Study of the tectonic structure and modern geodynamics of the nickel-copper-sulfide Kun-Manyo deposit at the stage of its field the development

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Abstract. Currently, the Kun-Manyo nickel-copper-sulfide deposit in the north of the Khabarovsk Krai is being prepared for development, with part of the reserves expected to be mined by underground mining. To justify the rational order of opening and excavation of subore reserves it is necessary to have objective information on rock mass condition, which can be received as a result of complex geodynamic and geomechanical investigations.

The established geodynamic position of the deposit, determined by its location at the junction of actively interacting large tectonic elements of the Euro-Asian tectonic plate – the tectonic stress of the North Asian craton and the Amur plate, as well as within the modern Olekmo-Stanovo seismic zone, has allowed the massif of the field area to be classified as tectonically stressed.

An analysis of the data of the GPS-observation points on the territory of the Russian part of the Amur tectonic plate, the results of calculations of the vector field of velocities of modern movements of points, made within the framework of the ITRF – 2000 coordinate system, as well as the results of in-situ geomechanical studies of rock massifs of the Amur Plate’s rock-bump hazardous deposits, have made it possible to establish the current tectonic regime of the deposit area – a region of intense modern compression with a predicted intensity of more than 50 MPa. By methods of morphometric analysis and remote sensing, it has been found that the relative relief excesses were significant (700–1000 m), which may lead to an uncompensated horizontal component of geostatic stress. The most extended lineaments of the relief have predominantly southeasterly extension. The identified features of the tectonic structure and regional neotectonics have made it possible to determine the most probable direction and magnitude of the current main horizontal compression, which could be further used in solving various geomechanical problems in the exploitation of the field.

1. Introduction
Currently, the Kun-Manyo nickel-copper-sulfide deposit is being prepared for the development involving open pit and underground methods. The experience of developing ore deposits shows that, as a rule, the transition to underground development is associated with deterioration of mining and geological and geomechanical conditions. Significant heterogeneity of natural stress fields, predetermined by the complexity and peculiarities of the tectonic and geological structure of the deposits, is further enhanced
by the technogenic impact on the rock mass as a result of mining operations. Redistribution of initial stresses in space and time, as well as concentration thereof in some areas, is one of the main causes of dangerous failure of massif areas in the dynamic form [1–3].

To ensure the safety of underground mining operations and reduce the risk of dangerous geodynamic phenomena in the mining enterprise, the organization of geomechanical observations in the continuous geophysical monitoring mode, and linking them with the regional and local neotectonic position of the operation object will be required here. As experience shows, the study of neotectonic processes and tectonic structure, which are associated with natural and anthropogenic seismicity, is of great importance [4–6].

2. Materials and Methods
The Kurumkanskoye ore field includes 8 deposits – independent areas, including the Malyi Kurumkan, Sobolevskaya, and Kubuk deposits. In plan view, the ore field (up to 2–3 km wide) is a linearly stretched in south-east direction 31 km long area consisting of numerous sheetlike and lenticular intrusions, less frequently dikes of mafic-ultramafic rocks with disseminated nickel-copper sulfide mineralization. The mining depth is determined by the base stratification depth and will be (by the maximum depth of the wall) from 20–25 to 150–200 m for different areas. A total of 121 thousand tonnes (C1 category) and 184 thousand tonnes (C2 category) of nickel reserves have been reported at the deposit.

Assessment of the tectonic structure and modern geodynamics of the Kun-Manyo field, which influence the choice of the stripping pattern and the most rational parameters of the underground development system, was carried out using a set of methods, including geostructural analysis and geodynamic zoning of the field. Geodynamic zoning of the field area with emphasizing of active faults and determining the nature of deformation of block rock massifs was carried out using morphometric analysis and Earth remote sensing (ERS) [7, 8]. The SRTM30 and GTOPO90 digital elevation models (DEMs) were visualized in QGIS software and presented with elevation wash images in WGS84 geographic projection [9, 10]. The DEM interpretation is based on the concept of tectonic flows [11–13], adapted for the East Asian region [9].

3. Results and Discussion
At the current stage of exploration, the Kun-Manyo nickel-copper-sulfide deposit is the only prospective property of Stanovaya copper-nickel province for industrial exploitation. According to Stepanov V.A.’s conclusions [14], platinum-copper-nickel potential of Northeast Russia can be significantly increased by further exploration of the North Baikal and Stanovaya provinces, which are located near the southern margin of the North Asian craton (figure 1).

Stanovaya province stretches along the southeastern margin of the mentioned craton for 1300 km, with a width of about 250–300 km. According to gravimetric data at depth, it corresponds to a commensurate giant stratified basite-hyperbasite abyssalite, manifested by a zonal maximum of the gravity field, with a pronounced centroclinal occurrence in the west and east [15]. The Kun-Manyo deposit is located on the eastern margin of abyssalite, in the marginal southwestern part of the Kun-Manyo Early Archean gabbro-anorthosite massif. The Stanovaya province covers the southeastern part of the Aldan Shield and coincides in direction with the transition zone of active interaction of the North Asian craton with the Amur lithospheric plate [16]. The current activity of the zone is expressed by the presence of the Olekmo-Stanovaya seismotectonic zone extending along the southern boundary of the craton. Due to variations in the thickness of the transition zone, where the modern northern boundary of the Amur tectonic plate is located, researchers’ opinions on its position differ significantly. The authors of the paper believe that it is most important for geomechanical studies that this boundary runs along seismically active faults. The copper-nickel mineralization of the described province belongs to the sulfide-platinum-copper-nickel formation and is genetically related to different-age basite-ultrabasite complexes – from Late Archean to Early Cretaceous ones.
Figure 1. Geotectonic position of Pt–Cu–Ni provinces of Eastern Russia (according to [14]).

The Early Proterozoic Kun-Manyo gabbro-norite-pyroxenite-peridotite complex is the most productive within the Kurumkan ore field, which includes the Kun-Manyo deposit [17]. Nickel-bearing intrusions are dominated by hornblende, olivine, and plagioclase websterites. These are small bodies of strata and plate shape with thickness from the first meters to 63 m. They can be traced in the northwest direction at a distance of up to 40 km. Gentle bedding and dip to the northeast and north predominate.

Structurally, rocks of the Kunmaniev Complex are confined to the junction area of the Dzhagdinsky and Tukskaya blocks of the Aldan Shield crystalline basement. Numerous ancient tectonic faults have been repeatedly activated, creating complex structures such as flake thrusts. Ore-bearing intrusions are located in such structures in tiers. As a rule, they are sharply discordant towards the folded structures of the crystalline basement [14].

Thus, the geodynamic setting of the ore field, including the Kun-Manyo deposit, determined by its location relative to large structural elements, is quite complex.

For the geomechanical analysis of the data set, the features of the regional stress field, which is being formed in the upper part of the Earth’s crust section in the recent period, are of the greatest interest. It is here that modern natural geodynamic processes take place, with which the mining engineering system, being formed for the mining of sub-ore reserves at the Maly Kurumkan deposit site, will interact. In this regard, the geometry of the rock massif zoning scheme by stability categories should, if possible, be similar to the current structural-tectonic situation in the territory and not contain elements of past geological epochs, which were not renewed in the new time. It is known that the best indicator of neotectonic processes in Eastern Russia is the relief. The mentioned natural surface better reflects modern deformations of the Earth’s crust. It is also important that it is uniformly studied by both terrestrial instrumental and remote methods, and there are well-developed and tested methods for the morphotectonic analysis of the relief (including the method of studying the upper crust.
stratification based on the analysis of 3D models of the relief). To date, numerous materials have been published [18–21, etc.], which indicate that the region’s lithosphere is under stress. However, it is possible to differentiate this territory by the degree of change in the internal state of the upper part of the Earth’s crust only by additional identification of different-scale zones (or regions) of “extension – compression” based on a set of indirect features.

The data from a network of GPS observation sites on the territory of the Russian part of the Amur tectonic plate [22–26], as well as the results of calculations of the vector field of current velocities of displacements carried out within the framework of ITRF-2000 coordinate system, have allowed us to determine the general nature and average velocities (about 30 mm/yr) of the upper crustal masses movements of the territory, the differential movements of local blocks in specific parts thereof, as well as the general direction of contemporary mass drift, which for the whole area is stable (to the southeast) and is used as an indicator to determine the regional direction of maximum contemporary compression of the upper parts of the Earth’s crust.

The geomechanical information model of the Amur lithospheric plate, developed on the basis of an integrated analysis of multi-scale data, including the results of morphometric analysis, numerical modeling and instrumental measurements of the stress state, was used to predict the state of the upper part of the Earth’s crust within the study area [27]. According to the geodynamic position, the Kun-Manyo deposit is located within a local area of intense modern compression with a predicted level of 50 MPa or more at depths of 500–700 m. Only Antaeus, one of the most rock-bump hazardous deposits of the territory, characterized, in addition, by changes in the direction of the main horizontal compression with depth and severity of other signs of the high-stress state of the massif of host rocks, is located in such a situation. Judging by the materials of geomechanical study of the Antaeus deposit [5], which is located in a similar zone, the ratio of the main stresses in the Kun-Manyo field is expected to be as follows – \( \sigma_1: \sigma_2: \sigma_3 = 2.5:1.4:1.0 \).

In addition, the field is localized within the northern end of a major Border Fault, which divides the Amur Plate into first-order blocks and is clearly expressed by the regional gravity field gradient. This fault controls the morphology of the largest Meso-Cenozoic depression. The orientation of the long axis of the Kun-Manyo ore field is orthogonal to the direction of the fault.

The study of the regional neotectonic features of the area including the Kun-Manyo field revealed that the relative elevations are significant (700–1000 m), which in turn may lead to the appearance of an uncompensated horizontal component of geostatic stress. The lineaments of the relief have considerable variation in direction, although, a south-eastern extension can be distinguished among the

**Figure 2.** Morphotectonic scheme of Kun-Manyo ore district and adjacent areas based on DEM visualized in the form of a color relief map.
longest, having an average azimuth of approximately 119°. Figure 2 shows that a very high degree of topographic dissection can be observed over most of the area. All this testifies to a frequent change in the direction of lateral movement of the upper crust layers, complicated by chaotic movements of tectonic flakes relative to each other.

Hard rock massifs are identified in the considered area and beyond, which are confidently identified by the smoothed landforms of low dissection. The massif located in the northern part of the plate has a complex composition of rocks: granitoids, gneisses, diafluorites, tuffs, and metagabbro.

All considered similar objects outside the area are, in one way or another, associated with granites, i.e. are inside the contour of the outcrop massif, or entirely contain it. A small massif of Proterozoic granites, or rather its eroded part, is also located inside the northern rigid block contour. The thrust front is mapped along its southern contact.

Based on the interpretation, two main cycles of horizontal displacements of the tectonic flow in the considered area can be distinguished. The first cycle is a southward submeridional drift. This resulted in the formation of sublatitudinal and submeridional lineaments. In some places, they are disturbed by diagonal structures formed as a result of the second cycle of displacements in the southeasterly direction, which continues to the present day. As already mentioned, everything is compounded by the chaotic oscillation of separate tectonic elements.

4. Conclusion
The ore field of Kun-Manyo deposit is located in a complex geodynamic environment, which is determined by its location at the junction of actively interacting large tectonic elements of the Euro-Asian tectonic plate: North Asian craton and the Amur plate (which began to form as an independent tectonic element in the Jurassic), as well as within the modern Olekmo-Stanovoi seismic zone. The geodynamic position of the Kun-Manyo deposit determines its association with the local area of intense modern compression with a predicted intensity of more than 50 MPa.

Based on the results of morphometric analysis of the relief according to satellite geodesy data, it has been found that the field area, in general, is characterized by a compression regime and the vector of the modern main horizontal compression at the site is directed to the SE. The direction of flow and horizontal tectonic stresses determined from the relief comfortably coincides with GPS data [28]. Since the mineralization is concentrated in a mountain range oriented towards modern movement, if the deposit is developed by underground mining, a deviation of the main direction of the horizontal compression vector to the south can be expected at lower elevations.

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