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MATTER AND PHYSICAL ANISOTROPY OF ULTRAMAFITES OF THE BARKHATNY MASSIF (KUZNETSK ALATAU RIDGE, WESTERN SIBERIA) AS CRITERIA OF THEIR MINERAL POTENTIAL FOR GEOLOGICAL PROSPECTING WORKS

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A complex of petrographic, petrofabric, and paleomagnetic analyses that was carried out for rocks from an ultrabasic massif of the Barkhatnaya Mountain in the Northern part of the Kuznetsk Alatau allowed us to prove that internal anisotropy of mineral aggregates had deformation-type evolution, which indicates possible plastic exhumation of lithosphere mantle fragments into upper crust levels. Complete conformity of geophysical and petrofabric parameters points out high possibility of multistage model for obduction of ophiolite association segments proposed for this region. Taking into account specifics of mineragenу for such complexes (chromite ores and noble metals, asbestos and nephrites), we offer a new technology for geological prospecting works at the stage of estimating mineral potential of such geological objects, which is based on the presence of differently oriented systems of mineral plane orientation.

Проведенный нами комплекс структурно-петрологических и палеомагнитных исследований для ультрабазитов Бархатного массива на северном склоне Кузнецкого Алатау подтверждает, что внутренняя анизотропия минеральных агрегатов имела деформационную эволюцию, которая указывает на возможную пластическую эксгумацию фрагментов мантии литосферы в верхние горизонты земной коры. Полное соответствие геофизических и петроструктурных параметров отмечает высокую вероятность многостадийной обдукции фрагментов офиолитовой ассоциации, предлагаемой для этого региона. Принимая во внимание особенности минерагении (хромитовые руды и благородные металлы, асбест и нефрит) для таких комплексов мы предлагаем новые методы геологоразведочных работ на стадии оценки рудоносности геологических объектов, которые характеризуются дискретными вариациями пространственной ориентировки элементов текстурной анизотропии пород.

Introduction

Fragments of lithosphere mantle like dunite-harzburgite tectonic complexes are an essential part of structural zones of modern mountain-folded formations. Their relation to country-rock structural assemblages has tectonic nature. They are often assumed to have a complicated exhumation evolution into upper crust levels. Hyperbasite massifs of the Severnaya, Zelenaya, Zayachya, and Barkhatnaya mountains located on the northern slope of the Kuznetsk Alatau Ridge are typical representatives of such formations within Altay-Sayan Folded Area (ASFA). They form an arch-shaped chain, which points out block-type style of geological composition of this certain region and ASFA in general (Goncharenko, 1989). The main tectonic elements of the northern part of the Kuznetsk Alatau are faults, grabens, linear intrusions, and dike belts spreading in two directions: North – North East (to submeridian strike) and North-West (to sublatitude one). Oceanic crust fragments are drawn towards axial part of the ridge and form isolated horse shoe-shaped structures, where margins are composed by mantle hyperbasites, and the core is composed by basites (starting with cumulative ultramafic rocks and gabbroids, and to their hypabyssal and volcanic analogues).

The Barkhatny Massif forms the Eastern side of ophiolite paragenesis and is a linear body (20×2-3 km^2) with submeridian orientation with a well-defined deformation zoning. Its central zone is composed by eutaxitic/banded harzburgite, dunite, and chromitite complex, which is supposed to have following evolution sequence of deformation petrofabrics: “protogranular → protogranular-parquet-like → leystic → mosaic-leystic” (fig. 1, row I) that corresponds to axial compression mode. Outer zones of the massif are composed by rocks with mesa granular and porphyroclastic structures (fig. 1, row II), including serpentinites, which form more often during recrystallization under shear deformations or significant gradient of static pressure and temperature. Specifics of the deformation zoning observed in couple with data on other ultrabasite massifs of ophiolite paragenesis let us developed a multistage model of obduction for lithosphere mantle fragments (Krasnova, 2005). It is assumed that there are at least three stages of exhumation, which indicate main steps of tectonic evolution of the Kuznetsk Alatau folded assemblage structure. The first stage corresponds to forming an accretion prism of an active island arc, where obduction of oceanic lithosphere fragments occurs that keeps NW-strike orientation in central blocks of hyperbasite bodies and in the Barkhatny Massif in particular. Age range for these events covers Late Riphean – Middle Cambrian. The second stage is mostly controlled by vertical movements along submeridian tectonic faults and broad development of recrystallization on the sides of ultrabasite blocks. It is accompanied by linear type intrusions of large basites, syenitoids and granitoids. Geodynamic setting for forming these intrusions correlates to the stage of collision increase in the Altay-Sayan super terrain that occurred in Late Cambrian-Ordovician. The third stage is usually correlated to Devonian rifting processes and is accompanied by building up a series of inland depressions and grabens composed by high-alkaline volcanites and “red-colored” terrigenous sediments. In the studying ophiolite paragenesis, real tectonic events of this stage were expressed in transforming the core block of basites southward relative to hyperbasite sides. This process was accompanied by forming serpentinite mélange on the Zayachya Mountain, and activization of crossing faults with corresponding orientation in the massifs of the Severnaya and Barkhatnaya mountains. Another indicator of these events is formation of the Barkhat-Kiyasky intrusive of subalkaline gabbroids and pulaskites. Its rocks “break” through ultrabasites of the Barkhatnaya Mountain and Early Devonian volcanic rocks of the Rastaysk graben.

In this research, we focused on studying internal structure of the Barkhatnyi ultrabasite massif as the most representative object regarding broad range of minerals (chromite ores, gold, platinum group elements, asbestos et al.), which has relatively low degree of low-temperature rock changes, and which has obvious deformation zoning. Besides, this massif is considered to be a petrographic type of the Barkhatnyi complex according to the most recent regional geological legend (Shokal’sky et al., 2000).

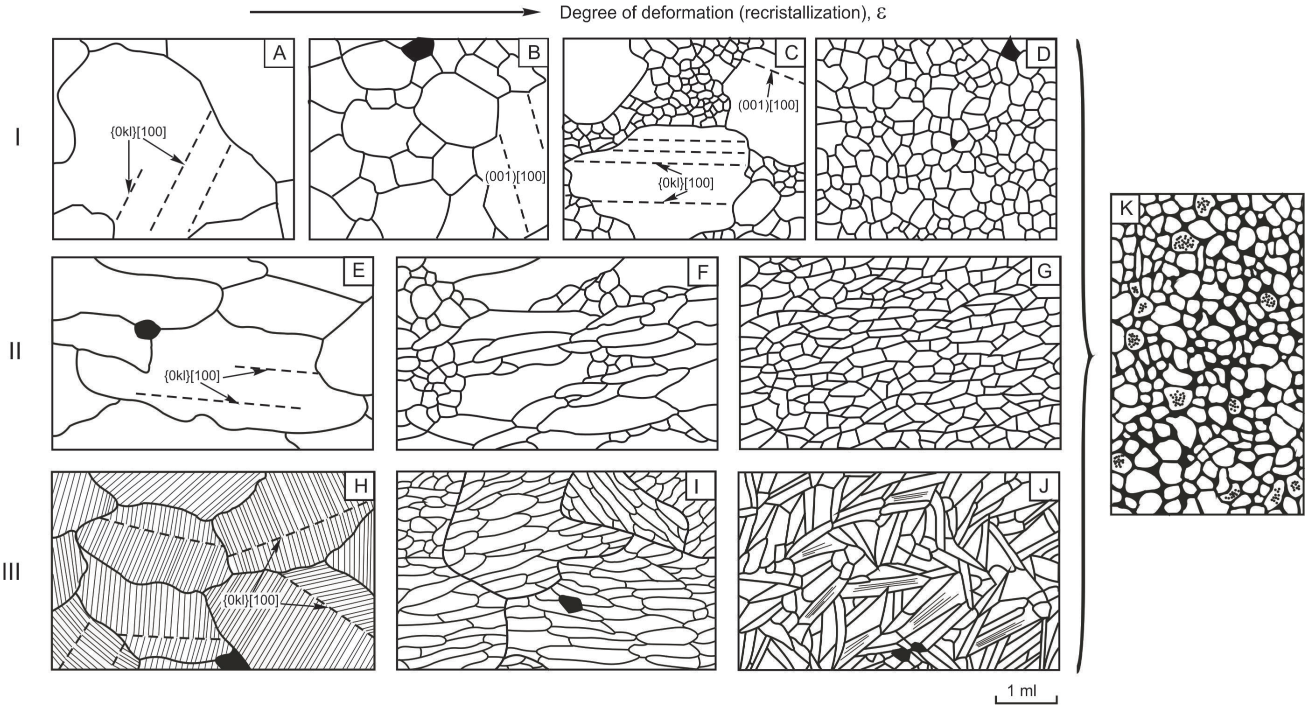

Figure 1. Deformation types of olivine microfabrics according to (Krasnova, 2005): A – protogranular; B – mesogranular; C – porphyroclastic; D – mosaic; E – leystic; F – porphyroleystic; G – mosaic-leystic; H – protogranular-cleavaged; I – parquet-like; J – pseudospinifex; K – regenerated.

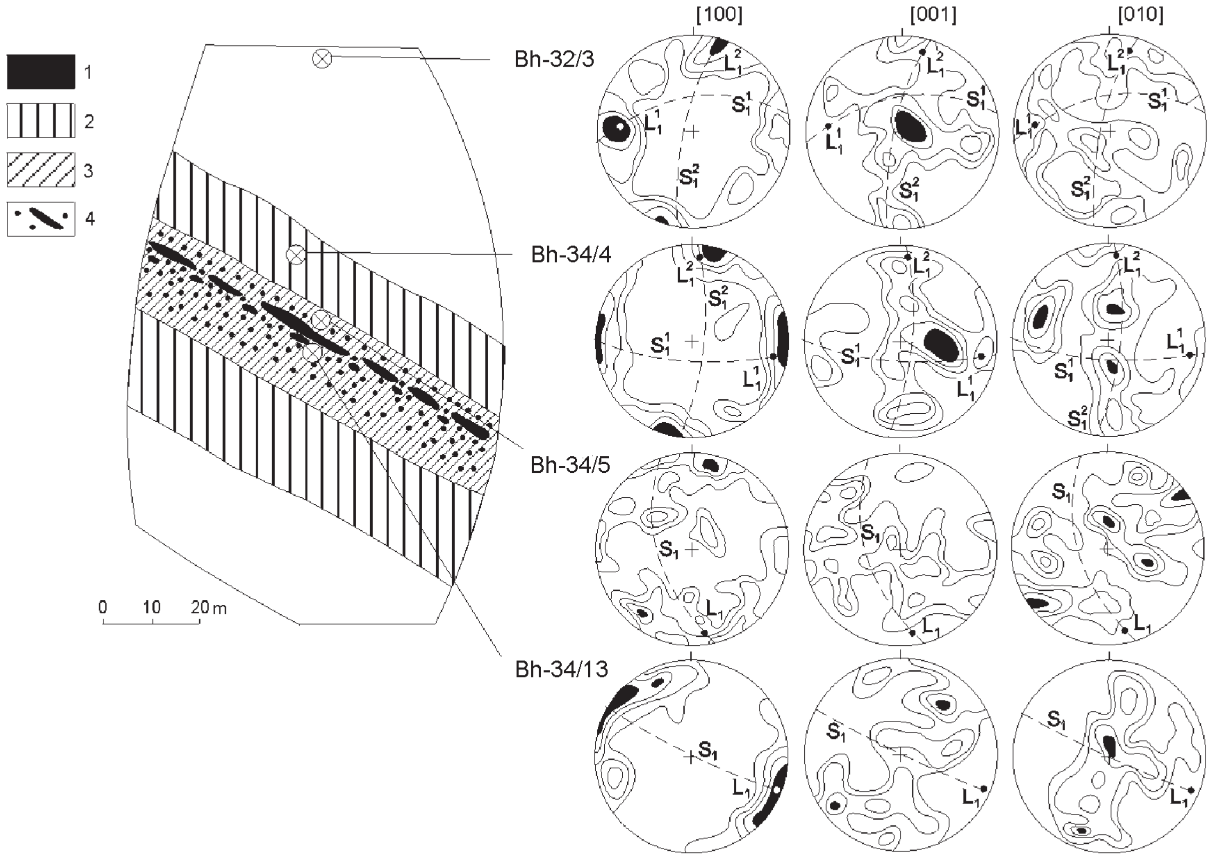

Figure 2. Optic orientation of olivine in chromite-bearing ultramafic rocks from the Barkhatny Massif: 1-3 – types of deformation microstructures: 1 – protogranular; 2 – protogranular – protogranular - parquit-like; 3 – leystic, mosaic, mosaic-leystic; 4 – zone of chromite mineralization.

Research methods and objects

The object for research was ultrabasites of the Barkhatnyi Massif and specifics of their internal anisotropy obviously shown on mineral and geophysical levels of matter structure. Such a complex approach to the research implies not only defining criteria for integrating obtained results, but also creating a unified genetic model of formation of mineral associations at different stages of metamorphic evolution of restitic hyperbasites.

Studying structural anisotropy of the rocks suggests multilevel analysis of their matter structure, including determining spatial orientation of plane and linear mineral elements, as well as defining specifics of olivine grain crystallographic orientations, and diagnosing paleomagnetic characteristics (Krasnova et al., 2002). The main methods used in this work are geometric analysis of textural anisotropy of oriented samples, microfabric analysis and measurement of geophysical parameters (defining coordinates and absolute values of remanent magnetization vector (In), measuring magnetic susceptibility of the rocks (æ) and calculating the Koenigsberger ratio (Q)).

Results

Based on the detailed analysis of spatial orientation of plane and linear structural elements in ultramafic rocks from the Barkhatnaya Mountain, we identified a complex folded structure of the massif. There are two main geometric types of S- and L-elements indicating staging in dynamic metamorphic transformation of an ultramafic body. The first type of mineral plane orientation (S_1) is defined in samples as a planar orientation of large pyroxenes, olivines, and chromespinelides, and was seen in dunites and harzburgites from the core part of the Massif. We statistically analyzed the entire massif and defined for this type of plane orientation sub vertical or inclined bedding with North-West strike and NE and SW dipping. Directions and flatness of this bedding coincide with ones of rocks from the chromite mineralization zone. Variations in spatial orientation of S_1 system suggest formation of a cylindrical folded structure, whose axial plane has NW-strike (azimuth 320°) and SW dipping (at the angle of 65-70°), and whose fold axis goes down in Northwest at the angle of 10°. In general, this structure can be described as a folded assemblage of parallel or close to parallel shapes with a wavelength of 4-6 km, which was damaged by reverse fault - thrust type deformations. However, there is a well-defined local zone (thickness~ 3 km) of more compressed folding in the center of the Massif that is believed to belong to the chromite mineralization zone and alkaline intrusions. Its forming was probably caused by a hidden thrust of the North block onto South one. There is a minimum hypsometric content of ultramafic rocks from the North block in a vertical cross section of the restite complex that is proven by graphic reconstructions, as well as their primarily harzburgite composition, absence of chromitites, but presence of high-aluminous orthopyroxene and chromespinelide (Krasnova et al., 2002).

The second type of mineral plane orientation (S_2) was found in ulatramafites and serpentinites, which belong to endocontact zones of the Massif, and is recognized in samples by preferable elongation of small grains of pyroxenes, olivines and ore component aggregates. Development of a cleavage system crossing S_1 is also typical for second type orientation. S_2 plane orientation is characterized by subvertical bedding with submeridian and Northeast strike, which coincides with general orientation of the ultramafic body. We have acknowledged for system S_2 a tendency to form sub vertical mineral linearity L_2, whose outputs concentrate along small circle arch on stereograms. S_2-system development was caused by later plastic flow of matter into endocontact zones of the ultramafic body, and was accompanied by intensive occurrence of fragile dislocations (foliation, cleavage) that initiated serpentinization and other metasomatic processes. Direction of the rock flow was inversed from subvertical at earlier stages, all the way to subhorizontal at the last stage of dynamic metamorphism. At the same time, left-sided dislocation of country-rock blocks along endocontact surfaces of the ultramafic massif in the Barkhatnaya mountain initiated its tectonic disintegration by crossing shears and normal faults, which might be more ancient reverse fault-thrust dislocations.

One of the important results of microfabric studying is analysis of olivine optic orientation showing nature of development of coaxial deformations in different petrofabric-type hyperbasites in the Massif's central zone. Despite primarily West-strike plane orientation system in these rocks, diagnosing optic orientation of olivine's crystallographic axes demonstrated their complicated evolution. Intracrystal "kink bands" were found in all studied ultramafic rocks of this type, which correlate to high-temperature systems of translational slipping according to (010) [100] and (0kl) [100] systems. However, two maximums of [100] axes oriented at the angle of 60-80° relative to each other and symmetrically in respect to the average plane orientation and linearity are typical for the petrofabric pattern of rocks with protogranular fabric. This assumes development of two independent systems with olivine grain mineral orientation (S_1^1 with L_1^1 and S_1^2 with L_1^2). Axis outputs on the stereogram form wide bands with local orthogonal "scattering trends" oriented subnormally to the planes S_1^1 and S_1^2. As approaching chromite mineralization zone, the angle between these two systems reduces, and tends to zero in leystic and mosaic type, thus indicating general orientation of olivine grains in the Barkhatny Massif (fig. 2). Forming bimodal patterns in "protogranular - parquit-like" olivine can be explained by specifics of initial deformation stage of polycrystalline aggregate under axial compression. According to A. Nicolas, early activization of intracrystal slipping systems can occur only in grains with potential translational systems oriented in respect to two shear directions (Nicolas, 1976).

In rocks of mesogranular, porphyroclastic, and mosaic types from endocontact margins of the Massif, we noted intracrystal deformations indicating translational slipping through lower-temperature systems (001) [100] and (110) [001]. Herewith, overlapped recrystallization processes are characterized by development of S_2 submeridian plane characteristics, as well as scattering of [100] and [001] axes along initial plane orientation S_1 during localization of [010] axes near S_1 plane pole. Further transformations of rocks imply foliation with forming a definite S_2 system and mineral aggregates of serpentine and magnetite.

Additional research in mineralogy of basites from Barkhatnaya and Zelenaya Mountains confirm multistage metamorphic transformations at different P-T conditions and different stages of obduction of oceanic fragments. During studying of mineral composition of metabasites, we found that feldspars are represented by a wide spectrum of composition: from albite to bytownite; not less common amphiboles are also characterized by a wide diapason: edenite, ferro-edenite, ferropargasite, magnesiohastingsite, magnesian, ferrous and actinolite hornblende. The data obtained by the phase relationships and changes in chemical composition of the mineral pair "plagioclase - amphibole" suggest several stages of transformations for studied rocks with signs of progressive and retrograde metamorphism. Using bimineral geothermobarometers we established two stages: progressive metamorphism peak occurs at T = 500-700 °C and P = 2-6 kbar, and regressive stage occurs at T = 350-510 °C and P = 2-9 kbar. This is also confirmed by the results of amphibole geothermobarometer, where minerals of marginal parts formed at T = 340-440 °C and P = 1kbar, being superimposed over higher-temperature amphiboles from central parts, which were generated at T = 550-650 °C and P = 2-7 kbar. Thus, compositional evolution of the basic component of ophiolite association from Barkhatnaya, Severnaya and Zelenaya Mountains correlates to the stages of plastic deformation of restitic ultramafic rocks, and in some cases fulfills it (Dugarova et al., 2017).

A complex of paleomagnetic analyses was conducted for 31 oriented samples of ultrabasites taken from the Barkhatny Massif. This studying covered definition of coordinates and absolute values of remanent magnetization vector (In), measurement of magnetic susceptibility of the rocks (æ), and calculation of the Koenigsberger ratio (Q). The obtained results confirm structural discontinuity of the ultramafic body and multiple stages of processes of its dynamic metamorphic transformation. Correlating these results with data obtained by a geometric analysis showed that vector (In) is subparallel to mineral plane orientation of ultrabasites in most cases, coinciding with linearity or at an angle ~ 50-90° to it (fig. 3).

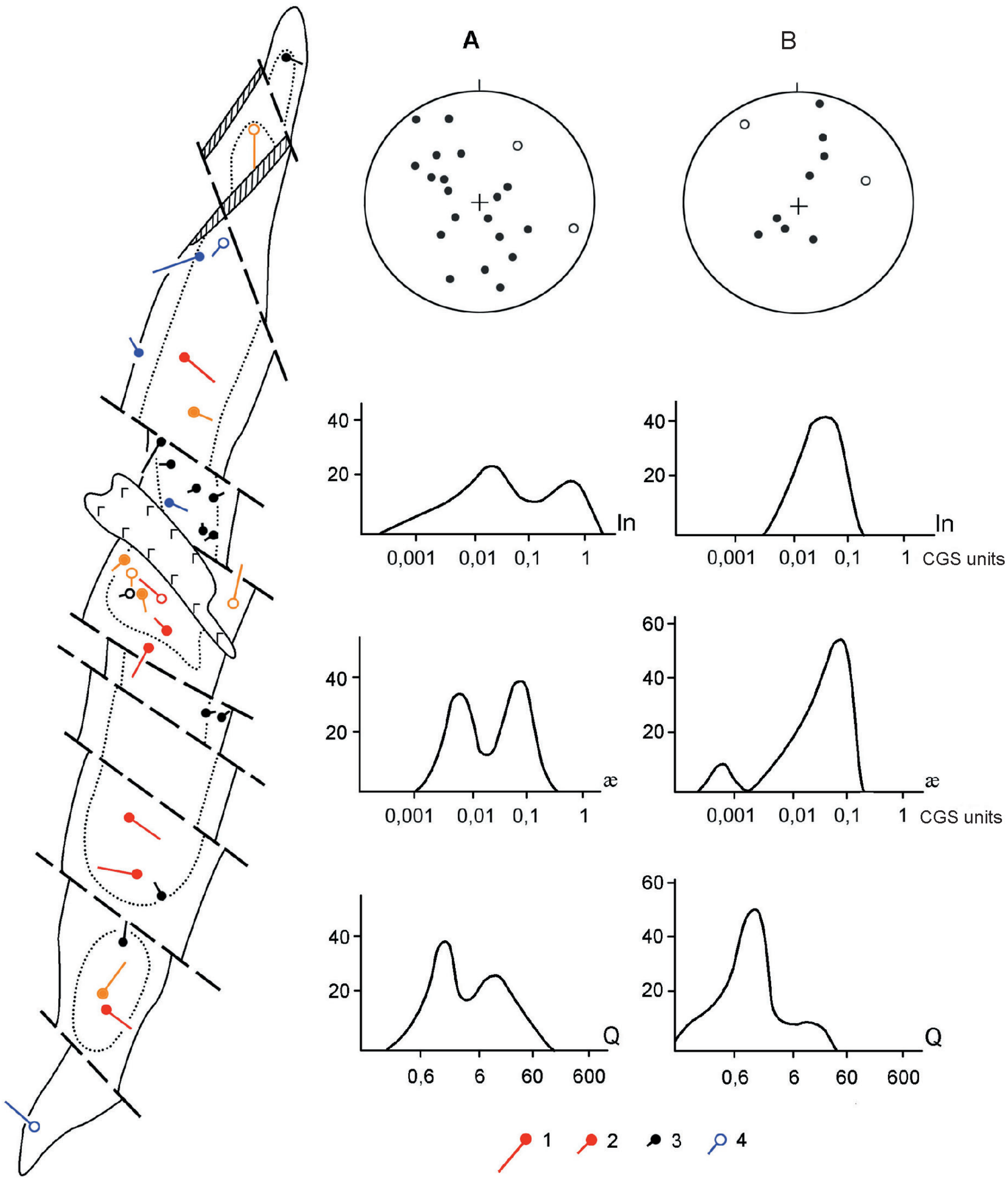

Figure 3. Vector orientations of remanent magnetization (In), stereograms of their spatial orientations and histograms of absolute petromagnetic characteristics for the rocks from the Barkhatny ultrabasite Massif: 1 - vectors with inclination angles 0-30°; 2 - vectors with inclination angles 31 - 60°; 3 - vectors with inclination angles 61 - 90°; 4 – vectors of inverse magnetization. On stereograms (on the right), projections of (In) vectors are shown in rocks from the axial (A) and rim (B) zones of the Massif. Filled dots are vectors oriented along mineral plane orientation, and blank ones are vectors oriented perpendicular to mineral plane orientation. It is shown on histograms how often values of main petromagnetic parameters meet with each other (on the left – in rocks from the Central part of the Massif, on the right – in rocks from the rim zones).

Such a pattern is caused by morphological specifics of ore mineral crystallization, whose aggregates trace either direction of primary matter flow (i.e. mineral linearity L_1) or development of crossing shears and gashes, where magnetite resedimentation occurs and secondary linearity L_2 forms as a result of serpentinization. In general, distribution of vector (In) projections on stereograms plotted for rocks from the central and endocontact zones of the Massif is controlled by trajectory of axial planes of corresponding folded systems. In the ultramafic core part, outputs of a magnetic vector form a sub vertical belt with NW strike (fig. 3, A), thus confirming legitimacy of primary plane orientation S_1. Whereas in rocks from endocontact zones, these outputs scatter along a submeridian- or N-NE-plane that coincides with S_2 system (fig. 3, Б) except of a few points (blank dots on the stereograms). They represent subnormal orientation of (In) vector in respect to mineral plane orientation.

Variations in inclination angle of remanent magnetization vector mostly indicate degree of dynamic metamorphic transformation of ultramafic substrate. In particular, the steepest inclinations are observed in rim zones of the Massif and near crossing tectonic deformations. Let us note that their maximum values are registered near intrusion of subalkaline gabbroids and chromite mineralization in a zone of intensive folding. Inverse polarity of In vector (blank dots on the fig.2, B) is local and can be connected with either inverted bedding of some fold limbs or secondary thermal impact of intrusive bodies and hydrothermal solutions on ultramafites. Particularly within the Middle Tersinsky ophiolite paragenesis, inverse magnetization is found in the hinge of ultramafic synform in the zone with minimum stresses (Goncharenko et al., 1982).

In order to estimate nature of changes in absolute values of petromagnetic parameters, we plotted histograms of their distribution in logarithmic abscissa scale for rocks from both the core and endocontact zones of the Massif (fig. 3). These histograms demonstrate primarily bimodal distribution of In, æ and Q parameters in ultramafites from the central zone of the Massif, whereas close to unimodal graphs are observed in the Massif rim zones. We determined two main ranges for remanent magnetization values: from 0,005 to 0,1 CGS units, and from 0,1 to 1 CGS units. High remanent magnetization is observed in rocks from core parts of the largest blocks of the ultramafic body, which have relatively uniform structure. In the rim parts of the Massif and around intrusion of subalkaline gabbroids, moderate and low values of (In) prevail (less than 0,1 CGS units) that might be explained by the presence of several components with inverted inclination/slope orientations in the vector of remanent magnetization, and indicates multiple thermal transformations of the rocks.

Bimodal nature of magnetic susceptibility (æ) is caused by the presence of two types of ore minerals with different ferromagnetic properties in Barkhatnaya mountain ultramafites: chromespinelide (æ<0,01 CGS units) and magnetite (æ=0,2-2,0 CGS units). Therefore, distribution pattern of values æ throughout the Massif area more than likely demonstrates development of serpentinization processes accompanied by formation of fine-grained (finely dispersed) magnetite, as well as metasomatic change of primary chromespinelide with formation of "magnetite jackets". High magnetic susceptibility is seen most often in rocks from endocontact zones or near tectonic damages. However, high values of æ are also typical for some rocks from the core part of the Massif. For example, this value varies from 0,32 to 0,8 CGS units in ultramafites from NE exocontact zone of subalkaline gabbro intrusion, whereas it is in the range from 0,002 to 0,9 CGS units in SW one (in the zone of chromite mineralization).

One of the most informative parameters of primary nature of magnetization vector is the Koenigsberger ratio (Q), which represents ratio of remanent and inductive magnetization. We should consider these two ranges of Q values ¸ 0,6-2,0 and 6,0-40,0 as the most popular for ultramafites from the Barkhatnaya Mountain. First range is apparently typical for rocks that underwent multiple magnetizations. The second one is typical for varieties formed in relatively homogeneous magnetic field, and more than likely indicates primary thermal remanent magnetization. Maximum Q values (from 2 to 50) are also found in the Massif's axial zone away from crossing tectonic damages. An exception is the NE exocontact zone of subalkaline gabbro intrusive body, where a full transformation of primary magnetization is the most probable. Low values of this parameter (0,6-2,0) are more typical for rocks from the rim zones or parts adjacent to the crossing tectonic damages. Minimum Q values (less than 0,6) can be found only in ultramafic rocks from the West endocontact zone of the Barkhatnyi Massif, on the border with gabbroids from internal basite core of ophiolite paragenesis. That assumes longer and multistage activity of this disjunctive border.

Discussion

Modern technologies for prospecting and estimating mineral potential of a geological object suggest complex assessment of its structural and physical parameters, and construction of a possible genetic model for a given deposit, as well as proof of stages of mineral accumulation in regional structures. As a rule, one of the most important factors for a precision research is multistage analysis studying a given object at macro-, mesa-, and micro-levels. In order to build a genetic model of an ore-bearing geological system, it is necessary to indicate specifics of its structure and matter composition, which can be obtained by studying petrography, detail mineralogy, petro- and geo-chemistry, distribution of radiogenic and stable isotopes, as well as diagnosing spatial orientations of fabric and structural specifics of rocks and minerals (results of field observations, geometric analysis of oriented samples, microfabric analysis, and X-ray structural dizgnosis using electron microscope). This set of analyses has been applied multiple times to prospecting works of gold-ore deposits of the Middle Tien-Shan (Abad et al., 2003), the Enisey Ridge (Gertner et al., 2011), and nickel-bearing complexes of the Eastern Sayan (Kulkov et al., 2014). Potential of this research complex is proven by many projects implemented with actual Russian and foreign mineral development companies.

The main specific feature of the Barkhatny Massif minerageny is development of chromite mineralization zone, whose rocks are enriched in Pd, Pt, and Au. Content of chrome oxide in full (compact) ores reaches up to 43%. In some chromitite varieties/types (with chromespinelide content from 15 to 90 %), we noted presence of nickel sulfides (heazlewoodite, millerite, pentlandite), iron and copper (pyrrhotine, pyrite, and calkopyrite), as well as free high karat- gold (983-989‰ Au). Moreover, industrial contents of Pt (up to 5 ppmw), Pd (up to 1.2 ppmw) and Au (up to 5.4 ppmw) were found in these rocks using the atomic absorption method. Orientation of the chromite mineralization zone indicates anisotropy elements of hyperbasite body at an early stage of its exhumation, and is almost orthogonal in respect to main rims of the Barkhatnaya mountain massif. In the case when a standard approach was applied to prospecting works, excavations would be made perpendicularly to the main meridian-strike structures. In this case, it is not only difficult but also not economically efficient to find a quite local zone of chromitites without knowing deformation history of mantle hyperbasites, since exploration grid has to be minimized down to 50-100 meters.

Another aspect in forecasting minerageny specifics of such hyperbasite massifs is zones of metasomatic recycling represented by listwanites with potential gold mineralization and serpentinization with chrysotile-asbestos revealing. However, their orientation does not coincide with observed boundaries of hyperbasite bodies either. For example, gold-bearing listwanite bodies of massifs from the Severnaya and Zelenaya Mountains have North-Eastern strike and indicate later (three of them) deformation stages and metasomatic recycling of hyperbasites in local pull-apart zones. The most asbestos-potential serpentinites of the Barkhatny Massif are also controlled by crossing shear zones with NW orientation, where bedding elements vary from W-NW to N-NW strike at steep dip angles.

We should note that ophiolite parageneses often control spatially the largest placer gold deposits in this region. Nevertheless, there is an important pattern, which shows style of tectonic composition of the Kuznetsk Alatau northern slope. As a rule, large gold placers are localized/concentrated in developed river systems draining the internal core of "horseshoe-like" ophiolite parageneses, whose branches/ends underwent significant tectonic and metasomatic recycling. Typical examples are placers of the Kiya and Semenovka river sources. The main specific of these placers besides gold presence is constant presence of heavy platinoid alloys (ruthenium, osmium, and iridium), which are typical for chromitite mineralization zones of mantle hyperbasites. The given mineral association demonstrates paragenetic relation of gold placers to ophiolites. The studied paragenesis of the Severnaya, Zelenaya, Zayachya, and Barkhatnaya mountains forms/composes one of the highest mountain massifs in the region. Its drainage is carried out by small watercourses of the Rastay River and the left tributary of the Kiya River. Such a geomorphological scenario does not allow active exploiting of placer deposits industrially (using dredgers and so on), but can be useful for hand mining with attracting population. This experience was actively applied during the Second World War and promoted free labor in Siberian regions with poorly developed economics.

Conclusion

The results obtained during this research allowed us to conclude following. First, developing modern technologies for prospecting and estimating natural mineral deposits requires detailed studying of ore-bearing geological systems and building their possible petrogenetic models. Secondly, such studying should have complex approach with using methods of petrofabric analysis, detailed diagnosis of matter composition, and definition of geophysical field parameters indicating structural compositional heterogeneity of a studied object. Thirdly, an important element in forecasting ore and mineragenic potential of ophiolite complexes is nature of their tectonic disintegration and formation of noble metal placers.

On the example of the Barkhatny Massif, authors tried to validate new approaches to estimating potentials of ophiolite paragenesis studying in structures of the Altay-Sayan folded area, which have block-type tectonic composition. Such researches are in demand of both Russian and foreign mining companies at the stage of prospecting works in areas where ophiolite complexes develop, as well as in suture zones of modern mountainous land formations.

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