УДК 551.243:553.3(477.62)

TECTONICS OF THE BALKA KRUTA ORE CLUSTER OF THE NEAR-AZOVIAN MEGABLOCK OF THE UKRAINIAN SHIELD

N.N. Shatalov

(Recommended by doctor of geological-mineralogical sciences L.S. Galetsky)

State institution «Scientific Centre for Aerospace Research of the Earth
Institute of Geological Sciences of NAS of Ukraine», Kiev, Ukraine, E-mail: shatalov@casre.kiev.ua
Doctor of Geological Sciences, Senior Leading Researcher.

The results of investigations for the large structural Balka Kruta Sorokinska graben-syncline and Near-Azovian megablock of the Ukrainian Shield are presented. The features of fault-block tectonics and its influence on the forming the ore knot are defined. The Sorokinska graben-syncline and other fault zones of the orthogonal and diagonal systems and their significance in the localization of unique the Balka Kruta rare-metal deposit are characterized. Using geological, geophysical and remote sensing data the features of rare-metal pegmatites and manifested magmatism, metasomatosis, mineral and ore geneses are studied.

Key words: remote sensing data, tectonics, faults, geoblocks, graben- syncline, dikes, rare-metals deposit.

ТЕКТОНІКА РУДНОГО ВУЗЛА БАЛКА КРУТА ПРИАЗОВСЬКОГО МЕГАБЛОКУ УКРАЇНСЬКОГО ЩИТА

М.М. Шаталов

(Рекомендовано д-ром геол.-мінерал. наук Л.С. Галецьким)

Державна установа «Науковий центр аерокосмічних досліджень Землі
Інституту геологічних наук НАН України», Київ, Україна, E-mail: shatalov@casre.kiev.ua
Доктор геологічних наук, провідний науковий співробітник.

Наведені результати досліджень великого рудоносного вузла Балка Крута, розташованого в межах Сорокинської грабен-синкліналі Приазовського мегаблоку Українського щита. Визначені закономірності розломно-блокової тектоніки та її роль у формуванні рудного вузла. Охарактеризовані Сорокинська грабен-синкліналь та інші розломні зони ортогональної та діагональної систем і їх значення в локалізації унікального рідкіснометалевого родовища Балка Крута. За геолого-геофізичними даними та матеріалами ДЗЗ досліджені особливості рідкісніснометалевих пегматитів і проявленого магматизму, метасоматозу, мінерало- і рудогенезу.

Ключові слова: ДЗЗ, тектоніка, розломи, геоблоки, грабен-синкліналь, дайки, рідкісніснометалеве родовище.

ТЕКТОНИКА РУДНОГО УЗЛА БАЛКА КРУТАЯ ПРИАЗОВСКОГО МЕГАБЛОКА УКРАИНСКОГО ЩИТА

Н.Н. Шаталов

(Рекомендовано д-ром геол.-минерал. наук Л.С. Галецким)

Государственное учреждение «Научный центр аэрокосмических исследований Земли
Института геологических наук НАН Украины», Киев, Украина, E-mail: shatalov@casre.kiev.ua
Доктор геологических наук, ведущий научный сотрудник.

Приведены результаты исследования крупного рудоносного узла Балка Крутая, расположенного в Сорокинской грабен-синклинали Приазовского мегаблока Украинского щита. Определены закономерности разломно-блоковой тектоники и ее роль в формировании рудного узла. Охарактеризованы Сорокинская грабен-синклиналь и другие разломные зоны ортогональной и диагональной систем и их значение в локализации уникального редкометалльного месторождения Балка Крутая. По геолого-геофизическим данным и материалам ДЗЗ исследованы особенности редкометалльных пегматитов и проявленного магматизма, метасоматоза, минерало- и рудогенеза.

Ключевые слова: ДЗЗ, тектоника, разломы, геоблоки, грабен-синклиналь, дайки, редкометалльное месторождение.

Introduction

The Balka Kruta ore site includes the same-named deposit. It is located in a pretty picturesque place – in the valley of the river Berda, near the Berdyansk reservoir, 31 km north of Berdyansk. The unique Balka Kruta deposit is a vivid example of complex rare metal objects. In addition to beryllium, industrial contents of tantalum, lithium and cesium were found in it. The deposit was discovered by geologists of the Pryazovsky geological exploration expedition (GRE) in 1964. It is localized within the boundaries of the ancient Precambrian structure, which is identified under different names «Sorokin graben-syncline», «Sorokin fault zone», «Sorokin greenstone structure» (Fig. 1). Destruction The Steep Baikal is formed within the eponymous ore cluster, which is part of the larger Surozhsky structural-metallogenic cluster. In the boundaries of the structural-metallogenic complex, in addition to rare metal pegmatites, the Sourozh gold deposit was later discovered. In this regard, a unique ore site, formed over 2 billion years ago at a depth of about 5 km from the surface, should be attributed to the so-called **geological exclusives**.

In the context of creating a mineral resource base, beryllium is essentially the second most important deposit in Ukraine after the Perzhanskiy beryllium deposit in Volhynia [Шаталов, 2015]. Beryllium, tantalum, lithium and cesium are metals of high technology. Therefore, the demand for them in the world is growing. Consequently, the industrial development of the complex unique rare metal deposit Balka Kruta can not only strengthen the export potential of our country, but also and provide high-tech and science-intensive industries of Ukraine with domestic raw materials.

Geologic-structural position and Sorokinskaya graben-syncline structure

This original geo-tectogene [Глевасский, 1996] is the tectonic boundary between the two lager plicative Precambriant structures having a different age from the Near-Azovian – Manhush synclinorium and Saltychansk anticlinorium, in the center of which same-name dome fold is identified. Some investigators describe this structure as the deep linear zone of rifting embedded in the Achaean (more 3.3 Ga) on the Precambrian granulite-gneissic basement. In the plan this is the narrow local strip of the Precambrian supracrustal units continued down to 35-40 km at the maximum width (in the bulges) to 2 km. Graben-syncline is cut off from the “frame” of rocks by subparallel deep faults having North-Western spread direction (320-330°) and South-West steep dip (75-85°). In its northern part the strike of structure changes from the north-western direction to sub latitudinal one and there its knee-band is created. The level of erosional truncation within the structure can reach up to 5-6 km. Thus at the present time only the abyssal features remained on the comparatively large fissure-like, fosse-shaped trough-suture (graben-syncline) (Fig. 1, 2).

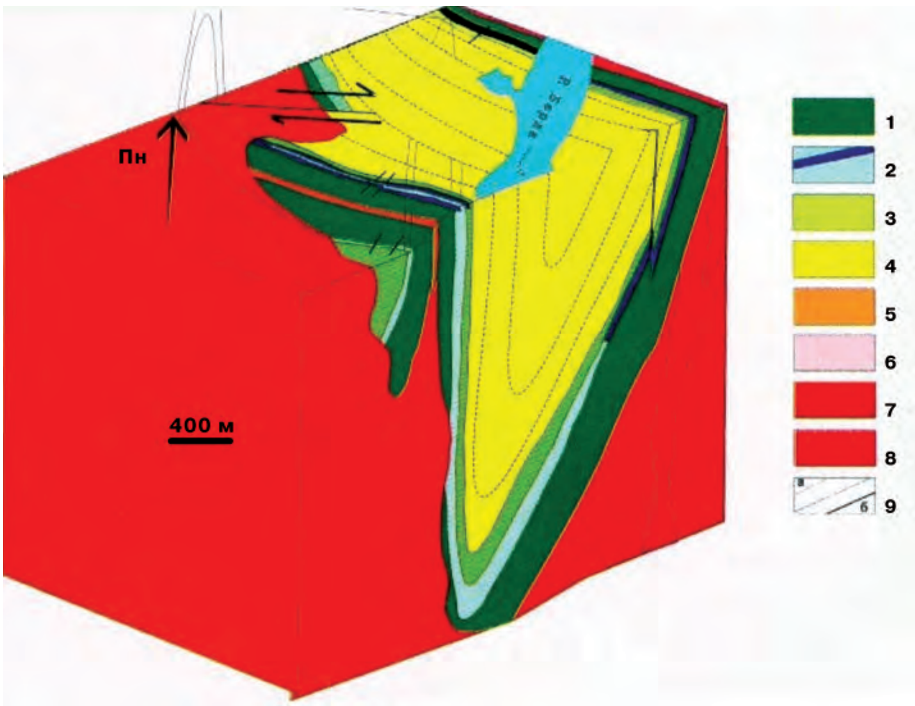

Fig. 1. Volumetric model of the structure of the Sourozh site of the Balka Krutaya deposit of the Sorokin graben-syncline [Чорнокур, Яськевич, 2010]

1 – metabasites; 2 – meta-ultrabasites; 3 – metabasites of the upper part of the section; 4 – metaconglomerates and schists of the Osipenkovo suite; 5 – lava-subvolcanic formations of the Surozh suite; 6 – hypabyssal formations; 7 – intrusive plagiogranitoids of the Shevchenko complex; 8 – two-feldspar granites; 9 – contacts and structural lines

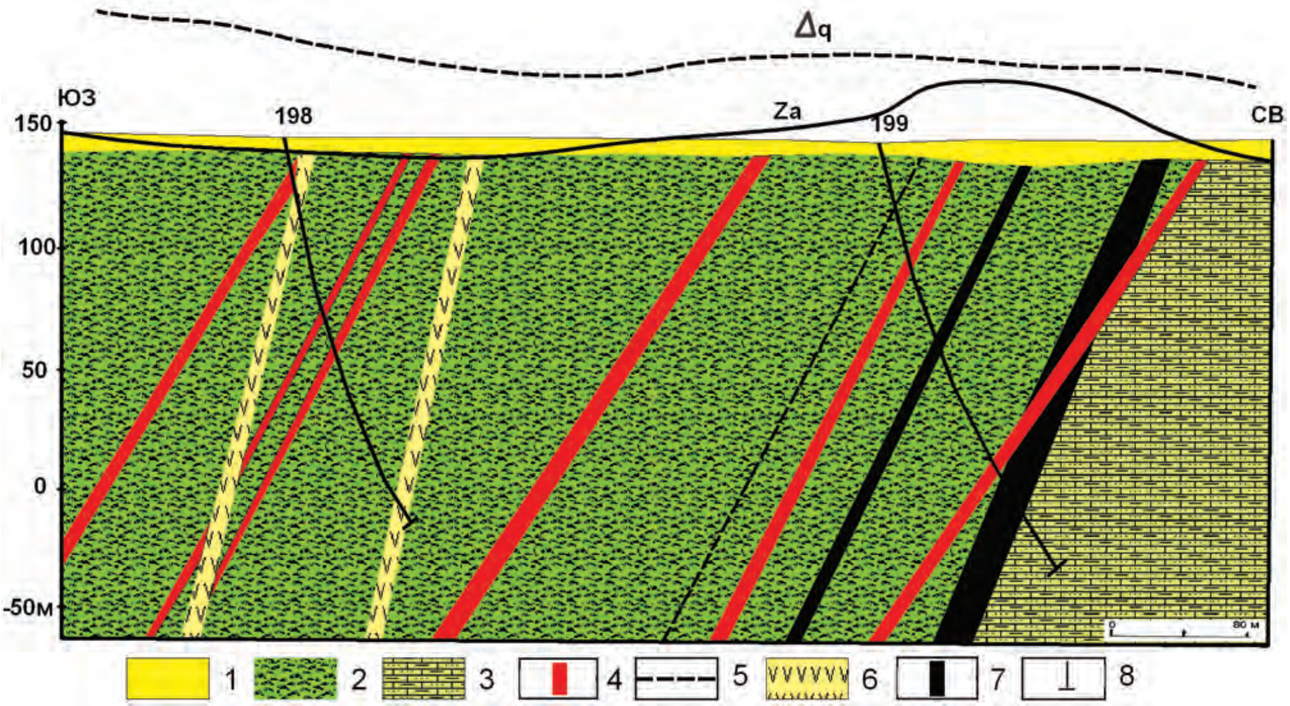

Fig. 2. Fragment of the geological-geophysical section across the strike of the Sorokinskaya trough structure. Compiled by the author on the basis of the materials of Artemovskaya GRE (Н.Ф. Русаков и др., 1981)

1 – sedimentary rocks; 2 – gneisses and migmatites of the Central Priazov Series; 3 – rocks of the Ospenkovo suite; 4 – ore-bearing veins of pegmatites; 5 – faults; 6 – dolerite dykes; 7 – метabasite dikes; 8 – boreholes and their numbers

Sorokinskaya graben-syncline has revived multiply. This is proved by the numerous predominantly concordant dykes, compression zones, as well as cataclasis and milonitization ones. In addition to the longitudinal (against the structure) fault tectonic zones, here there are also the transverse (north-eastern) and transcurrent (sub-meridional and sub-latitudinal) faults. Graben-syncline is dissected by the systems of orthogonal and diagonal faults into the discrete small-sized blocks (Andriievskiy, Sorokinskiy, Osipenkovskiy, and Sadovyi ones), which have undergone the shift along the lateral and vertical directions. As a result it turned into the peculiar "keyed" structure, where the rock complexes of the different depths (density) appear at the recent erosion truncation level. Such block structure is a base of atypicality for its anomalous gravitational and magnetic fields (Fig. 3). In the direction from northwest to south-east the erosion truncation depth within the graben-syncline considerably decreases

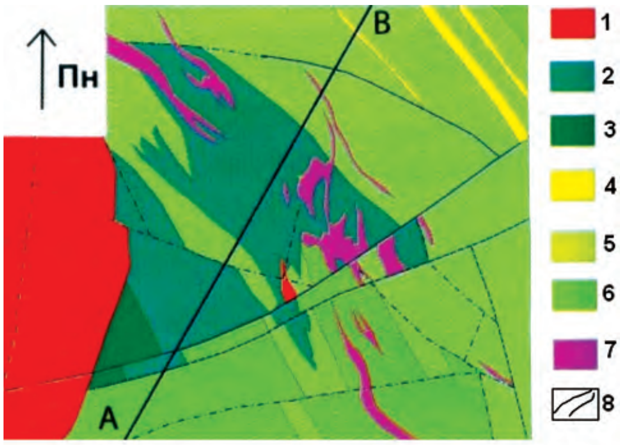

Fig. 3a

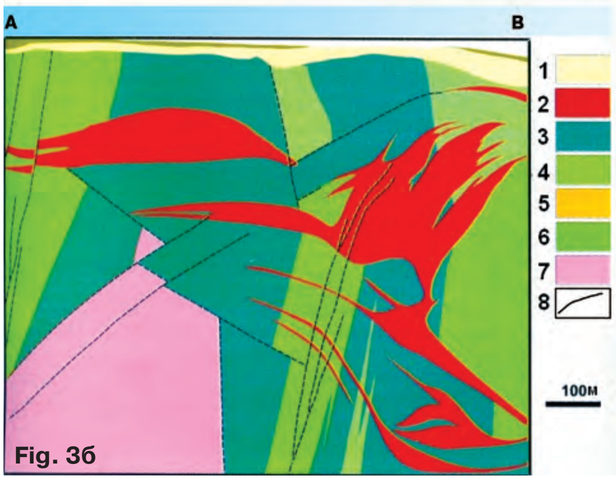

Fig. 3б

Fig. 3. A large-scale scheme of geological structure (a) and a geological section along the A-B (b) line of the Balka Krutaya deposit [Чорнокур, Яськевич, 2010]

1 – tonalites and plagiogranites of the Shevchenko complex; 2 – ultrabasites; 3 – metabasites; 4 – quartzites; 5 – the lower part of the section of the Krutobalkovskaya suite; 6 – the upper part of the section of the Krutobalkovskaya suite; 7 – rare-metal (with beryllium mineralization) pegmatites; 8 – contacts and structural lines

that can be seen from the compositions of metamorphic rocks of the different its parts, as well as on the degree of their metamorphism. Thus, within the Andriievskaia magnetic anomaly manifested to the most elevated block the relics of highly-metamorphic volcanosedimentary formations of granulite facies are defined, and in south-eastern graben-syncline at the Sadoviy site (downthrown block) the most complete section of low-metamorphic rocks (epidot-amphibolitic facies) are revealed. Geoblocks occupy the intermediate position at which the Surozh deposit and Sorokinskiy site are located, where diaphthorites are well represented along the rocks of amphibolites facies.

The thickness of rocks building up the graben-syncline is 1.2 km [Глевасский, 1996]. In the present stratigraphical sectional planes they are divided into the Lower and Upper Osipenkovian suite associated with the Achaean and Lower Proterozoic. The thickness of the lower “greenstone” suite is 700 m. It is composed of amphibolites, green sheets, meta-ultrabasites, ferruginous quartzites and intruded by numerous metamorphosed dykes of ultrabasite – basite and acidic compositions. In the north-eastern slope of graben-syncline in the section of Lower Osipenkovian suite the high alumina and two-mica gneisses are wide-developed. The Achaean age of Lower Osipenkovian suite is proved by geological and structural data and the dating on the mineral zircon from both the Osipenkovian granodiorites having the sharp active contacts with amphibolites and metamorphosed quartz porphyrys, i.e. 2.79 and 2.66 b.y.a. [Глевасский, 1996; Лавриненко, 1974].

The Upper Osipenkovian suite at the thickness of about 500 m is composed essentially of terrigene formations and broken by the dykes of lamprophyres, diabases, and younger dolerites. Its rhythmic structure can be observed at the exposed areas of graben-syncline along the Berda River as an alternating two-mica gneisses or schists with the relicts of meta-detritus structures and high aluminous (staurolite-, andalusite-, cordierite-, and sillimanite-bearing), garnetiferous, graphitic and other gneisses and schists.

In the southern Sorokinskaya graben-syncline the low-thickness (about 200 m) sedimentagenous package including marbles, meta-conglomerates and grafite-bearing schists (“Sadovaia suite”) lies at the rocks of the lower and upper Osipenkovian suite.

In the graphitic schists of Sadovaia suite the geologists have determined the complex of microphytofossils typical of the rocks of the Hdantsevian suite for the iron-ore Krivoy Rog belonging to the early Proterozoic.

The characteristic feature for the lower and upper Osipenkovian suite and particularly “Sadovaia suite”, developed within the Sorokinskaya graben-syncline is weak metamorphism (epidote – amphibolitic stage) relatively to Achaean – Proterozoic kratogen and a lot of dykes with the different compositions and ages indicated the ertain stages of tectonomagmatic activation and destruction of the Earth’s crust [Шаталов, 1986].

Tectonic position of the deposit

The Balka Kruta rare-metal deposit (Fig. 3, 4) is tectonically associated with the western instrument part of the Sorokin graben-syncline. Due to the original superposition of the sublatitudinal and northeastern fault tectonic zones, there was a significant «inflation» of the Sorokin graben-syncline. It was here that the large Surozh structural and metallogenic cluster was formed. In this unit, the Sourozh gold deposit and the rare-metal Balka Kruta deposit were discovered. The smaller, «Kruta Balka pegmatite knot», is mapped on the right slope of the Kruta gully, 0.6 km north of the Surozh gold deposit. The pegmatite field of rare-metal pegmatites «Central» is confined to one of the raised horsts of the Sorokin graben-syncline. The individual bodies of pegmatites here come out on the surface of the day (Fig. 4). Pegmatite field «Central» is located in the apical part of the local horst-like uplift. In the structural plan, rare metal pegmatites tend to break the frames of this horst structure, i.e. to the contacts of the rocks of the Archean (granodiorites), meta- and ultrabasites and the shale sequence of the Paleoproterozoic.

So, the Balka Kruta deposit is located in the center of the structural-metallogenic unit, in the most extended part of the Sorokinsky trough, which was formed in the zone of its horizontal pivot and branching [Лавриненко, 1974; Розанов, Лавриненко, 1979; Чорнокур, Яськевич, 2010]. The formation of the field of rare metal pegmatites is associated with numerous longitudinal and secant disruptive trod disturbances. The faults here form orthogonal and diagonal systems. The fault systems of the following directions are most developed here: NW 315-325°, NW 280-290°, NE 60-70°. However, the main in the field are the faults of the north-western and north-eastern orientations. This is clearly illustrated in Fig. 3, 4. The subordinate and submeridional orientation faults have a subordinate significance here.

Fig. 4a. Exposure of rare metal pegmatites from the Balka deposit. Bird near the village. Rodionovka.
Photo by A. Ivchenko [Гурський та ін., 2005]

Fig. 4b. Berdyansk reservoir and the same outcrop. Photo of twinpeaks, 2014

The faults of the northwest orientation are more ancient and deep. They are laid in the archaea and play an important ore-controlling role. They involve significant vertical displacements of the instrument zones of the Sorokin graben-syncline, the formation of ultra- and metabasites, ferruginous quartzites, various dikes and rare-metal pegmatites in the deposit. Together with fault systems of the north-eastern orientation, they also create the basic «frame» of the fault-block structure as Sorokinsky graben-syncline as a whole, and the field in particular. Numerous secant fault systems of the northeastern orientation, rare-metal bodies of the Balka Cool field, are divided into separate small geoblocks, displaced relative to each other (Fig. 1-3) up-shifts predominate here. In particular, in the area of the Balka deposit, the steep southern wing of the Sorokin graben-syncline along the line of the sublatitudinal fault is displaced laterally by 650 m [Чорнокур, Яскевич, 2010]. It was established that the northern geoblock (with the Balka Krutaya field) was moving eastward, and the southern geoblock (containing the Surozh gold deposit) was in the west. This sublatitudinal fault undoubtedly also has a vertical amplitude of displacement, but it is not defined. Dyke-like bodies of meta and ultrabasites, packs of ferruginous quartzites and numerous dykes of diabases, lamprophyres and quartz porphyries (Fig. 2) are widely used for the establishment of fault- and upslope shifts and their displacement amplitudes by good marking bodies.

Red-metal pegmatitic veins of rather complex morphology within the Balka Steep deposit are spatially and structurally gravitating toward the node of the north-west fault crossing with the sub-latitudinal and northeastern directions. As can be seen in Fig. 3, the strike of most of the veins of pegmatites here is northwest. A similar northwesterly direction is also contained by the bodies of meta-rubbazites and ferruginous quartzites that contain them. Systems of disruptive violations of the northeastern orientation of the body of rare metal pegmatites are usually blocked or displaced. This structural-geological position indicates that, at the time of formation of ore-bearing pegmatite bodies, fracture-fault systems of the northwestern direction were in the regime of tectonic extension (spreading), and of the north-east – shear (up-and-down or shear-shift). Deep faults and cracks were supply channels for the penetration of pegmatite melts and ore-bearing fluids from the deep parts of the lithosphere into metabasites, quartzites, shales and other host rocks of the near-surface parts of the Sorokin graben-syncline. As a result, a stratified body of pegmatites was formed in the structural node of the Steep Balk, resembling, in generalized form, the usual «Mushroom» or Kalla flower (Fig. 3)

According to L.F. Lavrinenko [Лавриненко, 1974; Розанов, Лавриненко, 1979], three systems of fracture tectonic cracks are clearly traced within the pegmatite field. The first, more ancient system has a NW stretch of 280-300^{o} and a northeast drop at angles of 70-85^{o}. These fracture-cracks are accompanied by wide bands of crushing, myolitization and cataclasis. Large bodies of metabasites and meta-rubbasites are confined to them. These faults also cause vertical block movements within the Sorokin graben-syncline. The second system of fracture-cracks of the north-western direction carries traces of repeated tectonic activation everywhere. Stretching of the cracks of this system – NW 320-340^{o}, and a fall to the southwest at angles of 85-90^{o}. This system of fracture-cracks is developed inside the horst-like uplifts. Sometimes it cuts a graben structure and forms large horizontal discharge-swing movements. The faults of the second system limit the elevated geoblocks of the foundation. Therefore, the ore-bearing pegmatite bodies here are exposed to the surface of the day. Most of the fracture-cracks in the deposit are post-ore fractures. They shift separate areas of ore-bearing pegmatite veins, forming in this pegmatite zones of crushing, myonitization and cataclasis. The latter are often made by later quartz veins. To the southwestern faults framing the graben, the third system of discontinuous violations of the sublatitudinal direction adjoins. Often it passes here into the gently sloping fissures of the northeasterly strike. This system of fracture-cracks controls the spread and sharply breaks the bodies of pegmatites in the southern part of the deposit (Fig. 3). The fault-crack systems of the northeastern strike are widely manifested in the field. They are long-lived, limit the ancient Archean geoblocks and, together with the faults of the north-western direction, control the development of rare metal pegmatites. Consequently, the ore-bearing bodies of the pegmatites at the Balka Steep deposit are clearly controlled by the junction of the fracture faults of the three directions: northwestern, northeastern and sublatitudinal.

The material composition of pegmatite rocks

The host for rare metal pegmatite is Archean palingenic-anatectic granodiorites linearly elongated in the northwest direction metabasite body and metaultabazitov (amphibolite, pyroxenite, olivinites, serpentinite, aktinolitity et al.) and metamorphic rock of shale stratum from the Osipenkovian formation. Depth of amphibolites and metaultrabazites body ranges from 3-15 to 300 m, the length – from 0.5 to 5.11 km [Лавриненко, 1974]. Ultramafic band on the Balka Kruta field participates in the structure of the Surozh gold deposit geological section [Розанов, Лавриненко, 1979]. Amphibolites include bodies of magnetite quartzites, calcareous skarns, garnet-biotite, two-mica and other shales. The rocks of the shale strata in the field are characterized by a number of specific features. They are mainly represented by metapelites. Among them are different in mineral composition shales – garnet-biotite, muscovite, biotite, two-mica, garnet, tourmaline, biotite, staurolite and other less developed here amphibole and barren magnetite quartzite, calciphyres and diopside-plagioclase schists.

Metagravellites and metaconglomerates, biotite, amphibole and feldspar quartzites are widely developed on the flanks of the pegmatite field. At the bottom of shale stratum section (700 m thickness) there are biotite, two-mica, garnet, tourmaline and sillimanite shales. Above of that it is traced the stratum (600 m thickness) of calciphyres phlogopite and diopside-plagioclase with the interbeds of gangue quartzite. The section is completed by the stratum (up to 500 m thickness) of amphibole diopside-plagioclase schists [Розанов, Лавриненко, 1979].

Structure and morphology of ore bodies

The Balka Kruta deposit is composed of gently sloping veins (with a thickness of 0.5 to 70 m) of quartz-microcline-albite composition with muscovite, tourmaline, biotite, garnet, magnetite, apatite, beryl, spodumene, tantalite and columbite. In the plan and section of the deposit, pegmatite veins form a kind of «layered pie». In its borders there are at least 10 large pegmatite bodies. The deposit is mainly composed of flattening pegmatite bodies of plate or mushroom shape. The ratio of length to width of bodies here is 6:1 and more [Лавриненко, 1974; Розанов, Лавриненко, 1979; Чорнокур, Яськевич, 2010]. In the lower parts of the section, the pegmatites of the Central field are composed mainly of low-power veins with a microcline, and in the upper parts – by thick veins of quartz-albite and albite-spodumene compositions. A similar zoning is observed along the strike of the entire pegmatite field «Central». From the north-west to the south-east, in the direction of the fall of the veins, a major microcline vein and veinlet change is observed in quartz-albite and quartz-albite-spodumene (Fig. 3).

The most pronounced zoning in the deposit is found in large pegmatite bodies. In this case, the nature and composition of the zones depend on the depth of occurrence of pegmatite bodies. Thus, a series of near-surface pegmatite veins, partially overlooking the day surface, is characterized primarily by a quartz-albite composition. In the central parts of the veins there were developed rocks consisting of block quartz. This «quartz core» is composed of fractured quartz of a large-block structure with rare inclusions of crystals of pink microcline and accessory beryl. According to the fall, the «quartz core» can be traced to tens of meters and forms a continuous zone in large veins. In smaller pegmatite bodies, separate blocks of fissured quartz are separated. In the direction of the recumbent side, the «quartz core» smoothly passes into the block microcline zone of pale pink or gray color. In this zone there are nests of crystals of pale green spodumene up to 0.8 m in size [Розанов, Лавриненко, 1979]. A quartz-muscovite zone is developed at the contact with the block microcline. In individual pegmatite veins, it passes into the muscovite-quartz-albite zone. This zone is composed of sugar-like albite with a minor admixture of quartz, muscovite, apatite and black tourmaline.

Then there is the quartz-albite-spodumene zone, the most common in all the powerful pegmatite veins. In blowing it takes from 20 to 60% of the volume of veins. By falling pegmatite veins, it can be traced in the form of a continuous band, where quartz, albite and spodumene predominate. In addition to them, muscovite, microcline, tourmaline, apatite, beryl, garnet, tantalite, and trifilin-lythiofilite are present here in various amounts. In the direction of the endocontact, the next is the zone composed mainly of quartz and albite. Muscovite, microcline, tourmaline, apatite, garnet, beryl, columbite and other minerals have also been found in this zone. Consequently, at the Balka Kruta deposit there is an original vertical zonation of the pegmatite field. The pegmatites of the lower structural stage of the deposit are characterized by a vein form and an apographic quartz-albite- microcline structure. The veins of this type are composed of blocks of sugar albite, quartz, microcline and thin-scaly muscovite. The second, quartz-albite-spodumene type dominates the deposit. The general direction of the fall of veins within the «Central» field is southeastern (10-140°) at angles of 5-25°.

The eastern direction of «rolling» at an angle of 20-35^{o} is noted in the largest veins of pegmatites [Лавриненко, 1974; Розанов, Лавриненко, 1979; Чорнокур, Яськевич, 2010].

The morphology of bodies in the field is rather complicated. As a detailed study of the largest veins showed, their morphology depends entirely on the physicomechanical properties of the enclosing rocks and on the conditions of fissuring in rocks composing the sides and internal parts of the Sorokin graben-syncline. Thus, all veins of pegmatites in granodiorites are morphologically sustained. Their power gradually decreases towards the sides of graben-syncline. In the transition to the rocks of the basic and ultrabasic compositions, the thickness of the ore-bearing pegmatite veins increases sharply. The veins form inflations here, numerous apophyses and ramifications. When the veins have disappeared into the shale body, the pegmatite bodies are very quickly split and wedged out. Thus, it has been established that rare metal pegmatites exhibit a predominant relationship with meta-rubbazites. However, it is not uncommon for large bodies of pegmatites to break through ultrabasites, schists and granodiorites. In such cases, the composition of pegmatite is changed.

Thus, within the granodiorites, pegmatites have a quartz-albite composition with mineral paragenesis: quartz, plagioclase (pink microcline), muscovite, apatite, tourmaline, cassiterite, rarely zircon, columbite tantalite, spodumene, magnetite, sulphides. In the slate thickness, the pegmatites are represented by a quartz-albite zone with intermittent sections of zones of block quartz, block microcline and, less frequently, the quartz-albite-spodumene zone. For these pegmatites, the parageneses of minerals are characteristic: quartz, albite, muscovite, microcline, spodumene with accessory – columbite-tantalite, cirtolite, trifilin-lithophilite, beryl sulfides, apatite, fluor apatite and chloropatite. In the ultrabasites, pegmatites form blow-ups and complexly differentiated bodies. Their structure and mineral composition are distinguished here by a great variety of accessory mineralization. Pore-forming minerals of these pegmatites are quartz, microcline (blocks), albite and less often muscovite. Of accessory minerals spodumene, tantalite, tapiolite, cassiterite, cirtolite, ambligonite-montebrasite, trifiline-lithophyllite, rutile, cesium-containing beryl, apatite and various sulphides are characteristic. Because of the physicomechanical and chemical properties of the rocks of the ultrabasic series, they «provide» not only inflations and differentiation of pegmatites, but also a considerable enrichment of ore bodies with rare metals.

Mineralogy of rare metal pegmatites

The rock-forming minerals of the pegmatites of the Balka Kruta deposit are silicates, which constitute 97% of the mass of pegmatite bodies. Ore mineralization of the productive zones of the rare-metal deposit is very diverse. The main ore minerals are beryl, chrysoberyl and emerald (Be ore), columbite-tantalite, tapiolite, microlite and eschinite (ore on Nb and Ta), spodumene, trifiline-lithiofilite, ambligonite-montebrasite, hillkvistite, kukite and petalite Li) [Розанов, Лавриненко, 1979]. Beryl is the main mineral, in which beryllium is concentrated. At the deposit, it occurs in most veins of the pegmatite field. It predominates in block quartz and muscovite-quartz-albite zones. The size of crystals from 1 to 10 cm (Fig. 5), the color – from white and grayish-white to bright green. The glitter of the mineral is glass, the crack is uneven, the hardness is about 8, and the density is 2.74-2.79 g/cm^3. Chrysoberyl is installed in small quantities in quartz-albite and biotite-phlogopite zones, where it forms small isometric grains. The color is colorless or green, the size of the grains is from 0.05 to 0.5 mm, the gloss is glassy, the crack is uneven, the hardness is about 8, and the density is 3.76 g /cm^3. Emerald forms short-prismatic crystals up to 2 cm in the phlogopite margin of pegmatites. It is rare. The glitter of the mineral is glass, the fracture is uneven, the shell is green, the color is emerald green, and the density is 2.79 g/cm^3.

Columbite-tantalite forms nests and veins. It is present in all zones of pegmatite bodies. It is represented by plate, tabular and short-prismatic crystals ranging in size from fractions of a millimeter to 2 cm. Color black, gloss semi-metallic, fracture resinous, semi-glossy. The hardness is 6-6.5, the density is 6.18-6.73 g/cm^3. Concentrations of Nb_2O_5 and Ta_2O_5 in the mineral reach 80%. Tapiolite occurs in pegmatites in the zones of quartz-muscovite and quartz-muscovite-albite compositions. It occurs frequently, is formed at the final stages of pegmatite formation. Tapiolite in pegmatite veins makes up to 10% of all tantalum minerals. Spodumene is the main concentrator of Li, it forms quartz-albite-spodumene zones in all pegmatite bodies. It forms large columnar and lamellar crystals of light gray, yellowish-green, sometimes pink in color. Cleavage is perfect, the gloss is silky or glassy, the hardness is 6.0-6.5, the density is 3.05-3.18 g/cm^3. The content of Li_2O in spodumene is 6.2-7.8%. Triphylite-lithio-

Fig. 5. Pegmatite with beryl crystal, Balka Krutaya deposit. Photo by K. Esipchuk [Гурський та ін., 2005]

philites are ferrous-manganese lithium phosphates. These minerals form aggregative accumulations and are developed along microcline, albite and spodumene. The grain size varies from 0.2 to 0.8 mm, and aggregative accumulations attain up to 20-40 cm. Minerals are gray-green in color, with an uneven break, hardness is 4.5-5.0, density is from 3.36 to 3.47 g/cm^3. Triphylite-lithiophilites are characterized by constant content of lithium (3.0-4.2%), phosphorus (up to 20%) and high rubidium content (0.15-0.35%). Holmquistite is a characteristic mineral for metasomatically altered exocontact amphibole-containing rocks enclosing rare-metal pegmatites. In small amounts, it occurs in pegmatites. The size of the crystals is from 2 to 20 cm, the color is blue-violet, lilac. Cleavage is perfect, hardness is 5.0-5.5, and density is 3.02-3.10 g/cm^3. The content of Li_2O in the holmquistite is 2.88-3.50%.

Geochemistry of rare metal pegmatites

The nature of the distribution of rare elements in pegmatites and their host rocks has been studied well [Лавриненко, 1974; Исаков, 2005]. It was estimated from the results of chemical analyzes of minerals (Be, Ta, Nb, Sn) and flame photometry (Li, Rb, Cs). The furrow samples taken in the cross of the strike of the veins of albit-spodumene composition were analyzed.

Beryllium. Within the pegmatite veins of the Balka deposit, the steep content of beryllium ranges from 0.011 to 0.015%. The only exception is the block zones of quartz and microcline, where the concentrations of beryllium are somewhat smaller. The main beryllium mineral-concentrator is accessory beryl, which is widely distributed in the rare-metal pegmatites described. Beryl is found in all mineral complexes, differing only in color, chemical composition and habitus of minerals. The content of beryllium oxide in the beryl mineral varies from 10.7 to 11.6%. The highest concentrations of beryllium are found in the spodumene zones, where sodium and sodium-lithium beryl are present.

Tantalum. The highest concentrations of tantalum (Ta_2O_5 to 0.75%) are recorded in albite pegmatites. However, the distribution of tantalum here has a nesting character, i.e. only certain sections of the veins are enriched. In albit-spodumene pegmatites tantalum is distributed more evenly, although the maximum values are only 0.17%. However, for these pegmatites, sufficiently strong zones with contents of about 0.02-0.04% Ta_2O_5 are characteristic. In general, elevated tantalum concentrations are noted in almost all veins of the pegmatites of this deposit. They are associated here with quartz-spodumene-albite (up to 0.015% Ta_2O_5) mineral complexes and later with albite (0.0083% Ta_2O_5), quartz-albite (0.011% Ta_2O_5) and quartz-muscovite (0.019% Ta_2O_5) ones. The amount of tantalum in albit-spodumene pegmatites and in the marginal spodumene-containing zones at the deposit is maximal. The main minerals-concentrates of tantalum are the minerals of the columbite-tantalite group and tapiolite, which are present in all the complexes: here the tantalum concentration reaches 90% and niobium up to 65% of the total sum of these elements in the pegmatite. The distribution of tantalum throughout the thickness of albite and albite-spodumene pegmatites is characterized by certain regularities. The content of Ta_2O_5 from the outer zones to the central zones varies regularly from 0.005 in the apographical zone to 0.015% in the spodumene zones.

Niobium. The distribution of niobium in pegmatites differs slightly from the distribution of tantalum. High concentrations of niobium (up to 0.007% Nb_2O_5) in the rare-metal pegmatites of this deposit are associated with quartz-spodumene-albite mineral complexes and subsequent albite (0.0091% Nb_2O_5), quartz-albite (0.01% Nb_2O_5) and quartz-muscovite (0.0117% Nb_2O_5). The distribution of niobium over the entire thickness of albite and albite-spodumene pegmatites also shows some regularity. Niobium in albite and albite-spodumene pegmatites shows a regular decrease in concentrations from the marginal zones to the center of the veins. This pattern can also be observed by a change in the tantalum-niobium ratio, which can be used to determine the prospects for the tantalum region of the region.

Tin. For pegmatites of this rare metal deposit, tin is noted in small amounts and has no industrial significance. In various zones of the pegmatite field, 0.006 to 0.04% SnO_2 is contained. Cassiterite is the main concentrator of tin. Here, this mineral is present in small amounts. In the form of microinclusions, a small part of the tin is contained in tantalite and tapiolite.

Lithium. The highest concentrations of lithium are associated with spodumene-containing zones of pegmatite bodies. In quartz-spodumene zones, the content of lithium, for example, averages 0.4%, with a maximum of 1%. In pegmatites that do not have a structural and spatial connection with amphibolites and meta-ultrabasites, lithium does not form its own carrier minerals and is concentrated in muscovites and feldspars. The concentration of lithium is small. Higher lithium contents are associated with zones where lithium-containing muscovite and accessory spodumene are present. In the near-surface veins of the albite composition, the concentration of lithium is much less than for veins with spodumene from deeper horizons. Consequently, lithium is accumulated in the thickness of pegmatite veins in the direction of deeper horizons. The tendency of lithium accumulation in minerals of pegmatites is also observed from the early stages to the later stages.

Rubidium. The content of rubidium in rare-metal pegmatites ranges from 0.009 to 0.10%. Its accumulation occurs in feldspars and late mica, where rubidium occupies the position of potassium in the crystal lattice. This, as we know, is due to the proximity of the crystal-chemical properties of these chemical elements. High concentrations of rubidium are characteristic for micaceous zones of pegmatites. In the quartz-spodumene and quartz-spodumen-albite complexes of minerals, the high rubidium content is due to the presence of muscovite and lepidolite.

Cesium. Concentrations of cesium in pegmatites of the Steep Baikal range range from 0.0088 to 0.042%. In the albit and albit-spodumene zones of pegmatites, a clear increase in the cesium content from the marginal zones to the central zones was observed. This phenomenon is explained by researchers as increasing in this direction the concentrations of potassium, to which cesium is geochemically gravitating. The maximum concentration of cesium is characteristic for the zone of block microcline (0.05% Cs_2O), where beryl (0.45% Cs_2O) is also present. The increase in cesium content in the marginal zones of albite pegmatites is due to the presence of cesium-containing biotite (0.52% Cs_2O) and beryl (0.24% Cs_2O). Cesium does not detect significant accumulations in the pegmatites of the deposit, although its concentration in albit-spodumene pegmatites is considerably higher than that in albite pegmatites. A characteristic regularity for cesium is that it is often completely dispersed in rock-forming minerals.

Genesis of rare metal pegmatites

As is known, the genesis of pegmatites is very controversial. Many works of A.E. Fersman, A.I. Ginzburg, A.A. Beus, K.A. Vlasov, D.S. Korzhinsky, A.N. Zavaritsky, V.D. Nikitin, L.N. Ovchinnikov, N.A. Solodov, M.V. Kuzmenko, K.A. Shurkin, N.G. Sudovikov, et al. To date, there are three points of view regarding the genesis. The first, the most common (A.E. Fersman, K.A. Vlasov, et al.) considers pegmatites as a product of crystallization from a special melt-solution, genetically related to mother granites. The second one (D.S. Korzhinsky, A.N. Zavaritsky, V.D. Nikitin, et al.) represents pegmatites as a product of recrystallization and metasomatism under the influence of postmagmatic solutions. The third (N.G. Sudovikov, K.A. Shurkin, et al.) connects the origin of pegmatites with phenomena of ultrametamorphism. According to Rosanov A.I. [Розанов, Лавриненко, 1979], the formation of the rare-metal pegmatites in question is closely related to the processes of crystallization of specialized pegmatite melts-solutions, which determined the natural composition of pegmatites, their morphology and the distribution of veins in ultrabasites, shales and granodiorites. Such pegmatites should be attributed to the typical formations of graben-synclinal structures and zones of deep faults–conductors of intrusions of mother granites. Analysis of the materials also indicates that metasomatites in the host rocks and near large veins with rare metal mineralization have been developed at the Krutaya Balka deposit. These data confirm that only a part of the rare metal mineralization in the field has a metasomatic origin, while pegmatites have already been rare metal before the development of metasomatic processes.

Age of rare metal pegmatites

The age of the enclosing rocks and rare metal mineralization at the Balka Krutaya deposit should be determined from a comprehensive analysis of geological-structural ratios of rocks and isotopic data. Tectonic, geological-structural and geochronological data on the Sorokin graben-syncline indicate its long-term development. Zircon in biotite gneisses according to morphological characteristics corresponds to the clastogenic type, its age is determined on the Surozhsky suite as 3320 ± 30 Ma. The uranium-lead age of zircon from granodiorites, secant amphibolites and biotite gneisses, is 2800 ± 30 Ma, and the dikes of leucocratic porphyritic granites that cut amphibolites are 2680 ± 30 Ma (Розанов, Лавриненко, 1979; Щербак и др., 2008]. So, granodiorites with an age of 2.8 billion years cut the rocks of the Osipenkovo suite, and acid effusives of 2.66 Ga form consonant reservoir bodies in these rocks. Red-metal pegmatites in the structural-ore cluster under investigation should be younger than the surrounding rocks. They cut granodiorites, meta- and ultrabasites and schists of the Ospenkovo suite. The isotopic age of metamorphism of amphibolites and schists of the Ospenkovo suite is 2.3-2.0 Ga. Numerous definitions of the age of rare metal pegmatites, determined at the Institute of Mineralogy and Geochemistry of Rare Elements for minerals as 2312-2226 Ma (average 2240Ma). Consequently, the formation of rare metal pegmatites, coinciding with the Karelian tectonic-magmatic cycle, should be dated to the border – 2.3-2.0 Ga [Розанов, Лавриненко, 1979].

Conclusions

The above data indicate that the rare-metal Balka Krutaya deposit is confined to the unique and long-developed Sorokin graben-synclinal (paleorift) structure of the Priazovsky megablock USH. This most ancient intracontinental paleorift has a northwest strike and is laid on the Archean granulite basement. The field of rare metal pegmatites is formed inside the graben-synclinal structure, at the intersection of the faults of the northwestern, northeastern and sublatitudinal directions. The deposit is unique, has no analogues in the world and was formed as a result of changes in the rotational regime of our planet in the Karelian cycle of tectogenesis approximately 2.3-2.0 Ga. In connection with the rotational stresses, during that period of the evolution of the Earth, faulty tectonic zones of the orthogonal and diagonal systems became active within the boundaries of the described part of the lithosphere. A high-gradient dynamic environment also emerged here, where sections with maximum fragmentation and permeability of the lithosphere were formed, favorable for localization of deep magmatic melts, fluids, metasomatites and ore matter.

In connection with the activation of the deep earth energy processes within the Sorokinsky graben-syncline, the Surozhsky structural-metallogenic cluster was formed, where the Sourozh gold deposit and the Balka Krutaya rare metal deposit are located. The Balka Steep deposit was formed at a depth of about 5 km as a result of activation of fault-block, often up-and-over and shift-fault tectonic movements and tectonic magmatic processes taking place in the Archean and Paleoproterozoic. An important role in oreogenesis here was played by deep, probably mantle, fluids. As a result of hydrothermal-metasomatic processes, gold ore bodies of metasomatites were formed. They were imposed on rare-metal pegmatites and host rocks – granodiorites, amphibolites, ultrabasites and various shales. The deposit was explored to a depth of 250 m. The formation of productive rare metal mineralization occurred in several stages. The ore site recorded an increase in the number of rare metals with depth, and the wedging of ore-bearing pegmatite bodies was not established. Taking into account the level of erosion cut at the Balka Krutaya deposit, one should expect that rare metal mineralization extends to great depths. In the course of geological exploration, in the opinion of [Гурский, 2005; Исаков, 2005], only part of the pegmatite site was identified at the field. Therefore, it is necessary to search for albite-microcline and albite-spodumene pegmatites laterally and to depth.

This forecast will significantly increase the potential reserves of the unique rare metal deposit Balka Krutaya. Strong beryllium mineralization revealed in the pegmatites of the Balka deposit makes it possible to classify them as a complex rare-metal type (Be-Cs-Li-Ta).

To date, the Balka Krutaya deposit is a well-studied facility, its resources are sufficient for industrial development. Ores for mining are highly technological. The extraction of ores from the deposit can be highly profitable. The deposit occupies an ungovernable and untamed land on the northern slope of the Krutaya gully (Fig. 6). The ore bodies of the central, most productive, part of the rare metal deposit actually exit to the surface of the day, but at the depth they do not wedge out. The developed infrastructure of the region and favorable geographic-economic and technological conditions make the unique Balka Krutaya deposit attractive for investments.

Fig. 6. Location of the rare-metal deposit Balka Cool on the space image Image Landsat from 24.10.2013. Overview of the Krutaya and Berdyansk reservoirs from an altitude of 1.62 km. The height of the surface is 30 m above sea level

Список літератури / References

1. ***Глевасский Е.Б.*** Зеленокаменные пояса и перспективы поисков золотого оруденения в Приазовье. *Минерал. журн.* 1996. № 4. С. 72-88.

Glevassky E.B., 1996. Greenstone belts and the prospects of the search for ore gold-grade mineralization in the Near-Azovian. *Miniralogicheskiy Zhurnal*, № 4, p. 72-88 (in Russian).

2. ***Гурський Д.С., Єсипчук К.Ю., Калінін В.І. та ін***. Металічні корисні копалини. Київ; Львів: Центр Європи, 2005. Т. 1. 710 с.

Gursky D.S., Yesypchuk K.E., Kalinin V.I. et al., 2005. Metalichnyi korisni kopalini. *Kyiv-Lviv: Tsentr Evropy, v*ol. 1, 710 p. (in Ukrainian).

3. ***Ісаков Л.В.*** Про одну з особливостей рідкіснометалевих пегматитів вузла Крута Балка. *Мінер. ресурси України.* 2005. № 2. С. 21-22.

Isakov L.B., 2005. On one feature of the rare-metal pegmatites of the Krutaya Balka node. *Mineralni resursi Ukrainy*, № 2, p. 21-22 (in Ukrainian).

4. ***Лавриненко Л.Ф***. Некоторые особенности поисков редкометалльных пегматитов в закрытых районах докембрия. *Разведка и охрана недр.* 1974. № 8. С. 21-25.

Lavrinenko L.F., 1974. Some features of searches for rare metal pegmatites in the closed areas of Precambrian. *Razvedka i ohrana nedr*, № 8, p. 21-25 (in Russian).

5. ***Розанов К.И***., ***Лавриненко Л.Ф***. Редкометальные пегматиты Украины. Москва: Наука, 1979. 139 с.

Rozanov K.I., ***Lavrinenko L.F.,*** 1979. Redmetal pegmatites of Ukraine. Moskow: Nauka, 139 p. (in Russian).

6. ***Чорнокур І.Г.***, ***Яськевич Т.Б.*** Деякі нові дані щодо геологічної будови району рідкіснометалевого родовища Балка Крута. *Мінер. ресурси України*. 2010. № 2. С. 18-24.

Chornokur I.G., Jaskevich T.B., 2010. Deyaki novi dani geodeticheskii budovy to the district of the Ridkisnometelevoye Birthplace Balka Kruta. *Mineralni resursy Ukrainy,* № 2, p. 18-24 (in Ukrainian).

7. ***Шаталов Н.Н.*** Дайки Приазовья. Киев: Наук. думка, 1986. 192 с.

Shatalov N.N., 1986., The Near-Azovian dykes. Kiev: Naukova Dumka, 192 p. (in Russian).

8. ***Шаталов М.М.*** Пержанське берилієве родовище – Український ексклюзив світового масштабу. *Вісн. НАН України*. 2015. № 12. С. 65-72.

Shatalov N.N., 2015. Perzhanske beryllium deposit – Ukrainian exclusive of the world scale. *Visnyk NAN Ukrainy*, № 12, p. 65-72 (in Ukrainian).

9. ***Щербак Н.П., Артеменко Г.В., Лесная И.М., Пономаренко А.Н., Шумлянский Л.В.*** Геохронология раннего докембрия Украинского щита. Протерозой. Киев: Наук. думка, 2008. 240 с.

Cherbak N.P., Artemenko H.V., Lesnaia I.M., Ponomarenko A.N., Shumliansky L.V., 2008. The Early Pre-Cambrian Geochronology of the Ukrainian Shield. The Proterozoic. Kiev: Naukova Dumka, 240 p. (in Russian).

Received
April 15, 2016