UDC 552.63+523.681.2

FEATURES OF MINERAL AND GEOCHEMICAL COMPOSITION OF CHELYABINSK METEORITE

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Особенности минерального и геохимического состава метеорита «Челябинск»

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Фрагменты метеорита состоят на 25–35 % из хондр, на 65–75 % из матрицы и содержат не более 3–4 % железо-никелевых металлов и сульфидов. Метеорит является каменным хондритом и относится к петрологическому типу LL5. Во фрагментах метеорита отмечены повышенные содержания Na, U, Ag и пониженные содержания Cr, Mn, Ni, Zn, Cs по сравнению со средними содержаниями в обыкновенных хондритах. Метеорит сложен оливином, ортопироксеном, клинопироксеном, плагиоклазом, хромитом, металлами железа и никеля, сульфидами, хлорапатитом и стеклом полевошпатового состава. В ходе высокотемпературной перекристаллизации матрицы метеорита произошла сегрегация сульфидов и интерметаллидов в линейные зоны, перемежающиеся с участками, сложенными исключительно силикатами. В черных фрагментах метеорита наблюдаются ударные прожилки и ветвящиеся сульфидные микропрожилки, образовавшиеся в результате трех этапов импактного воздействия, которые сопровождались полным или частичным плавлением метеоритного вещества. Во фрагментах серого хондрита фиксируется один этап ударного воздействия, который привел к формированию черных прожилков. Зерна троилита в сером хондрите с поверхности окислены, что, по всей видимости, произошло при взаимодействии с водой во внеземных условиях. В черном хондрите около 2–3 % объема слагают поры, образовавшиеся при аккреции твердых фрагментов метеорита. Находящиеся свободно в порах полностью ограненные кристаллы плагиоклаза, клинопироксена и оливина были захвачены в поры при их формировании и свидетельствуют об одновременном нахождении в среде формирования хондрита как недифференцированных образований, ставших впоследствии хондрами, так и отдельных минералов, являющихся продуктами дифференциации силикатного вещества.

Ключевые слова: Урал; метеорит «Челябинск»; хондрит; минералогия; геохимия; ударные прожилки; сульфидные микропрожилки; поровое пространство.

A meteorite is a chondrite and belongs to petrological type LL5. Meteorite fragments have higher contents of Na, U, Ag and lower contents of Cr, Mn, Ni, Zn, and Cs compared with an average of ordinary chondrites. The meteorite is composed of olivine, orthopyroxene, clinopyroxene, plagioclase, chromite, metals of iron and nickel, sulfides, Cl-apatite and glass, which has feldspar composition. During high-temperature recrystallization of the meteorite matrix, sulfide and Fe, Ni-metals are segregated in linear zones, interleaved with silicate areas. In black meteorite fragments, shock veins and sulfide micro-branching veins, formed by the effects of three stages of impact, accompanied by full or partial melting of meteoritic material, are observed. In fragments of gray chondrite, one stage of impact is observed giving rise to the formation of black veins. Pores are formed by accretion of solid fragments of the meteorite account for 2–3% of chondrites. Plagioclase, clinopyroxene and olivine, located freely in the pores, have complete crystalline facets. They were captured in the pores during their formation and indicate that undifferentiated formations, which later became the chondrules, and minerals that are the products of the differentiation of silicate substances, were in the parental environment of chondrites.

Keywords: Ural; Chelyabinsk meteorite; chondrite; mineralogy; geochemistry; shock veins; sulfide micro veins; porous space.

Introduction

The Chelyabinsk meteorite, which is one of the biggest ([Russia…, 2013] gives estimates: diameter about 17–20 m, weight about 1000 tons), and the most famous in the Urals, entered Earth's atmosphere on February 15, 2013 at about 9:20 a.m. (GMT +5).

It exploded in the atmosphere at a height of 50 km [Chelyabinsk…, 2013] and the fragments fell over a wide area of the Chelyabinsk region. The explosion of the extraterrestrial was seen by tens of thousands of people in the Middle Urals and North Kazakhstan and it was recorded by car video cameras and substantially represented on the Internet. Major fragments of the meteorite fell near Chebarkul Lake (they broke particularly thick ice (about 1 m) and created a hole about 6 m in diameter) close to the city of Chebarkul, situated 78 km to the west of the city of Chelyabinsk. Many observers were in-

В сокращенном варианте на русском языке основные положения этой статьи были опубликованы в научном журнале “Литосфера” за 2013 г., № 3, с. 106–117.

jured by window glass debris when the blast wave hit their homes.

Meteorite fragment detection

All fragments of the Chelyabinsk meteorite studied by the authors were found seven days after the event, within an area 2–3 km south of the Deputatskoe settlement (Yetkulskiy area of Chelyabinsk region). The productivity of discovery of Chelyabinsk meteorite fragments (having sizes from 0.5 to 3.5 cm) was about six to eight pieces per hour per person. The density of the discoveries was about one fragment per 80–600 m^2. The fragments had not reached the soil stratum; they were extracted from the 60–70-cm-thick snow, at depths of 20–50 cm. The inlet holes were vertical or slightly slanted (with vertical deviation up to 20°) and sometimes twisted. The lower parts of the inlets were filled with granular ice while the fragments themselves were surrounded with a 2–5-mm layer of ice. Obviously, this is a consequence of their high temperature as they entered the snow. Thus, the fragments under investigation did not undergo impact action, did not contact with chemical compounds in the soil and did not undergo weathering in terrestrial conditions. It should be noted that (predictably) none of the Chelyabinsk meteorite fragments have radioactivity beyond background values.

Roundish fragments, entirely enclosed by a 0.5-mm-thick black glassy hardened zone, dominate the fi dings. However, several fragments had additional thin hardened zones on one or several sides. These zones represent separate drops of black glass on the gray background of the fracture. Furthermore, fragments that were found were bounded by a roundish surface with a black hardened zone, as well as by an uneven gray surface of the fresh fracture formed by the destruction in atmosphere prior to entering the snow.

Texture and classification of the fragments

The majority of the meteorite fragments is light gray chondrite. About 20% of the fragments no bigger than 1 cm are of black color because their matrix is threaded with a dense net of fi e sulfide veinlets, which is no more than 2–3 microns thick. Many fragments of gray chondrite are intersected by black linear veinlets, 0.3–1 mm in size, forming breccia (Fig. 1a). Plagioclase fills the interstices between the olivine grains in the gray chondrite, whereas only melted feldspar glass fills the interstices in the black chondrites. The absence of zonality of the olivine and orthopyroxene grains enables the gray chondrite to be classifi d as equilibrium low temperature chondrites (type III), according to [Zinov'eva, 2001, Zinov'eva et al., 2010], and the black chondrite as intermediate medium temperature chondrites (type II). All of the fragments may be classifi d as LL type [Weisberg et al., 2006] because they contain no more than 2–3 % iron-nickel intermetallides with an increased content of iron in silicates. All the fragments are of petrological type 5, because they consist of 25–35 % chondrules and 65–75 % matrix having high-temperature transformation traces.

Chemical and microelement composition of meteorite fragments

Two samples of chondrite were used to determine the contents of the main petrogenic elements by X-ray fluorescent analysis (device XRF-1800, analysts were Gorbunova, N. P., Tatarinova, L. A. and Petrischeva, V. G.).

The first sample of gray chondrite shows contents (wt. %): SiO_2 36.06, TiO_2 0.13, Al_2O_3 2.94, Cr_2O_3 0.54, FeO 33.33, MnO 0.33, MgO 19.13, CaO 2.09, Na_2O 1.78, K_2O 0.12, P_2O_5 0.31, Ni 0.21, S 2.85, and the sum is 99.84.

The second sample of black chondrite shows contents (wt. %): SiO_2 32.80, TiO_2 0.13, Al_2O_3 2.75, Cr_2O_3 0.50, FeO 36.04, MnO 0.32, MgO 17.97, CaO 2.05, Na_2O 1.59, K_2O 0.12, P_2O_5 0.32, Ni 0.42, S 4.09, and the sum is 99.10.

Thus, in the black chondrite sample there is an increased content of Ni, S and Fe in comparisons with the sample of light gray chondrite. Considering that the main difference between the light gray and black chondrites is the presence of thin sulfide veinlets, it is possible to suppose that the process of their formation was not an isochemical one, but was related to sulfide migration from outside. In should be noted that in both samples there is an increased content of Na in comparison with the composition of chondrites typical of the LL type.

Three other samples were used to determine the microelement contents. In relation to the microelements (Table 1), the meteorite samples are similar to ordinary chondrites of types L and LL, the average composition of which is given by [Wasson et al., 1988]. To a very small degree, the samples demonstrate an increased amount of U and Ag, as well as decreased amounts of Cr, Mn, Ni, Zn, and Cs. Rare earth element content is shown on spider-diagrams normalized by CI-chondrite (Fig. 2). All three samples demonstrate gently sloping trends with negligible enrichment in the area of light lanthanides, and contain cumulatively more rare earth elements than do average chondrites of such type.

Meteorite mineral composition

The mineral composition of the meteorite presents: olivine, orthopyroxene, clinopyroxene, plagioclase, chromite, iron and nickel metals, sulfides, chlorapatite, and glass of feldspar composition. The most signifi ant part of the meteorite is composed of silicate matrix with high-temperature recrystallization traces. Olivine and pyroxene grains the form of granoblastic poikiloblastic structures similar to structures of terrestrial metamorphic rocks. In the

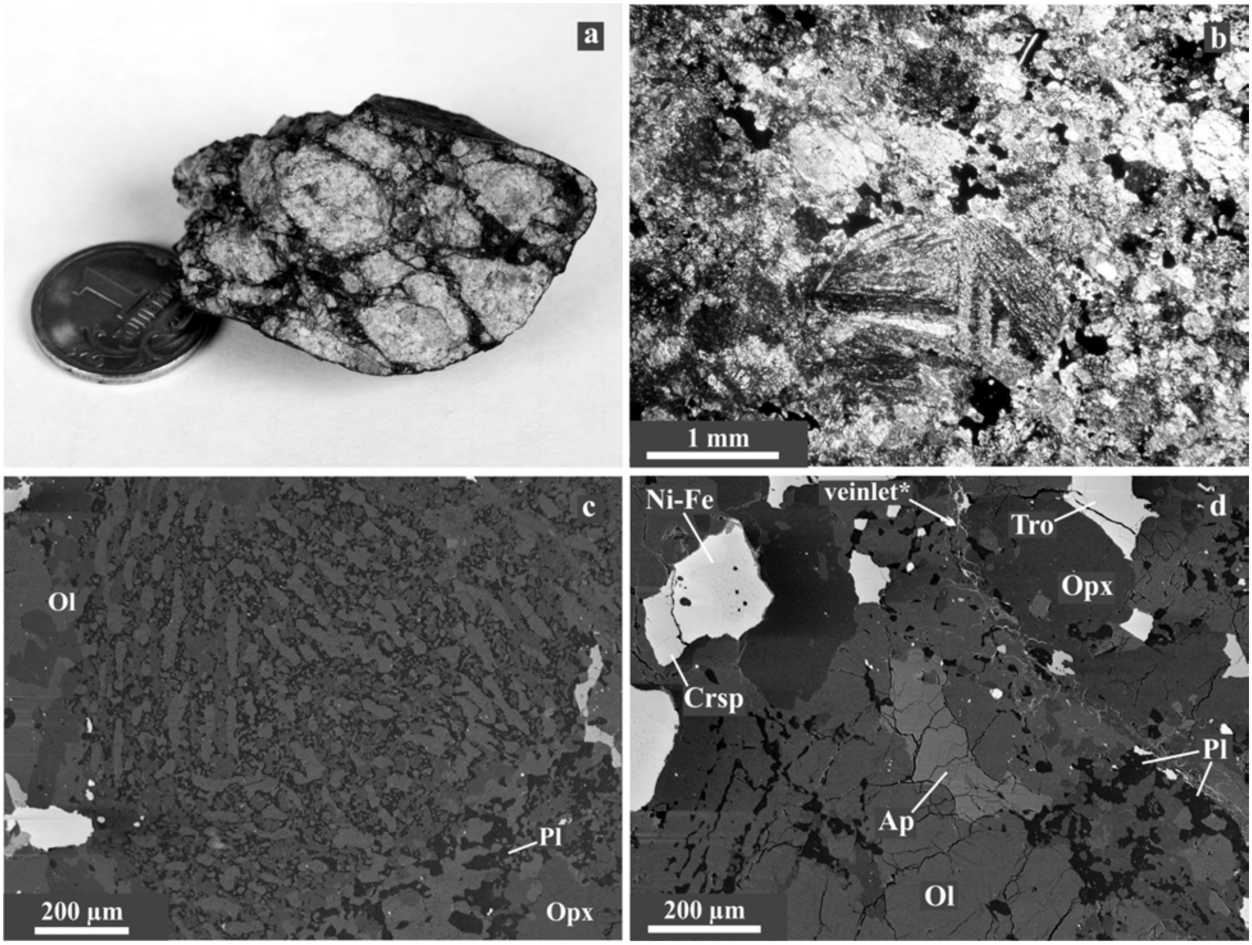

Figure 1 | Structure of the gray chondrite from Chelyabinsk meteorite. Hereinafter: Ap – apatite, Crsp – chrome spinel; Fe-Ni – metals of iron and nickel, Ol – olivine, Opx – orthopyroxene, Pl – plagioclase, Tro – troilite, veinlet* – a black veinlet intersecting the gray chondrite. a – a fragment of the gray chondrite intersected by black impact veinlets, photo by Pavel V. Shalaev; b – structure of the gray chondrite: round chondrules surrounded by uneven granular matrix with traces of high-temperature recrystallization (light coming though, crossed nicols); c – grate chondrule, backscattered electron imagine, The Zavaritsky Institute of Geology and Geochemistry of the Ural Branch of the Rus-sian Academy of Sciences, Cameca SX 100 (hereinafter the analyst is V. V. Khiller); d – apatite in chondrule matrix, backscattered electron imagine, Cameca SX 100.

interstices between these minerals, there is plagioclase, melted glass and apatite grains (Fig. 1d). Chondrules of different texture (grate, radiant, porphyritic) comprise about 25–30% rock volume (Fig. 1b, c) with sizes of up to 1.5–2 mm. Chondrules consist mainly of olivine and orthopyroxene grains submerged into the basis of plagioclase or glass, which are difficult to distinguish from each other (Fig. 1c).

Olivine in the meteorite matrix is the main rock constituent mineral (Fig. 1d) with grains of 0.03–0.5 mm in diameter. As a whole, olivine has light-gray color, apparently because of the small grain size and microfracturing. It occurs in the meteorite matrix as well as in the chondrules. It is characterized by stable chemical composition (Table 2, test 1–4) and it belongs to forsterite with 30% fayalitic minal. In addition, it contains unremarkable manganese, nickel and chromium impurities. Orthopyroxene is more xenomorphic with respect to olivine grains, but is also a rock constituent mineral of the meteorite. It presents in the chondrules as well as in the rock matrix. As with olivine, it has stable chemical composition (Table 2, test 5–8) and belongs to enstatite with 25% ferrosilit minal. The mineral consistently contains calcium impurity (CaO up to 1 wt. %).

Clinopyroxene is xenomorphic with respect to olivine and enstatite grains, and occurs frequently in the matrix as single grains among the orthopyroxene aggregate. It is characterized by variable composition (Table 2, test 9–11), but all tests fall in the fi ld of augite (En43-45Wo41-45Fs10-16). The mineral consistently contains aluminum, chromium, titanium, and sodium impurities.

The interstices between the grains of the above-mentioned minerals are filled with plagioclase and melted glass. Plagioclase belongs to albite-oligoclase and contains potassium and iron impurities (Table 2, test 12–14). By composition, the melted glass is similar to plagioclase (Table 3), but differs

Table 1. Rare element composition (ppm) of Chelyabinsk meteorite

Elements	1	2	3	Elements	1	2	3
Li	1,65	1,67	1,72	La	0,76	0,45	0,47
Be	0,03	0,01	0,03	Ce	1,99	1,23	1,31
Sc	7,41	7,80	7,67	Pr	0,25	0,15	0,18
Ti	586,06	539,00	542,27	Nd	1,25	0,76	0,85
V	69,78	61,53	61,01	Sm	0,47	0,20	0,33
Cr	2083,3	1683,2	1736,0	Eu	0,09	0,09	0,11
Mn	1160,3	1244,5	1188,0	Gd	0,37	0,23	0,30
Co	450,19	473,51	361,85	Tb	0,07	0,06	0,07
Ni	5601,5	7309,4	6901,0	Dy	0,54	0,39	0,43
Cu	73,82	55,49	57,84	Ho	0,12	0,08	0,11
Zn	8,08	4,66	4,89	Er	0,35	0,25	0,28
Ga	4,65	4,89	4,53	Tm	0,05	0,03	0,04
Ge	10,03	7,56	6,68	Yb	0,34	0,28	0,26
Rb	3,24	3,31	3,62	Lu	0,06	0,04	0,05
Sr	12,01	12,48	13,08	Hf	0,20	0,16	0,23
Y	2,68	1,96	2,23	Ta	21,66	0,02	18,18
Zr	5,37	6,24	6,30	W	0,66	0,13	0,39
Nb	29,44	0,44	29,28	Tl	0,03	0,002	0,01
Mo	1,08	0,79	0,89	Pb	0,26	0,14	0,20
Ag	2,57	0,79	2,33	Bi	0,005	n.d.	n.d.
Cd	0,01	0,002	0,002	Th	0,22	0,11	0,08
Sn	0,71	0,26	0,36	U	0,14	0,04	0,13
Cs	0,09	0,02	0,03	Sb	0,08	0,05	0,07
Ba	9,92	6,81	11,01	Te	0,46	0,38	0,33

Note: tests made by ICP-MS method on mass-spectrometer ELAN 9000 in IGG UB RAS, analyst N. N. Adamovich. Tests: 1–2 – gray chondrite, 3 – black chondrite.

from plagioclase in respect of decreased sodium and increased potassium contents. The glass was not registered by optic methods, especially in particularly thin intergrowth with the matrix minerals, but was remarkably different from the plagioclase of stable non-stoichiometrical chemical elements relations.

Inside the interstices between the chondrules, xenomorphic apatite grains up to 0.8 mm are found. According to microprobe analysis, phosphate is related to chlorine-apatite with chlorine (3.04–4.07 wt. %) and fluoride (0.24–0.72 wt. %). In addition, the indicated variation of halogen content is met within the limits of one apatite grain. The apatite under consideration contains noticeably less Cl and F, and accordingly more (OH)-group calculated stoichiometrically in comparison with the apatite from LL chondrites [Lewis et al., 2013, Dreeland et al, 2011]. It is established that iron (FeO up to 0.5 wt. %) is the only substantial impurity that is quite typical for chondrite apatites [Dreeland et al., 2011].

Chrome spinel xenomorphic grains up to 0.2 mm in size presented in the matrix are frequently associated with Fe, Ni-metals and troilite clusters. In addition, the chrome spinel is observed as small inclusions (up to 50 microns) in the olivine or pyroxene grains. According to microprobe analysis, chromoshpinelide (Table 4) belongs to chromite with insignifi ant content of hercynite (up to 13%), ulvospinel (up to 10%), and magnesiochromite (up to 17%).

In the associations with metal and sulfid, the chromite is more ferriferous (Table 4, test 4–5), but in the olivine and orthopyroxene inclusions, the chromite is a more magnesian one (Table 4, test 6–7). The presence of the significant titan impurity (or ulvospinel minal) in chromite tells us that the mineral might have a partly reverse structure.

The Fe, Ni-metals form roundish and interstice grains of up to 0.3 mm in size. Usually, they form

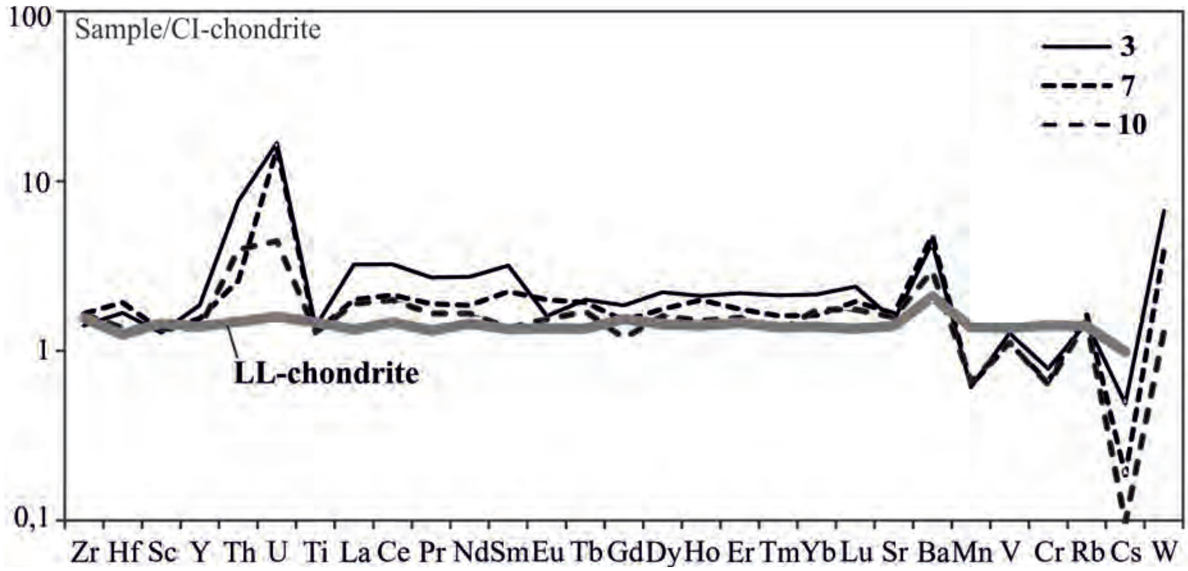

Figure 2 | Spider-diagram of rare earths content in the fragments of Chelyabinsk meteorite. The contents were normalized to CI-chondrite according to [Sun et al., 1989]. Un-filled squares (sample 3) and unfilled triangles (sample 10) are the gray chondrite; filled squares (sample 7) are the black chondrite; gray line is mean contents of rare earths in LL-chondrites by [Wasson et al., 1988]. Sample numbers correspond to numbers in Table 1.

grains in association with troilite, which, as a later mineral, grows around them. The Fe, Ni-metal grains exhibit zonal structure: the kamacite aggregate is developed in the central part of the grain (Table 5, test 1–5), and the taenite aggregate is developed in marginal zones (Table 5, test 6–10). It is interesting that the nickel content varies signifi antly in the grain matrix, but it reaches maximal value (Ni up to 48%; Table 5, test 9–10) only in the periphery. Therefore, we were unable to find Fe, Ni-metals with nickel predomination with respect to iron (awaruite and others). The troilite makes separate grains of up to 0.3 mm, built of polygonal-granular aggregate, and forms fringes of accretion around

Table 2. Silicate chemical compound (wt. %) from Chelyabinsk meteorite

№	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	NiO	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total	Fe/(Fe+Mg)
1	37,35	n.d.	n.d.	0,11	0,11	26,66	0,46	34,77	0,03	n.d.	n.d.	99,49	0,30
2	37,19	0,01	n.d.	0,03	0,04	26,35	0,44	35,06	0,02	0,01	n.d.	99,16	0,30
3	37,21	n.d.	0,01	0,03	0,06	26,6	0,49	34,97	0,01	n.d.	n.d.	99,38	0,30
4	37,61	0,03	0,02	0,19	0,03	26,07	0,59	34,68	0,02	0,01	n.d.	99,24	0,30
5	55,16	0,2	0,11	0,15	n.d.	16,12	0,44	26,84	0,69	0,04	0,01	99,76	0,25
6	54,68	0,24	0,11	0,13	0,03	15,72	0,45	26,88	0,87	n.d.	n.d.	99,12	0,25
7	54,89	0,2	0,13	0,12	n.d.	15,87	0,56	26,98	0,88	0,02	0,01	99,66	0,25
8	55,21	0,15	0,13	0,14	0,02	16,02	0,37	26,94	0,83	0,01	n.d.	99,83	0,25
9	51,32	0,4	0,42	0,6	0,32	10,37	0,24	15,64	20,93	0,44	n.d.	100,69	0,27
10	51,76	0,35	0,49	0,7	0,08	8,52	0,21	15,63	21,48	0,54	n.d.	99,76	0,23
11	53,67	0,36	0,46	0,8	0,05	6,14	0,16	15,89	21,88	0,58	0,01	99,99	0,18
12	64,57	0,03	20,34	0,09	0,23	1,27	n.d.	0,02	2,26	9,77	0,68	99,26	
13	65,86	0,02	20,94	0,03	0,06	0,62	n.d.	n.d.	1,99	10,44	0,58	100,54	
14	65,48	0,04	20,88	0,02	0,03	0,66	n.d.	0,01	2,23	9,84	0,82	100,01	

Note: hereinafter tests made on microanalyser Cameca SX 100 at IGG UB RAS, analyst V.V. Khiler; test 1-4 – olivine, test 5-8 – orthopyroxene, test 9-11 – clinopyroxene, test 12-14 – plagioclase.

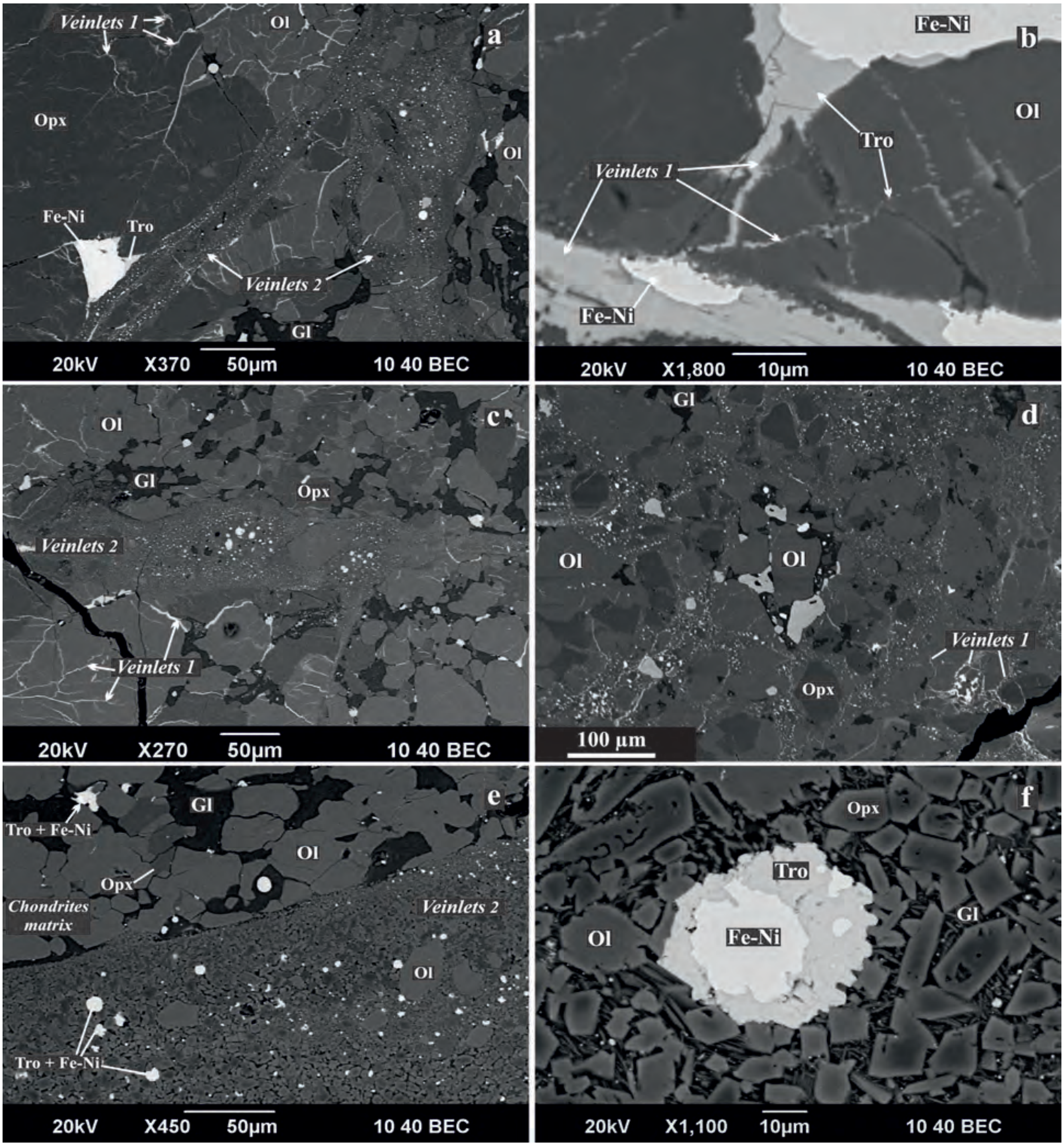

Figure 3 | Impact veinlets in the fragments of Chelyabinsk meteorite. a, c – sulfide microveinlets. Gl – melted feldspar glass, «veinlets 1» – branching sulfide microveinlets, «veinlets 2» – linear or branching veinlets made from glass with olivine microinsets and drop-like metal-sulfide isolations. Picture was made by refl cted electrons. Device JSM-6390LV at "Geoanalitik" Analytical Centre of the Ural Branch of Russian Academy of Sciences (hereinafter the analyst is S. P. Glavatskikh).

the Fe, Ni-metals, and participates in the structure of the veinlets of any type. According to microprobe analysis, as this takes place, the troilite (Table 5, test 11–14), independent of an association, features stable chemical composition. Among the impurities, only nickel is noted (not more than 1 wt. %). In the biggest troilite grains, one can find small, 20–25 microns, roundish inclusions of other sulfides. On evidence derived from microprobe analysis (Table 5, test 15–17), they are ferriferous pentlandite. In addition, the mineral contains copper (up to 1 wt. %) and cobalt (up to 0.6 wt. %) impurities.

Impact veinlets

As mentioned above, the gray and black chondrites demonstrate some distinctions. In the gray chondrite, the interstices between the olivine grains are filled with plagioclase, whereas in the black chondrites, they are filled with melted glass. The color of the

Table 3. Composition of melted glass (wt. %) in Chelyabinsk meteorite

№	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	NiO	Total
Black chondrite												
1	68,44	0,02	22,49	0,10	1,34	0,01	0,26	0,10	2,95	1,54	0,03	97,29
2	67,91	0,03	22,31	0,13	1,18	0,00	0,31	0,14	2,92	1,37	0,05	96,35
3	67,64	0,05	22,27	0,09	1,10	0,02	0,22	0,08	3,02	1,85	0,02	96,36
4	66,85	0,06	22,20	0,06	0,66	0,00	0,10	2,12	5,46	1,08	0,03	98,61
Black veinlet in gray chondrite												
5	67,77	0,01	21,75	0,04	0,89	0,06	0,17	1,54	4,02	1,88	0,02	98,17

black chondrites is caused by the net of branching out sulfide microveinlets pierced through them and made from troilite («veinlets 1» in Fig. 3a-c). Their thickness varies from 0.1 to 2–3 microns. Such veinlets intersect olivine, pyroxene and chrome spinel grains, but never intersect the melted glass (Fig. 3a, c). Additionally, sulfide veinlets do not intersect iron-nickel metal grains and are in continuous intergrowth with big troilite grains. Maximal density and thickness of sulfide veinlets is observed along lengthy cracks cemented together by troilite with drop-shaped taenite inclusions.

Table 4. Chemical composition of chromite (wt. %) from Chelyabinsk meteorite

№	1	2	3	4	5	6	7
TiO_2	2,25	2,45	2,16	2,18	3,63	3,63	3,65
Al_2O_3	6,08	6,05	6,07	5,83	5,15	5,09	4,97
Cr_2O_3	56,55	56,61	56,41	57,06	55,65	56,09	56,47
Fe_2O_3	0,31	0,64	0,72	0,26	0,11	0,27	0,12
NiO	0,02	0,08	0,03	0,05	0,03	0,04	0,07
FeO	31,85	31,77	31,34	31,55	33,05	30,63	30,91
MnO	0,44	0,57	0,71	0,55	0,55	0,47	0,41
MgO	1,63	1,59	1,64	1,63	1,59	3,15	3,03
CaO	n.d.	n.d.	0,09	0,04	0,03	n.d.	0,02
Total	99,13	99,75	99,17	99,16	99,78	99,37	99,65
Crystal chemical recalculation (on 3 cations)							
Ti	0,06	0,07	0,06	0,06	0,1	0,1	0,1
Al	0,26	0,26	0,26	0,24	0,22	0,21	0,21
Cr	1,61	1,59	1,61	1,63	1,58	1,58	1,6
Fe^{3+}	0,01	0,02	0,02	0,01	n.d.	0,01	n.d.
Fe^{2+}	0,96	0,96	0,93	0,95	0,99	0,92	0,92
Mn	0,01	0,02	0,02	0,02	0,02	0,01	0,01
Mg	0,09	0,08	0,09	0,09	0,09	0,17	0,16
$Cr/(Cr+Al+Fe^{3+})$	0,83	0,82	0,83	0,84	0,83	0,83	0,84
$Fe^{2+}/(Fe^{2+}+Mg)$	0,91	0,92	0,91	0,91	0,91	0,83	0,84

Note: test 1-5 – big grains in meteorite matrix, test 6-7 – small inclusions in olivine an orthopyroxene; Fe_2O_3 – calculated stoichiometrically.

Table 5. Chemical compound of Fe, Ni-metals and sulfides (wt. %)

№	Mineral	Fe	Ni	Co	Cu	S	P	As	Сумма
1	Kamasite	94,85	4,92	2,03	n.d.	0,01	0,04	0,04	101,89
2		93,69	5,85	2,19	0,08	n.d.	n.d.	n.d.	101,82
3		87,23	11,46	1,69	n.d.	n.d.	0,03	n.d.	100,42
4		84,81	14,61	0,95	n.d.	0,01	0,11	n.d.	100,48
5		82,60	17,07	0,96	0,10	n.d.	0,09	0,02	100,85
6	Taenite	73,67	24,90	1,00	0,03	0,01	0,13	0,01	99,75
7		63,94	34,71	0,92	0,08	0,02	n.d.	n.d.	99,68
8		55,72	43,32	0,33	0,16	n.d.	0,04	0,04	99,59
9		51,54	47,94	0,22	0,19	0,04	n.d.	n.d.	99,92
10		50,73	48,08	0,25	0,21	0,01	n.d.	0,01	99,29
11	Troilite	63,85	0,37	0,02	n.d.	35,60	n.d.	0,01	99,85
12		64,07	0,65	0,07	0,02	35,45	n.d.	n.d.	100,26
13		63,92	0,60	0,04	0,07	35,70	n.d.	n.d.	100,34
14		63,25	1,07	0,06	0,04	35,23	n.d.	0,03	99,68
15	Pentlandite	46,08	20,79	0,51	0,66	33,15	n.d.	0,02	101,21
16		46,10	20,06	0,51	0,81	32,19	n.d.	n.d.	99,68
17		45,09	20,95	0,54	0,97	32,48	n.d.	0,02	100,04

Veinlets from 10 microns to 3 mm pass though fragments of the black chondrite. The veinlets are filled by glass with drop-shaped isolations of troilite and Fe, Ni-metals («veinlets 2» on Fig. 3). The thin (up to 150 microns) and the thick (2–3 mm) veinlets vary in structure. The thin veinlets have a linear, as well as a branched form arising from “fl wover” of fragmental grains of the chondrite matrix (Fig. 3a, c). They consist of glass, thin (up to 0.5 microns) olivine grains and drop-shaped troilite isolations with inclusions of iron-nickel metals. At the edges of such veinlets, one can observe distinct hardened zones, which express a decrease in the size of the olivine grains and drop-shaped troilite isolations. It was not possible to measure the glass compound by microprobe, in order to determine the presence of olivine microcrystals in the veinlets. However, from backscattered electron images, it appears lighter than glass from the interstices of the chondrite matrix. Th s distinction indicates that they have a different chemical composition. The thick veinlets, in contrast to the thin ones, are made of angular olivine and orthopyroxene, 5 to 50–200 microns grains, cemented by melted glass with drop-shaped troilite isolations (Fig. 3e, f). Boundaries of such veinlets are smooth and accompanied by a thin hardened zone, which expresses a decrease of the size of the silicate grains and drop-shaped troilite isolations (Fig. 3e). Iron-nickel drop-shaped Fe, Ni-metals inclusions are found in troilite (Fig. 3f). The olivine and pyroxene grains from a veinlet have zonal structure that is shown clearly in Fig. 3e. For this reason, rock formed with veinlets can be classifi d as a high-temperature non-equilibrium chondrite [Zinov’eva et al., 2010].

Thick veinlets are not intersected with sulfide microveinlets, but some sulfide microveinlets do take intersecting positions with respect to the thin veinlets, which can be seen clearly from Fig. 3a. However, there are few such microveinlets; most parts of the sulfide microveinlets are cut off and tapered near the thin veinlets.

The structure of the veinlets is in many ways similar to that of impact dykes described for ordinary chondrites by [Hutson et al., 2013], and obtained by experiment in ordinary [Horz et al., 2005] and in carbonaceous chondrites [Tomeoka et al., 1999]. On the sulfide grain contacts of the thin veinlets, one can see hardened sulfide-s licate emulsions, similar to those described in [Tomkins et al., 2013].

The structure of the black veinlets intersecting the gray chondrites is similar to the structure of the black chondrites. Most thin black veinlets are linear zones with branching sulfide veinlets (Fig. 2d). With greater thickness, their structure demonstrates glass zones with olivine microcrystals and drop-shaped troilite isolations (Fig. 3d), and instead of plagioclase in the chondrite matrix near the black veinlets, one can observe glass, which differs from plagioclase by composition.

All of this allows us to draw an analogy between the black veinlets of the gray chondrite and fragments of the black chondrite; however, obviously, an external impact is the cause of the formation of the black veinlets in the gray chondrite. Troilite and Fe, Ni-metals grains in the gray chondrite are distributed unevenly. In Fig. 4a, one can see that they are concentrated in linear intersecting clusters, and encircling chondrite parts consisting exclusively of

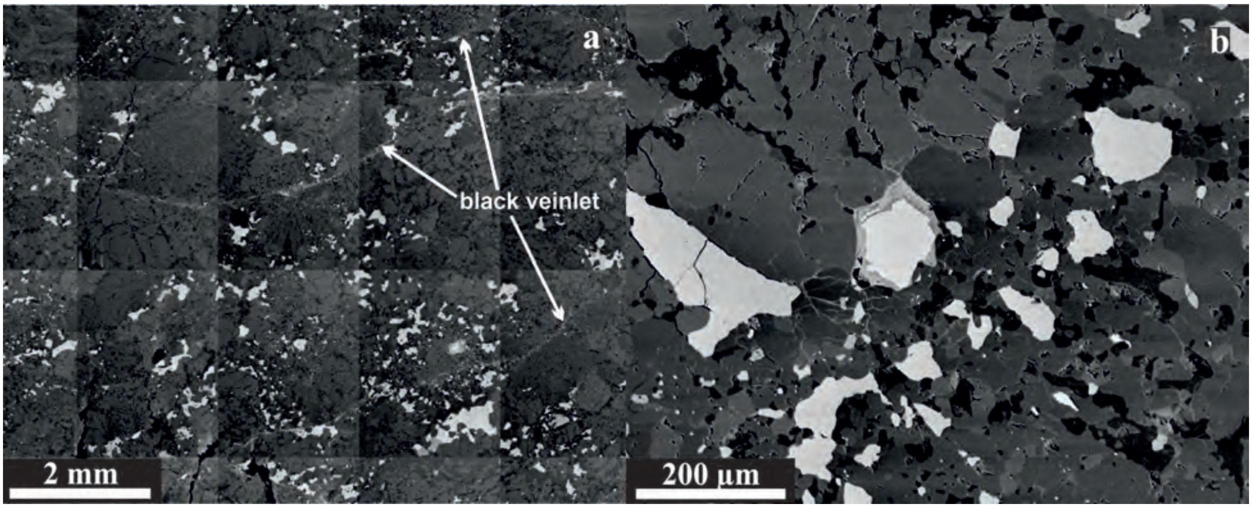

Figure 4 | Linear clusters of troilite and iron-nickel metals (white) in the gray chondrite of Chelyabinsk meteorite (a) and structure of linear cluster (b). The black veinlets take a secondary position with respect to such clusters. Backscattered electron imagine. Cameca SX 100.

silicates. Sulfide and Fe, Ni-metals grains in linear clusters having complicated shapes are situated at the border of the olivine and pyroxene grains. The small grains make inclusions in these minerals (Fig. 4b). Because the olivine and orthopyroxene have complicated borders and penetrate each other as inclusions, it may be inferred that troilite and Fe, Ni-metals segregation occurred at the same time as the high-temperature chondrite matrix recrystallization. Formed under the influence of a later impact, the black veinlets intersecting the gray chondrite took a secondary position with respect to the troilite and metal clusters.

Pores in meteorite

In fragments of the Chelyabinsk meteorite one can see pores up to 0.5 mm in size. The pores are mostly within fragments of the black chondrite and the porosity does not exceed 1–3% of the total volume.

The protrusion of matrix individuals from the pore walls caused uneven curved pore forms with concave surfaces (Fig. 5a, c). Mineral protrusions are usually uneven or roundish. On some roundish surfaces of the protruding minerals, one can observe striations caused by oscillatory combinations (Fig. 5c). Apparently, the pores were formed in a process of accretion as free space between stuck chondrules and mineral individuals of the matrix. The group of scientists studying the pore geometry in ordinary stone chondrites by synchrotron X-ray microtomography, arrived at the same conclusion on the nature of the pores [Sasso et al., 2009]. From their data, porosity caused by incomplete compaction at metamorphosis is widely presented in all types of usual ordinary chondrites, and is the feature of the asteroid belt.

The clinopyroxene (Fig. 5c) crystals, plagioclase crystals and roundish olivine individuals (Fig. 5b) are observed in pores. The crystals are freely situated near the veinlet walls or they are adhered to them.

The minerals were examined by the energy-dispersion attachment INCA Energy 450 X-Max 80 of the scanning electronic microscope JSM-6390LV at the Analytical Centre "Geoanalyst" of the Institute of Geology and Geochemistry of the Ural Branch of the Russian Academy of Sciences by analyst S.P. Glavatskikh. The plagioclase and pyroxene crystals have typical facings and slightly rounded edges. By scrutinizing a round olivine isolation (Fig. 5b), small facets can be found, and on the round surface between the facets, striations caused by oscillatory combinations are noticeable.

At the intersections pores and thin sulfide veinlets one can see sinter troilite buildups situated generally along the walls of the cavity. Rarely, sinter buildups of complicated form are met in the center of the pore space (Fig. 5e). The surface of such buildups is a stairstep one. The steps form round outlines in agreement with the buildups. At high magnifi a- tion, the steps exhibit an angular shape and they are built by combinations of parallel crystal facets or fi - er striations because of oscillatory combinations on the square of the sinter buildups (Fig. 5f). Thus, such steps are themselves striations due to oscillatory combinations, which provides evidence of the slow crystallization of the sulfide melt, because many of the sinter buildups are crystalline individuals.

Sulfide oxidation

Micropores with small crystal plates of ferrum hydroxides are observed around some troilite grains in the gray chondrite (Fig. 6). Gross observed that they look like "rusty" halos around sulfide grains. The crystals are no greater than 2 micrometers (Fig. 6b). The hydroxides are formed on troilite grains as well as on the nearby pore walls. The surface of the

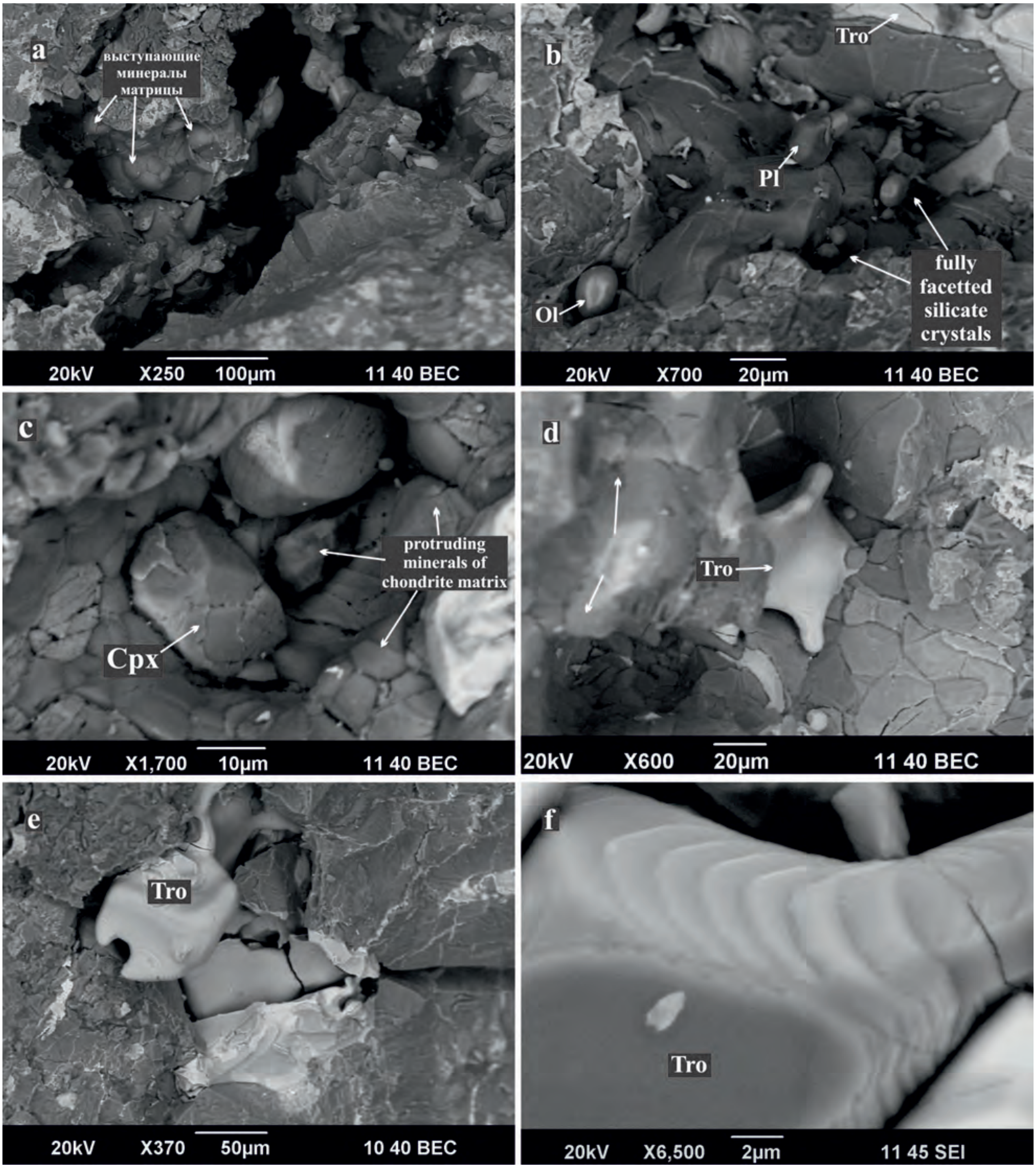

Figure 5 | Pore structure in the black chondrite of Chelyabinsk meteorite. a – pores with protruding minerals of chondrite matrix, b – pores with fully facetted silicate crystals situated along pore walls, c – crystals and globular individuals of minerals in pores, d-e – sinter aggregate of troilite in pore space, f – steps of grow on surface troilite sinter aggregates. a-e – pictures in back scattering electrons, f – image made in secondary electron mode. Device JSM-6390LV.

troilite grains exposed in the pores is partly covered with the fi est film of ferric oxides, detected by the EDX-attachment of the electron microscope.

Conclusion and discussion of the results

The black and the gray fragments of the Chelyabinsk meteorite are classified as ordinary chondrites of type LL5. Their formation was accompanied by thermal metamorphism recrystallization resulting in the formation, inside the chondrite matrix, of a granoblastic poikiloblastic structure similar to the structure of terrestrial metamorphic rocks. Thermal metamorphism recrystallization was accompanied by sulfide and metal

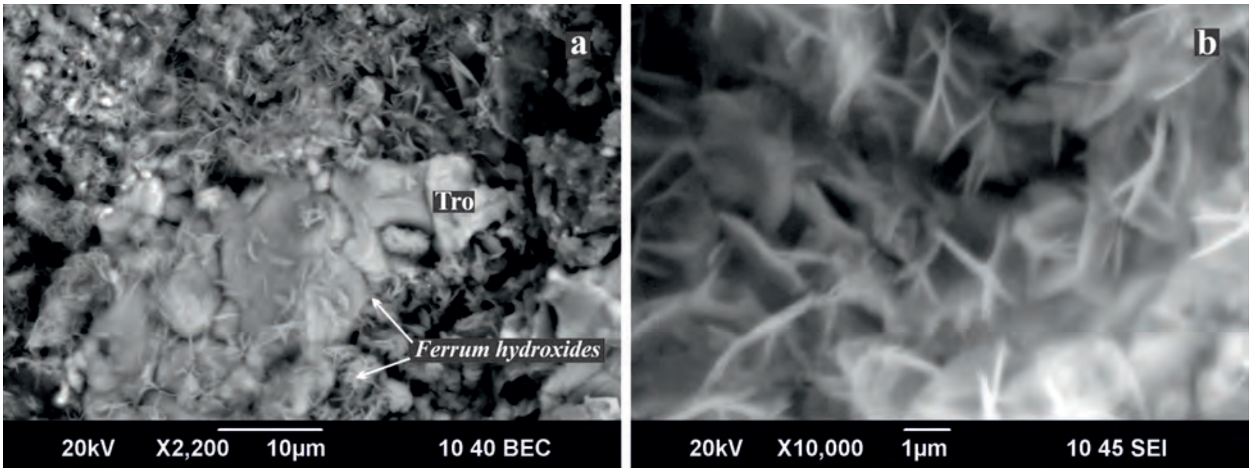

Figure 6 | A grain of troilite surrounded with microcavities with plate-like crystals of ferrum hydroxides from the gray chondrite of Chelyabinsk meteorite. a – picture in back scattering electrons, b – picture of plate-like crystals in back scattering electrons. Device JSM-6390LV.

segregation forming linear clusters around silicate spots. A common blastic structure of the chondrite interstices position of apatite and plagioclase grains is kept.

In the black chondrite, one can identify three impact phases accompanying brittle deformation following crack cementation by melt: thin veinlets formation, branching sulfide microveinlets formation, and thick impact veinlets formation. At the fi st phase, complete melting occurred along separate cracks following cementation with silicate and sulfide-metallic emulsion. The latter frizzed in a form of separate drops in a silicate glass of thin veinlets. In the second phase, brittle olivine, orthopyroxene and chromite cracking occurred followed by a fill with sulfide fusion originating due to partial melting. It is the partial melting that distinguishes the second phase of impact from the first. In the second phase, thin veinlets that arose earlier cracked to a significantly lesser degree than the matrix silicates and the melted plagioclase glass was not exposed to brittle deformation. In the third phase, the thick impact veinlets (first millimeters) composed of high-temperature non-equilibrium chondrites appeared.

In the gray chondrite, only one phase of impact is registered, leading to black veinlet formation, in which the black veinlets in some areas intersect themselves and create a breccia texture.

By composition, the black veinlets are similar to the black fragments of the meteorite.

The fragments of the Chelyabinsk meteorite were discovered in snow cover several days after the event, were not in contact with the soil and did not undergo weathering in terrestrial conditions.

Therefore, sulfide oxidation with the formation of cavities filled by ferrum hydroxides most probably happened under extraterrestrial conditions.

The structure of the pore space deserves a mention. The fact that mineral individuals in the pores mainly have full faceting and only join the wall of the interstices from one side tell us that their origin and growth took place in space free from gas and liquid. Theoretically, it could take place in the pore space provided that there is an absence of gravity capable of drawing crystals to one of the walls of the cavity. However, this hypothesis contradicts the absence of crystals growing from the walls of the cavities that might be natural, considering that a cavity surface is more preferable than a volume of gas or liquid for nucleation [Krasnova et al., 1997]. Probably, the crystals grew in a gas environment before the formation of the meteorite body and then became located in cavities between segregated meteorite fragments.

The difference in composition of the crystals and chondrules participating in the formation of the meteorite indicates the polymictic nature of the samples under study. The meteorite formed in an environment that included round chondrules constituted from undifferentiated silicate melt, as well as separate silicate crystals, which might be the products of the differentiation of a silicate substance.

Acknowledgments

The authors are thankful to the head of the Center of Geoecological and Mineral Tourism “Uralskie rudoznatzy” N. B. Belenkov for invaluable aid in searching for meteoritic material. The authors are grateful to N. P. Gorbunova, S. P. Glavatskikh and N. N. Adamovich of the Zavaritsky Institute of Geology and Geochemistry of the Ural Branch of the Russian Academy of Sciences and others.

The study was funded by Russian Federal Property Fund (RFBR) according to the research project № 14-05-00464-a.

Accepted 29.02.2016

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