Neotectonics and geodynamics of the Streltsovsky ore region
according to the analysis of digital elevation models

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Abstract In the case of underground mining of mineral deposits under difficult mining and
geological conditions and at great depths, one of the most urgent problems is the prevention of
dangerous geodynamic events. The use of digital elevation models significantly expands the
possibilities of preliminary assessment of the potential hazard of their manifestation. This
article discusses the results of an assessment of the neotectonics and geodynamics of the
Streltsovsky ore region carried out using digital elevation models. The interpretation of the
obtained data is based on the concept of lateral tectonic flows adapted for the Far Eastern
region of Russia. Digital elevation models based on the GTOPO30 made it possible to identify
and evaluate the drift direction of three tectonic flows in the region. The direction determined
by the relief coincides satisfactorily with the GPS direction.

1. Introduction
In the case of the mineral deposits underground mining under difficult mining and geological
conditions and at great depths, one of the most difficult problems is the prevention of such
dangerous geodynamic events as rockburst and mining-induced earthquakes. Assessment of these
risks and hazard prediction should be carried out at all stages of deposit development, starting
from the earliest.

The modern relief of the Earth's surface is determined by a compromise of the oppositely
directed impact of endogenous and exogenous processes on a given territory at a given moment of
geological time [1]. It contains, in a hidden form, information about neotectonic, geodynamic
phenomena and the stress-strain state of rock mass in the study area. Therefore, the study of relief
forms and their distribution over the area is an urgent task. The purpose of the research is to
identify the neotectonics and geodynamics of the Streltsovsky ore region based on the analysis of
digital elevation models.

2. Research method
Geodynamic zoning of ore areas is carried out at the initial stage of deposit development using
lineament and morphostructural analysis of the Earth's surface from satellite images and
topographic maps. With the development of mining operations, the amount of information about
the rock mass increases significantly and the created models of geodynamic zoning are refined
and supplemented.
In the Mining Institute of the FEB RAS geodynamic zoning of ore areas was supplemented and modified through the use of digital elevation models (DEM), which are based on elevation matrices. DEM is a data set for various studies that include morphometric, neotectonic, hydrological, etc. studies [2]. The GIS platform is ideally suited for morphometric analysis because of its capabilities in processing and quantifying topographic data [3].

The main sources of information for digital terrain modeling are large-scale topographic maps, materials of field instrumental surveys, as well as data from remote sensing of the Earth (RSE). Each of the data sources has its advantages and disadvantages, but in general, it should be noted the tendency of the growing role of RSE data in the analysis of the relief of a particular territory.

The use of GIS technologies and RSE data makes it possible to significantly simplify not only obtaining quantitative relief data, but also to conduct modeling on them. In many GIS software products known today, there are methods for constructing DEM, in addition, global DEM have been developed, such as ASTER and SRTM, which are freely available on the Internet. A number of studies conducted by Farr [4] has shown that the digital flight altitude of the SRTM shuttle radar topography is much better than that of ASTER, provided that relatively accurate data is needed to perform morphometric analysis. SRTM data is recommended because of their high vertical and horizontal accuracy [5]. The most accurate representation of the relief allows you to reduce risks when solving various tasks, to develop measures for the safe use of land. The DEM is created on the basis of digital data from the air and gives complete information about the coordinates of points on the terrain, elevation marks, water edges, etc. in triangulation or matrix form.

To conduct research at the Streltsovsky ore field, the publicly available SRTM30 (GTOPO30) matrices were loaded from the NASA portal [6] in increments of 30'' (~1 km) and SRTM03, respectively 3'' (~100 m) [7]. The advantage of this approach is that the work is carried out with a "clean" relief, without the influence of details in the form of landscape features, infrastructure facilities, especially linear – communication routes, energy lines, and, also, it becomes possible to visualize and interpret the DEM in different versions [8, 9]. When using color, another visual element is added to visually display the elevation of the relief. The use of an anaglyphic map with the help of special glasses allows you to work with a stereo image.

During the research of the Streltsovsky ore field, a methodical technique was applied using the latter option, but it is unsuitable for the presentation of reporting and illustrative graphics. Therefore, the final thematic maps and plans have, as a basis, an image either in shades of gray or color.

The interpretation of the obtained data is based on the concept of lateral tectonic flows adapted for the Far Eastern region of Russia [10–12]. According to this concept, in the upper part of the lithosphere, stratification occurs into separate tectonic layers that move in a horizontal direction. Due to the fact that the horizontal dimensions of the layers are many times larger than the vertical ones (capacities), they are split into separate scales, which forms ensembles. As a result, a peculiar wave pattern is formed, consisting of structures of crowding and pulling apart, which appear in relief in the form of alternating mountain ridges – intermountain depressions, elongated parallel to each other. The extension of these structures is almost perpendicular to the direction of drift of the tectonic flow. Often the stream is broken by stratiform faults according to the direction of movement of the plate blocks limited by them, which are expressed in relief in the form of canyon-like valleys, dissecting both ridges and intermountain depressions.

3. Results and discussions

The GTOPO30-based DEM made it possible to identify and estimate the drift direction of three tectonic flows in the region shown in figure 1. The direction determined by the relief satisfactorily coincides with the GPS direction (see figure 2) [13, 14].
Tectonic flows: 1 – Baikal; 2 – Amur; 3 – Sikhote-Alin; 4 – contours of rigid flows; 5 – directions of flow drift. The basis is a shaded relief map built according to the DEM using the GTOPO30 matrix.

Figure 1. Map tectonic flows and rigid arrays in the folded belts of the Far Eastern region of Russia.

Figure 2. Map modern horizontal velocities according to GPS data in the global reference coordinate system ITRF 2008 according to [13].
The analysis of the DEM made it possible to note one previously unknown natural phenomenon, which probably sheds light upon the origin of the abnormal stress-strain state of mountain massifs, provoking their tendency to dangerous geodynamic events during the development of deposits. Within the mentioned tectonic flows, accompanied by a high degree of dissection of the relief, plateaus of various shapes are observed, where this dissection is much lower. Such structures are confidently registered by anaglyphic relief maps, maps with shadow washing in the color version of the elevation horizontal map. They usually have forms close to isometric, often accompanied by a decrease in the density of small-focus earthquakes within their limits.

It is logical to represent such objects as rigid mountain massifs, lowly destructured by discontinuous disturbances, drifting in streams. Their low disturbance indicates a rare discharge of horizontal stresses and, conversely, their concentration and accumulation. Accordingly, the probability of their discharge increases in case of violation of massifs by mining operations and provoking dangerous geodynamic events. The model of rigid arrays is most clearly manifested in deposits with an increased risk of rockbursts and mining-induced earthquakes in the Dalnegorsky ore district (Primorsky Krai) [16].

Figure 3 shows an overview map of the relief of the Baikal region and Transbaikalia in shades of gray, based on the GTOPO30 DEM. Morphostructures in the form of plateaus with smoothed relief, probably displaying rigid arrays, are confidently identified on the territory. Streltsovsky ore district is located in the convergence zone of three such structures, possibly exposed parts of one shield-shaped mountain massif. As we can see from the data shown in figure 2, these directions correspond to the instrumental GPS measurements given in [13, 14].

1 – contours of rigid massifs in plan; 2 – Streltsovsky ore field; 3 – thrust fronts; 4 – faults; 5 – tectonic disturbances of various kinematics; 6 – separation lines of hanging wings of reversed thrusts; 7 – rear edges of hanging wings of reversed thrusts; 8 – direction of reversal of the eastern part of the flow; 9 – general direction of drift of the tectonic flow. The yellow arrow (C) indicates the Streltsovsky ore district.

**Figure 3.** Morphotectonic scheme of the Baikal region and Transbaikalia, based on the GTOPO30 matrix.
On the map, one can note a characteristic feature for this, and probably other flows. Local motion anomalies are often superimposed on the general drift. For example, attention is drawn to the southeastern part of the flows, near which the study area is located. Here you can observe the clockwise reversal of allochthonous masses. This is evidenced by the change in the stretch of the lineaments reflecting the position of the elongated relief elements. The center of rotation is located near the Streltsovsky ore field. Probably, there is a rigid protrusion of autochthon here—a structure that exerts the maximum inhibitory effect on the flow.

Figure 4 shows the morphotectonic scheme of the Streltsovsky ore field, based on the analysis of the SRTM 03 DEM on a larger scale (in detail close to 1:100 000). The assumed main flow direction (as well as compression) is shown by an arrow on the plan.

![Morphotectonic scheme of the Streltsovsky ore field](image)

1 – settlements; 2 – hidrografic network; 3 – upthrow faults, bergstrichs are directed towards the upthrow wing; 4 – faults, bergstrichs are directed towards the lowered wing; 5 – discontinuous disturbances of uncertain kinematics; 6 – general direction of the tectonic flow.

**Figure 4.** Morphotectonic scheme of the Streltsovsky ore field. The basis is the SRTM 03 height matrix.

The details of the morphotectonic scheme suggest that the decisive influence on the geodynamic situation of this area is exerted by upthrow faults, primarily the step series 1. Series 2 appears to be identified by the anomaly of the flow drift. The ratio of the average modern heights of the lowered and upthrow wings indicates that these structures are currently active.

According to [17], most of the main ore regions of the Far East are confined to the global fault zone. At the same time, it is believed that within the eastern edge of the Eurasian continent, probably in the Mesozoic, a left-sided fault has been formed, during the long development of which the faults have been repeatedly activated. As a result, numerous fault dislocations of various types are recorded within the global zone. These are extended faults of the north–northeastern strike, which limit narrow tectonic blocks and lenses, as well as obliquely oriented upthrow faults, thrust faults and upthrow–
thrust faults. The article [8] presents the results of research to identify the most common patterns of formation of regional natural stress fields of the Amur geoblock. And in the book by Rasskazov [18], data on the stressed state of rock massifs of a number of ore deposits in the Far Eastern region are given. According to the author, in the upper part of the Earth's crust at the depths from 300 to 800 m and more, unequal stress fields act with a predominance of subhorizontal compressive stresses oriented in the direction from sublatitudinal to southwestern. The results of the conducted studies have shown compliance with the conclusions presented in these publications.

4. Conclusion
The analysis of the DEM made it possible to note one previously unknown natural phenomenon, which probably sheds light upon the origin of the abnormal stress-strain state of mountain massifs, provoking their tendency to dangerous geodynamic events during the development of deposits. Within the mentioned tectonic flows, accompanied by a high degree of dissection of the relief, plateaus of various shapes are observed, where this dissection is much lower. Such structures are confidently registered by anaglyphic relief maps, maps with shadow washing in the color version of the elevation horizontal map.

Due to the complex interaction of the displacement vectors of individual parts of the flow, a complex field of abnormal compression stresses is also formed. This explains the increased risks of dangerous geodynamic phenomena in the deposits of the region.

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