Analysis of Tectonic Ore-Controlling Factors Using of Geophysical Data on the Example of the Elkon Ore District (Aldan Shield, North-Asian Craton)

Evgeny Loskutov 1
1 Diamond and Precious Metal Geology Institute, Siberian Branch of Russian Academy of Science, 39, prosp. Lenina, Yakutsk, 677000, Russia
loskutov@diamond.ysn.ru

Abstract. The author investigated the gravitational and the magnetically fields of the Elkon ore unit. The gold-uranium deposits of the Elkon ore district this is unique of his scale and matching with biggest ore units of world. The study of the regularities of forms, location and direction of extension of tectonic ore-controlling structures in magnetic and gravitational fields, the study of their transformation using Surfer 8, Koscad 3D and ArcGIS. As a result, the author obtained get two-dimensional autocorrelation functions, local and regional components of geophysical fields, and their gradients. The most informative transformations of fields are regional component of the magnetically field and local component of the gravitational field by results statistical analysis to study the tectonic structure like Elkon ore unit.

1. Introduction
The analysis of ore-controlling factors is a complex of techniques and methods at middle and large-scale metallogenic studies, which end with drafting of a special metallogenic and predictionary maps [1]. Metallogenic studies are carried out in the following sequence.: 1) identification of type of ore district; 2) determination the most important ore-controlling factors; 3) matching of the most important ore-controlling factors using spatial-genetic relationships with them mineralization of ore, deposits and ore occurrences; 4) drafting of special metallogenic map; 5) drafting the diagram of age location of ore occurrence; 6) a metallogenic zoning; 7) drafting of a special predictionary map, where combines all the favorable ore-controlling factors. This scientific work completes the second stage of metallogenic investigations, and it is here that the most important tectonic ore-controlling factors are analyzed using geophysical data (magnetic and gravitational fields). To implement this analysis, the author of the work applied the method of transforming geophysical fields in order to identify the most informative transformants of potential fields [2], which will subsequently allow us to study the structure of similar ore clusters and regions.

2. Geological characteristics of the area
The gold-uranium deposits of the Elkon ore district localization in deep-seated regional faults of the early Proterozoic (?) age. The territory is confined to a horst-like of crystalline basement raising – the Elkon horst, whose location in the edge part of the Nymnyrsky granulite-orthogneiss terrane of the Central Aldan superterrane (Figure 1A). The magmatic activity of the Mesozoic age corresponding to the regime of the active continental margin is intensely manifested here. [3,4]. In the north, the territory is overlain by the thickness of the platform Vendian-Lower Paleozoic cover, and in the east it is limited.
by the Tyrkandinsky zone of tectonic melange. In the history of the geological development of the Elkon horst, a complex geodynamic evolution is traced and more than ten stages of tectonic-magmatic activity are identified. In the Archean – Early Proterozoic period, the territory was characterized by intense dislocations, which were accompanied by repeated injections of ultrabasic and acid magma. This period is characterized by at least twofold metamorphic transformations under the conditions of the granulite and amphibolite facies of metamorphism. In the Early Paleozoic, along the orthogonal fault system, the Sivaglinsky complex of dikes was introduced. The Mesozoic period of tectonic-magmatic activation was accompanied by the repeated introduction of large masses of magma, mainly alkaline composition. During the Mesozoic-Cenozoic geodynamic stage, modern block structures were formed, and in the neotectonics period, due to the predominance of the uplift amplitudes, the Elkon horst forms. The studied area belongs to the areas of tectonic-magmatic activation where gold ore and complex gold-uranium deposits are located in zones of alkali metasomatism, potassium chemistry.

The most important ore-controlling factor in the region’s structure is faults that are well manifested in the basement rocks and very weakly in the platform cover. Basically, they are subparallel to the fold axes, but have a steeper fall than the bedding of the rocks composing the territory. The length of the faults is up to several tens of kilometers, the width of zones from several meters to the first tens of meters. According to the laying time and development history, among them are distinguished: 1) Early Proterozoic, not experienced refurbishment; 2) Early Proterozoic, updated in the process of Mesozoic tectonic-magmatic activation; 3) the faults of Mesozoic age. Gold-uranium mineralization of the vein stockwork type is localized in the faults of the second, as well as the third group. In the faults of the second group, both Early Proterozoic and Mesozoic structural elements are always present.

3. Research methods
The regularities of the forms, location, and direction of the strike of ore-controlling tectonic structures in geophysical anomalies are studied by transforming geophysical fields in modern automated software products for processing the primary results - Surfer 8, Koscad 3D and ArcGIS. As source materials, data of magnetic and gravitational field schemes of a scale of 1: 500 000 were used (Utrobin and etc., 2000, 2002, 2004). The process of interpreting physical fields faces great difficulties associated with the identification of “pure anomalies”. Finding these anomalies in physical fields, which include gravitational and magnetic fields, is associated with the principle of superposition. This principle means that the observed differentiated physical fields are presented as a result of the interaction of many geological objects that differ in physical data. Some of these objects have a regional scale, and their influence on the physical field is expressed in large areas, some have a local scale, and their effect on the physical field is manifested in limited areas.

Finding “pure anomalies” in physical fields is carried out by the method of their transformation, and modern geographic information systems can accelerate the whole process, and most importantly, eliminate the so-called “human factor”, thereby approaching as much as possible the objectivity of the data obtained.

4. Reflection of ore-controlling tectonic structures in a magnetic field
Using the Two-dimensional autocorrelation function (TDAF) method, a map is constructed on which two systems of linear magnetic anomalies (Figure 2A) of the northwestern and northwest-west strike are clearly distinguished, the orientation of which coincides with the linear disturbance systems of the ancient formation and updated in the Mesozoic tectono -magmatic activation, respectively. At the same time, a third system of north-eastern strike is noted, tracing other discontinuous violations.
Figure 1A. Tectonic diagram of the Aldan shield [3]. Legend: Figure: 1 – granite-greenstone terrains (WA – Weast-Aldan, BT – Batomgsky); 2 – granulite-orthogneiss terrains (NM – Nimyrsky, CG – Chogarsky); 3 – granulite-paragneiss terrains (AST – Sutamsky, Uch – Uchursky); 4 – Tonalite-trondhjemite-gneiss terrains (TN – Tyndinsky); 5 – Zones of tectonic mélange (am – Amga, kl – Kalar, tr – Tyrkandin); 6 – linking Early Proterozoic granites; 7 – Siberian platform cover; 8 – faults (dj – Dzheltulak, ts – Taksakandin).

Figure 1B. Tectonic diagram of the Elkon ore district. Legend: 1 – quaternary alluvium; 2 – Mesozoic subalkaline intrusions; 3 – lower Jurassic terrigenous complex; 4 – Vendian-Cambrian platform carbonate sequence; 5 – leitogranit and granite-migmatite formation (early proterozoic); 6-9 – archean rocks of crystal basement: 6 – ultrabasic-basic formation; 7 – charnockite formation; 8 – marble-slate, gneiss-slate and quartzite-gneiss formations; 9-10 – faults: 9 – regional fault of the early Proterozoic age (Dz – Dzhekondinskiy, K – Kurumkanskiy, Sh – Sohosoloohskiy, Ud – Udzhinskiy, F – Fedorovskiy, Em – Emeldzhaksiy, Yz – Yuzhnaya, Yk – Yukungrskiy, Yh – Juhtinskiy, Yk – Yakokutskiy); 10 – faults of second order; 11-12 – tectonites: 11 – blastomilolites; 12 – undivided tectonites; 13-14 – ore zones: 13 – Au-U zones (El – Elkonkan, Vl – Volodina zone, 511 – zone 511-516, 517 – zone 517, In – Interesnaya, N – Nadezhda, M – Magnitnaya, Md – Medvezh’ya, Sn – Snezhnaya, Nv – Nevskaya, Gl – Glavnaya, S – Severnaya, Y – Yuzhnaya, T – Taezhnaya, V – Vesennyaya, Mn – Mineevskaya); 14 – Au zones (R – Ryabinovaya, L – Lunnaya).
The direction of the strike of structures in the selected systems coincides with the orientation of the main ore-controlling disjunctive disturbances, which mainly have a northwestern strike (Figure 1B). At the same time, the TDAF graph of the magnetic field of the Elkon ore cluster does not show faults of northeast strike.

By the method of Nikitin A.A. et al. [12,13] carried out two-dimensional adaptive energy filtering of the initial field, local (Figure 2B) and regional (Figure 2C) components are distinguished. The diagram shows that the local and regional components of the magnetic field have a differentiated structure, while the overall pattern is represented by elongated, complex configuration linear anomalies from sub-latitudinal orientation in the southern part of the region to the north-western in the central one.

![Figure 2. Transformants of magnetic field. A – Two-dimensional autocorrelation function; B – local component; B – regional component; C – gradients of regional component (other key in figure 1).](image)

In the field of the regional component of the magnetic potential in the studied area, three systems of anomalies are contrastingly distinguished - the north-western orientation in the central part, which are associated with long-lived regional faults, isometric in the north-west, associated with Mesozoic alkaline magmatism, which is intensively developed here, and sub-latitudinal in the south. In the local component of the magnetic field, the described anomalies have a more differentiated structure (Figure 2D), but general patterns are observed in both cases.
The elongated linear anomalies in the central part of the area spatially coincide with the zones of discontinuous disturbances. Also, discontinuous disturbances are clearly recorded in a gradient field calculated from the regional component of the magnetic field (Figure 2D). Gradient values show areas with the most disturbed (permeable) zones. So, in the north-eastern part of the Elkon ore cluster, the Emeldzhak fault zone is manifested by elongated anomalies of high gradient value. The largest fractured fault zones (Yuzhny, Sokhloohsky, Yukungsky) are recorded on the magnetic field map in low gradient zones, which clearly repeat their linear anomalies. This magnetic field pattern is explained by the multi-stage hydrothermal processes that “healed” the zones of open fractures by leucocratic rocks.

5. Reflection of ore-controlling tectonic structures in a gravitational field

On the map of the anomalous gravity field of the Central Aldan granulite-gneiss region in the Bouger anomalies, the Elkon gold-uranium node is located on the eastern flank of the unique regional Yakokut gravity minimum - the regional anomaly of lowered gravity field intensity below 48 mGal (Figure 3A).

![Image of Figure 3](image-url)

**Figure 3.** Transformants of gravitation field. A – Regional map of gravitation filed (V-Ya – Verhne-Yakokut graben cavity; Elk – Elkon horst); B – Two-dimensional autocorrelation function; C – local component with fold axis: 1 – syncline folds (Elk – Elkonkanskaya; Bel – Beliberdinskaya; Del – Delindinskaya; Ker – Keribikanskaya; Yk – Yukungsky); 2 – anticline folds (VE – Verhneelkonkanskaya; Rd – Rederginskaya; Ku – Kurungskaya; Em – Emeldzakskaya; Vi – Verhneirelyahskaya)
Structurally, this regional anomaly of the gravity field reflects the location of the Upper Yakokut graben depression. Using the TDAF method, we plotted the gravitational field over the entire territory of the Elkon ore cluster (Figure 3B). The graph shows that all the main gravitational anomalies have a submeridional orientation.

A similar orientation of the gravitational anomalies of the region under consideration is explained by the fact that it is divided into two gravitational zones, each of which has its own structure and levels of the regional component of gravity — eastern and western. The western part of the gravitational region corresponds to the marginal part of the epicenter of the Mesozoic tectonomagmatic activation and the eastern flank of the Upper Yakokut graben depression. The negative gravitational field of the western part (up to -30 mGal) reflects the subsidence of the crystalline basement and a gradual increase in loose deposits and a carbonate platform cover.

The eastern gravitational region is characterized by high positive gravity (up to 10 mGal). Where local areas with lower and higher values of the gravity field, which reflect the general block structure of the Elkon ore cluster, are also highlighted.

In the local component of the gravitational field, the axes of plicative tectonic structures are clearly traced (Figure 3C). The main axes of anticlines coincide with the distribution of local gravitational anomalies, the axes of synclinal structures basically coincide with negative local gravitational anomalies. The general orientation of folded tectonic structures, as well as fault zones, has a northeastern strike. Such a spatial orientation of the strike of the main tectonic structures allowed us to conclude that the formation of dislocations of the study area occurred under the influence of the same dynamic processes.

6. Conclusions

According to the results of the TDAF calculation of the magnetic field, two systems of linear anomalies of the northwest and northwest-west strike have been identified, the orientation of which coincides with the systems of linear disturbances of the ancient formation and updated into Mesozoic tectono-magmatic activation, respectively. Вместе с тем отмечается третья система северо-восточного простирания, трассирующая иные разрывные нарушения.

To study the second-order gravitational anomalies, the TDAF of their local component was calculated. As a result of the procedure, submeridional and northwestern strike of geological structures were revealed. It has been established that the northwestern strike is characteristic of plicative and disjunctive tectonic disturbances, submeridional - to the junction of the Elkonsky horst anticlinorium and the Upper Yakokut graben.

Using TDAF geopotential anomalies allows at the initial stage of processing geophysical information to outline the most effective transformations of geophysical fields to study the structure of the studied objects and clarify the patterns of location of mineral deposits.

Based on the calculated TDAF, adaptive energy filtering of gravitational and magnetic potentials was performed to distinguish their regional and local components.

The regional component of the magnetic field is represented by elongated linear anomalies of sublatitudinal orientation in the southern part of the region and northeastern in the central. In the north-west of the territory, a large isometric anomaly of a negative sign is manifested spatially coinciding with the massifs of Mesozoic tectono-magmatic activation. General discontinuous violations of the northeastern orientation are recorded by both positive and negative magnetic anomalies.
On the diagram of the local component of the gravitational field, the axes of plicative structures are clearly traced. It is characteristic that the axes of anticlines and synclines correlate with positive and negative gravitational anomalies, respectively.

Acknowledgment
The paper was designed according to the Diamond and Precious Metal Geology Institute scientific research project № 0381-2016-0003.

References
[1] Russian Metallogenic Dictionary [Text]: scientific publication / ed. I. A. Nezhensky [et al.]. - St. Petersburg: VSEGEI Publishing House, 2003. - 320 p.
[2] Loskutov E.E., Adarov T.D. Possibilities of the two-dimensional autocorrelation function of geophysical fields in the study of tectonic structure (using the example of the Elkon ore cluster) // Geology and Mineral Resources of the North-East of Russia: Materials of the All-Russian Scientific and Practical Conference, March 31 - April 2, 2015./ Otv . ed. A.Ya. Biller. - Yakutsk: NEFU Publishing House, 2015. - 16-18 p.
[3] Tectonics, geodynamics and metallogeny of the territory of the Republic of Sakha (Yakutia) / Ed. L.M. Parfenova, M.I. Kuzmina. M., MAIK "Science / Interperiodics", 2001, 571 pp.
[4] Goroshko M.V., Malyshev Yu.F., Kirillov V.E. Uranium metallogeny in the Russian Far East; [resp. ed. N.P. Romanovsky]; Institute of Tectonics and Geophysics Yu.A. Kosygina FEB RAS. - M. : Nauka, 2006 - 372 p.
[5] Zhizhin V.I., Loskutov E.E. Elkon suture zone, sector of large magmatetectogen or horst // Science and Education 2013. No 1 (69). 54-61 p.
[6] Boytsov V.E., Pilipenko G.N., Solodov N.A. Deposits of noble, radioactive and rare metals / Ed. L.V. Hovhannisyan. - M.: NIA-NATURE, 1999. - 220 p.
[7] Krupennikov V.A. High-temperature uranium-bearing potassium metasomatites (microclinites) in pegmatoid granites and Precambrian migmatites - In: Metasomatism and ore formation. L., ed. VSEGEI, 1967, 58-60 p.
[8] Franz J. Dahlkamp. Uranium Deposits of the World. Asia. Springer. 2009.
[9] Krupennikov V.A., Kashpor A.A., Likhomanov A.G. Features of localization of uranium mineralization in large faults of the crystalline basement. - In: Geology and questions of the genesis of endogenous uranium deposits. M., "Nauka", 1968, p. 15-28.
[10] Loskutov E., Kravchenko A., Ivanov A., Zhuravlev A. Geological and geophysical back-ground of gold-rare metal minerali-zation of the Tyrganid ore region (Aldan Shield, North-Asian craton)/ 19th International Multidiscipli-nary Scientific GeoConference SGEM 2019. Albena, Bulgaria. P. 221-229
[11] Loskutov E.E., Kravchenko A.A., Zhuravlev A.I., Ivanov A.I. Interpretation of geophysical fields using the ArcGIS geoinformation system // Geology and Mineral Resources of the North-East of Russia: Materials of the All-Russian Scientific and Practical Conference, Yakutsk - 2018. Volume 1. 91-95 p.
[12] Nikitin A.A., Petrov A.V., Zinovkin S.V. Development of statistical techniques for processing and interpreting geophysical fields in computer technology COSCAD 3D // Izv. universities. Geology and exploration, 2007. No. 6. 68 – 73 p.
[13] Nikitin A.A. Statistical methods for isolating geophysical anomalies. M., Nedra, 1979. 280 p.