic, with contours constrained by the surrounding silicates, but still the contours of the grains are smooth and oval. Very typical are the shapes of grains at void borders; they from knobs slightly protruding into the voids and not filling them. Consequently, it is evident that the pressure of the surrounding rocks was weaker than the mechanical resistance of the metal, indicating that the Songyuan matter originates from a shallow horizon of its parent body. Only twelve arbitrary selected metal grains were analysed. Eleven grains show a content of Ni (11–46 wt.%) specific for taenite or tetrataenite, whereas only one represents a mixture of taenite and kamacite (Table 7).

Besides the grains and particles described, rare aggregates of millimetric metal, troilite and rare chromite particles were observed in the Songyuan meteorite. The aggregates of the opaque minerals are often confined, with interrupted accretion rims composed of olivine and rare orthopyroxene grains. Metal-silicate contacts are here evidently different than those described above, the metal seeming to have been more plastic at the moment of the accretion of the aggregate than during the sedimentation of the regolith. The aggregates together with their silicate rims are separated from the enclosing matrix by trains of dashed lines of bordering fractures (the fractures were partly closed during equilibration of the chondrite), showing the aggregate as an entity. In the metal, and locally in the troilite, are oval "windows", filled by microcrystalline grains of anhedral olivine, exceptionally by orthopyroxene.

Troilite (a few vol.%) is present in the Songyuan material as two structural varieties: massive, and more widespread in porous modified form (for chemical composition see Table 6). They appear as allotriomorphic, irregular grains, in form and dimensions comparable to that of the metal. The shapes when surrounded by silicates are as the case with iron. Accessory grains of chromite are morphologically similar to taenite and troilite. For chemical composition of the chromites see Table 5.

The grains of the FeNi and troilite could also be fragments of the crumbled metallic core of an unknown, primary object.

BASALT FRAGMENTS

Rare, angular fragments of pyroxene-olivine basalt are present in the material analysed (Fig. 2E). The rock displays a porphyritic texture with subhedral orthopyroxene and anhedral olivine phenocrysts and a cryptocrystalline pyroxene-plagioclase mesostasis. The rock shows two-stage crystallization: a relatively slow crystallization of phenocrysts and rapid crystallization of the mezostasis. The abundance of chromite crystals, associated with an evident scarcity of metal and troilite is significant, there is some textural similarity to lunar olivine basalt (Papike *et al*., 1998).

SOME REMARKS ON SECONDARY PROCESSES

In general the effects of weathering are rare and in consequence they were analysed at very few points. In the case of the taenite it has been stated that the first stage of weathering transformed the metal to magnetite, and then to iron oxide and hydroxides: hematite and goethite (see Table 8). The Ni ions of taenite entered into the structure of nickel sulfide; millerite. The weathering took place in an environment enriched in oxide, water and sulfur; most probably in the Earth's atmosphere. The akaganeite identified in Songyuan may have formed from troilite by a ferric-sulfate-bearing solution earlier, probably in an extraterrestrial environment.

Withlockite and chlorapatite that occasionally appear (often with chromite and porous troilite) in the mineral paragenesis, close to voids and fissures and pores in the chondrite matrix, are affected by weathering (Fig. 2G). An apatite-withlockite grain was found in one of the fissures bordered with metal and porous troilite, olivine and chromite. Phosphates are present along the straight contact. The mean contents of P and Ca in both phosphates are similar but the variability of the composition is significantly higher in the apatite. Moreover the apatite is porous, whereas the withlockite shows a massive structure. These features suggest that the apatite has grown by the removal of Na and Mg and the import of Cl, most probably in the terrestrial environment. For chemical composition of the phosphates see Table 4.

A grain of diopside (22×20 µm in size) was noticed in the one of the fissures together with other products of weathering. The grain, identified by microanalysis, displays a very variable composition, indicating unstable crystallization conditions, probably also related to weathering alteration.

CONCLUSIONS ON THE SONGYUAN CLASSIFICATION

The chemical homogeneity of olivine grains from different structural objects in the Songyuan meteorite shows a high level of equilibration with the exception of the manganese, which shows some deviations. Also the orthopyroxene, the second main component, shows a high level of the homogeneity with some outliers in the distribution of Fe, K and Ti. Taking into the account some chemical and mineralogical heterogeneities, classification of the chondrite as L5 is proposed. A low (S1) stage of shock metamorphism of the Songyuan material is recognized because of the homogeneous extinction in the olivine grains and the absence of planar fractures. Rare products of the terrestrial weathering are present only as partial fills of fractures, pores or as irregular spots, whereas there are no weathering rims around the metal grains; in consequence, a low weathering stage (W_0) is proposed in the classification of Songyuan. We propose the modification of the Songyuan classification from the L6(S2)W_1 suggested by Rubin (Grossman, 2000) to L5(S1)W_0 (this paper).

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