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NORTHWEST AFRICA 7915: A NEW APPROVED LL5 CHONDRITE FROM MOROCCO

Maciej BRAWATA[1], Ryszard KRYZA[1], Tomasz JAKUBOWSKI[2], Tadeusz Andrzej PRZYLIBSKI[3], Jacek ĆWIĄKALSKI[1], Katarzyna ŁUSZCZEK[3]

[1] University of Wrocław, Institute of Geological Sciences, ul. Cybulskiego 30, 50-205 Wrocław, Poland
[2] ul. Drzewieckiego 44/7, 54-129 Wrocław, Poland
[3] Wrocław University of Technology, Faculty of Geoengineering, Mining and Geology, Division of Geology and Mineral Waters, Wybrzeże S. Wyspiańskiego 27, 50-370 Wrocław, Poland

Abstract: A 415 g single meteorite was purchased in 2010 by T. Jakubowski from a dealer in Morocco. The meteorite was isometric in shape, ca. 8 cm in size, with distinct regmaglypts on the original ablated surface, and covered mostly in primary crust with one broken surface. The weight of the sample studied was 69 g. The meteorite is composed of several types of chondrules including porphyritic-Ol-Px, barred-Ol, radial-Px, granular and cryptocrystalline with distinct and diffused (not sharp) boundaries, and opaque grains and aggregates, enclosed in a very fine-grained matrix. The average compositions of minerals are: *olivine* (both in chondrules and matrix) – $Fo_{70.4}Fa_{29.1}Te_{0.5}$, *pyroxenes,* represented by Mg-Fe (Ca-poor) orthopyroxene (and minor clinopyroxene?) – $En_{73.9}Fs_{24.1}Wo_{2.0}$, *feldspars* (small in the matrix and in barred chondrules), with $An_{12\text{-}37}$, and $Or_{\sim 3\text{-}4}$, *taenite* – Fe 70.80, Ni 25.50 and Co 1.67 wt. %, *troilite* – $Fe_{0.98}S_{1.00}$, *chromite* $(Fe^{2+}{}_{0.96}Mg_{0.12}Mn_{0.01}Zn_{0.01})$ $(Cr_{1.52}Al_{0.23}Fe^{3+}{}_{0.02}Ti_{0.10}Si_{0.02})O_4$; altered accessory minerals including *apatite* and *iron-rich secondary phases* have also been identified and analyzed.

The meteorite is of petrologic type 5, as evidenced by the observed recrystallization of the matrix, relatively good preservation of the chondrule structures, homogeneous composition of olivine and pyroxene, and the presence of only secondary small feldspar grains. The shock stage, S2, is based on the presence of undulatory extinction and irregular fractures in olivine crystals. The weathering grade, W3, is confirmed by the observation that kamacite is totally altered into secondary iron phases, whereas Ni-rich taenite, and troilite are only partly weathered.

The specimen shows many bulk- and mineral-chemical parameters corresponding, mostly, to the LL chondrite group (e.g., Fe/SiO_2 0.49, SiO_2/MgO 1.62, Fa in olivine 29.05). However, concentrations of several other elements, including REE, are not fully consistent with the average values for the LL ordinary chondrites. Apparently, the parent body of the studied NWA 7915 meteorite was depleted in Dy, Tm, and Yb, compared to typical LL-type ordinary chondrite parent bodies. Also, relatively high concentrations of other elements, including Ba and Sr, have been measured, which may result from terrestrial weathering in hot desert conditions.

The meteorite has been classified as LL5 ordinary chondrite, S2, W3, and registered in the Meteoritical Society database as NWA 7915. The type specimen is deposited in the Mineralogical Museum of the University of Wrocław.

Keywords: chondrite, NWA 7915, Morocco, chondrule, chondrite chemistry, chondrite weathering

INTRODUCTION

This study aimed at mineralogical, petrographic and geochemical characterization of a new ordinary chondrite from Morocco which was formally registered in the Meteoritical Society database. The results of the study extend our knowledge on the mineral chemistry and bulk chemical composition of ordinary

Corresponding author: Tadeusz A. PRZYLIBSKI, Tadeusz.Przylibski@pwr.edu.pl

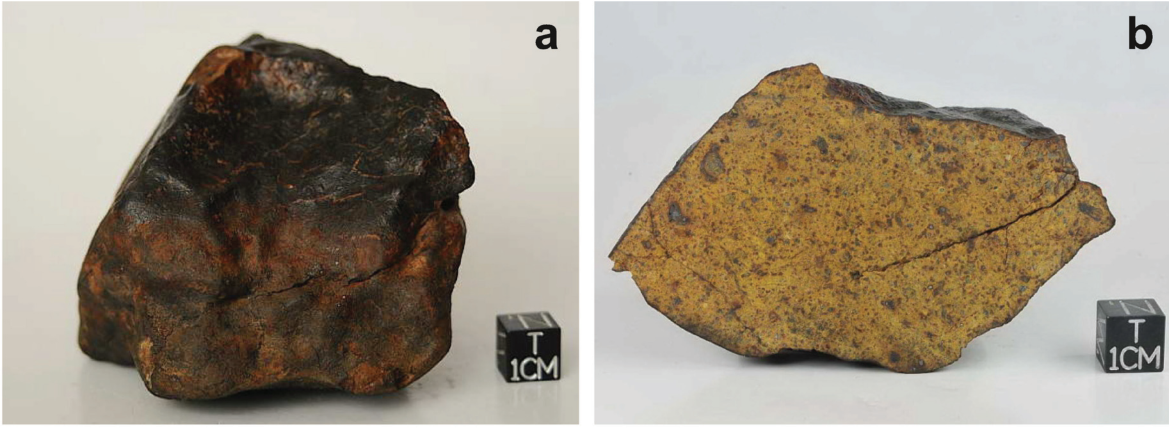

Fig. 1. Original (415 g) specimen of NWA 7915 meteorite (a), and polished cut face of this chondrite (b)

chondrites and their parent bodies that formed in the young Solar System. Though this subject has been studied intensively by many authors (i.e. Grossman & Larimer, 1974; Wanke & Dreibus, 1988; Kallemeyn et al., 1989; Brearley & Jones, 1998; Davis & Richter, 2004; Yin, 2005; Ebel, 2006; Alexander et al., 2008), our knowledge remains incomplete.

The studied meteorite (Fig. 1) comes from the collection of Tomasz Jakubowski who purchased it in Morocco in 2010. The geographic coordinates of the find and the name of the finder are unknown. The type specimen is deposited in the collection of the Mineralogical Museum of the University of Wrocław.

The studied meteorite, now registered as NWA 7915, is a yellowish-brown colored stone, broadly isometric in shape, ca. 8 cm in size (Fig. 1a). Its original surface is ablated, with distinct regmaglipts. It is moderately magnetic. The total weight (TKW) was 415 g, the weight of the sample studied was 69 g (Fig. 1b).

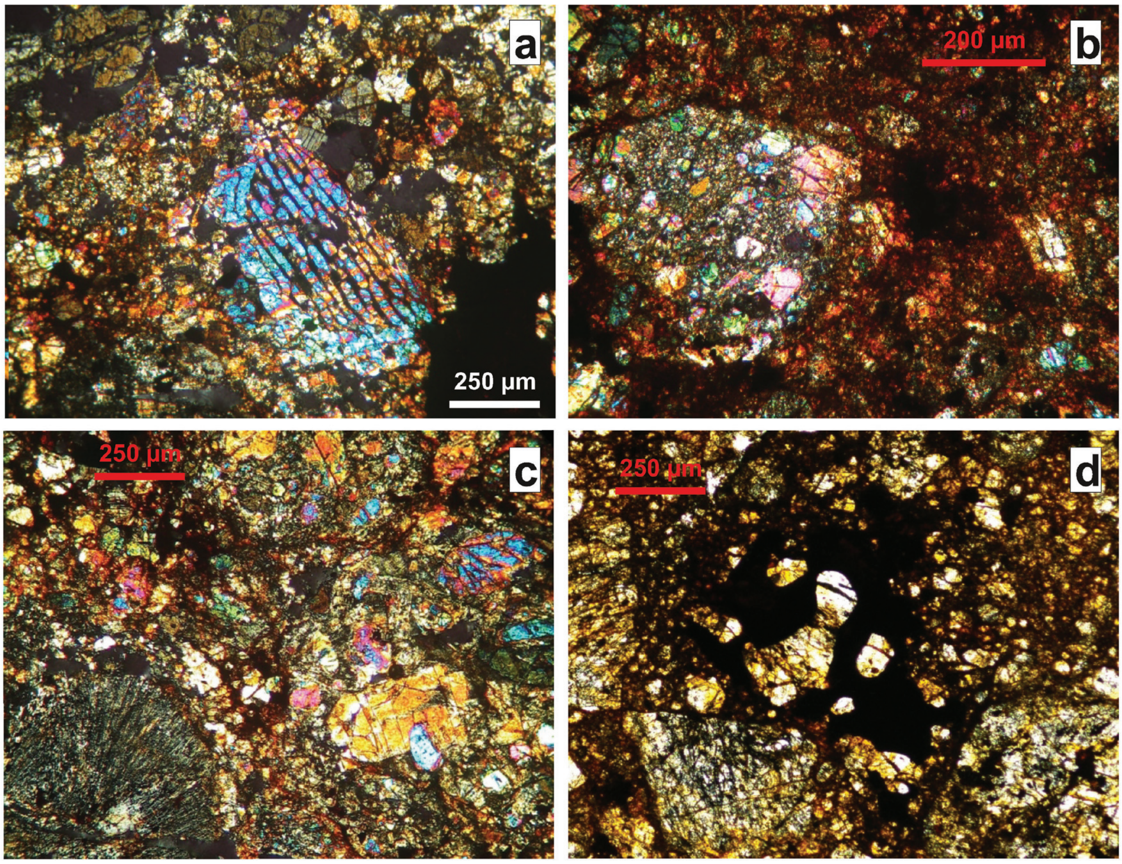

Fig. 2. NWA 7915: textures and composition: (a) – barred-olivine chondrule and opaque in a fine-grained matrix; (b) – porphyritic chondrule in a couloured matrix; (c) – radial-pyroxene chondrule in a grainy matrix; (d) – opaque aggregate enclosing olivine crystals; (a–c – crossed nicols, d – one nicol)

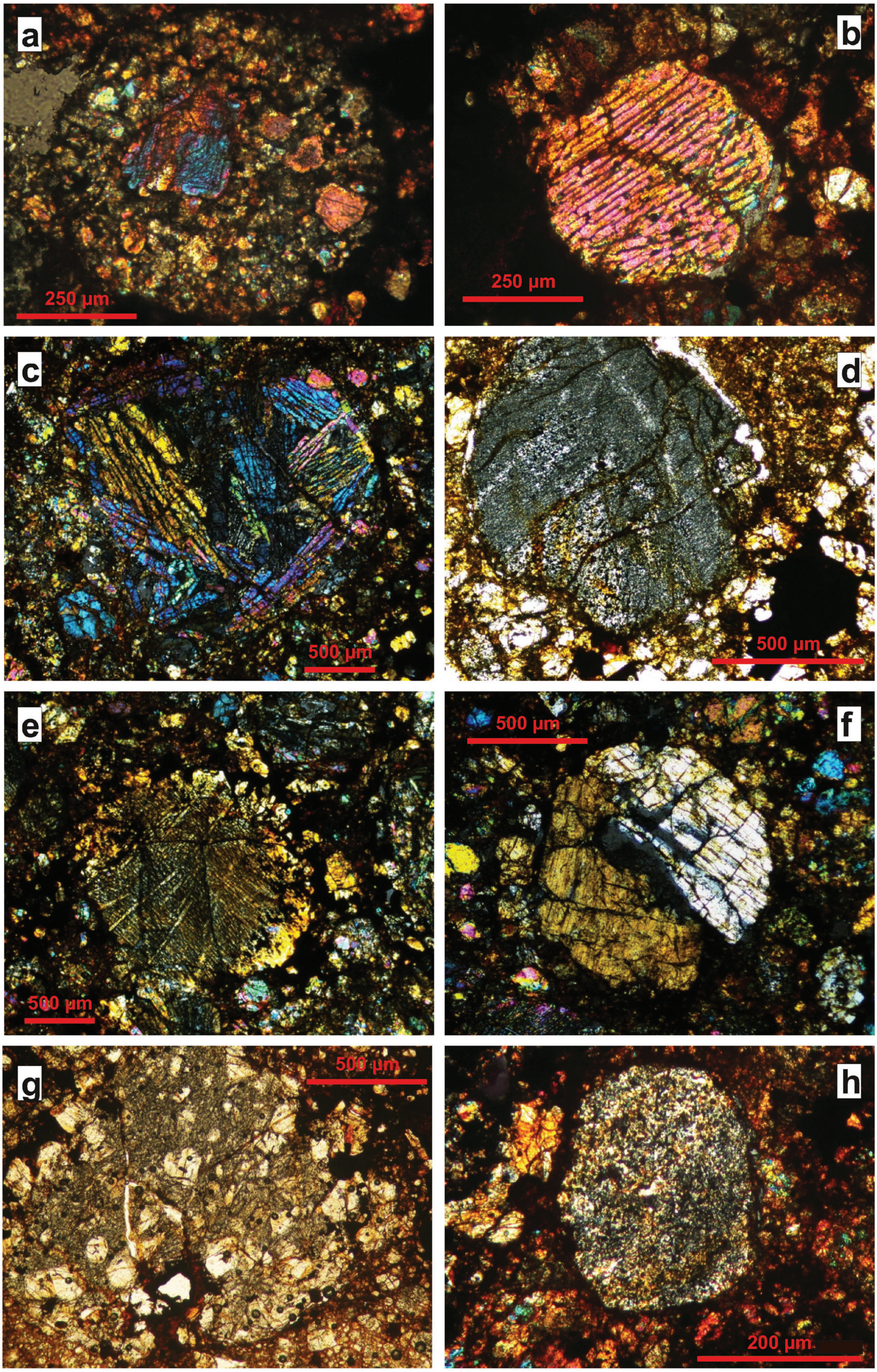

Fig. 3. Various types of chondrules in NWA 7915: (a) – porphyritic-olivine; (b, c) – barred-olivine; (d, e) – radial-pyroxene; (f) – orthopyroxene; (g) – porphyritic-cryptocrystalline; (h) – cryptocrystalline (g – one nicol, all others – crossed nicols)

METHODS

Conventional mineralogical and petrographic investigations were made in three polished thin sections, using the polarizing microscope, in transmitted and reflected light. Chemical compositions of minerals were determined with the electron microprobe Cambridge M9 at the Department of Mineralogy and Petrology, University of Wrocław (instrument donated by the Free University of Amsterdam). Both EDS and WDS techniques were used. WDS quantitative analyses were performed at the following analytical conditions: 15 kV accelerating voltage, 50 nA beam current, 20 s counting time, a set of natural mineral and synthetic standards, and ZAF correction.

Part of the sample studied, 11 g in weight, was ground in an agate mortar and used for bulk chemical analysis of major and trace elements. The analyses were performed in ACME Analytical Laboratories Ltd, Canada, by means of ICP-MS and XRF analysis. ICP-MS was used to determine the content of the major and trace elements (including REE). XRF analysis was used to measure the nickel content which was too high to be accurately determined by the ICP-MS. The content of volatile elements (C and S) was measured by means of the Leco method (see ACME web site: http://acmelab.com/).

RESULTS

Petrography

On the cut surface of the meteorite (Fig. 1b), chondrules and shiny metal grains are distinguishable within an orange-gray, fine-grained matrix. The grains are uneven with serial and directionless texture (Fig. 2). The matrix grains vary from sub-microscopic to several tens of μm in size, but individual grains attain ca. 0.5 mm in size. Olivine dominates over pyroxene, both in the chondrules and matrix. Minor components include metal phases, largely replaced by secondary iron oxides/hydroxides, occasional troilite and chromite, and partly altered apatite. The rock is rather

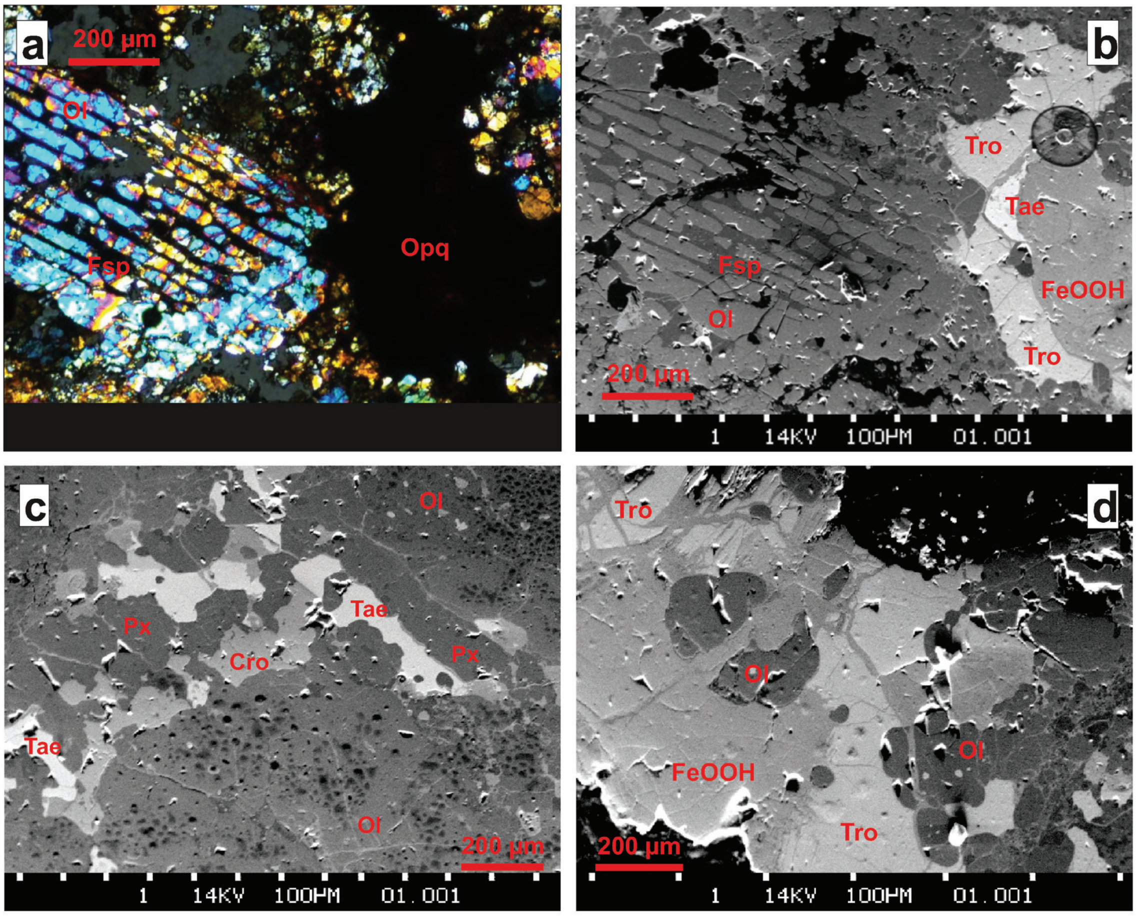

Fig. 4. (a) – barred-olivine chondrule with feldspar intercalations (crossed nicols); (b) – BSE image of the same field; (c, d) – BSE images showing opaques among silicates; Cro – chromite, FeOOH – iron oxide/hydroxide, Fsp – feldspar, Ol – olivine, Opq – opaques, Px – pyroxene, Tae – taenite, Tro – troilite

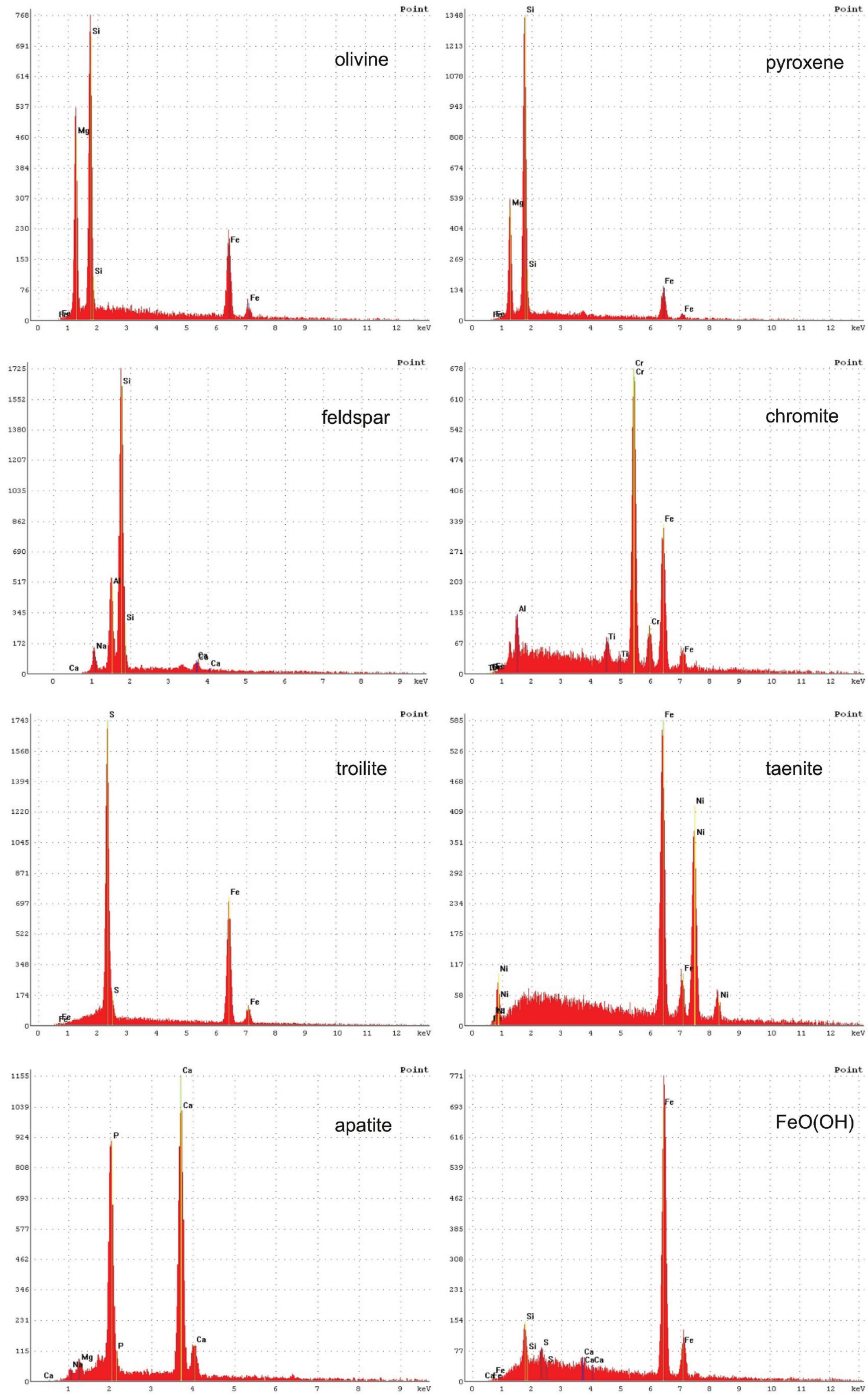

Fig. 5. EDS spectra of minerals of NWA 7915

massive (compact) and pores observed in thin sections are most likely the result of grinding and polishing of the brittle material.

The relatively well-defined component of the meteorite are chondrules (Fig. 3) composed mainly of olivine and pyroxene, and displaying several types of textures (c.f. Lauretta et al., 2006): POP – porphyric-olivine-pyroxene, BO – barred-olivine, RP – radial-pyroxene, G – granular, and CC – cryptocrystalline. All types of chondrules are found in the studied meteorite (Table 1). Their size varies between 0.2 and 4 mm. Some of them have regular spherical shape, but most display various degree of deformation: brecciation, flattening or veining. Many chondrules have distinct outlines but quite often, in particular in porphyritic chondrules, their borders against the matrix are not sharp (Fig. 3g).

The common porphyritic chondrules (Fig. 3a) are composed of relatively large olivine and, less frequently, pyroxene crystals dispersed in a microscopically translucent mesostasis. Olivine is clearly dominant.

The barred-olivine chondrules (Fig. 3b, c), 0.4–4.0 mm in size and having well defined borders, are formed of olivine crystals, all showing the same crystallographic orientation (single skeletal crystals) and sparse mesostasis. In BSE images, the olivine crystals appear to be separated by feldspar mesostasis, which was confirmed by EDS and WDS analyses (c.f. compositional EDS profiles in Figs. 6 and 7).

The radial-pyroxene chondrules (Fig. 3d, e), ranging between 0.5 and 2 mm, are formed of thin acicular pyroxene crystals most commonly arranged into several distinct fans within one chondrule. The observed low birefringence suggests that orthopyroxene is more common than clinopyroxene in these chondrules. Locally, thin olivine lamellae and opaque veinlets are observed. Rather scarce chondrules are formed of typically two or three large orthopyroxene crystals (Fig. 3f).

Table 1. Size of chondrule types in NWA 7915

Chondrule type	size (mm)		
	min	max	average
Porphyritic Ol-Px	0.5	1.2	0.9
Porphyritic Ol	0.4	4.0	1.1
Porphyritic Px	0.4	2.0	0.9
Radial Px	0.5	2.0	1.2
Barred Ol	0.3	4.0	1.1
Granular	0.5	1.2	0.6
Cryptocrystalline	0.2	1.5	0.8
All	0.2	4.0	0.9

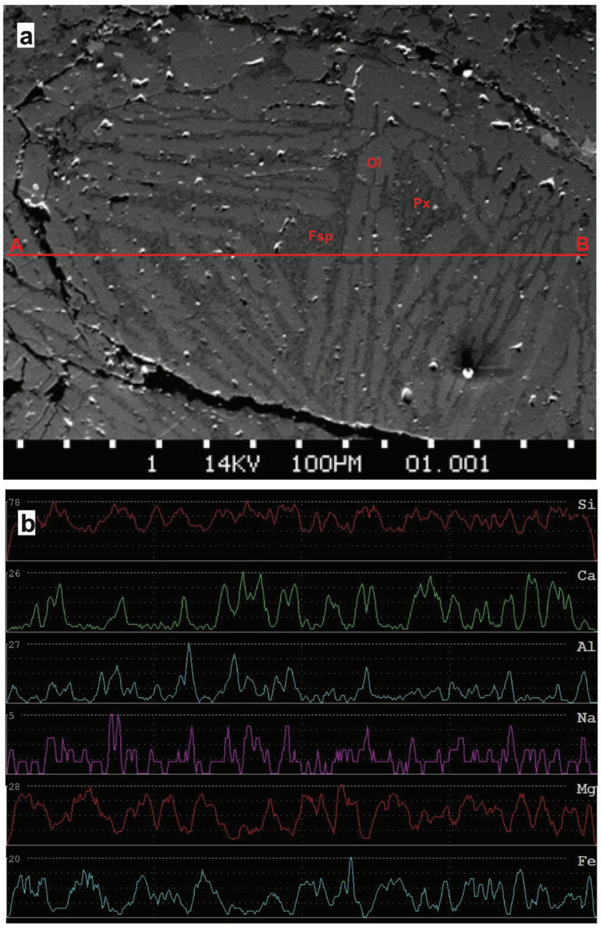

Fig. 6. (a) – BSE image of barred-olivine chondrule with mesostasis composed of feldspar and pyroxene; (b) – EDS compositional profiles. Notice coinciding peaks of Na, Ca and Al corresponding to feldspar intercalations in the chondrule

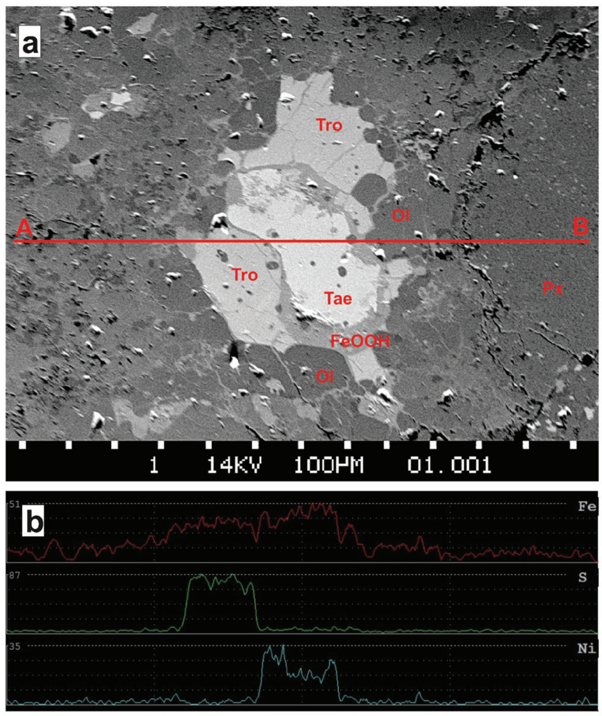

Fig. 7. (a) – BSE image of an opaque cluster composed of taenite (Tae) (partly replaced by secondary FeOOH) and troilite (Tro); Ol – olivine, Px – pyroxene; (b) – EDS compositional profile A–B; notice variable Ni content in taenite

Table 2a. Average chemical analyses of silicates and chromite in NWA 7915 (n – number of analyses, nd – not determined, sd – standard deviation, FeO* – all Fe as Fe^{2+})

olivine (n6)		sd	pyroxene (n3)		sd	feldspar (n2)		sd	chromite (n4)		sd
SiO_2	36.940	0.998	SiO_2	54.714	0.858	SiO_2	62.062	2.409	SiO_2	0.426	0.197
TiO_2	0.039	0.029	TiO_2	0.158	0.003	TiO_2	0.239	0.061	TiO_2	3.631	0.160
Al_2O_3	0.298	0.266	Al_2O_3	0.979	0.718	Al_2O_3	18.387	2.710	Al_2O_3	5.446	0.119
Cr_2O_3	0.066	0.094	Cr_2O_3	0.236	0.190	Cr_2O_3	nd		Cr_2O_3	52.499	1.059
Fe_2O_3			Fe_2O_3	0.476	0.578	Fe_2O_3	1.968	0.369	Fe_2O_3	0.694	0.636
FeO*	26.067	1.235	FeO	14.670	0.329	FeO			FeO	31.452	0.413
MnO	0.456	0.035	MnO	0.444	0.030	MnO	0.008	0.011	MnO	0.467	0.052
NiO	0.158	0.170	NiO	0.037	0.020	NiO	nd		NiO	0.209	0.144
MgO	35.460	0.708	MgO	26.776	1.097	MgO	2.254	2.355	MgO	2.249	0.169
CaO	0.044	0.028	CaO	0.996	0.148	CaO	5.424	3.969	CaO	0.032	0.008
Na_2O	0.097	0.075	Na_2O	0.267	0.361	Na_2O	8.566	1.816	Na_2O	nd	
K_2O	0.001	0.002	K_2O	0.016	0.026	K_2O	0.636	0.158	K_2O	nd	
CoO	0.071	0.045	CoO	nd		CoO	nd		CoO	nd	
ZnO	0.024	0.040							ZnO	0.385	0.096
Total	99.719	0.706	Total	99.770	0.756	Total	99.543	0.013	Total	97.490	0.512
Si^{4+}	0.985	0.015	Si^{4+}	1.976	0.015	Si^{4+}	2.803	0.062	Si^{4+}	0.016	0.007
Ti^{4+}	0.001	0.001	Al^{4+}	0.022	0.017	Ti^{4+}	0.008	0.002	Ti^{4+}	0.100	0.004
Al^{3+}	0.009	0.008	T site	1.999	0.002	Al^{3+}	0.978	0.128	Al^{3+}	0.234	0.005
Fe^{2+}	0.582	0.035	Al^{+6}	0.019	0.031	Fe^{3+}	0.067	0.014	Cr^{3+}	1.516	0.024
Mn^{2+}	0.010	0.001	Ti^{4+}	0.004	0.000	Mn^{2+}	0.000	0.000	Fe^{3+}	0.019	0.018
Mg^{2+}	1.410	0.012	Cr^{3+}	0.007	0.005	Mg^{2+}	0.153	0.161	Fe^{2+}	0.961	0.013
Ca^{2+}	0.001	0.001	Fe^{3+}	0.013	0.016	Ca^{2+}	0.264	0.197	Mn^{2+}	0.014	0.002
Na^{+}	0.005	0.004	Fe^{2+}	0.443	0.007	Na^{+}	0.749	0.146	Mg^{2+}	0.122	0.009
K^{+}	0.000	0.000	Mn^{2+}	0.014	0.001	K^{+}	0.037	0.010	Ca^{2+}	0.001	0.000
Co^{2+}	0.002	0.001	Ni^{2+}	0.001	0.001	Total	5.059	0.048	Ni^{2+}	0.006	0.004
Zn^{2+}	0.000	0.001	Mg^{2+}	1.442	0.056	O^{2-}	8.000	0.000	Zn^{2+}	0.010	0.003
Ni^{2+}	0.003	0.004	Ca^{2+}	0.039	0.006				Total	3.000	0.000
Cr^{3+}	0.001	0.002	Na^{+}	0.019	0.025	An	24.668	17.313	O^{2-}	4.000	0.000
Total	3.011	0.016	K^{+}	0.001	0.001	Ab	71.855	18.041			
O^{2-}	4.000	0.000	M1,M2	2.001	0.002	Or	3.477	0.727			
			O^{2-}	6.002	0.003						
Fo	70.440	1.311									
Fa	29.046	1.294	Wo	1.986	0.367						
Te	0.514	0.038	En	73.927	0.515						
			Fs	24.088	0.311						

Table 2b. Average chemical analyses of troilite and taenite in NWA 7915 (n – number of analyses, sd – standard deviation)

	troilite (n6)	sd	taenite (n6)	sd
Na	0.09	0.05	0.06	0.05
Mg	0.05	0.01	0.16	0.25
Al	0.03	0.02	0.05	0.06
Si	0.09	0.06	0.25	0.37
S	34.39	0.73	0.02	0.02
Ti	0.01	0.01	0.01	0.01
Cr	0.00	0.01	0.00	0.00
Mn	0.01	0.01	0.00	0.00
Fe	63.46	0.54	70.88	2.62
Co	0.16	0.05	1.67	0.27
Ni	0.18	0.13	25.50	1.48
Zn	0.04	0.06	0.03	0.06
Total	98.52	0.91	98.65	0.99

A rarer type of porphyritic chondrules, granular/cryptocrystalline chondrules (Fig. 3g), are composed mainly of very fine-grained olivine in a cryptocrystalline mesostasis. The composition of the cryptocrystalline aggregates (Fig. 3h) is difficult to determine under the microscope.

The opaque grains in the meteorite matrix are often oval and rounded in shape and variable in size, from microcrystalline to larger ones, clustering in places into aggregates up to 4 mm in diameter. Locally, they concentrate around chondrules or form small inclusions inside them. Ni-rich taenite is associated with rather fresh troilite and secondary iron oxide/hydroxide phases, the latter apparently formed mostly after totally altered kamacite (Figs. 4 and 7). Sparse chromite appears to cluster with taenite (Fig. 4).

The matrix is totally recrystallized into a very fine-grained aggregate and no traces of glass have been detected. The yellowish-brown coloration comes from secondary iron-rich compounds likely due to terrestrial weathering.

Mineralogy and mineral chemistry

EDS spectra of the most common mineral components are shown in Fig. 5. Average chemical compositions are given in Table 2.

Olivine, both in chondrules and matrix, has a rather constant composition, with the mean value $Fo_{70.4}Fa_{29.1}Te_{0.5}$, and with traces of Ni (0.02–0.42 wt. %).

Pyroxenes are represented by Mg-Fe (Ca-poor) compositions. In larger grains, e.g. in some chondrules, they show orthogonal extinction and low birefringence typical of orthopyroxene, however, it is usually difficult to distinguish between ortho- and clinopyroxene (and olivine) in the fine-grained matrix. Analyses recalculated to cation proportions and the basic end-members give an average of $En_{73.9}Fs_{24.1}Wo_{2.0}$, with only very slight variation (below 0.5 mol. %).

Feldspars form small (10–50 µm) crystals in the matrix; they are also detected in BSE images and EMPA analyses from olivine-feldspar intergrowths in barred olivine chondrules. In Figures 4 and 6, they are visible as thin stripes between barred-shape olivine crystals. Their composition is reflected in the EDS element-distribution profiles, in sections with high concentrations of Na, Ca and Al. Quantitative WDS analyses show relatively high, though variable An contents, between 12 and 37 mol. %, and rather low Or of ca. 3–4 mol. %. The relatively high amounts of Fe and Mn (Table 2) are caused by the small size of the analyzed grains and resulted contamination from neighbouring olivine.

Taenite forms individual grains in the matrix, locally clustered in aggregates, with associated chromite and troilite (Fig. 4). It shows moderate symptoms of replacement by secondary iron phases. The taenite composition varies insignificantly, around the average concentration of Fe 70.80, Ni 25.50 and Co 1.67 wt. %, and with detectable traces of Si and Mg (0.25 and 0.16 wt. %, respectively).

Troilite is moderately abundant, often associated with taenite and secondary iron phases (Fig. 7). The sulphide shows nearly stoichiometric ratios: $Fe_{0.98}S_{1.00}$, with trace admixtures of Ni (up to 0.34 wt. %) and Co (up to 0.24 wt. %).

Chromite is also not very abundant opaque phase, often associated with the Fe-Ni metal (Fig. 4). The chromite composition is very constant, though not ideally stoichiometric, with an average formula: $(Fe^{2+}_{0.96}Mg_{0.12}Mn_{0.01}Zn_{0.01})(Cr_{1.52}Al_{0.23}Fe^{3+}_{0.02}Ti_{0.10}Si_{0.02})O_4$. Ni content is around 0.006±0.004 wt. %.

Apatite, as a rare accessory mineral, is partly altered, but its approximate composition was confirmed by WDS analysis (F and Cl were not analyzed).

Fe secondary phases, replacing the primary Fe-bearing components including apparently common kamacite (?), are fairly abundant; they form rather compact, pseudomorphic aggregates but also penetrate interstitial spaces. Their measured compositions vary considerably, within the range: Fe_2O_3 68.50–77.90 and NiO 3.21–13.00 wt. %, and with variable admixtures of SiO_2, Al_2O_3, and MgO, and minor CoO, CaO and Na_2O.

Bulk chemistry

The consolidated results of NWA 7915 bulk chemical composition analysis are presented in Table 3 and Figs. 8–10. Out of 59 analyzed elements, the content of Be, Hf, Nb, Ta, Th, Cd, Sb, Bi, Ag, and Tl were below the analytical method's detection limits. The chemical data are discussed below.

DISCUSSION

Chondrite group

The above presented results of petrologic investigations, comprising determination of the texture, mineralogy and mineral composition, as well as the bulk chemical composition, provide the basic data for the classification of the meteorite. Further parameters, important for classification of a chondrite, comprise the petrologic type (thermal metamorphic grade), shock stage (S) and weathering grade (W).

The NWA 7915 meteorite has a range of petrologic features typical of the ordinary chondrites: it is composed of various types of olivine and pyroxene chondrules enclosed in a fine-crystalline matrix, and contains opaque phases represented by Fe-Ni metal and troilite.

The bulk chemical composition and the chemical composition of mineral phases are used to define the classification group within the class of ordinary chondrites. Based on the classical systematics of the ordinary chondrites by Van Schmuss & Wood (1967) and Weisberg et al. (2006), the studied NWA 7915 meteorite shows parameters corresponding to the LL group (values in parentheses): Fe/SiO_2 0.49 (0.49±0.03), SiO_2/MgO 1.62 (1.58±0.05), Fa in olivine 29.05 (29±2). Referring to the bulk element ratios reported by Wasson & Kallemeyn (1988), NWA 7915 displays similar values of Al/Si (0.77) and Mg/Si (0.86) to groups L and LL. However, the Ni/Si and Zn/Si ratios in the studied meteorite are considerably different from those in most of the groups of the ordinary chondrites. In the classification of the ordinary

Table 3. Bulk chemical composition of NWA 7915 ordinary chondrite (MDL – Minimum Detection Limit)

element		abundance	MDL	element		abundance	MDL
Si	weight %	18.59	0.01	Ni	ppm	7 417.3	0.1
Al		1.17	0.01	Ba		15	1
Fe		19.57	0.04	Be		<1	1
Mg		14.81	0.01	Co		365.1	0.2
Ca		1.26	0.01	Cs		0.1	0.1
Na		0.68	0.01	Ga		4.4	0.5
K		0.10	0.01	Hf		<0.1	0.1
Ti		0.07	0.01	Nb		<0.1	0.1
P		0.087	0.01	Rb		2.7	0.1
Mn		0.26	0.01	Sn		1	1
Cr		0.361	0.002	Sr		30.3	0.5
LOI		0.2	0.1	Ta		<0.1	0.1
Sum		99.51	0.01	Th		<0.2	0.2
C_{TOT}		0.07	0.02	U		0.1	0.1
S_{TOT}		0.39	0.02	V		54	8

element		abundance	MDL	element		abundance	MDL
W	ppm	9.7	0.5	Sc	ppm	8	1
Mo		0.6	0.1	Y		1.9	0.1
Cu		85.3	0.1	La		0.7	0.1
Pb		1.2	0.1	Ce		1.2	0.1
Zn		21	1	Pr		0.19	0.02
As		1	0.5	Nd		0.6	0.3
Cd		<0.1	0.1	Sm		0.19	0.05
Sb		<0.1	0.1	Eu		0.08	0.02
Bi		<0.1	0.1	Gd		0.27	0.05
Ag		<0.1	0.1	Tb		0.05	0.01
Hg		0.02	0.01	Dy		0.14	0.05
Tl		<0.1	0.1	Ho		0.07	0.02
Se		5.4	0.5	Er		0.2	0.03
Zr		8.1	0.1	Tm		0.02	0.01
Au		0.1237	0.0005	Yb		0.15	0.05
				Lu		0.04	0.01

chondrites by Jarosewich (1990), based on selected major element contents and ratios, NWA 7915 also corresponds to groups L and LL.

The new bulk-chemical results from NWA 7915 (Table 3) allow to compare its composition with the average values found in H, L, LL ordinary chondrites and CI carbonaceous chondrites. The chemical composition of NWA 7915 is slightly inconsistent with typical LL-type ordinary chondrites and also differentiates this meteorite from other ordinary chondrites.

The LL-type ordinary chondrite classification of NWA 7915 was undoubtedly confirmed by the total content of iron (Tables 4 and 5). Table 4 contains additional chemical properties which allowed for NWA 7915's classification as an LL-type chondrite. However, further examination of the chemical data (Table 4) led to the conclusion that, with the exception of Fe, P, as well as Al, and Au, the contents of several other elements are not fully consistent with the average values found in other LL-type ordinary chondrites.

The affiliation of NWA 7915 with other LL-type ordinary chondrites is depicted on Figure 8. The diagram also reveals a low nickel and high iron content. The content of Cr and Ca in NWA 7915 chondrite is more closely aligned with H-type chondrites. On the other hand, the Si, Mn and Mg contents in NWA 7915 chondrite are more closely aligned with L-type chondrites (Table 4). Such differences in particular element concentrations, compared to the values typical of ordinary chondrites, H, L and LL, are not unusual. A good example is, e.g., the Nyirábrany chondrite (Meszaros et al., 2014).

The analysis of data from Fig. 9 and Table 5 reveals further characteristic properties of NWA 7915's bulk chemical composition. The content of major elements (excluding Ni) is typical of LL-type ordinary chon-

Table 4. Bulk chemical composition and selected atomic ratios of NWA 7915 chondrite in relation to the composition and characteristic atomic ratios of ordinary chondrites' groups and CI carbonaceous chondrites (after Hutchison, 2006)

Element		Chondrites				
		H	L	LL	NWA 7915	CI
Si	weight %	16.9	18.5	18.9	18.59	10.5
Ti		0.060	0.063	0.062	0.07	0.042
Al		1.13	1.22	1.19	1.17	0.86
Cr		0.366	0.388	0.374	0.361	0.265
Fe		27.5	21.5	18.5	19.6	18.2
Mn		0.232	0.257	0.262	0.256	0.19
Mg		14.0	14.9	15.3	14.81	9.7
Ca		1.25	1.31	1.30	1.26	0.92
Na		0.64	0.70	0.70	0.86	0.49
K		0.078	0.083	0.079	0.100	0.056
P		0.108	0.095	0.085	0.087	0.102
Ni		1.60	1.20	1.02	0.74	1.07
Co		0.081	0.059	0.049	0.037	0.051
S		2.0	2.2	2.3	0.39	5.9
C		0.11	0.09	0.12	0.07	3.2
Au (ppb)		215	162	140	123.7	144
Atomic ratios		H	L	LL	NWA 7915	CI
Mg/Si		0.957	0.931	0.935	0.920	1.068
Al/Si($\cdot 10^4$)		696	686	655	655	853
Ca/Si($\cdot 10^4$)		518	496	482	475	614
Fe/Si($\cdot 10^4$)		8184	5845	4923	5294	8717
Ca/Al		0.74	0.72	0.74	0.73	0.72
Ni/Si($\cdot 10^4$)		453	310	258	190	488
CI normalized Atomic ratios		H	L	LL	NWA 7915	CI
Mg/Si		0.90	0.87	0.88	0.86	1.0
Al/Si		0.82	0.81	0.77	0.77	1.0
Fe/Si		0.94	0.67	0.56	0.61	1.0

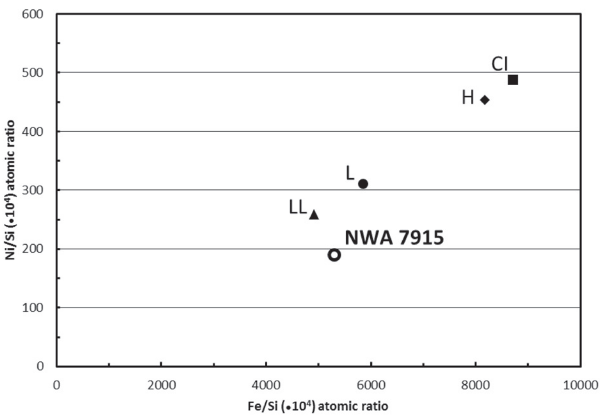

Fig. 8. The diagram of Ni/Si($\cdot 10^4$) versus Fe/Si($\cdot 10^4$) for NWA 7915 chondrite in comparison to CI, H, L and LL chondrites (after Hutchison, 2006). The ratios are atomic

drites and thus confirms the accuracy of NWA 7915's original classification. Among these elements, however, the content of K is slightly higher than the values observed in other LL-type ordinary chondrites (Fig. 9a).

The content of the rare earth elements (REE) in NWA 7915 diverges from the average values observed in LL-type ordinary chondrites (Fig. 9b; Table 5) including higher levels of La (more than twice), Ce and Pr, and lower levels of Dy (less than half), Tm, and Yb. These results are rather surprising and should be verified by additional analyses. The plot of REE abundances in NWA 7915 and CI-type carbonaceous chondrites normalized to LL ordinary chondrites (Fig. 9b) shows a totally different trend. These results indicate the enrichment of LL-type ordinary chondrites in REE in general, and of NWA 7915 in particular, as opposed to CI-type carbonaceous chondrites, excluding Dy, Tm, and Yb in the case of NWA 7915. The three above mentioned elements are present in NWA 7915 in lower concentration than in CI-type carbonaceous chondrites (Fig. 9b). As far as the parent rock on the parent body of NWA 7915 is concerned, it seems that the enrichment had a little bit different origin and character compared to "typical" LL-type ordinary

Table 5. Selected elements' abundances (ppm) in NWA 7915 chondrite in relation to average (McSween & Huss, 2010), maximum and minimum abundances of these elements in LL-type chondrites (based on data after Koblitz, 2010). The maximum and minimum values for LL-type ordinary chondrites were determined on the basis of at least 3 data points for Pb, and up to 188 data points for Fe

element	NWA 7915	average LL	range LL	element	NWA 7915	average LL	range LL
Si	185 928	189 000	93 000–237 600	Pb	1.2	nd	0.058–0.35
Al	11 699	11 800	8 300–25 400	Zn	21	56	16.5–370
Fe	195 664	198 000	78 900–892 000	As	1	1.3	0.08–37.7
Mg	148 130	153 000	57 000–194 800	Cd	<0.1	0.04	0.00039–1.248
Ca	12 580	13 200	6 400–27 400	Sb	<0.1	0.075	0.0345–2.460
Na	6 825	6 840	34–11 900	Bi	<0.1	<0.03	0.00069–0.153
K	996	880	170–12 450	Ag	<0.1	0.075	0.00994–0.554
Ti	659	680	36–2 520	Hg	0.02	0.022	0.098–5.3
P	873	910	170–2 840	Tl	<0.1	<0.03	0.00024–0.114
Mn	2 556	2 600	56–5 950	Se	5.4	9	1.68–21.8
Cr	3 607	3 690	315–6 980	Zr	8.1	7.4	3–10.69
Ni	7417.3	10 600	100–356 000	Au	0.1237	0.146	0.000011–0.00466
Ba	15	4	1.2–7.3	Sc	8	8	5.9–11.6
Be	<1	0.045	0.041–0.062	Y	1.9	2	2–3.58
Co	365.1	480	81.1–13 900	La	0.7	0.330	0.23–0.66
Cs	0.1	0.150	0.009–3.070	Ce	1.2	0.880	0.637–14.1
Ga	4.4	5.3	1.1–19.9	Pr	0.19	0.130	0.109–0.213
Hf	<0.1	0.170	0.14–0.29	Nd	0.6	0.65	0.495–0.998
Nb	<0.1	nd	0.42–0.49	Sm	0.19	0.205	0.161–0.34
Rb	2.7	2.2	0.26–50.8	Eu	0.08	0.078	0.031–0.1
Sn	1	nd	0.083–1.9	Gd	0.27	0.29	0.242–0.458
Sr	30.3	13	9–12.6	Tb	0.05	0.054	0.036–0.087
Ta	<0.1	nd	nd	Dy	0.14	0.36	0.257–0.461
Th	<0.2	0.047	0.032–0.086	Ho	0.07	0.082	0.0615–0.112
U	0.1	0.015	0.0046–0.186	Er	0.2	0.24	0.178–0.327
V	54	76	4–85	Tm	0.02	0.035	0.032–0.052
W	9.7	0.115	0.064–3.28	Yb	0.15	0.23	0.178–0.287
Mo	0.6	1.1	0.86–9	Lu	0.04	0.034	0.025–0.06
Cu	85.3	85	20–4040				

chondrites parent bodies. Parent bodies of LL-type chondrites are enriched with all analyzed REE, while the parent body of NWA 7915 chondrite seems to be depleted in Dy, Tm, and Yb in comparison to respective REE concentrations which are characteristic for CI-type carbonaceous chondrites (Fig. 9b). This is an interesting problem for further and more detailed studies.

The content of the remaining elements in NWA 7915 exhibits a different (even opposite) trend to that observed in CI-type carbonaceous chondrites (Fig. 9c). Among these elements, the average content only of Co, Ga, Rb, Cu, As, Hg, Zr and Au shows the affiliation with other LL-type ordinary chondrites. On the other hand, NWA 7915 exhibits the highest deficiency in Zn, Mo, Se, and V compared to other LL-type ordinary chondrites, whereas the highest noteworthy enrichment exists for Ba and Sr (Fig. 9c). The positive anomaly for Ba and Sr was also observed by Hezel et al. (2011) in meteorites found in the United Arab Emirates (W2–W4); however, they report positive anomaly for Mo while in the case of NWA 7915 it is negative. The higher content of Ba and Sr may be related to higher content of feldspars, that may also be supported by the observed slightly higher content of K. Another reason for the increased concentration of Ba and Sr could be terrestrial weathering, as reported from ordinary chondrites weathered in hot desert climate conditions (Velbel, 2014). It is also noteworthy that meteorites found on the Arabian Peninsula have the tendency to preferentially accumulate Sr whereas the Saharan and Australian meteorites have a stronger Ba signal (Zurfluh et al., 2012). However, the increase in Ba and Sr should be combined with elevated concentration of Rb, which should display a similar trend. However, that is not the case for NWA 7915.

Figure 10 shows the content of selected elements in NWA 7915 in order of decreasing volatility. The content of all these elements best matches their trends typical of LL-type ordinary chondrites. Nevertheless,

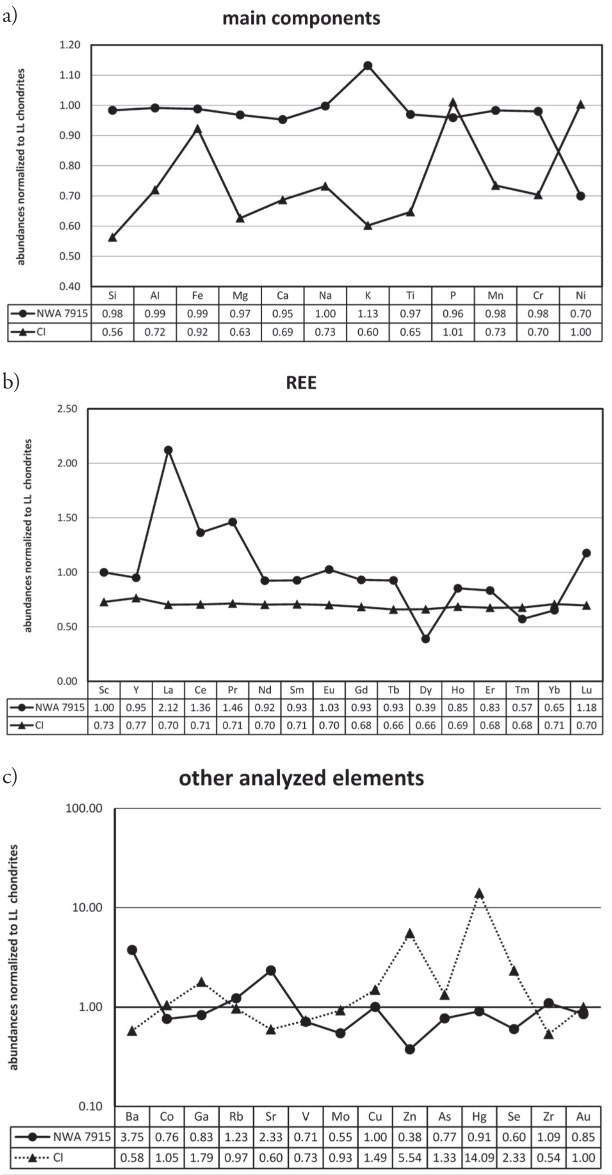

Fig. 9. Abundances of elements analyzed in NWA 7915 chondrite normalized to LL chondrites in comparison to CI chondrites' abundances (after McSween & Huss, 2010).

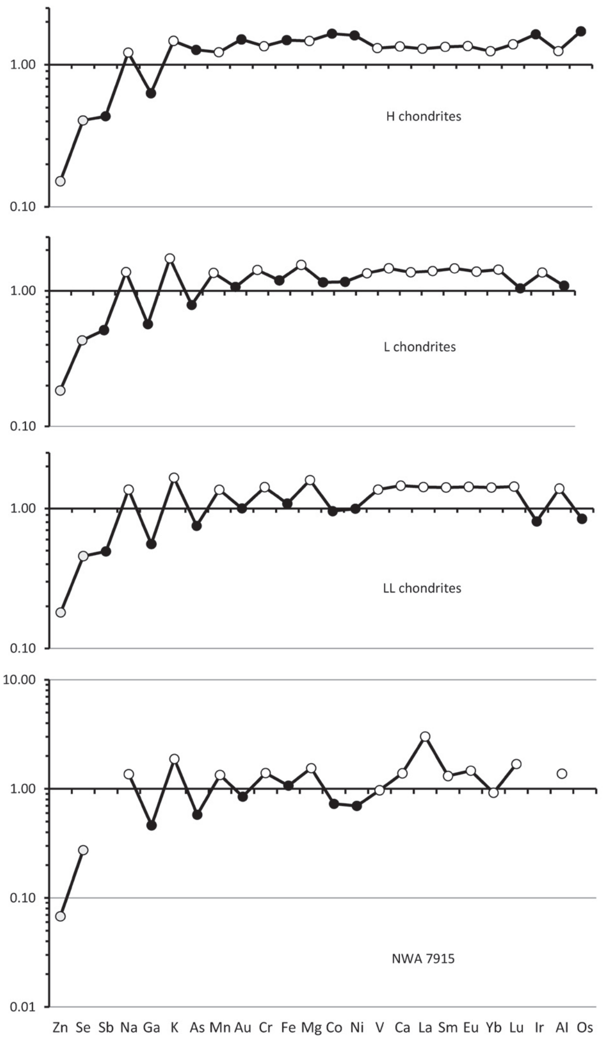

Fig. 10. CI-normalized abundances of lithophile (open symbol), siderophile (black symbol) and chalcophile (gray symbol) elements of NWA 7915 chondrite in relation to H, L and LL chondrites (after McSween & Huss, 2010)

the presence of certain deviations can be identified. As we have already pointed out, the content of Ni is significantly lower, as well as the contents of Co, V, and Yb. The content of La is also higher (Fig. 10).

The content of all the analyzed elements in NWA 7915 is presented in Table 5, along with their average values and the minimum and maximum values observed in other LL-type ordinary chondrites. The content of Mo, Hg, and Dy, as well as Ba, Sr, W, and Pb in NWA 7915 deserves particular attention. The amounts of Mo, Hg, and Dy are lower than the values ever observed in any of the 121 analyzed LL-type chondrites registered in the MetBase® database (Table 5; Koblitz, 2010). On the other hand, the contents of Ba, Sr, W, and Pb are higher than the values ever observed in any of the 121 analyzed LL-type ordinary chondrites registered in the MetBase® database (Koblitz, 2010). The higher concentration of W may be explained by the use for sample grinding a tungsten carbide (WC) mill. NWA 7915 is depleted of Ni due to terrestrial weathering. It is also possible that some other element concentrations present in strongly weathered kamacite grains may be underestimated in this analysis (i.e. Mo?). The content of all other elements may reflect chemical composition of the parent rock of NWA 7915 chondrite. However, it is also possible that some of these chemical inconsistencies result from terrestrial weathering processes that occurred in the hot desert in NW Africa.

Petrologic type

The petrologic type reflects the thermal metamorphic grade of a meteorite (Weisberg et al., 2006). The fol-

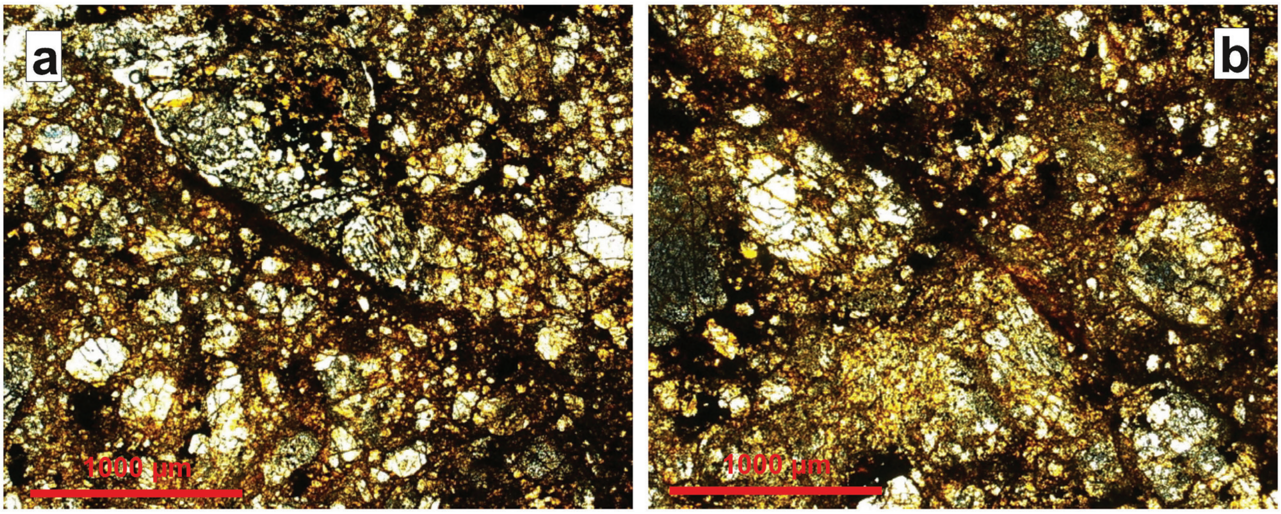

Fig. 11. (a) and (b) – veins cutting the NWA 7915 chondrite (from top left to bottom right in both photos) and adjacent spots filled with iron oxides and hydroxides (opaque, black on the photos), which are possible relics of shock veins and pockets (one nicol)

lowing features observed in NWA 7915 have been used to define its petrologic type:

1. homogeneous olivine and pyroxene composition (type 5-6),
2. large orthopyroxene phenocrysts present (type 5-6),
3. small secondary feldspars discernable only in BSE (type 5),
4. matrix composed of olivine, pyroxene and opaques (no glass preserved) (type 5–6),
5. chondrules with distinct and diffused boundaries (type 4–5).

In conclusion, the NWA 7915 meteorite represents petrologic type 5, i.e. it experienced a strong, but not the highest possible, thermal exposure. The main arguments are the observed recrystallization of the matrix, but moderately good preservation of the chondrule structures, the homogeneous composition of olivine, and the presence of only secondary small feldspar grains.

Shock stage and weathering grade

The shock stage in the NWA 7915 meteorite has been classified as very weak, S2, according to shock classification of chondrites based on effects seen in thin sections, combined by Hutchison (2006) and referring to Stöffler et al. (1991) and Rubin et al. (1997). Among the main argument for this assignment is the undulatory extinction and irregular fractures clearly visible in many of olivine crystals. The evidence for the S2 shock stage comprises also veinlets and cracks observed in chondrules, as well as undulose extinction in some radial pyroxene chondrules. Also, some rare veins and spots filled with iron oxides and hydroxides have been observed (Fig. 11) that may be relics of shock veins and pockets. However, these structures are rare and their origin rather problematic, thus they were not taken into account for defining the shock stage of the stone. It is possible that the shock pressures were close to the upper limit of the S2 stage, i.e. ~10 GPa.

The weathering grade (Wlotzka, 1993) has been estimated at W3. Kamacite has not been found, apparently being totally altered into secondary iron oxide/hydroxide phases, whereas Ni-rich taenite, and troilite are only partly weathered. The matrix and opaque minerals are strongly coloured by secondary rusty Fe-rich compounds. As mentioned above, the observed specific chemical characteristics, e.g. the relatively high abundancy of Ba and Sr, may also reflect terrestrial hot desert weathering processes in the NWA 7915 chondrite.

CONCLUSION

The studied meteorite has been classified as LL5 ordinary chondrite, shock stage S2, weathering grade W3, and approved in the Meteoritical Society database as NWA 7915. The chemical composition of NWA 7915 is somewhat different from the average characteristics of the LL chondrite group, displaying deficiencies in Ni, Co, Zn, Mo, Se, V, Hg, Dy and Yb, and enrichment in Ba, Sr, Pb and La. Some of these chemical characteristics may reflect specific chemical features of the NWA 7915 parent body whose composition is slightly different from that of the main LL chondrite group. However, some chemical anomalies, e.g.

the elevated concentrations of Ba and Sr, may result from terrestrial weathering processes that occurred in hot desert environment. These chemical "anomalies" in weathered ordinary chondrites are potentially interesting problems for more detailed future studies.

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