

Boundaries of Intergrowths between Mineral Individuals: A Zone of Secondary Mineral Formation in Aggregates

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Abstract—Intergrowth boundaries between mineral individuals in dunite of the Gal'moenan massif in Koryakia was studied in terms of crystal morphology, crystal optics, and ontogenesis. The results obtained allowed us to trace the staged formation of olivine and chromite and four generations of these minerals. Micro- and nanotopography of boundary surfaces between intergrown mineral individuals of different generations was examined with optic, electron, and atomic force microscopes. The boundaries between mineral individuals of different generations are distinguished by their microsculpture for both olivine and chromite grains. Both minerals demonstrate a compositional trend toward refinement from older to younger generations. The decrease in the iron mole fraction in olivine and chromite is accompanied by the crystallization of magnetite along weakened zones in olivine of the first generation and as outer rims around the chromite grains of the second generation observable under optic and electronic microscopes. The subsequent refinement of chromite results in the release of PGE from its lattice, as established by atomic power microscopy. The newly formed PGM are localized at the boundaries between mineral individuals and, thus, mark a special stage in the ontogenetic evolution of mineral aggregates. Further recrystallization is expressed in the spatial redistribution of grain boundaries and the formation of monomineralic intergrowth boundaries, i.e., the glomerogranular structure of rock and substructures of PGM, chromite, and olivine grains as intermediate types of organization of the granular assemblies in the form of reticulate, chain, and cellular structures and substructures of aggregates.

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INTRODUCTION

The boundaries of mineral individuals and their intergrowths in mineral aggregates mark energetic and force fields in the systems of mineral and rock formation, i.e., mobility, distribution, the frequency of boundaries, as well as the intensity of pressure, temperature, and concentration gradients during crystallization and other kinetic characteristics of the growth and dissolution of mineral grains. During recrystallization, the lattice is refined from the defects and impurities captured by an individual during its growth. The process is realized by means of defect migration. The variation in the thermodynamic conditions of a mineral system as a whole or in the vicinity of particular grains gives impetus to this process. This is the heart of the previously stated model that elucidates one possible mode of the formation of ore minerals and their concentration in aggregates (Brodskaya and Marin, 2000, 2001). The objective of this study is to provide insights into the specific mechanism of this model, i.e., the formation of boundaries of mineral individuals at different stages of their ontogenetic evolution. The boundaries of mineral grains of different generations observed in a raster of

magnification, their surface, topography, and composition are the subjects of our investigation.

To develop the criteria and attributes of the recrystallization of Cr-spinel-bearing rocks, the boundaries of mineral individuals were preliminary studied and characterized in quantitative terms on samples from the collections of L.I. Gurskaya, B.A. Markovsky, and E.G. Sidorov (Brodskaya et al., 2003). In this publication, we present the results of the study of the structure and intergrowth boundaries of mineral individuals in PGM- and chromite-bearing ultramafic rocks of the Gal'moenan massif examined with optic, electron, and atomic force microscopes.

GEOLOGY AND PETROGRAPHY OF THE GAL'MOENAN MASSIF

The Gal'moenan massif situated in the interfluvium of the Vetvei and Gal'mitapelvayam rivers in the Olyutor Zone of the Koryak Highland is an element of the extended Koryak-Kamchatka belt of the zonal dunite-clinopyroxenite-gabbro intrusions (*The Koryak-Kamchatka...*, 2002). Along with the country Upper Cretaceous cherty-volcanic sequence, the massif pertains to the Seinav Allochthon. Being a rootless tectonic sheet as thick as 1000–1200 m, the Gal'moenan massif nev-

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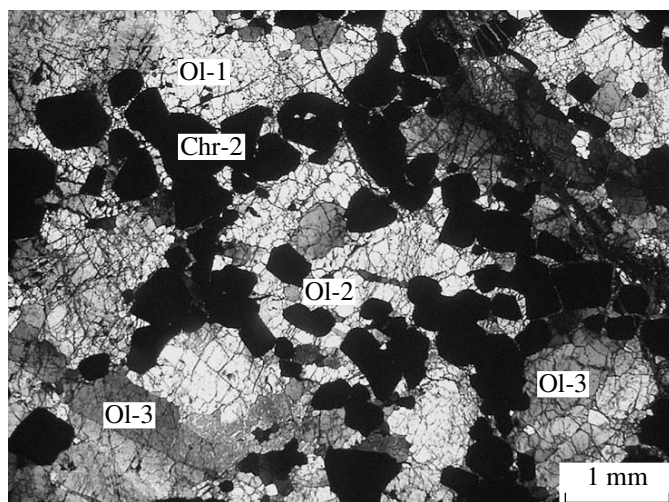


Fig. 1. Relationships between various generations of olivine and chromite. Ol-1, Ol-2, and Ol-3 are generations of olivine and Chr-1 and Chr-2 are generations of chromite grains and subaggregates. Transmitted light with an analyzer.

ertheless is characterized by a well-retained concentrically zoned structure. This is an oval $16 \times 2.0\text{--}3.5$ km² in size (in plane view); its area is ~48 km². The core of the massif is occupied by dunite surrounded at the margins by clinopyroxene-bearing dunite, wehrlite, olivine clinopyroxenite, and clinopyroxenite. The amphibole-magnetite clinopyroxenite that occurs in the northern part of the massif grades into clinopyroxene-bearing hornblendite. In the east and north, the massif is framed by lenticular bodies of gabbro and monzogabbro, which cut through clinopyroxenite and locally reveal a gradual transition with the latter via plagioclase-bearing clinopyroxenite. The western boundary of the massif is largely tectonic and accompanied by serpentinite melange along the thrust fault. On the northern and eastern sides, segments of the intrusive contact of clinopyroxenite, hornblendite, and gabbroids with country rocks are retained and emphasized by the aureole of biotite-pyroxene-quartz hornfels.

Dunite is characterized by an extremely unaltered appearance and underwent serpentinization only along the fault zones, especially along the thrust fault at the western boundary of the massif. The coarse-grained porphyroblastic dunite with indications of intense ductile deformation (mosaic and wavy extinction, simple and polysynthetic twins, etc.) is predominant in the core and tends to grade into medium- and fine-grained varieties with a granular (granoblastic) structure in the zone transitional to the outer dunite-clinopyroxenite shell. The rocks of this shell make up a rim 200–500 m wide and are characterized by the occurrence of euhedral olivine and, as a rule, by the absence of evidence for ductile deformation. This general zoning is complicated by the occurrence of layers and lenses of inequigranular and more or less recrystallized dunite in the core of massif with the formation of local banded

zones. The banding is locally emphasized by plate jointing of the same orientation in support of the syntectonic nature of dunite recrystallization. The lenses and blocks of coarse-grained dunite are also embedded into the fine-grained, allo-hypidiomorphic-granular dunite of the marginal zone. The transition to the porphyroclastic variety is marked by the appearance of relatively large olivine crystals and isometric, polygonal and rounded grains incorporated into the fine-grained matrix. Further recrystallization leads to the development of the porphyritic appearance of rocks with relics of frequently elongated and tectonized olivine porphyroclasts incorporated into the fine-grained matrix. This physiographic diversity of dunites predetermined equivocal genetic concepts and different opinions about the relationships of Cr-spinel and PGM grains to certain types of dunites.

The central portion of the dunite core, especially in its southern, most eroded part is enriched in Cr-spinel, which occurs as disseminations, veinlets, small schlieren, and pockets up to 0.5–1.0 m in size. A gray dunite variety saturated with minute Cr-spinel grains is noteworthy. The PGE mineralization is related to chromite-bearing dunite and chromite segregations that serve as the primary source of placer PGM deposits (*Petrology...*, 2001; *The Koryak-Kamchatka...*, 2002).

The examination of thin sections and samples of rocks from the Gal'moenan massif allowed us to recognize several generations of olivine, Cr-spinel, and serpentine, which testify to the multistage history of the massif and the particular rocks therein. The certain generation of olivine and chromite differ from one another in the morphology and anatomy of individuals and reveal visible breaks in the mineral and crystal formation that are consistent with their compositional differences. The morphology, anatomy, and spatial relations of olivine and chromite grains pertaining to different generations are shown in Figs. 1–4.

The anatomy of mineral individuals and the character of their boundaries indicates that the rocks underwent multistage recrystallization with contemporaneous self-refinement and annihilation (both thermal and deformational) of lattice defects in olivine as the major rock-forming mineral. This follows from observations on the subboundaries of mineral grains, inclined walls, and loops with the occasional retention of fine serpentine relics. This is also supported by observations on the formation of porphyroblasts and their granulation. Each generation of minerals is distinguished by the specific spatial distribution of the grains and the special matrix of intergrowth boundaries and neighboring grains. The rocks are not uniform in their structure. The panidiomorphic-granular structure is predominant in combination with hypidiomorphic-granular and glomerogranular structures. The latter is typical of both olivine and chromite. The glomerogranular segregations of chromite appear as chains and half-closed cells. In some cases, they frame olivine crystals or their subag-

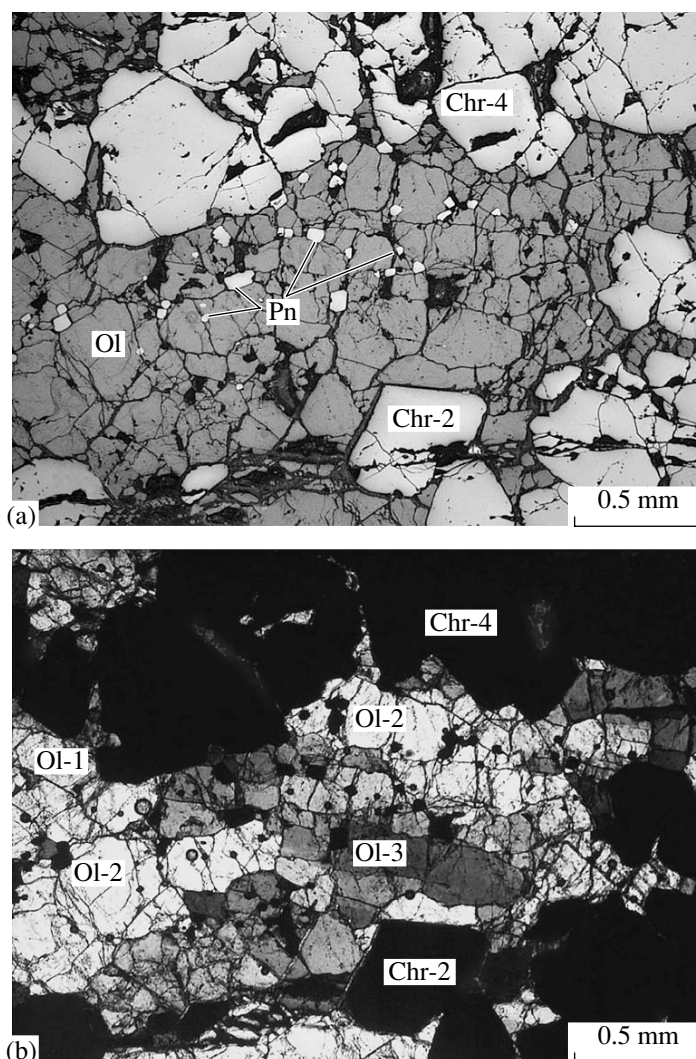


Fig. 2. Regular distribution of small pentlandite grains in olivine of the second and third generations: (a) reflected light without an analyzer and (b) transmitted light with an analyzer.

gregates. The distribution of chromite subaggregates tends to the formation of separate pockets. The texture of the aggregate is massive.

PHYSIOGRAPHY OF MINERALS

Olivine is observed as three generations; four generations are distinguished in particular samples. The olivine individuals pertaining to the first generation Ol-1 (the earliest of the retained) reveal an exsolution microstructure in form of chromite and magnetite grains, which indicate the presence of Fe^{3+} and Cr^{3+} in the olivine lattice. In some areas, the exsolution structure is decorated by the remains of marginal dislocations with distinctly discernible serpentine relics. Grains of the ore mineral are often seen in the same areas. The size of these grains correspond to the detection limit of an optic microscope (5–7 μm). Small pentlandite grains identified in the reflected light are regularly arranged in

the space of olivine grains (Fig. 2a). Mineral individuals of olivine of the second generation (Ol-2) are organized in subaggregates of relatively small isometric grains. It is noteworthy that the boundaries of the olivine crystals that make up the outer boundary of glomerogranular segregations have euhedral outlines. Some segments of the outer boundaries coincide with the faces of an orthorhombic prism and pinacoids. At the same time, the internal boundaries within the subaggregate and the boundaries of intergrown olivine individuals are distinguished by the faces of high-symmetry forms or relics of subboundaries. Olivine grains of the third generation (Ol-3) are identified from their characteristic anatomy in the form of “quasi-twinning” that resembles polysynthetic twins in their outward appearance. Serpentine relics replaced by younger olivine are seen within these grains as well. The last generation of olivine is characterized by the richest euhedral faceting of

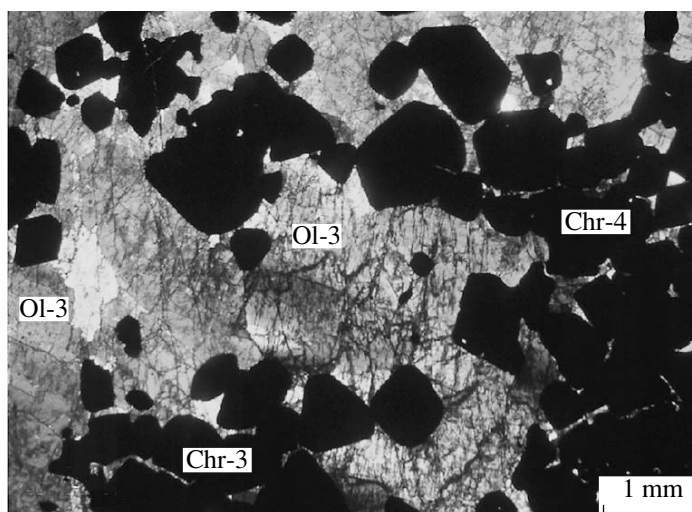


Fig. 3. Relationship of the boundaries between individuals of olivine (third generation, Ol-3) and individuals of chromite (third generation, Chr-3). Olivine reveals mechanical polysynthetic pseudotwins. Euhedral chromite individuals make up subaggregates during the process of aggradation recrystallization. Transmitted light with an analyzer.

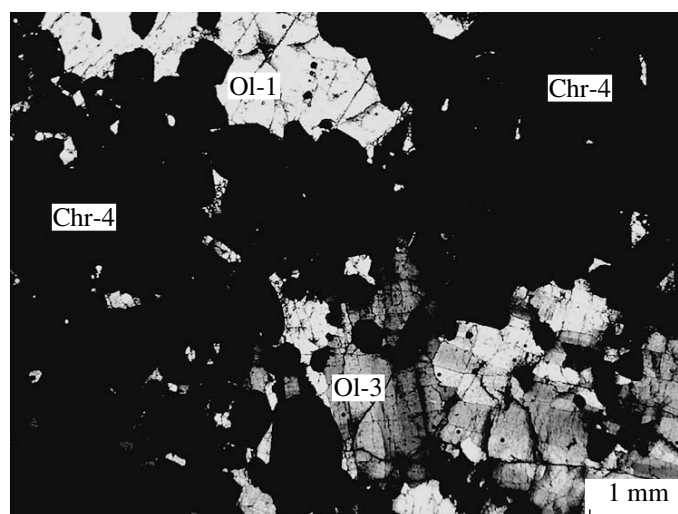


Fig. 4. Relationship of the boundaries between individuals of olivine (first and third generations, Ol-1 and Ol-3) and individuals of chromite (fourth ore-forming generation, Chr-4). Transmitted light with an analyzer.

mineral individuals, an isometric shape of all sections, and the most uniform grain size. The mineral individuals of this generation are devoid of inclined walls, loops, wavy extinction, “polysynthetic twins,” and other attributes of the preceding olivine generations that acquired new boundaries. Most likely, this is the youngest generation of olivine.

Chromite was established in four generations: accessory (Chr-1) (see Fig. 1); the second generation of intergrowths at the initial stage of refinement and subaggregation (Chr-2) (see Fig. 1); and the third generation of chromite (Chr-3) is recognized as loose subaggregates with euhedral outer boundaries (Fig. 3). The

fourth generation (Chr-4) occurs as relatively large subaggregates (Fig. 4). The boundaries between intergrown chromite grains are largely high-symmetry faces with an appreciable roughness. Small PGM grains (isoferrroplatinum, intermetallides, sperrylite, laurite (Fig. 5), etc.) may be incorporated into these subaggregates. The small pyrrhotite and pentlandite grains observed here are younger relative to the silicate framework of the rock as follows from the absence of habit forms in the faceting of sulfides (Brodskaya, 1990), which are inherent to accessory minerals (Fig. 2a).

An examination of the boundaries of mineral individuals with an electron microscope performed at the

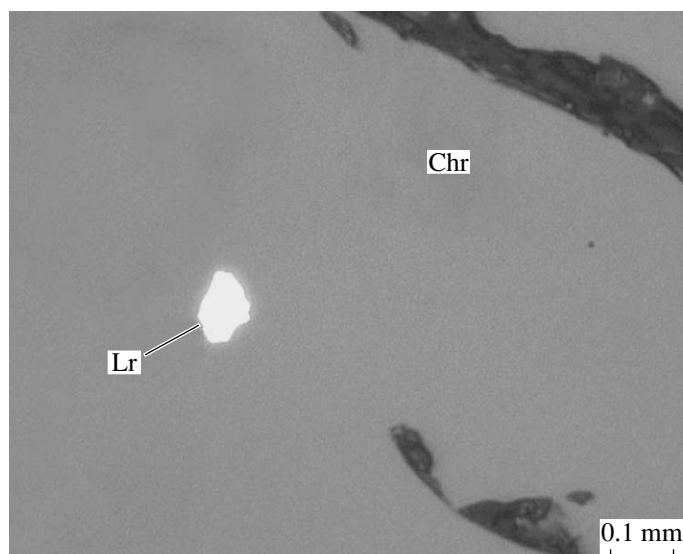


Fig. 5. A grain of laurite RuS_2 (Lr) with isomorphic Pt in chromite (Chr). Reflected light without an analyzer.

Institute of Geology, Komi Scientific Center, Ural Division, Russian Academy of Sciences (IG UD RAS) by V.N. Filippov showed a different degree of roughness for particular generations. The smoothest boundaries and the most homogeneous composition are inherent to chromite of the first generation termed *accessory*. The boundaries of mineral individuals of Chr-2 have rougher surfaces at their intergrowth with one another. The elemental composition of chromite is characterized by a decrease in the Fe content and an increase in the Cr content from older generations to younger (Table 1). A rim of magnetite that is released owing to the recrystallization and self-refinement of chromite intergrowths and subaggregates is clearly seen under optic and electron microscopes (Figs. 6 and 7).

An examination of the boundaries of individual minearls of intergrown chromite and olivine with an atomic force microscope at the IG UD RAS allowed us to reveal some indicative microtopographic features. The surface of olivine individuals of the first generation bears the character of numerous shears, where smooth flat segments alternate with sharp projections and grooves. The surface of mineral individuals of Ol-2 is marked by chaotically oriented hummocks of growth. At the boundaries of Ol-3, the hummocks and spherical juts are arranged into elongated rows of different sizes. Unfortunately, we failed to determine the optic orientation of these “ranks.”

Different micro- and nanosculptural features are observed at the boundaries of the intergrown olivine grains, olivine with chromite, olivine with serpentine, and chromite with serpentine (Fig. 8). The surface of an individual is commonly deemed to be a 2D phase, which is accessible to examination using optic, elec-

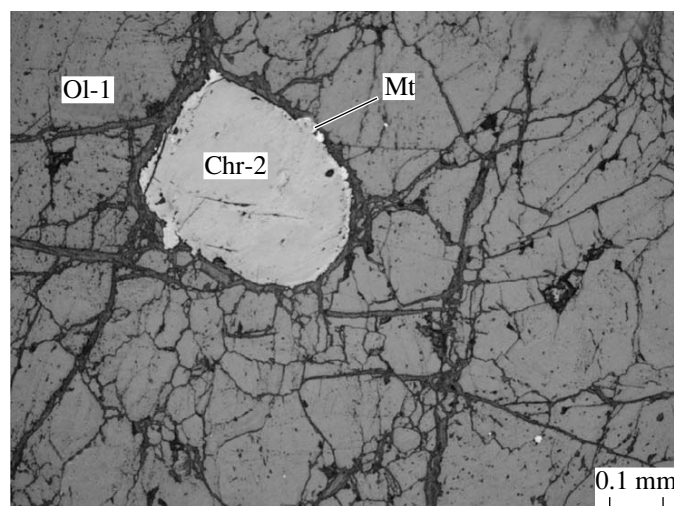


Fig. 6. Subaggregate of chromite grains of the second generation (Chr-2) with a brighter magnetite rim (Mt). Reflected light without an analyzer. The result of the recrystallization with a change in the morphology and the position of the boundaries with a contemporaneous self-refinement of the crystalline lattice. Reflected light without an analyzer.

tron, and atomic force microscopy; characterized by a sculpture or roughness; and may be compared with the surface of a face. It is noteworthy that the degree of roughness depends on the degree of coherence of the structure in the boundary zone, its thickness, and the rate of relaxation of the crystal lattice of an individual in the direction toward a certain boundary. Hence, the topography of the surface of the individual is controlled by the kinetic parameters of the growth of mineral individuals and the formation of aggregates. In terms of the physics, it is precisely the dislocation structure of the boundary and weak, undersaturated bonds, i.e., energy

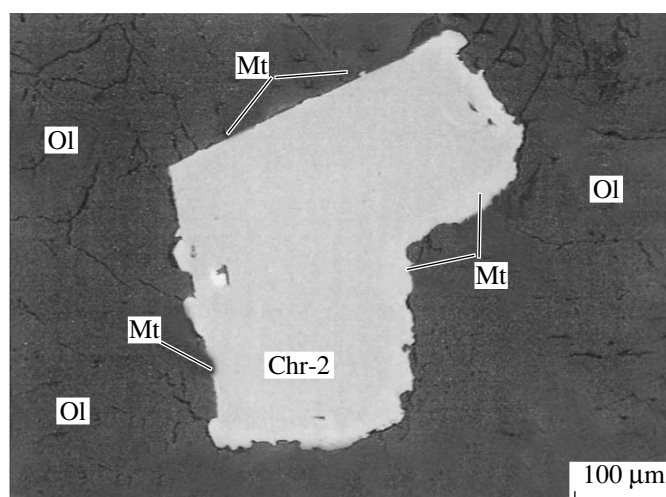


Fig. 7. A grain of chromite of the second generation (Chr-2) with a magnetite rim (Mt) in a subaggregate of olivine grains (Ol). SEM image.

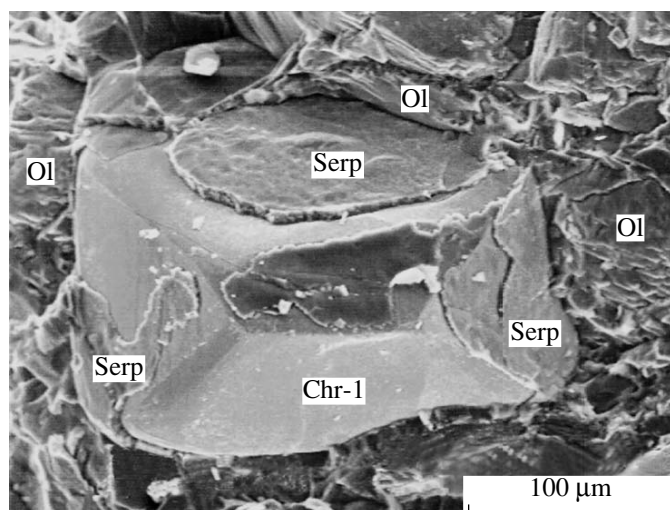


Fig. 8. Crystal of an accessory chromite of the first generation (Chr-1) in olivine (Ol) surrounded by serpentine (Serp). SEM image.

capacity of the planar defect of the crystalline body (Tauson et al., 2004), that provide the mobility of the boundary under variable outer conditions of crystallization or relaxation, the growth of an individual, or its dissolution. Namely these causes likely provide different features of the micro- and nanotopography of the boundary surfaces of the individuals referred to as distinct generations.

The character of the surface of individuals of Chr-2 and Chr-3 attracts special interest. As soon as the crystal lattice of chromite is freed from the magnetite end member during the process of recrystallization, chromite experiences PGE exsolution. The released PGM look like near-parallel oblong grains of a similar size and orientation localized at the boundaries of the chromite grains (Figs. 9a–9c). The aggradation recrystallization of this new mineral phase is also a staged process. The exsolution structure of PGM in chromite and the inhomogeneity of platinum and its zoning are clearly seen in Fig. 9. It is evident that this zoning is controlled by the pulses of exsolution.

Furthermore, the process is going on in several directions. The PGM phases appear in the center of the glomerogranular chromite aggregates and, over time, are involved in aggradation recrystallization forming large monomineralic subaggregates. As follows from the analytical data, the PGM composition does not remain unchanged for all grains detected even within the same polished section (Table 2) or the same subaggregate of mineral individuals (Table 3). This is caused by the incomplete aggradation recrystallization and self-refinement of the lattice. In the one place, a solid solution with prevalent Pt is noted; in others, Os is prevalent; elsewhere, there is a predominance of Ru. The heterogeneity and diversity of PGE compounds within

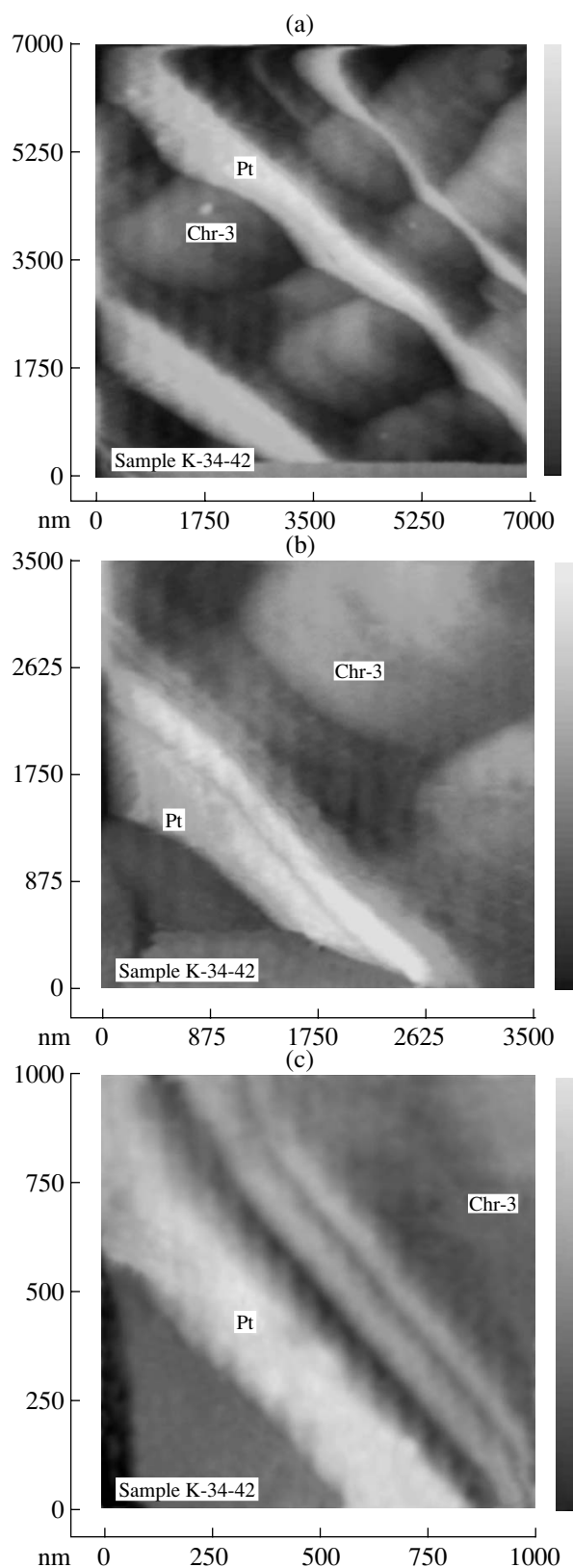


Fig. 9. Exsolution structure of platinum and chromite at the boundary of individuals of chromite (third generation, Chr-3) in the nanometric range, sample K-34-42. Images were made in a raster of magnifications on an ARIS 3500 Burleigh Instruments atomic force microscope.

Table 1. Chemical composition of Cr spinel, wt %

Compo- nent	K-34-42					242-10	24						27-1			
	12c	13c	14m	16c	17c	1c	1c	2m	3c	4m	5c	6m	6c	7m	8c	
	Chr-3					Chr-1	Chr-1			Chr-2	Mt	Chr-1			Chr-2	
MgO	6.42	6.54	6.64	6.61	6.56	6.17	3.38	1.87	5.15	1.97	5.13	1.8	6.22	5.28	7.19	
Al ₂ O ₃	4.82	4.91	4.94	4.58	5.1	4.02	0.47	0.83	6.76	0.23*	6.24	0.49	5.8	5.99	5.66	
TiO ₂	0.54	0.64	0.43	0.63	0.52	0.29	0.51	0.5	0.28	0	0.43	0.52	0.38	0.21*	0.34	
Cr ₂ O ₃	41.76	40.74	43.13	41.32	40.85	43.62	23.55	17.22	48.15	0.27	47.67	24.81	49.56	48.05	50.93	
MnO	1.11	0.78	0.72	0.76	1.17	0.55	1.85	0.71	0.99	0.48	0.86	1.26	1	1.52	0.91	
Fe ₂ O ₃	45.72	45.43	43.36	44.93	46.33	46.9	70.25	80.66	39.64	94.79	39.37	73.48	37.72	38.56	36.08	
NiO	0	0	0	0.18	0.42	0.09*	0	0.28*	0	0.08*	0	0	0.16*	0	0.21*	
ZnO	0.16	0.2	0.2	0.2	0	0.08*	0.86	0.14*	0.57*	0	0.45*	0.35*	0.46*	0.94	0.33*	
Total	100.53	99.24	99.42	99.21	100.95	101.55	100.87	101.79	101	99.19	99.7	102.4	100.68	100.3	101.11	
Compo- nent	27-2		27-3			27-4		21-1			21-2					
	11c	12m	3m	4c	18c	3m	4c	3m	4c	8m	9c	10c	11c	12c	1c	
	Chr-2		Chr-3			Chr-3		Chr-2		Chr-3?			Chr-1-			Chr-2
MgO	5.36	7.04	6.31	7.1	6.59	6.93	6.73	8.12	7.57	4.8	7.18	6.29	6.07	1.61	5.29	
Al ₂ O ₃	5.65	5.84	5.66	5.88	5.78	4.62	4.65	4.53	4.57	4.34	4.67	4.5	4.38	0.02*	5.59	
TiO ₂	0.4	0.3	0.45	0.39	0.22*	0.49	0.42	0.48	0.49	0.43	0.42	0.43	0.49	1.05	0	
Cr ₂ O ₃	49.63	50.77	52.01	52.14	51.47	48.82	48.3	49.99	49.94	45.09	48.39	47.65	47.8	8.19	51.32	
MnO	1.42	0.93	1.37	0.9	1.11	0.63	0.48*	0.39*	0.56	0.53	0.88	0.54	0.75	0.67	0	
Fe ₂ O ₃	39.63	38.78	37.18	36.7	38.37	38.84	39.15	37.09	37.42	44.09	38.91	41.96	39.19	90.82	36.97	
NiO	0	0.3*	0.17*	0.23*	0.15*	0.21*	0.13*	0.28*		0.1*	0.17*	0.03*	0.05*	0	0.3*	
ZnO	0.48*	0.44*	0.66	0.04*	0.46*	0.17*	0	0.11*	0.22*	0.09*	0	0.17*	0	0.43*	0	
Total	102.09	103.66	103.64	103.11	103.32	100.33	99.25	100.21	100.6	99.28	100.45	101.4	98.68	102.3	99.17	

Note: The upper line in the heading is the sample number; the second line is the analyzed point numbers (c is the core and m is the margin of grains); the third line is the generations of Cr spinel; Mt is magnetite. Measurements were performed on a JSM-6400-Link SEM/EDS at the Institute of Geology, Komi Scientific Center, Syktyvkar, analyst V.N. Filippov.

Table 2. Chemical composition of platinum group minerals, wt %

Ele- ment	24			27-1				27-2							
	awaruite	wairauite		nameless	irarsite	sperrylite	tetraferro- platinum	sper- rylite	irarsite		sper- rylite	nameless			
		1	2						3	4		5	6	7	8
Cr	15														
Fe	2.61	26.35	54.98	25.79	9.09	0.54	0.41	0.76	0.38				0.37	0.91	1.03
Co	23.61	0.07	37.70	0.00	15.98	0.15	0.50	0.91	21.13				0.50	1.32	1.01
Ni	73.44	72.21	2.83	74.04	36.11	0.46									
Cu						68.30	0.55	0.07	6.76					2.93	0.93
Ru			0.01	0.21			2.03	0.05							
Rh								0.45			3.93	5.33			
Os								0.07							
Te				0.41										0.94	1.02
Ag															
Pd			0.05												
Ir			0.12	0.52			58.14	2.25			54.22	55.17			
Pt						31.40	1.49	50.62	71.62		51.72		51.29	40.82	41.80
S				0.04	39.30	0.41	9.20	0.83			9.14	9.76			
As							25.43	42.75	1.22		46.62	26.83	45.15	18.76	13.83
Sb														23.48	26.64
Total	99.66	98.63	95.69	101.01	100.48	101.26	97.75	98.76	101.11		98.34	97.47	97.31	89.16	86.26
Formula coefficients															
Cr	0.03						0.01	0.05	0.01				0.03	0.04	0.10
Fe	0.25	0.28	0.59	0.27	0.33	0.01	0.01	0.06	0.43			0.01	0.03	0.05	0.09
Co		0.00	0.38		0.55	0.00									
Ni	0.73	0.72	0.03	0.73	1.25	0.01								0.11	0.08
Cu						0.85	0.01	0.00	0.12						
Ru								0.00							
Rh			0.00	0.00			0.03	0.02			0.06	0.08			
Os								0.00						0.02	0.04
Te				0.00											
Ag			0.00												
Pd			0.00												
Ir				0.00			0.50	0.04			0.45	0.45			
Pt						0.13	0.01	0.92	0.42		0.31		0.93	0.48	1.07
S				0.00			0.47	0.09			0.45	0.48			
As					1.00	0.00	0.53	1.91	0.02		0.69	0.52	2.00	0.54	0.87
Sb														0.44	1.09

Table 2. (Contd.)

Ele- ment	27-2		27-3		27-4				21-1		21-2				19/71
	tetraferro- platinum	sper- rylite	isoferro- platinum	iridium	isoferroplatinum	nameless			tulameenite		nameless		sper- rylite	nameless	
	9	10	1	2m	14	15m	16m	17m	1	2	1	2m	5	6	7
Cr	2.14	0.33	1.70	2.64		1.05	2.89	3.13	1.66	2.46	1.17	1.58	1.39	0.98	0.87
Fe	21.18	0.62	8.87	2.28	8.55	9.05	13.59	13.76	10.82	11.42	10.69	10.89	2.04	8.60	11.99
Ni	2.73	0.21					0.47	0.63	1.08	1.08	1.07	0.72		1.18	3.78
Cu									0.28						4.31
Ru				1.38											
Rh				1.48											
Os				5.94			2.45	2.82						53.97	1.28
Te													0.12		
Ir			4.58	78.11	3.63	4.42	49.03	49.84	0.89	0.99	2.99	3.22	2.65	4.41	1.04
Pt	62.58	51.07	85.32	6.39	85.55	85.89	21.20	18.83	81.62	83.44	82.17	81.78	49.63	26.10	67.98
Hg											0.38	0.22	0.31		
Pb												0.50	0.62		
S					0.12				0.22			0.23	0.91		0.10
As	2.41	46.42											37.96	1.42	3.91
Sb			100.47	98.22	97.85	100.41	89.63	89.01	96.57	99.39	98.47	99.14	4.54	96.66	0.79
Total	91.04	98.65											100.17		100.82
Formula coefficients															
Cr	0.05	0.02	0.05	0.09		0.03	0.08	0.09	0.05	0.07	0.03	0.04	0.10	0.03	0.02
Fe	0.46	0.04	0.24	0.07	0.25	0.25	0.35	0.35	0.29	0.29	0.29	0.29	0.13	0.24	0.27
Ni	0.06	0.01					0.01	0.02	0.03	0.03	0.03	0.03		0.03	0.08
Cu									0.01						0.09
Ru				0.02											0.01
Rh				0.02											
Os				0.05										0.44	0.02
Te													0.00		
Ir			0.04	0.69	0.03	0.04	0.37	0.37	0.01	0.01	0.02	0.02	0.05	0.04	0.01
Pt	0.39	0.90	0.67	0.06	0.71	0.68	0.16	0.14	0.62	0.61	0.63	0.61	0.93	0.20	0.44
Hg											0.00	0.00	0.01		
Pb											0.00	0.00	0.01		
S					0.01				0.01			0.01	0.10		0.00
As	0.04	2.00											1.74	0.03	0.06
Sb													0.14		0.01

Note: The upper line in the heading is the sample number; the second line is the mineral name; the third line is the analyzed point numbers (m is the margin of the grains; other measurements were made in the cores of the grains). Measurements were performed on a JSM-6400-Link SEM/EDS at the Institute of Geology, Komi Scientific Center, Syktyvkar, analyst V.N. Filippov.

Table 3. Platinum group minerals from an area of local transformation of chromite and PGM and their composition, wt %

Element	Sample K-34-42							
	sperrylite		(Ni, Co)As	irarsite	(Ir, Ni) ₂ AsS	tetraferro-platinum	sperrylite	
	1	2	3	5	6	7	8	9
Ir				42.29	47.31	11.73	0.56	0.74
Pt	51.24	51.28	1.56	13.65	2.29	61.83	50.17	50.08
Rh				2.38	0.00	0.91	0.13	0.41
Fe	0.25	0.44	0.89	0.31	0.54	17.27	0.6	0.52
Ni			41.56	1.75	14.16	5.02	0.32	0.28
Co			7.53	0	0.15	0.12	0	0.28
S				8.12	7.92			
As	46.73	45.7	46.83	27.22	21.48	4.64	46.31	44.51
Sb				1.97	4.64	0.43	0.24	0.1
Total	98.22	97.42	98.37	97.69	98.49	101.95	98.33	96.92
Formula coefficients								
Ir	0.00	0.00	0.00	0.72	0.23	0.07	0.01	0.01
Pt	0.89	0.92	0.01	0.23	0.01	0.37	0.88	0.92
Rh	0.00	0.00	0.00	0.08		0.01	0.00	0.01
Fe	0.02	0.03	0.01	0.02	0.01	0.37	0.04	0.03
Ni	0.00	0.00	0.49	0.10	0.23	0.10	0.02	0.02
Co	0.00	0.00	0.09	0.00			0.00	0.02
S	0.00	0.00	0.00	0.83	0.23		0.00	0.00
As	2.00	2.00	0.41	1.12	0.25	0.07	1.99	2.00
Sb	0.00	0.00	0.00	0.05	0.04		0.01	0.00

Note: Measurements were performed on a JSM-6400-Link SEM/EDS at the Institute of Geology, Komi Scientific Center, Syktyvkar, analyst V.N. Filippov.

a deposit, massif, or aggregate are reported rather often (Nazimova et al., 2003; Lazarenkov et al., 2006). It can-

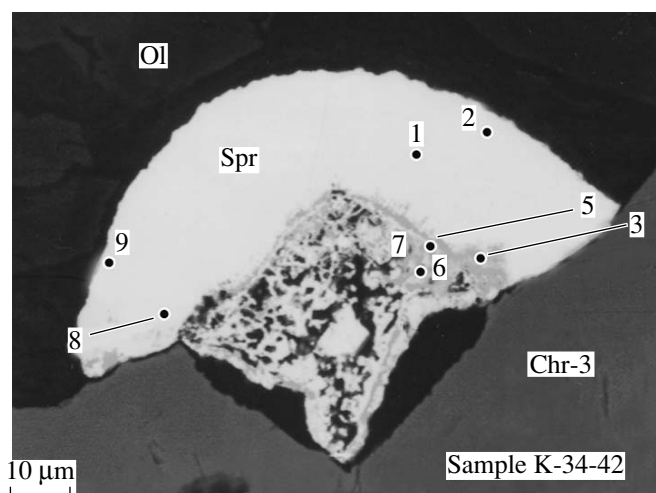


Fig. 10. Subaggregate of Pt and Ir arsenide grains at the boundary of the intergrowth of subaggregates of chromite (Chr-3) and olivine (Ol). Point numbers correspond to the determination of the composition on microprobe: (1, 2, 8, 9) sperrylite, (5, 6) irarsite, sample K-34-42. SEM image.

not be ruled out that such heterogeneity is explained by PGM differentiation after exsolution and their locally differentiated behavior in the inhomogeneous matrix of a mineral aggregate. A subaggregate of PGM grains with incomplete aggradation recrystallization is shown in Fig. 5. Some segments of the outer boundaries appear as sections of a monocrystal with simple face forms. Other segments are rough fractal surfaces, energy-consuming in our terminology. The native minerals behave in this way. Another branch of mineral formation has been revealed as well. A segment of the subaggregate of chromite grains shown in Fig. 10 demonstrates that a new mineral species—sperrylite—is formed on the front of the refined platinum. In electron microscope, one can see a porous, rather loose aggregate state of a new phase (Fig. 10). In other areas of the same assemblage of grains, mineral individuals of sperrylite and other newly formed compounds make up compact subaggregates and even monocrystals. Their composition is shown in Table 3. However, the metallic PGE compounds—alloys or solid solutions—appreciably prevail in the studied aggregates over Pt arsenates and sulfides (Tables 2 and 3).

CONCLUSIONS

The performed investigations lead to the following conclusions concerning the formation and functioning of individual boundaries in mineral aggregates. The boundaries of mineral individuals control the volume and morphology of mineral aggregates. The boundaries of intergrown grains have an additional function, converting the energy of differently oriented mineral individuals into the internal energy of mineral aggregates. This implies that the free surface energy of mineral individuals is substituted for the energy of a buffer zone of intergrowth boundaries. Precisely these intergrowth boundaries control the balance between the internal and total energy of the geological system affected by the external compression or extension and influx or loss of thermal energy. For instance, if a rock massif is affected by tectonic stress, the binding of the energy of stresses that do not overcome the elastic limit of the aggregate and mineral individuals results in an increasing total area of boundaries. The granulation of the boundaries is initiated, and the area of the boundaries grows, including the effect of their roughness. The release of stresses or their equating decelerates the increase in the boundary density or ceases this process; the increase in the roughness may be stopped or start to evolve in the opposite direction. It should be kept in mind that the interfaces of individuals' intergrowth at the same time are assemblies of marginal dislocations in the crystal lattices of contacting mineral phases. It may be the case that the energy of mineral individual boundaries does not equilibrate the energy of the crystal lattice volume. As a result, the lattice begins to free from the superfluous ions and defects. In this case, both the admixtures and dissolved compounds that correspond to other thermodynamic conditions may be superfluous. The observed refinement of chromite from magnetite, the appearance of new mineral phases with a simultaneous change in the character, and the orientation of boundaries that gives birth to the new structure of the renewed aggregate illustrate this process.

As mentioned above, the annihilation of defects in the crystalline lattice of each mineral grain predates this process. The annihilation of defects is realized in their migration to the marginal dislocation of the lattice volume, i.e., to the boundary of mineral individuals. The ion admixtures, being shifted from their sites in the lattice or from its defects, moves along the point, screw dislocations, mobilizing the internal energy of the crystalline individual, and partly compensating it by the energy consumed by the formation of new ion clusters, which may be either monoelemental or complex, consisting of several elements. The structured cluster can acquire their own marginal dislocations—a boundary—and, only in this case, it becomes a new mineral individual, a new generation, and often a new mineral species in the given system. In our opinion, the PGE individuals in the rocks of the Gal'moenan massif, as well as the intergrowths and subaggregates of PGM, appear

precisely in this way. They are formed owing to the necessity to bind energy via aggradation recrystallization.

It is well known that the surface energy creates significant forces of transformation of individuals measured by a few micrometers. The surface/volume ratio of a crystal falls in a logarithmical rate with an increasing size. We suggest that two factors become crucial during the process of the further migration of boundaries. First, the factor of geological time can be significant even with a recognition that boundaries of millimeter-sized crystals migrate much slower than micrometer-sized crystals. The second factor that controls the adaptive properties of the mineral grain boundary is the degree of its roughness and saturation with dislocations. In this case, separate defects of the boundary (planar defects, after Tauson et al., 2004) behave as nanoindividuals. Therefore, the boundary of two intergrowing individuals may be imagined as a set of separate flat segments with a high density of dislocations that determine its buffering position.

We repeat once again that the rocks experienced a multifold recrystallization with a contemporaneous self-refinement and annihilation of defects in the crystalline lattice of olivine and chromite as the major rock-forming minerals. Each next wave of recrystallization initiated by changes in the geologic and thermodynamic conditions of the system as a whole serves as an impetus to transformation of not only the boundaries of mineral individuals but also its crystalline lattice. While the duration of the process is sufficient, the region that adjoins the boundary and its surface are the place where a new mineral phase is born and localized. As is evident from the presented illustrations, in our case, these are new generations of chromite, newly formed magnetite, and MPG. The exsolution structure of platinum in chromite revealed using an atomic force microscope in the nanometric range at the boundaries of chromite grains confirms the validity of these statements. Therefore, this process proceeds after the exsolution of magnetite from chromite rather than concurrently with such exsolution. A new phase was noted to occur only at the boundaries of chromite grains of the third generation. The formation of its own mineral phase of PGE is related to the fourth (ore-forming) generation of chromite. Individuals of the fourth generation make up massive glomerogranular segregations with PGM macroaggregates in their cores. The simultaneous change in the texture of the mineral aggregate attracts interest. The uniformly dispersed chromite grains gradually give way to the formation of loop and cellular segregations, and finally, chromite individuals concentrate as compact subaggregates. Such a differentiation of mineral matter in a solid state testifies to the equilibration of internal forces and energy with the development of a mineral aggregate and the binding of energy. It may be suggested that monomineralic clinopyroxenite and olivinite lenses mapped in the Gal'moenan massif are products of the same processes as the above-described monomineralic subaggregates of chromite and PGM.

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