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The Structural Evolution of Dunite and Chromite Ore from the Kharcheruz Massif, the Polar Urals

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Abstract—The Kharcheruz block of the Syumkeu ultramafic massif is a southern fragment of the Khadata ophiolitic belt, which closes the ophiolites of the Polar Urals in the north. The block, striking in the latitudinal direction, is sheetlike in shape and primarily composed of dunite with nearly latitudinal zones of chromite mineralization. The dunites are subject to ductile deformation various in intensity, and this variability is displayed in their heterogeneous structure and texture. The following microstructural types are distinguished by the variety and intensity of their deformation: protogranular → mesogranular → porphyroclastic → porphyrolath → mosaic. The petrostructural patterns of olivines pertaining to the above types reflect conditions of ductile deformation. Protogranular dunite is formed as a product of pyroxene decomposition in mantle harzburgite accompanied by annealing recrystallization at a temperature above 1000°C. Mesogranular dunite is formed as a product of high-temperature plastic flow by means of translation sliding in olivine and diffuse creep at a temperature dropping from 1000 to 650°C and at a low rate ($<10^{-6}$ s^{-1}). Cr-spinel segregates into linear zones of disseminated chromite mineralization within zones of bedding-plane plastic flow. Porphyroclastic and mosaic dunites are formed under conditions of intense deformation at a temperature of 500–750°C and at a significant rate ($>10^{-6}$ s^{-1}). Dunite is deformed by means of syntectonic recrystallization and subordinate translation gliding. Linear zones of disseminated mineralization undergo destruction thereby, with the formation of lenticular chromitite bodies from which ductile olivine is squeezed out with the formation of densely impregnated and massive ores.

Keywords: ductile deformation, deformation conditions, microstructural heterogeneity, petrostructural analysis, dunite, chromitite, olivine

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INTRODUCTION

The established attributes of plastic flow in ultramafic rocks of ophiolitic complexes predetermine the approach to their study as metamorphic rocks with the implementation of unconventional methods of structural and petrostructural analyses. The use of these methods makes it possible to reconstruct the chronological sequence of their formation and the ductile deformation of ultramafic ophiolitic complexes at the mantle and crustal levels and to resolve a number of the topical problems of their minerageny. Many authors have drawn attention to the plastic flow, which modifies the structural and textural features of ultramafic rocks and their composition [2, 3, 10–12, 15–17, 20]. Ultramafics of ophiolitic complexes are potentially chromite-bearing rocks, and chromite deposits are often related to them. At the same time, the problem of chromitites is a matter of debate, and their origin has been discussed from various viewpoints.

The Kharcheuz block has remained poorly studied until now, in contrast to the main body of the Syumkeu massif, where the internal deformational structure and microstructural features of ultramafic rocks have been investigated in detail [13, 18, 19]. In this paper, we consider the petrostructural evolution of the plastic flow of dunite and associated chromite ore in the Kharcheuz block of the Syumkeu massif, the Polar Urals. To achieve our object, we have studied the distribution of structural elements in both host dunite and chromitite itself. The deformational microstructures of olivines in ultramafic rocks have been identified. The conditions of the ductile deformation of ultramafic rocks have been reconstructed on the basis of in-depth petrostructural research, and its results have been compared with experimental data. It is suggested that ductile deformation plays a leading role in the formation and localization of chromite mineralization. A concept for the evolution of ultramafic rocks at the upper mantle and crustal levels is proposed.

GEOLOGY OF THE KHARCHERUZ BLOCK

The Kharcheruz block of the Syumkeu ultramafic massif is a southern fragment of the Khadata ophiolitic belt, which closes the ophiolites of the Polar Urals

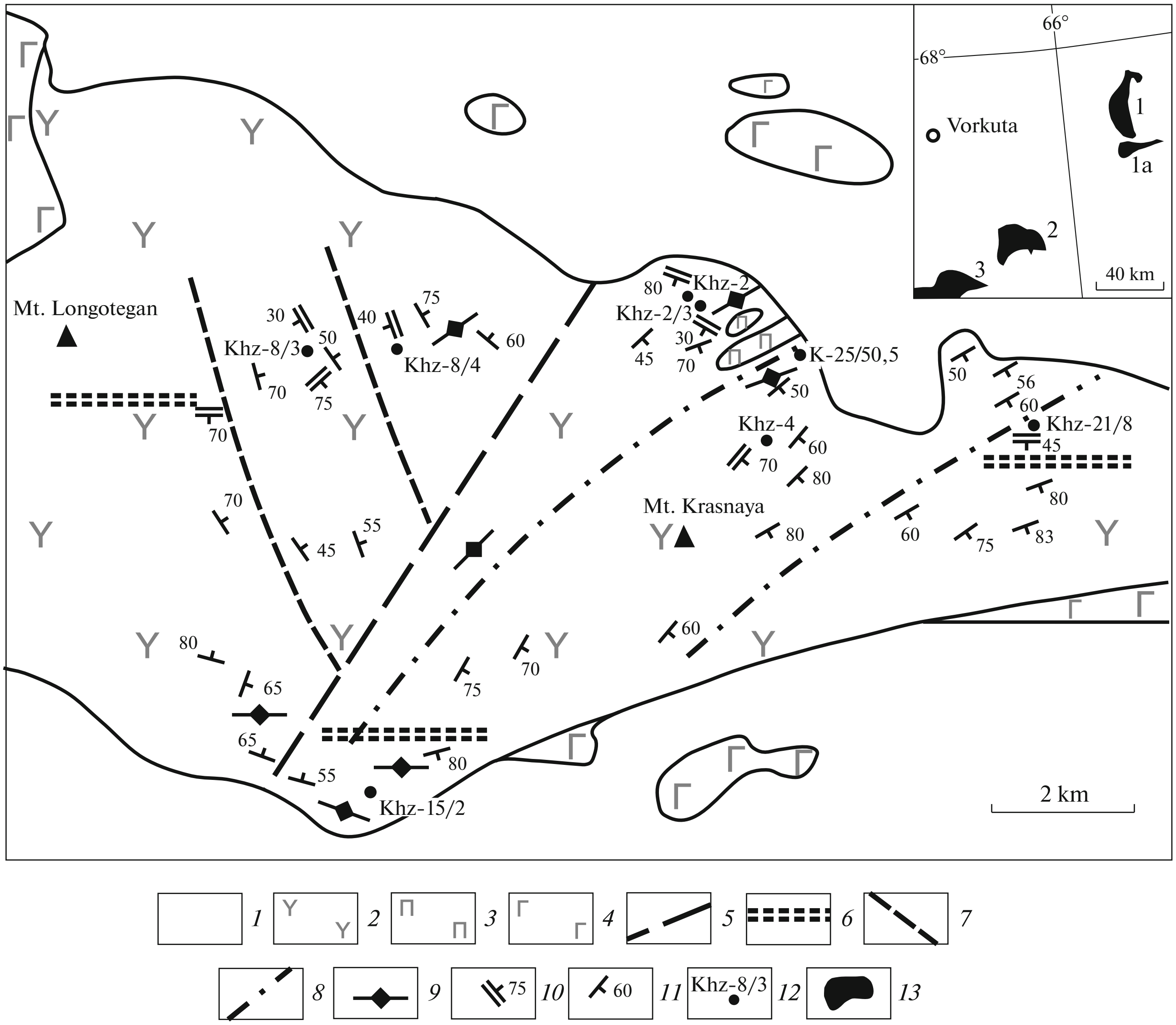

Fig. 1. Schematic geological map of Kharcheruz block. (*1*) Quaternary sediments; (*2*) dunite and harzburgite; (*3*) wehrlite and clinopyroxenite; (*4*) gabbroic rocks; (*5*) fault; (*6–8*) structural lines: (*6*) S_1, (*7*) S_2, (*8*) S_3; (*9–11*) strike and dip symbols: (*9*) chromitite body, (*10*) flattening of olivine grains, (*11*) plastic flow slip planes; (*12*) location of oriented samples; (*13*) ultramafic massifs location (inset). Geographic location of ultramafic massifs pertaining to ophiolitic complexes of the Polar Urals, after [20]. Numerals in inset: 1, Syumkeu (1a, Kharcheruz block); 2, Rai-Iz; 3, Voikar.

in the north (Fig. 1) [5, 8]. According to geological and geophysical data obtained by geological mapping on a scale of 1 : 50 000 (published with author's permission by A.K. Afanas'ev), the Kharcheruz block is an isolated structural unit separated from the larger Syumkeu ultramafic massif by metagabbro and amphibolite. It is interpreted as an erosional–tectonic klippe of the Syumkeu massif. The localization of the Kharcheruz block is apparently controlled by one of the transregional latitudinal and NW-trending vertical faults that determine the tectonic features on the eastern slope of the Polar Urals. The Kharcheruz block is a near-latitudinal body that pinches out eastward. It is ~18 km in extent, at a maximal width of 7 km in the western part (Fig. 1). The block is subdivided by a NE-trending fault into eastern and western parts.

The Kharcheruz block is composed primarily of dunite and extremely rare harzburgite. Minor gabbroic bodies, commonly metasomatically altered, are also known. Wehrlite and clinopyroxenite, which are identified in contact zones of the gabbroic bodies, are regarded as high-temperature metasomatic rocks.

Medium- to coarse-grained dunites are commonly fresh rocks, unaltered in appearance, with light yellow weathering crust. Less frequently, they are serpentinized and tremolitized to a variable degree. Black Cr-spinel grains stand out distinctly against the light yellow crust of weathering and are observed as sporadic fine accessory disseminations. Their content, which is commonly below 1%, reaches 5–10% in areas of segregation and substantially increases in ore zones. Cr-spinel grains frequently reveal a chain and banded arrangement, more frequently in the near-latitudinal direction.

Linear and lenticular chromitite bodies hosted in dunite commonly strike in a near-latitudinal direction. Their thickness is usually less than 1 m and their length does not exceed 10 m. Orebodies are frequently clustered together into near-latitudinal zones, where Cr-spinel contents vary from 10 to 50–90%, with the formation of low-grade disseminated to densely impregnated and massive ores. The ore zones are occasionally banded, owing to regular Cr-spinel distribution. The width of the bands varies from 0.5 to 2.0 m. The banding is oriented obliquely to the strike of ore zones and conformably to the NE-trending slip planes of plastic flow.

The ultramafic rocks undergo intense ductile deformation and constantly reveal a metamorphic appearance, with flattened olivine grains and flow slip planes represented by fine platy jointing. The detailed structural analysis of the planar elements of ultramafic rocks allowed us to recognize three consecutive stages of ductile deformation (Fig. 1).

The first (early) stage is expressed in the latitudinal nearly vertical plane-parallel orientation of minerals (S_1) recorded in flattened olivine in coarse- to medium-grained dunite and by the general latitudinal strike of linear zones with chromite mineralization conformable to the strike of the block (Fig. 1).

The second stage of the ductile deformation is expressed in ultramafic rocks from the western part of the block and recorded in flow slip planes and the reoriented flattening of olivine grains (S_2), which strike in the northwestern direction and steeply dip to the northeast or southwest (Fig. 1).

At the final syntectonic stage of the deformation of ultramafic rocks in the eastern and, less frequently, western parts of the block, the NE-trending flow slip planes dip to the southeast. This deformation is recorded in mineral flattening S_3 (Fig. 1). The reorientation of structural elements at this stage facilitated the destruction and partial reorientation of chromitite bodies conformably to S_3. The formation of flow slip planes is apparently caused by horizontal shearing in the latitudinal direction, along the fault that controls the localization of the Kharcheruz block.

MICROSTRUCTURAL HETEROGENEITY OF DUNITE AND CHROMITITE

Dunites

Dunite underwent nonuniform ductile deformation. Olivine grains decrease in size with increases in the degree of deformation and acquire a nonuniform extinction; kink bands appear; the role of syntectonic recrystallization is enhanced; and olivine grains are split along the cleavage. All these phenomena are reflected in the diversity of microstructures. The following sequence of microstructural types is based on the variation in number and intensity of the ductile deformation features: protogranular → mesogranular → porphyroclastic → porphyrolath → mosaic (Fig. 2). Similar microstructural types have been recognized in dunite and harzburgite from the Syumkeu massif by V.R. Shmelev [18]. Their regular arrangement allowed him to establish dynamometamorphic zoning. We noted similar deformational microstructures more than once in peridotites from ophiolitic complexes in other regions [2, 3, 16, 17].

A complete and diverse set of microstructures has been identified precisely in dunite. The mesogranular, porphyroclastic, and porphyrolath types are predominant. The mesogranular and porphyroclastic types have been established in less abundant harzburgite.

The protogranular type (Fig. 2a) is initial. Protogranular dunite occurs rarely, because this microstructure is eliminated by subsequent ductile deformation. The structure is coarse-grained, up to pegmatoid. Olivine is represented by large grains, up to 10 mm in size, with rounded and embayed boundaries. Signs of ductile deformations are poorly developed as heterogeneous extinction, wide kink bands, and the splitting of grains along cleavage fractures (010). Veinlet-shaped zones of syntectonic recrystallization composed of microgranular olivine aggregate occasionally appear along grain boundaries.

The mesogranular type of dunite and harzburgite is characterized by a medium-grained structure and a homogeneous or directional texture (Fig. 2). Olivine and enstatite are represented by grains 2–5 mm in size. They are commonly almost isometric or elongated and are oriented nearly in parallel. The grain boundaries are rounded or rectilinear. The olivine grains underwent ductile deformation to various degrees. In slightly deformed dunites, olivine reveals homogeneous or poorly developed wavy extinction; sporadic kink bands are noted. The intensely deformed grains are characterized by distinctly expressed wavy or block extinction and numerous kink bands (Fig. 2b). The splitting of grains along cleavage fractures (010) with the formation of a parquetlike microstructure (Fig. 2c) is abundant. The bending of cleavage fractures and the disintegration of grains into small individuals are noted. Porphyroclasts composed of microgranular olivine aggregates with a grain size of less than 0.3 mm develop along grain boundaries and fractures.

The porphyroclastic type is the most abundant in dunite. The structure is medium- to fine-grained; the texture is homogeneous or directional. Olivine is represented by two modifications: porphyroclasts and mosaic cementing mass syntectonically recrystallized (Fig. 2d). Porphyroclasts are represented by isometric

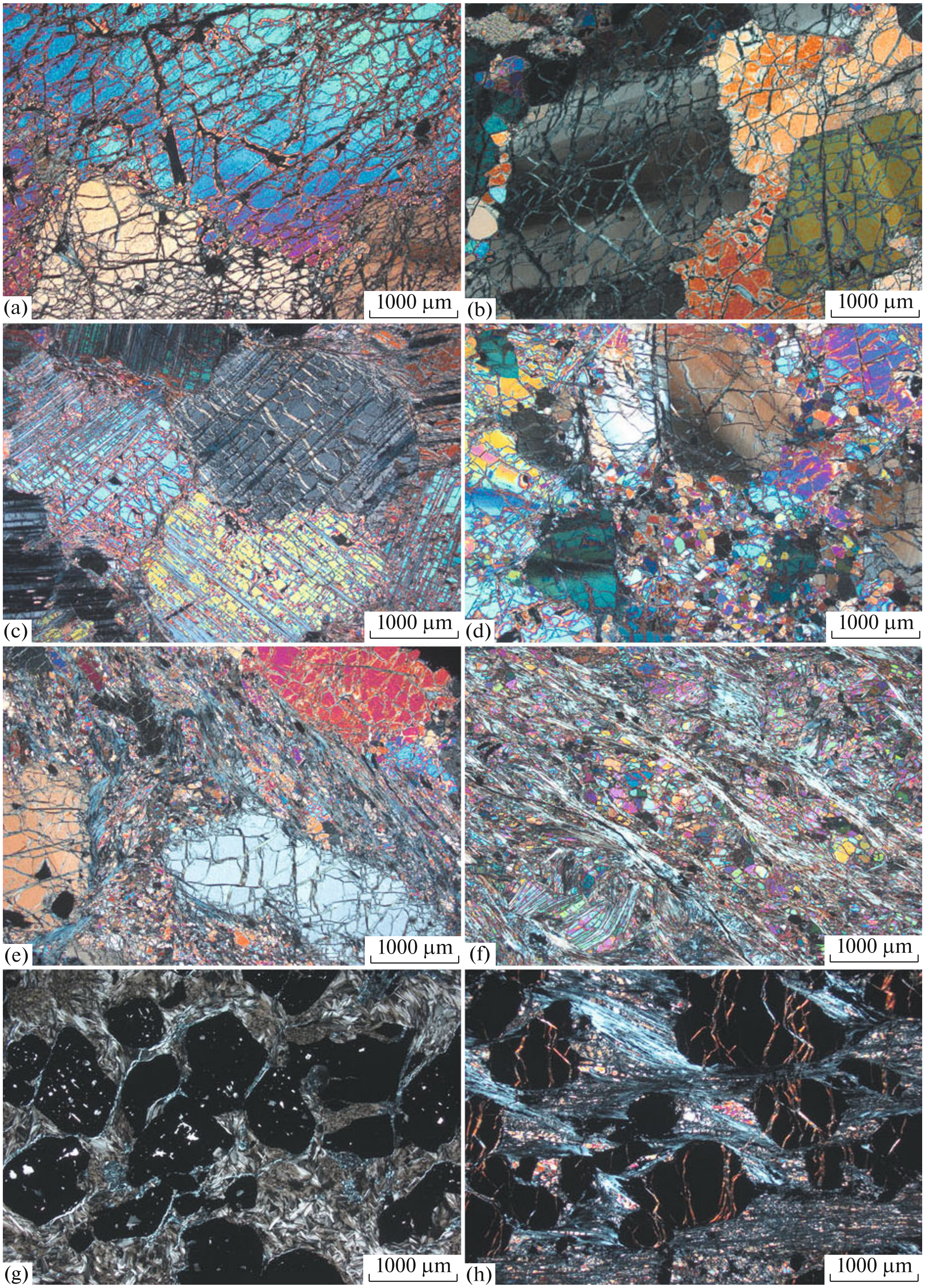

Fig. 2. Dunites and chromitites of Kharcheruz block subject to ductile deformation. Dunites: (a) protogranular (sample 044N/7), (b) mesogranular (sample 057N/3), (c) mesogranular parquetlike (sample Khz-5), (d) porphyroclastic (sample Khz-8/3), (e) porphyrolath (sample Khz-2/1), (f) mosaic (sample Khz-4); chromitites: (g) densely impregnated (sample K-15/37), (h) massive, fissile (sample K-25/50,5). Microphotograph, crossed polars.

or elongated grains, which are oriented parallel to directivity. The boundaries of grains 4–6 mm in size are uneven with denticulate margins. The extinction of porphyroblasts is wavy or block; kink bands are typical; the grains are split along cleavage fractures (010). Cleavage fractures frequently reveal a symmetric feather structure relative to directivity. Particular grains are disintegrated into small individuals. The cementing mass consists of microgranular or fine-grained mosaic olivine aggregates formed as a product of syntectonic recrystallization. Fine equant or oblong olivine individuals are less than 0.5 mm in size. The elongated grains reveal a ribbonlike arrangement and smoothly flow round porphyroclasts. In other cases, they are oriented at an acute angle to directivity, reflecting shear deformation.

The porphyrolath type of dunite is less abundant than the porphyroclastic type. The structure is fine- to medium-grained; the distinctly directional texture is often emphasized by fissility (Fig. 2e). Olivine occurs as porphyroclasts and fine-grained cementing mass. Porphyroclasts are mainly elongated and lenticular in shape. The lateral boundaries are commonly even and rounded, whereas the butt-ends occasionally are horsetailed in shape. Porphyroclasts reveal a strictly predominant orientation and reflect directivity, often emphasized by fissility. Porphyroblasts are 2–5 mm long, up to 8 mm in rare cases. They are intensely deformed and constantly display sharply expressed heterogeneous extinction, numerous kink bands, and splitting along cleavage fractures (010) into parquetlike individuals. Cleavage fractures are often characterized by a feather arrangement relative to directivity. The disintegration of grains into small individuals is noted. Thin crush zones of microgranular ground material are identified along cleavage fractures. The groundmass is composed of fine-grained syntectonically recrystallized and cataclastic aggregates of olivine grains less than 0.5 mm in size. They are isometric, angular, or prismatic in shape. Aggregates of fine-grained olivine are enriched in antigorite individuals. They frequently are fissile in appearance, envelope porphyroclasts, and impart to them the shape of boudins.

The mosaic type is established in the most intensely deformed boudins, which sporadically occur in the eastern part of the block. Their structure is fine-grained; their texture is distinctly directional and fissile (Fig. 2f), occasionally with fragments of microplication. The rock is composed of syntectonically recrystallized microgranular and fine-grained olivine aggregates incorporated into foliated serpentinite. Olivine is represented by nearly isometric and slightly elongated grains less than 0.5 mm in size. The oblong individuals are oriented along fissility or at an acute angle relative to it, as a result of shearing.

Chromitite

Three chromitite varieties, namely disseminated, densely impregnated, and massive, are distinguished from one another by their relative amounts of Cr-spinel. Chromitite is fine- to medium-grained in structure; its texture is homogeneous, occasionally fissile, and frequently brecciated. The Cr-spinel contents are 40–60, 60–90, and >90% for disseminated, densely impregnated, and massive chromitites, respectively.

In **disseminated and densely impregnated chromitite,** the Cr-spinel grains are isometric and irregular in shape with smooth, rounded, or rectilinear boundaries (Fig. 2g). *Massive chromitites* are aphanitic aggregates of Cr-spinel, which are commonly broken by numerous near-parallel fractures into numerous angular fragments. In massive chromitite with fissile texture, the fragments are ellipsoidal and lenticular in shape, oriented nearly parallel. They are mainly 1–2 mm in length (Fig. 2h).

Cr-spinel is translucent and dark brown-red and black at the margins and along fractures, due to replacement with magnetite. Cr-spinel occasionally displays near-parallel cleavage fractures {111} and in some cases the fractures are oriented in three directions at angle of ~60°.

The cementing mass is composed of serpentine–chlorite aggregate, with variable proportions of minerals up to monomineralic varieties. Occasionally the cement is distinctly fissile in appearance, envelopes porphyroclasts, and imparts to them shape of boudins.

THE DUCTILE DEFORMATION OF ULTRAMAFIC ROCKS AND ITS EFFECT ON OLIVINE AND Cr-SPINEL COMPOSITIONS

Olivine

The compositions of olivine from dunite involve all deformation types (protogranular, mesogranular, porphyroclastic, mosaic) that correspond to an increase in the degree of ductile deformation (Table 1). The following ranges of fayalite component (Fa) contents in olivine characterize the deformation types of dunite (mol %): protogranular (9.39–10.35), mesogranular (9.98–11.50), porphyroclastic (10.13–10.18 for porphyroclasts and 8.00–8.10 for mosaic aggregate), and mosaic (8.46). These data show a tendency to decrease in the Fa mole fraction of olivine, with an increase in the degree of its ductile formation as a result of syntectonic recrystallization (Table 1). A similar tendency has been noted for ultramafic rocks from the ophiolitic complexes of Siberia [2]. The NiO contents in olivine of all deformational types are close to one another (0.24–0.44 wt %). CaO and MnO contents in olivine are commonly undetectable. This is apparently caused by the exhaustion of dunite in the process of depletion. The CaO and MnO contents, reaching 0.30 wt % in

Table 1. Chemical composition (wt %) of olivine from dunite subject to ductile deformation

Sample	049N/2	069N/2	009N/1	027N/1	052N/2	005N/1p, p	005N/1m, m	028N/1p, p	028N/1m, m	046N/4
structure	protogranular		mesogranular			porphyroclastic				mosaic
SiO_2	40.71	40.43	40.89	40.79	41.28	43.60	42.57	40.84	41.29	41.27
FeO	9.20	10.09	10.22	9.71	11.04	9.42	7.77	9.89	7.83	8.27
MnO	n.d.	n.d.	0.21	n.d.	n.d.	n.d.	n.d.	n.d.	0.18	n.d.
MgO	49.79	49.04	48.46	49.10	47.68	46.90	49.41	48.95	50.50	50.16
CaO	n.d.	n.d.	n.d.	n.d.	n.d.	0.24	0.28	n.d.	n.d.	n.d.
NiO	0.31	0.44	0.38	0.38	0.21	0.24	0.24	0.43	0.30	0.31
Total	100.01	100.00	100.16	100.03	100.21	100.40	100.26	100.11	100.09	100.00
Fa (%)	9.39	10.35	10.58	9.98	11.50	10.13	8.10	10.18	8.00	8.46

Here and hereafter, analyses have been performed on a VEGA II LMU SEM equipped with Oxford INCA Energy350 and Oxford INCA Wave spectrometers, analyst A.S. Kul'kov. Fa, content of fayalite molecule [Fa (mol %) = 100 × Fe/(Fe + Mg)]; p, olivine from porphyroclast; m, olivine from syntectonically recrystallized mosaic aggregate; n.d., not detected.

Table 2. Chemical composition (wt %) of Cr-spinel from dunite subject to ductile deformation

Sample	049N/2	069N/2	009N/1	018N/2	005N/1	028N/1	046N/4
structure	protogranular		mesogranular		porphyroclastic		mosaic
mineral	ferrichromite	chromite	alumochromite	subferrialumo-chromite	ferri-alumo-chromite	chromite	chrome-magnetite
TiO_2	2.02	1.47	n.d.	0.39	n.d.	0.54	1.12
Al_2O_3	0.32	0.34	11.93	16.94	7.98	2.05	0.45
Cr_2O_3	38.77	51.80	53.79	43.64	43.87	55.81	19.08
V_2O_5	0.56	n.d.	n.d.	n.d.	n.d.	0.62	0.48
FeO*	55.88	42.14	26.81	30.33	44.49	36.98	75.87
MnO	0.82	0.40	n.d.	0.94	n.d.	n.d.	0.67
MgO	1.62	3.15	6.98	7.56	4.41	3.77	2.43
NiO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.57
ZnO	n.d.	0.70	0.52	0.60	0.49	0.47	n.d.
Total	100.00	100.00	100.02	100.39	101.24	100.24	100.67
$F^{\#}$	91.5	83.5	65.1	62.8	77.6	80.1	87.2
$Cr^{\#}$	98.8	99.0	75.2	63.3	78.7	94.8	96.6
$F^{\#\#}$	40.0	21.8	5.0	10.5	24.6	15.1	71.3

FeO*, total iron; $F^{\#} = 100 \times Fe^{+2}/(Fe^{+2} + Mg)$; $Cr^{\#} = 100 \times Cr/(Cr + Al)$; $F^{\#\#} = 100 \times Fe^{+3}/(Fe^{+3} + Cr + Al)$. Fe_2O_3 (wt %) = 52.832 × [(FeO* + MgO + MnO + NiO) – (Cr_2O_3 + Al_2O_3 + 2 × TiO_2)]/1000, mol. quantities [1]; n.d., not detected.

rare samples, are likely caused by secondary alteration, e.g., tremolitization.

Chromium-Spinels

Cr-spinel is not abundant in dunite (commonly <1 vol %). The grains are close to isometric, occasionally euhedral in morphology and less than 1 mm in size, up to 1.5 mm in some cases. The color of the grains is commonly dark brown. The mineral is distinguished by a substantial variation of chemical composition and is represented by alumochromite, chromite, subferrialumochromite, ferrialumochromite, ferrichromite, and Cr-magnetite [7] (Table 2). The diversity of Cr-spinel compositions is apparently caused by the variable grade of metamorphism in the process of high-temperature ductile deformation and superimposed amphibolization and serpentinization. The least metamorphosed alumochromite is identified in single instances, whereas Cr-magnetite is a product of high-grade metamorphism. However, the chemical compositions of Cr-spinel cannot be unambiguously correlated with the petrostructural types of olivine contained in dunite. A distinct zoning of Cr-spinel is

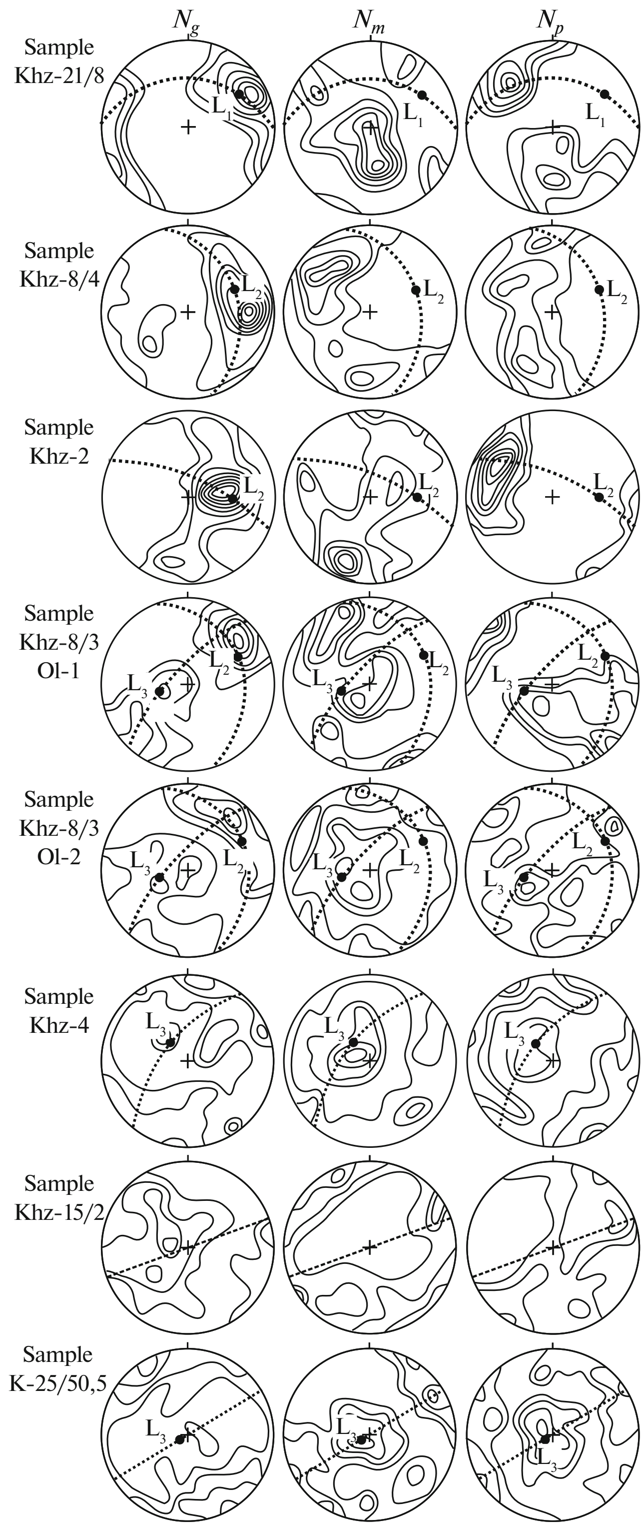

Fig. 3. Orientation of crystal optic axes of olivine in dunites and chromitites of the Kharcheruz block. Deformation types of dunite: protogranular (Khz-21/8), mesogranular (Khz-2, Khz-8/4), porphyroclastic (Khz-8/3), mosaic (Khz-4) and chromitite: disseminated (Khz-15/2), massive (K-25/50,5). Ol-1, olivine porphyroclasts; Ol-2, syntectonically recrystallized mosaic olivine aggregates. Diagrams were constructed on the basis of 100 measurements of crystal optic axes. Contour lines in Schmidt net (1%): 1–2–4–6–8–10–12–14%. Projection on the upper hemisphere. Dotted lines are planes of mineral flattening with lineation (L); dashed line is plane of chromitite body.

noted. Thereby, cores of Cr-spinel grains are represented by alumochromite, while the marginal rims are composed of ferrichromite.

Cr-spinel from chromite ore reveals lesser compositional variations than that in dunite (Table 3). Disseminated chromites are represented by alumochromite, while massive ores are represented by chromite. This indicates that massive chromitites underwent higher-grade metamorphism caused by high-temperature ductile deformation. The increase in metamorphic grade of Cr-spinel facilitates the enrichment of them in Cr_2O_3 and the depletion in Al_2O_3, MgO, in ZnO at practically constant FeO contents. As a result, $Cr^{\#}$ grows substantially, whereas $Fe^{\#}$ of Cr-spinel is reduced in massive chromitite.

ANALYSIS OF PETROSTRUCTURAL DATA

Detailed petrostructural study carried out on ultramafic rocks from the main body of the Syumkeu massif by V.R. Shmelev [18] serves as the basis of general conclusions about the optic orientation of olivine in various microstructural types of ultramafic rocks, which are formed under conditions of high-temperature ductile deformations, including intracrystal gliding and partial recrystallization. The data published by Shmelev, however, do not involve the Kharcheruz block. In turn, we have, for the first time, thoroughly studied olivine from dunites and chromitites of this block that pertain to various types of microstructure reflecting increases in the degree of ductile deformation. Our microstructural analysis, using the techniques described in [14, 17], made it possible to reveal the predominant orientations of the shape and internal structure for the olivine contained in dunites and chromitites. The dynamic and kinematic interpretation of the obtained petrostructural patterns of crystal optic axes of olivine was carried out using published data [2, 4, 6, 15, 20–23]. Based on the results obtained, we have shown that olivines from dunite and chromitite are subject to high-temperature ductile deformations, according to the mechanisms of translation gliding, diffusion creep, annealing recrystallization, syntectonic recrystallization, and cataclastic flow, in a wide range of temperatures and deformation rates.

Dunite

Petrostructural analysis was performed for the protogranular, mesogranular, porphyroclastic, and mosaic

Table 3. Chemical composition (wt %) of Cr-spinel from chromitite

Sample	15/2	K-15-37	T-1-4	K-26-10	K-25-50.5
structure	disseminated		massive		
mineral	alumo-chromite	alumo-chromite	chromite	chromite	chromite
TiO_2	0.18	0.09	0.19	0.07	0.03
Al_2O_3	12.16	16.62	4.75	6.71	5.68
Cr_2O_3	54.46	52.09	62.83	61.49	62.44
V_2O_5	0.15	0.10	0.19	0.09	0.11
FeO*	23.15	19.40	23.15	21.91	24.02
MnO	0.51	0.41	0.55	0.54	0.55
MgO	9.14	11.06	8.18	8.98	6.99
NiO	0.07	0.12	0.07	0.15	0.10
ZnO	0.27	0.15	0.11	0.07	0.10
Total	100.10	100.00	100.00	100.02	100.01
$F^{\#}$	54.7	46.67	57.66	54.04	63.49
$Cr^{\#}$	71.5	65.82	85.62	82.24	85.07
$F^{\#\#}$	5.0	2.87	4.74	4.39	3.41

FeO*, total iron; $F^{\#} = 100 \times Fe^{+2}/(Fe^{+2} + Mg)$; $Cr^{\#} = 100 \times Cr/(Cr + Al)$; $F^{\#\#} = 100 \times Fe^{+3}/(Fe^{+3} + Cr + Al)$. Fe_2O_3 (wt %) = $52.832 \times [(FeO^* + MgO + MnO + NiO) - (Cr_2O_3 + Al_2O_3 + 2 \times TiO_2)]/1000$, mol. quantities [1]; n.d., not detected.

types of dunite, the sequence of which reflects an increase in the degree of ductile deformation.

The protogranular type

The study was carried out on sample Khz-21/8 (see Fig. 1). The structure of this sample is coarse-grained, with indications of porphyroclast formation; the texture is homogeneous. Olivine is primarily represented by coarse grains, varying in size from 3 to 15 mm. Their shape is isometric and less frequently elongated with rounded boundaries. The flattening (S_1) of olivine grains strikes in the latitudinal direction and dips to the south at moderate angles. Olivine is characterized by homogeneous or slightly expressed wavy extinction; wide kink bands are noted along with perfect cleavage along (010).

Olivine is characterized by a strictly prevalent orientation (Fig. 3). The N_g axes are clustered into a distinct maximum of high density (12%), which reflects predominant the plunging of axes in the southwestern direction. This maximum is combined with lineation (L_1) and is localized in the plane of mineral flattening (S_1), which strikes in the latitudinal direction and plunges to the south. A weak tendency is noted to stretch the maximum in the plane of mineral flattening (Fig. 3). The N_m and N_p axes form more complex patterns. They are clustered into the belts normal to maximum $N_g \parallel L_1$. Two maxima of the N_m and N_p axes are distinctly established in each belt. The N_m maximum, with a density of 10%, and the N_p maximum, with a density of 6%, are located almost normal to mineral flattening (S_1). Thereby, the nearly horizontal maximum N_p, with a density of 10%, occurs in the plane of flattening (S_1). The tendency of the N_m and N_p axes to stretch into near-horizontal belts is noted.

The optic orientation of the protogranular olivine suggests two stages of formation. The first stage apparently is characterized by the pyroxene breakdown of initial mantle harzburgite with the formation of dunite at a high temperature and is accompanied by annealing recrystallization. High-temperature annealing facilitates the growth of favorably oriented olivine grains at the expense of unfavorably oriented grains, with the formation of large grains devoid of ductile deformation, and with smooth accidental boundaries [6].

The second stage is related to a high-temperature plastic flow at a great depth within the mantle. At this stage, the ductile deformation of protogranular olivine is implemented by means of homogeneous high-temperature translation gliding, primarily along the systems (001)[100], {0kl}[100], and the less frequent (010)[100]. This is reflected in the character of the petrostructural pattern, where maximum $N_g \parallel L_1$ displays near-horizontal plastic flow (σ_1) in the near-latitudinal direction, i.e., along the strike of the Kharcheruz block. Thereby, the N_p maximum, which reflects the meridional direction of compression (σ_3), is localized normally to mineral flattening. The ductile deformations of this type proceeded at a high temperature (≥1000°C), with a low rate ($<10^{-6}$ s^{-1}) and under significant confined pressure (>10 kbar) [23].

The mesogranular type

The study was carried out for samples Khz-2 and Khz-4 (Fig. 1). Their structure is medium-grained, occasionally with a superimposed parquetlike structure (Khz-2); a porphyroclast formation is noted. The texture is homogeneous or directional. The olivine grains have an isometric, irregular, or oblong shape with rounded boundaries, and are 2–5 mm in size. Elongated individuals reveal a near-parallel orientation and indicate the direction of their NW-trending flattening (S_2), with a dip to the southwest. The lineation (L_2) plunges to the west. The extinction of grains is homogeneous and becomes wavy in deformed grains. Kink bands and sporadic splitting along cleavage fractures (010) are noted. Syntectonic recrystallization develops with the formation of fine-grained olivine aggregates.

Olivine in the studied samples makes up two types of petrostructural patterns of crystal optic axes. The first type is established for mesogranular dunite in sample Khz-8/4 (Fig. 3). The N_g axes are clustered into a distinct near-horizontal maximum with high density (up to 14%), combined with lineation (L_2), which reflects the gentle plunging of axes, primarily in the western direction. A tendency to stretching of the maximum into the belt in the plane of mineral flattening is noted. The maxima of N_g axes in samples of this type are spatially contiguous with the maxima of N_g axes in protogranular olivine. The N_m and N_p axes are clustered into juxtaposed belts located normally to the N_g maximum. Local maxima with a density of up to 8% are noted in the belts. They are arranged at an angle to mineral flattening.

The second type has been established for mesogranular parquetlike dunite (sample Khz-2), see Fig. 3. The N_g and N_m axes form combined near-vertical belts of clustering oriented normal to the plane of mineral flattening. Two maxima are distinctly separated in each belt. The high-density N_g maximum (14%) and low-density N_m maximum (4%) plunging to the west occur in plane of mineral flattening and are combined with lineation (L_2). Thereby, the high-density N_m maximum (10%) and the low-density N_g maximum (4%), characterized by a nearly horizontal arrangement, are oriented normally to mineral flattening. The N_p axes are clustered into a high-density maximum (12%) in the plane of mineral flattening. The combined belts of clustered N_g and N_m axes are oriented normally to the plane of mineral flattening.

The mesogranular dunite type arises instead of the protogranular type, when the degree of ductile deformation by means of intracrystalline gliding increases. This process is apparently accompanied by superficial diffusion creep. Deformation apparently proceeds within a wide temperature range (~650–1000°C) with a slow rate (less than 10^{-6} s^{-1}) under conditions of axial compression [6, 15, 23]. As a result, dunite with an equilibrium medium-grained microstructure is formed. Thereby, the olivine grain boundaries become smooth, rectilinear, and frequently converge in triple points at an angle of 120°. The optic orientation of olivine grains is controlled by the retained external stress field, as with protogranular olivine.

The petrostructural patterns of optic olivine orientations make it possible to establish various mechanisms of the ductile deformation of mesogranular dunites. In the first petrostructural type, the ductile deformation of olivine is implemented mainly by means of high-temperature translation gliding in system {0kl}[100]. This is reflected in the strong $N_g \parallel L_2$ maximum and the orthogonal combined belts of the N_m and N_p axes. Thereby, local maxima are oriented at acute angles to mineral flattening.

In the second petrostructural type, the ductile deformation of olivine apparently develops under conditions of temperature drop and is realized in change from moderately high-temperature to low-temperature gliding systems: (001)[100] $\rightarrow$ (110)[001] $\rightarrow$ (100)[001]. The ductile deformation of olivine is accompanied by intracrystalline stress increasing above the breaking point. As a result, the cleavage along the favorable crystallographic plane (010) appears with the subsequent splitting and dismemberment of grains into separate parallel individuals and the formation of a parquetlike structure. The realization of this mechanism of ductile deformation is reflected in the high-density N_g maximum (14%) and N_m maximum (4%) located near L_2. Thereby, local N_g (4%) and N_m (10%) maxima, oriented normally to the mineral lineation, set in. The formation of the cleavage with a subsequent splitting of grains apparently facilitates the formation of the N_p maximum in the plane of mineral flattening and the combined N_g and N_m belts perpendicular to this maximum.

The porphyroclastic type

Dunite sample Khz-8/3 (see Fig. 1), with a distinct porphyroclastic structure and directional texture, has been studied. The amounts of olivine porphyroclasts and mosaic aggregates are ~40 and ~60%, respectively. Porphyroclasts are observed as solitary grains or small clusters. They are isometric or oblong and extend nearly parallel, emphasizing the directivity in the rock. The porphyroclastic grains are 2 to 6 mm in size. The grain boundaries are uneven and denticulated. The porphyroblasts are intensely deformed; this is expressed in the distinctly heterogeneous wavy extinction and appearance of numerous kink bands. The porphyroblasts are incorporated into fine-grained mosaic aggregates of syntectonically recrystallized olivine grains less than 0.5 mm in size. Oblong individuals are stretched along the directivity and frequently envelop the porphyroclasts.

Two planes of mineral flattening are identified in porphyroclastic dunite. The earlier plane (S_2) strikes in the northwestern direction and gently plunges to the southwest. Mineral lineation (L_2) also plunges to the southwest. The attitude of this plane is close to the plane of mineral flattening for mesogranular dunite situated nearby. The orientations of their mineral lineation are also spatially converged. The later mineral flattening (S_3) strikes in the northeastern direction and dips steeply to the southeast. Mineral lineation L_3 reveals nearly vertical plunging.

Porphyroclastic and recrystallized grains of this type have similar petrostructural patterns (Fig. 3). The N_g axes of porphyroclastic grains make up a vertical belt striking in the northeastern direction, norma to mineral flattening. Density maxima are distinctly identified in this belt. The highest-density maximum (10%) is nearly horizontal and is combined with mineral lineation L_2. Another near-vertical low-density maximum (4%) is combined with mineral lineation L_3. The N_m and N_p axes make up more complex patterns with a tendency to cluster into combined belts normal to the high-density N_g maximum. Local near-vertical and horizontal maxima are noted in these belts. The near-vertical maxima are spatially combined with mineral lineation L_3. The recrystallized grains are distinguished by a more complex pattern of petrostructural patterns. This complication is caused by the tendency of all three axes to separate into a horizontal belt normal to mineral lineation L_3.

A porphyroclastic type of dunite is formed instead of protogranular and mesogranular dunites, apparently owing to the displacement of ultramafic rocks in the Earth's crust at moderately high and relatively low temperatures (~500–750°C), increasing rates (higher than 10^{-5} s^{-1}), and under conditions of axial and shear deformations [15, 21, 23]. The ductile deformation of olivine grains is implemented by means of both translation gliding and syntectonic recrystallization.

The analysis of petrostructural patterns of the optic orientation of porphyroclastic grains allowed us to discern two stages of their ductile deformation. The first stage apparently corresponds to the formation of initial proto- or mesogranular dunite and is reflected in the orientation of porphyroclastic olivine grains devoid of destruction. The process was mostly realized in translation gliding along the high-temperature systems (010)[100], {0kl}[100], and (001)[100]. As a result, an N_g maximum corresponding to the direction of plastic flow (L_2) has been formed. The combined belts of clustered N_m and N_p axes are formed normal to this maximum. Local maxima oriented perpendicular to the primary mineral flattening are noted therein.

At the second stage, dunite is affected by intense syntectonic recrystallization, along with subordinate translation gliding and cataclastic flow. Thereby, the mosaic olivine grains retain the previously formed orientation established in porphyroclasts subsequently complicated by plastic flow, controlled by newly formed near-vertical lineation L_3; N_m and N_p maxima appear nearby. This combination of N_m and N_p maxima provides evidence for translation gliding in olivine along relatively low-temperature systems (100)[001], (110)[001], and (100)[010].

The mosaic type

Sample Khz-4 (Fig. 1) of dunite has been studied. Its structure is fine-grained and mosaic; its texture is distinctly directional. Dunite is composed of syntectonically recrystallized olivine grains less than 0.5 mm in size. In some areas they are isometric, and prismatic in others. In the latter case, these are primary olivine grains disintegrated along cleavage fractures. The oblong individuals are frequently oriented along the directivity emphasized by fissility. The tabular packets of prismatic individuals are also frequently arranged symmetrically to directivity, in the form of feather segregations.

The mineral flattening distinctly developing in the mosaic type is controlled by intense slip planes. The flattening strikes in the northwestern direction and steeply plunges to the southeast. A nearly vertical mineral lineation in the plane of flattening also dips to the southeast.

The rather complex petrostructural patterns of crystal optic axes are characteristic of the mosaic type (Fig. 3). These patterns reveal a certain regularity in orientation. A part of all three axes displays a tendency to cluster into near vertical maxima combined with lineation L_3. The N_m maximum is distinguished by the highest density (6%). Another part of the faxes makes up combined belts of clustering normal to L_3. Two local maxima are noted in each N_g and N_p belt. They are localized at an acute angle and symmetrically to the mineral flattening. One maximum normal to mineral flattening occurs in the N_m belt.

The petrostructural patterns of the optic orientation of the mosaic olivine are close to those for mosaic aggregates in the porphyroclastic type. The ductile deformation of the mosaic olivine apparently proceeds under conditions of right-lateral horizontal shear in the latitudinal direction and is implemented mainly by means of syntectonic recrystallization and cataclastic flow, along with subordinate low-temperature translation gliding along systems (100)[001], (110)[001], and (100)[010]. The occurrence of the two symmetrical maxima of N_g and N_p relative to mineral flattening is a characteristic attribute of the ductile shear deformation [15].

Chromitite

The petrostructural analysis of olivine has been performed in disseminated and massive chromitites.

Disseminated chromitite

Sample Khz-15/2 (see Fig. 1). The chromitite sample has been taken from the southern Kharcheruz block from a vertical lenticular orebody up to 1 m thick, which strikes in near-latitudinal direction (~70° ESE). No mineral flattening and lineation have developed in this sample. Cr-spinel grains with rounded boundaries are irregular in shape and 1–2 mm in size. Intergranular olivine is serpentinized and occurs as small fragments.

Olivine reveals an optic orientation with complex patterns of crystal optic axes (Fig. 3); certain trends of these patterns are established. The N_g axes are localized in a vast field, where a near-vertical maximum is noted in the plane of the orebody. The N_m axes are clustered into a horizontal belt with two local near-horizontal maxima. One is localized in the plane of the chromitite body and another is oriented normally to the former. The N_p axes make up a diffuse belt with local maxima, which occur near the local N_m maxima. One is localized in the plane of the chromitite body, and another is oriented normally to the former.

This complex orientation of intergranular olivine in disseminated chromitite allows us to suggest that ductile deformations were realized as high-temperature translation gliding along the systems (010)[100], {0kl}[100], and (001)[100] in a weak stress field [15].

Massive chromitite

Sample K-25/50.5 (see Fig. 1). The chromitite sample has been taken from the eastern part of the northern slope of the Kharcheruz block. Chromitite is represented by schlieren and banded segregations up to 4 m thick, which strike at an azimuth of 60°–70° NE and plunge almost vertically. The tructure of chromitite is massive and its texture is fissile. Cr-spinel occurs as isometric, frequently lens-shaped grains 0.5–2.0 mm in size, which often make up intimate intergrowths. The grains are frequently disintegrated and dragged apart along fissility. The cementing mass is primarily composed of antigorite with small fragments of olivine grains, less than 0.1 mm in size. The elongated antigorite and olivine individuals reveal a near-parallel orientation that reflects distinct fissile texture. They often smoothly turn Cr-spinel grains, imparting to them the appearance of boudins. Larger lens-shaped olivine porphyroclasts, up to 3 mm in size and oriented parallel to fissility, are incorporated into the marginal zone of chromitite.

The intergranular olivine in this type of chromitites differs in the distinct prevalent optic orientation of crystal optical axes, close in pattern character to the orientation of mosaic olivine in porphyroclastic and mosaic types (Fig. 3). The N_g axes are clustered into a horizontal belt with a distinct maximum (6%) oriented normally to the vertical flattening coinciding with the strike of the orebody. The N_m and N_p axes make up similar patterns. A part of these axes are clustered into near-vertical maxima (4%), combined with mineral lineation L_3. The clusters of another part of the N_m and N_p axes reveal a tendency to stretch into horizontal belts with local maxima, 6 and 4% in density. These maxima occur in the plane of mineral flattening normal to lineation L_3.

Ductile deformations of intergranular olivine in fissile chromitites apparently proceed under conditions of horizontal shearing in the near-latitudinal direction. They are realized mainly by means of tectonic recrystallization, cataclastic flow of olivine, and subordinate low-temperature translation gliding along the systems (100)[001], (110)[001], and (100)[010] [6, 22].

Ductile deformation apparently facilitates squeezing the ductile olivine out of chromitite.

THE ULTRAMAFIC ROCKS OF KHARCHERUZ BLOCK: A STRUCTURAL MODEL OF EVOLUTION

The Kharcheruz block is an erosion–tectonic klippe of the main Syumkeu ultramafic massif, which is composed of intensely depleted dunite–harzburgite complex. Dunite is the predominant rock, occurring as small relic areas that have avoided the complete decomposition of pyroxene. Dunite contains linear bodies and zones of chromitites mainly striking in the latitudinal direction conformably to the strike of the block as a whole. The banding of chromitite is caused by the nonuniform concentrations of Cr-spinel, varying from lean to densely impregnated and massive ores. Banding is oriented obliquely to the northeastern strike of mineralized zones and is apparently controlled by ductile shear deformation, which facilitates the nonuniform squeezing of ductile olivine out from chromitite.

Dunite is characterized by significant variations of structure from coarse- to fine-grained varieties. The coarse- and medium-grained dunites are the earliest mantle-derived rocks that originated as a result of pyroxene decomposition accompanied by high-temperature annealing recrystallization, translation gliding, and diffusion creep. During subsequent crustal evolution, dunite undergoes intense ductile deformation. The size of olivine grains diminishes with the increasing degree of deformation. The heterogeneous wavy and block extinction appears along with kink bands, slip planes, syntectonic recrystallization, and cataclastic flow. The following microstructural types of dunite and harzburgite are distinguished by the intensity of ductile deformation: protogranular → mesogranular → porphyroclastic → porphyrolath → mosaic. This sequence reflects an increasing degree of ductile deformation of olivine grains.

Olivine from dunite of the Kharcheruz block corresponds to forsterite (Fa = 8.0–11.5 mol %). The $Fe^{\#}$ of olivine decreases with the increasing degree of its ductile deformation as a result of syntectonic recrystallization. CaO and MnO contents in olivine are commonly undetectable. This is apparently caused by the exhaustion of dunite in the process of depletion.

The Cr-spinels contained in dunite of the Kharcheruz block are distinguished by a significant variation in chemical composition, from the less metamorphosed alumochromite to chromite, and then to Cr-magnetite, due to variable conditions of high- and low-temperature metamorphism. Cr-spinels from dunite of the Kharcheruz block are distinguished by enrichment in Fe and Cr, providing evidence for high-grade metamorphism. The substantial increase in $Cr^{\#}$ of spinel from massive chromitites is apparently caused by high-temperature ductile deformation.

The performed petrostructural analysis of olivine in dunite and chromitite allowed us to reveal preferential patterns in its optic orientations, which reflect the formation conditions and the subsequent superimposed ductile deformations in the mantle and crust. Our model of evolution of ultramafic rocks in the Kharcheruz block is consistent with the structural and compositional scenario of the ultramafic rock evolution of the Syumkeu massif as a whole, proposed by V.R. Shmelev [11]. This scenario comprises the depletion of mantle matter, the fluid and magmatic transformation of ultramafic rocks, and their subsequent metamorphism.

The first stage is characterized by the depletion of initial mantle material with the formation of the banded dunite–harzburgite complex, which then is subject to fluid and magmatic transformation. The breakdown of pyroxene resulting in the formation of large dunite bodies is controlled by large-scale folding [11]. The transformation of harzburgite into dunite proceeds at a high temperature and is accompanied by annealing recrystallization. The annealing facilitates the growth of favorably oriented olivine grains at the expense of unfavorably oriented grains with the formation of large olivine individuals with smooth boundaries, devoid of attributes inherent to ductile deformation [6]. In the course of the decomposition of pyroxene in harzburgite, Al, Mg, Fe, and Cr are released and then consumed in Cr-spinel crystallization [9]. As a result, dunite is enriched in Cr-spinel.

The second stage is mainly characterized by a high-temperature plastic flow under settings of cooling in the transitional mantle–crust zone. The degree of ductile deformation of dunite increases, and protogranular olivine is replaced with a medium-grained mesogranular type of dunite. The ductile deformation of olivine is implemented largely by high-temperature translation gliding along systems {0kl}[100], and (001)[100], apparently accompanied by surficial diffusion creep. The ductile deformation of olivine at this stage proceeds in a regime of cooling from 1000 to 650°C, a low rate (less than 10^{-6} s^{-1}), a confined pressure higher than 10 kbar, and axial compression [22, 23]. As a result, dunite with an equilibrium medium-grained microstructure is formed. Olivine grain boundaries become smooth, rectilinear, and often converge at triple points at an angle of 120°. Thereby, the optic orientation of olivine grains is controlled by the retained external stress field. The chromite mineralization hosted in dunite was apparently formed at this stage in zones of intense high-temperature bedding-plane plastic flow [13], which facilitates the segregation of Cr-spinel in linear zones and the formation of disseminated ore.

At the third stage, the ultramafic rocks are subject to intense axial and shear ductile deformations at moderately high and relatively low temperatures (500–750°C), a significant rate ($>10^{-4}$ s^{-1}), and a confined pressure (~5 MPa) in the process of displacement of these rocks along deep-seated thrust faults in the upper crust [22, 23]. The plastic flow in olivine was realized primarily by means of syntectonic recrystallization, with subordinate translation gliding along the systems (001)[100], (110)[001], (100)[010] and cataclastic flow. As a result, porphyroclastic, porphyrolath, and mosaic dunites are formed. At this stage, dunite undergoes medium- and low-temperature metamorphism, in particular, tremolitization and antigoritization. Under the effect of the intense plastic deformation of this stage, the linear zones of disseminated mineralization are destroyed with the formation of lenslike chromitite bodies, and olivine is squeezed out from them with the formation of densely impregnated and massive chromite mineralization. The metamorphism developing at this stage facilitates a substantial increase in the $Cr^{\#}$ of chromite ore.

CONCLUSIONS

The Kharcheruz block is composed primarily of extremely depleted ultramafic rocks of a dunite–harzburgite complex. Dunite is the most abundant rock, whereas harzburgite occurs sporadically as sporadic relict fragments, which managed to avoid the complete decomposition of pyroxene. The rocks are subject to various degrees of ductile deformation, and this diversity is expressed in olivine grain size, the appearance of heterogeneous extinction, kink bands, slip planes, and porphyroclasts as products of syntectonic recrystallization. By the intensity of the manifestation of these attributes, the types protogranular, mesogranular, porphyroclastic, porphyrolath, and mosaic petrostructural are identified. Their succession corresponds to the increasing degree of ductile deformation. The meso- and porphyroclastic types are predominant. The lenticular bodies and linear zones of chromitite hosted in dunite extend in a latitudinal direction conformably to the strike of the block as a whole.

The petrostructural analysis of olivine makes it possible to reveal the preferential patterns of its optic orientation, which allow us to trace the conditions and sequence of the ductile deformation of dunite and chromitite during their evolution at the mantle and crustal levels. Under mantle conditions, the ductile deformation of olivine is mainly realized by translation gliding and annealing recrystallization at a high temperature, low rate, significant confined pressure, and axial compression. Being displaced to the upper crust, ultramafic rocks are subject to intense axial and shear deformations, including translation gliding in olivine with a growing contribution of syntectonic recrystallization under conditions of temperature drop, confined pressure, and increasing rate.

The lenticular chromitite bodies and linear zones of chromite mineralization strike in the latitudinal direction conformably to the strike of the Kharcheruz block as a whole. Their localization is contolled by linear zones of intense bedding-plane flow of mantle material and is caused by the segregation of Cr-spinel into linear ore bodies and zones in the course of high-temperature plastic flow. Under the effect of crustal ductile shear deformation, the olivine is squeezed out from chromitite with the formation of densely impregnated and massive orebodies. Thereby, the accompanying metamorphism facilitates formation of high-Cr spinel.

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