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A NEW CLASSIFICATION OF NYIRÁBRANY, AN ORDINARY CHONDRITE FROM HUNGARY

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Abstract: The Nyirábrany meteorite is an ordinary chondrite from Hungary that fell in 1914 and, to date, has been studied very little. The aim of this work was to carry out a more detailed examination of this meteorite (using optical polarization microscope, energy dispersive X-ray spectroscopy and Raman microspectroscopy) and re-investigate its previous classification as an LL5 type ordinary chondrite, moreover to complete its classification with a shock stage and a weathering grade. Our new results indicate that Nyirábrany could be a transition type between the L and LL chondrites. The main mineral phases of Nyirábrany are olivine, pyroxene and opaque minerals (e.g. Fe-Ni metal, troilite, chromite), minor constituents are plagioclase, Cl-apatite, cristobalite and glass. The Fe-Ni metal content (1.32 vol%) of Nyirábrany is typical of the LL group, the Fa-content of olivines (26.71 mol%) is between the range of the L and LL types, while the Fs-content of the low-Ca pyroxenes (20.51 mol%) is typical of the L-chondrites. Chondrules appear in different sizes, mineral compositions and textures. The textural and mineralogical features (e.g. mostly homogeneous silicate minerals, dominance of clinopyroxenes, recrystallized matrix, well-defined chondrules) indicate petrological type 4-5 for Nyírábrány. The shock stage and the weathering grade of this meteorite were examined for the first time. On the basis of the observed optical and textural features of the olivine grains (e. g. sharp optical extinction, irregular and planar fractures) Nyirábrany has an S2 shock stage. About 30–40% of the opaque phases are affected by oxidation, which shows a W2 weathering grade.

Keywords: chondrite, classification, L and LL chondrites.

INTRODUCTION

The aim of this study is the re-analysis of the ordinary chondrite called Nyirábrany. We present the results on its classification according to chondrite groups based on the Fe-Ni metal content, and the chemical composition of olivine and low-Ca pyroxene. The assignment of the petrologic type was based on the van Schmus and Wood (1967) petrologic type scheme. The shock stage of Nyirábrany was defined by using the shock classification of Stöffler et al. (1991) and the weathering grade was defined according to the weathering scale of Wlotzka (1993). Using up-to-date methods, we present new details and characterization of this meteorite. The results here could be used to target further analysis.

Nyirábrany is one of the 27 meteorite falls and finds from the Carpathian Basin. It fell on the 17th of July, 1914 on the north-western part of Hajdú-Bihar County, Hungary (N 47°33', E 22°1'30") (Fig. 1) and was named after the village in the vicinity of which it fell. The meteorite was recovered right after the fall by an eyewitness as a single stone with a mass of 1104 g. Nyirábrany is a poorly studied meteorite whose first investigation was undertaken by Sztrókay et al. (1977). At that time no advanced instrumental analysis methods were available, the chemical composition of the main silicate phases was determined by optical methods. Kubovics et al. (2004) re-investigated Nyirábrany together with five other meteorites from

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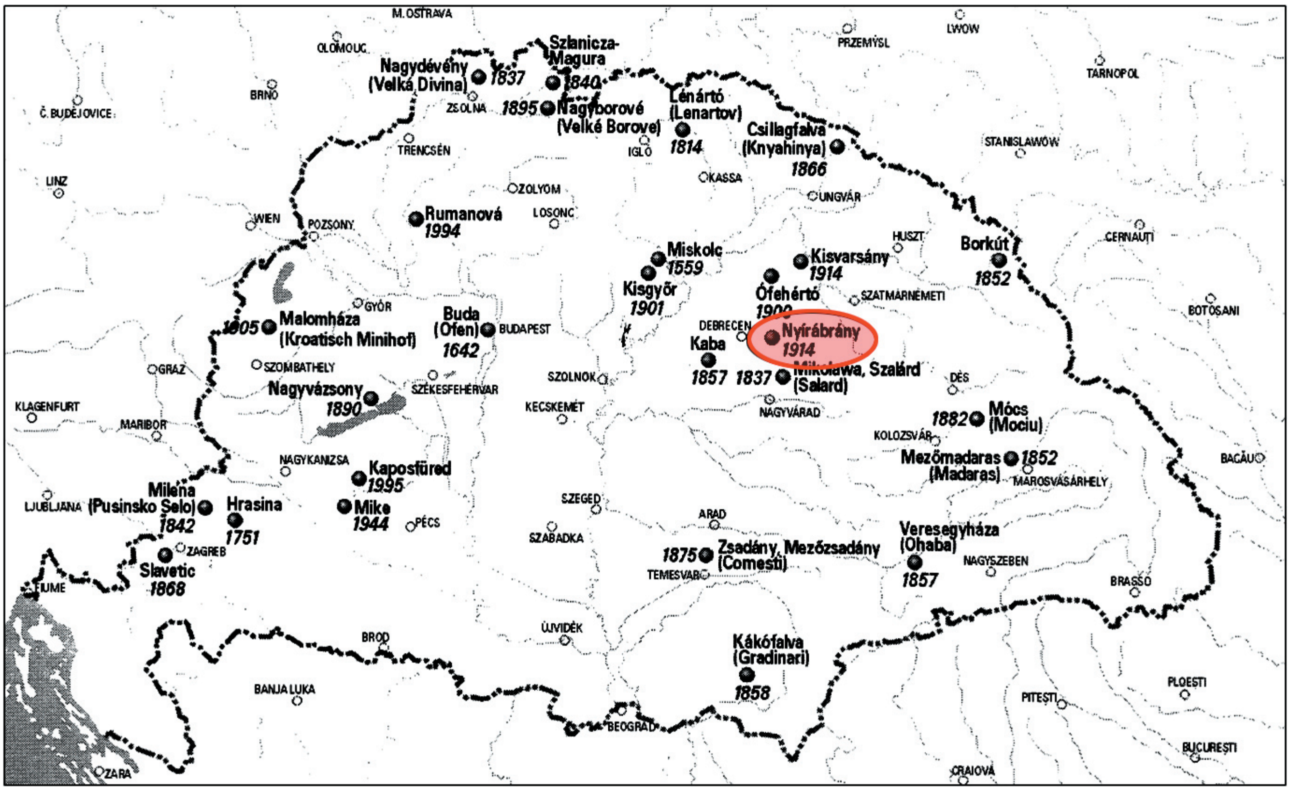

Fig. 1. Map of the Carpathian Basin showing the meteorite falls and finds from this area. The location of Nyirábrany is marked by an ellipse (Kubovics et al., 2004)

the Carpathian Basin, but no detailed analyses were made on its mineralogical and chemical composition. Nyirábrany was mentioned in other publications in connection with its reflectance spectra as one among other meteorite samples (Paton et al., 2011), and another work mentioned its chromium and manganese content (Yates et al., 1968), while most of this meteorite's basic properties have remained unexplored.

ANALYTICAL METHODS

Due to the limited availability of Nyirábrany samples, only one polished thin section of the meteorite was used for the investigation – as a result, our findings are not absolutely representative for the whole meteorite, but still provide important insights into its properties. The polished thin section was studied with an optical microscope in transmitted light to identify the main mineral phases and chondrules, and to observe the textural features. The semi-quantitative chemical analysis and BSE imaging was undertaken on the same thin section of the meteorite to identify minor components, to determine the chemical composition of the main mineral phases and to observe the textural features in details. This measurement was conducted using energy dispersive X-ray spectroscopy on an AMRAY 1830i scanning electron microscope with up to 4 nm spatial resolution at the Petrology and Geochemistry Department of Eötvös Loránd University. During the analysis 20 kV acceleration voltage and 1 nA beam current intensity were used. Counting time was 100 s and the ZAF procedure was used to correct matrix effect. The Raman measurement was made by HORIBA JobinYvon LabRAM HR type Raman-microspectrometer, equipped with Olympus BXFM type optical microscope, and thermoelectrically cooled CCD detector, 532 nm wavelength excitation, recording spectra between about 895 and 1080 cm^{-1} with 2×30 second intervals, 1800 line/mm optical lattice and 100-times magnification.

The estimation of shock level is important to evaluate the past collisional history of any meteorite and their parent bodies. Various micro- and macroscopic structural changes, specific phases and mineral assemblages in meteorites are related to the shock produced deformation and transformation, and could be used to estimate the shock level. These shock indicators include deformation bands, planar deformation features (Stöffler, 1967; Nagy et al., 2008), mosaicism, twin lamellae formation, isotropization (Stöffler et al., 1986), recrystallization (Ostertag et al., 1986), formation of new minerals (Bridges et al., 2001), or melt veins (Gillet et al., 2000), transformation of plagioclase to jadeite (Kubo et al., 2010) and olivine to spinel structures (Putnis & Price, 1979). The methods to identify these shock markers include nuclear magnetic resonance (Stöffler & Langenhorst, 1994), cathodoluminescence (Kayama et al., 2009), Raman spectroscopy (Miyamoto & Ohsumi, 1995; Gucsik et al., 2004, 2010), refractive index (Lambert, 1981; Fritz et al., 2003), X-ray diffraction (Nakamura et al., 2011) analysis. A recently emerging new field is the alkali feldspar analysis by cathodoluminescence as shock barometers in meteorites (Kayama et al., 2012), what looks as an universal tool to estimate wide pressure range between about 4.5 and 40.1 GPa.

Due to equipment availability and various technical reasons, the shock stage was estimated using the simple method of polarization microscopy. Here we use the Stöffler et al. (1991) classification system developed for ordinary chondrites with six distinct shock stages labelled from S1 to S6. The aim was an improved classification of this meteorite in order to better target future investigations. The authors would like to conduct detailed shock analysis in the future on this meteorite.

RESULTS

In this section we give an overview of the analysis of the meteorite, focusing on the general microscopic appearance, including petrography, mineralogy, chemical composition of mineral phases, and the shock stage and weathering, to support a more precise classification and characterization.

Macroscopic description

For the macroscopic description, we used a ~50×35×5 mm rock slice of Nyirábrany (Fig. 2a), which was investigated with a stereomicroscope. The sample has a dark fusion crust along its surface which was produced during the transport trough the atmosphere. The fusion crust is usually ~50 µm thick (Fig. 2b), but the thickness can go up to ~400 µm at certain locations. The meteorite has a light grey coloured matrix in which different sized chondrules, chondrule-fragments and usually sub-millimeter sized opaque constituents are embedded. Porphyritic and radial textures of some of the chondrules are also vis-

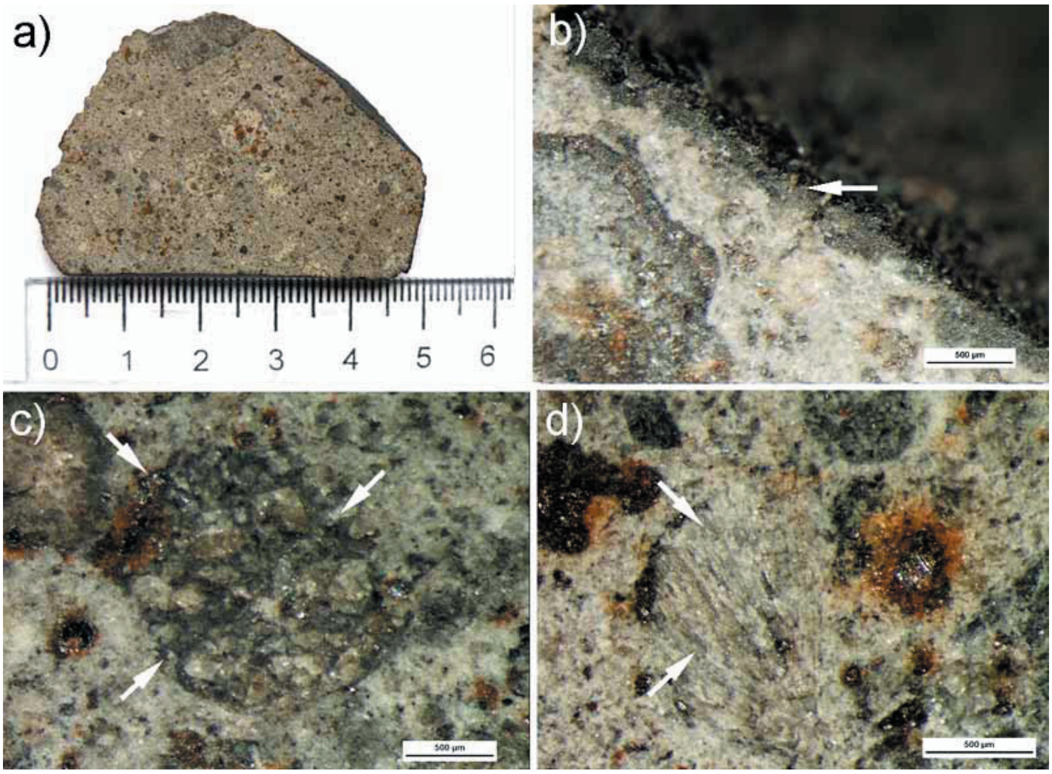

Fig. 2. General images of the Nyirábrany meteorite: a) cross section of the meteorite with bright reflecting opaque minerals; b) fusion crust on the surface of the meteorite; c) porphyritic textured chondrule; d) radial textured chondrule

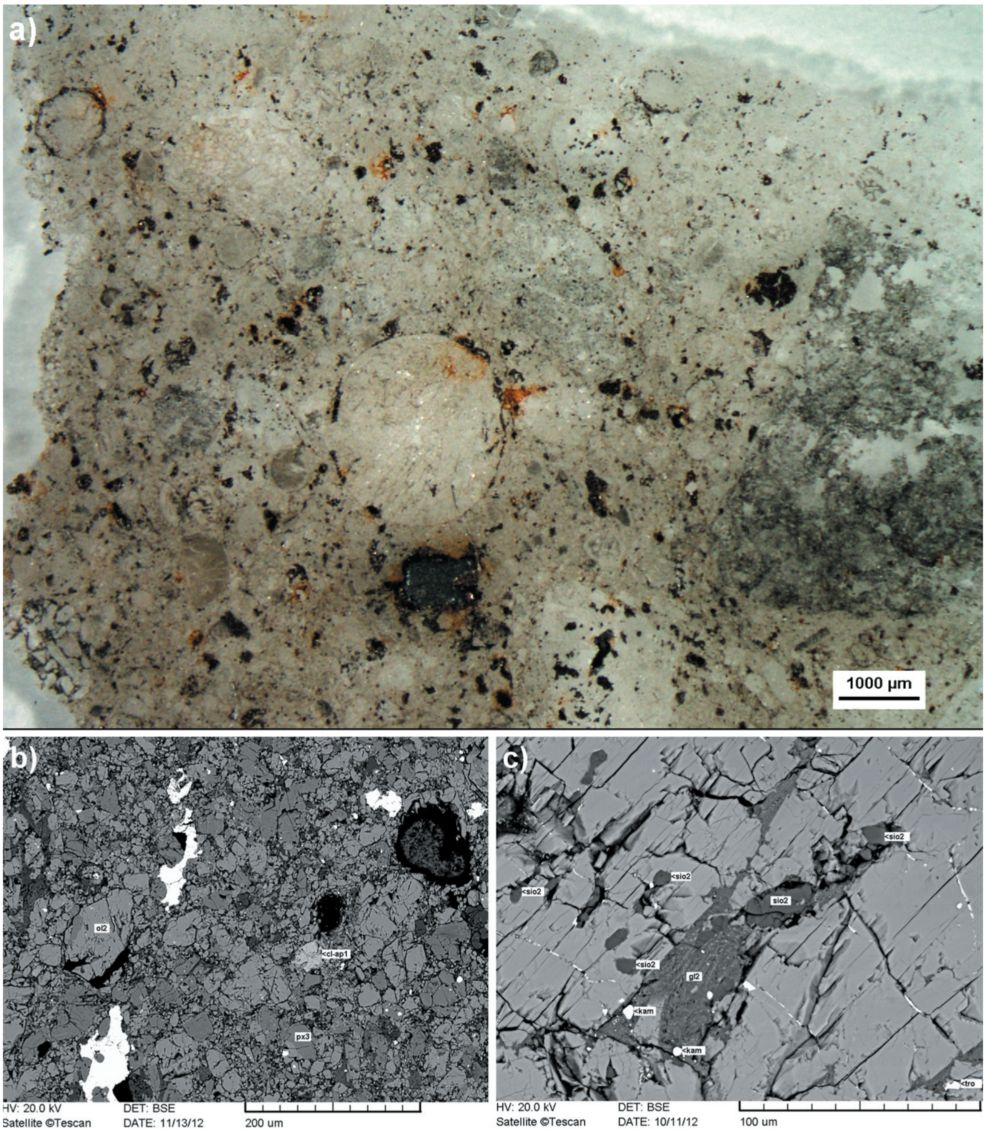

Fig. 3. Images of Nyirábrany: a) overview image of the examined thin section of Nyirábrany with well-defined and diffuse chondrules; b) Cl-apatite (light gray) in the crystallized matrix of the meteorite (cl-ap-chloroapatite, ol-olivine, px-pyroxene); c) cristobalite (middle gray) in the pyroxene crystals of a radial textured chondrule (acronyms: SiO_2-cristobalite, gl-glass, kam-kamacite, tro-troilite)

ible with stereomicroscope (Fig. 2c and d). Reddish-brown weathering products occur around the opaque phases as a result of terrestrial alteration.

Petrography

The matrix is composed of fine (5–50 µm) grains and is completely crystalline as can be seen on the BSE images (Fig. 3b). Chondrules appear in diverse sizes, mineral compositions and textures, like radial pyroxene, porphyritic olivine, poikilitic pyroxene-olivine and barred pyroxene chondrules. In some cases, chondrules are well-defined, in other cases they are diffuse, which makes difficult to define their exact abundance (Fig. 3a). The size of the well-defined chondrules ranges from ~560 µm to ~2200 µm. Most of the chondrules are fractured and some of them are broken too.

We have selected eight well-defined chondrules in the thin section of Nyirábrany to illustrate the main, characteristic chondrule types and their features (Fig. 4), that listed in Table 1. The various types of chondrules provide evidence for different cooling speed values. Refractory inclusions were not identified in the thin section of Nyirábrany.

Mineralogy

The main mineral phases of Nyirábrany are olivine, pyroxenes and opaque constituents. Minor amount of plagioclase, Cl-apatite, cristobalite and recrystallized glass were also identified.

Olivine is the most abundant mineral phase of Nyirábrany, it has an amount of ~58.5% (Sztrókay et al., 1977).

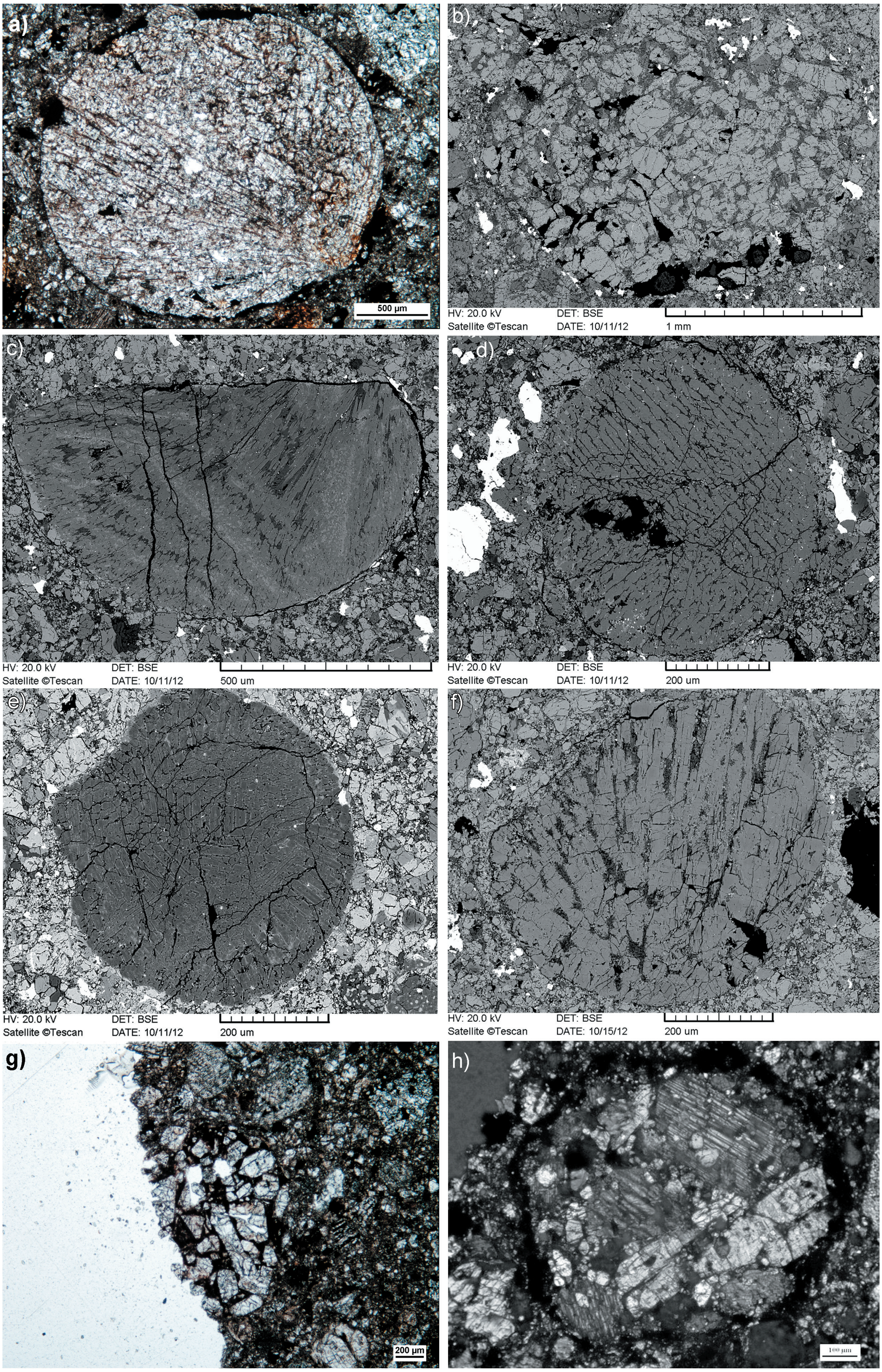

Fig. 4. Main chondrule types of Nyirábrany showing the following features: a) radial pyroxene chondrule (Ch1) (optical microscope image with 1 polar); b) porphyritic olivine chondrule (Ch2) (BSE image); c) fractured radial pyroxene chondrule fragment (Ch3) (BSE image); d) fractured barred pyroxene chondrule (Ch4) (BSE image); e) fractured barred pyroxene chondrule (Ch5) (BSE image); f) radial pyroxene chondrule fragment (BSE image) (Ch6); g) porphyritic olivine chondrule with euhedral crystals (Ch7) (optical microscope image with 1 polar); h) poikilitic pyroxene-olivine chondrule (Ch8) (optical microscope image with crossed polars)

Table 1. Main chondrule types and their characteristic features

	Size (μm)	Texture	Main mineral phase	Minor components	Outline	Comments
Ch1	2200	radial	pyroxene	opaque, cristobalite, glass	well-defined	-
Ch2	2000	porphyritic	olivine	plagioclase, pyroxene, glass, opaque	moderately delineated	-
Ch3	1000*	radial	pyroxene	olivine, opaque	well-defined	fractured and broken
Ch4	560	barred	pyroxene	opaque, glass	moderately delineated	fractured
Ch5	570	barred	pyroxene	opaque, glass	moderately delineated	fractured
Ch6	700*	radial	pyroxene	plagioclase	well-defined	broken
Ch7	1200*	porphyritic	olivine	glass	moderately delineated	broken
Ch8	1000	granular/poikilitic	pyroxene-olivine	opaque	moderately delineated	-

Ch – chondrule
* – estimated original size

Pyroxenes are the second most abundant mineral phases in the meteorite.

Opaque minerals in the meteorite include Fe-Ni metal, troilite and chromite. The amounts of Fe-Ni metal and troilite are ~1.32% and ~2.5%, respectively, which were calculated by analyzing the BSE images of the thin section using a software called “ImageJ”. Opaque constituents can be found inside chondrules, at the chondrules’ rims and in the matrix (Fig. 5).

The amount of plagioclase is ~2.5% (Sztrókay et al., 1977). It is present in the mesostasis (Fig. 6) of some of the chondrules, in the matrix and in the melt veins of some olivine crystals.

Traces of cristobalite and Cl-apatite were also identified in the meteorite. Cristobalite was identified first as an SiO_2 phase by the SEM-EDX analysis, the Raman microspectroscopic study showed, this phase is cristobalite, regarding to the crystal structure. Cristobalite can be found as rounded grains in pyroxene crystals in a radial chondrule (Ch1) (Fig. 3c). Observations and modelling show cristobalite could form by metamorphic processes (example: ALHA 76003, Olsen et al., 1981) and high temperature (example: Parnallee and Farmington meteorite, Bridges et al., 1994) from silica melt and by inversion from stishovite or coesite, always at high temperature (Heaney et al., 1994). Cl-apatite was identified by SEM-EDX analysis in the matrix (Fig. 3b).

Mineral compositions

In the following section we present the characteristics of minerals and their chemical composition. The main mineral phases of Nyirábrany are olivine, pyroxenes and opaque constituents. Minor amount of plagioclase, Cl-apatite, cristobalite and recrystallized glass were also identified.

Olivine

Olivine is the most abundant mineral phase of Nyirábrany, it has an amount of ~58.5% (Sztrókay et al., 1977). It is present in chondrules and in the matrix. Olivine grains are homogeneous, no zoning was observed. The crystals have sharp optical extinction. Irregular fractures (Fig. 5) were visible in the grains, but no planar deformation features or any hint of undulatory extinction could be identified, possibly due to the relatively low shock level.

The chemical composition of olivines was measured at 22 points of the thin section by SEM-EDX, out of which 16 were in the chondrules and 6 in the matrix. Olivine grains were selected randomly in the matrix. The chemical composition and Fa-content of olivines are summarized in Table 2. The matrix olivines are a little more fayalitic in composition, compared to the olivines in the chondrules. In chondrules, the average Fa-content is 25.99 mol% with a standard deviation of 1.15 mol%, while in the matrix these values are 27.44 and 0.18 mol% respectively. The measured Fa-contents are relatively close to each other but some difference is visible in the standard deviation. Smaller standard deviation for matrix olivines, compared to chondrule olivines is present and it fits well with the expectation that chondrules formed in different regions of the solar nebulae, while the components of the matrix were formed at the same location and under the same conditions. The calculated average Fa-content for Nyírábrány is 26.71 mol%, which falls between the range of L and LL type ordinary chondrites. For comparison, the mean Fa-content of olivines measured in the preliminary studies were 25 mol% (Sztrókay et al., 1977) and 27–28 mol% (Kubovics et al., 2004), which are typical of the L and LL group ordinary chondrites.

Table 2. The chemical composition of olivines in chondrules and matrix of Nyirábrany measured by SEM-EDX

	Oxide content (wt%)						Fa-content
	SiO_2	FeO	MnO	MgO	total		(mol%)
Ch2_ol1	37.68	23.89	0.46	37.68	99.71		26.24
Ch2_ol2	38.29	23.77	0.36	37.59	100.01		26.19
Ch2_ol3	37.97	24.25	0.42	37.35	99.99		26.70
Ch2_ol4	38.26	23.69	0.48	37.56	99.99		26.14
Ch2_ol5	38.10	23.93	0.39	37.58	100.00		26.32
Ch7_ol1	38.33	23.79	0.52	37.36	100.00		26.32
Ch7_ol2	38.19	24.20	0.46	37.15	100.00		26.77
Ch7_ol3	37.95	24.50	0.30	37.25	100.00		26.96
Ch7_ol4	38.38	23.82	0.33	37.47	100.00		26.29
Ch7_ol5	38.12	24.03	0.35	37.50	100.00		26.45
Ch8_ol1	38.54	21.48	0.46	39.52	100.00		23.37
Ch8_ol2	38.36	21.85	0.35	39.45	100.01		23.71
Ch8_ol3	38.67	22.06	0.32	38.95	100.00		24.11
Ch9_ol1	38.20	24.18	0.32	37.30	100.00		26.67
Ch10_ol1	38.01	24.18	0.58	37.23	100.00		26.71
Ch10_ol2	38.19	24.28	0.48	37.05	100.00		26.88
						Mean	25.99
						σ	1.15
M_ol1	37.94	24.71	0.46	36.89	100.00		27.32
M_ol2	38.10	24.74	0.27	36.88	99.99		27.35
M_ol3	37.95	24.74	0.41	36.90	100.00		27.34
M_ol4	37.79	24.92	0.56	36.72	99.99		27.58
M_ol5	37.78	25.08	0.51	36.63	100.00		27.75
M_ol6	37.94	24.67	0.54	36.86	100.01		27.30
						Mean	27.44
						σ	0.18
	Average olivine composition for Nyirábrany						26.71
						σ	0.80

Ch = chondrule
M = matrix
ol = olivine
σ = standard deviation

Pyroxene

Pyroxenes are the second most abundant mineral phases in the meteorite. According to the first study of Nyirábrany, the amount of orthopyroxene is ~25% (Sztrókay et al., 1977). The extinction features of pyroxene crystals were investigated under an optical microscope. In contradiction to earlier findings, we identified clinopyroxene in many chondrules, based on the inclined extinction of the crystals. Pyroxenes are presented as main mineral phases in a number of chondrules, or in the chondrules' mesostasis, but can be also found as single crystals in the matrix. Ca-poor clinopyroxenes (clinohypersthene, clinobronzite) make up the radially structured no. 1 chondrule, and the barred no. 4 chondrule. Normal zoning was observed at the pyroxenes of the no. 5 chondrule, while inverse zoning was present in some cases at the pyroxenes of the no. 1 chondrule. Ca-poor pyroxenes make up the radially textured no. 6 chondrule, and orthopyroxenes can be found in the poikilitic structured no. 8 chondrule.

Pyroxenes are present in a wide compositional variation in Nyirábrany. The chemical composition of pyroxenes was measured at 25 points of the thin

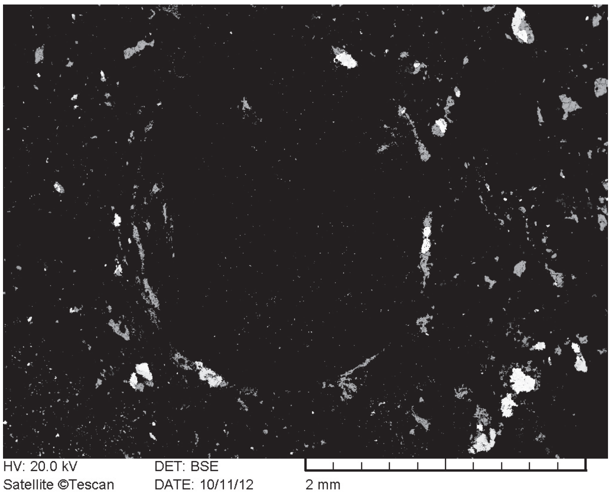

Fig. 5. FeNi-metal (white) and troilite (grey) at the rim and inside of Ch1. Opaque phases can be found in the matrix as well

section by SEM-EDX, out of which 19 were in the chondrules and 6 in the matrix. Pyroxene grains were selected randomly in the matrix. Although pyroxenes appear in diverse chemical compositions in the meteorite, most of them belong to the group of the low-Ca pyroxenes ($Wo_{1.61}$), both monoclinic and rhombic in structure, but most of them are clinopyroxenes, as mentioned above. The Fs-content of low-Ca pyroxenes are summarized in Table 3. There is also a small group of Ca-rich pyroxenes ($Wo_{36.03}$) and pyroxenes with intermediate composition ($Wo_{10.99}$). The average Fs-content of Ca-poor pyroxenes is 20.51 mol%, which is typical for L type chondrites. The average (and standard deviation values in parentheses) of enstatite and wollastonite in Nyirábrany are: 77.97 (11.65), 1.31 (1.14) mol%, respectively; while these values in the matrix are: 77.78 (9.95), 1.92 (0.74) mol%, re-

Table 3. The chemical composition of low-Ca pyroxenes in chondrules and matrix measured by SEM-EDX

	Oxide content (wt%)										En	Wo	Fs
	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	total		(mol%)		
Ch1_px1	54.23	n.d.	n.d.	0.25	20.45	0.72	23.87	0.49	100.01		66.11	0.98	32.91
Ch1_px2	55.68	n.d.	n.d.	0.16	14.48	0.47	28.62	0.60	100.01		76.44	1.15	22.41
Ch1_px3	51.81	n.d.	1.97	0.84	22.69	0.79	19.81	2.09	100.00		57.43	4.36	38.21
Ch1_px4	53.86	n.d.	n.d.	0.53	20.86	0.62	23.38	0.75	100.00		64,99	1.50	33.51
Ch1_px5	55.97	n.d.	n.d.	n.d.	14.26	0.41	29.07	0.28	99.99		77.51	0.54	21.95
Ch4_px1	54.15	n.d.	n.d.	0.50	14.82	0.45	29.50	0.57	99.99		76.66	1.06	22.27
Ch4_px2	55.05	n.d.	n.d.	0.16	14.96	0.29	28.99	0.56	100.01		76.39	1.06	22.55
Ch5_px1	58.89	n.d.	n.d.	0.54	2.73	0.25	37.31	0.28	100.00		95.21	0.51	4.27
Ch5_px2	59.03	n.d.	n.d.	0.47	2.28	n.d.	38.03	0.19	100.00		96.41	0.35	3.24
Ch6_px1	54.64	n.d.	2.56	0.54	11.26	0.27	29.29	1.45	100.01		79.58	2.83	17.58
Ch6_px2	55.74	n.d.	n.d.	0.16	14.59	0.36	28.82	0.33	100.00		76.96	0.63	22.41
Ch8_px1	58.80	n.d.	n.d.	0.31	3.09	0.25	37.38	0.17	100.00		94.93	0.31	4.76
Ch9_px1	55.46	0.23	n.d.	0.16	14.90	0.49	27.88	0.89	100.01		75.03	1.72	23.25
										Mean	77.97	1.31	20.72
										σ	11.65	1.14	11.09
M_px1	52.82	0.29	3.44	1.09	14.53	0.40	26.20	1.22	99.99		73.89	2.47	23.63
M_px2	59.52	n.d.	n.d.	n.d.	0.63	0.16	39.21	0.48	100.00		98.03	0.86	1.11
M_px3	55.44	n.d.	n.d.	n.d.	15.16	0.49	27.66	1.25	100.00		74.07	2.41	23.52
M_px4	55.35	n.d.	n.d.	0.25	15.72	0.50	27.62	0.56	100.00		74.39	1.08	24.52
M_px5	55.17	n.d.	n.d.	0.18	16.25	0.45	26.75	1.19	99.99		72.34	2.31	25.35
M_px6	55.47	n.d.	n.d.	n.d.	15.37	0.36	27.58	1.22	100.00		73.97	2.35	23.68
										Mean	77.78	1.92	20.30
										σ	9.95	0.74	9.43
Average low-Ca pyroxene composition for Nyirábrany											77.88	1.61	20.51
										σ	9.95	0.74	7.58

Ch = chondrule
M = matrix
px =pyroxene
σ = standard deviation
n.d. = not detected

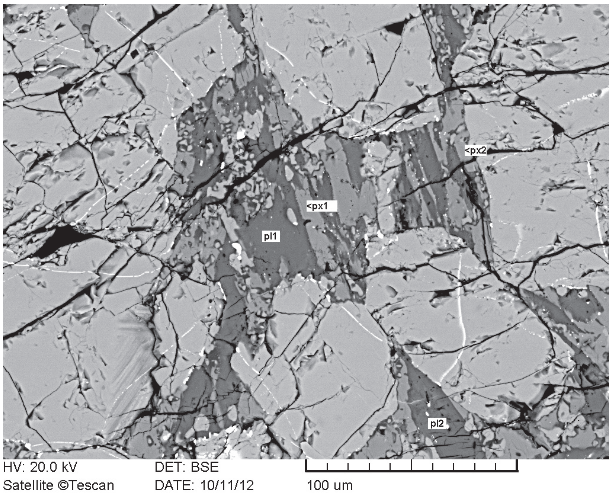

Fig. 6. Plagioclase (pl) and pyroxenes (px) in the mesostasis of a porphyritic olivine chondrule (Ch2)

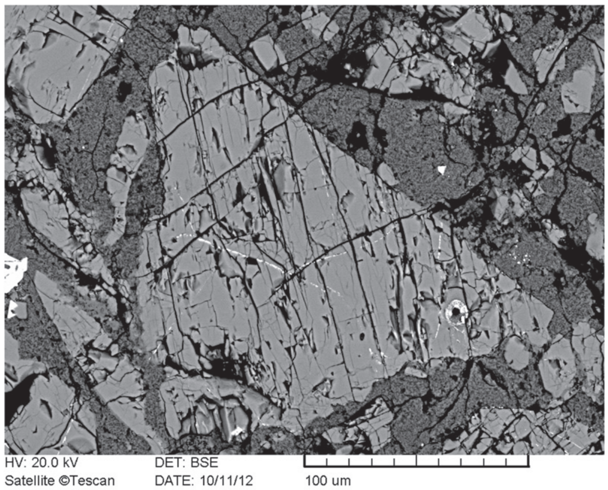

Fig. 7. BSE image of a planar fractured olivine crystal in a porphyritic olivine chondrule

spectively. To compare the diversity of pyroxenes regarding the chondrules and matrix values, the standard deviations for the above mentioned two pyroxenes are (chondrules/matrix): 11.65/9.95, 1.14/0.74. The same trend is visible and expected as in the case of olivine where the chondrules formed under more diverse conditions and larger deviations can be observed than in the matrix.

Plagioclase

The amount of plagioclase is ~2.5% (Sztrókay et al., 1977). It is present in the mesostasis of some of the chondrules, in the matrix and in the melt veins of some olivine crystals. Plagioclase crystals are present as xenomorph grains, mostly between other silicate crystals (Fig. 6), in the matrix or inside melt veins of olivine grains. Sztrókay et al. (1977) identified An-content between 14 and 23 mol%, while Kubovics et al. (2004) identified only sodic plagioclase and measured 11 mol% An-content of the plagioclase. In addition to the above mentioned compositions, we also identified mafic plagioclase in a small quantity with an An-content of 78.6 mol%, however this composition was measured only in the mesostasis of chondrule no. 2. During our SEM-EDX investigation, we also analyzed sodic plagioclase with average $An_{23.7}$ and $An_{10.4}$ in chondrule no. 6 and in another, diffuse chondrule (not mentioned in the text).

Opaque minerals

The main opaque minerals in the meteorite are Fe-Ni metal and troilite, beside these phases minor amount of chromite is also present. These opaque constituents were identified by opaque microscopy and SEM-EDX. The amount of Fe-Ni metal and troilite are ~1.32% and ~2.5%, respectively, which were calculated by analyzing the BSE images of the thin section using a software called "ImageJ". Opaque constituents can be found inside chondrules, at the chondrules' rims and in the matrix (Fig. 5). They appear as xenomorph crystals or crystal agglomerates, or as tiny round grains with a diameter of a few µm.

The Ni content of the metal grains was measured by SEM-EDX. Fe-Ni metal is arranged in an inhomogeneous pattern with highly variable Ni content. The Ni contents of kamacite varies between 3.19 and 5.10 wt% with an average of 4.4 wt% (σ = 0.77) and the Ni content of taenite varies between 27.36 and 54.28 wt% with an average of 40.67 wt% (σ = 10.75).

Shock stage and terrestrial weathering

We characterized the shock metamorphic stage of Nyirábrany using the 6 level scale for ordinary chondrites developed by Stöffler et al. (1991) and presented in Table 4. It was the first time that such an analysis was conducted on this meteorite.

Fragmented chondrules were identified in the meteorite, suggesting early shock events, but their analysis does not give exact information on the characteristics of these shocks. During the optical study, we searched for shock markers in olivine and plagioclase crystals, as referred previously by Stöffler et al. (1991). Due to its small quantity, plagioclase was identified only with SEM-EDX analysis, so we only used the optical and textural features of the olivine crystals for this purpose. Most olivine grains show sharp optical extinction in transmitted, plane polarized light, with irregular fractures in most of them. Planar fractures were visible only in very few cases (Fig. 7), and undulatory optical extinction could not be observed in

Table 4. Characteristics of shock stages by Stöffler et al. 1991

Shock stage	Olivine	Plagioclase	Local Scale effects	Pressure (GPa)
S1 (completely unshocked)	sharp extinction, regular fractures	sharp extinction, regular fractures	–	<4–5
S2 (very weakly shocked)	undulating extinction, irregular fractures	undulating extinction, irregular fractures	–	5–10
S3 (weakly shocked)	undulating extinction, planar and irregular fractures	undulating extinction	melt veins	15–20
S4 (moderately shocked)	weak mosaicism, planar deformational fractures	undulating extinction, planar deformation features, partially isotropic behaviour	melt pockets, melt veins crossing each other	30–35
S5 (strongly shocked)	strong mosaicism, planar deformational fractures	maskelynite	melt pockets, extended melt veins system	45–55
S6 (very strongly shocked)	solid phase recrystalization, melting, Ringwoodite	melting, glass formation	melt pockets, extended melt veins system	75–90

any crystals, including those with planar deformation fractures.

These findings suggest that the shock stage of Nyirábrany is around S2, but some of its signatures show that it could rarely reach the S3 level. Although the former presence of S3 or even higher shock level cannot be excluded (as post shock thermal event might overprint them), presenting observable signatures of only lower shock levels (Rubin, 2004), for the whole meteorite we could estimate only a very low degree of shock which is consistent with an S2 shock level in general.

There are chromite minerals in the meteorite that might be also produced by shock effects. Chromite is present as small opaque crystals in chondrules but also in the matrix, often in the form of anhedral clusters or as tiny isometric grains. Chromite could be produced by moderate level of thermal metamorphism (Rubin, 2003; Huss et al., 2006) and its presence also suggests shock event(s) (Lauretta et al., 2005) in the history of the meteorite.

Terrestrial alteration was determined by analyzing mineralogical changes and identification the oxidation of different mineral groups. For such an observation, a 7 level scale can be used, originally proposed by Wlotzka (1993).

Analyzing Nyirábrany with naked eye, reddish-brown oxidation products could already be observed at several locations around opaque phases. Using polarizing microscope, the reddish-brown weathering rind was even more evident around many minerals. While the weathering process influenced about 30 – 40% of the metal and sulfides in Nyirábrany, no similar features were present on the silicates. Based on this observation, we classified Nyirábrany in the W2 class of Wlotzka's scale.

Cristobalite and Cl-apatite

Cristobalite can be found as rounded grains in pyroxene crystals in a radial chondrule (Ch1) (Figure 3c). Observations and modelling show cristobalite could form by metamorphic processes (example: ALHA 76003, Olsen et al., 1981) and high temperature (example: Parnallee and Farmington meteorite, Bridges et al. 1994) from silica melt and by inversion from stishovite or coesite, always at high temperature (Heaney et al., 1994).

Cl-apatite was identified by SEM-EDX analysis in the matrix (Fig. 3b). The presence of cristobalite indicates that the cristobalite-bearing chondrule could have experienced a temperature as high as ~2000 K during its formation (Hezel et al., 2006). The presence of Cl-apatite could be the evidence that halogene-rich fluids affected the chondritic material inside the parent body (Jones et al., 2011).

CLASSIFICATION

Chondrite Group

To define the chondrite group of Nyirábrany, Fe-Ni metal content was calculated using BSE images, and the chemical composition of olivines and low-Ca pyroxenes were analyzed by SEM-EDX in the thin section. Unfortunately, detailed bulk chemistry analysis was not possible due to the limited access to the sample, but such measurement has been done before, details can be seen in the Table 5 and 6. According to Sztrókay et al. (1977) Nyirábrany was classified as an

Table 5. Bulk chemical composition of Nyirábrany by H. B. Wiik (Sztrókay et al., 1979)

Element/sulfide/ oxide	wt%	Element	atom%
Fe	2.34	Fe_{total}	20.38
Ni	1.04	Ni	1.04
Co	0.0085	Co	0.08
FeS	5.70	Si	18.76
SiO_2	40.09	Ti	0.09
TiO_2	0.15	Al	1.16
Al_2O_3	2.19	Cr	0.49
Cr_2O_3	0.72	Mn	0.22
FeO	18.55	Ca	1.25
MnO	0.28	Mg	15.45
MgO	25.63	K	0.12
CaO	1.77	Na	0.90
K_2O	0.09	S	2.08
Na_2O	1.21	P	0.10
P_2O_5	0.24	C	0.12
H_2O	0.10		
C	0.12		
Total	100.30		

Table 6. Trace element content of Nyirábrany (Sztrókay et al., 1979)

Trace element	ppm
Ag	25
B	16
Ba	1000
Cu	60
Sr	900
Zn	1000
Li	600
Pb	<10
V	<10

LL type ordinary chondrite. Our results showed that Nyirábrany can't be classified clearly as an LL chondrite, because some of its main chemical features are typical of L group chondrites (Fig. 8):

- On the basis of the 1.32% Fe-Ni metal content, Nyirábrany belongs to the LL group chondrites.
- The average Fa-content of olivines ($Fa_{26.71}$) falls between the ranges of the L and LL type ordinary chondrites (Fig. 8).
- The average Fs-content of low-Ca pyroxenes ($Fs_{20.51}$) falls within the value of the L chondrites, however the composition varies between 1 and 38 mol%.

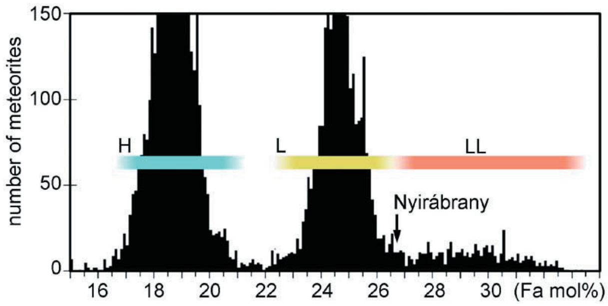

Fig. 8. Visualization of the average Fa-content of olivines (mol%) in Nyirábrany that puts this meteorite between the L and LL groups. The data for the ordinary chondrite groups (H, L, LL) is from Rubin (1990), the data for the histogram is selected from Met-Base (Koblitz, 2005 in Trigo-Rodríguez et al., 2009)

Petrologic type

On the basis of the van Schmus and Wood (1967) petrological type scheme, Nyirábrany was previously classified by Sztrókay et al. (1977) as petrologic type 5 ordinary chondrite. Our investigation showed that some of Nyirábrany's mineralogical and textural features indicate a smaller degree of thermal metamorphism:

- all the olivines and the majority of pyroxenes are homogeneous, the inhomogeneity of zoned pyroxene crystals is usually less than 5%, indicating petrologic type 4,
- monoclinic pyroxenes dominate in the sample, which is typical for petrologic type 4; the majority of chondrules contain only a small amount of recrystallized glass, which indicates petrologic type 4–5,
- some chondrules are well-defined, while others have diffuse outline, indicating petrologic type 5.
- the matrix is crystalline, it is composed of mineral grains with different size, which is typical for petrologic type 4-5.

Shock stage and weathering grade

The optical and textural features of olivines, like sharp optical extinction, irregular and a few planar fractures, but no observed undulatory extinction, suggest S2 shock stage for Nyirábrany, which is consistent with a very low degree of shock metamorphism.

The terrestrial alteration affected only the opaque phases of the meteorite. About 30–40% of the metal and sulfide minerals were oxidized, which is consistent with a W2 weathering grade.

COMPARISON TO OTHER CHONDRITES

To exploit the gained data and also provide suggestions for future research directions for this meteorite, we compared our results to other well studied LL5/6 meteorites below. Such comparison might give insight into the general properties of this meteorite group, and also to identify differences between them. The main goal would be to improve the knowledge of the parent bodies of these meteorites in the future.

In the case of Bensour LL6 chondrite, signatures of probably impact induced compaction and brecciation was observed (Gattacceca et al., 2003) with shock remnant magnetization. Bensour is possibly connected to Kilabo meteorite that also fell in Africa, this later one shows thick, black shock veins, and its shock stage was determined to be S3 (Gorin & Alexeev, 2006). The Ni and Co concentration both in Bensour and Kilabo was high together with relatively small bulk metal content (The Ni content of Nyírábrany can be seen in Tab. 5). Bensour and Kilabo meteorites are probably among the most oxidized ones (Cole et al., 2007). Both meteorites show the same fayalite content ($Fa_{30.7}$ for Bensour, and $Fa_{30.9}$ for Kilabo), and they show a microbrecciated structure with very few chondrules, though relict chondrules could be identified. These two meteorites might come from the same parent body, although the different cosmic exposure ages suggest complex history. A possible source candidate for them is the 3628 Boznemcova asteroid (Ustinova et al., 2008). The Ensisheim meteorite (fell in 1492), an LL6 chondrite, is also important target for comparison.

The average chondrule abundance in both L and LL chondrites varies between 60 and 80%. In Nyirábrany, because of the 4-5 petrologic type, the identification of chondrules was not evident in every cases, but their total amount was around 65%, and their size ranged between ~560 μm and ~2200 μm in diameter. The metal abundance for L chondrites is between 4-9%, while in LL chondrites around 0.3-3% (Weisberg et al., 2005), in Nyírábrany it was around 1.32%. The fayalite content in Nyírábrany is between the characteristic L and LL values, suggesting intermediate situation among these two groups.

Mineral composition suggests that LL chondrites especially thermally metamorphosed LL5 and LL6 like Tuxuac (Matsumoto et al., 2012), where the ratio of poly/mono-mineralic particles and the characteristic grain size (Tsuchiyama et al., 2012) resemble to the small samples acquired by Hayabuse mission from the surface of asteroid Itokawa (Matsumoto et al., 2012; Nagano et al., 2012; Yakame et al., 2012). This observation enhances the importance of LL chondrites and other objects that are close to them in properties, including Nyirábrany, as they could provide insight into the geological evolution of Itokawa-like asteroids. Such comparison is important as LL chondrites present a wide range of thermal metamorphism, also presenting decreasing mineral variability from LL4 to LL7 (Reid, 1997).

CONCLUSION

Our new petrological, mineralogical and chemical results show that the Nyirábrany meteorite can be classified as an L/LL type ordinary chondrite, which has undergone a moderate to high degree of thermal metamorphism and has equilibrated to petrologic type 4-5. Moreover, it has experienced a very low degree of shock metamorphism and weak terrestrial alteration. In summary, Nyirábrany can be designated as an L/LL4-5, S2, W2 ordinary chondrite. In the future, we are planning to investigate more the shock stage of the meteorite using Raman microspectroscopy that could support to draw conclusions on the formation and early history of this meteorite's parent body.

Comparing Nyírábrany to other meteorites, Nyírábrany is a well metamorphosed object representing a section of its parent body that differentiated substantially and lost substantial part of its metal content. However, impact processes did not erase the much earlier formed features. It is known that peak temperature during metamorphism increases from petrologic type 4 to 5 to 6, while the cooling times are poorly known (Dodd, 1981). Nyírábrany might provide useful information on the ancient process, above all impact and thermal driven alteration in parent bodies that is connected to the geological evolution of asteroids. The importance of Nyirábrany as being an intermediate type between L and LL groups, just like Bjurböle, Cynthiana, Knyahinya, Qidong, Xi Ujimgin meteorites (Weisberg et al., 2005) is increased after the Itokawa asteroid sampling event by Hayabusa spacecraft, as some mineral features in the LL group resemble to those found in that asteroid samples.

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