552.63

МИНЕРАЛЬНЫЕ АССОЦИАЦИИ В ПУСТОТАХ ТЕМНОЙ ЛИТОЛОГИИ МЕТЕОРИТА ЧЕЛЯБИНСК (ЧЕБАРКУЛЬСКИЙ ФРАГМЕНТ)

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MINERAL ASSOCIATIONS IN CAVITIES FROM DARK LITHOLOGY OF CHELYABINSK METEORITE (CHEBARKUL FRAGMENT)

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(
,
Fe-Ni- -
- $Fo_{70-84}Fa_{16-30}$,
$Fo_{41-69}Fa_{31-59}$. Mg, Ti Al, $(Fe_{0.98}Mn_{0.02})(Cr_{1.89-1.94}Fe_{0.04-0.09}V_{0.02-0.03})O_4$.
-
Ni (13.5-19.6 -33. Ni).
, Na-Fe-
$(Fe^{2+},Mn^{2+})_3(PO_4)_2$ $Na(Fe^{2+},Mn^{2+})_4(PO_4)_3$
Na-Fe- $Na_2(Fe^{2+},Mn^{2+})_5(PO_4)_4$.
Fe-Ni-S-O

Ключевые слова: Fe-Ni-

Ideally faceted crystals of olivine, chromite and Fe-Ni-metal (taenite) as well as aggregate of dendritic-skeletal metal crystals in association with troilite were found on the walls of the gas cavities in areas with complete shock-induced melting of host chondrite (dark lithology of the Chelyabinsk meteorite, Chebarkul fragment). It is suggested that mineral formation in the cavities was with participation of gas phase. Olivine on the cavity walls and near is zoned: centre - $Fo_{70-84}Fa_{16-30}$, rim $Fo_{41-69}Fa_{31-59}$. Octahedral chromite is virtually free in Mg, Ti and Al: $(Fe_{0.98}Mn_{0.02})$ $(Cr_{1.89-1.94}Fe_{0.04-0.09}V_{0.02-0.03})O_4$. Skeletal metal crystals from metal-troilite aggregate are also zoned: centre kamacite with high Ni (13.5-19.6 wt.%), rim taenite (28.1-33.6 wt.% Ni). Chromite, Na-Fe-phosphate globules and pentlandite also occur in these aggregates. Three mineral phases were found in the phosphate globules: sarcopside $(Fe^{2+},Mn^{2+})_3(PO_4)_2$, galileiite $Na(Fe^{2+},Mn^{2+})_4(PO_4)_3$ and unidentified Na-Fe-phosphate $Na_2(Fe^{2+},Mn^{2+})_5(PO_4)_4$. Their formation is due to the separation of a phosphatic liquid from the Fe-Ni-S-O melt on the final stages of metal crystallization.

Figures 11. Tables 4. References 40.

Key words: meteorite Chelyabinsk, impact melt, phosphate globules, Fe-Ni-metal, olivine, chromite, sarcopside, galileiite, skeletal crystals

Введение

).

Borovicka et al., 2013; Grokhovsky et al., 2013; Popova et al., 2013,

-

(

- Popova et al., 2013; Sharygin et al., 2013a-b; Kohout et al., 2014; Ozawa et al., 2014;

Методы исследования

у

Olympus BX51 .

TESCAN MIRA 3MLU

) - (BSE)

SE). ,

-

, 20-40 , TESCAN MIRA 3MLU Energy 450+ (Oxford Instrument Analytical Ltd

$_2$ (Si, O), Al_2O_3 $_2P_2O_7$ (P), BaF_2 (F), Cr_2O_3 Cl Ni , Co

(EBSD) -

FE SEM Sigma VP EBSD .

Краткие сведения о метеорите Челябинск

LL5 (S4-5, W0) (

- ;
Popova et al., 2013; Sharygin et al., 2013a-b; Kohout et al., 2014).

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- < 10

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. **Светлый тип**

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HPT- .

Темный тип

-

Промежуточный тип -

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HPT-

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Mg_2SiO_4

Ozawa et al. (2014)

-

- -2000

PT-

2014) SiO_2

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, SiO_2

(-965

-1

PT-

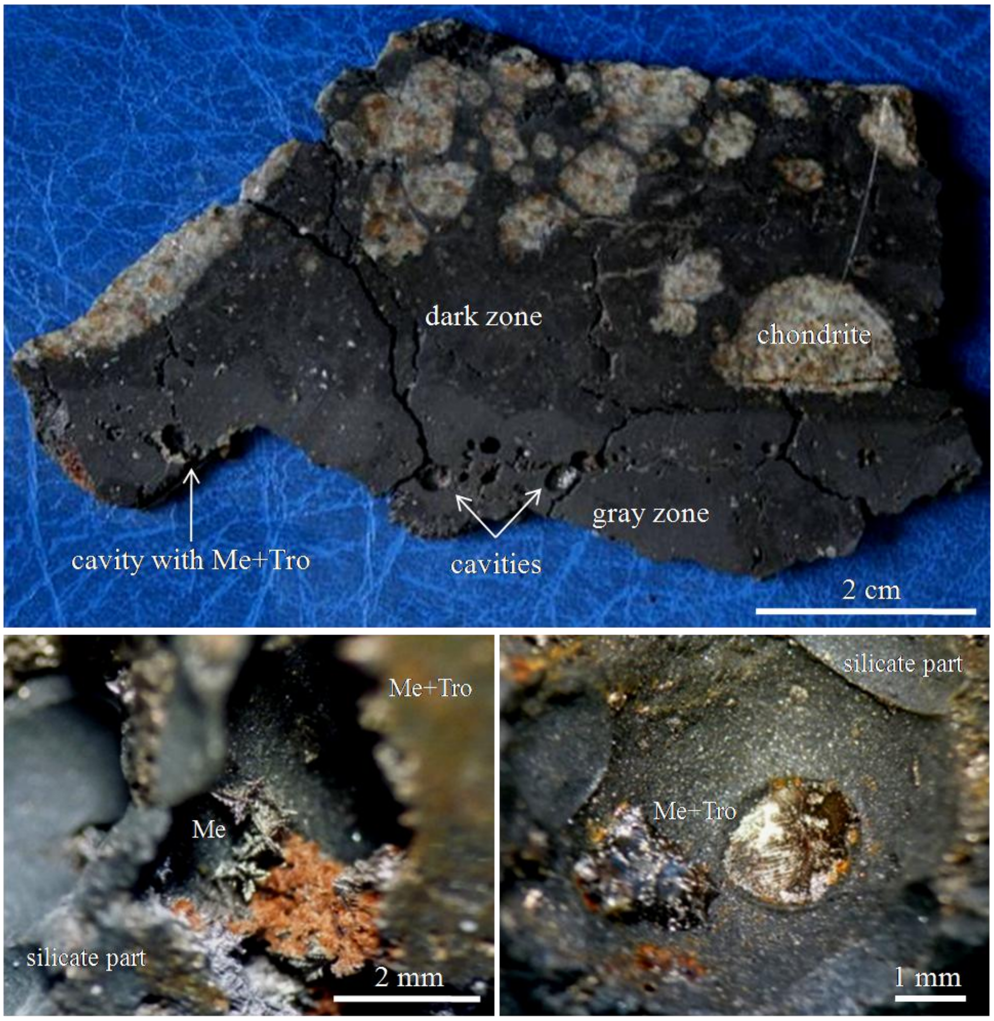

Рис. 1.

-

Примечание: chondrite dark zone, gray zone avities Me+Tro - Fe-Ni-

Fig. 1. Relationship between initial chondritic paragenesis with product of its metlting (dark lithology) and large cavities with aggregate of dendritic/skeletal metal crystals and with blebs and films of metal-troilite composition in the gray zone of the dark lithology, section of the Chebarkul fragment of the Chelyabinsk meteorite.
Notes: chondrite initial chondritic paragenesis; dark zone, gray zone different zonet of the dark lithology; dendritic/skeletal metal crystals covered by troilite; Me+Tro metal-troilite aggregate; red-brown Fe-Ni-hydroxides.

Чебаркульский фрагмент метеорита Челябинск

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Первая зона - ,

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Вторая зона - -

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Scott, 1982; Rubin, 1985).

-

; -

Минералогия силикатной части вокруг газовых пустот

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-5).

- 20-30 .

$Fo_{70-84}Fa_{16-30}$, $Fo_{41-69}Fa_{31-59}$, $Fa_{>50}$

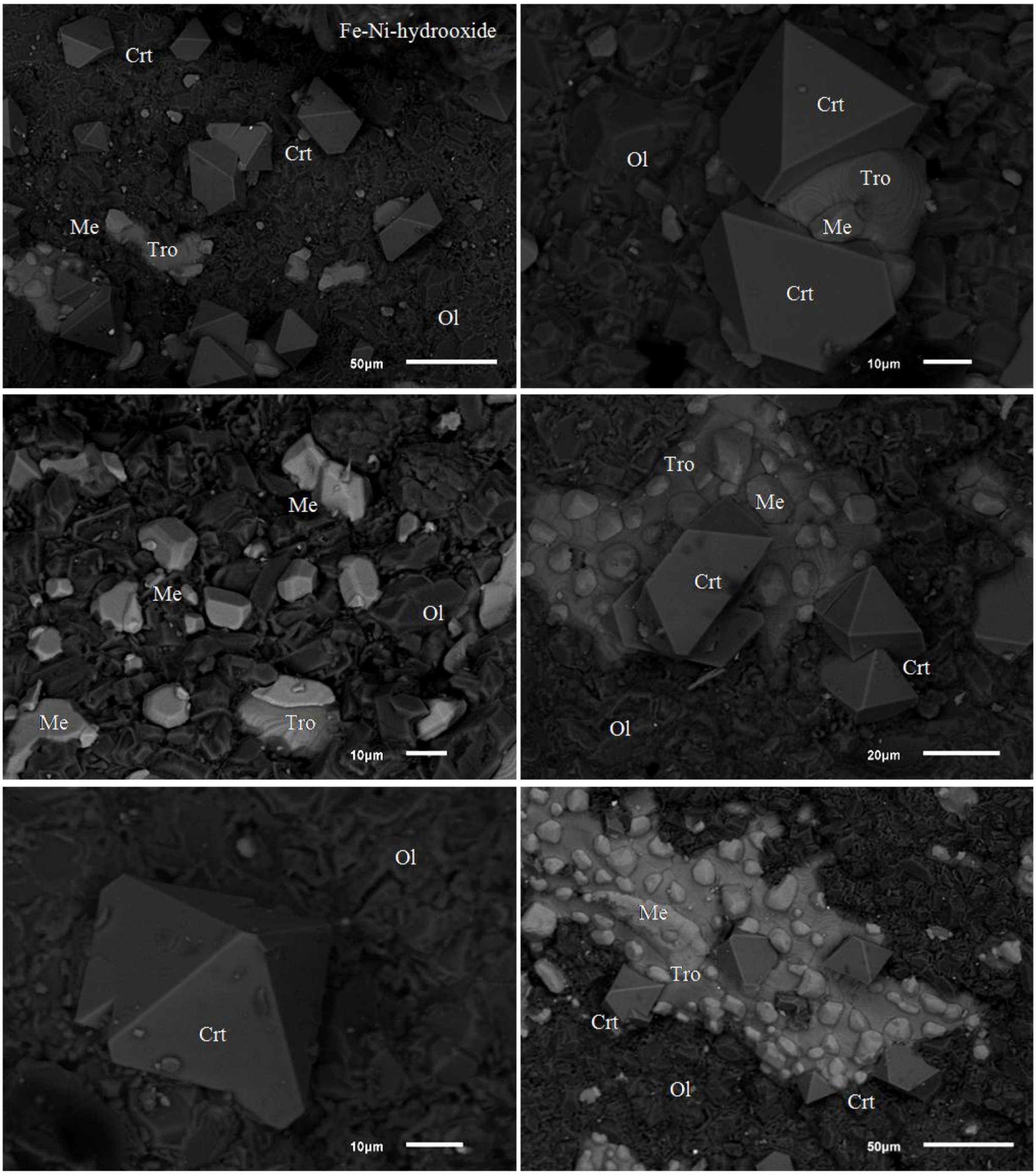

Рис. 2. BSE

Примечание: Crt Me Tro Ol

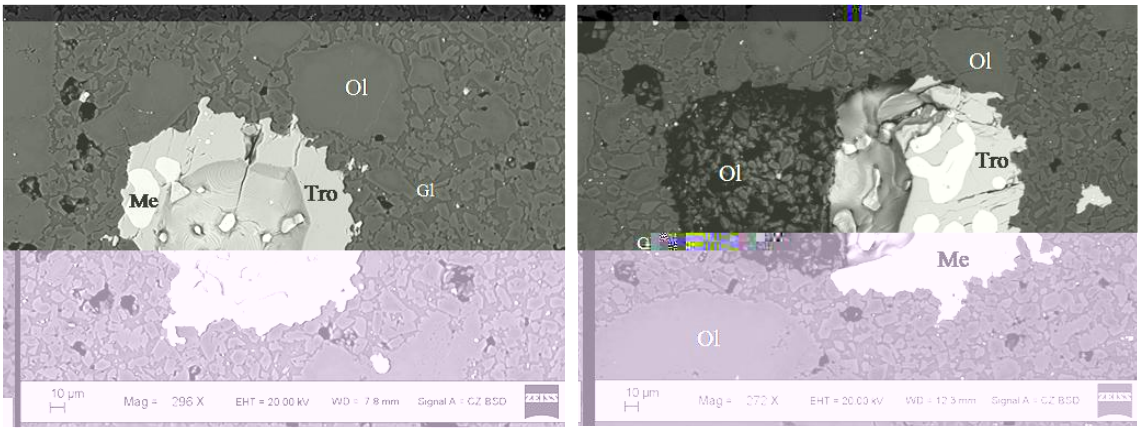

Рис. 3. -
BSE
Примечание: Me Tro Ol Gl

Fig. 3. Small cavities are partially filled by metal+troilite aggregate, gray zone, Chebarkul fragment of the Chelyabinsk meteorite (BSE images).
Note: Me metal; Tro troilite; Ol olivine; Gl interstitial devitrified aggregate (former glass).

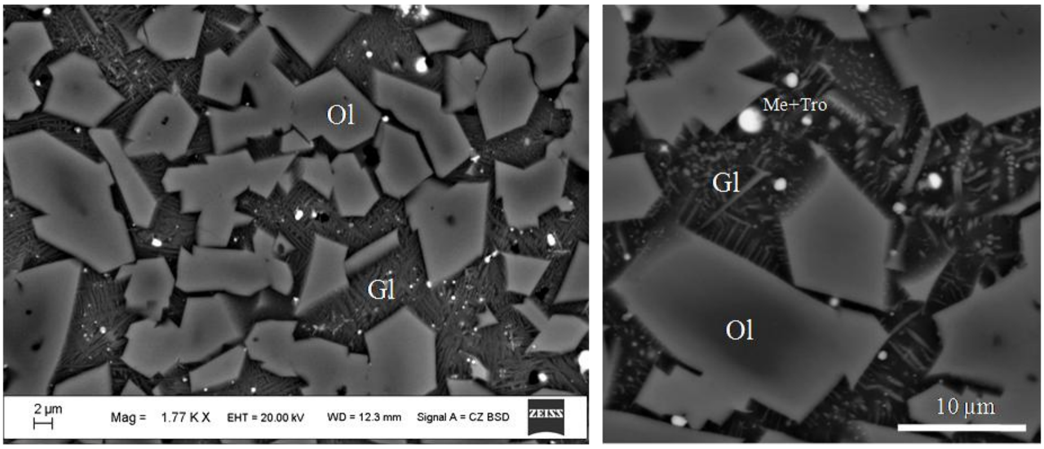

Рис. 4.
Gl), BSE

Fig. 4. Silicate part near the cavities: zoned olivine crystals and rapid-quenched interstitials (Gl), BSE images.

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Mg-Fe- .
-

-
EDS
Mg-Fe- -

-
$NaCa_9(Mg,Fe)(PO_4)_7$.
EDS Fe,
Mg Na Ca

EDS .

Table 2. Chemical composition (EDS, wt.%) of zoned olivine in silicate part near cavities.

Sample	Grain		SiO_2	Cr_2O_3	FeO	MnO	MgO	CaO	Sum	Fo	Fa	Lar
Me-2	large	c	37.64	0.00	25.94	0.44	35.79	0.00	99.81	70.74	29.26	0.00
		m	38.24	0.28	24.52	0.39	35.92	0.56	99.91	71.41	27.79	0.80
Me-2	large	c	37.63	0.00	26.93	0.41	35.33	0.00	100.30	69.72	30.28	0.00
		m	38.25	0.38	22.47	0.39	38.34	0.13	99.96	74.79	25.03	0.18
Me-2	large	c	37.41	0.00	26.72	0.56	34.98	0.00	99.67	69.55	30.45	0.00
		m	38.37	0.37	22.00	0.36	38.36	0.14	99.60	75.20	24.60	0.20
Me-2-2	small	c	39.70	0.38	14.63	0.18	44.93	0.00	99.82	84.39	15.61	0.00
		r	37.52	0.47	26.18	0.46	34.22	0.15	99.00	69.44	30.34	0.22
Me-12	small	c	39.23	0.31	19.88	0.46	39.85	0.21	99.94	77.50	22.21	0.29
		r	37.24	0.50	27.77	0.68	33.52	0.13	99.84	67.60	32.21	0.19
Me-25-1	large	c	37.28	0.00	26.51	0.48	35.13	0.00	99.40	69.87	30.13	0.00
		c	37.38	0.00	26.89	0.48	35.16	0.00	99.91	69.59	30.41	0.00
		c	37.56	0.00	26.31	0.41	35.68	0.00	99.96	70.41	29.59	0.00
		m	38.76	0.32	20.69	0.36	39.72	0.11	99.96	76.96	22.89	0.15
		m	38.48	0.28	19.85	0.43	40.48	0.17	99.69	77.87	21.90	0.24
		m	39.08	0.44	19.06	0.25	40.93	0.14	99.90	78.91	20.90	0.19
		r	37.43	0.41	25.56	0.48	35.24	0.00	99.12	70.68	29.32	0.00
Me-25-3	small	r	33.58	0.38	46.85	0.50	18.64	0.00	99.95	41.23	58.77	0.00
Me-25-4	small	c	36.71	0.25	28.94	0.40	33.00	0.24	99.54	66.48	33.17	0.35

Примечание: large - >80-100 small - c, m, r - - - ; Ni (<0.05 Fo ; Fa (+); Lar . %.

Note: large - large olivine grains (>80- m); small small olivine grains (10- m); c, m, r - core-middle-rim of crystal; Ni is below detection limit (<0.5 wt.%). Fo forsterite; Fa fayalite (+tephroite); Lar larnite in mole %.

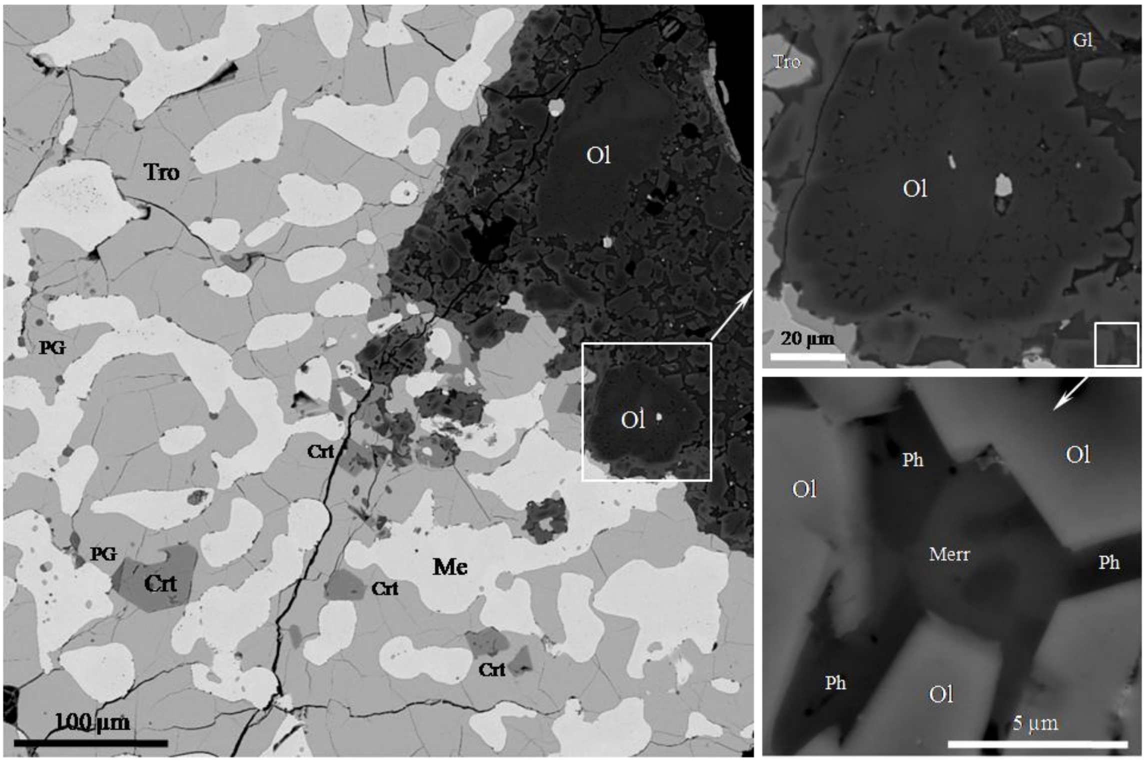

Рис. 5. - BSE

Примечание: Crt PG Merr Ph Na-Ca-Mg-Fe- . 1-4.

Fig. 5. Silicate part in the contact of large cavity with metal-troilite aggregate, BSE images.

Note: Crt chromite; PG phosphate globules; Merr merrillite?; Ph unidentified Na-Ca-Mg-Fe-phosphate. Other symbols see Figs. 1-4.

(30)

Mg, Ti Al,

$(Fe_{0.98}Mn_{0.02})(Cr_{1.89\text{-}1.94}Fe_{0.04\text{-}0.09}V_{0.02\text{-}0.03})O_4$,

$(Fe_{0.87\text{-}0.90}Mg_{0.10\text{-}0.13}Mn_{0.02})(Cr_{1.55\text{-}1.65}Al_{0.22\text{-}0.28}Fe_{0.09\text{-}0.15}Ti_{0.06\text{-}0.10}V_{0.01\text{-}0.02})O_4$

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2. EDS .

Table 2. Chemical composition (EDS, wt.%) of chromite in and near cavities.

Sample		TiO_2	Cr_2O_3	V_2O_3	Al_2O_3	FeO	MnO	MgO	Sum
Me-2	in Ol	2.40	55.15	0.84	6.22	33.02	0.49	1.53	99.65
Me-2	c	0.00	64.14	0.71	0.00	33.75	0.74	0.20	99.54
Me-7-2	c	0.00	64.91	0.85	0.00	33.28	0.44	0.00	99.48
	r	0.00	64.36	0.50	0.23	33.64	0.75	0.00	99.48
Me-12	c	0.00	63.53	0.65	0.00	34.71	0.52	0.00	99.41
Me-12	c	0.00	64.39	0.88	0.00	33.70	0.77	0.00	99.74
Me-12	c	0.00	64.40	0.60	0.00	33.94	0.41	0.00	99.35
Me-25	c	0.00	64.29	0.68	0.00	33.86	0.61	0.00	99.44
	r	0.00	63.74	0.74	0.00	34.39	0.59	0.00	99.46
	r	0.00	63.57	0.51	0.00	34.65	0.68	0.00	99.41
	r	0.00	63.56	0.50	0.00	34.73	0.67	0.00	99.46

Примечание: in Ol c, r - - ; Ni (<0.05

Note: in Ol inclusion in large olivine; c, r - core-rim of crystal; Ni is below detection limit (<0.05 wt.%).

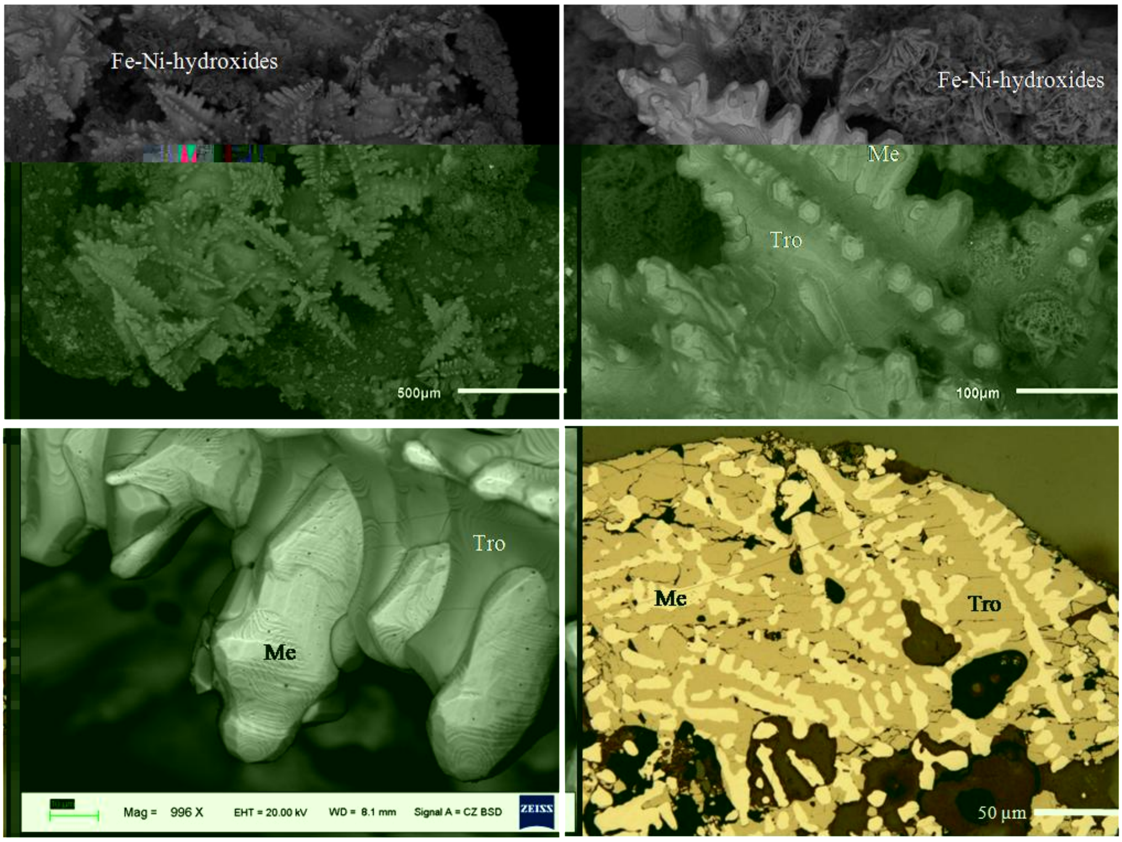

Рис. 6. BSE

Fig. 6. Morphology of dendritic/skeletal metal crystals from large cavities, images in BSE and reflected light.

Металл-троилитовый скелетный агрегат в пустотах

EDS)

-

-

(EDS EBSD 7-8).

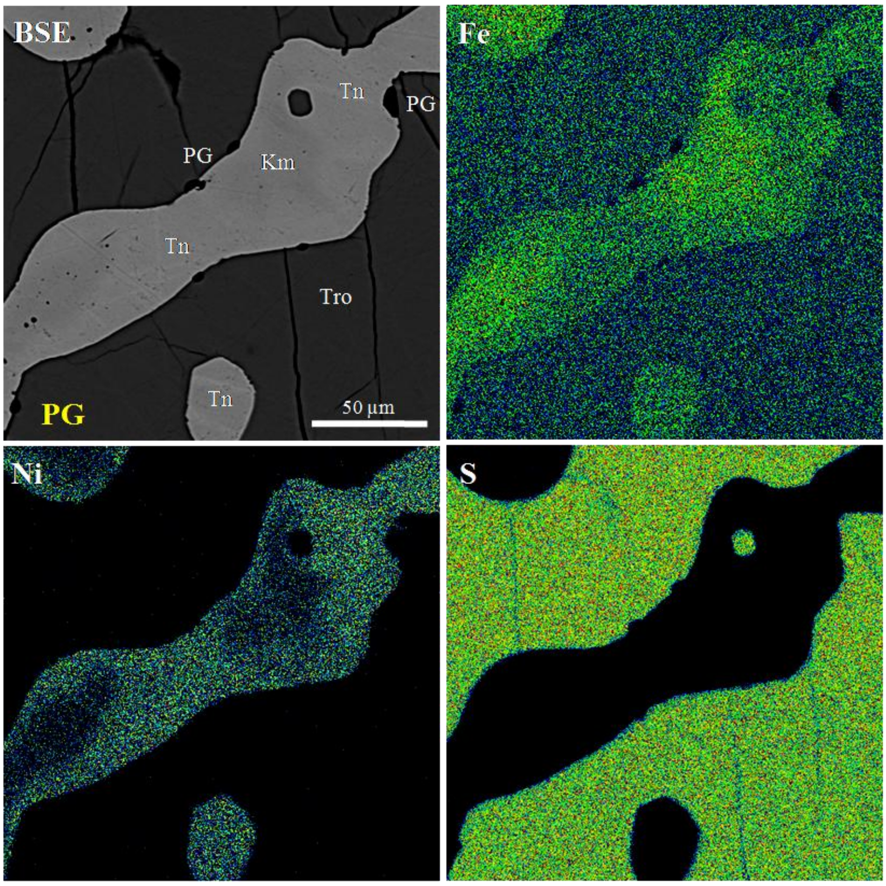

Рис. 7. BSE -

Fig. 7. BSE image and elemental maps for a part of dendritic-skeletal metal crystal.

Ni

Fe.

: Fe 77.4-85.2; Ni 13.5-19.6; Co 1.2-1.6).

Ni

EBSD

: Fe -64.7-70.1; Ni 28.1-33.6; Co 1.2-1.6).

-

Ni -

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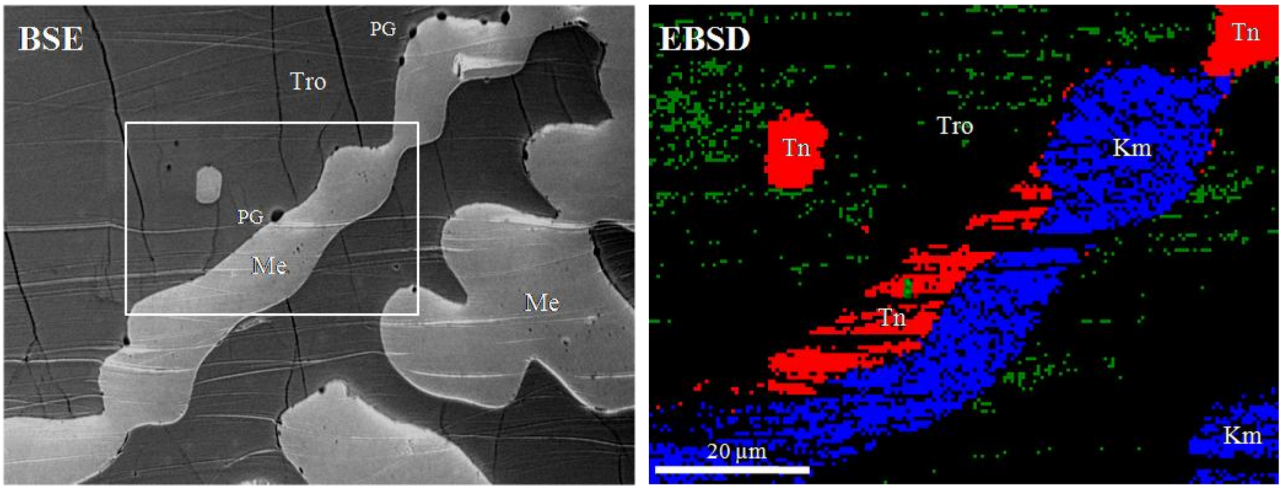

Рис. 8. EBSD -
Примечание: -

Fig. 8. EBSD mapping for a part of dendritic-skeletal metal crystal.
Note: reference standards kamacite, taenite and troilite.

FeS

Ni .

-

EDS): Fe 44.5; Ni 18.7; Co 0.6; Cu 2.7; S 33.0.

- Fe-

Ni- FeO NiO

NiO (<2

NiO

Фазовый и химический состав фосфатных глобул в металл-троилитовом агрегате

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- -

$Na(Fe^{2+},Mn^{2+})_4(PO_4)_3$ $\{Fe^{2+}\}\{Na_8\}\{Fe^{2+}{}_4Na_4\}\{Fe^{2+}{}_{43}\}(PO_4)_{36}$ -

, $(Fe^{2+},Mn^{2+},Na)_3(PO_4)_2$ Na-Fe- (NFP)

$Na_2(Fe^{2+},Mn^{2+})_5(PO_4)_4$. Na

$Na_4Fe^{2+}{}_7(PO_4)_6$, -

3. (EDS , .%)

- .

Table 3. Chemical composition (EDS, wt.%) of kamacite and taenite from dendritic/skeletal crystals in metal-troilite aggregate.

Sample	Mineral	Fe	Co	Ni	Sum
Me-3-1	Kamacite	84.22	1.44	14.26	99.92
Me-3-3	Kamacite	83.87	1.34	14.55	99.76
	Kamacite	82.49	1.30	15.37	99.16
Me-3-4	Kamacite	78.71	1.67	18.74	99.12
Me-3-5	Kamacite	83.05	1.41	14.66	99.12
Me-4-1	Kamacite	85.07	1.45	13.30	99.82
	Taenite	67.19	1.35	31.63	100.17
Me-4-2	Kamacite	83.15	1.39	14.80	99.34
	Kamacite	79.66	1.39	18.73	99.78
	Taenite	69.55	1.04	28.92	99.51
	Taenite	64.87	1.16	33.78	99.81
	Taenite	66.21	1.30	32.50	100.01
	Taenite	66.97	1.23	31.63	99.83
Me-5-1	Kamacite	84.38	1.30	13.98	99.66
	Taenite	66.34	1.34	31.56	99.24
	Taenite	66.14	1.25	32.40	99.79
Me-5-2	Kamacite	85.17	1.23	13.63	100.03
Me-7-2	Kamacite	79.61	1.45	17.95	99.01
	Kamacite	83.90	1.59	14.28	99.77
Me-14-1	Kamacite	83.00	1.21	15.38	99.59
	Kamacite	82.61	1.37	15.40	99.38
	Taenite	69.40	1.55	28.36	99.31
Me-25-1	Kamacite	83.21	1.28	15.15	99.64
Me-25-5	Taenite	70.06	1.47	28.06	99.59
Me-25-6	Taenite	70.02	1.47	28.12	99.61
Me-25-8	Taenite	69.32	1.43	28.78	99.53
Me-25-11	Kamacite	79.26	1.48	18.92	99.66
Me-30	Kamacite	83.94	1.47	14.16	99.57
	Kamacite	83.40	1.58	14.60	99.58
	Kamacite	82.07	1.33	16.61	100.01
	Kamacite	82.31	1.38	15.61	99.30
	Kamacite	83.67	1.39	14.51	99.57

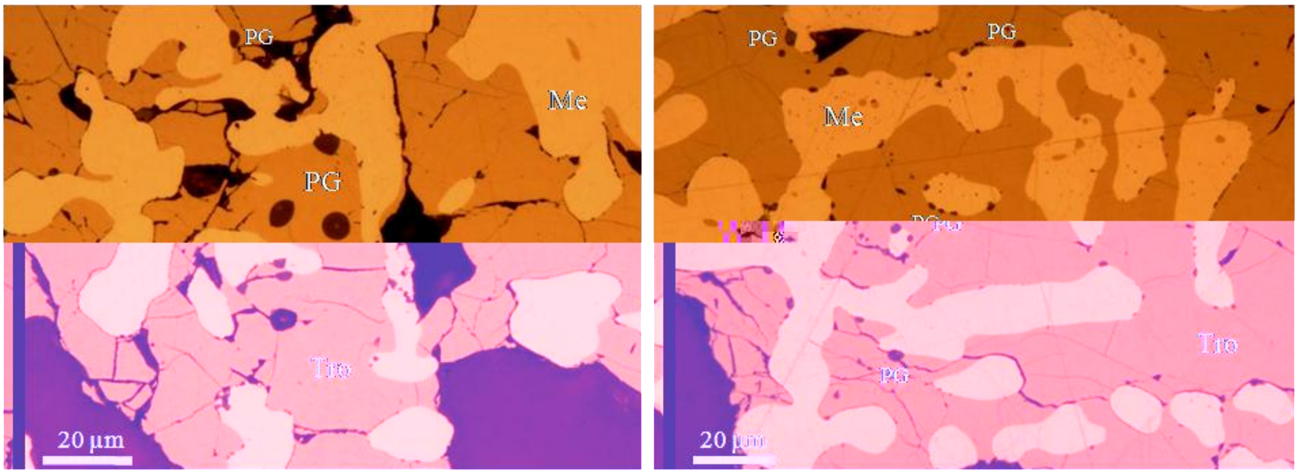

Рис. 9. -

Fig. 9. Position of phosphate globules in the metal-troilite aggregate (reflected light).

Fe-
- .

-
(Olsen et al., 1999; Grew et al., 2010).
-11

NFP NFP, NFP + Fe-
NFP

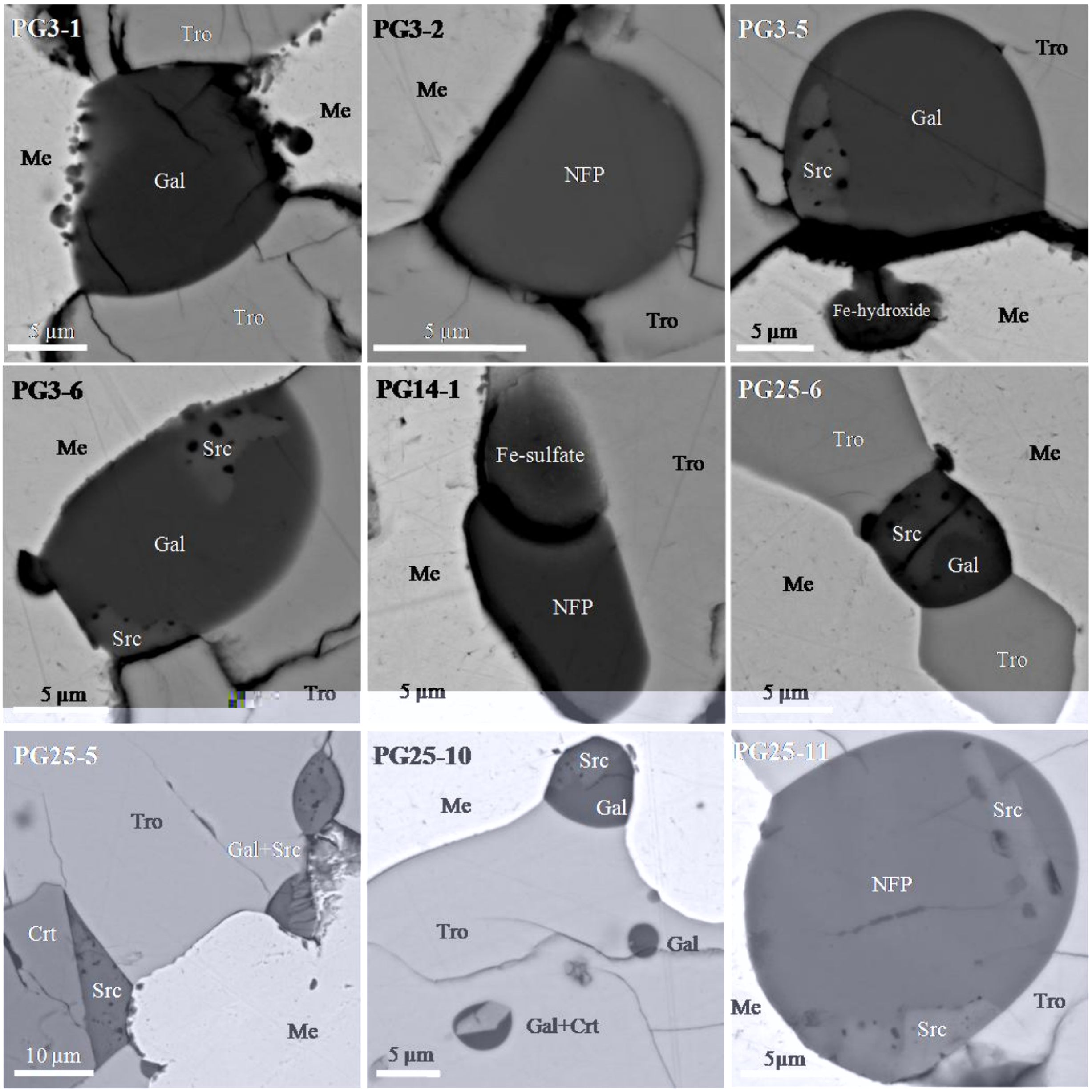

Рис. 10. - BSE Src ; Gal NFP Na-Fe-

Fig. 10. Phase composition of phosphate globules in the metal-troilite aggregate (BSE images). Src sarcopside; Gal galileiite; NFP unidentified Na-Fe-phosphate.

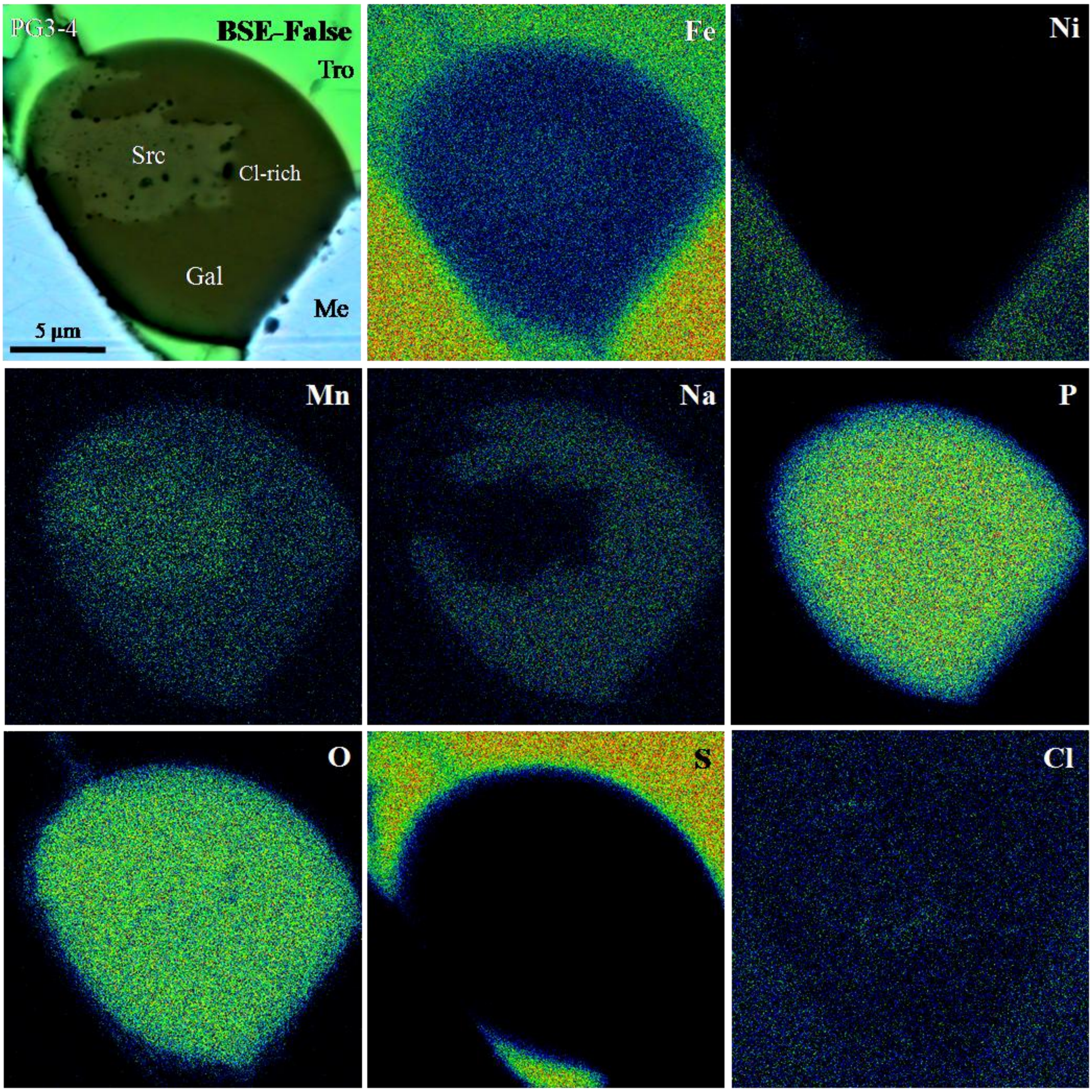

Рис. 11. -

Fig. 11. Elemental maps for a phosphate globule in the metal-troilite aggregate.

BSE , (. 11).

-11).

SO_3 SiO_2, NiO, Cr_2O_3 Cl MnO NFP K_2O NFP SiO_2 (0.7 MgO (1.5 aO (0.8

4 EDS -

Table 4. Chemical composition (EDS, wt.%) of phosphate minerals from globules in metal-troilite aggregate.

Globula	*n*	Phas	SiO_2	P_2O_5	SO_3	Cr_2O_3	FeO	MnO	NiO	Na_2O	K_2O	Cl	Sum
PG3-1	*3*	Gal		38.10	0.54	0.00	49.68	4.72	0.98	6.27	0.07		100.37
PG3-2	*3*	NFP		39.96	0.51	0.31	42.34	7.69		8.83	0.20	0.45	100.28
PG3-3	*1*	Gal		39.62	0.57	0.00	48.93	5.16	0.00	6.17	0.12		100.57
PG3-4	*3*	Src		38.59	0.52	0.05	51.33	7.93	0.09	0.41	0.00	0.17	99.11
	3	Gal		38.81	0.54	0.00	48.71	5.10	0.34	6.11	0.00	0.00	99.61
PG3-5	*2*	Src		39.34	0.70	0.00	50.94	8.42	0.00	0.39	0.00		99.78
	5	Gal		38.88	0.47	0.00	48.49	4.71	0.00	6.10	0.15		98.80
PG3-6	*3*	Gal		38.99	0.34	0.00	49.30	4.67	0.00	6.39	0.10	0.19	99.99
PG14-1	*4*	NFP		40.10	0.50	0.00	46.74	3.87	0.00	8.09	0.06	0.00	99.35
PG25-6	*1*	Gal		38.49	0.87		47.84	5.71	0.36	6.34	0.00		99.61
	1	Src		38.69	0.51		55.63	3.95	0.38	0.82	0.00		99.98
PG25-10	*1*	Gal		38.65	0.65		50.52	4.21	0.28	6.19			100.50
	1	Src		38.82	0.52		52.94	5.46	0.53	0.78			99.05
PG-25-11	*4*	NFP	0.26	39.75	0.43		47.21	3.86	0.00	8.28	0.12	0.24	99.81
	1	Src	0.34	38.56	0.95		53.24	5.55	0.32	0.61	0.00	0.10	100.15
PG-25-9*	*4*	NFP	0.74	38.55	0.98	0.00	43.38	6.63	0.32	7.38	0.14	0.38	100.73

Примечание: Src ; Gal ; NFP Na-Fe- ; Ca Mg (<0.1 .%). -11. * - 1.48 .% MgO 0.75 .% CaO.

Note: Src sarcopside; Gal galileiite; NFP unidentified Na-Fe-phosphate; Ca and Mg are below detection limits (<0.1 wt.%). Globule numbers see Fig. 10-11. * - sum includes 1.48 wt.% MgO and 0.75 wt.% CaO.

Na_2O (%).
Na
Na-Fe- -
Na .

(Calvo, 1968; Moore, 1972; Nord, Ericsson, 1982; Steele et al., 1991; Grew et al., 2007)
$^{2+})_3$ $](PO_4)_2$ -

$+ P^{5+}$ $^{+}$ $+ Si^{4+}$, 2 $+ P^{5+}$ $^{+}$ $+ Al^{3+}$ $+ Fe^{2+}$ $^{+}$ + Na^{+}

$FeFe_2(PO_4)_2$
$LiLiFe_2(PO_4)_2$ (Moore, 1972).
, Na-Fe-
- (
Na-Ca-Mg-Fe-
LL Jones et al., 2014).
$_3(PO_4)_2$ -Mg-Mn-

IIIAB (Olsen, Fredriksson, 1966; Bild, 1974; Steele et al., 1991; Floss, 1999; McCoy et al., 2006; Grew et al., 2007; 2010) Na-Fe-
(
-Mn-Mg-
IIIAB (Floss, 1999; Olsen, Steele, 1993, 1997; Olsen et al., 1999; Grew et al., 2010). -
Na-Fe- (Yanzhuang H6
, Krymka LL3.1 -
(Chen, Xie, 1996; Semenenko, Perron, 2005; Xie et al., 2014). Na-Fe-
Na-Fe-
Yanzhuang
$Na_2(Fe,Mn)_{17}(PO_4)_{12}$ (Xie et al., 2014).

Обсуждение

-
, Rubin, 1985)

PT-

S5 S6.

Mg, Ti Al;
- (

Sharygin et al., 2013 a-b).

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Fe-Ni-

, Na-Fe- (NFP).

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Yanzhuang Xie et al. (2014)

Na-Fe-

Fe-Ni-S-O

- -

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Na-Fe-

Fe-Ni-S-O

(NFP) -

Yanzhuang H6 Krymka LL3.1 (Chen, Xie, 1996; Semenenko, Perron, 2005; Xie et al., 2014).

C, O, Cl

$(Fe,Ni)_{23}C_6$ - Grokhovsky et al., 2015). Fe-

Благодарности

(-35-21164 mol_a_ved)
ОРТЕС .

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