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# Ore-controlling factors as the basis for singling out the prospective areas within the Syrymbet rare-metal deposit, Northern Kazakhstan

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**Abstract**

**Purpose** is prediction of the prospective areas within the Syrymbet deposit basing on the systematization and complementing of the ore-controlling factors of ore localization and predictive-prospecting criteria.

**Methods.** The methodology of carrying out the research in terms of the indicated problem involves complex application of empiric, theoretical, and logical techniques of a general-purpose method of scientific knowledge. To model the ore bodies and distribution of ore content in them in the 3D format, the computer modelling (GIS-Micromine) methods were used; 2D modelling of a temperature field of the ore-bearing Syrymbet mass involved methods of mathematical modelling (Maple 10). The main conclusions were drawn by means of analysis and synthesis of the results obtained by the indicated methods.

**Findings.** The ore-controlling factors of the localization of rare metal ores were systematized and complemented by synthesizing the results of the analysis of 3D models of the deposit under consideration with the visualization of ore component contents within the ore bodies and their 2D sections in terms of the survey profiles where spatial distribution of tin content in the vertical section of this deposit was obtained. The factors were also updated by analyzing the thermodynamic conditions of the formation of ore stockworks where temperature conditions of the enclosing media in the area of ore formation were considered along with the intervals of the ore deposition temperatures.

**Originality.** The results of scientific studies (computer and mathematical modelling) based on the empiric geological data helped solve not only the problems of ore formation theory but also the practical tasks concerning the improvement of methods for predicting the prospective areas within the deposit.

**Practical implications.** The methodology of scientific study dealing with systematization of ore-controlling factors can be also used for other endogenous ore objects.

***Keywords:*** *deposit, rare metals, 3D deposit models, content of ore components, ore-controlling factors, thermodynamic conditions, temperature fields*

## 1. Introduction

In terms of scientific and technical progress, economic competitiveness of different countries is determined first of all by the current state and development of high-technology productions – aircraft industry, electronics, machine building, precision instruments industry, nanoindustry, petrochemical industry, and nuclear energetics. Modern science-capacity technologies are the basis to provide national economic competitiveness at the global international level. In this context, it is strategically important to create all the necessary conditions for their intense development; material support of those technologies is of the utmost importance here.

Currently, rare metal and rare earth metals are gaining more and more importance in the production. They are used in various high-technology industries. Experts believe that these are the elements that will play an important role in future in the development of global economy. Kazakhstan is known for its numerous deposits and ore occurrences of rare metals, many of which are known worldwide. Unfortunately, the mineral and raw material base tends to depletion with the course of time; thus the necessity to carry out research aimed at identifying prospective areas for further geological prospecting is rather topical [1]-[3].

A problem of forecasting the prospective areas for identification of new ore deposits or sites within the known deposits is in the determination of the ore-controlling factors of ore localization and predictive criteria, respectively [4]-[6]. At the modern stage of geology development, optimal system of the forecast criteria can be based on the results of studies carried out by means of up-to-date innovative methods (GIS-technology) [7], [8]where stable connections are identified best of all in the spatial location of mineralization in the geological structural complexes with their definite matter types as well as features of composition and structure [9]-[14].

That is why, to solve the problems of that kind, we have selected the tin deposit Syrymbet that is located within the

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Syrymbet coalfield where tin mineralization is associated with the zones of exocontact of granite-porphyres intrusion and, in a lesser degree, to granite-porphyres. The ore-bearing thickness is represented by the terrigenous-sedimentary rocks of Sharykskaya series subjected to the intense hydrothermal-metasomatic processing within the contact zone (silification, biotitization, seritization, tourmalinization, amphibolization, skarnification etc.). The deposit is a stockwork where the upper part is made up by a thick weathering crust. The deposit area is divided into three sites: Southern-Western, Central, and Northern-Eastern.

Tin is the main valuable component of this deposit; this mineral is represented mainly by cassiterite (80.4%). The accompanying components are as follows: tungsten (scheelite, tungstenite), molybdenum (molybdenite), bismuth (bismuthine, wittichenite), tantalum (tantalite), niobium (columbite), and beryllium (beryl, danalite). The primary ledge ore of the deposit is close to the cassiterite-quartz formation and associated with the cassiterite-quartz and cassiterite-skarn industrial types. The ore-bearing weathering crust represents a new industrial category of the tin ore raw material. According to its genotype, it is an alluvial deposit of the ancient crusts of chemical weathering; it corresponds to the cassiterite minute-thin-flaked low-sulfidation industrial type [15].

Currently, scientific and geological studies carried out by the innovative methods make it possible to complement a system of ore controlling factors with new prediction criteria [16]-[20]. Owing to that, we consider the criteria based on the model constructions as the additional criteria to predict rare-earth mineralization: three-dimensional models of the deposit with the visualization of tin content in terms of ore bodies; in addition, we use a thermodynamic model of the deposit representing the relations of the ore-localizing and ore-forming heating systems [21]-[26].

The abovementioned model constructions are characterized by the great geological informational content generating additional ore-controlling factors; thus, along with the analysis of other researchers of geological content, they will result in systematization of the ore-controlling factors and predictive criteria with the singling out of the prospective areas within the Syrymbet deposit.

To achieve the specified purpose, the following problems were solved:

– to construct and analyze 3D frame and block models of the deposit and their 2D sections in terms of the survey profiles;

– to construct and analyze a thermodynamic model of the deposit;

– to systematize the geological and geophysical ore-controlling factors of the rare-metal ore localization and complement them with the new data;

– to single out the prospective areas within the deposits.

## 2. Methods

The specified problems were solved involving a complex of methods of general-scientific level of knowledge (logical, theoretical, and empiric).

1. To construct a computer-based digital model of the deposit, the Micromine GIS software was used where a method of spatial modelling according to the data on the prospecting well sampling was implemented with the possibility of clarifying the parameters of location of ore bodies and deposits [20], [22].

A process of constructing the geological digital models consists of several stages:

– development of the database (DB) structure to store the primary information on the geological surveying data;

– one of the main features of the formation and maintenance of the pioneer well database for the ore deposits is the available mechanism of averaging the intervals of the primary geological sampling;

– analysis and interpretation of the geological data in the wells; in this context, the mineralization zones are outlined according to the cutoff grade values;

– three-dimensional frame models are to be developed with the specification of the ore body morphology;

– the final modelling stage involves creation of three-dimensional models with the visualized distribution of the ore component contents in terms of the deposit ore bodies.

The initial data for constructing the Syrymbet deposit 3D models were represented in the form of graphics (geological map, geological sections and plans of sampling of the surface and underground levels) and calculation tables (data on the pioneer wells sampling). Generally, 1011 information units were fed into the computer database.

The software has helped develop the frame and block models of the deposit under consideration as well as the sections of a block model according to the survey profiles. After the creation of a frame model of the mineralized zone, a block model was built; as a result, the content of the main ore element (tin) within the Syrymbet deposit was visualized.

The applied software (Micromine) helps visualize the tin content in terms of the survey profiles as well (2D sections). To do that, a block model of the deposit was cut according to the selected direction to visualize the tin content in the internal parts of the mineralized zone.

The main difference of the models developed by means of the Micromine software is the possibility of their further use and clarification according to the results of the deposit development. In this context, a general model size is limited only by the computer capacity. The reliability of the computer-base modelling results was tested by the comparison with the geological data of the deposit.

2. A thermodynamic model of the deposit is connected with the interrelation of two heat flows: conductive ones from the ore-bearing masses and convective ones from the high-temperature ore-forming solutions. A conductive heat flow from the cooling rock-bearing mass will result in the temperature redistribution within the near-intrusive space; that will result in the formation of temperature fields within the ore-localizing medium.

The ore stockworks are formed in terms of functioning high-temperature ore-forming solutions, which are the heat carriers by the convective means; they influence the regularities of heat propagation within the bearing medium. In this case, certain interaction arises between the ore-forming and ore-localizing heat systems; it is the basis of a thermodynamic model of the deposit.

Propagation of a conductive heat flow was obtained by solving an equation of heat conductivity with the help of computer algebra system – Maple 10 [27]. This system was developed by a group of scientists dealing with symbolic calculations and organized by Keith Geddes and Gaston Gonnet in 1980 in the University of Waterloo, Canada. Numerical solution of the heat conductivity equation according to the abovementioned computer algebra system (Maple 10) is given in the form of graphic dependences of the temperatures of host medium and granite intrusion in time and space;

in its turn, that helps model and analyze the dynamics of a thermal field of the intrusive mass as well as its influence on the ore formation process at all its stages.

The reliability of the obtained results of the mathematical modelling was checked by the results of thermobarogeochemical studies of microinclusions in the minerals.

3. To systematize the ore-controlling factors of the localization of rare-metal ores, a logical method (analysis and synthesis) of the general scientific level of knowledge was adopted.

## 3. Results and discussion

The necessity to carry out the research in this area is based on the following: despite the fact that industrial mineralization in the context of the Syrymbet deposit is outlined within the northern-eastern flank (surface geochemistry and drilling, Kostanai geological company, 1996), it is not outlined towards the south-west. Ore mineralization is recorded (according to Kostanai prospecting and surveying party) within the area of 3-4 km more, preserving its uniform structural position; moreover, it has a tendency for deepening. The mineralization is not outlined to the depth; maximum depth of its intersection within the central part of the deposit (profile No. 71) is 578 m [14], [15].

A preliminary analysis of the geological materials shows that there are certain gaps in the determination of the boundaries of mineralization zones; thus, it is possible to predict new prospective areas within this deposit.

The represented scientific and research problems were solved sequentially as follows:

– analysis of the results of the developed computer-based models of the deposit;

– analysis of the constructed thermodynamic model of the deposit;

– systematization and complementing of the ore-controlling factors of the localization of rare-metal ores;

– singling out the prospective areas within the Syrymbet deposit.

*Analysis of the results of the developed computer models of the deposit.* As is known, digital models of the deposits (framed, blocked) not only visualize the ore body morphology and content of ore elements in it, but also identify the interconnection of localization of ore elements with the geological and structural features of the ore formation area. Owing to that, the ore-controlling factors of the deposit are complemented with a substance factor, the predictive-prospecting criteria – by the regularity of distribution of content of ore elements within the known ore bodies both along the strike and along the exploration-evaluation pits [28].

The main criterion of the mineralization of ore body boundaries in terms of Micromine computer modelling is the determination of cutoff grade content of an ore component. As for the deposit under consideration, the ore body boundaries were outlined according to the tin cutoff grade being 0.05%.

Geometrization and visualization of the ore bodies were performed basing on the obtained frame model of a general mineralized zone of the deposit; as a result, the following was emphasized (Fig. 1):

– morphology of a tin-bearing mineralized zone is of complex nature. It has considerable thickness and length with upswells and ore columns. A structure of the central part of the deposit is complex; it consists mainly of the main ore body and ore vein rocks that are feathering and parallel subconformable to the occurrence;

– generally, about 40 tin-bearing ore bodies are singled out within the ore zone (according to the geological data); their thickness varies from several up to 200 m. While distancing from the central part of the deposit, the ore body is divided into several branches, veins (Southern-Western, Northern-Eastern sites). They are clearly seen in the frame model of the mineralized zone;

– the tin-accompanying elements form a mineralized zone as follows: tantalum-niobium – within the endocontact share of the deposit, 200-300 m from the tin ore area as the geological data show; polymetallic ores – within the deposit flanks, especially within the southern-western flank they form an independent linear mineralized zone. These zones are not represented in the frame model.

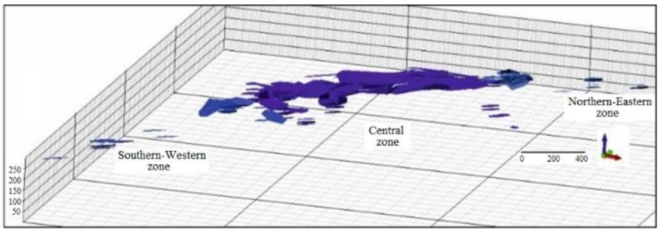


***Figure 1. Framed model of a general mineralized zone of the Syrymbet deposit in 3D format***

The Central part, where the ore stockwork is developed, demonstrates the most complex structure of the mineralization zone. In terms of computer modelling, geometrization of the Central area is as follows: length of a mineralized zone is 1200 m; its width is 230 m; and its thickness is up to 250 m.

A blocked model of the deposit visualizes the fact that tin content in the weathering crusts varies from 0.199 up to 2.335%; as for bedrocks, it reaches 1%; and the conditioned mineralization localizes within the exocontact part in the form of zones being from 50 up to 200 m (Fig. 2).

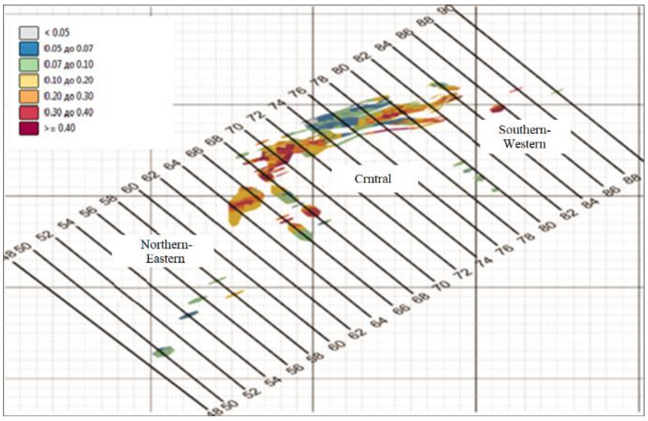


***Figure 2. Blocked model of the Syrymbet deposit with the survey profile (plan view)***

Besides, the model shows that there are certain regularities in the distributions of tin contents. Horizontally, one can observe its reduction from the Central share to the ore field flanks down to the cutoff one; the highest tin contents are found within the Central area where it reaches 1% and more. Vertically from the lower layer (clayey-rubble) of the weathering crust to the upper (clayey) layer, one can see the tin content growth from the cutoff one (0.05%) up to 0.30% and more. The richest weathering crust occurs above the primary ore columns; its maximum thickness reaches 50 m.

According to the geological data, Southern-Western and Central areas are of practical interest; that is proved by the results of 3D computer models of the deposit, i.e.:

– within the Southern-Western area of the deposit, it has been established, according to the results of tin visualization in terms of survey profile (2D sections), that certain regularity is observed within this site in the tin content distribution where its reduction towards the area flanks is recorded while the growth is fixed along with the depth. Here, the sites with rich tin content (from 0.30 to 0.40%) are observed along the profile No.58; in terms of survey profiles No. 54 and 60, tin contents have approximately similar values being up to 0.20% (Fig. 3).

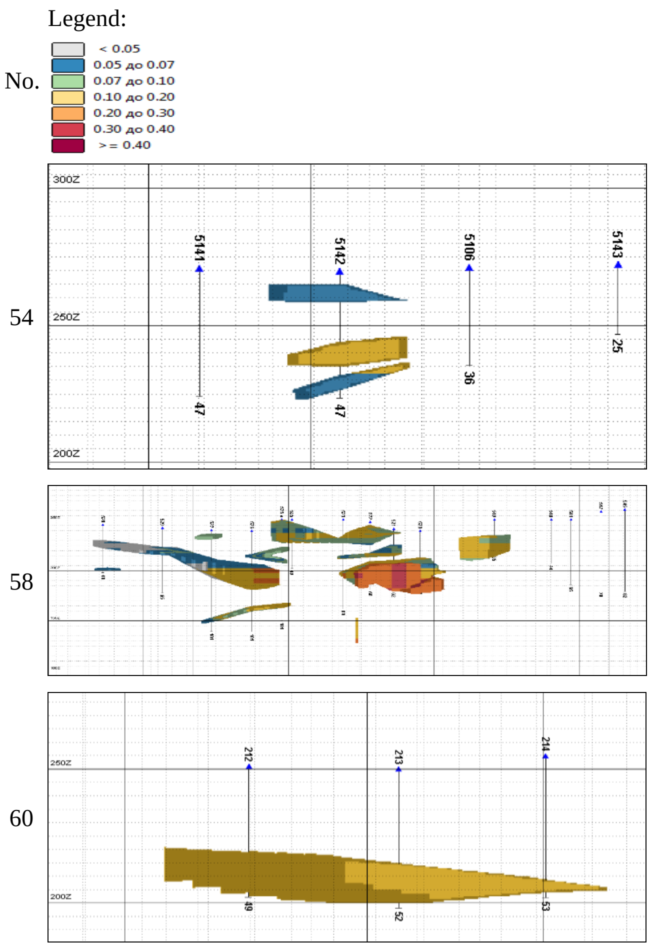


*Figure 3. 2D sections of a blocked model of the deposit within the Southern-Westerns site*

As for the geomechanical data, here a southern-eastern stripe of the geochemical anomaly, associated with the dome share of granite porphyres, passes [14], [15].

– within the Central part, the main reserves of the deposit are concentrates; visualization of the tin content throughout the survey profiles No. 68-73 shows that the tin content reaches 0.7%; down with the depth, high tin content is preserved;

– closer to the Northern-Eastern share (profile No. 78), the tin content decreases down to 0.07% (Fig. 4).

In this case, it should be noted that the obtained results of the interpretation of 2D sections of a block model in terms of the survey profiles demonstrate that each ore site is characterized by its own regularity, i.e.:

– within the Southern-Westerns site, one can observe decrease in the tin content towards the site flanks while with the increase it is observed along with the depth;

– within the Central site, high tin content is observed in all directions;

– within the Northern-Eastern site, decrease in tin content is seen towards the north as well as along with the depth.

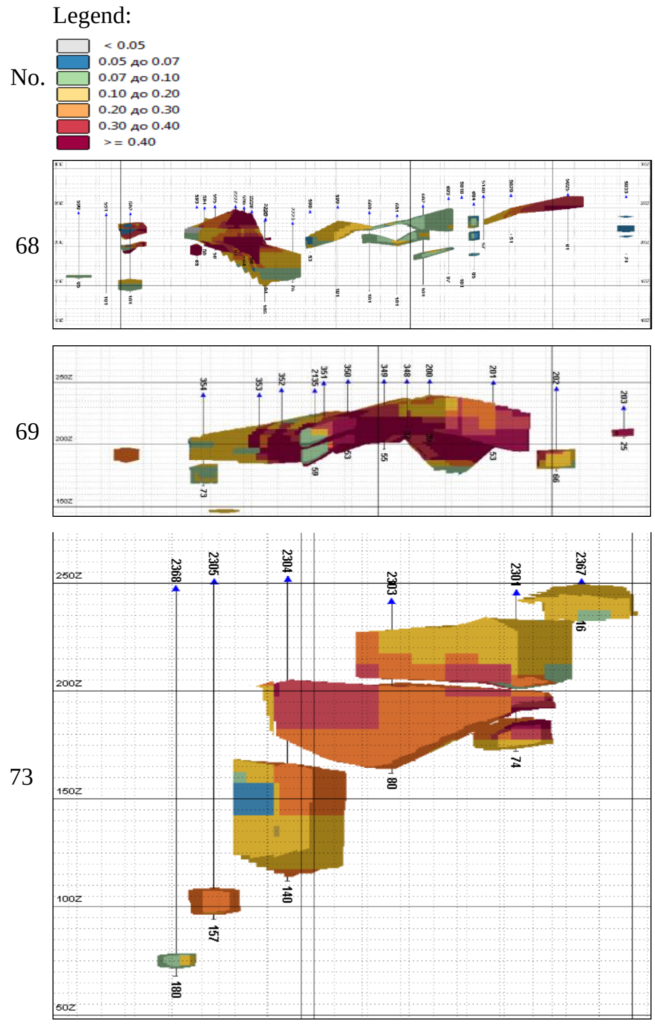


*Figure 4. 2D sections of a blocked model of the deposit within the Central site*

Consequently, the results of the computer modelling analysis coincide completely with the geological assumptions concerning the existing prospective areas within the deposit under consideration.

Thus, the analysis of the obtained three-dimensional computer models shows that much smaller-size ore bodies with high tin content are identified at deep levels (Fig. 1-4).

As for the geological data, they are localized within the endocontact share of granitoids, not united in the ore zones. The thickness of such bodies from the first meters is up to 15-30 m at the tin content being from 0.1 up to 1.0% and more. This fact predetermines the prospectivity of deep levels of the Central site of the deposit for the primary tin ore discovering. It should be also highlighted that according to the geological data all other rare-metal minerals (molybdenum, tungsten and others) are dissociated with tin to different extents; thus, it is expedient to evaluate deep levels not only for tin but also for the ores of other metals.

*Analysis of a thermodynamic model of the deposit.* Thermodynamic models of the endogenous deposits that consider changes in temperatures of the ore-forming and ore-localizing systems also identify the connections of mineralization with a thermal field of the ore-bearing intrusion. In this case, zones of isothermal stabilizations are the ore-controlling factors – the zones where a thermal field stays the same during a long period of time. Duration of the thermostatting zones is in direct proportionality with the mineralization scales; thus, the quickly crystallizing small intrusive bodies cannot provide the geologically significant time for the existence of the conditions that are favourable for metal concentration. They also do not possess the resources of thermal energy necessary for the ore-forming processes. The temperatures within the thermostatting zones should be in compliance with the most favourable conditions of the development of the indicated processes for each of the ore elements.

A thermodynamic model of the deposit along with its results reflects the main information on the energy state of the system in terms of rare-earth metal ore formation. According to the geological data, ore-bearing masses within the Syrymbet deposit are divided into two groups: the middle-late Devonian; boundary of the early and late Permian (355-392 mln years, 266-277 mln years). These age intervals tell about the formation of the zones of isothermal stabilization of temperatures within the contact zones and within two stages of the formation of ore-bearing rocks. The first one – with the invasion of granite-porphyre intrusion during the middle-late Devonian, under which effect the exocontact stockwork zone is formed; the second one – with the activation of hydrothermal activity at the boundary of the early and late Permian resulted in the formation of under-roof stockwork zones [29].

Development of a thermodynamic model of the deposit involved the use of regularities of temperature distribution within the host medium from the cooling granite-porphyre intrusion during the period of active ore formation and three-dimensional block model of the Syrymbet deposit with the visualization of tin content in the mineralized zone [21].

As it is seen, the zones with isothermal stabilization of temperatures within the range of 480-330°C in the endo- and exocontact areas facilitate the deposition of rare-metal ores at the deposit; and a mineralized stockwork with industrial mineralization with 50-250 m thickness is localized completely between these isotherms; according to the thermometry, they were formed at the temperatures of 330-280°C (Fig. 5).

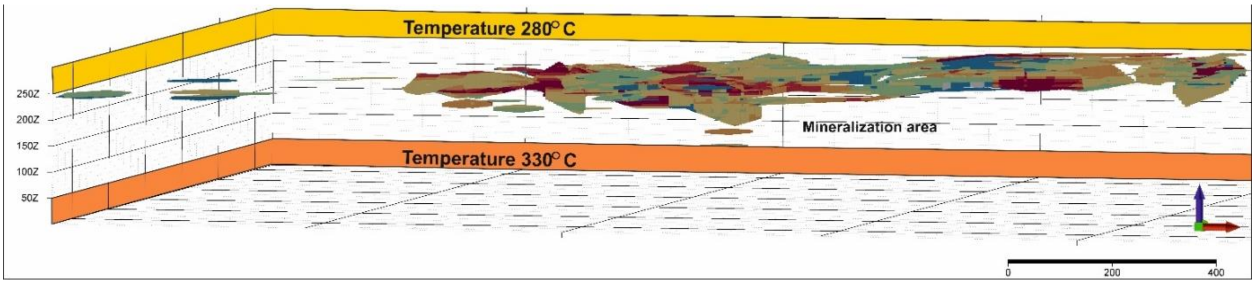


***Figure 5. Thermodynamic model of the deposit during the period of ore stockwork formation, with the visualized tin content***

The geological data make it possible to know well that the main share of the ore mass within the Syrymbet deposit is concentrated in the metasomatically changed rocks (skarns and greisens). As the modelling data show, the width of the aureoles of metasomatic changes within the zones of granite-porphyre exocontacts reaches 300 m; it is quite compatible with the area of tin-bearing ore propagation [21].

Convergence of the temperatures of ore mineral deposition with the temperature of the ore-deposition area and geometrical parameters of the ore formation zone is the indicator of a degree of reliability of the mathematical modelling.

*Systematization and complementing of the ore-controlling factors.* The analysis of the modelling has helped complement the ore-controlling factors with new data relative to the substance content and energy state of the ore object. Synthesis of the available and additional ore-controlling factors has resulted in their systematization in the context of the deposit under study [30]-[34] (Table 1).

***Table 1. Main ore-controlling factors and predictive-prospecting criteria in terms of the Syrymbet deposit***

| Main ore-controlling factors | Characteristics of the factors | Ore-bearing structures | Predictive-prospecting criteria |
|---|---|---|---|
| Structural-tectonic | Long-lived tectonic plate associated with the deep faults of the northern-eastern strike (Shok-Karagaiskyi, Kruglovskyi, Saumalkolskyi) | Geological medium of the localization of ore-bearing masses | Crush zones of tectonic faults |
| Lithological | Weathering crust, its thickness is from 0 to 50 m | Geological medium of the ore deposit localization | Weathering crust throughout the intrusive formations |
| Magmatic | Leucocratic graphite-porpheres of the middle-late Devonian Orlinogorskyi intrusive complex | Source of the rare-metal rare-earth mineralization | Exo-endocontacts of the granite-porphyre body of the Orlinogorskyi complex |
| Metasomatic | Kalifeldsparization, albitization, greisenization in granite-porphyres | Ore-bearing medium | Development of the metasomatic processes affected the intrusive rocks |
| Geophysical | Increased values of a magnetic field | Geological medium of the ore body localization | Positive magnetic anomalies under the ore zone |
| Substance | Regularities of content distributions in the ore bodies | Area of ore mineralizations | Tin content is more than 0.05% |
| Thermodynamic | High temperatures connected with the intrusion inbreaking | Zones of isothermal stabilization of the temperatures within the host medium | Temperature values within the thermostatting zones is within the range of 480-330°C |

*Singling out the prospective areas within the Syrymbet deposit*. Basing on the additional ore-controlling factors, the prospective areas within the deposit and local scale of the mineralization area occurrence have been singled out, i.e.:

– for tantalum-niobium and molybdenum mineralization, an endocontact albitized area is defined within the limits of 500-550 m where maximum temperatures of deposition of such minerals are within the range of 450°C; for mineralized stockwork – it is an exocontact area within the range of 300 m from the granite-porphyre contact with the formation temperature of 280-330°C; a vertical range of the mineralization area is estimated from 800 up to 850 m;

– dome parts of the granite-porphyre intrusions are the prospective area to discover rare-metal ores as this is the region where zones of isothermal stability are formed. The geological data demonstrate that the main mineralization is associated with the closest exocontact of granite-porphyres but other rare-metal elements (molybdenum, tungsten etc.) are dissociated with tin in different degree. That predetermines the estimations of deep levels not only for tin but also for ores of other metals;

– the results of computer and mathematical modelling aimed at singling out the prospective areas within the deposit can be combined into one schematic picture. As is known, the Syrymbet deposit like other rare-metal deposits of Kazakhstan are formed in the "intrusive-aboveintrusive zone" system. While using these geological materials, one can represent a schematic picture of the prospective area in vertical section taking into consideration the outlining of survey profiles on the actual data maps (Fig. 6);

– 2D sections of the deposit model visualizing the tin content within the survey profile sections also prove the prospects of deep levels of dome shares of granite-porphyres. In this case, it is possible to identify the prospective areas on the map of actual materials where the areas between the survey lines No.68-74 are outlined for the Central part (Fig. 7a) while the territory between the survey lines No. 54 (Fig. 7b) is defined for the Southern-Western area.

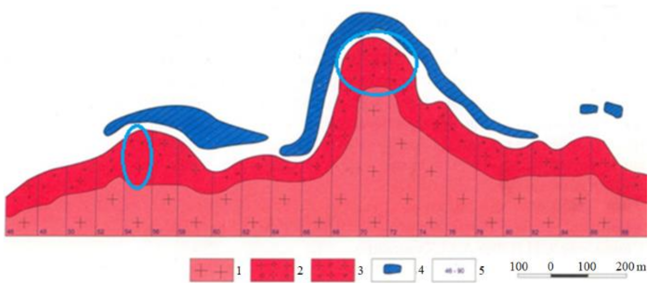


***Figure 6.*** ***Schematic of a vertical section of the prospective areas within the Syrymbet intrusion roof: 1-3 – leucocratic granites: 1 – porphyraceous medium-grained; 2 – fine-grained albitized; 3 – fine-grained greisenized; 4 – tin ore bodies; 5 – profile numbers***

The ore bodies are located within the apical areas of the ore-bearing intrusions and repeat consistently the shape of their roof. The main ore body of the deposit (65% of tin reserves) is associated with the central hump. This is supposedly the above-root section of the intrusion in the "root-dome" system. The southern-western hump of the intrusion, being less in its dimensions, is connected with the ore body being second in its size; and two small ore bodies are located above the northern-eastern dome.

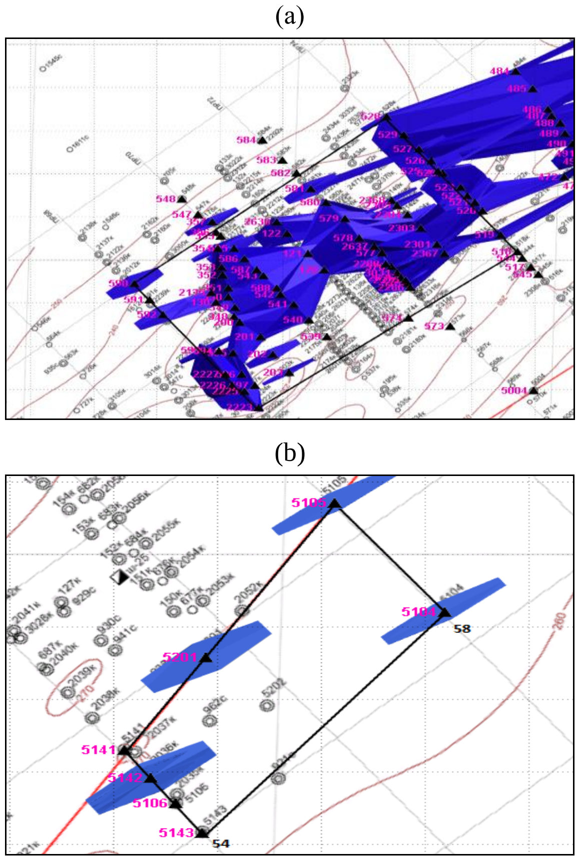


***Figure 7.*** ***Prospective areas defined on the actual data maps: (a) between the survey profiles No. 68-74; (b) between the survey profiles No.54-58; numbers of survey wells are in pink***

## 4. Conclusions

To systematize the ore-controlling factors of rare-metal ore localization, the methods of computer modelling for visualizing the morphology of ore bodies and their ore element content were used as well as the methods of mathematical modelling of the ore formation process to estimate the energy state of the ore-forming and ore-localizing systems.

The ore-controlling factors were complemented with new data with the resulting predictive-prospecting criteria. The prospective areas within the known Syrymbet deposit were singled out basing on the results of synthesis of model constructions and geological data. The synthesis of model constructions and geological data made it possible to define the prospective areas within the known Syrymbet deposit.

Practical implication of the model constructions in terms of ore endogenous deposits gives new opportunities as for interpretation of their formation; it also improves the forecasting technique in the theory of ore formation.

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## Рудоконтролюючі фактори як основа для виділення перспективних площ у межах рідкометалевого родовища Сиримбет, Північний Казахстан

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**Мета.** Прогнозування перспективних площ у межах родовища Сиримбет, виходячи із систематизації та доповнення рудоконтролюючих факторів локалізації руд і прогнозно-пошукових критеріїв.

**Методика.** Методика проведення наукового дослідження з цього напряму полягає у комплексному застосуванні емпіричного, теоретичного та логічного прийомів загальнонаукового методу наукового пізнання. Для моделювання рудних тіл і розподілу вмісту рудних елементів у них у 3D форматі використані методи комп'ютерного моделювання (GIS-Micromine). Для моделювання температурного поля рудоносного Сиримбетського масиву у 2D форматі застосовані методи математичного моделювання (Maple 10). Основні висновки були сформовані з аналізу та синтезу результатів, отриманих вищезазначеними методами.

**Результати.** Систематизовано та доповнено рудоконтролюючі фактори локалізації руд рідкісних металів за допомогою синтезу результатів: аналізу 3D моделей даного родовища з візуалізацією вмісту рудних елементів у межах рудних тіл та їх 2D зрізів за розвідувальними профілями, де отримано просторовий розподіл вмісту олова у вертикальному зрізі даного родовища; аналізу термодинамічних умов формування рудних штокверків, де враховуються температурні умови вміщуючих середовищ у галузі рудоутворення та інтервали температур рудовідкладення. Виділено перспективні площі у межах відомого родовища Сиримбет на основі результатів синтезу модельних побудов і геологічних даних.

**Наукова новизна.** Результати теоретичних наукових досліджень (комп'ютерного та математичного моделювання) засновані на емпіричних геологічних даних, вирішували не лише питання теорії рудоутворення, а й практичні завдання щодо вдосконалення методів прогнозування перспективних площ у межах родовища.

**Практична значимість.** Методика наукового дослідження із систематизації рудоконтролюючих факторів, яка може бути використана і для інших ендогенних рудних об'єктів.

***Ключові слова:*** *родовище, рідкісні метали, 3D моделі родовища, вміст рудних компонентів, фактори рудоконтролювання, термодинамічні умови, температурні поля*