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ХАБАРЛАРЫ

ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ
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Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

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NEW DATA ON THE MINERALOGY OF SUPRA-SUBDUCTION OPHIOLITES OF THE TEKTURMAS MOUNTAINS (CENTRAL KAZAKHSTAN)

Abstract. The article is devoted to one of the typical problems of the geology of plutonic ophiolites of Central Kazakhstan. For the first time, mineralogical and geochemical studies of peridotites of the Tekturmas mountains have been carried out using precision methods of analysis, which gave grounds to substantiate their supra-subduction environment of formation. The electron-probe method showed that peridotite chips, obtained from heavy mineral concentrate (earlier, source of zircon), contain orthopyroxene, olivine-chrome spinel and olivine-magnetite aggregates, which allowed not only to determine the chemical composition of the minerals but also to calculate such important parameters of chrome spinel as Cr-number (Cr#), Mg-number (Mg#) and iron oxidation level (Fe^{+3}#=Fe^{+3}/(Fe^{+3}/Fe^{+2})). Chromospinelides in peridotites are in their majority related to subferrialumochromite (Cr#=0.63-0.75, Mg#=0.23-0.33, Fe^{+3}#=0.222-0.333), rarely to alumochromite (Cr#=0.54-0.69, Mg#=0.27-0.46, Fe^{+3}#=0.165-0.279); extremely rare are ferrialumochromite (Cr#=0.64-0.76, Mg#=0.16-0.24, Fe^{+3}#=0.394-0.434), ferrichromite (Cr#=0.78, Mg#=0.29, Fe^{+3}#=0.248) and chromite (Cr#=0.85, Mg#=0.26, Fe^{+3}#=0.174). Secondary magnetite contains impurities of NiO =0.01-0.28 wt%, Cr_2O_3=0.10-0.21 wt% typical for chromespinelides, which it replaces. The primary magnetite does not contain such impurities. Along with the presence of polyform chromite in the pre-arc peridotites, extensive development of secondary magnetite masses was identified. The secondary nature of the harzburgites was established based on the presence of secondary orthopyroxene in the dunite. They contain high-magnesium olivine (Fo=90.25-92.47), high-magnesium orthopyroxene (En=89-91) and have low concentrations of CaO (0.01-0.50 wt%), Al_2O_3 (0.35-2.47 wt%) and high-chromium chromespinelides, which is typical for pre-arc peridotites of supra-subduction zones. This is not contradicted by high concentrations of REE harzburgites, reflecting their high degree of refertilisation (secondary enrichment) resulting from the melt-rock interactions.

Key words: serpentinite, olivine, chromite, forearc peridotites, Tekturmas, Central Kazakhstan.

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ТЕКТҰРМАС ТАУЛАРЫНЫҢ СУБДУКЦИЯ ҮСТІЛІК ОФИОЛИТТЕРІНІҢ МИНЕРАЛОГИЯСЫ ТУРАЛЫ ЖАҢА МӘЛІМЕТТЕР (ОРТАЛЫҚ ҚАЗАҚСТАН)

Аннотация. Мақала өзекті мәселелердің бірі – Орталық Қазақстанның плутондық офиолиттер геологиясына арналған. Алғаш рет сараптаудың дәл әдістерін қолдану арқылы Тектұрмас тауларының перидотиттеріне минералогиялық және геохимиялық зерттеулер жүргізілді, бұл олардың субдукция үстілік түзілу жағдайын дәлелді түсіндіруге негіз болды. Бұрын электронды зонд әдісімен зерттелген концентраттан циркон, перидотит сынықтары бөлініп алынған, оның құрамында ортопироксен-, оливин-хром-шпинель, оливин-магнетит өсінділері болды, бұл минералдардың химиялық құрамын анықтап қана қоймай, сонымен қатар хром-шпинельдердің маңызды параметрлерін есептеуге мүмкіндік берді: хром құрамы (Cr#=Cr/(Cr+Al)), магний мөлшері (Mg#=Mg/(Mg+Fe) және темірдің тотығуы (Fe+3)#=Fe+3/(Fe+3/Fe+2)). Перидотиттердің хромшпинельдері көбіне субферриалюминохромитке жатады (Cr#=0,63-0,75, Mg#=0,23-0,33, Fe+3#=0,222-0,333), сирек алюминохромиттерге жатады. (Cr#=0,54-0,69, Mg#=0,27-0,46, Fe +3#=0,165-0,279), өте сирек ферриалюминохромит (Cr#=0,64-0,76, Mg#=0,16-0,24, Fe+3#=0,394- 0,434), феррихромит (Cr#=0,78, Mg#=0,29, Fe+3#=0,248) және хромит (Cr#=0,85, Mg#=0,26, Fe+3#=0,174) кездеседі. Екінші магнетитте ол алмастыратын хром шпинельдерге тән NiO=0,01-0,28 %мас., Cr_2O_3=0,10-0,21 %мас., қоспалар бар. Бірінші магнетитте мұндай қоспалар жоқ. Доғаға дейінгі перидотиттердің құрамында подиформды хромиттердің болуымен қатар, екінші магнетит массаларының кең дамуы анықтады. Дунит құрамында екінші ортопироксен болуының негізінде гарцбургиттердің екінші табиғаты анықталды. Олардың құрамында жоғары Mg# оливин (Fo=90,25-92,47), жоғары Mg# ортопироксен (En=89-91), төмен концентрациялы CaO (. 0,01-0,50 %мас), Al_2O_3 (0,35-2,47 мас.%), жоғары хромды хромшпинельдері, бұл субдукция үстілік белдемдердегі доғаға дейінгі перидотиттерге тән. Оған гарцбургиттерде жоғары шоғырланған сирек жерлі элементтер қайшы келмейді, ол балқыма мен тау жыныстарының өзара әрекеттесуіне байланысты оның жоғары деңгейде рефертилизациясын (екінші байытылуын) көрсетеді.

Түйін сөздер: серпентинит, оливин, хромит, доғаға дейінгі перидотит, Тектұрмас, Орталық Қазақстан.

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НОВЫЕ ДАННЫЕ ПО МИНЕРАЛОГИИ НАДСУБДУКЦИОННЫХ ОФИОЛИТОВ ГОР ТЕКТУРМАС (ЦЕНТРАЛЬНЫЙ КАЗАХСТАН)

Аннотация. Статья посвящена одной из актуальных проблем геологии плутонических офиолитов Центрального Казахстана. Впервые прецизионными методами анализа выполнены минералогические и геохимические исследования перидотитов гор Тектурмас, что дало основание аргументировано обосновать их надсубдукционную обстановку формирования. Из шлиха, в котором ранее был выделен циркон, сколки перидотитов, изученные электроннозондовым методом, содержали ортопироксен-, оливин-хромшпинелиевые, оливин-магнетитовые сростки, что позволило не только определить химический состав этих минералов, но и рассчитать такие важные параметры хромшпинелидов, как: хромистость

(Cr#=Cr/(Cr+Al)), магнезиальность (Mg#=Mg/(Mg+Fe) и окисленность железа (Fe+3#=Fe+3/(Fe+3/Fe+2)). Хромшпинелиды перидотитов в своем большинстве относятся к субферриалюмохромиту (Cr#=0.63-0.75, Mg#=0.23-0.33, Fe+3#=0.222-0.333), реже алюмохромиту (Cr#=0.54-0.69, Mg#=0.27-0.46, Fe+3#=0.165-0.279), крайне редко встречается ферриалюмохромит (Cr#=0.64-0.76, Mg#=0.16-0.24, Fe+3#=0.394-0.434), феррихромит (Cr#=0.78, Mg#=0.29, Fe+3#=0.248) и хромит (Cr#=0.85, Mg#=0.26, Fe+3#=0.174). Вторичный магнетит содержит примеси NiO=0.01-0.28 мас. %, Cr_2O_3=0.10-0.21 мас. %, типичные для хромшпинелидов, которые он замещает. Первичный магнетит таких примесей не содержит. Наряду с присутствием подиформных хромитов в составе преддуговых перидотитов установлено широкое развитие масс вторичного магнетита. Установлена вторичная природа гарцбургитов на основании присутствия вторичного ортопироксена в дуните. Они содержат высоко-Mg# оливин (Fo=90.25-92.47), высоко- Mg# ортопироксен (En=89-91), низкие концентрации CaO (0.01-0.50 мас%), Al_2O_3 (0.35-2.47 мас%), высокохромистые хромшпинелиды, что характерно для преддуговых перидотитов надсубдукционных зон. Этому не противоречат высокие концентрации РЗЭ гарцбургитов, что отражает их высокую степень рефертилизации (вторичного обогащения), обусловленного взаимодействием расплава и породы.

Ключевые слова: серпентиниты, оливин, хромиты, преддуговые перидотиты, Тектурмас, Центральный Казахстан.

Introduction. The Urtynzhal gold-copper occurrence is part of the Tekturmas subduction-accretionary (TSA) complex, which is exposed about 45 km south of Karaganda (fig. 1). It is one of the fragments of supra-subduction ophiolites in Central Kazakhstan, which are incorporated into the cover-fold structures of the western part of the Central Asian Orogenic belt. Ophiolites of the TSA complex are exposed along the northwestern margin of the Zhongar-Balkhash folded system. They are traced for 350 km along with the sub-latitudinal branch of the Devonian volcanic-plutonic belt (fig. 1A).

The outline of formation, structural features, age, and geotectonic position of constituent parts of ophiolites within this area have been repeatedly discussed in publications of Soviet, later Russian, and Kazakh geologists (Antonyuk, et al., 2021).

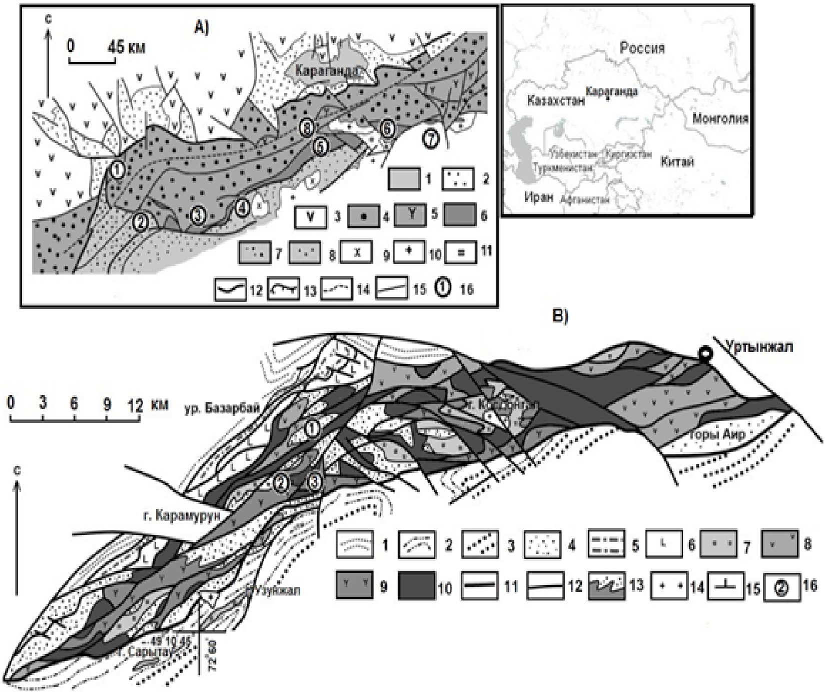

Figure 1 (A) Geodynamic diagram of the Devonian active continental margin (Stepanets, 2016):
1 - Mesozoic cover (J); 2 – siliciclastic and carbonate marine deposits (D_3-C_2); 3 - Devonian volcanic-plutonic belt (D_1-$_2$), 4-5 - formations of forearc Nura-Karasor basin: 4 – volcano-sedimentary deposits (O_3-D_3); 5 - Baidaulet active continental margin (O_2-$_3$); 6 - accretionary prism; 7-8 - deposits of Zhaman-SarySu marginal sea: 7 - turbidite formations of Atasu zone, 8 - siliciclastic flysch; 9 - mid-Devonian granodiorites; 10 - mid-Carboniferous granitoids; 11 - rhyolites and rhyodacites of Uspensk intracontinental rift;12 - Karaganda thrust; 13 - Tekturmas thrust; 14 - buckling zone; 15 - faults; 16 - geographical locations: 1 - Satybai city, 2 - Aktasty city, 3 - Zhaman-Imanak city, 4 - Arkalyk city, 5 – Tort-Aul valley, 6 - Nurcheken town, 7 – Sarykul-Baldi town.

(B) Schematic geological map of Krasnaya Polyana segment of the Tekturmas accretionary prism after N.A. Gerasimova, M.Z. Novikova, L.L. Herman and author's personal observations (1987-1990, unpublished):

1 - green-coloured siliciclastic rocks of Yermek Formation (lower Silurian) of Nura-Karasor forearc trough; 2 - presumably Upper Ordovician green-coloured siliciclastic rocks with extended olistoplacs of cherts; 3 - Silurian siliciclastic deposits of Sary-Su marginal sea; 4 - olistostromes of Sarytau Formation (O_3-S_1); 5 – volcano-sedimentary Bazarbai Formation (O_3sa^1-S_1) 6 – basalt volcanic rocks of Kuzek Formation (O_3sa1), with diabase, keratophyre and stratified gabbro-plagiogranite complex at the base; 7 - Tekturmas silicites (O_2da_3-O_3sa); 8 - Duan-Kora basalts (O_2da^3-O_3sa); 9 – Karamurun basalts (O_2da^3); 10 - serpentinite melange 11 - thrust; 12 - tectonic

faults; 13 – boundaries of rock units and boundaries separating allochthons of serpentinites, basalts and silicites; 14 - diorites and gabbro-diorites (C_2-$_3$); 15 - bedding elements; 16 – geographical sites (1 - Duan-Kora town, 2 - Tekturmas Mountains (49°16'N, 73°20E)), 3 – Tort-Aul valley. Coordinates (49°20'29''N; 73°32'46''E) of the U-1 well drilled at the Urtynzhal site.

Two independent tectonic structures are recognised within the TSA complex: (1) the Bazarbai parautochthon with a complete succession of forearc ophiolites in the north, and (2) a polymictic serpentinite melange exposed in the central part, thrusted by terrigenous deposits of the Zhaman-Sary-Su trough from the south (fig. 1B). The polymictic serpentinite melange, as well as the tectonic cover of Karamurun (O_2dw^3) and Duan-Kora (O_2dw^3-O_3sa) basalts and Tekturmas jaspers (O_2dw^3-O_3sa), are connected to Sarytau olistostromes (O_3-S_1), which builds up sections of the Zhaman-Sary-Su terrigenous trough.

The polymictic serpentinite melanges have been studied systematically within the Krasnaya Polyana segment (fig. 1B), where it is cropping out in the vicinity of Sarytau, Karamurun, Tekturmas, Duan-Kora, Kosdongal, Ayir and Tort-Aul valley. It is exposed as extended linear melange zones, lenses and folded serpentinite protrusions. Blocks of variable size and boudins of dunites, spinel and plagioclase lherzolites and veined clinopyroxenites are integrated into apoharzburgitic serpentinites, forming the melange base. There are also ramified bodies of dolerites, gabbro-dolerites, gabbro, gabbro-amphibolites and rodingitized rocks.

Along with rocks of the gabbro-peridotite complex, blocks of gneisses, quartzites, basalts, jaspers and fragments of rocks of the olistostromic complex occur in the serpentinite melange in the Tort-Aul valley. In the northern foothills of the Tekturmas Ridge, extended blocks of plagiogranites, syenites, migmatites and plagiogranite gneisses, amphibolites with bluish-green hornblende, syenite-gneisses with garnet are recorded; also blocks of amphibolites in paragenesis with marbleized limestone, containing oncolite-like structures, and ferruginous quartzites are known.

In the southern Sarytau Ridge and to the south of Pozharishche, podiform bodies of chromites are found in serpentinites. One of the characteristic features of serpentinite composition of TSA complex is the presence of accessory microdiamond, moissanite, zircon, baddeleyite and corundum grains (Antonyuk, et al., 2021).

The age of volcanogenic and sedimentary members of ophiolitic associations of the Tekturmas subduction-accretionary complex is reliably dated by conodonts (Novikova et al., 1991). In contrast, the age and geological position ophiolite plutonic rocks of ophiolites are not reliably determined and have been actively discussed in recent years (Stepanets, 2016a, b; Khassen et al., 2020). Only recently U-Pb zircon dating (467±3 Ma) was obtained for the plutonic rocks in ophiolites of the TSA complex (Antonyuk, et al., 2021). However, it is not helpful in the determination of the geodynamic setting of the zircon-bearing ultramafic rocks, which remains controversial. In order to solve the issue, additional studies were carried out on geochemistry of peridotites, chemical composition of rock-forming and accessory minerals in peridotites of the Urtynzhal site.

Geological structure of the ore occurrence. The Urtynzhal ore field site is located on the left bank of the Kyzyl-Koi River (Antonyuk, et al., 2021) near the north-eastern margin of the Krasnaya Polyana sector (Fig. 1B). Apoharzburgite and apodunite serpentinites exposed within the ore field are over thrusted by blocks of gabbro-amphibolites and amphibolitized gabbro. Tectonic breccias with gold-copper mineralization have been documented at the contact zone between amphibolites and ultramafic rocks. The entire rock complex is penetrated by zones of Au-Cu mineralization. Nickel and copper sulphides occur occasionally in ultramafic rocks. Also, two thin lamprophyre dikes were documented within the ore field area.

Petrography and mineralogy. According to Yu.A. Nuzhnykh, the nodular-stained and in some areas nodular-striped apoharzburgitic and apodunitic serpentinites without clear boundaries contain nests and phenocrysts of magnetite (5-10%), chrome spinel (1-3%) and, rarely, nickel sulfides. We have additionally identified chalcocite, galena and zircon. Magnetite is irregularly distributed in the rock, has rounded and hypidiomorphic crystals, but most often forms xenomorphic clusters along the cleavage and in the spaces between grains of serpentinized olivine. Chromospinel forms sparse and scattered phenocrysts of hypidiomorphic and xenomorphic grains ranging from 0.05 to 0.5 mm. Chromospinel grains are often peripherally grown with chromomagnetite; rarely, chromospinel contains small inclusions of serpentinized olivine, and occasionally fresh olivine. Small grains of pentlandite and chislevudite occur in the rims and micro veins of chromomagnetite. Pentlandite and Millerite, which develop on it, form xenomorphic grains, less often tabular crystals, but they are usually found as thin clusters along orthopyroxene cleavage planes. Zircon is represented by transparent and semi-transparent colourless sub-idiomorphic crystals of short-prismatic and isometric habitus and their fragments. The size of the crystals varies from 60 to 200 μm. Most of the grains have well-expressed magmatic zoning. Elements of sectorial structure are observed in some crystals (Antonyuk, et al., 2021).

Research methodology and the material. In total, 45 crystal aggregates from serpentinized spinel peridotites were investigated, and only ten grains of olivine and four grains of orthopyroxene were suitable for petrochemical analysis. All oxides are given in wt%. The chemical composition of chrome spinel, olivine and orthopyroxene was converted into cationic one based on 32, 6 and 4 oxygen atoms, respectively. The ratio of divalent and trivalent iron was calculated based on stoichiometry. Due to the high degree of serpentinization of harzburgites, the diffractometric X-ray analysis was performed. The instrumental neutron activation (INAA), the energy dispersive X-ray fluorescence analyses (XRF), as well as inductively coupled plasma mass spectrometry (ICP-MS) were carried out on the same samples.

Results. Mineralogical composition of harzburgites. According to the results of semi-quantitative X-ray diffraction analysis, serpentinite consists of (%): enstatite (49.4), olivine (21.2), monticellite (12.9), lizardite (6.9), hematite (3.2), nickel chromite (2.4), magnetite (2.2), and chlorite (1.6), Σ 99.8%.

Rock-forming minerals. Olivine. Significant quantity of olivine grains was affected by serpentinization. Relatively fresh olivine grains, the oxide sum of which varies from 98.31 to 101.81 wt%, are scarce. Olivine is consistently enriched in NiO (0.40-0.62 wt%). The Cr_2O_3 content in olivine varies from 0.0 to 0.26 wt%. The presence of Cr_2O_3 is usually associated with micro-inclusions of chromospinelides. The forsterite content varies in a narrow range from 89.36 to 93.32 wt%.

Orthopyroxene. Rare orthopyroxene grains are mainly represented by enstatite (En 90.82-93.32; Fs 6.68-8.83) with Mg#=91.1-93.3. The Al_2O_3 and Cr_2O_3 concentrations vary from 0.39 to 0.83 wt% and from 0.26 to 0.38 wt%, respectively; NiO=0.21 wt% and CaO=0.13-0.21 wt% are observed less frequently.

The accessory minerals of the spinel group

Chromospinelides. Chromospinelides in peridotites of the Urtynzhal site mostly belong to sub-ferrialuminochromite, less often to aluminochromite; extremely rare are ferrialuminochromite, ferrichromite and chromite.

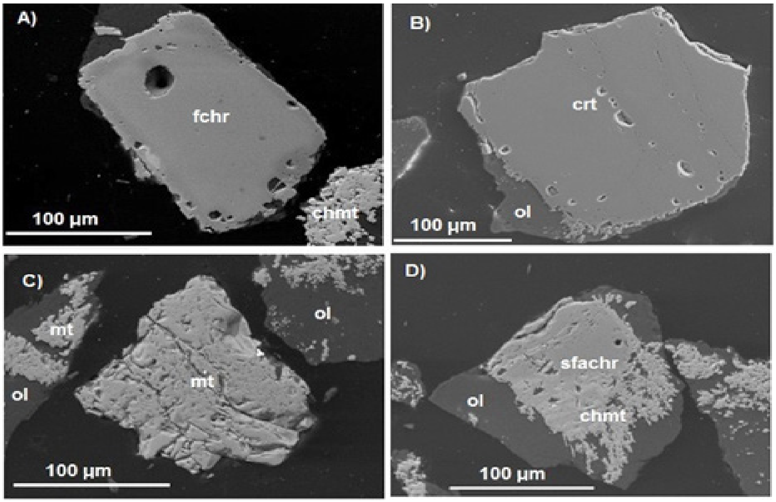

Figure 2. The image in back-scattered electrons of slide parts of spinel and olivine aggregates:
ol - olivine, crt - alumochromite, fchr - ferrialuminochromite, sfachr - sub-ferrialuminochromite, mt - magnetite, chrm - chrome magnetite

The chromium and magnesium content in the chromespinelides varies within narrow limits (Cr#=0.54-0.85; Mg#=0.23-0.46), while the ($Fe_3/(Fe_3+Fe_2)$) degree of oxidation varies in a wide range (0.165-0.519). The isomorphic impurities in chromespinelides vary in a wide range (wt%): (MnO=0-00-0.64-0.88; V_2O_5=0.00-0.12-0.72; ZnO=0.00-0.117-0.60; NiO=0.00-0.05-0.56). The isomorphic impurity TiO_2 in chromespinelides, olivine and orthopyroxene, are below the analysis's detection limit. All chromespinelides contain an admixture of V_2O_5. Two groups can be distinguished by combining isomorphic admixtures: the first (V_2O_5, NiO ± ZnO) is observed in sub-ferrialuminochromite and sub-ferrichromite; the second (MnO, V_2O_5) is typical for ferrialuminochromite and chromite. The highest level of MgO concentrations (8.63-11.70 wt%) is observed in aluminochromite, but it does not contain MnO, CaO, NiO admixtures, and the V_2O_5 admixture is low (0.12-0.38 wt%) and inconstant. The highest concentrations of V_2O_5 (0.35-0.73 wt%) and MnO (0.72-0.76 wt%) admixtures are in ferrialuminochromite relatively to other chromespinelides. The highest chromium content (Cr#=0.85) belongs to chromite at low Mg# (0.26), chromomagnetite also has high Cr# (0.84), but with extremely low Mg#= (0.05), which seem to be a product of partial replacement by secondary magnetite (Fig.2D) by subferrialumochromite.

Magnetite. Two generations of magnetite were identified. Magnetite of an earlier generation (magmatic) is rare and forms crystals of regular shape (Fig. 2C). Its impurity elements are limited to MnO (0.56 wt%) and MgO (0.83 wt%). The porosity of early-generation magnetite is relatively small and reaches 4.0%. Late-generation (secondary) magnetite is predominant. It forms rims around the subferrialumochromite, or occurs as micrograins dispersed around (Fig. 2D). Late-generation magnetite is characterized by constant presence of impurity MgO (0.40-1.02 wt%), Cr_2O_3 (0.10-0.24 wt%), NiO (0.01-0.28 wt%). The presence of Cr and Ni impurities in the secondary magnetite indicates its formation by substituting chromium spinelide. A high Fe_2/Fe_3 ratio (0.514-0.540) is typical for the late generation magnetite. The formation of magnetite is reflected in the decrease of the Fe^{2+}/Fe^{3+} ratio.

Sulphides. Previously detected nickel sulphides in peridotites of the Urtynzhal site are not found in the schlich. However, one grain of chalcosine (Cu_2S) and four grains of galena (PbS) are present. They fill voids or cracks in olivine and chromospinel.

Geochemical composition of harzburgites. Geochemical features of the harzburgite composition were determined with the help of a set of nuclear-physics analytical methods, including EDRFA and INAA and ICP-MS.

The complete spectrum of rare-earth elements is for the first time determined in harzburgites Urtynzhal ore deposits. The total LREE=7.544-14.12 content is higher than HREE=1.581-3.22. This value considerably exceeds the REE content in depletive peridotites of supra-subduction complexes (Pearce et al., 2000).

The geochemical peculiarity of harzburgites is the extremely high Pb concentrations (<13990 ppm), which the presence of galena grains can explain. One of the peculiarities of harzburgite (sample U-1) is that, in the presence of modal zircon, the Zr concentration is only <2 ppm. The presence of copper, nickel and cobalt sulphides is resulted in the enrichment of harzburgite in Ni (<2210 ppm), Co (<80.3 ppm), Cu (<278 ppm). The platinum metal group is represented only by Ir (0.0014-0-0052 ppm).

Discussion. Analysis of compositions of rock-forming and accessory minerals. The petrochemical composition of minerals (chromospinel, olivine and pyroxene) documented from peridotites of recent volcanic arcs is commonly applied for the reconstruction of original conditions of their formation in ancient ophiolitic complexes.

In particular, chemical composition of chromospinelides, olivine and orthopyroxene give important information on physical and chemical conditions of formation of mafic-ultramafic complexes.

The Cr# to Mg# ratio of chromospinelides is commonly used to determine the geodynamic setting of peridotite formation in ancient ophiolites. It is helpful also in discrimination of abyssal peridotites from supra-subduction peridotites. The chromospinelides under study belong to peridotites of forearc basins, as shown by the Cr#-Mg# diagram (Fig. 3); Chromospinelides from harzburgites of the Krasnaya Polyana site belong to the same type (Stepanets, 2016).

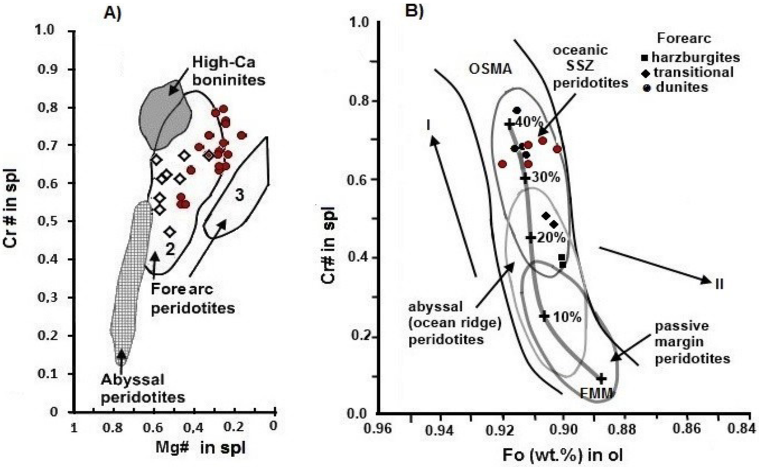

Figure 3. Geodynamic diagrams: Cr#-Mg# (A) and Cr#-Fo (B) for chromespinelides of harzburgites from Krasnaya Polyana segment (rhombus) and Urtynzhal site (bold red dot). A) Field of abyssal peridotites and boninites (Dick & Bullen, 1984), the field of forearc peridotites two (Ishii et al., 1992). B) Bold lines show composition field of equilibrium olivine-chromium-spinel mantle paragenesis (OSMA) (Aral, 1994). Contours of field showing composition of minerals from abyssal, supra-subduction and passive margins of mantle peridotites are shown as per (Pearce et al., 2000); figures on the curve correspond to the basalts melting from the primary unexhausted mantle source (FMM), I-trend of fractional crystallisation, and II-trend of partial melting as per (Pearce et al., 2000).

Determination the geodynamic setting of harzburgite formation is not limited to the Cr# to Mg# ratio diagram. High values of chromespinelides Cr# and molecule olivine Fo of the studied harzburgites are consistent with their attribution to forearc peridotites (fig. 3B, (Aral, 1994), characterised by high (more than 30%) degree of basalts melting from a primary non-depleted mantle source. The degree of partial melting of harzburgites, calculated from the Cr# value of primary spinel, is lower and does not exceed 23%.

The most convincing evidence that the Urtynzhal chromespinelides belong to forearc basin peridotites is also extremely low, below the limit of analysis sensitivity, TiO_2 concentrations (fig. 4A), which find the analogy with the Tonga forearc basin peridotites (Birner et al., 2017) in the Cr# - TiO_2 binary diagram (Pearce et al., 2000).

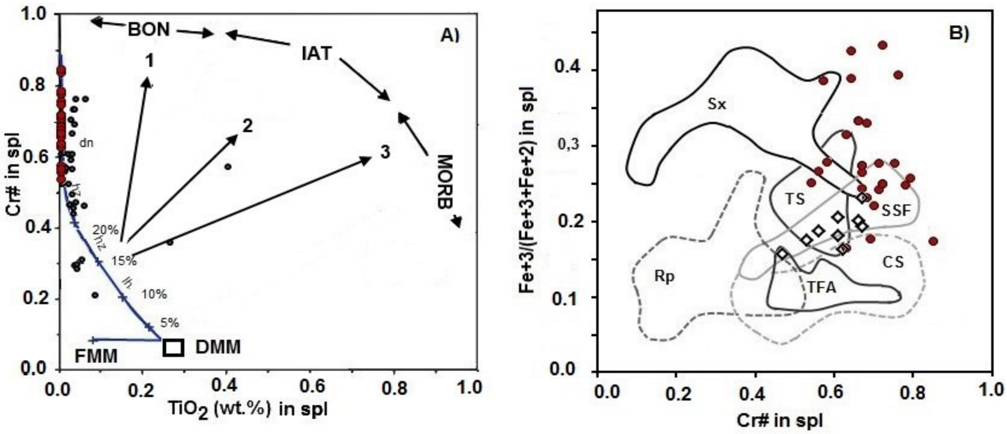

Figure 4. (A) Diagram of chromite composition of forearc peridotites in the system Cr# and TiO_2 spinel (Pearce et al., 2000), showing the melting degree of mantle rocks (curve marked 5%, 10%, 15%, 20%) and reaction trends with boninite melts (1), island arc tholeiite melts 2), MORB melts (3). The mantle dunites and harzburgites of Urtynzhal are consistent with their residual nature after more than 20% melting of the fertile MORB mantle source (FMM). For comparison, the bold black dots show the chromite of the Tonga forearc basin peridotites. (B) The Fe+3/(Fe+3+Fe+2) to Cr# (Parkinson et al., 2003) ratio for chromespinelides of the Krasnaya Polyana segment and the Urtynzhal deposit. Forearc peridotites: SSF–South Sandwich Forearc, CS–Conical Seamount, TS–Torishima Seamount, TFA – Tonga Forearc; Sx–Subduction xenoliths, Rp–Ridge peridotites.

The degree of iron oxidation ($Fe^{+3}/(Fe^{+3}+Fe^{+2})$) of chromospinelides and their Cr# have recently been proposed to discriminate abyssal and supra-subduction peridotites. The diagram (Fig. 4B) clearly shows that figurative points of chromospinelides of the Krasnaya Polyana segment fit into the field of chromospinelides from peridotites of the South Sandwich forearc trough. Some figurative points of chromospinelides from Urtynzhal peridotites are also located in this field, but significant part of them spread beyond it, and their degree of iron oxidation is comparable with peridotites of xenoliths in subduction zones and from the forearc basin of the Izu-Bonin-Marian Island arc at the Torishima Island (fig. 4B).

As shown by the Fe3+ to Cr# ratio (Fig. 5A), the chromospinels from these two TSA localities are also different, because figurative points of Urtynzhal chromospinels are in significant part confined to the field formed by peridotites of forearc basins. Probably, these TSA peridotite complexes were formed under different geodynamic conditions created in the intra-oceanic subduction zone. These differences are also evident from the character of Al_2O_3 accumulation (fig. 5B) for chromospinel of Urtynzhal peridotites, which are considered as a stratiform complex, but it is not consistent with their extremely low concentrations of TiO_2 (Arai et al., 2004).

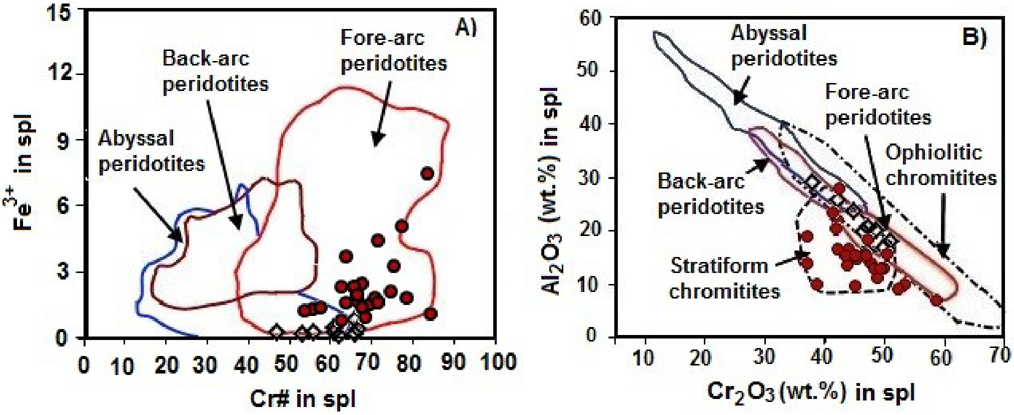

Figure 5. Geodynamic diagrams: A) Fe^{+3}-Cr# (Lian et al., 2016). and B) Al_2O_3 to Cr_2O_3 (Farre-de-Pablo et al., 2020) for chromespinelides harzburgites of Krasnaya Polyana town area (rhombus) and the Urtynzhal deposit (red circle)

The clinopyroxene composition is also of great importance for interpretation of the plutonic ophiolitic rocks formation condition. The earlier studied clinopyroxenes from vein pyroxenites of Tort-Aul valley of the Krasnaya Polyana sector of the TSA complex (Stepanets, 2016), on covariant diagrams (fig. 6 (Beccaluva et al., 1989) do not spread outside the boninite fields of forearc complexes.

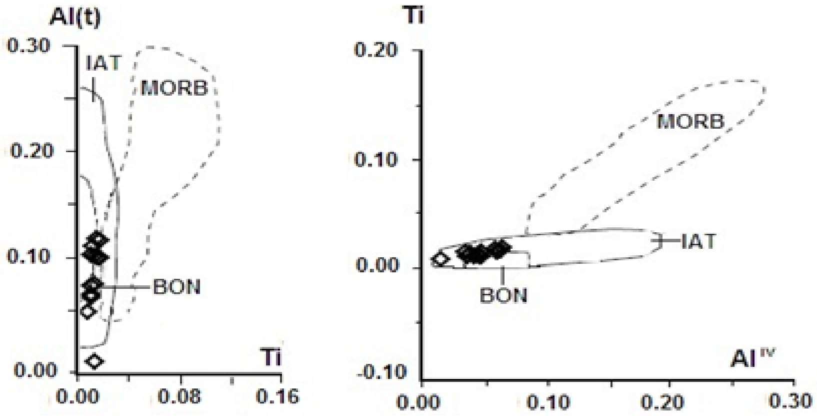

Figure 6. Covariant diagrams of clinopyroxenes of the Tort-Aul valley pyroxenite veins of the Krasnaya Polyana site.
Fields: IAT - island-arc tholeiites, BON - boninites, MORB - mid-ocean ridge basalts (Beccaluva et al., 1989); Al(t) - Ti (atomic ratios); Ti - Aliv (atomic ratios).

The analysis of petrochemical data indicates that chromospinels of the TSA harzburgite complex are characterized by a higher degree of iron oxidation than the spinels from abyssal peridotites and peridotites of the Tango forearc basin.

It may be caused by fluids derived from the uplifted plate, or by mantle diapir melt interaction with the overlying lithosphere (e.g., depleted mantle of the previous melting cycle (abyssal peridotites)). Their remelting produces boninite magma (Pearce et al., 2000). The presence of boninite in the polymictic serpentinite melange of the Tort-Aul valley was noted earlier (Stepanets, 2016), which is consistent with the model of magmatism development within forearc basins.

Proceeding from the degree of iron oxidation in chromospinelides, chromospinelides of the Krasnaya Polyana sector harzburgites, including harzburgites of the Urtynzhal site, can be reliably compared with those of South Sandwich forearc basin. However, some spinelides from Urtynzhal site can be compared with spinelides of the Torishima island of the forearc basin of the Izu-Bonin-Marian island-arc system.

If we accept that REE distribution is a reliable indicator for determining the protolith of abyssal and supra-subduction serpentinites as well as magmatic processes such as the melt-rock interaction, the Urtynzhal serpentinites can be considered as mantle wedge harzburgites, significantly modified by secondary enrichment (refereeing) (fig. 7A).

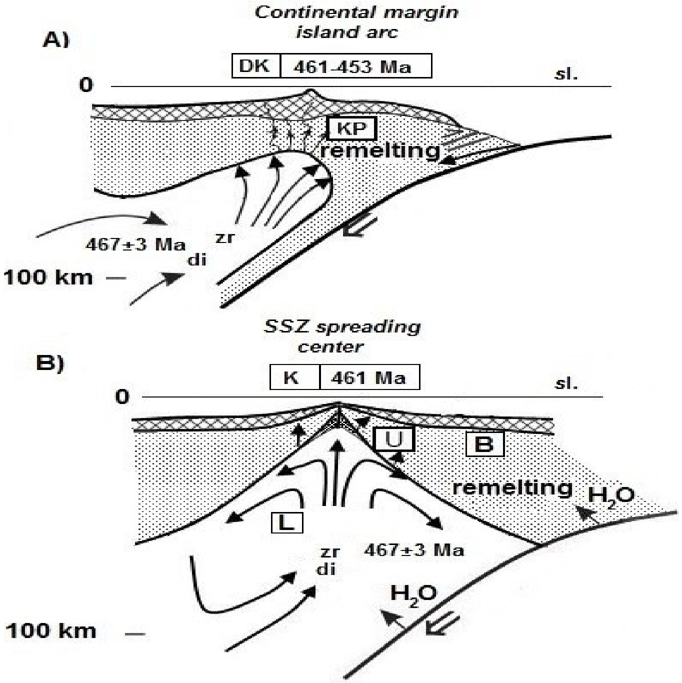

Figure 7. Schematic diagram illustrating the formation of peridotites of the Tekturmas subduction-accretionary complex (modernised version from (Pearce et al., 2000).

DK-Duan-Kora volcanites, K- Karamurun basalts, KP-harzburgites of the Krasnaya Polyana sector, U-harzburgites of Urtynzhal, B-boninites, L-lherzolites, di- microdiamond, zr-zircon. (A) Represents probable geodynamic formation conditions of forearc peridotites and Duan-Kora ensialic island arc (continental margin island arc). B) illustrates probable geodynamic formation conditions of forearc peridotites of the Urtynzhal occurrence area.

Possible stages are formed by supra-subduction zone peridotites. Referring to geodynamic models of magmatism within forearc basins developed by (Pearce et al., 2000), we may suggest with certain confidence that the formation of harzburgites of the Krasnaya Polyana sector in the TSA complex occurred as a result of the impact of the mantle diapir, or more precisely, from its separating melts, which favoured the re-melting of overlaying (previously existent) oceanic lithosphere.

Apparently, at this stage, the island-arc tholeiite and calcareous-alkaline volcanites of the Duane-Kora layer are volcanites pouring out in the island arc containing Late Darriwilian and Sandbian (461-453 Ma) conodonts.

The Bowen differentiation trend characterises rocks, i.e. magmas of such mantle reservoirs, which are not subject to fluids separating from the subducted plate. Blocks of such complexes with plagiogranite-gabbroid fragments are known eastward from the Krasnaya Polyana town (Stepanets, 2016).

With the increase of the mantle diapir volume (fig. 7B), new portions of magma were brought in. It was resulted also in increased water supply and oxygen fugacity; both were derived from the subducted plate. Harzburgites of the Urtynzhal ore deposits were formed apparently on that stage. They are characterized by the high degree of iron oxidation due to re-melting of abyssal peridotites, which were formed from the asthenosphere mantle during a previous melting cycle. Basalt volcanic rocks of the Karamurun Group with plume geochemical signatures were formed at that stage in the back-arc basin. The late Darriwilian age of the unit is confirmed by conodont occurrences.

When magmatic chamber reaches significant size, magma in such reservoir stratifies. It is distinctly displayed in Al-chromites associated with Urtynzhal harzburgites (fig. 5B), but it is not consistent with their low TiO_2 content. For spinelides of typical layered complexes, the TiO_2 content is usually more than 0.3 wt% (Arai et al., 2004). According to Ir content, harzburgites also do not belong to the stratified peridotites, and high Ir concentrations (0.0014-0.0052 ppm) characterise them as anhydrous mantle peridotites (Deschamps et al., 2013).

Zircon crystals extracted from Urtynzhal harzburgites apparently have a magmatic origin and their ages are close to the time of the Karamurun and Duan-Kora groups formation. The minerals associated with zircons, including microdiamonds, moissanite, and corundum, cannot crystallize from residual ultramafic melts. Therefore, their source and delivery mechanism into plutonic rocks of TSA ophiolite complex require special consideration.

Experimental data (Anfilogov et al., 2015) on heating of zircon and dunite above 1450°C indicates the possibility of an equilibrium mineral association formation, which includes zircon, olivine and pyroxene. All these minerals are present in zircon bearing harzburgites and therefore they may be considered as syngenetic. Yet, observed substitution of subferrialuminochromite with chromomagnetite and magnetite, as well as the presence of secondary orthopyroxene in harzburgite put in doubt the original existence of zircon in dunite. There is no doubt; however, that subferrialuminochromite is replaced by magnetite, whereas chromite, ferrichromite and zircon remained stable at temperatures above 1450°C. There is no indication of baddeleyite in association with zircon and orthopyroxene in the present study; however, it was reported earlier on harzburgites from the Krasnaya Polyana site (Antonyuk, 1974). The presence of baddeleyite can be taken as evidence of high-temperature impact on zircon-bearing rocks (Anfilogov et al., 2015).

Genesis of diamonds and related accessory minerals. The obtained zircon ages are close to the time of formation of the Karamurun and Duan-Kora alkaline and subalkaline basalts are in favour of a possible presence of the mantle diapir, which could be a source of exotic minerals in plutonic rocks associated with ophiolites.

The nature and composition of this mantle diapir, apparently, can be inferred based on the geochemical composition and isotopic data of alkaline and subalkaline basalts of the Karamurun and Duan-Koran groups using principles of geochemical geodynamics (Zindler & Hart, 1986).

Taking in account data presented in (Khassen et al., 2020), Karamurun and Duan-Koran basalts can be considered as partial melts form HIMU and EM-I reservoirs (Hofmann, 1997). The EM-I reservoir is a recycled lower continental crust or subcontinental lithosphere. HIMU is considered as an enriched (U+Th/Pb) mantle formed at about 1.5 - 2.0 Ma ago (Hofmann, 1997). The HIMU source is usually attributed to the subducted blocks of the ancient oceanic crust submerged down to the mantle or core boundaries (Zindler et al., 1982). Another possible mechanism is mobilization of Pb in metasomatic fluids. It was also inferred that HIMU may represent a dispersed core component in the mantle (Zindler & Hart, 1986).

All these models suggest enrichment of the mantle diapir melt at significant depths, possibly at mantle depths of 150-300 km, in the transition zone mantle (TZM) and more, where diamonds, implanted in ophiolitic peridotites, could originate (Liou et al. др., 2014). Therefore, diamonds may occur in ophiolite peridotites, including supra-subduction peridotites and chromites irrespective of their geodynamic origin (Dilek & Yang, 2018).

It also implies that microdiamonds implanted in chromites and peridotites, which originated near MTZ, most probably were transported to shallower mantle depths in their host rocks with very high velocities (Dilek & Yang, 2018). Probably, this process was caused by the mantle plume upwelling. It takes into account that diamond, moissanite, zircon, baddeleyite and corundum were formed under different geodynamic conditions (Liou et al., 2014), and a multi-stage mechanism of their formation and incorporation into ophiolitic peridotites and chromites (Dilek & Yang, 2018) cannot be excluded. It implies also a higher rate of uplift and cooling of mantle diapir (Xu et al. (2018).

Interaction of the mantle plume frontal part with the overlying depleted mantle may result in repeated melting and diamond, moissanite, zircon and corundum implanting into this melt. Subsequent recrystallisation of the melt produced harzburgite-dunite forearc peridotite associations containing these minerals.

Subsequent plume melts derived from EM-I + HIMU reservoirs are contaminated with diamond, zircon and corundum. They represent a source of ultramafic, mafic and felsic rocks, incorporated into ophiolite complexes. However, lherzolites, dunites and plagiogranites from such complexes are unknown within the polymict melange of the TSA ophiolites.

Conclusion. The accessory chromospinelides of the Urtynzhal site differ essentially from those of the Krasnaya Polyana by the presence of such impurities like MnO, V_2O_5, ZnO, NiO. The common feature of these chromospinelides is the absence of TiO_2 in the main petrogenic components. Almost all Urtynzhal chromospinelides, with the exception of accessory chromite, were subjected to secondary alterations. This is particularly relevant for subferrialuminochromite, which is replaced by secondary magnetite. A sift of secondary magnetite was probably formed due to interaction of the mantle melt with chromospinelides. Urtynzhal chromospinelides are comparable with those of forearc peridotites in their high chromicity and low magnesianity. A constant presence of V_2O_5 in chromospinelides of the Urtynzhal ore deposit can be considered as one of the characteristic features of peridotites formed in the forearc environment. The high degree of iron oxidation in chromomagnetite and ferrialuminochromite is also apparent.

Olivine (Fo >0.89), which co-occurs with chromospinelides, is constantly enriched in NiO, whereas Cr_2O_3 varies in a relatively wide range from 0.0 to 0.26 wt%. Olivine-chromospinel pairs are located within OSMA (mantle association of olivine and spinel) and are considered as dunites of the forearc complexes. In case orthopyroxene is a secondary rock-forming mineral, it would be correct to refer to the Urtynzhal peridotites as dunites. The high level of nickel concentration in olivine, as well as the presence of nickel and copper sulphides in dunites, suggests their possible ore-bearing capacity. Characters of aluminium distribution in dunite chromospinelides indicate their cumulative origin as a part of the stratified complex.

The Tekturmas and Duan-Kora alkaline and subalkaline basalts are the mantle plume derivatives, therefore they are not complementary with the tectonically related forearc peridotites. Therefore, they cannot be considered within a single ophiolite complex. Restite peridotites complementary to the alkaline basalts have not been identified in the TSA complex. OIB-like basalts of the Tekturmas and Duan-Kora groups were formed as a result of adiabatic decompression melting of the mantle plume intruded into the continental or transition crust.

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