GEOLOGIJA *53/2*, 139-146, Ljubljana 2010

doi:10.5474/geologija.2010.011

Meteorite Jesenice: Mineral and chemical composition of the fusion crust of ordinary chondrite

Meteorit Jesenice: Mineralno-kemijska sestava žgalne skorje navadnega hondrita

Alenka LENART[1], Miha JERŠEK[2], Breda MIRTIČ[3] & Sašo ŠTURM[4]

Prejeto / Received 19. 10. 2010; Sprejeto / Accepted 25. 11. 2010

[1,4]Department for Nanostructured Materials, Jožef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia; e-mail: alenka.lenart@ijs.si, saso.sturm@ijs.si
[2]Slovenian Museum of Natural History, Prešernova 20, SI-1001 Ljubljana, Slovenia; e-mail: mjersek@pms-lj.si
[3]Faculty of Natural Sciences and Engineering, Department of Geology, University of Ljubljana, Aškerčeva ulica 12, SI-1000 Ljubljana, Slovenia; e-mail: breda.mirtic@guest.arnes.si

Key words: meteorite Jesenice, fusion crust, SEM, EDS analysis, precipitates, silicate melting
Ključne besede: meteorit Jesenice, žgalna skorja, SEM, EDS analiza, precipitati, nataljevanje silikatnih zrn

Abstract

The composition of the well-preserved fusion crust of the meteorite Jesenice was characterised by means of optical and scanning electron microscopy (SEM). The SEM investigations revealed three structurally distinct layers within the crust. The features of the first layer on the surface are precipitates, enriched in metal elements (iron, nickel), and the partial melting of silicate grains, which continues deeper into the second layer. The second layer beneath has veins with a heterogeneous composition that indicates a different source of melting minerals. The third layer, which is located deeper within the fusion crust, has not undergone any structural changes and its features are similar to the interior of the meteorite. This is additionally confirmed by the presence of cracks, which are a consequence of shock metamorphism, and irregularly shaped metal and sulphide grains. The structural changes of the thin fusion crust on the surface of this stony meteorite indicate high temperatures (more than 1500 °C) accompanied by high pressures.

Izvleček

Sestavo dobro ohranjene žgalne skorje meteorita Jesenice smo preučevali z optičnim in vrstičnim elektronskim mikroskopom (SEM). V okviru SEM preiskav smo po globini ločili tri plasti, ki se med seboj razlikujejo glede na stopnjo strukturnih sprememb. Za prvo plast so značilni precipitati, obogateni s kovinskimi elementi (železo, nikelj) ter nataljevanje silikatnih zrn, ki se nadaljuje globlje v drugo plast. Druga plast vsebuje žile, zapolnjene s talino heterogene sestave, kar nakazuje taljenje različnih mineralov. Notranji, tretji pas žgalne skorje ni bil podvržen nobenim strukturnim spremembam. Njegove značilnosti so podobne notranjosti meteorita, s številnimi nezapolnjenimi razpokami in nepravilnimi zrni kovin ter sulfidov. Strukturne spremembe žgalne skorje obravnavanega kamnitega meteorita kažejo na kratkotrajne visoke temperature (več kot 1500 °C) ter visoke pritiske pri prehodu skozi Zemljino atmosfero.

Introduction

Meteorites, as extraterrestrial objects that survive passage through the Earth's atmosphere and reach its surface, give important information about the formation of the early solar system as well as the origin and evolution of the Earth and other planets, comets, etc. Although meteorite falls are common phenomena, there are only limited numbers of meteorites with known orbits (Atanackov et al., 2010). One of them is the stony meteorite chondrite that fell in 2009 on the Mežakla plateau in the north-west of Slovenia. It was named meteorite Jesenice, after the nearby city. Altogether, three pieces with a total mass of approximately 2.3 kg were recovered. Usually, studies of chondrites focus more on the interior of the meteorite in order to reveal its origin based on investigations of the mineral assemblages. However, this study outlines the mineral and chemical properties of the well-preserved fusion crust on the surface of a fragment of the meteorite Jesenice. On the basis of the degree of the structural changes, different layers within the crust were distinguished. Of particular interest are the structural changes that occurred during its passage through the Earth's atmosphere. These changes could provide information about the high-temperature processes and the influence of terrestrial weathering.

All the minerals at the surface might not be completely melted and only partial mixing can occur. Recent investigations of meteorite fusion crust variability revealed that the composition of a fusion crust can only approximate the bulk composition from which it originated due to its inhomogeneity and variability. The general investigations included petrographic studies of thin sections, electron microprobe analysis (EMPA), instrumental neutron activation analysis (INAA), geochemical studies, etc. (Korotev et al., 1996; Day et al., 2006; Brandstätter et al., 2008; Thaisen & Taylor, 2009).

Stony meteorites

A meteorite is a recovered fragment of a meteoroid that has survived transit through the Earth's atmosphere (McSween, 1999). Meteorite Jesenice is a stony meteorite classified as an ordinary chondrite (Atanackov et al., 2010). Stony meteorites are very similar to the rocks on the Earth because they are composed mainly of silicate and oxide minerals, although they may also contain small metal grains (McSween, 1999). They are the most commonly observed fallen meteorites (MacDonald et al., 2003). Chondrites are the most common form of stony meteorites and represent 86 % of the mass of all the fallen meteorites on the Earth's surface. They consist of 40 %–90 % of chondrules (McSween, 1999; Triglav, 2000), which are subspherical or sometimes ellipsoidal structures with diameters of 0.1 mm up to 4 mm (Kohout, 2009). They may be porphyritic, granular or glassy in texture (MacDonald et al., 2003). Chondrules are composed of different minerals, although olivine and pyroxene tend to prevail and small amounts of feldspars are also present. In addition, impurities of iron and other metals can be found.

Stony meteorites usually have a thin, dark coating, called the 'fusion crust', which distinguishes them from the rocks on the Earth. When a meteoroid travels through the atmosphere at high speed, the air in its path is compressed and the temperature of this air increases. Because a meteoroid has no shields to dissipate the heat generated by the atmospheric friction, its surface melts. A meteoroid is heated to melting temperatures during its fall, which results in loss of most of the molten material due to ablation before impact itself. When the meteoroid slows down to the point where no melting occurs, the last melt to form cools down, leaving only a very thin rind of quenched fusion crust (McSween, 1999; Thaisen & Taylor, 2009). The fusion crust is a layer of solidified melt glass coating the exterior. Frequently, it is less than a millimetre thick, except for solidified pockets of melt on the trailing edges of oriented meteorites. Atmospheric heating does not significantly affect their interior because the heat conduction in stones, or even lumps of iron, takes much longer than a minute or so required for atmospheric transit. A stony meteorite's crust is originally black but lightens with prolonged exposure to the atmospheric conditions (McSween, 1999). The weathered fusion crust is rusty brown and looks like many of the rocks on the Earth.

Mineralogy of ordinary chondrite

Meteorites contain no elements that are not already present in terrestrial rocks; however, these elements are often combined to form compounds that may be different from those in terrestrial rocks. They contain unique assemblages of minerals that tell us about the composition of other planets or about the origins of the minerals on Earth. The bulk of stony meteorites is composed of several minerals that are commonly found on Earth, e.g., olivine (magnesium iron silicate), pyroxene (magnesium iron calcium silicate), plagioclase (a sodium-calcium aluminosilicate), chromite (chromium iron oxide) and magnetite (iron oxide). Troilite (iron sulphide), cohenite (iron carbide) and several forms of nickel-iron metal (kamacite and taenite) are abundant in meteorites, but are extremely rare in terrestrial rocks and ores (McSween, 1999). The main components of ordinary chondrites are the mafic silicates, Fe-Ni metal and troilite (Bland et al., 2006). Meteorite Jesenice contains the following mineral phases: olivine, low-Ca pyroxene, Ca-pyroxene, plagioclase, kamacite, taenite, troilite and less abundant quantities of chromite, whitlockite, Cl-apatite and ilmenite (Atanackov et al., 2010).

Samples and methods

In order to investigate the mineral-chemical composition of the fusion crust on the surface of the meteorite Jesenice and its structural changes in comparison with the interior of the meteorite, different samples and investigation techniques were applied. A fragment of the meteorite was cut perpendicular to the surface and prepared as three polished thin sections. One of them contained the fusion crust, which was investigated with a Zeiss Axio Z1-m optical microscope in reflected and transmitted light. For the scanning electron microscopy (SEM) two types of samples were prepared. The first type was the original surface of a small fragment of the meteorite with some preserved crust on its surface (Fig. 1). The second type represented a petrographic thin section (thickness of 30 μm) that contained the meteorite's crust (Fig. 2). The specimens were mounted on aluminum stubs with a double-faced conductive adhesive tape. For conductivity, all samples were coated with thin conductive film of graphite, using a Balzers SCD 050 sputterer.

Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) were used to characterise mineral phases. The investigations were carried out on a Jeol JSM 5800 scanning electron microscope, equipped with a Si-Li detector (LINK ISIS300, Oxford Instruments), at the Jožef Stefan Institute in Ljubljana, Slovenia. Mineral databases, supplied by the manufacturer, were used for quantification of the expected chemical elements. The chemical composition of the crust was therefore determined by standardless EDS quantitative analysis, from here on referred to as EDS analysis. The chemical analy-

Fig. 1. The interior of a fragment of the stony meteorite Jesenice is light-coloured, while its surface is covered by well preserved dark fusion crust.

Sl. 1. Notranji del fragmenta kamnitega meteorita Jesenice je sive barve. Na površini ima ohranjeno temno žgalno skorjo.

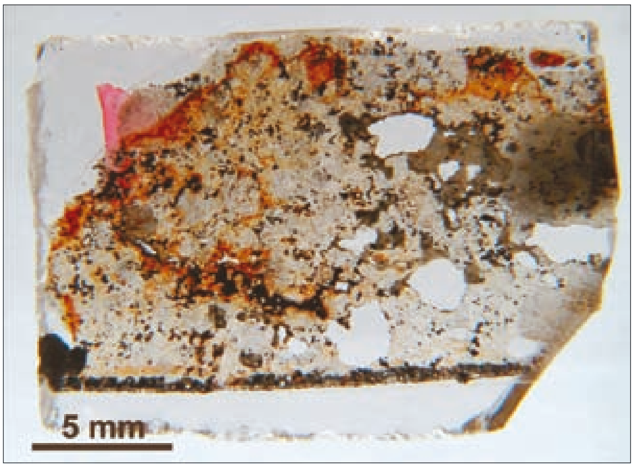

Fig. 2. Thin section of the meteorite Jesenice with the dark layer along the bottom corresponding to the fusion crust.

Sl. 2. Zbrusek meteorita Jesenice. Temna plast na spodnjem robu je žgalna skorja meteorita.

ses were performed at an accelerating voltage of 20 kV and a working distance of 10 mm. The spectra-acquisition time was 60 s.

To distinguish the different mineral phases, the BSE (backscattered electrons) mode was used. Backscattered electrons carry useful information about the specimen's chemical composition, the topography, the crystallinity, etc. (Goldstein et al., 2003). The intensity of the signal of backscattered electrons, which are electrons with high energy, depends on the average atomic number (Z) and the local topography of the sample. To eliminate the differences that arise when a specimen has an irregular topography, the investigated samples had a flat surface and sufficient thickness. The atomic number contrast (also called the compositional contrast or the Z contrast) with backscattered electrons enables detection of regions with different chemical compositions within the specimen. Atomic number is unique for every element in the periodic system. For example, phases rich in heavy elements appear brighter than those that contain lighter elements. Elements with a higher atomic number Z generate more backscattered electrons, which originate from the deflection of the electron beam at the atoms in the sample. The atomic number contrast between adjacent pairs of elements (separated by one unit of atomic number) is strong at low atomic numbers and decreases as the atomic number increases (Goldstein et al., 2003).

Results and discussion

The thickness of the fusion crust of meteorite Jesenice varies from 0.1 mm to 0.3 mm (Atanackov et al., 2010). The optical microscopy revealed that the inner part of the meteorite differs from the crust because the former contains chondrules of olivines and pyroxenes. In contrast, the latter provides information about the local structural alteration due to the exposure to conditions (changes in the temperature and pressure) during passage through the atmosphere. As viewed in thin sections, using an optical microscope, the boundary of the crust in reflected light was hard to distinguish from the rest of the rock (Fig. 3a). However, in transmitted polarized light the crust appeared as a black layer on the edge of a thin section (Fig. 3b).

Since optical microscopy is limited by its resolution and in order to obtain information about the chemical composition of the samples, scan-

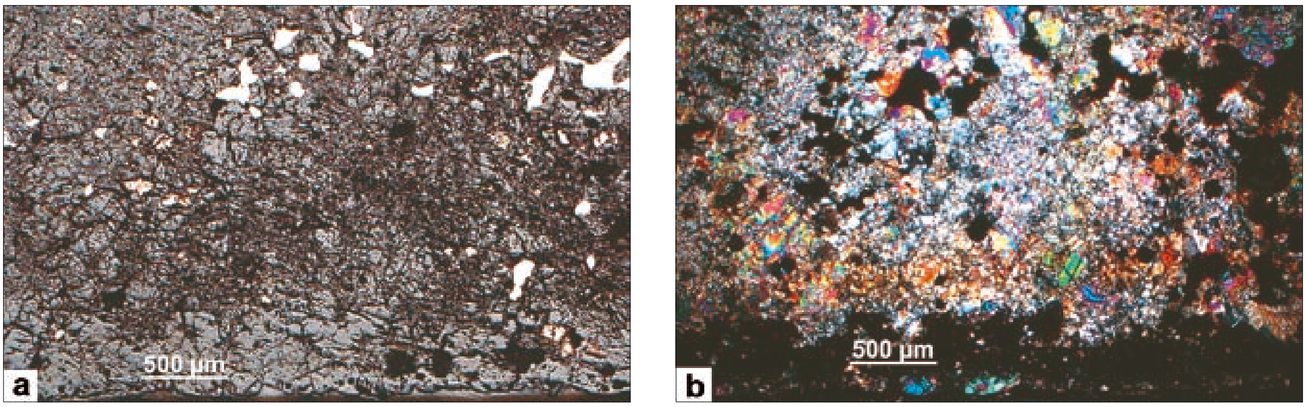

Fig. 3. Thin section of the meteorite Jesenice with fusion crust viewed in a) reflected and b) transmitted light in an optical microscope. The black layer in the lower part of a thin section, viewed in transmitted light, corresponds to the meteorite's crust.

Sl. 3. Zbrusek meteorita Jesenice z žgalno skorjo v a) odbiti in b) presevni polarizirani svetlobi pod optičnim mikroskopom. Temen pas v spodnjem predelu zbruska pod polarizirano presevno svetlobo ustreza skorji meteorita.

ning electron microscopy was applied. On the basis of the degree of structural changes, the SEM analyses revealed three layers within the meteorite's crust (Fig. 4).

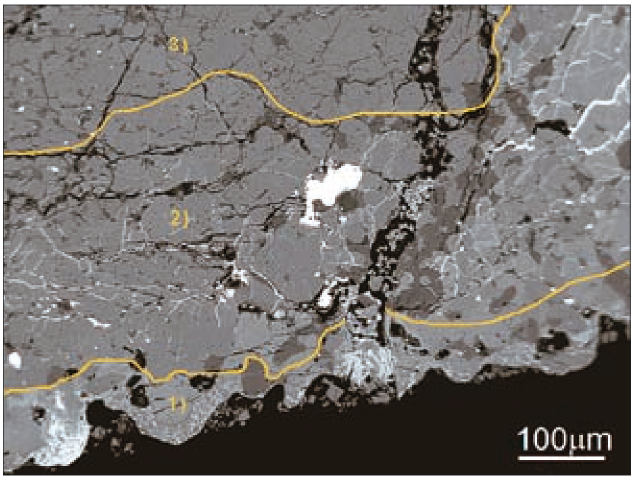

Fig. 4. Based on the degree of structural changes we distinguished three layers (1, 2, 3) within the meteorite's crust. This photomicrograph was taken with SEM in BSE mode.

Sl. 4. Glede na stopnjo strukturnih sprememb žgalne skorje meteorita se po globini razločijo trije pasovi (1, 2, 3). Slika je bila posneta z vrstičnim elektronskim mikroskopom v načinu povratno sipanih elektronov (BSE).

1) first layer of the meteorite's crust

The first layer of the fusion crust includes the surface of the meteorite and the outermost part of the crust. A characteristic of this layer are the precipitates (Fig. 5a). The dendritic growth of the precipitates indicates a fast precipitation from the melt (Fig. 5b). In BSE mode they are viewed as the brightest phases. EDS analyses of 15 measured precipitates revealed that in comparison with the glassy phase, their compositions mostly correspond to iron and nickel, although these compositions vary locally (Tab. 1). In the first layer, in addition to the appearance of the precipitates, the partial melting of silicate grains, such as olivines, pyroxenes and feldspars, is also significant (Fig. 6). According to REIMOLD et al. (2004), the frictional temperature excursions must have attained values in excess of 1500 °C to allow a complete melting of the forsteritic olivine.

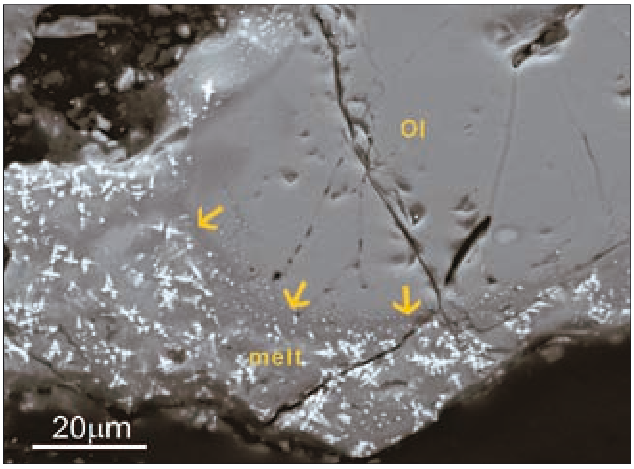

Fig. 6. BSE image of a thin section showing partial melting of an olivine grain. The line of melting progression is very sharp (marked by the arrows).

Sl. 6. BSE posnetek zbruska kaže nataljevanje zrna olivina z ostro nataljevalno fronto (označena s puščicami).

2) second layer of the meteorite's crust

The first layer of the meteorite's crust continues through the depth to the second layer. However, in some places the transition between the aforementioned layers is not sharp due to partial melting of the silicate grains, which continues from the first layer. Within the second layer there are abundant regions of melted feldspar grains and their melt partially covers the grains of minerals that belong to the pyroxene and olivine mineral group (Fig. 7). This is reflected in the fact that the plagioclases melt at lower temperatures than other major minerals in chondrites. The second layer within the

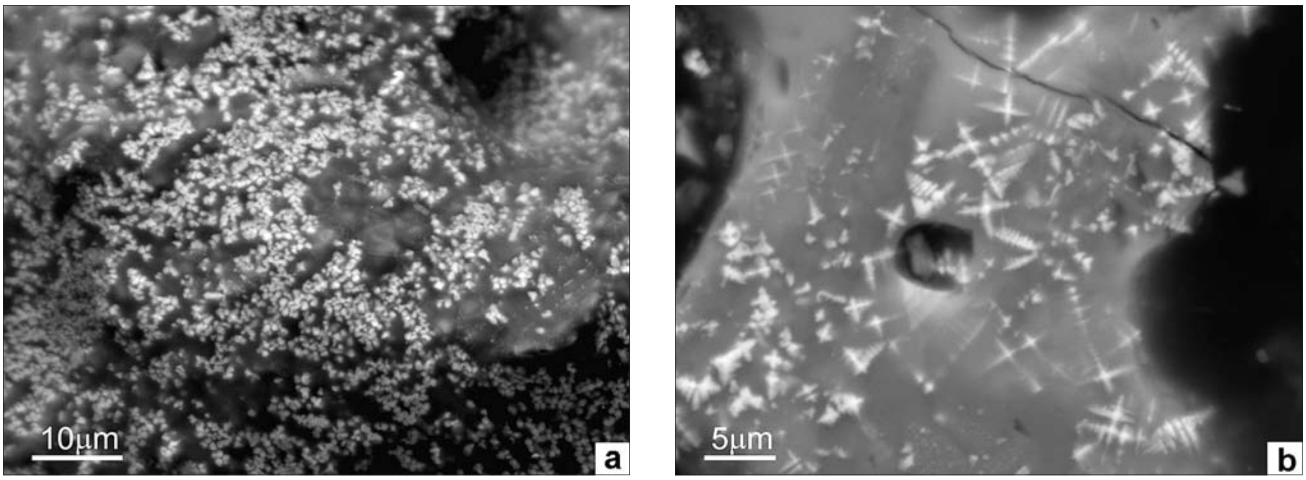

Fig. 5. a) Surface of a fragment of the meteorite Jesenice viewed in BSE mode. The white phases are precipitates rich in metal elements (iron, nickel). b) Closer view of the dendritic growth of precipitates in a thin section of the fusion crust of the meteorite Jesenice. Magnification 3000x, BSE mode.

Sl. 5. a) Površina kosa meteorita Jesenice, posneta v načinu povratno sipanih elektronov. Svetle faze pripadajo precipitatom, obogatenim s kovinskimi elementi (železo, nikelj). b) Dendritska rast precipitatov v zbrusku z žgalno skorjo meteorita Jesenice. BSE način, povečava 3000x.

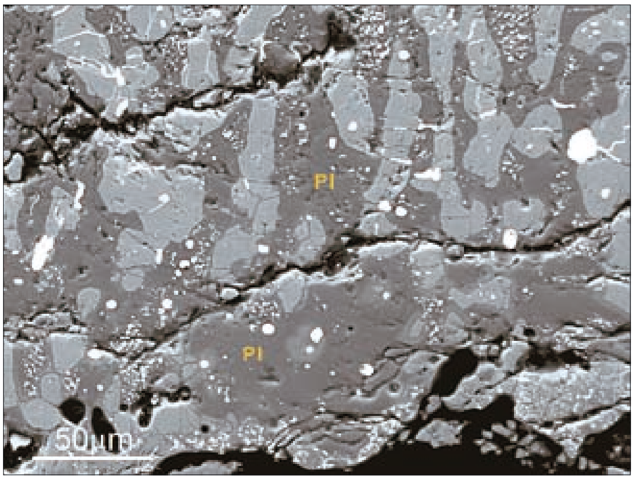

Fig. 7. Melting of plagioclase (Pl) grains, which appear dark grey in BSE mode.

Sl. 7. Nataljevanje zrn plagioklazov (Pl), ki so v BSE načinu opazovanja temno sive barve.

Tab. 1 EDS analyses of 15 precipitates, formed from the melt in the first layer of the fusion crust; average composition (x), standard deviation (s), range (min – max).

Tab. 1 EDS analize 15 precipitatov, ki so se izločili iz taline v prvi plasti žgalne skorje; povprečna sestava (x), standardni odklon (s), razpon (min – max).

element	x (at. %)	s (at. %)	min - max (at. %)
Si	32	8,8	17,8 – 44,0
Fe	31	16,1	7,8 – 54,7
Mg	26	10	14,0 – 42,4
Al	3	2,9	0,8 – 13,1
Ca	3	1,2	0,6 – 5,2
Na	2	1,2	0,8 – 4,8
K	2	5	0,0 – 19,6
Ni	1	0,4	0,2 – 1,4
Mn, Cr, S	< 1		

Tab. 2 EDS analyses of filling of the veins in the second layer of the fusion crust; average composition (x), standard deviation (s), range (min – max). Number of analyses is 5.

Tab. 2 EDS analize polnitve žil v drugi plasti žgalne skorje; povprečna sestava (x), standardni odklon (s), razpon (min – max). Število meritev je 5.

element	x (at. %)	s (at. %)	min - max (at. %)
Fe	41,0	8	29,1 – 49,6
S	29,1	12,5	12,7 – 40,0
Si	15,1	9,7	4,8 – 28,7
Mg	14,9	11,4	3,1 – 33,7
Ni	6,2	5,2	0,6 – 13,4
Ca	0,6	1	0,0 – 2,4
Al, Na, Cr, Mn, Ti, P, K	< 1		

fusion crust differs from the first layer in terms of the presence of the veins that intersect the silicate grains (Fig. 8a). These veins are up to 2 µm wide, but they are often thinner. They are heterogeneously filled with metal-rich compounds, which are viewed as phases with different brightnesses in BSE mode (Fig. 8b). A heterogeneous filling of the cracks on a micrometer scale was formed from the melting of different local mineral assemblages

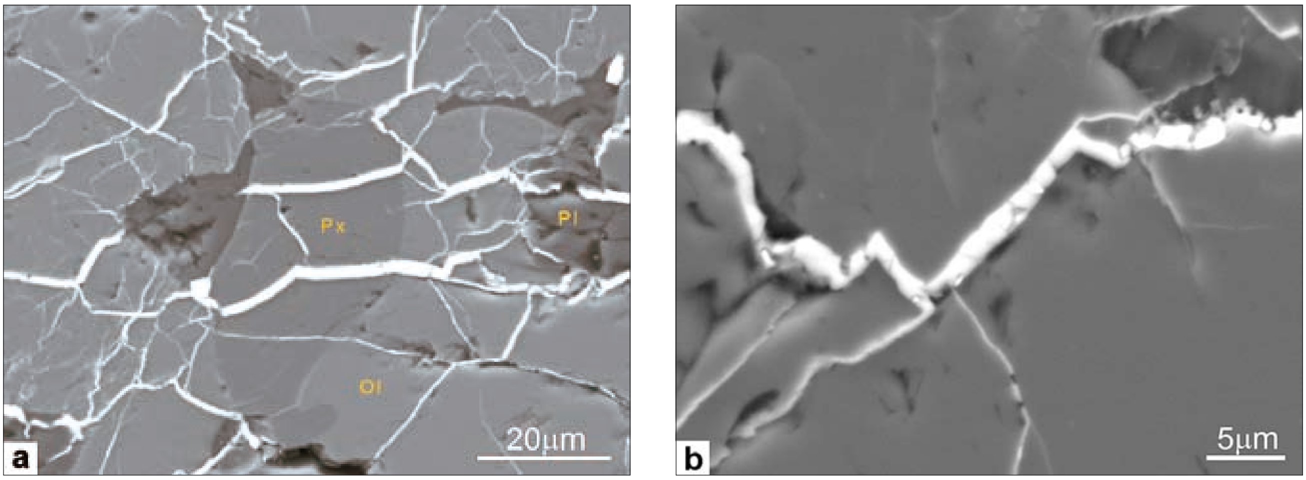

Fig. 8. BSE image of veins, intersecting different silicate grains. a) Olivine (Ol) and pyroxene (Px) grains are medium grey. Plagioclase (Pl) is dark grey. b) Inhomogeneous filling of the vein (magnification 3300x). Visible are phases with different Z contrast.

Sl. 8. Žile taline sekajo različna silikatna zrna. Posneto v BSE načinu. a) Zrna olivinov (Ol) in piroksenov (Px) so srednje siva. Zrna plagioklazov (Pl) so temno siva. b) Nehomogena polnitev razpoke (povečava 3300x). Vidne so faze z različnim Z kontrastom.

(Tab. 2). The large amount of detected Si and Mg is due to the melting of the olivine and/or pyroxene grains. Some fragments within the vein also show small abundances of Ca, which presumably derive from melted pyroxene or plagioclase.

3) third layer of the meteorite's crust

The third layer is located deeper than the second layer and it differs from the latter significantly. There is a clear evidence of numerous primary cracks, which shows that at this depth of the fusion crust the temperature was lower than in the first two layers, and consequently these irregular fractures were not filled with the melt (Fig. 9). Extensive fracturing is typical for all types of silicate minerals within the specimen. A significant feature of the third layer are the well-preserved and abundant xenomorphic metal and sulphide grains (Fig. 10). This additionally suggests the absence of melting. These metal and sulphide grains have a large size distribution and are commonly intergrown. Individual smaller grains occur in euhedral crystal shapes. These grains belong to metallic Fe-Ni and troilite (FeS). Within the Fe-Ni, according to the chemical composition, the

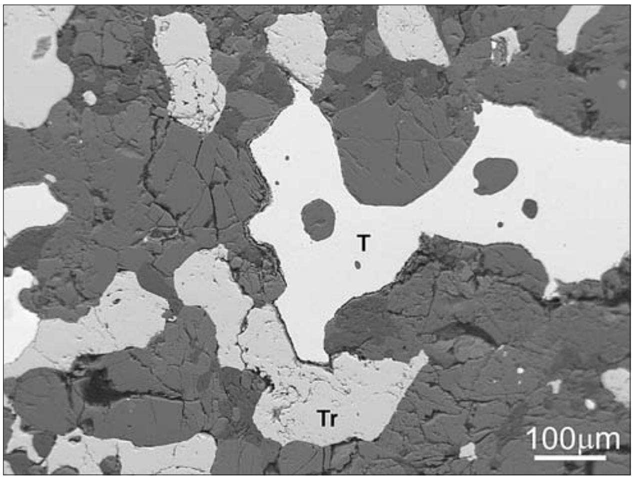

Fig. 9. Cracks in the silicate grains are not filled with the melt, which indicates lower temperatures within the third layer of the meteorite's crust.

Sl. 9. Nezapolnjene razpoke v silikatnih zrnih kažejo na nižjo temperaturo v tretji plasti skorje meteorita.

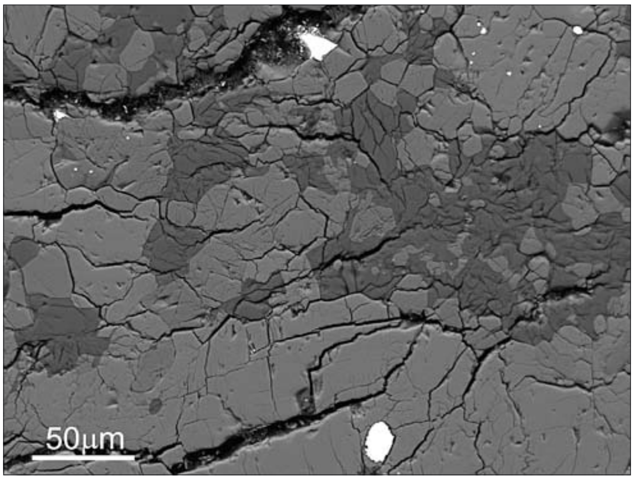

Fig. 10. SEM backscattered-electron image of the third layer within the fusion crust of the meteorite Jesenice showing the major metal and sulfide phases. Silicate is dark grey, troilite (Tr) is light grey and taenite (T) is white.

Sl. 10. Tretja plast žgalne skorje meteorita Jesenice, posneta v načinu povratno sipanih elektronov, vsebuje zrna kovin in sulfidov. Silikati so temnosivi, troilit (Tr) je svetlosiv, taenit (T) je bel.

polymorphs taenite γ-(Fe, Ni) and kamacite α-(Fe, Ni) are visible. The third layer within the fusion crust is represented by structurally unchanged rock, which does not significantly differ from the interior of the meteorite.

Conclusion

Meteorite Jesenice is a stony meteorite chondrite that fell in Slovenia in 2009. It has a well-preserved fusion crust on its surface. This is a thin black coating that forms as the meteorite partially melts while passing through the Earth's atmosphere. The SEM investigations of its fusion crust revealed three structurally distinct layers within the crust. The features of the first layer are precipitates, enriched in metal elements (iron, nickel) and the partial melting of silicate grains (olivines, pyroxenes and feldspar). The aforementioned melting of the silicate grains continues deeper into the second layer. In the second layer there are veins, heterogeneously filled with metal compounds with a range of chemical compositions, which were determined by EDS analyses. These veins intersect different silicate grains. In the third layer, which is located deeper within the fusion crust, there is no evidence of any structural changes and its features are similar to the interior of the meteorite. This is confirmed by the presence of cracks, which intersect silicate grains, and larger irregularly shaped metal and sulphide grains. The structural changes of the thin fusion crust on the surface of this stony meteorite indicate high melting temperatures (more than 1500 °C). At the same time the preserved fusion crust presumably represents protection against further weathering, to which the meteorite was exposed after it landed on the Earth's surface.

References

ATANACKOV, J., JERŠEK, M., KAC, J., KLADNIK, G. & MIRTIČ, B. 2010: Meteorit z Mežakle. Gornjesavski muzej Jesenice in Prirodoslovni muzej Slovenije. Ministrstvo RS za kulturo, Občina Jesenice in Občina Gorje: 1-55.

BLAND, P. A., ZOLENSKY, M. E., BENEDIX, G. K. & SEPHTON, M. A. 2006: Weathering of Chondritic Meteorites. ln: MCSWEEN, H. Y. (ed.): Meteorites and the Early Solar System II. University of Arizona Press (Arizona): 853-867.

BRANDSTÄTTER, F., BRACK, A., BAGLIONI, P., COCKELL, C. S., DEMETS, R., EDWARDS, H. G. M., KURAT, G., OSINSKI, G. R., PILLINGER, J. M., ROTEN, C.-A. & SANCISI-FREY, S. 2008: Mineralogical alteration of artificial meteorites during atmospheric entry. The STONE-5 experiment. Planetary and Space Science (Amsterdam) 56: 976-984.

DAY, J. M. D., TAYLOR, L. A., FLOSS, C., PATCHEN, A. D., SCHNARE, D. W. & PEARSON, D. G. 2005: Comparative petrology, geochemistry, and petrogenesis of evolved, low-Ti lunar mare basalt meteorites from the LaPaz Icefield, Antarctica. Geochimica et Cosmochimica Acta (Amsterdam) 70: 1581-1600.

GOLDSTEIN, J. I., NEWBURY, D. E., ECHLIN, P., JOY, D. C., LYMAN, C. E., LIFSHIN, E., SAWYER, L. & MICHAEL, J. R. 2003: Scanning Electron Microscopy and X-Ray Microanalysis. Third edition, Kluwer Academic/Plenum Publishers (Boston): 1-296.

KOHOUT, T. 2009: Physical properties of meteorites and their role in planetology. Report Series in Geophysics, no. 60. Academic Dissertation in Geophysics. University of Physics, Department of Physics (Helsinki): 1-60.

KOROTEV, R. L., JOLLIFF, B. L. & ROCKOW, K. M. 1996: Lunar meteorite Queen Alexandra Range 93069 and the iron concentration of the lunar highlands surface. Meteoritics & Planetary

Science, University of Arizona, Department of Geosciences (Arizona) 31: 909-924.

MacDonald, J. G., Burton, C. J., Winstanley, I. & Lapidus, D. F. 2003: Coolin's dictionary of Geology. HarperCollins Publishers (Glasgow): 1-480.

McSween, H. Y. 1999: Meteorites and Their parent Planets. Second edition, Cambridge University Press (Cambridge): 1-310.

Reimold, W. U., Buchanan, P. C., Ambrose, D., Koeberl, C., Franchi, I., Lalkhan, C., Schultz, L., Franke, L. & Heusser, G. 2004: Thuathe, a new H4/5 chondrite from Lesotho: History of the fall, petrography, and geochemistry. Meteoritics & Planetary Science, University of Arizona, Department of Geosciences (Arizona) 39/8: 1321-1341.

Thaisen, K. G. & Taylor, L. A. 2009: Meteorite fusion crust variability. Meteoritics & Planetary Science, University of Arizona, Department of Geosciences (Arizona) 44/6: 871-878.

Triglav, M. 2000: Meteorji. Društvo matematikov, fizikov in astronomov Slovenije, Knjižnica Sigma (Ljubljana): 1-207.