doi:10.5474/geologija.2013.002

Structure of the chondrules and the chemical composition of olivine in meteorite Jesenice

Tekstura hondrul in kemijska sestava olivina v meteoritu Jesenice

Bojan AMBROŽIČ[1], Sašo ŠTURM[2], Miha JERŠEK[3] & Breda MIRTIČ[1]

[1]Faculty of Natural Sciences and Engineering,
Aškerčeva 12, 1000 Ljubljana, e-mail: ambrozicbojan@hotmail.com

[2]Jožef Stefan Institute, Jamova 39, 1000 Ljubljana
[3]Slovenian Museum of Natural History, Prešernova 20, 1000 Ljubljana

Prejeto / Received 20. 3. 2013; Sprejeto / Accepted 8. 5. 2013

Key words: quantitative EDS analysis, chondrules, olivine, ordinary chondrite, meteorite Jesenice
Ključne besede: kvantitativna EDS analiza, hondrule, olivin, navadni hondrit, meteorit Jesenice

Abstract

This paper presents a mineralogical analysis of various chondrule types and chemical analysis of olivine in different parts of meteorite Jesenice. Quantitative energy-dispersive X-ray spectroscopy with a scanning electron microscope was used in the analyses. The results showed that the chemical composition of the olivine was homogeneous throughout the meteorite with an average olivine composition of Fa 26.4 ± 0.6. The results of this study were in agreement with previous study of the meteorite, which showed that the meteorite Jesenice was an equilibrated L chondrite.

Izvleček

V prispevku so predstavljene mineraloške raziskave različnih tipov hondrul ter kemijske raziskave olivina v različnih delih meteorita Jesenice. Pri raziskavah smo uporabili točkovno kvantitativno energijsko disperzijsko spektroskopijo rentgenskih žarkov z vrstičnim elektronskim mikroskopom. Rezultati so potrdili, da je kemična sestava preiskanih olivinovih zrn v različnih delih meteorita Jesenice homogena s povprečno sestavo olivina Fa 26,4 ± 0,6. To potrjuje rezultate dosedanjih raziskav, ki so pokazale, da meteorit Jesenice sodi med homogenizirane L hondrite.

Introduction

Chondrites are the most common type of stony meteorites, representing 70 % of all falls (Norton, 2002). Meteorite Jesenice is the first known Slovenian chondritic meteorite. It fell on the Mežakla plateau, near the town of Jesenice, in April 2009 (Spurný et al., 2010).

The classification of stony meteorites is based on their chemical and mineralogical composition. Stony meteorites are divided into two classes: chondrites, i.e. meteorites containing chondrules, and achondrites, i.e. meteorites without chondrules (Norton, 2002).

Bischoff and coworkers (2011) were the first to investigate the chemical and mineral composition of meteorite Jesenice. They determined the composition of the olivine to be Fa $_{25.1 \pm 0.4}$ with a compositional range from 23.9 to 25.8 mole % of iron. Based on these criteria Bischoff and coworkers (2011) classified meteorite Jesenice as a weakly shocked (S3), low total iron (L) ordinary chondrite of petrologic type 6. Bischoff and coworkers (2011) claim that meteorite Jesenice is an equilibrated chondrite, which means the chemical composition of minerals in meteorite Jesenice is homogenous in all parts of the meteorite.

EDS (quantitative and/or semi-quantitative) is considered a standard method petrographic and mineralogical characterization of meteorites and was also used in similar studies of meteorites (Bischoff et al., 2010, 2011; Greshake et al., 1998; Horstmann et al., 2010; Sokol et al., 2005, 2007; Keil et al., 2008; Llorca et al., 2010; Metzler et al., 2011). In addition, Sepp and coworkers (2001) used WDX in the chemical analysis of a meteorite. Some authors performed their chemical analyses of chondrites using averaged samples (Bischoff et al., 2011) such as INAA and XRF (Greshake et al., 1998; Metzler et al., 2011). Although this method gives reliable information about the chemical composition, the major drawback is that it provides an average, i.e. the bulk chemical composition. On the other hand some authors (Šmit et al.,

2011) used single-point analyses by PIXE. Some authors (Greshake et al., 1997; Keil et al., 2008; Metzler et al., 2011; Simon et al., 2011; Sokol et al., 2005; Llorca et al., (2010), found the zonal composition in mineral grains and in chondrules by using EMPA alone/and LA ICP MS.

Prior to the quantitative EDS analysis of meteorite Jesenice the microstructures of different types of chondrules and chondrule rims were investigated to understand the genesis of the chondrules and consequently the possible differences in the chemical composition of the olivines. On the basis of these results locations in the sample for chemical analysis were chosen.

Our goal was to determine the exact degree of homogeneity of meteorite Jesenice. In this study the mineral olivine was chosen, because it is by far the most common mineral found in the meteorite Jesenice. Olivine is a solid solution between forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4). Consequently, even small changes in the crystallization conditions in different parts of the meteorite can result in a variation of the chemical composition of the mineral olivine, which can give valuable information about the crystallization history of the whole meteorite body. For this reason the composition of the olivine was studied in detail in relations to the following criteria:

- the homogeneity of the olivine inside the individual mineral grains,
- the differences in the olivine composition between the chondrules and the matrix,
- the compositional variations of the olivine between the rim and the core, within the individual chondrules,
- the compositional variations of the olivine between different types of chondrules,
- the compositional differences of the olivine between relict olivine grain, porphyritic and olivine chondrule.

This paper follows the classification of meteorites, the classification of chondrules, the genesis and the structure of chondrules which were summarized in the paper *Classification of stony meteorites and chondrules – the case of meteorite Jesenice* (Ambrožič et al., 2012) after different authors.

Samples and methods

To investigate the interior of the meteorite, the mineral phases and the structure of the chondrules, small fragments of the meteorite were cut into slices. From these slices a few polished thin sections were prepared. Thin sections were observed with a Zeiss Axio Z1- polarized optical microscope in reflected and transmitted light. The thin sections were additionally coated with a 3 nm thick layer of amorphous carbon to ensure the conductivity of samples for further scanning electron microscopy/energy-dispersive X-ray spectroscopy (SEM/EDS) analyses.

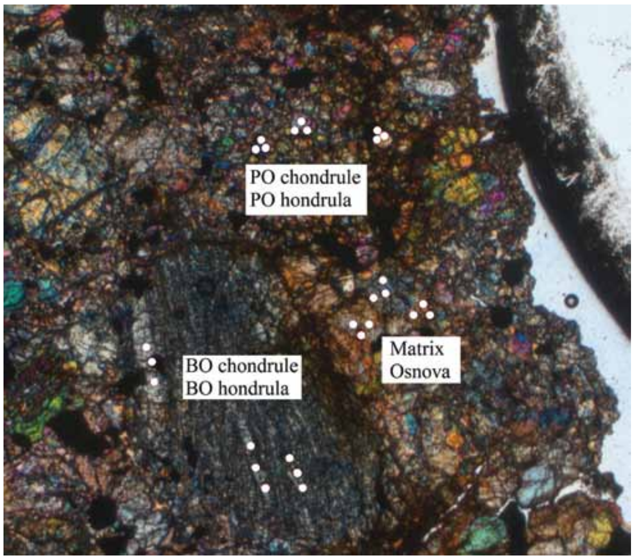

Fig. 1. Scheme of selection of locations for EDS analyses
Sl. 1. Shema izbire lokacij za EDS analizo

The optical microscopy was used mainly for identifying different minerals in meteorite Jesenice. However, a second benefit of this method, compared with electron microscopy, is large field of view, which allows us to observe an entire chondrule. In addition, the places damaged by oxidation were identified with an optical microscope and were later excluded from the SEM/EDS analysis. The data obtained with the optical microscopy were later used to select the best areas for chemical EDS analyses in the SEM.

Prior to the quantitative EDS analysis the microstructures of different types of chondrules and chondrule rims were investigated to understand the genesis of the chondrules and consequently the possible differences in the chemical composition of the olivines. On the basis of these results regions in the sample were chosen for chemical analysis.

In order to distinguish between the areas with different mineral composition we used a scanning electron microscope (SEM) and backscattered electrons (BSE). The signal in BSE mode is dependent on the average atomic number (Z) of a certain mineral. Minerals with higher Z-number appear brighter than minerals with a lower Z-number (Goldstein et al., 2003). Unfortunately, when using BSE the oxidized areas related to iron-bearing minerals were difficult to distinguish.

In order to perform a detailed quantitative analysis of the olivine composition, scanning electron microscopy (SEM) combined with quantitative energy-dispersive X-ray spectroscopy (EDS) was chosen. Different mineral reference materials were used as the calibration standards for the quantitative EDS analysis. The chemical analyses of the olivine in the meteorite were made with a Jeol JSM 5800 scanning electron microscope equipped with an EDS system (Oxford instruments ISIS 300). The analyses were performed at an accelerating voltage of 20 kV (Greshake et al., 1998; Sokol et al., 2005; Metzler et al., 2011) and a working distance of 10 mm. The spectra acquisition time was set to 100 s and the beam current was adjusted to reach the value of dead time between 25 and 30 %. Every 20 min of analysis the instrument was calibrated and optimized for quantification with a cobalt standard. The spectra

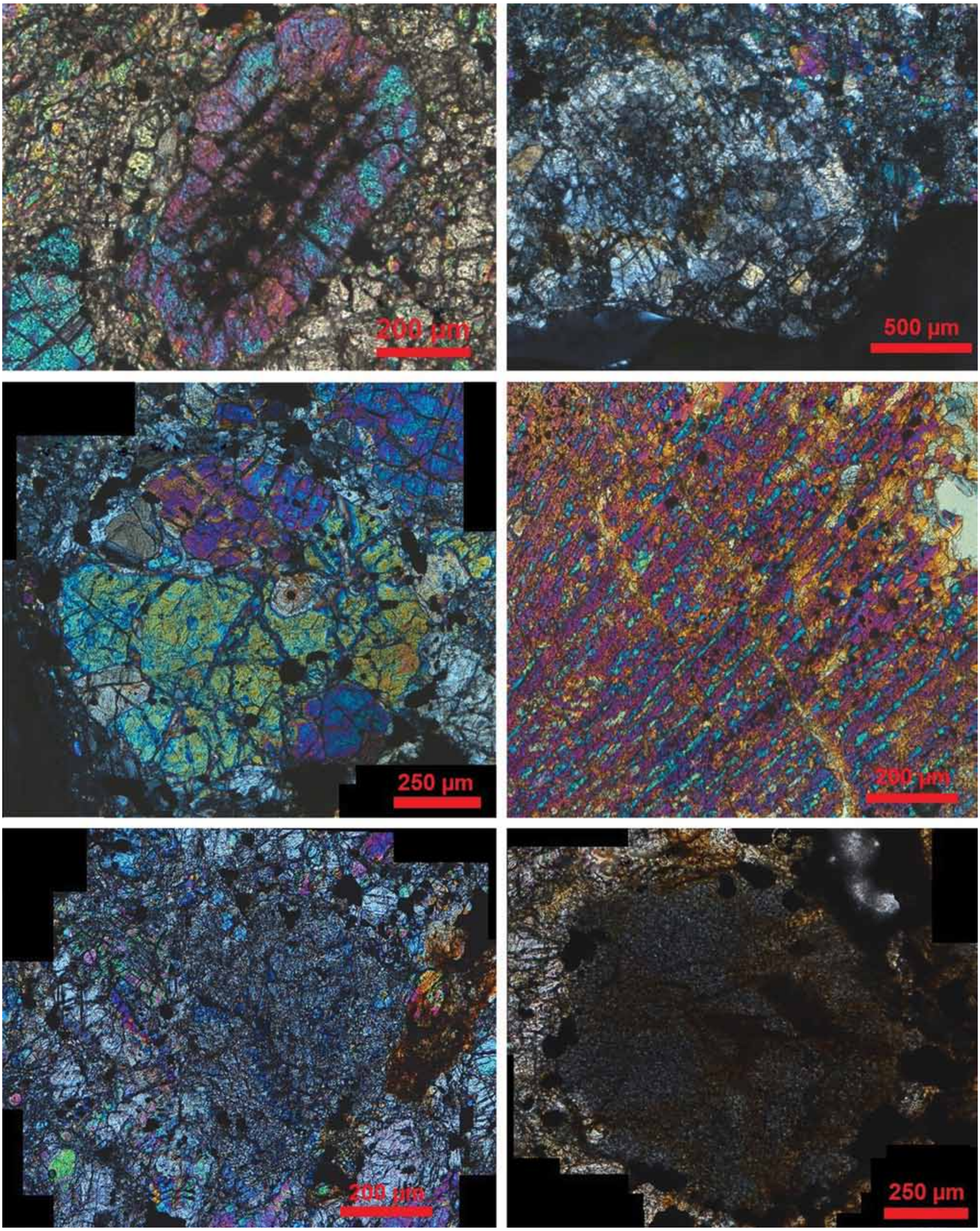

Fig. 2. Various different types of chondrules in meteorite Jesenice. Plane-polarized light, x nicols. A) barred olivine chondrule (BO), B) porphyritic pyroxene chondrule (PP), C) porphyritic olivine chondrule (PO), D) radial pyroxene chondrule (RP), E) porphyritic pyroxene chondrule, F) cryptocrystalline chondrule (C)

Sl. 2. Različni tipi hondrul v meteoritu Jesenice. Presevna polarizirana svetloba, x nikoli. A) lamelarna olivinova hondrula (BO), B) porfirska piroksenova hondrula (PP), C) porfirska olivinova hondrula (PO), D) pahljačasta piroksenova hondrula (RP), E) kriptokristalna hondrula (C).

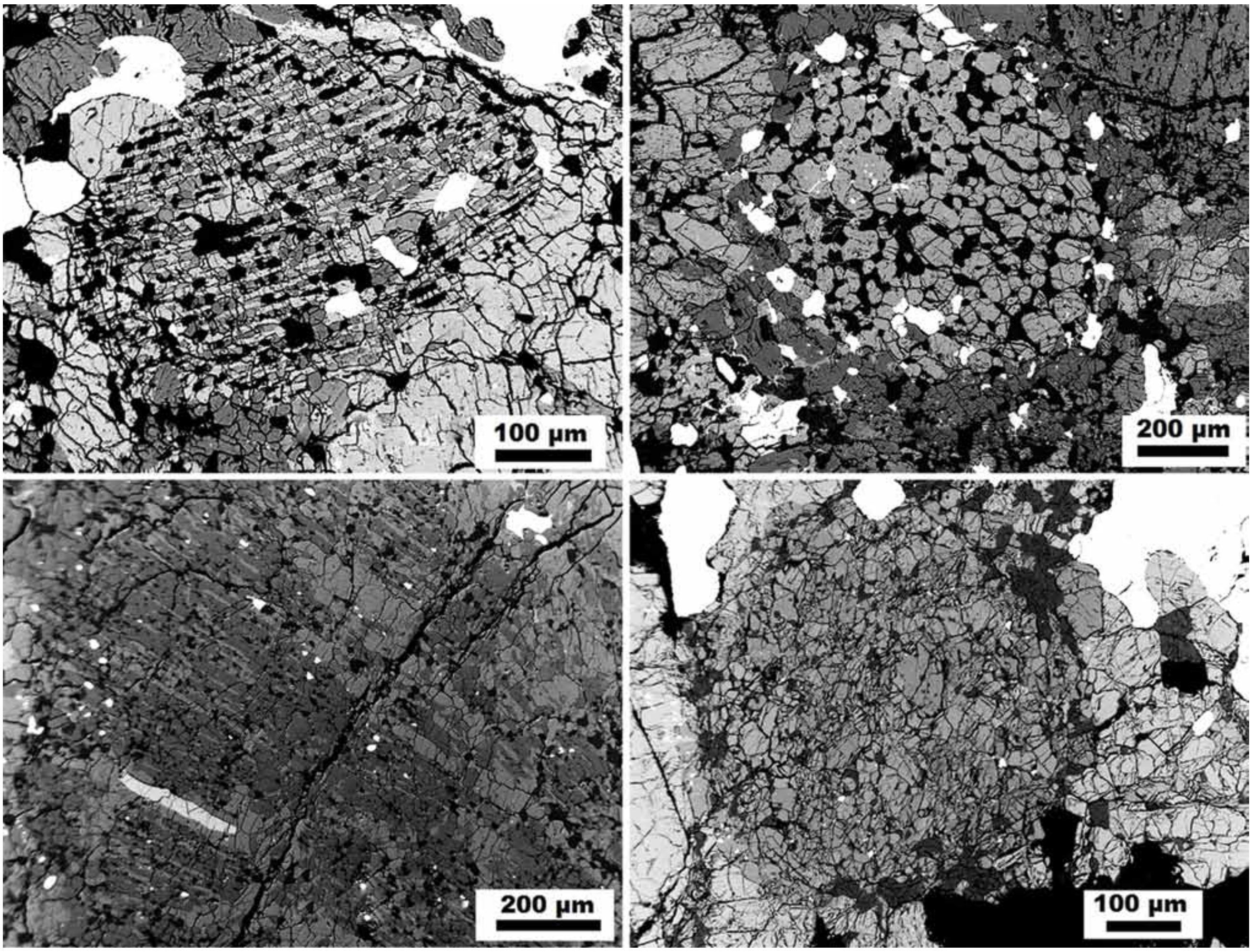

Fig. 3. Various types of chondrules in meteorite Jesenice. SEM, BSE. A) Barred olivine chondrule, B) Porphyritic olivine chondrule, C) Radial pyroxene chondrule, D) Porphyritic pyroxene chondrule

Sl. 3. Različni tipi hondrul v meteoritu Jesenice. SEM, BSE. A) lamelarna olivinova hondrula , B) porfirska olivinova hondrula, C) pahljačasta piroksenova hondrula, D) porfirska piroksenova hondrula

were quantified using reference materials with a well-defined chemical composition obtained from C. M. Taylor Company. The following mineral reference materials were used: α-quartz (SiO_2) for silicon, almandine ($(Fe, Mg, Mn)_3 Al_2(SiO_4)_3$) for iron and manganese and diopside ($MgCaSi_2O_6$) for magnesium. Bischoff and coworkers (2011) used olivine (Mg, Fe, Si), jadeite (Na), plagioclase (Al), sanidine (K), diopside (Ca), rutile (Ti), chromite (Cr), rhodonite (Mn) and pentlandite (Ni).

Prior to the EDS analysis of the olivine in the meteorite, spectra from the reference materials were acquired. The calibration factors for the quantitative EDS analysis were calculated by assigning a given composition of the reference materials to the related reference spectra. The oxygen concentration was calculated from the stoichiometry. This procedure was performed using Link ISIS computer software (Oxford Instrument Limited, 1995). Since this instrument does not have the capability to measure the absolute current values and in order to minimize the influence of the random fluctuations of the microscope's instabilities on the reliability of the EDS analysis, this procedure was repeated every time prior to the EDS measurements on a daily basis.

The percentage of the unknown mass concentration (C_i) of the chemical element i in the sample was calculated using the equation:

$$C_i = C_i^* \cdot (I_i / I_i^*) \cdot [ZAF]_i = C_i^* \cdot k_i \cdot [ZAF]_i$$

where C_i^* is known mass concentration of element i in reference material, I_i and I_i^* are the intensities of emitted X-ray radiation of a certain spectral line of element i in the sample and in the reference material, respectively, and k_i is the k-ratio for the element i in the sample. $[ZAF]_i$ is the product of matrix-correction factors Z, A and F. Z is an atomic correction factor, A is an absorption factor and F is a secondary fluorescence correction factor (Reed, 1996). ZAF corrections are commonly applied in the EDS analyses of meteorites (e.g. Greshake et al., 1998; Sokol et al., 2005; Metzler et al., 2011).

In each of eight examined chondrules we picked three olivine mineral grains and within each grain we chose three spots where the EDS analyses were performed (Fig. 1). Similar procedures were also used in the analyses of the matrix, the chondrule rims and in the relict olivine grain. All studied chondrules are displayed in Table 1.

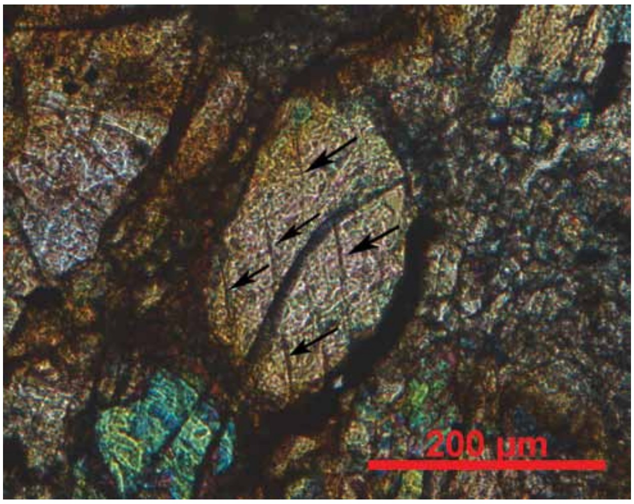

Fig. 4. Planar deformations in olivine grain marked by arrows. Plane-polarized light, x nicols.

Sl. 4. Planarne razpoke v olivinu, označene s puščicami. Presevna polarizirana svetloba, x nikoli.

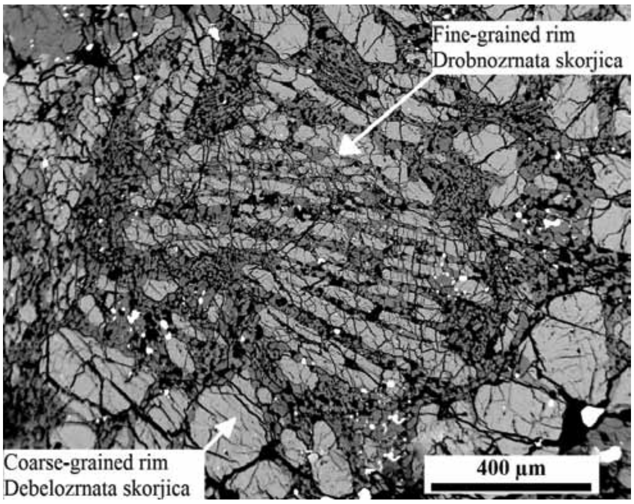

Fig. 5. Barred olivine chondrule with coarse-grained and fine-grained rim. SEM, BSE.

Sl. 5. Lamelarna olivinova hondrula z drobnozrnato skorjico znotraj debelozrnate skorjice. SEM, BSE.

Results

Chondrules and their structure

Meteorite Jesenice contains a variety of different chondrule groups and types. The texture of meteorite Jesenice is highly recrystallized, as a result of the large degree of thermal metamorphosis (Bischoff et al., 2011). The rims of the chondrules are often very deformed and mixed with the surrounding matrix. The chondrules are usually surrounded by a thin rim of metal grains. The smallest measured cross-section of the chondrules measures about 200 μm and the largest around 7000 μm.

In meteorite Jesenice, chondrules that belong to the groups of porphyritic chondrules, nonporphyritic chondrules and granular chondrules were found (Ambrožič et al., 2012; Ambrožič, 2012).

Porphyritic chondrules are the most abundant chondrule group in meteorite Jesenice. This group of chondrules usually contains a large number of olivine and pyroxene crystals, which were weakly resistant to processes during the thermal metamorphosis. Consequently, many porphyritic chondrules lack a rim. In meteorite Jesenice all three types of porphyritic chondrules were found (Ambrožič et al., 2012): porphyritic olivine (PO) chondrules, porphyritic olivine-pyroxene (POP) chondrules and porphyritic pyroxene (PP) chondrules. Out of these, the PO chondrules are by far the most common. They are composed of euhedral to subhedral olivine crystals. The olivine grains in most of the PO chondrules seem to have a random arrangement. However, several PO chondrules show olivine grains oriented in a few dominant directions. Inside one of the PO chondrules a relict olivine grain (R) was found. The relict is a possible remnant of a previous generation of chondrules. PP chondrules are rare, but, on the other hand, they are easily spotted because they are formed mostly out of large pyroxene phenocrysts. POP chondrules are composed of both pyroxene and olivine crystals; however, in most cases olivine is dominant over pyroxene (Figs. 2 and 3).

Nonporphyritic chondrules or droplet chondrules are chondrules that formed from the melt. Barred olivine (BO) chondrules were the most common type found in meteorite Jesenice. They are easily recognized under crossed-polarized light by their characteristic structure. BO chondrules are formed out of a series of alternating bars of olivine and plagioclase. Olivine crystals are monosomatic and can be observed in the same optical orientation under a polarized optical microscope. Olivine bars are more resistant to thermal metamorphosis in comparison to the surrounding chondrule rim. Consequently, many chondrules in meteorite Jesenice lack a rim, whereas their morphology is defined as irregular polygonal forms instead of spheres. BO chondrules with a different orientation of olivine bars (or so called polysomatic BO chondrules) are also present. Some BO chondrules occur with bended olivine bars, while radial pyroxene (RP) chondrules are made of fan-shaped pyroxene and plagioclase crystals. The fan shape is a consequence of the crystallization of minerals from one eccentric point. There are also chondrules with more than one crystallization point. In meteorite Jesenice the RP chondrules are almost all without a rim, which is why their outer parts are chemically corroded into a shape of a sea shell (Figs. 2 and 3).

Granular olivine-pyroxene (GOP) chondrules are composed of a tight package of very small olivine and pyroxene crystals. These minerals are too small to be distinguished using an optical microscope. On average, the mineral grains in the GOP chondrules in meteorite Jesenice measure around 10 μm. On the other hand, the metal grains in GOP chondrules are significantly larger – measuring 20 –100 μm. All the metal grains are of an anhedral shape. Cryptocrystalline (C) chondrules are also present; they are composed of mineral grains, which are too small to be individually observable using an optical microscope (Fig. 2).

Besides the previously noted, more common types of chondrules, we also found some rarer

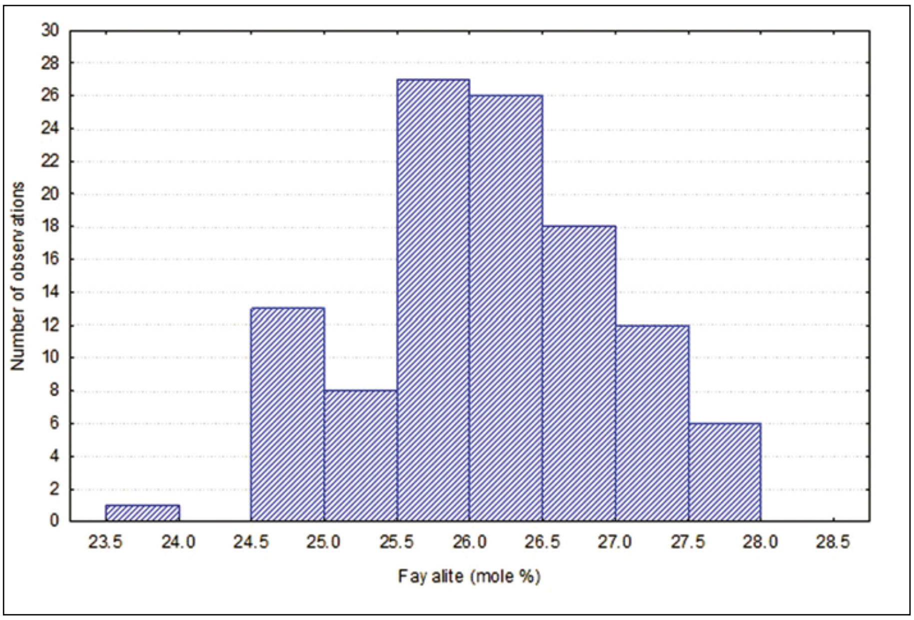

Fig. 6. Histogram of average composition of olivine in meteorite Jesenice, in mole % of fayalite (N=93).

Slika 6. Histogram povprečne sestave olivina v meteoritu Jesenice, v mol. % fayalite (N=93).

types of chondrules in meteorite Jesenice. One such example are metal (M) chondrules. The M chondrules in meteorite Jesenice are composed of euhedral metal grains embedded in feldspar. The metal grains are concentrated in a thick ring around the centre of the chondrule, while the feldspar embeds the rest of the chondrule. In optical microscope these chondrules look like black flakes. Compound chondrules are another interesting group of chondrules found in meteorite Jesenice. These chondrules are composed of two chondrules joined together. Compound chondrules that have both the same structure and mineralogy are called sibling compound chondrules or independent compound chondrules. Sometimes one chondrule can envelop another. These chondrules are called enveloping chondrules. In Jesenice we found independent compound chondrule composed of PO and POP chondrule.

Shock metamorphosis

Some olivine and pyroxene crystals show shock lamellae or planar deformations (Fig. 4), which were only observed on a few larger grains at higher magnifications. Most grains lack planar deformations. We also found several sets of planar deformations in a relict grain inside a porphyritic olivine chondrule. The olivine and plagioclase also show undulatory extinction. The shock features observed in this study were in agreement with S3 shock stage determined by Bischoff and coworkers (2011).

Weathering of the meteorite

Meteorite Jesenice had lain on the ground atop of Mežakla plateau for 39 days before it was found in April 2009 (Spurný et al., 2010). The meteorite fragment (later named BOJO) was found in shallow impact pit partially covered with a mixture of snow and leaves (Bischoff et al., 2011). The severe weather conditions of the Mežakla plateau had already partially altered the meteorite. The meteorite fusion crust, in some places, seems “rusty”. Rust is a mix of secondary iron minerals as a result of the oxidation of metallic iron. The meteorite’s interior is also partially weathered. There are oxide rims around the metal and around the major cracks and veins. Olivine and pyroxene grains are unaltered.

Chondrule rims

In meteorite Jesenice most of the chondrules lack chondrule rims due to the high degree of thermal metamorphosis. Nevertheless, all the observed porphyritic chondrules have coarse grained rims with an average thickness of 150 µm. It is also possible that some porphyritic chondrules once had fine-grained rims, which were later destroyed by the process of thermal metamorphosis.

Of the nonporphyritic chondrules most BO chondrules have a fine-grained rim with an average thickness between 50 and 100 µm (Figs. 2 and 3). We also found a BO chondrule with a fine-grained rim inside of a larger, coarse-grained rim (Fig. 5). The BO chondrule rims in meteorite Jesenice are chemically classified as high-FeO rims (Bischoff et al, 2011). On the other hand, we did not find a single RP chondrule with at least part of its rim preserved (Figs. 2 and 3).

Chemical composition of olivine

Chemical composition of olivine in various areas of meteorite Jesenice was determined by EDS using a spot-mode technique. These areas were located within three BO chondrules, three PO chondrules, one BO chondrule rim, one PO chondrule rims, the matrix, an olivine relict grain and a PO chondrule that contains a relict grain and are marked in Table 1. The concentrations of magnesium, silicon, iron and manganese were determined. The measured chemical composition

Table 1. Chemical composition of olivine at different spots of the analyses, in wt.%
Preglednica 1. Kemična sestava olivina po posameznih mestih preiskav, v mas.%

Spots of the analyses	**Labels**	**Number of analyses**	**MgO (wt.%)**	**SiO_2 (wt.%)**	**FeO (wt.%)**	**MnO (wt%)**
Barred olivine chondrule 1	BO 1	9	37.3 ± 0.2	39.0 ± 0.2	23.1 ± 0.3	0.6 ± 0.1
Barred olivine chondrule 2	BO 2	9	37.4 ± 0.1	38.9 ± 0.2	23.2 ± 0.1	0.6 ± 0.1
Barred olivine chondrule 3	BO 3	9	37.5 ± 0.3	38.9 ± 0.2	22.9 ± 0.2	0.6 ± 0.1
Average of barred olivine chondrules	Average BO	27	37.4 ± 0.2	38.9 ± 0.2	23.1 ± 0.2	0.6 ± 0.1
Rim of Barred olivine chondrule 1	BO S	9	36.9 ± 0.3	38.9 ± 0.2	23.7 ± 0.4	0.5 ± 0.1
Porphyritic olivine chondrule 1	PO 1	9	36.8 ± 0.2	39.1 ± 0.2	23.7 ± 0.2	0.4 ± 0.1
Porphyritic olivine chondrule 2	PO 2	9	36.8 ± 0.3	39.0 ± 0.3	23.8 ± 0.4	0.4 ± 0.1
Porphyritic olivine chondrule 3	PO 3	9	36.7 ± 0.3	38.8 ± 0.2	24.0 ± 0.3	0.5 ± 0.1
Porphyritic olivine chondrule 4	PO 4	9	36.5 ± 0.3	38.7 ± 0.3	24.3 ± 0.5	0.4 ± 0.1
Average of porphyritic olivine chondrules	Average PO	36	36.5 ± 0.2	38.8 ± 0.2	24.2 ± 0.3	0.5 ± 0.1
Rim of Porphyritic olivine chondrule 1	PO S	9	37.3 ± 0.1	38.8 ± 0.2	23.4 ± 0.2	0.6 ± 0.1
Matrix of the meteorite	M	9	36.5 ± 0.2	38.8 ± 0.2	24.2 ± 0.3	0.5 ± 0.0
Relict grain in porphyritic olivine chondrule	R	3	37.1 ± 0.1	38.8 ± 0.2	23.5 ± 0.2	0.6 ± 0.1
Olivine grains around relict grain in porphyritic olivine chondrule	R-o	9	37.1 ± 0.1	38.8 ± 0.1	23.5 ± 0.1	0.7 ± 0.1
Average	**/**	**/**	**37.0 ± 0.4**	**38.9 ± 0.2**	**23.6 ± 0.5**	**0.5 ± 0.1**

in wt.% of oxides is shown in Table 1. In addition, the fayalite content in the olivine was also quantified. The results are shown in Fig. 6. All the gathered data show a Gaussian distribution.

The calculated average composition of the analyzed olivine grains is $Fa_{26.4 \pm 0.6}$ with a compositional range from 23.9 to 27.7 mole% (Fig. 6). No statistically significant deviations were found in the composition of the olivine between the different spots of the analyses in chondrules (Tab. 1) and between the different parts of the meteorite (Tab. 1). On average, the olivine in meteorite Jesenice contains 37.2 ± 0.7 wt.% MgO, 18.2 % ± 0.6 wt. % FeO, 38.8 ± 0.3 wt.% SiO_2 and 0.5 ± 0.1 wt.% MnO.

Discussion

There are many different types and groups of chondrules in meteorite Jesenice, which were classified according to the Gooding-Keil classification (Gooding & Keil, 1981). Among porphyritic chondrules we found the POP, PP and PO chondrules in meteorite Jesenice, of which the PO chondrules were the most common. The group of nonporphyritic chondrules is represented by BO and PO chondrules in meteorite Jesenice. We also found some rarer types of chondrules, like granular olivine-pyroxene chondrules and independent compound chondrules. Knowledge about the different chondrule types was necessary for the subsequent EDS analyses. We used this knowledge to locate suitable olivine grains and the appropriate spots for the EDS analyses. Different types and groups of chondrules have very different origins (Norton, 2002), which could imply differences between the chondrule types and groups.

The rims of the chondrules are often very deformed and mixed with the surrounding matrix or are completely missing. For this reason it is sometimes hard to distinguish between the matrix and some of the chondrule types. There are two basic types of chondrule rims: fine-grained and coarse-grained (Norton, 2002). Fine-grained chondrule rims in meteorite Jesenice formed with accretion from the nebular dust after the chondrules were already formed. On the other hand, the coarse-grained rims formed partially from the host chondrule and partially out of the solar nebula dust. In meteorite Jesenice the coarse-grained chondrules are more common in the porphyritic chondrules and the fine-grained chondrules in the non-porphyritic (BO) chondrules. There are also chondrules with both coarse- and fine-grained rims (concentric to each other), which implies the chondrules were exposed to multiple heating and dusting events (Norton, 2002).

We could not successfully determine the average size of the chondrules in meteorite Jesenice because it was difficult to deduce the exact cross-section geometry of the chondrules inside the thin section and because most chondrules are destroyed due to high grade of thermal metamorphosis.

The presence of planar deformations in the pyroxene and olivine and undulatory extinction in the olivine grains indicates that meteorite Jesenice is a weakly shocked (S3) (Bischoff et al., 2011) ordinary chondrite according to classification by Wlotzka (1993). The presence of planar deformation in relict grain indicates that relict had been a part of meteorite Jesenice before the shock metamorphosis took place.

The presence of oxide rims around the metal, major cracks and veins indicate that meteorite Jesenice is a weakly weathered meteorite (W1) (Bishoff et al., 2011) according to classification by Wlotzka (1993). The low degree of oxidation was crucial for the successful EDS analysis. In order to prevent further oxidation our samples are kept in a vacuum chamber.

Chemically, the chondrules are divided according to the Scott-Taylor-Jones (Scott & Taylor, 1983; Jones & Scott, 1989; Jones, 1990, 1994) scheme into FeO rich and FeO poor. The chondrules in meteorite Jesenice are FeO rich or Type-II, which is typical for an ordinary chondrite. Type-II chondrules are further divided in Type-IIA, Type-IIB and Type-IIAB. Meteorite Jesenice contains all these types of chondrules; however, type Type-IIA is the most common. The dominant mineral in meteorite Jesenice is olivine, which is a direct consequence of being chemically L chondrite. Besides olivine, the major minerals are low Ca-pyroxene, plagioclase (oligoclase) and iron-nickel minerals. The average fayalite content in the olivine put meteorite Jesenice into the upper boundary of L ordinary chondrites according to Bischoff and coworkers (2011) (Tab. 2) and into the lower boundary of LL chondrites according to Norton (2002) (Tab. 2).

Table 2. Classification of ordinary chondrites by fayalite composition. Adopted by Bischoff et al., (2011) and Sears (2002).

Preglednica 2. Klasifikacija navadnih hondritov glede na sestavo fayalita. Povzeto po Bischoff et al. (2011) in Sears (2002).

Group of ordinary chondrites	Fa (mole %)	
	According to Bischoff et al., (2011)	According to Norton (2002)
H	16-20.5	16-20
L	21-26.5	21-25
LL	27-31	26-32

The results show meteorite Jesenice is homogeneous inside the individual grains. There is also no statistically significant difference in the composition of the olivine inside the chondrule or in the matrix (Tab. 1). We carried out analyses in several different types of chondrules. The results (Tab. 1) show no difference in the composition of the olivine between the different chondrule types. Also, the chondrule rim has the same composition as the chondrule itself. What came as a surprise was the fact that the composition of the relict olivine grain is exactly the same as that of all the other analyzed olivine grains. If we sum up, the olivine in meteorite Jesenice is homogeneous, which confirms the claim of Bischoff and coworkers (2011). The extreme degree of homogeneity implies that the relict grain was part of meteorite Jesenice long before the thermal metamorphosis event took place. This thermal metamorphosis was strong enough to cause ion migration and homogenization of the whole meteorite.

The standard errors in the detection of the elements using our EDS analyses are similar to those obtained by Metzler and coworkers (2011) using similar method (Tab. 3). The results shown in Tab. 3 indicate that quantitative EDS is one of the most accurate methods, combining a high spatial resolution and a reliable quantitative analysis, making it extremely suitable for analyses of heterogeneous meteorite bodies.

EDS analyses are also subject to the counting error of the detector. This error is therefore related to the quantity of a certain element in the sample, if we assume the same acquisition time for all the elements. A higher quantity of a certain element

Table 3. Accuracy of EDS / EMP / PIXE analysis by different authors

Preglednica 3. Natančnost EDS / EMP/ PIXE analiz na meteoritih po različnih avtorjih

Oxide	Reference	Method	Error (wt. %)
MgO	Llorca et al. (2008)	EMP	1-5
	Janots et al. (2010)	EMP	1-5
	Šmit et al. (2011)	PIXE	4.6
	Metzler et al. (2011)	EDS	0.37
	This study	EDS	0.4
SO_2	Llorca et al. (2008)	EMP	1-5
	Janots et al. (2010)	EMP	1-5
	Šmit et al. (2011)	PIXE	4.9
	Metzler et al. (2011)	EDS	0.32
	This study	EDS	0.2
FeO	Llorca et al. (2008)	EMP	1-5
	Janots et al. (2010)	EMP	1-5
	Šmit et al. (2011)	PIXE	6.55
	Metzler et al. (2011)	EDS	0.39
	This study	EDS	0.5

in the samples results in a lower counting error and vice versa. The lowest counting error was detected with Si (0.5 %), followed by Mg (0.6 %) and Fe (1.3 %). On the other hand, Mn was at the limit of detection for our quantitative EDS method. For this reason the counting error was as large as 21 %.

Conclusions

Present study of the meteorite Jesenice showed that olivine in meteorite has a composition of Fa 26.4 ± 0.6 and confirmed conclusions made by Bischoff and coworkers (2011) that it is an ordinary L chondrite of petrologic type 6. The planar deformation and the undulatory extinction of the mineral grains, determined also in this study, indicate that meteorite Jesenice is a weakly shocked (S3) meteorite. Analyses with quantitative energy-dispersive X-ray spectroscopy proved that the olivine in meteorite Jesenice is homogeneous. We did not notice any anomalies in the composition of the different chondrule types, the chondrule rims, the relict grain and the matrix. All this confirms that meteorite Jesenice is an equilibrated meteorite.

Acknowledgments

We would like to thank the Department for Nanostructured Materials, Jožef Stefan Institute, Ljubljana, for providing access to the scanning electron microscope. We are also very grateful to dr. Paul J. McGuiness for proofreading of the paper.

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