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Two spinel-bearing compound chondrules from the Baszkówka meteorite

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The present paper describes two compound chondrules labelled panda and chevron, discovered in the Baszkówka meteorite. Optical microscope, electron microscope and electron microprobe studies revealed an unusual mineral composition and fabric. Both chondrules include “primary” and “secondary” components. The panda and chevron chondrules have apparent diameters of ~0.86 and ~0.54 mm respectively with spinel dominant in primary components and olivine-plagioclase in secondary components overlain by thin microcrystalline rims. Euhedral or subhedral Mg, Fe^{2+}/Al, Cr-spinel crystals from the panda’s primary component (zoned, cavernous or homogeneous) were not found in Mg-Fe chondrules in Baszkówka, where Cr occurs exclusively as chromite. Olivine crystals from panda’s primary ($Fa_{27.1}$) and secondary ($Fa_{26.5}$) component have similar compositions to those from panda’s rim ($Fa_{26.4}$) and comparable to olivine from other Baszkówka Mg-Fe chondrules (average ~$Fa_{25.7}$). The Ca-plagioclase laths from the groundmass of panda’s primary component has an extremely variable composition (~An_{49} to ~An_{60}), evidently more calcic than those in other chondrules of the meteorite (mean ~An_{13}). The primary components of the two spinel-bearing chondrules may have been formed in a fireball generated by powerful impact during early accretion of a protoplanet. After crystallisation the spinel crystals were abraded and polished, probably during rapid flight through a dense cloud of interplanetary dust. The moderately reducing conditions of the hypothetical fire ball were replaced by a more reducing environment during the condensation of the rims of both chondrules.

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INTRODUCTION

In spite of the thermal alteration of Baszkówka, some of its primary fabric and composition remain, probably because of the negligible compaction and the absence of shock effects (Stępniewski *et al*., 1996, 1998*a*, *b*; Wlotzka *et al*., 1997). One of the peculiarity of Baszkówka’s composition is the recent find of two compound, spinel-bearing chondrules termed panda and chevron. The O-isotopic analysis of panda’s minerals displayed a complex pattern of an ^{16}O-rich group comprising primary olivine and spinel crystals *versus* an ^{16}O-poor group composed of secondary olivine and groundmass plagioclase (Maruyama *et al*., 1999).

The most frequent spinel (Rubin, 1997) in meteorites is a Mg-Al-spinel coexisting with hibonite, melilite, fassaite, Ti-pyroxene, anorthite and magnetite in Ca-Al-inclusions (CAI’s) of different groups and types of carbonaceous chondrite (e.g. Wark and Lovering, 1982; Bischoff *et al*., 1993; Davis and MacPharson, 1996; McKeegan *et al*., 1998). Other, frequently relict spinel grains, are often present within chondrules (Rambaldi, 1981; Kracher *et al*., 1984; Misawa and Fujita, 1994; Connolly and Hewins, 1996; Connolly and Burnett, 1998) or in chondrule rims (El Goresy *et al*., 1984) of the carbonaceous chondrites.

Chromite, another member of the spinel group, is a frequent accessory component of the matrix and chondrules in ordinary chondrites (OCs) (e.g. Ramdohr, 1963; Nagahara, 1982; McCoy *et al*., 1997). Magnetite, another species of spinel, has been observed in some metamorphosed chondrites (Noguchi, 1993). Sporadic Al-rich, Fe-Mg spinels have also been noticed in some OCs (e.g. Fudali and Noonan, 1975; McCoy *et al*., 1991; Krot *et al*., 1993; Semenenko and Girich, 1998).

In Baszkówka, as in the other members of the L-group, accessory chromite is present in the matrix of chondrite, in chondrule rims and inside chondrules (Stępniewski *et al*., 1998*b*). Some microscopic observations, partly confirmed by *EMA* (Electron Microprobe) analysis, suggest also that magnetite might be present on weathered (oxidised) surfaces of Fe/Ni-metal and Fe-sulphide grains (Stępniewski *et al*., 1998*a*). Here, we describe the mineralogy and petrology of the

Table 1

SEMQuant analyses of spinel (mean ± standard error of mean) (in wt.%)

Element	Element (11 cases) [wt.%]	Atoms per 4 oxygens
Mg	6.8±0.4	0.48
Al	22.4±0.7	1.45
Ti	0.20±0.04	0.01
Cr	14.9±1.0	0.50
Mn	0.6±0.1	0.02
Fe	17.9±0.5	0.56
Zn	0.29±0.1	0.01
O	36.8±1.6	4.00
Total	99.89	7.03

chondrules chevron and panda and discuss the origin of these objects.

SAMPLES AND METHODS

Samples for chemical and petrographic analysis were cut off one side of the meteorite using a diamond disc. This yielded a heel up to 15 mm thick, and then a slice about 10 mm thick, which was saw up into pieces for preparation of polished, uncovered thin sections about 50 μm thick (Borucki and Stępniewski, 2001). After the optical microscopy they were covered with a thin layer of silver for observation with a scanning electron microscope (SEM) and for electron microprobe analysis (EMA).

Petrographic observations were made using an *Ernst Leitz* polarizing microscope (*Wetzlar*, Germany) and a *MIN-8* (USSR) equipped with a universal 5-axes table. A set of birefringence comparators was used. Magnifications were from 17.5 x to 1500 x (immersion). Panda was analysed by electron microscope; the semiquantitative determinations were made with an Oxford electron microprobe and SEMQant analytical program. Different sets of artificial and/or natural standards were selected for each object analysed. Aluminum, Si, Fe, Mg present in quantities over 10 wt.% were determined with good precision, relative standard deviation: RSD = ~1 to 5 relative %. The determinations of Na and Ca in the range of 1 to 10 wt.% were determined with RSD = ~5 to ~15 relative %. The errors in determining elements at and below 1 wt.% means the values lack quantitative significance.

RESULTS

The two spinel chondrules (panda and chevron) found in the chondrite Baszkówka are both compound chondrules consisting of the spinel dominated primary components "...which were rigid enough to retain their original shape..." in the sense of Wasson *et al.* (1995) and an olivine-plagioclase adhering secondary component "... which had viscosities low enough to allow them to conform to the shape to the primary in the suture zone..." (*op. cit.*). Both chondrules are covered with microcrystalline condensation rims.

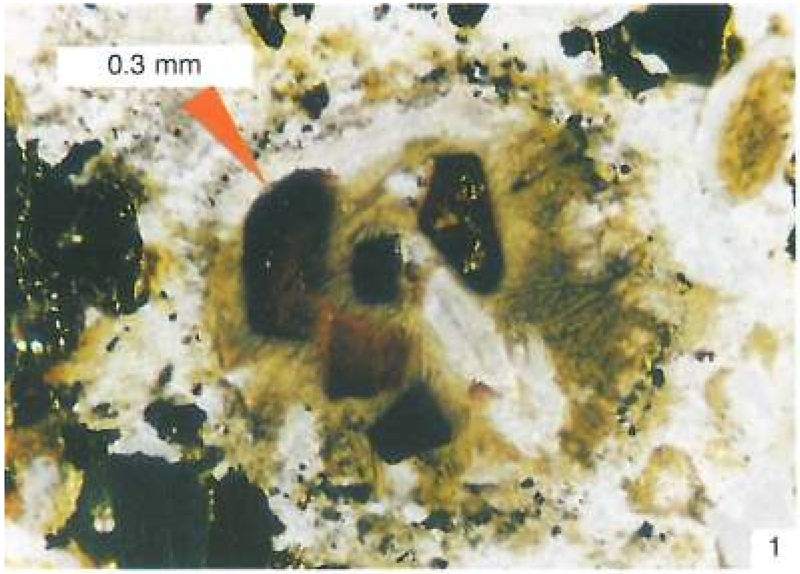
Table 2

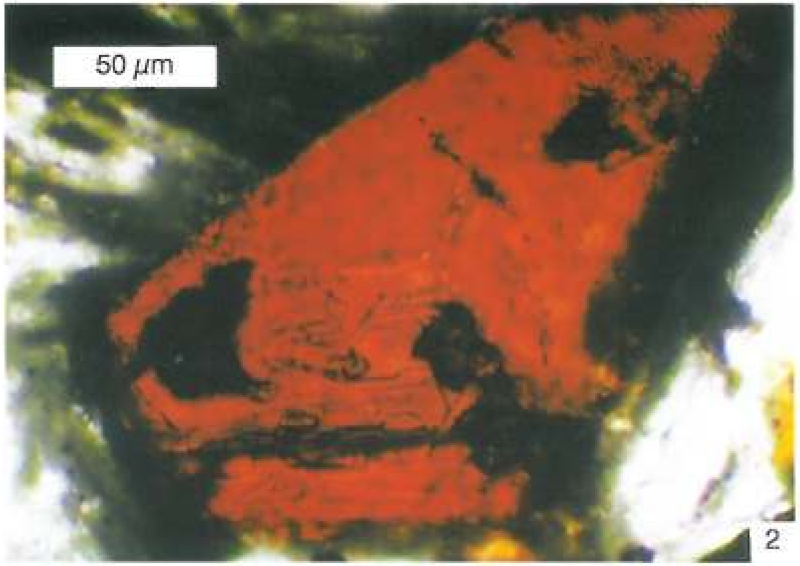
SEMQuant analysis of olivine (mean ± standard error of mean), oxygen isotopes, and Fo/Fa contents (in wt.%)

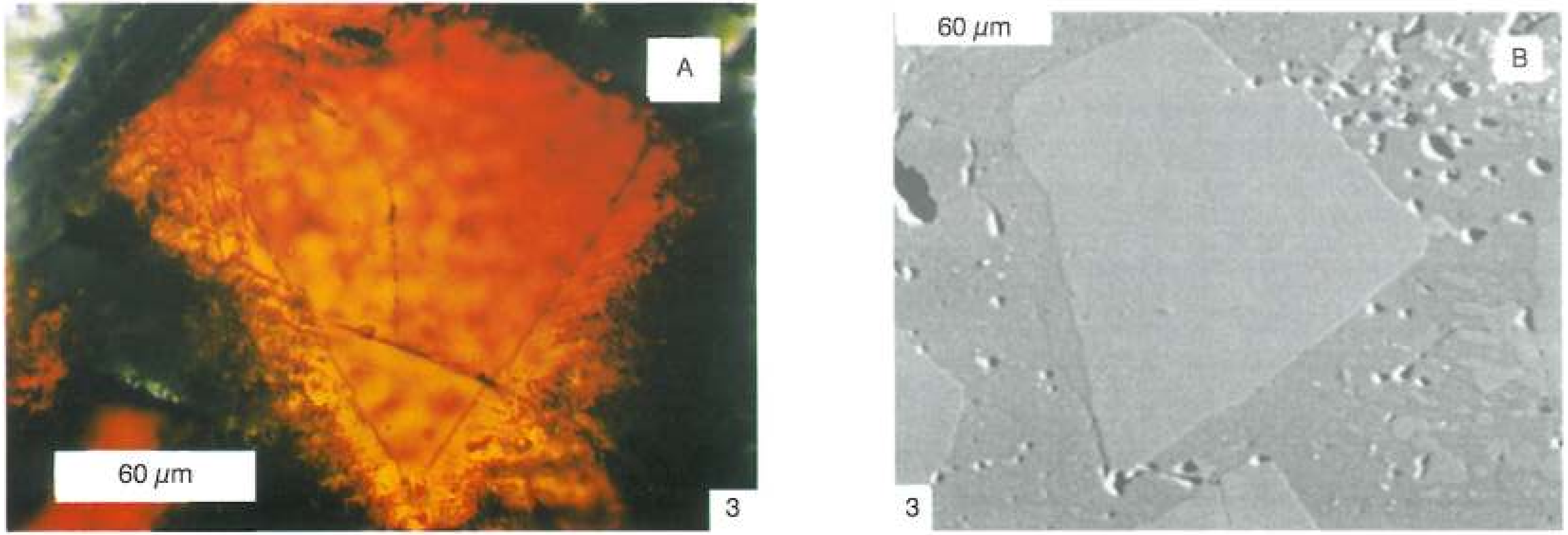
Element	Primary phenocryst	Secondary component	Panda's rim	Baszkówka* Mg-Fe chondr.
NC	1	1	1	5
Na	nd	nd	0.3	<dl
Mg	22.5	21.5	21.1	22.5±0.17
Si	18.6	18.9	18.8	18.0±0.11
Ca	<dl	<dl	1.0	0.07±0.01
Ti	<dl	<dl	<dl	0.01±0.009
Cr	<dl	<dl	<dl	0.03±0.02
Mn	<dl	<dl	0.4	0.35±0.05
Fe	18.9	17.6	17.4	17.5±0.2
O	41.2	41.4	41.0	40.9±0.3
Total	101.2	99.4	100.0	99.36
δ^{17}O**	–3.3	2.8	–	–
δ^{18}O**	–3.5	–1.1	–	–
Forsterite (Fo)	72.9	73.5	73.6	74.3
Fayalite (Fa)	27.1	26.5	26.4	25.7

* — four PO and one BO chondrules; ** — in relation to SMOW, recalculated from Maruyama *et al*. (1999); NC — number of cases; nd — no data; <dl — below the limit of detection

PLATE I

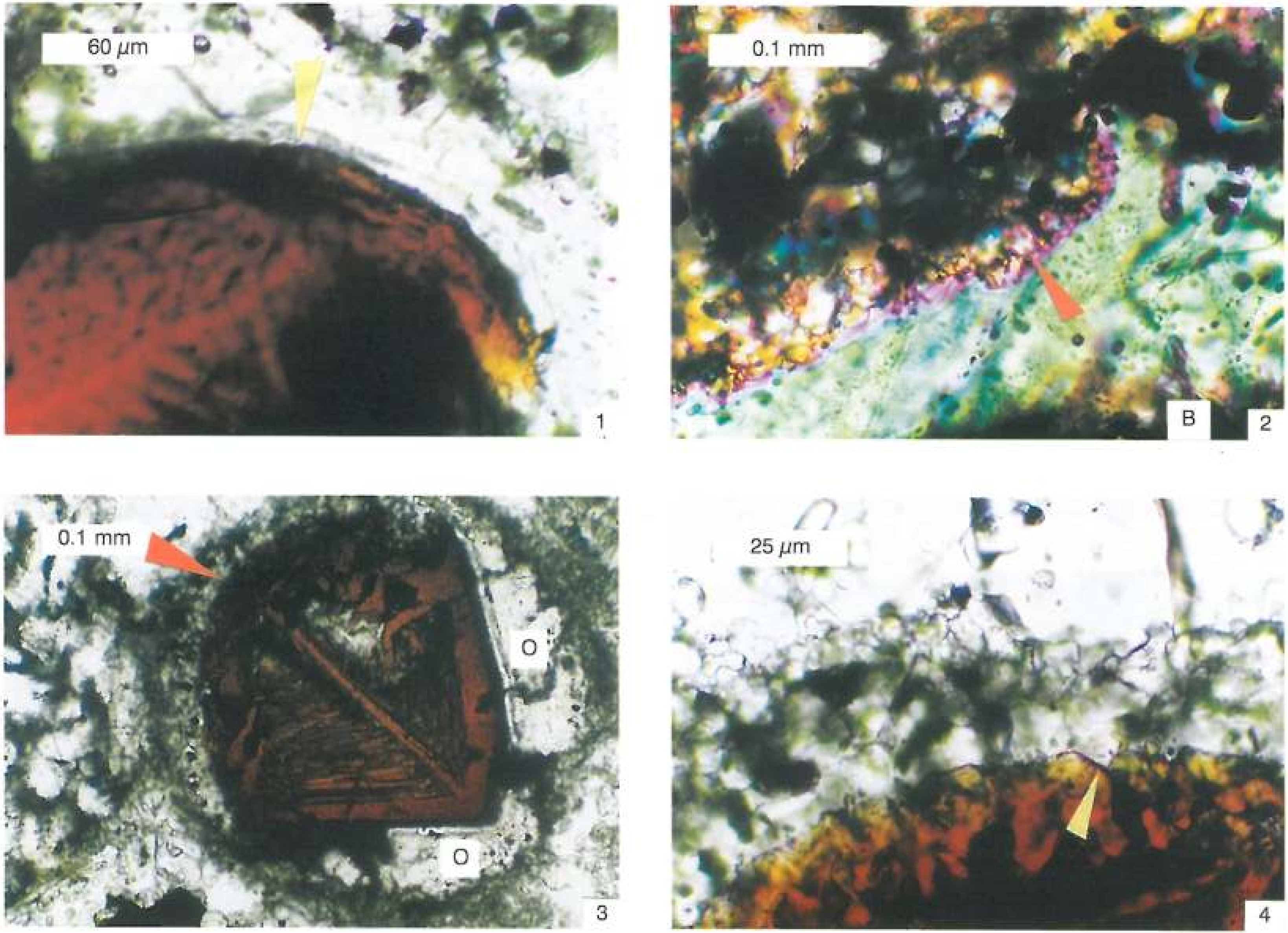






1. Chondrule panda: spinel crystals (dark-red semi-transparent) and olivine (white-gray) immersed in a groundmass of plagioclase laths; upper-left (arrowed) spinel displays a protruding rounded and polished surface; numerous opaque grains, absent in the chondrule, appear in the chondrule rim; plane polarised light. ***2.*** Panda: etch pits and euhedral accretions in a spinel crystal; plane polarised light. ***3***. Panda: a subhedral spinel grain with a ghost crystal inside (discontinued crystallisation); outer crystal faces: bottom-right and bottom-left display multiple scratches, upper-right and -left look undamaged: A — plane polarised light, B — BSE image

PLATE II



1. Panda: a smooth surface of spinel — a possible result of polishing during the flight of the primary (and secondary?) component in an interplanetary cloud of small, hard particles; a thin plagioclase pellicle (arrow) between primary spinel and secondary olivine is the result of external cooling; plane polarised light. ***2***. Panda: sharp contact of the secondary olivine (light green) with the rim of the chondrule (arrow); a shallow sinus in the smooth external contour of the olivine is coated with a thin plagioclase layer (magenta-red) enclosing numerous tiny chromite grains (black points); a hazy and rough contact of the olivine with the primary groundmass (b) is exposed in the bottom-right corner of the picture; crossed polars. ***3***. Chevron: dark red spinel building the primary displays a remarkable chevron structure; abraded and polished surface (arrow) is covered with a thick rim of a relatively coarse-grained, mostly olivine-bearing aggregate; a thin oligoclase pellicle between secondary olivine (o) and primary spinel proves external cooling; plane polarised light. ***4***. Chevron: a fragment of the abraded and polished surface of primary spinel (dark red); the small breach (arrow) in the face of the spinel could be the result of collision with an energetic particle; plane polarised light

Panda is a globular chondrule with an apparent diameter of about 0.86 mm and a porphyritic primary with spinel and olivine phenocrysts in a groundmass composed of Ca-plagioclase laths (Pl. I, Fig. 1). The upper quarter of the primary's surface is smooth, except for a spinel phenocryst and small hollows in the groundmass. This part of the primary is covered with an adhering secondary confined to a single elongated, anhedral olivine crystal. The secondary olivine adheres directly to the surface of the groundmass but is separated from the spinel surface by a ~10 µm thick oligoclase layer. Such texture in the secondary could result from the external cooling with crystallisation inward from the outer surface of the chondrule. The remaining three quarters of the primary exterior are extremely rough, covered with multiple sharp points, irregular voids and deep, narrow hollows. This part of the primary exterior is filled and covered with a microcrystalline aggregate of olivine, pyroxene, plagioclases and opaques making the rim of the chondrule.

The SEMQuant analyses of spinel phenocrysts from the primary displayed high contents of aluminum, chromium, iron and magnesium. Atomic relations, set to 4 atoms of oxygen on the basis of the mean from 11 analyses of three phenocrysts (Table 1), approximate the composition of spinel. Calculated contents of atoms (set to 4 oxygens) show an excess of bivalent ions (Mg + $\mathrm{Fe}^{(\mathrm{total})}$ + Mn + Zn = 1.07) together with a smaller deficiency of trivalent ions (Al + Cr + Ti = 1.96) suggesting that less than 10% of $\mathrm{Fe}^{(\mathrm{total})}$ is in the trivalent state.

One spinel grain (Pl. I, Fig. 2) shows etch pits and euhedral accretions, and a ghost crystal is present inside another one (Pl. I, Fig. 3) — both features of a rapid, interrupted and unequilibrated crystallisation. The rounded and polished surface of the left-uppermost spinel grain (Pl. I, Fig. 1; Pl. II, Fig. 1) has another origin; it is probably caused by abrasion and polishing of the grain, perhaps by a jet of solid particles. Abraded, protruding grains of olivine were found at the edges of the Cold Bokkeveld (CM2) chondrules (Greenwood *et al.*, 1994). Such abraded surfaces should face an incoming, hypothetical jet of particles, or the flight direction of the spinel grain through a cloud of interplanetary dust.

Olivine. The main features of olivine crystals from the panda primary and secondary and comparison with other olivine grains from Baszkówka are shown in Tables 2 and 3.

The similarities between both olivine crystals within panda, in its rim and in other chondrules of Baszkówka are evident in the Fo/Fa contents, sizes, fracturing and character of extinction. Other features, however, reveal important differences between the primary and secondary olivine grains.

The internal contour of the secondary olivine crystal matches the curved and smooth surface of primary spinel (Pl. II, Fig. 1) along their mutual contact. However, the minerals do not touch each other, since their interface is lined by a ~10 µm thick oligoclase layer (Ab_{78}, An_{17}, Or_{5}). Thist is probably the result of external cooling, where crystallisation started from outside towards the primary core. No oligoclase layer is present at the contact of secondary with primary, where the olivine crystal adheres to the groundmass (Pl. II, Fig. 2, bottom right). Here the contact is hazy and rough, with a few fractures in the olivine filled with plagioclase similar to that of the groundmass. Probably the plagioclase melt of the secondary was resorbed by the partly solidified groundmass of the primary. The external contact of the secondary olivine with the rim is smooth with large and shallow sinuses (Pl. II, Fig. 2). At the border of the olivine crystal, a layer of fine-grained plagioclase matrix up to ~20 µm thick , containing some dispersed small (~2 to ~6 µm) chromite grains, covers the contact of the olivine with the rim and fills notches in the olivine. Although four small aggregate of olivine located at the lower left border of panda have an ambiguous structural status, they seems to be similar to clusters of granular olivines found in the POI's (plagioclase-olivine-inclusions) from some carbonaceous chondrites (Sheng *et al.*, 1991).

Table 3

Structural features of olivine

Features	Primary phenocryst	Secondary component
Size	0.47 x 0.16 mm	0.48 x 0.10 mm
Fractures	few irregular and/or planar	–
Extinction	slightly undulating (4–8°)	–
Structural status	enclosed in the groundmass	main component of the secondary
Crystal faces at the contacts	olivine/groundmass: euhedral olivine/spinel: anhedral	anhedral, with 10 µm thick oligoclase interlayer at the olivine/spinel contact
Ghost crystals	few euhedral, up to 4 x 15 µm, pyramids and pinacoids with parallel orientation to host	absent
Ovoid inclusions	rare	abundant, arranged in chains or clusters

The groundmass of panda, almost opaque in transmitted light with rare transparent and polarising patches, in reflected-oblique illumination (Pl. I, Fig. 1), displays a fabric composed of gray-olive laths mostly running side by side but locally having a quasi-radial arrangement. The laths have variable thickness from ~1 to ~10 µm with a mean of ~7 µm and according to the SEMQuant analyses (Table 4) are mostly composed of plagioclase.

The mean composition of plagioclase (Table 5), extremely variable on a micrometric scale, is roughly in the labradorite range, with a low orthoclase molecule content. Some unidentified silicate and oxide phases compose the remaining fraction of the groundmass. Opaque plagioclase mesostasis from Mg-Fe chondrules of Baszkówka display also rare translucent and weakly polarising points but, in contrast to the panda groundmass, it does not have any lath structure. Significant differences between the panda groundmass and the mesostasis of Mg-Fe chondrules of Baszkówka are given in Table 5.

Table 4

SEMQuant plagioclases of panda (mean ± standard error of mean) (in wt.%)

Element	Primary groundmass	Secondary pellicle	Rim	Baszkówka chondrules mesostasis
NC	11	1	2	6
Na	3.3±0.4	3.9	6.0	6.2±0.1
Mg	nd	6.4*	<dl	0.6±0.2
Al	14.1±0.6	7.9	10.9	10.9±0.2
Si	25.7±0.4	25.6	30.3	29.2±0.4
K	0.2±0.1	nd	0.9	0.8±0.1
Ca	7.4±0.9	1.5	1.24	1.9±0.3
Ti	0.7±0.2	nd	nd	nd
Cr	0.6±0.4	nd	nd	nd
Fe	1.0±0.3	7.7*	nd	0.5±0.1
O	47.0±0.2	45.1	47.3	46.2±0.4
Total	100.02	99.9	97.6	96.3
Albite	44.2±5.1	81.4	82.9	80.8±0.9
Anortite	54.1±5.5	12.4	9.9	13.2±1.5
Orthoclase	1.7±0.6	6.2	7.2	6.0±0.9

* — intergrowth with olivine; NC — number of cases; nd — no data; <dl — below the limit of detection

The chondrule rim matter, resting on a rough surface of the groundmass, has filled many deep and narrow hollows during condensation of gas. Olivine aggregates that, beside subordinate plagioclases, pyroxenes and opaques, are the most abundant component of the rim, consist of a few small (1–10 μm) anhedral and/or subhedral olivine particles with smooth, rounded corners and undulose borders. Olivine particles inside the aggregate have, for the most part, an almost concordant optical orientation with small deviations generating a faint mosaic extinction under crossed polars. From place to place the superposition of particles gives the effect of absent extinction.

Chevron is a globular chondrule that has an apparent diameter of ~0.54 mm (Pl. II, Fig. 3) and a compound structure, with the primary composed mostly of a single spinel grain, and the secondary formed of olivine grains with dark gray intergrowths of plagioclase glass. The chondrule is covered with a thin microcrystalline condensation rim.

The primary of the chevron chondrule is composed of the wine-red spinel grain (~0.52), which resembles the spinel phenocrysts from panda. The pronounced chevron-like structure of the spinel resulted from rapid crystallisation along the main axes and the growth of multiple laths parallel to the octahedron faces. Two cavities in the middle of the grain are filled with a plagioclase-olivine aggregate. The larger cavity visible in the upper part (Pl. II, Fig. 3) of the crystal is filled with plagioclase with tiny intergrowths of spinel. In contrast to the euhedral faces of spinel, its anhedral surface visible at the left side of the crystal is round and smooth with a few minor eroded craters (Pl. II, Fig. 4). In chevron the effects of strong abrasion and polishing is even more distinct than in the case of panda. Probably, in the same way as in panda, the rounded and polished surface was aimed in the direction of the hypothetical flight across a dense cloud of interplanetary dust.

The secondary of the chevron is composed mostly of four submillimetric heterogeneous, anhedral olivine crystals (Pl. II, Fig. 3, bottom-right) and cover almost all of the euhedral faces of the spinel primary. Olivine crystals display an internal mosaic structure composed of a few smaller domains with fuzzy borders delimited by clusters and chains of inclusions (mostly oval-shaped, from 1–8 μm in diameter; rarely euhedral up to 40 μm long) with lines of small fractures. Angles between the optical vectors in adjoining domains vary from zero up to 5° giving the effect of mosaic extinction. The spaces between the olivine crystals and the fractures within them are filled with the dark gray, translucent, amorphous, and isotropic glass (black on Pl. II, Fig. 3). All along the euhedral faces of primary spinel,

Table 5

Comparison of plagioclase from panda groundmass and Mg-Fe chondrules mesostasis

Characteristic	Groundmass of panda	Baszkówka chondrules mesostasis
Texture	felsitic (intersertal)	aphanitic
Plagioclase	labrador An$_{49}$– An$_{60}$	oligoclase An$_{12}$– An$_{15}$
Orthoclase in plagioclase	low Or$_{1}$–<Or$_{2}$	high Or$_{5}$– Or$_{7}$
Inclusions	spinel, ilmenite(?)	olivine, pyroxene

but only under the cover of secondary olivine, there has crystallised a thin (~10 μm) plagioclase pellicle, absent from the remaining part of this contact.

The rim, composed of granoblastic aggregates of subhedral grains, 6–17 μm in diameter (mean ~12 μm), has a variable thickness from less than 25 μm to over 75 μm. Directly on the abraded face of the spinel there has grown an irregular ~40–50 μm thick layer of homogeneous olivine aggregates which outwards becomes fine-grained and contains subordinate orthopyroxene and plagioclase (Pl. II, Fig. 4) as well as opaques, kamacite, rare taenite, troilite, and chromite. The thin rim (Pl. II, Fig. 3, bottom-right) on the secondary olivine thickens on the polished surface of the secondary spinel (Pl. II, Fig. 3, upper-left), suggesting an oriented condensation-sedimentation of the rim material.

DISCUSSION AND CONCLUSIONS

1. Both spinel-bearing compound chondrules have sub-millimetre, subhedral spinels in their primaries, mostly olivine-bearing adhering secondaries with a cognate composition of spinel (data for chevron, Maruyama, 2001). The absence of Fe-Ni metal in primaries and secondaries and the composition of spinel suggests a substantial prevalence of Fe^{2+} over Fe^{3+} and, in consequence, a moderately reducing milieu of their origin. Both chondrules are overlaid by microcrystalline condensation rims composed an aggregate of olivine, pyroxene, plagioclase and metal grains indicating an environmental shift towards more reducing conditions.

2. Some features of the panda primary are comparable to these typical for POIs of carbonaceous chondrites, younger than CAIs but older than Mg-Fe chondrules (Sheng *et al.*, 1991), i.e.: (a) the main components are plagioclase, olivine, pyroxenes and spinel; (b) the textures are sub-ophitic to intersertal and porphyritic; (c) the clusters of equigranular olivine crystals located near the periphery of the POIs roughly recall that observed in panda; (d) the exterior accretionary rims are similar to the rims around the Mg-Fe chondrules and also to that of the POIs. The isotopic Mg heterogeneity in the POI spinels and the igneous textures of the POIs suggest, according Sheng *et al.* (1991), that spinel crystals may be the relict grains remaining after incomplete melting of unknown precursors. However, the isotopic oxygen composition of spinel from chevron does not support such a supposition (Maruyama *et al.*, 2000). In consequence, spinel crystal existing in panda primary could be inherited relict grains, whereas the one in chevron is not.

3. A significant enrichment of ^{16}O was found in the large chromium spinel from Murchison (Simon *et al.*, 1994), while the ^{16}O-excess found in small spinel grains, inherited probably from refractory inclusion, is much higher ($\delta^{18}O = -50‰$). The O-isotope composition of the panda spinel (Maruyama *et al.*, 1999) shows only a modest ^{16}O-enrichment, and chevron spinel is even poorer in ^{16}O (Maruyama *et al.*, 2001). Consequently, the panda spinel phenocrysts are poorer in ^{16}O than spinel grains "...directly related to CAI precursors or CAIs itself..." in the Allende meteorite (Maruyama *et al.*, 1998), but richer in ^{16}O than the bulk of panda (Hałas *et al.*, 1999) and they are, most probably, the oldest components of the primary.

4. Among the five spinels present in the panda primary, three are homogeneous, one contains an inner ghost crystal and vaguely resemble to the primary-rim type (Simon *et al.*, 1994) coarse spinels separated from the Murchison meteorite. The chevron (primary euhedral spinel) showing an unusual cavernous structure, and the hints of such structure visible in one of the panda spinels, suggests a similarity to small spinel grains found at the Cretaceous/Tertiary boundary as products of an impact fire-ball (Preisinger *et al.*, 1996).

5. Solidified and crystallised primaries of both chondrules were strongly and unilaterally abraded. The intensity of the abrasion was so high that even hard spinel crystals (hardness 7.5–8.0° of Mohs scale) were rounded and smoothed. Hence, the enigmatic, abrading grains have to be: (a) hard (≥ 8.0°), (b) small (micrometric?) not provoking the fragmentation of primaries, (c) energetic (rapid), and (d) abundant. Such numerous particles may be met during the high speed flight across a relatively dense cloud of nebular dust during clumpy disc accretion (Boss, 1996). The secondary of panda adhered to the abraded surface of the primary witnessing a succession of events, whereas that of chevron is stuck on the euhedral (non-abraded) spinel faces. In both cases, however, the external cooling resulted in the crystallisation from the outside of the olivine to an internal oligoclase layer at the surface of the primary. These circumstances are consistent with the formation of the compound chondrules in a jet flow (Liffman *et al.*, 1996).

6. Both chondrules are covered with a fine-grained olivine aggregate with subordinate plagioclase, kamacite, troilite and chromite. Internal structures of the olivine grains, consisting of a few small anhedral and/or subhedral particles with smooth, rounded corners and undulated, blurred borders, suggest a condensation origin rather than melt solidification and crystallisation. The appearance of opaques in the rims of panda and chevron, particularly of kamacite, absent from the primaries and secondaries of both chondrules, indicate a significant modification of the milieu which became more reducing. Secondary variations of textures and composition in both rims may be the result of gradual changes in environmental conditions and or of fractional crystallisation.

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