Mapping of folds and faults in metamorphic complexes of the Central Aldan and Prikolyma terranes using geophysical data

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Abstract. The study of the structure of the Precambrian crystalline complexes raised and exposed along the margins of the North Asian craton allows us to characterize the geological features of various stages of the evolution of the lithosphere. Based on these data identification of the promising metallogenic zones and local potentially ore-bearing objects can also be achieved. The goal of the performed research was to create objective models of the areas characterized by the presence of mineral deposits to identify characteristics and promising structures. Using modern geoinformation systems, the maps of the high gradient zones of the local components of geophysical fields have been created. These maps reflect the boundaries of geological complexes with contrasting physical properties. For clarity, the geophysical background was removed from the maps, and only the zones of high gradients of various geophysical fields were left. A combination of maps was performed and it was found that high-gradient zones of the various geophysical fields complement each other along the strike. Based on the obtained geophysical schemes, geological maps and field observations of geological structures, already known and new folds and faults have been deciphered. As a result, models of folds and faults that control the location of mineral resources were created. Models allow finding the common features and evaluating the minerals prospects of areas. In the framing of the Upper-Timpton dome of the Central-Aldan superterrane and in the Shamanikhin fault zone of the Prikolyma terrane, there are many high-gradient zones of the various geophysical fields observed. New ore objects can be expected to be discovered in these areas.

1. Introduction

The models of regional ore bearing objects are generalized patterns of geological blocks with commercial ore content. To create these models, the initial (observed, mapped) sets of geological features and analysis of their occurrence conditions are needed [1]. Predictive metallogenic constructions are usually based on forecasting principles [2], such as: 1) the principle of potential ore content – the composition and structure of geological divisions determine their potential ore content; 2) the principle of contrast – the potential ore content of geological divisions is due to the degree of their differentiation in composition and structure; 3) the principle of similarity - similar associations of geological divisions of integral structures are characterized by similar complexes of mineral resources and the scale of their occurrence; 4) the principle of successive approximation - implies the study of objects from larger to smaller. The method used in this paper is based on the principle of contrast used by many geologists to decipher geological structures and predict deposits [3-5]. To implement this principle, the maps of the high gradient zones of the local components of geophysical fields have been created. These maps reflect the boundaries of geological complexes with contrasting physical...
properties. To study the petrographic composition of rocks and to link geological and geophysical data field works was carried out. Fold and fault structures were interpreted.

2. The geological characteristics of the studied areas

Areas of the performed research are located in the Precambrian terranes, which were uplifted near the margins of the North-Asian craton (figure 1A).

The first area belongs to the Central Aldan granulite-orthogneiss terrane, composed of the Paleoproterozoic granulite complexes with relics of the Archean rocks [6]. Dome tectonics in this terrane is widely spread (figure 1B). The folding structures belong to the Precambrian [6], and the faults belong to the Precambrian and Mesozoic stages of evolution [5]. In the folded metamorphic complexes of the terrane and its surroundings, the predecessors identified several metallogenic zones. The formation of zones is related to the amalgamation of the Early Precambrian terranes into a single large continental block. Amalgamation involved the formation of wide and extended tectonic zones separating the Aldan-Stanovoy shield terranes, metamorphism of granulite and amphibolite facies within the terranes, and sub-alkaline granitoid magmatism, which is widely occurred both within the terranes and in the tectonic zones. The age of processes associated with the amalgamation of terranes is estimated at 2100-1900 Ma [7]. Dyos-Leglier and Timpton metallogenic zones with magnesian skarns and deposits of iron and phlogopite are identified on the territory of the terrane. Zones are located in an interdome synformal structure (figure 1B). The Paleoproterozoic platinum [8] and gold [9] mineralization, and few finds of diamond [10, 11] are known here. The Amga and Tyrkanda zones of melange, framing the terrane, are characterized by ore occurrences of gold in blastomylonites and in the quartz veins [6]. The ancient structures of the terrane were repeatedly activated in PR3, PZ and MZ-KZ. The largest gold reserves of the Aldan-Stanovoy shield are concentrated in the Mesozoic faults of the terrane [13]. Ore regions inherited the ancient heterogeneities [12]. On the territory of the Central-Aldan terrane, area of the upper Timpton granite-gneiss dome was studied (figure 1B) which framing contains disharmonic and boudinaged folds with the metabasites, iron skarns and gold (figure 2B).

Both Precambrian and Mesozoic faults and folds are observed on the territory of the second object – the Prikolyma terrane [14]. The studied area is composed of the Paleoproterozoic metamorphic complexes of amphibolite and greenschist facies overlain by various sedimentary rocks and broken numerous thrusts [6] (figure 1C). Predecessors identified the Erikit metallogenic zone (Chersko-Garmychan and Yasachnensk zone according to V.I. Shpikerman [15]) which spatially coincides with the Late Jurassic Uyandino-Yasachnensk volcanic belt, which is a magmatic arc conjugated with the subduction zone, located on the margin of the Kolyma-Omolon superterrane (figure 1A). In the course of the research, data were processed and geological structures were studied on the area adjacent to the extend Shamanikhin North-East fault of the Prikolyma terrane (figure 1C, 2A). A series of thrusts with gold mineralization is observed along this regional fault (figure 2A).
**Figure 1A.** Schematic geological map of the North-Asian craton [16] and terranes near the margin [6]: 1 – craton; 2 – margins; 3 – shields; 4 – superterranes with fragments of cratons; 5 – collage of accreted terranes; 6 – Mesozoic fault system; 7-9 – metallogenic zones: 7 – Precambrian; 8 – Mesozoic; 9 – combined.

**Figure 1B.** Schematic geological map of the Central-Aldan superterrane. Terranes: ANM– Nimnyr, AST– Sutam: 1 – plagiogneisses, rarely shales with interlayers of phlogopite-diopside rocks and calciphyres (with the skarn deposits of iron and phlogopite); 2 – quartzites and high-alumina gneisses with lenses of clay and diopside quartzites, refractory quartzites, granite-gneisses; 3 – garnet-biotite gneisses and plagiogneisses, ferruginous quartzites, plagiogneisses ±hypersthenes ±biotite ±diopside.
±amphibole; 4 – the domes composed of granite-gneisses, charnockite-gneisses, enderbite-gneisses with lenses by two-pyroxene schists (schists contain deposits of gold); 5 – tectonic zones (gold in blastomylonites and quartz veins); 6 – strike-slip faults; 7 – reverse faults and thrusts (SM–Seimsk); 8 – faults of unidentified kinematics; 9 – Mesozoic and gold-bearing faults according to V.G. Vetluzhskikh; 10 – cover of the Siberian platform.

**Figure 1C.** Schematic geological map of the Prikolyma terrane: SH – Shamanikhin block.

Conventional signs: 1 – Proterozoic metamorphic complex; 2 – Middle-Late-Riphean terrigenous-carbonate shelf (passive margin) complex; 3 – Vendian-Cambrian terrigenous-carbonate shelf complex; 4 – Ordovician carbonate shelf complex; 5 – Early Devonian-Middle Carboniferous terrigenous-carbonate shelf complex; 6 – Late Carboniferous terrigenous-volcanogenic rift complex; 7 – Omulevka block of the Omulevka terrane; 8 – Kular-Nera terrane (shale belt); 9-10 – post-amalgamation formations (conjugated with gold-bearing complexes): 9 – Late Jurassic volcanogenic-sedimentary formations Uyandino-Yasachensk magmatic arc; 10 – Cretaceous terrigenous; 11 – reverse faults and thrusts (YR–Yarkhondon).

![Figure 1C](image)

**Figure 2A.** Geological scheme of the Sokhatinoe gold-polymetallic deposit [6]: 1 – Early Proterozoic rocks; 2 – thrust zone; 3 – strike-slip faults; 4 – ore bodies.

**Figure 2B.** Geological scheme of the Evota gold-bearing region (in light of geophysical data) [17]. Conventional signs: 1 – iron skarns (deposits of iron: B-Bolotnoe, T-Taezhnoe, N-Nikak, Y-Utominelnoe, M-Magnetitovoe, TZ-Tinskoe and Zarechenskoe, P-Pionerskoe, K-Komsomolskoe, D-Desovskoe, L-Lesnoy place, S-Savgelskoe, Y-Yuzhnnoe, Nw-Nerichi); 2 – primary faults; 3 – secondary faults; 4 – metabasites; 5 – deposits and occurrences of gold.

![Figure 2B](image)
3. Research methods

In potential physical fields, which include gravity and magnetic fields, the principle of superposition applies [18]. This means that the observed field of gravity is the result of the interaction of several geological objects that differ from each other in physical data. Some of these objects have a regional character, and their action can be traced over large areas, while others have a local character and are observed in limited areas. When analyzing and interpreting gravity and magnetic fields, there are great difficulties related to the need to find the so-called "pure anomalies". These tasks can be solved by transforming the geophysical fields into local and regional components. The transformation used to solve practical problems consists of the following sequential procedures [19]:

1. Select a sliding window whose shape and size are determined by the task being solved;
2. Within the sliding window, nodes are specified, and each node is assigned a certain number, which is called a weighting factor;
3. The sliding window is superimposed on any part of the studied area, and the nodes are above the points where the anomalous field is measured;
4. The sum of the products of the weight coefficients in the nodes of the sliding window on the values of the anomalous field at the points of the section that fall under these nodes is calculated;
5. The calculated number is considered to relate to one of the points in the section, usually located below the center of the sliding window;
6. By placing a sliding window in different parts of the area and calculating each time the corresponding sum of the products of the weighting factors on the field values, the interpreter obtains values at a number of points that together describe a new function in the studied area, called a transform;
7. Point-by-point subtraction of the transform from the observed field leads to the determination of a residual field or residual anomalies in this area.

As a result, the observed field is divided into two components: the transform - regional background and the residual field - local anomalies.

Using modern geoinformation systems, the entire process of processing and transformation of geophysical fields can be accelerated, and most importantly, the so-called "human factor" can be eliminated, which, with the right approach, increases the objectivity of the results obtained. In ESRI ArcGIS software [20], the sliding window method is performed using the Focal statistics tool, which performs a neighborhood operation that calculates a new surface, where the value for each new cell is a function of all input values that are in the specified neighborhood. The function performed above the input data is the calculation of the average value of points located in a given neighborhood. Thus, the operation for calculating the transform - regional background is performed. Later to calculate the local component of the geophysical field, transform constructed using the focal statistics tool is subtracted from the basic data and the output is a surface with residual anomalies or a local component. This operation is performed using the Subtract (Minus) tool. Data from the magnetic (scale 1:500,000) and gravity field (scale 1:500,000) schemes were used as source materials. To get the gradient of the change in the geophysical field, a special mathematical tool is used to calculate the rate of maximum change in the vertical value of the vector between neighboring points. The calculation algorithm is as follows: for each point on the map, a plane of vertical values is calculated from the neighborhood with the specified size. The gradient value of this plane is calculated using the averaged maximum method.

4. The results of the research

As a result of processing of geophysical data, maps of gradients of geophysical fields on the characterized areas are constructed. For clarity, the geophysical background was removed from the maps, and only zones of high gradients of various geophysical fields are left. A combination of maps was performed and it was found that high-gradient zones complement each other along the strike. The
construction and combination of gradients of various geophysical fields among the outcrops of the Precambrian rocks showed that they emphasize the same elements of the structure of geological complexes. Contours of the folds or fault zones can be those elements. Based on the obtained geophysical schemes, geological maps and field observations of geological structures, already known and new folds and faults have been deciphered (figure 3).

**Figure 3.** Gradients of geophysical fields calculated from geophysical data from the archives of JSC Yakutskgeologiya (left) and interpretation (right) for the areas of the Central-Aldan terrane (A) and the Prikolyma terrane (B) indicated in figure 1A.
In letters on the figure 3A: Ore regions: К – Kuranakh gold-bearing, Е – Elkon gold-uranium; L – Lebedin gold-bearing, Ev – Evota gold-bearing. Faults: SP – Sap-Kuel, H – Khatyrstyr, Y – Yakokut, T – Tommot, D –Dzhekondin, IN–Idzheko-Nuyam.

In letters on the figure 3B: a – anticlinal folds, sa – plunging folds, S – Sokhatinoe deposit, V – Vostochnoe ore occurrence, Y – Yuzhnoe ore occurrence.

On the territory of the Central-Aldan terrane, ore-bearing ancient folds and faults are oriented along the framing of the Upper-Timpton dome (folds, Sap-Kuel and Idzheko-Nuyamsk faults, figure 3A). The Mesozoic fault system (transpressional faults, figure 1A) intersects the core of the dome and is represented by subparallel faults of the north-northeast strike with rarer northeast-striking faults (figure 3A). It is observed that young faults inherit elements of the structure of ancient folded structures. It should be noted that a large area of the Central-Aldan superterrane was not covered by field observations. Additional work is needed to verify the decryption results.

On the territory of the Prikolyma terrane, the ore-bearing zone is traced in the form of semi-closed contours of gradients of geophysical fields (figure 3B). In comparison with the geological data, the gradients probably reflect the ramp anticlines and plunging folds of the thrust zone. In addition to the folds with the north-east strike of elements, the presence of the north-west striking complicating folds is typical. Near the closure of the folds, the faults are often deciphered (figure 3B). The thrusts are oriented subparallel to the Shamanikhin fault zone (figure 1C, 2A) and are probably associated with the Mesozoic compression from the north-west [14]. The most promising areas of thrusts are represented by zones of folding and decollement near the axial planes of the folds (figure 3B).

5. Discussion

The nature of folding in the Precambrian complexes on the territory of the Prikolyma terrane is similar to the contortion folding typical of ore deposits (figure 4A) [21, 22]. The character of folding of the Central-Aldan superterrane is similar to disharmonic folds of the Archean greenstone belts (figure 4B) which gold content is usually associated with quartz veins in narrow zones of ductile-brittle strike-slip faults [23]. Ductile shears in the Central Aldan terrane are typical. In both cases, ore-bearing structures are well reflected in the gradients of geophysical fields, which can be used as a prospecting indicator for determining the strike of structures or an evaluation criterion for determining the number of tectonic structures (figure 3). Despite the structural features, granite-dome areas and zones of linear folding have common patterns in the location of ore objects: ore bodies are confined to the complicating folds and shears.
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Figure 4. (А) A generalized schematic section showing different folding styles in the rocks composing the Hill End anticline (J. Uindh). Mineralization (hatching) is confined to the thin stratified rocks [21]. (B) Geological diagram of a fragment of the Coolgardie gold field (according to Knight & Batten, 1993) framing a dome of Calooli monzogranites [23]. Metagabbro and metadolerites compose the cores of the anticlines. The faults in both figures are shown in bold lines.

6. Conclusions
In metamorphic complexes uplifted near the borders of the North-Asian craton, folds are favorable for the location of metal deposits. Such folds are evident in the gradients of geophysical fields and are widely distributed in the framing of the Upper-Timpton dome of the Central-Aldan superterrane and the Shamanikhin fault zone of the Prikolyma terrane. New ore objects can be expected to be discovered in these areas.

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