

METHODOLOGICAL ASPECTS OF PREDICTIVE MINERAGENIC STUDIES USING EARTH REMOTE SENSING DATA

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Abstract: The article considers methodological aspects of allocation and substantiation of exploration areas for scarce types of ore minerals taking into account the concept of mineral systems and using Earth remote sensing data with the application of geoinformation and neural network technologies using the example of the Argun metallogenic zone in South-Eastern Transbaikalia. Of the entire range of areas of fundamental and exploratory scientific research, the main attention within the framework of predictive and mineragenic studies is paid to solving the following problems: 1) allocation of lineaments (fault zones) based on processing of digital elevation models; 2) determination of hydraulically active fault structures for the period of ore formation based on tectonophysical reconstructions; 3) analysis of multispectral characteristics of pre-ore, ore-accompanying and post-ore metasomatites based on statistical processing of Landsat-8 satellite data; 4) assessment of fluid-dynamic settings of deposit formation based on data on the composition, properties and genesis of mineral-forming fluids. 5) creation of weight of evidence models based on statistical algorithms for processing data on the dynamics of ore-genetic processes. The feasibility of using such an approach for setting up predictive mineragenic studies on scarce types of strategic mineral raw materials in areas with complex climatic and landscape conditions is shown.

Keywords: South-Eastern Transbaikalia, Argun metallogenic zone, digital elevation model, remote sensing of the Earth, predictive mineragenic studies, strategic metals, lineaments, tectonophysics, mineral systems, ore deposits, geoinformation system.

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1. Introduction

For the reproduction and development of the mineral resource base (MRB) of the country's economy, it is necessary to scientifically substantiate the formulation of tasks for evaluation and exploration work, as well as the formulation of geological assignments for the discovery of deposits of scarce types of strategic mineral resources. The main role in the allocation and justification of exploration areas belongs to predictive-minerogenic studies (PMS) on a scale of 1:200,000–1:50,000, which should be classified as a new type of medium-scale regional work aimed at identifying promising areas suitable for exploration [Mashkovtsev and Petrov, 2023]. In terms of their objectives, PMS correspond to the previously existing general searches on a scale of 1:50,000, but in their goal-setting and methodological approaches they differ significantly from them, since they are aimed at identifying a certain geological and industrial type of deposits. This is associated with the creation of geological and genetic models of deposits based on the mineral systems approach.

The identification of structural and formational settings favorable for the localization of ore deposits is directly related to the determination of the causes and patterns, as well as the paths and conditions for the movement of ore-bearing solutions. It should be noted that this issue was formulated as one of the most important in the theory and practice of the study of ore deposits back in the middle of the last century [Betehtin et al., 1953]. In the

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chapter “On the causes of the movement of hydrothermal solutions” of this outstanding scientific work, Academician A. G. Betechtin determined that this “...issue should attract the serious attention of our geologists studying ore deposits. In general, we must achieve real ideas about the causes and directions of movement of ore-bearing solutions, since they are very important for solving a number of practical problems associated with the development of ore deposits, especially in the rational direction of exploration work.” These words have not lost their relevance even today due to the need to improve methods of predicting and searching for “hidden” mineralization, as well as planning geological exploration work (GEW) in areas with complex climatic and landscape conditions, for example, in the Arctic zone of the Russian Federation.

At present, there is no approved research algorithm that would allow one to reliably determine the paths of movement of ore-bearing solutions. At the same time, one of the most complex and poorly studied factors is the fluid-dynamic environment of ore formation, especially in terms of the hydrodynamic connection between the deep (ore-supplying) and near-surface (ore-distributing and ore-hosting) structures of mineral-forming deposit systems. In one of the latest reports on this issue [Chi et al., 2022], three types of systems are considered: magmatic-hydrothermal, structurally controlled hydrothermal with undefined fluid sources, and hydrothermal associated with sedimentary basins. A number of examples, including uranium deposits of ancient structural unconformities (unconformity-related deposits), show the role of the so-called “arterial” (let's call them ore-supplying) faults along which the “pumping” of ore-bearing solutions from the lower to the upper parts of mineral-forming systems occurs, including due to the valve hydrodynamic mechanism of the flow of intra-fault ore-bearing fluids and the participation of seismo-geodynamic and thermo-convective processes in ore genesis [Sibson, 2019]. For example, in the field of uranium geology, these developments in the hydrodynamics of mineral-forming systems reflect the currently occurring significant changes in the algorithm for substantiating geological exploration from the “classical” descriptive structural-formational classification of the IAEA, containing 15 types, 37 subtypes and 14 classes of uranium deposits, to geological-genetic models of deposits (models of uranium mineral systems) [International Atomic Energy Agency, 2020] with an emphasis on identifying the genesis, composition and properties of ore-bearing fluids.

The concept of mineral systems was first proposed in [Wyborn et al., 1994] as a multi-disciplinary approach aimed at analyzing “all geological factors that control the formation and preservation of mineral deposits, with particular attention to the processes of mobilization of ore components from their source, transportation and accumulation in a more concentrated form and preservation in subsequent geological history.” The methodology of mineral systems is used in the analysis of the conditions of formation of ore deposits of various genetic types in various geodynamic settings.

In application to uranium metallogeny, it was formulated in [Skirrow et al., 2009] for grouping mineral systems by parameters that “emphasized common features in the processes of uranium deposit formation,” with special attention to the conditions of uranium transport by aqueous fluids, since “aqueous fluids participated in the formation of almost all large uranium deposits... and differences in the geological settings of fluid generation and migration routes predetermined the diversity of uranium deposit types.” The currently accepted and used systematization of the parameters of mineral systems of ore deposits, including uranium deposits, concretizes the well-known paradigm “source→transport→deposition” with an emphasis on fluid mass transfer processes. Along with this, the practice of applying the mineral-system approach has shown that one of the unresolved fundamental problems of uranium ore formation is the frequently observed mixing of ore-forming fluids of magmatic, metamorphic and meteoric nature in mineral systems. For example, not only magmatic and magmatic-hydrothermal fluids, but also meteoric and sea waters participate in the formation of large-tonnage deposits of the volcanogenic type, related to systems associated with magmatism. This “links” uranium-

bearing volcanogenic mineral systems (magmatic) with sedimentary and near-surface systems, including calcretes, sandstone-type deposits and structural unconformities.

In our work we are guided by the hypothesis that hydrothermal systems that existed in the geological past have preserved evidence of their development in the form of fluid conductors, which, taking into account the level of erosion, are reflected in the modern relief. In this regard, the most important sources of information, given the significant area of exploration, are multi-scale cartographic materials and Earth remote sensing (ERS) data, for the collection, processing, analysis and interpretation of which geoinformation systems (GIS) are used. The procedure for solving the tasks set is briefly considered in [Petrov *et al.*, 2024]. Developing this direction of predictive mineragenic research, the proposed article considers in more detail the algorithm for creating a regional predictive and prospecting model for the location of ore objects in the Argun metallogenic zone (southeastern Transbaikalia) using geographic information and neural network technologies.

2. Identification of Lineaments (Fault Zones) Based on Processing of Digital Elevation Models

The objective of fundamental and exploratory scientific research in the context of predicting the location of ore deposits is to determine the patterns of structure and area distribution of such elements of the hydrothermal paleosystem as sources of ore substance and the framework of fault-fracture structures, which determined the migration paths and concentration of ore-bearing solutions from the source to the ore deposition zone. The guiding hypothesis is that the hydrothermal system that existed in the geological past has preserved evidence of the presence of fluid conductors in the modern relief. To determine the spatial position of faults, standard geological maps and detailed digital elevation models (DEMs) are used, forming the basis for lineament analysis.

A special method of integrated GIS lineament analysis [Ustinov and Petrov, 2016] has been developed and tested in the laboratory of geoinformatics of the IGEM RAS, which has recently been supplemented with neural network technology tools. It is known that the term “lineament” was introduced into scientific literature by the American geologist W. Hobbs in 1904 to denote linear relief elements and geological structures elongated in a certain direction: rectilinear negative forms, exposed rectilinear slopes, scarps and benches, rectilinear sections of small watercourses, axial lines of watersheds, etc. Lineaments play an important role in predicting the location of mineral deposits.

Let us consider an example of lineament analysis conducted for the territory of southeastern Transbaikalia (a fragment of the State Geological Map M-50 – Borzuya), conducted on the basis of a detailed DEM. The results of the Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 30 m/pixel were used as the DEM.

The method of automatic extraction of lineaments based on the neural network approach, developed in the laboratory of geoinformatics of the IGEM RAS, includes several key stages [Grishkov *et al.*, 2023]. The first stage is the author's method of data preparation, which helps to ensure the quality of the training sample and minimize the impact of noise. The second stage consists of developing an algorithm for vectorizing the results of the neural network, which allows for easy export of the results (lineaments) to the GIS. At the third stage, a method is used to minimize the noise component of the training sample and optimize the choice of synaptic weighting coefficients by further training the neural network using simulated data reflecting various conditions of lineament localization. To verify the obtained results, a spatial comparison is carried out between the linear structures extracted by the neural network and the lineaments identified by the operator (Figure 1).

On the rose diagrams, it can be seen that against the background of the dominance of sublatitudinal structures established manually, structures of other directions appear, identified by the neural network, but not by the operator. This indicates that with the help of the neural network, a more accurate structural plan of the territory is formed than by the deterministic actions of the operator, even with extensive experience in deciphering lineaments.

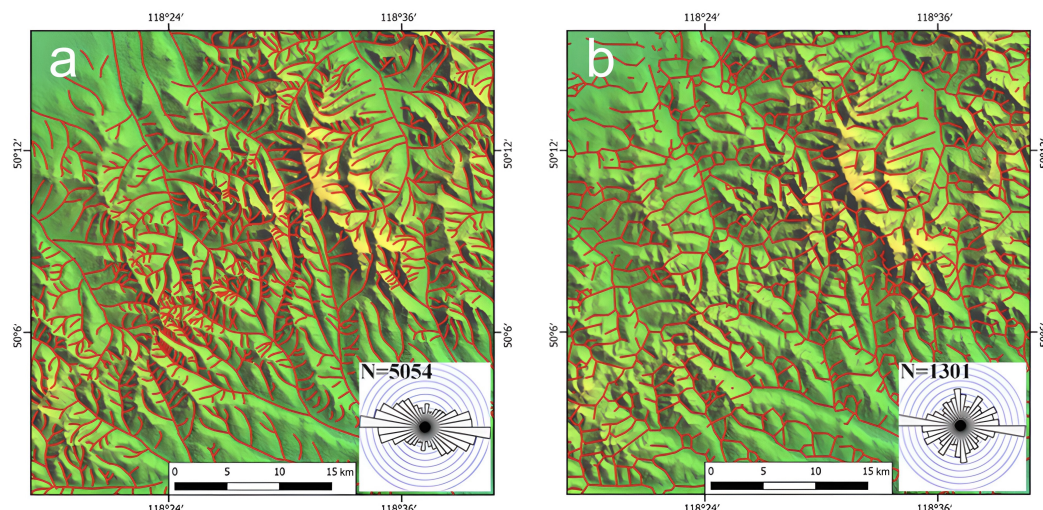


Figure 1. Structural plan of lineaments on the DEM of one of the sections of the Argun metallogenic zone, identified manually (a) and by a neural network (b). N is the direction to the north, N is the number of lineaments [Grishkov et al., 2023].

3. Determination of Hydraulically Active Fault Structures During the Period of Ore Formation Based on Tectonophysical Reconstructions

Following the lineament analysis, the structure of the stress-strain field (SSF) of the pre-ore, ore and post-ore stages of the territory's development is reconstructed. For this purpose, a set of tectonophysical field and laboratory methods and tools is used, a summary of which is given in [Rebetsky et al., 2017].

To reconstruct the parameters of the SSF and the kinematics of fault structures at the ore stage, the tectonophysical models (approaches) of V. Riedel [Riedel, 1929], M. V. Gzovsky [Gzovsky, 1975], V. I. Smirnov [Smirnov, 1976] and P. L. Hancock [Hancock, 1985] were analyzed. A comparative analysis showed the advisability of using the P. L. Hancock model, which includes the most complete scheme of secondary structures observed in shear zones before the formation of a master fault and after its formation (Figure 2).

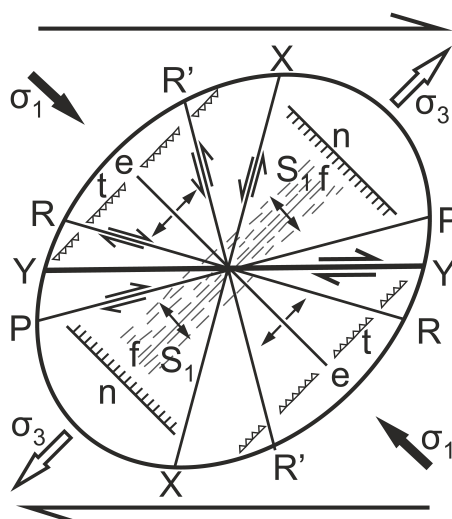


Figure 2. Systems of echelon structural elements formed in a strike-slip fault zone by pure shear [Hancock, 1985]: Y – main shear, R and R' – conjugate Riedel shears, X, P – secondary shears, e – tensile cracks, n – normal faults, t – reverse faults, f – folds, S_1 – cleavage, σ_1 – axis of maximum compression, σ_3 – axis of maximum extension.

A detailed description of the procedure for using this model is given in the work [Minaev et al., 2024]. Here we will only note that for the interpretation of the orientations and kinematics of the identified lineaments according to the P. L. Hancock model, in the laboratory of geoinformatics of the IGEM RAS created the Lineament Stress Calculator software (author A. D. Svecherevsky). The developed script allows for the automatic analysis of linear vector data, determining and classifying various types and scales of fracture systems based on their geometric and spatial characteristics.

Numerous calculated and in situ obtained data show that hydraulically active and fluid-permeable faults have a certain orientation in the field of acting stresses and deformations. Based on the reconstruction of the orientation of the axis of the main compressive and shear stresses of the ore stage, segments of fault zones (lineaments) are identified that, in a setting of regional compression, are under conditions of local extension (transtension). Such hydraulically active (arterial, according to [Sibson, 2019]) fault segments are characterized by the so-called “tendency to shear” ($\mu = \tau / \sigma_n$, where τ is the shear stress, σ_n is the effective normal stress), the values of which are equal to 0.6 on average [Zoback et al., 2002].

Based on reconstructions of the orientation of the axis of the main compressive forces of the stage of ore-generating late Mesozoic tectonomagmatic activation (TMA) in the region [Petrov et al., 2013a] and the calculation of the tendency to shift, reflecting the maximum hydraulic permeability of lineaments and confirmed faults in the stress and deformation field that was active at this stage of tectogenesis, a model was constructed in the GIS environment of the project that makes it possible to predict the location of mineralized zones that are most promising for setting up exploratory structural and mineralogical-geochemical work (Figure 3).

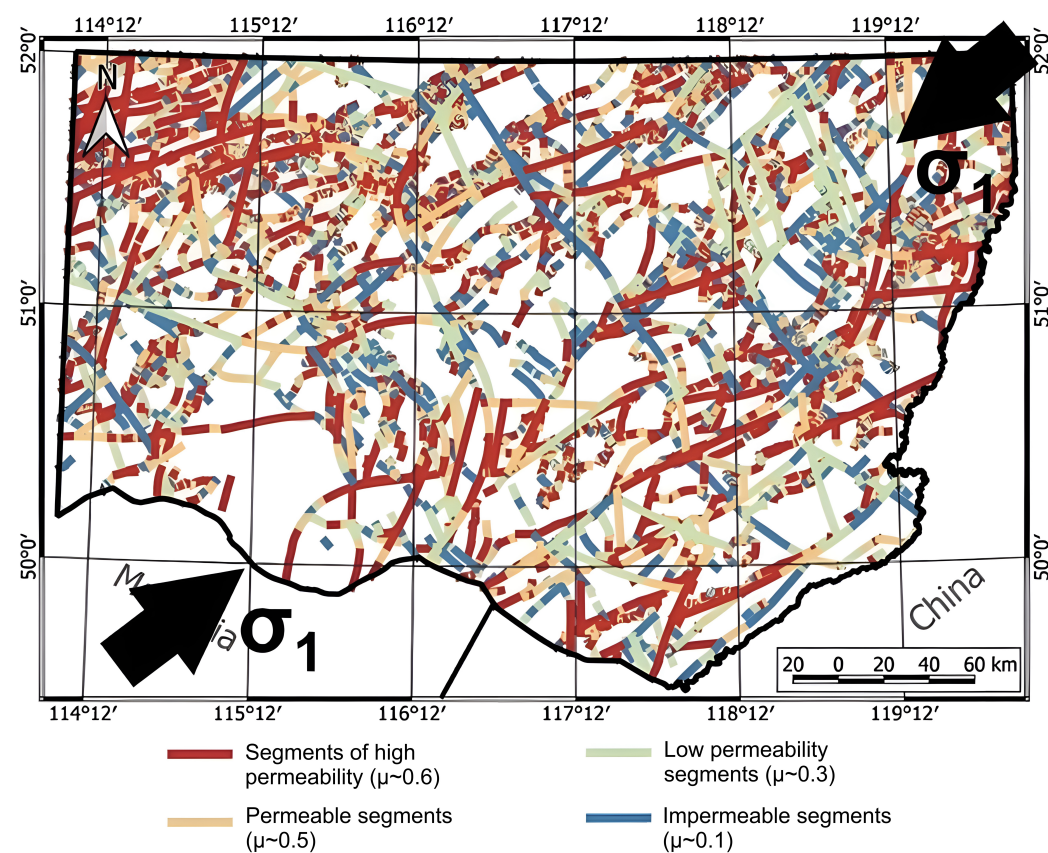


Figure 3. Visualization of segments of fault structures, to varying degrees predisposed to shear (transtension) at the stage of ore-generating late Mesozoic tectonomagmatic activation in southeastern Transbaikalia. σ_1 is the axis of maximum compression.

4. Analysis of Multispectral Characteristics of Pre-ore, Ore-Accompanying and Post-ore Metasomatites Based on Statistical Processing of Landsat-8 Satellite Data

The identified fault-fracture (arterial) structures and their intersection nodes, as a rule, represent a volume of geological space where long-term circulation of fluids of various genesis took place with the formation of pre-ore, ore-accompanying and post-ore metasomatites with specific spectral characteristics. To analyze these characteristics, an algorithm for statistical processing of Landsat-8 satellite data developed in the Geoinformatics Laboratory of IGM RAS is used, including the method of principal component analysis (PCA), minimum noise fraction (MNF) and independent component analysis (ICA) [Nafigin et al., 2022]. The results of statistical data processing are compared with such mineral components of metasomatites as minerals of the oxide/hydroxide group containing transition iron ions (Fe^{3+} and $\text{Fe}^{3+}/\text{Fe}^{2+}$; a group of clay minerals containing $\text{Al}-\text{OH}$ and $\text{Fe}, \text{Mg}-\text{OH}$; minerals containing divalent iron ion (Fe^{2+}). Multispectra associated with vegetation are also processed, and pseudo-color RGB composites are generated and interpreted, which reflect the distribution and multiplication of mineral components of metasomatites.

To construct a scheme of the potential of territories for the discovery of solid minerals, the integration of informative thematic layers is carried out using a fuzzy logic model. An example of the localization of areas promising for the implementation of geostructural and mineralogical-geochemical mapping within the framework of regional predictive-minerogenic studies is shown in Figure 4.

5. Evaluation of Fluid-Dynamic Conditions of Deposit Formation Based on Data on the Composition, Properties and Genesis of Mineral-Forming Fluids

A striking example of the combination in space and time of mineral systems associated with volcanoplutonic complexes are the deposits of the Streltsovskoye ore field in the southeastern Transbaikalia, localized in the caldera of the same name of the late Mesozoic stage of tectogenesis [Petrov et al., 2022]. The location here of coeval ore mineralization and the same type of ore-accompanying metasomatites at different hypsometric levels of the geological section in rocks of different origin (basement granites and caldera-filling volcanics) introduces significant uncertainties into genetic models in terms of determining the depth of ore formation. For its approximate assessment, one can use data on the range of pressure changes in fluid inclusions (FI) from their maximum to minimum values, taking into account the restrictions on the physically limiting values of this interval, which are specified by the values of lithostatic and hydrostatic fluid pressure [Prokofev and Pek, 2015].

However, this approach does not always give positive results, especially in cases where: 1) the mineral-forming system functioned for a long time (for example, according to data [Sheahan et al., 2016], at the Kianna deposit in the Athabasca Basin (Canada), the telescoped flow of ore-bearing solutions into a single structural trap occurred over about 1 billion years); 2) several highly productive uranium sources at different depths take part in ore genesis [Pek et al., 2020]; 3) the mineral-forming system developed and functioned in an environment of thermoconvective circulation of fluids against the background of seismic geodynamic processes [Petrov, 2017; Zlobina et al., 2020]. In this regard, there is a need to search for and use structural markers to reconstruct fluid-dynamic regimes at various stages of tectonic genesis.

The formation of transcrustal (arterial) fluid-conducting channels is a multistage process and in many ways not fully understood. Numerous geological and geophysical data indicate that fault-fissure channels permeable to hydrothermal ore-bearing solutions have specific structural features at different depths of ore-forming fluid-magmatic systems. Establishing the nature of changes in the structure of such a channel along its entire length is undoubtedly an important task. However, an equally, and perhaps even more important task (from the point of view of fundamental and applied aspects) is the reconstruction of the spatio-temporal relationship between the deformation of rock massifs, their fluid permeability and mineral formation in the fissure-pore volume of the ore deposition zone.

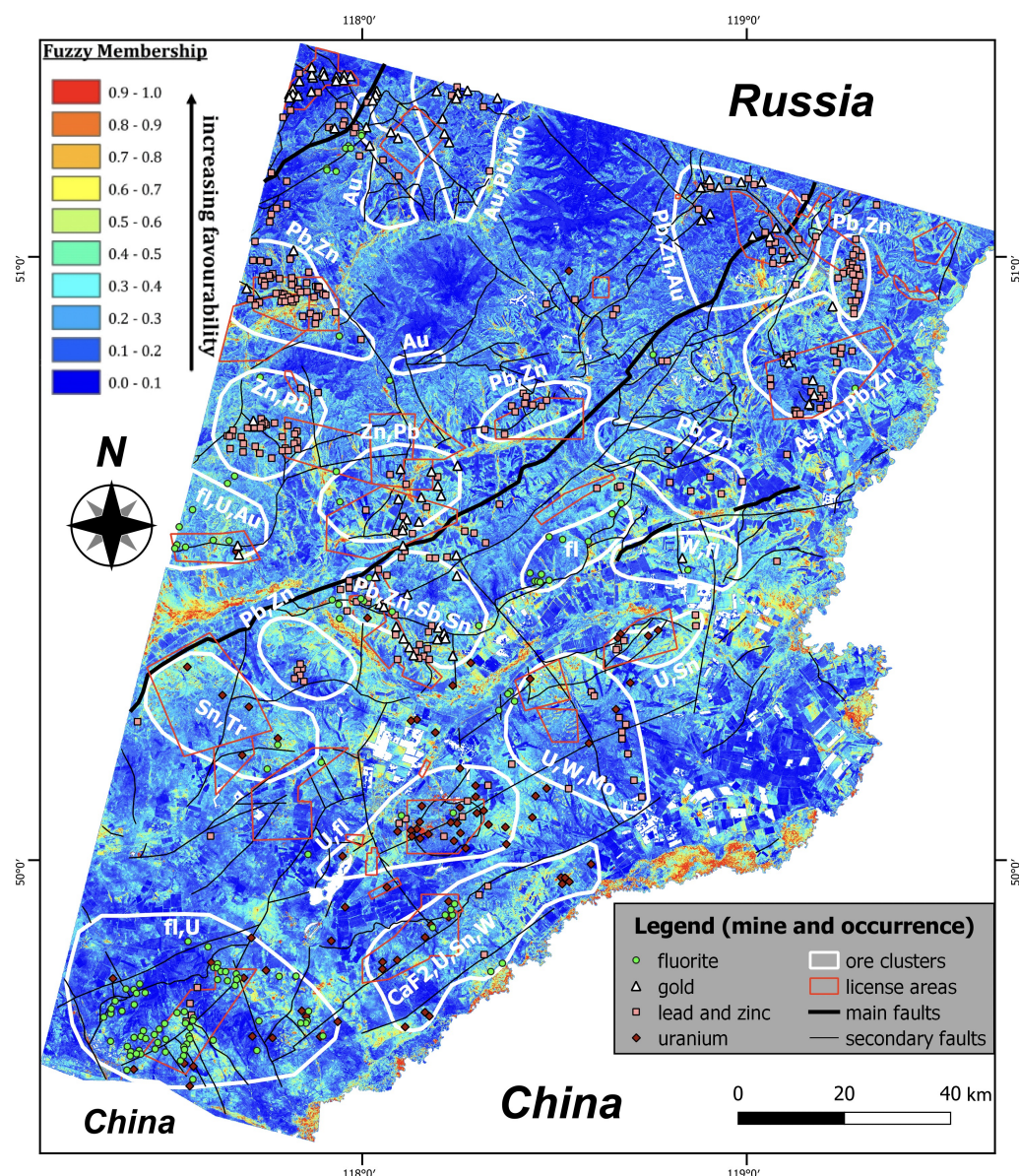


Figure 4. Distribution scheme of clusters promising (gradation from 0 (blue) to 1 (red) according to the fuzzy logic model) for ore mineralization (Au, U, Mo, Pb-Zn, Sn, W, Ta, Nb, Li, fluorite) in the territory of southeastern Transbaikalia), created on the basis of GIS modeling using fuzzy logic algorithms (according to [Nafigin et al., 2022]).

One of the rational ways to solve this problem is to reconstruct the dynamics of the formation of deformation microstructures depending on the parameters of the stress and deformation field in combination with the determination of the properties of paleofluids that are fixed (sealed) in microstructures as secondary FI. Secondary inclusions are those that form after the crystallization of the host mineral has been completed. FI chains are grouped into systems, which indicates the duration of the process of fluid passage through the rock matrix against the background of oriented stress [Lespinasse et al., 2005].

These systems, which we call “fluid inclusion planes” (FIP), are used as indicators of the evolution of ore-forming hydrothermal systems, since they are formed in rock-forming minerals as rupture microcracks, which, depending on the stage of tectonic development of the rock massif, accumulate fluids of different composition and properties [Petrov et al., 2013b]. FIPs visually differ in thin sections from other types of microcracks, and the crystallographic features of minerals have virtually no effect on their orientation. Therefore,

the possibilities for studying FIPs are usually high, which is especially characteristic of quartz, which demonstrates the rate of inclusion formation in the pre-ore, ore and post-ore stages of mineral formation that is most consistent with geological time.

The spatial orientation of the FIPs changes with the restructuring of the stress field [Lespinasse, 1999]. At the initial stages of deformation, tensile microcracks oriented perpendicular to the axis of least compression σ_3 are formed in the rocks (it is assumed that compressive stresses are positive: $\sigma_1 \geq \sigma_2 \geq \sigma_3$). The vector of maximum permeability of the structures lies in the $\sigma_1\sigma_2$ plane, along which fluids migrate. Over time and as a result of changes in the tectonic environment, fluid-conducting microcracks experience compression and close, “sealing” the PFSF of the first generation. A change in the tectonic environment leads to a new stage of deformation, which inevitably affects the orientation of the PFIS of the second generation, and a change in the thermobaric and physicochemical conditions affects the composition and properties of the inclusions. In the case of a new stage of deformation, PFSF of the third generation are formed, etc. As a rule, planar systems of each subsequent generation intersect systems of previous generations (Figure 5).

The chronology of the formation of the FIPs and their spatial parameters (strike, angle of incidence) can be established by the classical method of microstructural analysis (the universal Fedorov table) or with the help of special computer software. It was developed in the laboratory of geoinformatics of the IGEM RAS for statistical analysis of two-dimensional digital images of thin sections made from oriented rock samples [Ustinov and Petrov, 2018].

In addition to spatial parameters, the software allows calculating the main filtration (aperture, porosity, permeability) characteristics of rocks. The composition and properties of FI (temperature, pressure, salinity, content of H_2O , CO_2 , CH_4 , N_2 , etc.) associated with physicochemical processes in the fluid-rock system are revealed using microthermometric measurements and Raman spectroscopy. Determining the orientation of paleostress axes at regional and local levels using a set of tectonophysical field and laboratory methods and tools [Rebetsky et al., 2017] completes the procedure for recreating the tectonic history of the studied objects from regional to local levels, as well as reconstructing the migration paths of fluids.

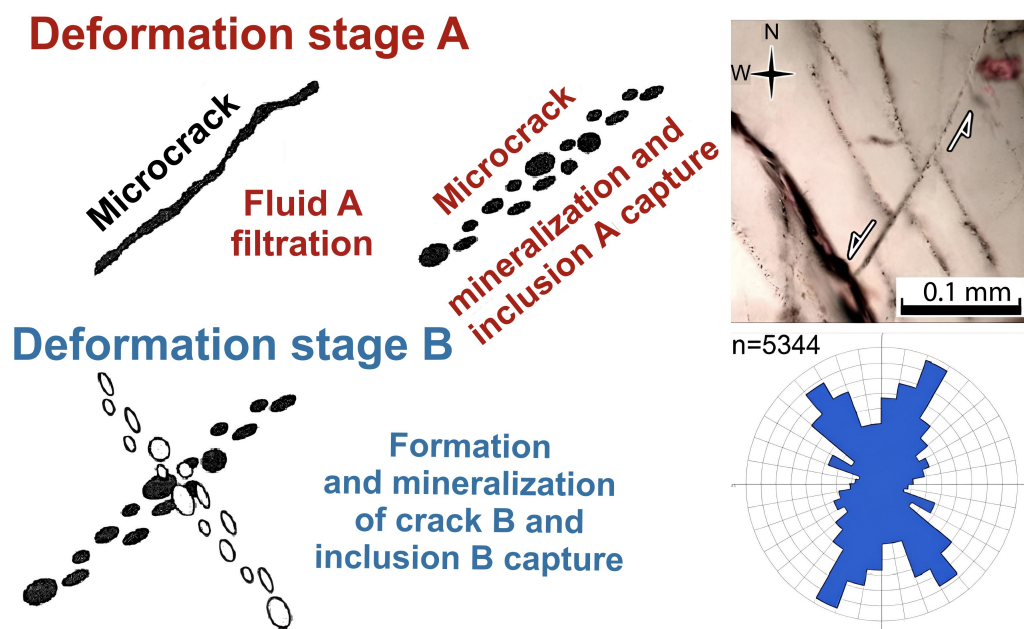


Figure 5. Scheme of formation of generations of the PFIS of different orientations with a change in the deformation plan (according to [Lespinasse, 1999]) and an example of the relationships of generations of the PFIS in an oriented thin section, where the NW-SE strike system, formed primarily, is intersected with an offset by the NE-SW strike system. A rose diagram of the PFIS (n is the number) in this thin section is shown.

Thus, the combination of methods of structural geology, microstructural analysis of fluid inclusion planes and thermobarogeochemistry with the use of data on geodynamics and fault tectonics allows us to reconstruct the routes and conditions of migration of ore-bearing hydrothermal solutions, establish the chronology of fluid permeability of rocks, determine the dynamics of changes in thermobaric and physicochemical conditions of ore formation at various stages of tectogenesis. We believe that this approach, tested in practice, should be included in the scientific and methodological support of predicting and mineragenic studies in order to identify spatiotemporal patterns in the formation of mineral systems of ore deposits.

6. Creation of Weight of Evidence Models Based on Statistical Algorithms for Processing Data on the Dynamics of Ore-Genetic Processes

The evolution of ore-bearing geological structures of the Argun metallogenic zone (southeastern Transbaikalia) is considered by us in the context of the change in geodynamic regimes of the Proterozoic, Caledonian and Hercynian tectonomagmatic cycles, as well as during the late Mesozoic intraplate TMA, which led to the formation of subalkaline magmatites of the Shakhtama complex with Au-, Cu–Mo-, Pb–Zn–Ag-metallogenic specialization, volcanoplutonic complexes of caldera structures with Mo–U, Pb–Zn and fluorite ores, and rare metal granites of the Kukulbey complex with the Sn–W–Li–Ta spectrum [Petrov *et al.*, 2017].

Important tasks within the framework of the GIS project creation for the location of uranium-bearing mineral systems in the Argun metallogenic zone were the establishment, formalization and standardization of quantitative parameters of the selected structural criteria. They represent heterogeneous data, including the position and orientation of linear structures of various ranks, central-type structures [Ustinov *et al.*, 2024], spatial-geometric and spatial-density parameters of these structures, areas of their dynamic influence and tectonophysical parameters reflecting the kinematics of displacements and the style of deformations during the period of ore formation. For each criterion, a membership function was determined that characterizes the range of parameter values from 0 to 1. This is necessary in view of the fact that the quantitative values of the criteria are in different intervals, sometimes differing from each other by orders of magnitude. Accordingly, the membership function allows for the “normalization” of the obtained values and their correct comparison with each other. Based on an expert assessment, analysis of literary and statistical data, weighting factors were determined for each criterion. They are used to take into account the “importance” of each criterion in assessing the probability of the presence of an ore object.

The result of this work is a comprehensive structural weight of evidence prediction and exploration model of the territory of southeastern Transbaikalia (Figure 6), for the creation of which spatial information on the morphogenetic parameters of discovered and verified fault structures, the results of the tectonophysical interpretation of their kinematics, as well as substantiated weighting coefficients were used.

This model creates a basis for designing predictive mineralogical studies for various types of minerals and can easily be supplemented with specialized information on geophysical and geochemical fields and other data depending on the type of ore mineralization being sought.

Regarding the placement of uranium-bearing mineral systems, the created model was modified taking into account the specifics of predicting and searching for uranium deposits. In particular, the results of airborne gamma-spectrometric surveys and measured uranium contents in bedrock obtained during field studies and laboratory analyses of rock sample collections were used. The accuracy of the predictive model for uranium-bearing mineral systems based on comparison with reference uranium ore objects was 80%. As a result, the most promising areas for uranium were identified using the created model, and the main proposals for setting up predictive and mineragenic studies were scientifically substantiated and formulated.

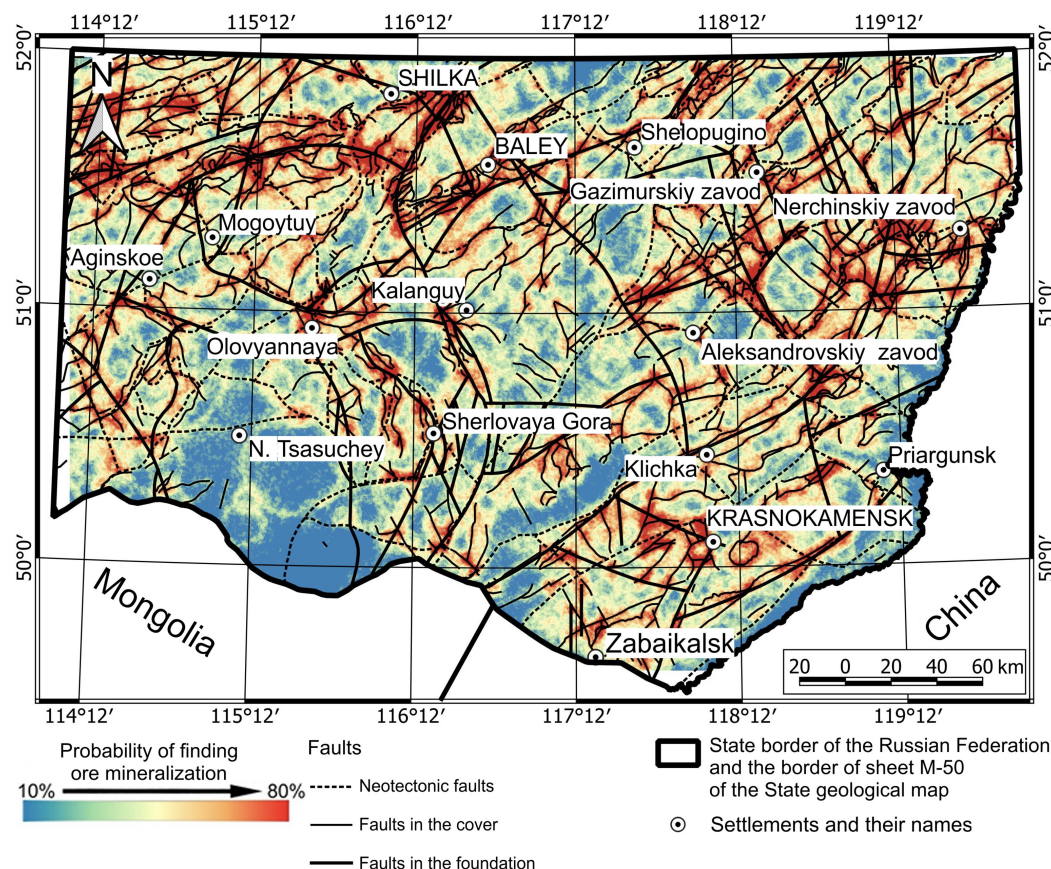


Figure 6. Weight of evidence predictive and exploration model of mineral deposit systems (Au, U, Mo, Pb–Zn, Sn, W, Ta, Nb, Li, fluorite) for the territory of southeastern Transbaikalia (map M-50). A database of 1239 deposits and ore occurrences was used.

An important tool for verifying the regional predictive and exploration model, in addition to the reconstructed structural and tectonic setting, is the analysis of the formation time of mineral systems of deposits in the Argun metallogenic zone. In the work of B. L. Rybalov [Rybalov, 2000], based on a generalization of materials on the metallogeny of southeastern Transbaikalia, a conclusion was made that all the late Mesozoic deposits developed here form three evolutionary series: gold–molybdenum (170 ± 5 – 150 ± 5 Ma), rare metal–polymetallic–uranium (140 ± 5 – 130 ± 5 Ma) and fluorine–gold–silver (120 ± 5 – 110 ± 5 Ma). Ore deposits of these series are concentrated in certain metallogenic belts and tectonic blocks.

Modern GIS technologies allow visualization of these conclusions. For this purpose, work was carried out on the selection of 1239 deposits and ore occurrences of the southeastern Transbaikalia (geological map M-50) to link the rows identified by B. L. Rybalov with the formation of a thermal map of the location of objects (Figure 7).

Comparative analysis of the structures of heat maps and the weight of evidence predictive and exploration model shows their good convergence. Moreover, a comparative analysis of the distribution of the density of ore objects of the evolutionary series identified by B. L. Rybalov and the distribution scheme of clusters promising for ore mineralization created on the basis of statistical methods for processing the multispectral characteristics of ore-accompanying metasomatites and GIS modeling using fuzzy logic algorithms also show good convergence. Based on this, it can be concluded that the predictive and exploration model of mineral systems of ore deposits in the Argun metallogenic zone is verified both by spatial and temporal parameters. Along with this, the coincidence in space of areas with the maximum density of ore objects belonging to different evolutionary series may indicate

the presence of nodes of long-term circulation of metalliferous fluids with the formation of mineral-forming systems of deposits with complex ores.

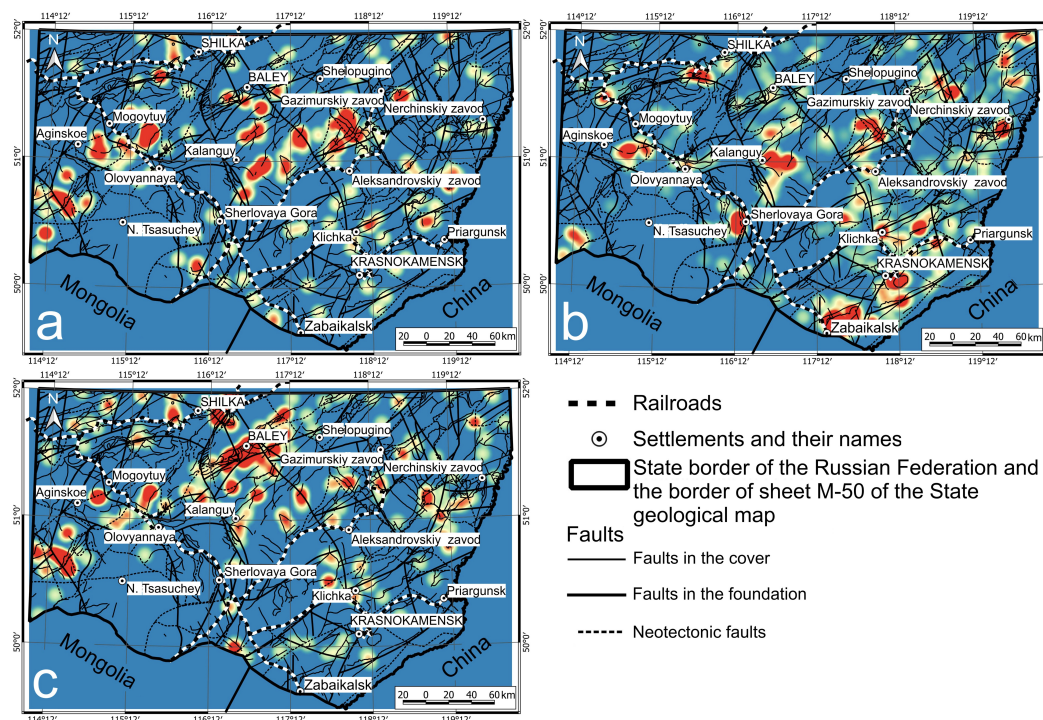


Figure 7. Heat maps of the location of ore objects of the gold–molybdenum (a), rare metal–polymetallic–uranium (b) and fluorine–gold–silver (c) series. The maps reflect the spatial density of mineralization (the number of ore objects per area unit according to S. S. Smirnov). Red areas are the maximum density (closeness) of ore objects, blue areas are the absence of objects. For visualization, the number of ore objects in a window with a radius of 10 km was considered.

7. Conclusion

Conceptual tasks that determine the basis of the technological architecture of GIS projects of ore-forming (mineral) systems of ore deposits, including uranium deposits of leading geological and genetic types, are associated with ensuring prompt access to information and implementing the capabilities of specialists to effectively work with geodata. The high level of theoretical tasks determines high requirements for software, mathematical and linguistic support of the system based on the theory of functioning of information (including GIS) systems. In particular, the operations of functioning of these systems are supported by such technologies as spatial-three-dimensional and four-dimensional (space-time) modeling of the objects under study. The main principles of construction of these systems are: 1) integration when combining information resources and 2) information interaction using a single multi-user software and hardware environment.

As a basis for the functioning of GIS projects for predictive-mineragenic studies, we use the principles of integration and information interaction of cartographic description and signs of manifestation of ore-forming (mineral) systems of mineral deposits. For example, signs of ore-supplying, ore-distributing and ore-bearing fault structures are uranium-specialized volcanoplutonic complexes and hydrothermal-metasomatic changes in rocks controlled by faults within them [Andreeva et al., 2020].

Taking into account the prospects for discovering new deposits for the purpose of reproduction and development of the mineral resource base of scarce types of strategic mineral raw materials, it is necessary to conduct predicting and mineragenic studies aimed at identifying the features of the tectonic structure of the areas as a whole, conducting geodynamic reconstructions, assessing the stress state of rock massifs and the kinematics

of movements in the zones of major faults in the pre-ore, ore and post-ore stages. In this context, work has been carried out for the territory of southeastern Transbaikalia to create an organizational structure of a territorially centralized and thematically distributed database, including all available geological and geophysical information.

Based on the models of ore-forming systems, a GIS project was created, which collected and analyzed extensive data on geology, metallogeny, geodynamics, tectonics, mineralogy, geochemistry and structural-geological features of southeastern Transbaikalia. A comprehensive GIS analysis established that the known deposits and ore occurrences of the region are localized in areas where zones of maximum density of linear structures (lineaments, faults, cracks) and areas of optimal values of the coefficient of tendency to shear dislocations (transtension) are combined. The obtained results made it possible to create a structural weight of evidence predictive and exploration model reflecting the most promising areas for predictive and mineragenic studies on a scale of 1:200,000–1:50,000 in the Argun metallogenic zone. The expediency and prospects of using this model are confirmed by good convergence with the spatial distribution schemes of three evolutionary series of ore deposits of the late Mesozoic age, as well as with the distribution schemes of multispectral characteristics of ore-accompanying metasomatites, compiled from the materials of remote sensing of the Earth. This approach is expedient to use for setting up predictive-minerogenic studies on scarce types of strategic mineral raw materials in other regions, including territories with complex climatic and landscape conditions.

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