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IOP Conf. Series: Earth and Environmental Science **319** (2019) 012003 doi:10.1088/1755-1315/319/1/012003

Plastically deformed ultramafites of the Ergaksky chromite-bearing massif (Western Sayan)

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Abstract. Dunites and harzburgites of Ergaksky massif constantly show signs of plastic deformation of olivine and enstatite as inhomogeneous extinction, bands of plastic fracture and sintectonic recrystallization. At level of the upper mantle dunites and harzburgites have undergone plastic deformation by translational sliding in olivine at high temperature and low speed. As a result, ultramafic with medium-grained, meso-granular texture formed. In the process of movement in the Earth's crust plastic deformation occurs mostly as sintectonic recrystallization at subordinate role of translational sliding in conditions of decreasing temperatures and growing speed of plastic flow. This has contributed to the formation of porphyroclastic textures, while translational sliding promoted the distortion of crystal structure and the emergence of non-homogeneous extinction and bands of plastic fracture. Olivinites appeared as a result of secondary recrystallization of annealing under influence of high-temperature fluids on ultramafites.

1. Introduction

Other paragraphs are indented (BodytextIndented style). Ergaksky ultramafic massif is the marginal north-eastern fragment of Kurtushibinsky ophiolite belt, situated in the north-eastern part of the West Sayan [1]. The massif consists of two different-sized blocks: the largest is the southern Lysansky block (~75 km^2) and northern Maloergaksky block (~10 km^2) (Figure 1). Lysansky block is composed of rocks of restitic dunite-harzburgite striped complex. Maloergaksky block in the central part is composed mainly of regenerated olivinites, rarer by harzburgites. Chromitites ore occurrences are situated in both blocks.

2. Materials and methods

The detailed petrographic characteristics of ultramafic rocks were carried on the polarizing microscope AxioScope-40 Carl Zeiss. That’s why it was possible to analyze the microstructural typification of dunites and harzburgites. In order to determine the chemical composition of minerals, we used a scanning electron microscope «VEGA II LMU» combined with energy dispersion (Oxford INCA Energy 350) and wave dispersion (Oxford INCA Wave 700) spectrometers.

Petrostructural research in ultramafic allows finding the preferred orientation of minerals on the interal structure and shape. Dynamic kinematic interpretation of microstructural diagrams was carried out using the data of both domestic and foreign researchers [2–5].

3. Petrography of ultramafites

3.1. Harzburgites

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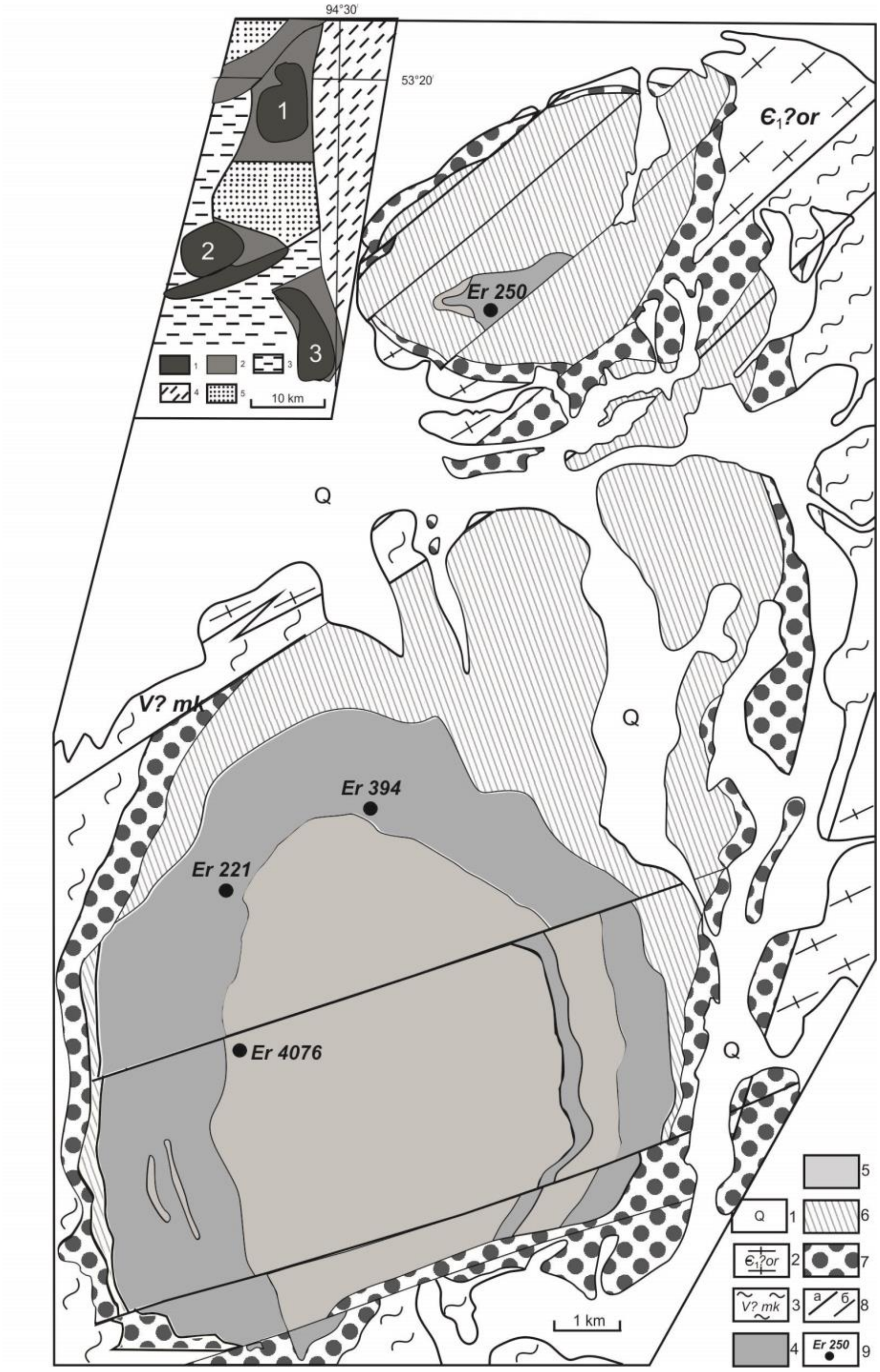

Figure 1. Geological scheme of Ergaksky chromite-bearing massif [6], edited by authors.
1 – alluvial sediments; *2* – siliceous-clay shale, carbonaceous, siliceous, horizons of quartzite, basalts, tuffs; *3* – metabasalts, their tuffs, siliceous shale, lenses of limestone; *4* – dunites, olivinites; *5* – harzburgites; 6 – serpentinites, serpentinous rock; *7* – serpentine melange; *8* – *a)* dislocations, *b)* – geological boundaries; *9* – sampling point.
In the inset: Scheme of ophiolite belt in the north-eastern part of Western Sayan. *1* – ultramafic massifs (*1* – Ergaksky, 2 – Kalninsky, 3 – Kyzyr-Burlyuksky), *2* – volcanic-sedimentary strata: metabasalts, plagiorhyolite, siliceous shale, carbonaceous, glaucophanitic; *3–4* – Caledonian fold system: *3* – West Sayan, *4* – Khemchiksky-Sistighemskaya; *5* – Middle Paleozoicbasin.

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The texture of harzburgites is mostly medium-grained, often shows signs of porphyroclasts. Structure homogeneous, or directional. Harzburgites composed of olivine, with the subordinate role of enstatite (15 %). Cr-spinels, diopside, and chlorite are present also. Olivine grains have sub-isometric or elongated shape. Their orientation reflects directivity. The grain size is of 4–5 mm. The grains of olivine constantly shows signs of plastic deformation in the form of a heterogeneous wavy extinction and bands of plastic fracture. Infrequently sintectonic recrystallization forms a fine mosaic olivine aggregates. The chemical composition of olivine corresponds to forsterite (Table 1). CaO and MnO aren't detected, probably because of the intense depletion of harzburgites. Orthopyroxene grains have an irregular shape, size up to 4 mm. They show weak inhomogeneous extinction. Chemical composition of orthopyroxene corresponds to enstatite with an iron content of 8.2–10.7 % (Table 2). Clinopyroxene is found as small subisometric grains with sizes of 0.2 to 0.4 mm and corresponds to diopside with an iron content of 5.7 % (Table 2). Chromespinelide is found as a dark brown granes with sizes up to 1.5 mm. Chromespinelides are replaced by magnetite. Chromespinelides are presented by picotite, chrompicotite and chromohercynite (Figure 2, Table 3).

Table 1. Chemical composition of olivine in the ultramafic rocks (wt.%).

Sample	Er 53	Er 206	Er 393-к[b]	Er 393-м	Er 220-к	Er 220-м	Er 268	Er 270	Er 394	Er 203	Er 264	Er 268
Rock	Harzburgites		Dunites				Olivinites		Chromitites[c]			
SiO_2	41.6	40.4	42.0	41.2	42.4	40.9	43.2	42.6	51.0	42.0	41.2	43.7
FeO	7.7	9.6	5.5	5.9	8.3	9.8	0.8	1.6	2.0	6.0	2.1	0.7
NiO	0.4	0.4	0.4	0.5	0.4	0.4	–	0.4	–	1.1	–	–
MgO	50.3	48.9	52.1	51.9	48.6	48.1	56.0	55.5	45.0	50.4	54.0	55.5
Total	100	99.4	100	99.5	99.7	99.2	100	99.9	99.9	99.5	97.3	100
Fa[a]	7.9	10.0	5.6	6.0	8.7	10.3	0.8	1.6	2.4	6.3	2.1	0.7

[a] Content of fayalite molecule [Fa = Fe/(Fe+Mg)×100%].
[b] K – big porphyroclastic individuals, m – grained recrystallized grains.
[c] Chromitites: Er 394, 203 – Lysansky block, Er 264, 268 – Maloergaksky block.

Table 2. Chemical composition of pyroxenes of harzburgites (wt.%).

Sample	Er 53	Er 206	4076	Er 206
Mineral		Enstatite		Diopside
SiO_2	56.8	56.1	56.9	53.9
Al_2O_3	1.7	2.9	3.0	3.4
Cr_2O_3	0.5	0.7	0.8	0.8
FeO	5.7	5.4	6.7	2.0
MgO	34.5	34.2	31.5	18.5
CaO	0.8	0.7	0.9	21.5
Total	100	100	99.8	100
F[a]	8.5	8.2	10.7	5.7
Wo[b]	1.5	1.3	1.8	44.1
Fs[c]	8.4	8.1	10.5	3.2
En[d]	90.2	90.7	87.7	52.7

[a] [F = Fe/(Fe+Mg)×100%].
[b] [Wo = Ca/(Ca+Fe+Mg)×100%].
[c] [Fs = Fe/(Ca+Fe+Mg)×100%].
[d] [En = Mg/(Ca+Fe+Mg)×100%].

3.2. Dunites

Usually have porphyroclastic texture and directional structure. They are composed of olivine, Cr-spinelides (up 5 %). The porphyroclast of olivine grains have an elongated, lenticular shape, reflecting the direction. Their length is up to 3 mm is. They are intensively plastically deformed, inhomogeneous wavy extinction and numerous bands of plastic fracture is typical for them. Sintectonic recrystallized fine grains of olivine occupy gaps between porphyroclast. Their size is usually less than 1 mm. They are also deformed and have an irregular extinction. Olivine of dunite corresponds by chemical composition of forsterite (Table 1). The iron content of the recrystallized olivine tends to increase compared with porphyroclastic. Dark brown grain Cr-spinelides are less than 0.5 mm. Cr-spinelides correspond to chromopicotite, alumochromite and chromite (Figure 2, Table 3).

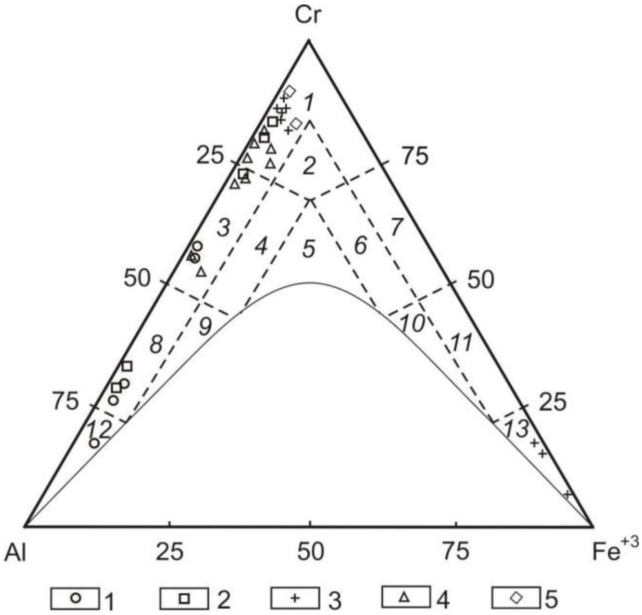

Figure 2. Composition of spinelides and magnetites of Ergaksky ultramafic massif on the classification diagram [7]. *1* – harzburgites, *2* – dunites, *3* – olivinites, *4–5* – chromitites: *4* – Lysansky block, *5* – Maloergaksky block. The fields in the diagram: 1 – chromite, 2 – subferrichromite, 3 – alumochromite, 4 – subferrialumochromite, 5 – ferrialumochromite, 6 – subalumoferrichromite, 7 – ferrichromite, 8 – chromopicotite, 9 – subferrichromopicotite, 10 – subalumochromomagnetite, 11 – chromomagnetite, 12 – picotite, 13 – magnetite.

Table 3. Chemical composition of spinelides of ultramafites and chromitites (wt.%).

Sample	Er 53	Er 206	Er 393	Er 220	Er 250	Er 268	Er 394	Er 101	Er 264	Er 268
Blocks	Lysansky				Maloergaksky		Lysansky		Maloergaksky	
Rock	Harzburgites		Dunites		Olivinites		Chromitites			
SiO_2	4.0	0.6	0.9	0.4	0.6	0.6	0.5	0.6	0.8	0.5
Al_2O_3	22.3	47.2	12.5	40.2	5.9	6.1	13.2	18.8	6.5	5.6
Cr_2O_3	45.2	21.2	57.0	27.9	62.2	64.9	58.0	50.1	60.0	65.1
Fe_2O_3 [a]	1.3	2.8	2.7	2.1	2.8	1.5	2.5	0.9	3.9	2.2
FeO	17.4	9.7	13.2	12.2	19.7	14.7	10.7	13.3	16.7	13.6
MgO	11.2	18.4	13.2	16.9	8.4	11.7	15.1	13.4	9.9	12.3
Na_2O	0.6	–	0.5	0.4	–	0.5	0.4	1.3	1.5	0.4
Total	100.0	99.9	100	100	99.5	100	100.3	98.5	99.3	99.7
F' [b]	46.8	23.0	36.6	29.2	57.0	41.6	29.2	36.6	48.0	38.8
Cr' [c]	57.6	23.2	75.3	31.7	87.5	87.7	74.7	64.4	86.1	88.6
F'' [d]	1.6	2.8	3.3	2.2	3.6	1.9	2.9	2.1	5.0	2.8

[a] Calculation of ferric and ferrous iron: [Fe_2O_3* = 52,832×[(ΣFeO+MgO+MnO+NiO+CoO)-(Cr_2O_3+Al_2O_3+2×TiO_2)]/1000], [FeO* = ΣFeO–0,9×Fe_2O_3*] [8].
[b] [F' = $Fe^{2+}/(Fe^{2+}+Mg)\times100$].
[c] [Cr' = $Cr/(Cr+Al)\times100$].
[d] [F'' = $Fe^{3+}/(Fe^{3+}+Cr+Al)\times100$].

3.3. Olivinites

Have the medium-grained texture. Olivinites differ from dunites by the absence of plastic deformation signs in grains of olivine. Olivinites composed of olivine. The content of Cr-spinelide is up to 10 %. Olivine grains have subisometric, prismatic shape. The grain boundaries are straight or sinuous. The size ranges from 1 to 5 mm. Olivine grains have regular extinction. The chemical composition of olivine corresponds to forsterite with a minimum iron content (Table 1). Cr-spinelides form small inclusions in olivine. Their size is up to 0.5 mm. The chemical composition of Cr-spinelides corresponds to chromite and magnetite (Figure 2, Table 3). They have a higher content of chromium and low content of Al_2O_3 compared to the dunites.

3.4. Chrometites
Have thickly dissemination texture. They composed primarily of Cr-spinelide grains (70–75 %) with the subordinate role of serpentinized olivine (25–30 %). Grains of Cr-spinelides usually have subisometric shape. Their fraction size is up to 3 mm. Grains often form close aggregative fusion and have red and brown colour. Cr-spinelides in chromitites of Lysansky block differ from those of Maloergaksky block by larger content of Al_2O_3, MgO, and lower content of Cr_2O_3, FeO (Table 3) and presented by alumochromites and chromites. They do not differ from Cr-spinelides of ore-bearing dunite. In Maloergaksky block of Cr-spinelides correspond to chromite. In the chromitites olivine is usually completely replaced by serpentine. Olivine of Lysansky block has iron content of 2.4–6.3 %, and olivine from chromitites of Maloergaksky block is notable for minimum iron content (Fe = 0.7 %) (Table 1).

4. Petrostructural analysis of ultramafic rocks
Analysis of the obtained petrostructural patterns of olivine was conducted serially. Firstly the analysis of patterns in harzburgites (protolithic mantle material) was conducted. Then the analysis of patterns in dunites and olivinites that were formed as a result of depletion of original harzburgites and subsequent secondary annealing was conducted.

4.1. Harzburgites
Formation of petrostructural pattern of olivine (Figure 3, Sample 4076 Ol) probably was carried out by high temperature translation sliding of the system {0kl} [100] and sintectonic recrystallization in dynamically active zone, obviously, in the transition zone of the upper mantle and root parts of the earth crust. Thus the direction of plastic flow of harzburgites is marked by the mineral linearity and consists of maximum of olivine Ng axes. The direction of compression reflects the maximum of axes Np, normal to the mineral flatness. This petrostructural pattern indicates the plastic flow proceeded under conditions of axial deformation in regime of temperature decrease (from 900°C), moderate and high speed ($10^{-5}c^{-1}$–$10^{-2}c^{-1}$) [5]. The plastic deformation at this stage had a heterogeneous character and carried out mainly by translation sliding and sintectonic recrystallization. As a result grains of olivine in harzburgites have a heterogeneous undulating extinction and characterized by the presence of numerous bands of break and undergone intensive porphyroclasts.

Enstatite in harzburgites is less subjected to plastic deformation. In the studied harzburgite established petrostructural patterns of crystal-optical orientations of axes of enstatite (Figure 3, Sample 4076 En) have similar character of distribution with crystaloptical axes of plastically deformed olivine. The optical orientations of olivine and enstatite are closely related. Many researchers paid attention to syngenetic in harzburgites from ophiolite complexes [3, 5]. Most of the plastic deformations of enstatite were carried by translational sliding in high-temperature system (100) [100], which corresponded to translational sliding in olivine in {0kl} [100].

4.2. Dunites
The petrostructural pattern of olivine in dunites with porphyroclastic texture (Figure 3, Sample Er-221 Ol) is caused by the activation of translational sliding in system {0kl} [100], which was carried out in two directions [3]. At the same time one of the directions is dominant and orients mainly in accordance with the direction of the superimposed shift. The second direction of translation is located at angle of 60–90° to the plane of shift. Numerous bands of break are symmetrically oriented to direction of elongation. Formation of such petrostructural pattern obviously was carried out in the

lower parts of earth crust at a high speed of plastic flow (up to ε $10^{-2}s^{-1}$), that led to temperature increasing (up to 1000°C) [4].

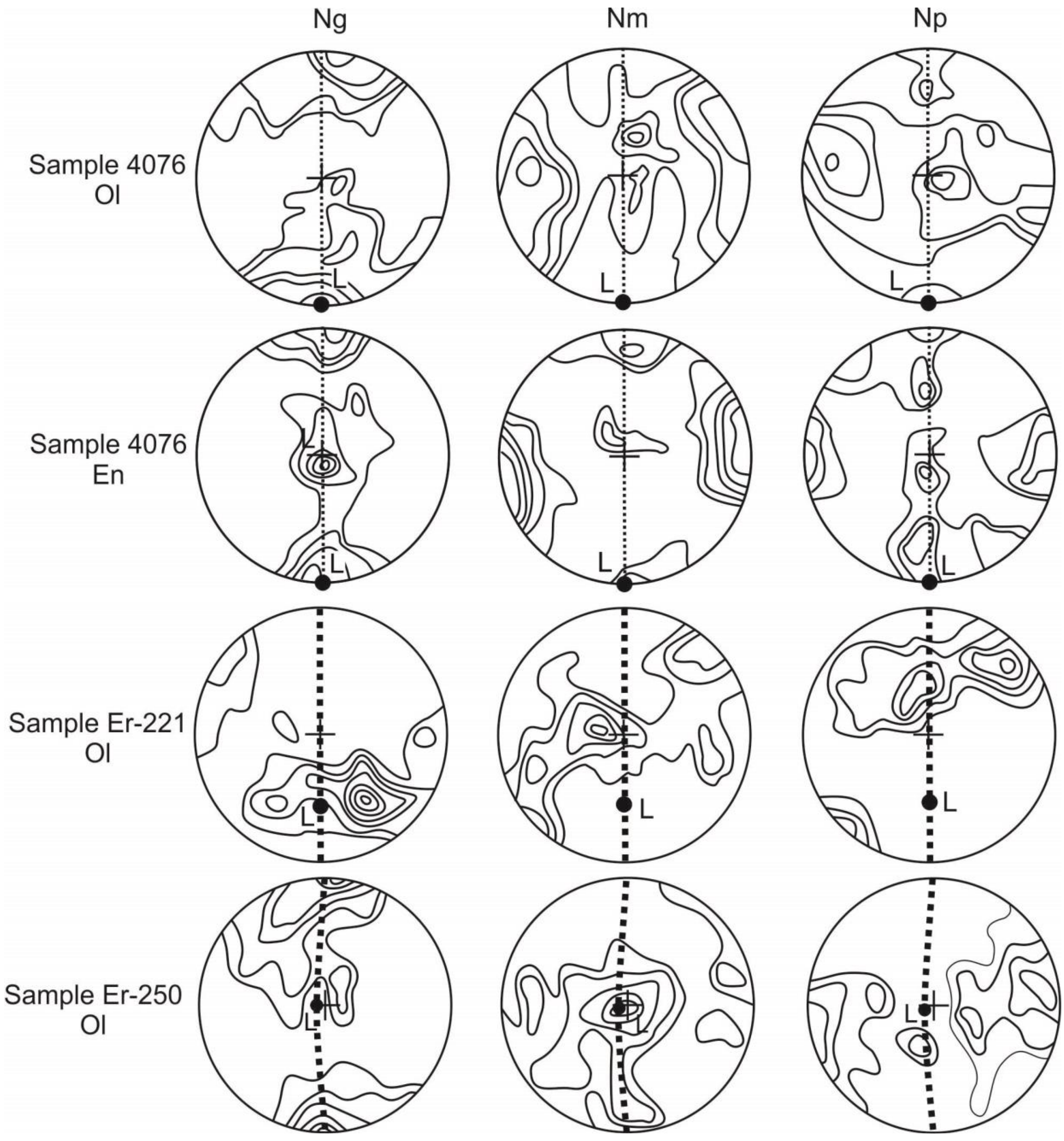

Figure 3. Diagrams of orientation of crystal optics axes of olivine (Ol) and enstatite (En) in harzburgites, dunites and olivinites of Ergaksky massif. Diagrams built on 100 measurements of crystal optical axes of minerals. Isolines: 1–2–4–6–8–10–12 % on 1 % of grid Schmidt, projection on the upper hemisphere. Dotted line – plane flatness, L – linearity.

4.3. Olivinites

They were formed by the high temperature secondary recrystallization of annealing, which promoted expansion of free-stress olivine individuals without signs of plastic deformation [3, 9]. In this case grains of olivine have a logical orientation of internal structure (Figure 3, Sample Er-250 Ol), which is controlled by an external stress field, fixed by a maximum of Np‖σ_3 axes and translation sliding in system (110)[001]. The direction of sliding is set on a maximum of Nm‖σ1 axes. The main factors of this process are a moderately high temperature (T = 500°C), slow speed ($\varepsilon<10^{-6}s^{-1}$) and low stress (10–20 MPa) [3].

5. Conclusion

Ergaksky ultramafic massif consists of two blocks: Lysansky and Maloergaksky that were tectonically separated and formed at different hypsometric levels. Lysansky block mainly composed of restitic dunites and harzburgites. Maloergaksky block composed primarily of regenerated olivinites. Ore body of chromitites occurs among ultramafic of both blocks.

Dunites and harzburgites undergone plastic deformation in varying degrees and they are characterized by significant variations in textures, from fine-grained to medium-grained. According to the intensity of plastic deformation actions two main types of microtexture dunite and harzburgite can be distinguished: mesogranular and porphyroclastic, which are assumed to two stages of plastic deformation ultramafic. Medium-grained, mesogranular dunite and harzburgite are the earliest mantle formations and apparently had arosed as a result of high-temperature plastic deformation, which was carried out by high-temperature translational sliding in olivine, enstatite, and accompanied by diffusion creep.

In second stage of crustal deformation of plastic dunites and harzburgites was carried by translational sliding during the growing role of sintectonic recrystallization in conditions of decrease of temperatures and high speeds. As a result, dunites and harzburgites with porphyroclastic texture are formed. The increasing of iron content of micrograin intensely of deformed olivine indicates the sintectonic recrystallization proceeding in reducing conditions [3].

Olivinite was formed in conditions of increasing temperatures and due to superimposed secondary annealing due to the original plastically deformed dunite. As a result, olivine grains with no signs of plastic deformation expanded. Olivine in olivinites differ from dunite and harzburgite by minimum iron content (Fa = 0.8–1.6 %).

The formation of chromitites is controlled by zones of intense mantle depletion and caused by the metamorphic segregation Cr-spinelides in ore zones in process of high-temperature plastic flow. In process of crustal plastic shearing deformation, there was uneven «extrusion» of chromitite from olivine and formation of copious impregnation and continuous disseminated ore bodies [10-12]. At the same time associated metamorphism promoted the formation of high-chromium chromitite.

This work was conducted as a government task of the Ministry of Science and Higher Education of the Russian Federation, project No. 5.2352.2017/4.6.

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