GEOPHYSICS

**Original article**
**EDN: WRZDYU**
**DOI: 10.21285/2686-9993-2024-47-4-389-399**

# Using complex low-altitude unmanned aerogeophysical survey to refine medium-scale geological maps of Bodaibo synclinorium

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***Abstract.*** The purpose of the work is to demonstrate the possibility to clarify and correct medium-scale geological maps of precursors (scale 1:200000–1:50000) using low-altitude unmanned aerial geophysical survey which is the fastest and low-cost method of obtaining geological and geophysical data. A quantitative assessment is given to the more accurate identification of the location of geological boundaries and potential ore-bearing structures of the Sukhoi Log type. The first stage of geological study of the area involved obtaining the data from low-altitude unmanned gamma and aeromagnetic surveys. The survey results were prepared, interpolated, visualized, and, finally, subjected to geological and geophysical interpretation. Lineaments of the highest and lowest values, as well as the maximum gradients were identified in the magnetic field while the areas with the least variability at the lowest values and positive anomalies were identified in the gamma field. Interpretation and cross-comparison of the specified data allowed to compile new geological maps of the day surface and pre-Quaternary formations without any ground geological survey but based on the ideas about the geology of the region and characteristic differences in the physical properties of rocks. Taking into account regional stratigraphic and structural search criteria, two sites promising for gold mineralization were identi-fied in the studied area. It is shown that the known geological boundaries in these areas are shifted relative to the real ones by 100–1400 m (on average by 300 m), which is a significant error both in terms of mining and drilling operation planning and general correct understanding of the geological situation. The results obtained are typical for the projects aimed at gold exploration in the Bodaibo District of the Irkutsk region. The results of the study allow to conclude that the express and inexpensive method is useful for the specification of the position of geological and promising ore-bearing structures in the area under investigation, as well as for similar areas in nearby licensed areas and other sites of the Bodaibo synclinorium.

***Keywords:*** unmanned magnetic survey, unmanned gamma survey, lode gold, Sukhoi Log-style deposits, prospecting for ore deposits, geophysical data interpretation

***Acknowledgements:*** The author is grateful to the colleagues from the Institute of the Siberian School of Geosciences of the Irkutsk National Research Technical University and the A.P. Vinogradov Institute of Geochemistry SB RAS for their assistance in carrying out the research.

***For citation:*** Savchenko V.A. Using complex low-altitude unmanned aerogeophysical survey to refine medium-scale geological maps of Bodaibo synclinorium. *Earth sciences and subsoil use.* 2024;47(4):389-399. https://doi.org/10.21285/2686-9993-2024-47-4-389-399. EDN: WRZDYU.

ГЕОФИЗИКА

**Научная статья**
**УДК 3179**

# Применение комплексной маловысотной беспилотной аэрогеофизической съемки для уточнения среднемасштабных геологических карт Бодайбинского синклинория

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***Резюме.*** Целью работы являлась демонстрация возможности объективизации и корректировки среднемасштабных (1:200000–1:50000) геологических карт предшественников с помощью наиболее быстрого и доступного метода получения геолого-геофизических данных – маловысотной беспилотной геофизической съемки. Была дана количественная оценка повышения точности фиксации положения геологических границ и потенциально рудовмещающих структур сухоложского типа. На первой стадии геологического изучения площади получены данные маловысотных беспилотных гамма- и аэромагнитной съемок. Результаты были подготовлены, проинтерполированы, визуализированы, а затем подвергнуты геолого-геофизической интерпретации. В магнитном поле выделены линеаменты наибольших и наименьших значений, а также наибольших градиентов, в гамма-поле – области наименьшей изменчивости при наименьших значениях и положительные аномалии. В результате интерпретации и перекрестного сопоставления указанных данных (без проведения наземной геологической съемки) составлены новые геологические карты дневной поверхности и дочетвертичных образований, основанные на представлениях о геологии региона и характерных различиях физических свойств горных пород. С учетом региональных стратиграфических и структурных поисковых критериев на изучаемой площади выделено два перспективных на обнаружение золотого оруденения участка. Показано, что известные геологические границы на них смещены относительно реальных на 100–1400 м (в среднем на 300 м), что является весьма существенной погрешностью как с позиции планирования горных и буровых работ, так и с позиции общего правильного понимания геологической ситуации. Полученные результаты типичны для проектов по поиску месторождений золота в Бодайбинском районе Иркутской области. Итоги исследования позволяют сделать вывод о полезности экспрессной и недорогой методики для уточнения положения геологических и потенциально рудоносных структур изучаемой площади, а также для аналогичных обстановок на близлежащих лицензионных площадях и других участках Бодайбинского синклинория.

***Ключевые слова:*** беспилотная магниторазведка, беспилотная гамма-съемка, рудное золото, сухоложский тип, поиски рудных месторождений, интерпретация геофизических данных

***Благодарности:*** Автор выражает признательность за помощь в проведении настоящей работы коллегам из института «Сибирская школа геонаук» Иркутского национального исследовательского технического университета и Института геохимии им. А.П. Виноградова СО РАН.

***Для цитирования:*** Савченко В.А. Применение комплексной маловысотной беспилотной аэрогеофизической съемки для уточнения среднемасштабных геологических карт Бодайбинского синклинория // Науки о Земле и недропользование. 2024. Т. 47. № 4. С. 389–399. https://doi.org/10.21285/2686-9993-2024-47-4-389-399. EDN: WRZDYU.

## Introduction

Russia, unlike many other countries, is characterized by complete state of regional geological exploration of its territory. Nevertheless, the limits of scale levels of this exploration are 1:200000, in the best case – 1:50000. In order to design and conduct modern prospecting (especially mining) works, which are usually carried out on a scale of 1:10000 and larger, the information and cartographic basis of the corresponding level is required. Since nowadays prospecting works are realized mainly in difficult areas, often remote from infrastructure, there are questions about increasing the speed and reducing the cost of the early stages of geological study of areas at the stage when the feasibility of significant expenditures on geological exploration works has not yet been confirmed. Often prospecting areas are characterized by low exposure of bedrock due to permafrost, kurum and other obstacles that make geological mapping difficult. In this regard, the reliability and accuracy of geologic boundaries on the available medium-scale maps are questionable, and additional geologic traverses may take considerable time, but do not provide a significant increase in information relative to the predecessors. The possibility of obtaining objective data on the geological structure of areas even in the absence of bedrock outcrops is provided by some methods of geophysical exploration, in particular, magnetic, gravity, radiometric. In the last 8–10 years, the technologies of unmanned geophysics (performed with the help of unmanned aerial vehicles (UAVs)) have been rapidly developing [1–7], which make it possible to quickly and easily obtain data on areas with difficult pedestrian accessibility, at least in areas of tens of square kilometers, that is, having the size corresponding to an average licensed area. Data for such an area can be obtained in just a few days, potentially allowing hypotheses to be tested and existing information on the geologic structure of the sites to be refined with minimal financial and time investment. However, the question arises as to how fast remote geophysical methods without the organization of lengthy geological survey work can solve the problem of accurate and reliable geological mapping of new areas. In fact, it can be formulated as follows: to what extent at the early stage of geological exploration at present it is possible to do without field geologists, at least in those areas where their work is likely to be very difficult? The purpose of this study was to investigate the possibility and demonstrate the effectiveness of correcting the geological maps of the predecessors, significantly clarifying the boundaries of geological formations and structures of prospecting areas solely on the basis of remote sensing data using low-altitude UAV methods of magnetic and gamma-ray survey without any surface work. The geological conditions of the Bodaibo synclinorium, promising for the discovery of new lode gold deposits, were assessed [8–13].

The hypothesis of the study was that at the study site, as well as in the region under consideration as a whole, it is possible to use detailed, fast and cheap methods of UAV geophysical surveys to clarify the geological boundaries and position of stratigraphic units and structures promising for gold mineralization without conducting on-land geological mapping. In case of successful proof of the above possibility, the early stage of geological exploration can be significantly optimized, as individual gold prospecting licenses in the area usually have an area of 20–50 km$^2$ and, due to their small size, can be surveyed using UAV methods with minimal logistics costs without any problems.

## Materials and methods

The work considers a typical site within the Bodaibo synclinorium, including one of the most promising geological formations of this region [11, 14], namely, the upper pack of the middle sub-formation of the Aunakit Formation. Accurate mapping of the boundaries of this unit is of primary interest for prospecting [15, 16]. For this purpose, a low-altitude UAV airborne geophysical survey (magnetometry and radiometry) was conducted in the area, the results of which were analyzed and subjected to geological-geophysical interpretation.

To perform low-altitude surveys, the SibGIS UAS complex – a multirotor-type unmanned aerial vehicle with a POS family magnetometer on the suspension and a scintillation gamma-ray radiometer was used. The characteristics of the complex and the methodology of surveying, including in the conditions of the Bodaibo region [14], are described in detail in sources [1, 7]. Let us note the most important aspects, such as the absolute character of the magnetometer channel measurement with sensitivity in hundredths of nanotesla and absence of the need for software filtering of any interference to achieve precision accuracy of measurements and surveying with precise passing round of the terrain. They allow obtaining data with the accuracy necessary for the production of detailed maps of the transformant field, so that due to the accurate height retention the obtained information-mapping materials can be correctly interpreted without additional corrections. The survey height in this case was 40 m above the ground under the magnetometer sensor (44 m under the gamma-radiometer sensor), the frequency of gamma-field dose rate measurements was 0.5 Hz, for the magnetic total field it was 2 Hz, which made it possible to obtain data with a spatial resolution of about 4–5 m for the magnetic and 15–20 m for the radiometric channels.

The methodology complied with the main provisions of the "Methodological Recommendations for Low-Altitude Aeromagnetic Survey, 2018"[1] [17], the requirement to comply with which is imposed when conducting high-precision surveys. The terrain passing round is provided by following the pre-created digital terrain model.

As a basis for geological-geophysical interpretation of the magnetic and radiometric surveys, the data of predecessors on the geological structure of the site according to the 1:50000 scale map were used (Fig. 1). Six subformations of four Upper Riphean and Vendian formations are distinguished: Aunakit ($R_3au_3$), Vacha ($R_3v\check{c}_1$, $R_3v\check{c}_2$), Anangra ($V_1an_1$, $V_1an_2$), and Dogaldyn ($V_1dg_1$) [17]. They are represented by meta-sedimentary rocks of greenschist facies – silty and carbonaceous shales, siltstones, quartzites, sandstones and their interlayering [18]. All contacts are conformable and are distinguished by changes in the granulometric or mineral composition of rocks or in the proportions of their interbedding. The rocks deposited in compressed, almost isoclinal folds with sublatitudinal strike of steeply dipping axes. The dip of the flanks within the area ranges from 30 to 70°. According to a priori data, the thickness of the formations ranges from 100 (Vacha) to 500 (Anangra) meters.

Thus, at this site it is possible to estimate the increase of information from the use of UAV survey at the site with the maximum level of regional geological study (1:50000), while most often in the Russian practice it will be at best at the level of 1:200000.

Processing and interpretation of UAV-geophysical data was realized according to the following graph:

– making variation corrections to magnetic survey data;

– removal of service parts of routes (flights to and from the surveying area);

– interpolation and construction of digital models of initial fields;

– calculation of transformants and construction of the following set of cartographic materials: map of magnetic field values; map of magnetic

[1] Parshin A.V., Tsirel V.S., Rzhevskaya A.K. Guidelines for low-altitude aeromagnetic surveys (Russian Federal Agency for Subsoil Use, 2018) – the main points and the authors' comments // GeoBaikal 2018. P. 1–7. https://doi.org/10.3997/2214-4609.201802012.

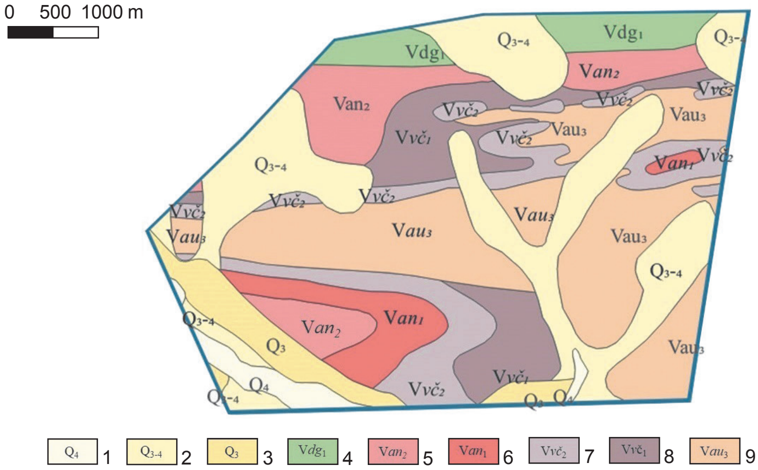


***Fig. 1. Geological map of predecessors:***
*1 – modern alluvial sediments; 2 – glaciolacustrine sediments; 3 – glacial, aqueoglacial sediments; 4 – Dogaldyn formation,lower subformation: sandstones, beds of siltstones and shales; 5 – Anangra formation, upper subformation: sandstones, beds of shales; 6 – Anangra formation, lower subformation: interbedding of shales and sandstones; 7 – Vacha formation, upper subformation: shales, sandstone beds; 8 – Vacha formation, lower subformation: shales; 9 – Aunakit formation, upper subformation: sandstones, interbedded silty shales*

***Рис. 1. Геологическая карта предшественников:***
*1 – современные аллювиальные отложения; 2 – озерно-ледниковые отложения; 3 – ледниковые, водно-ледниковые отложения; 4 – догалдынская свита, нижняя подсвита: песчаники, прослои алевролитов и сланцев; 5 – ананграская свита, верхняя подсвита: песчаники, прослои сланцев; 6 – ананграская свита, нижняя подсвита: переслаивание сланцев и песчаников; 7 – вачская свита, верхняя подсвита: сланцы, прослои песчаников; 8 – вачская свита, нижняя подсвита: сланцы; 9 – аунакитская свита, верхняя подсвита: песчаники, прослои алевритовых сланцев*

field pseudo-relief; map of horizontal magnetic field gradient; map of gamma radiation dose rate.

In addition, a satellite image of the site and a topo map at a scale of 1:50000 were used, visualization forms were selected, and the cartographic materials were interpreted. Figure 2 shows a map of magnetic total field values superimposed on a magnetic pseudo-relief with different azimuths of illumination corresponding to different strike of structures (visual and contrast combination).

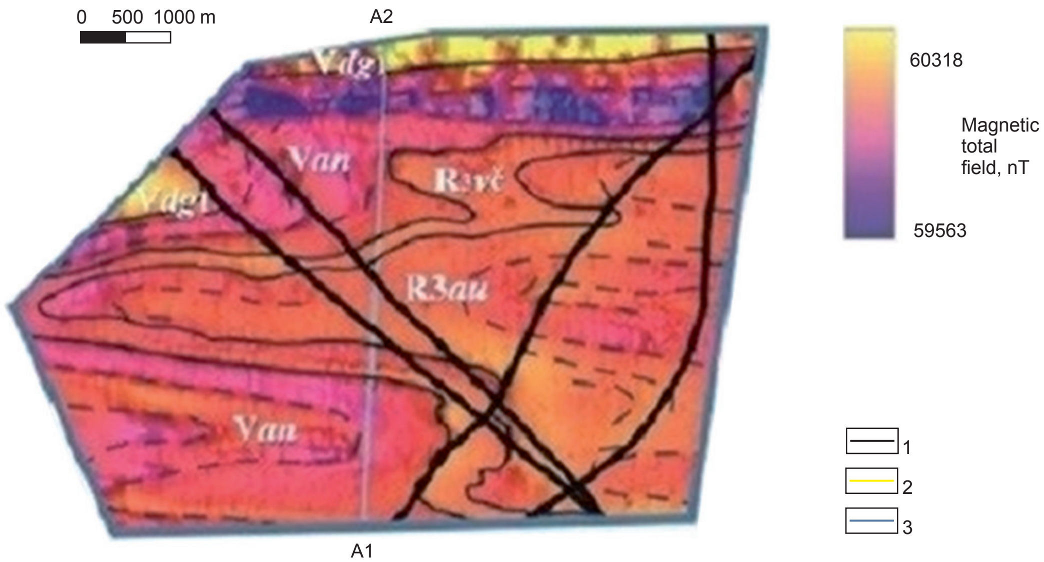


***Fig. 2. Map of magnetic field anomalies with lineaments:***
*1 – lines of maximum gradients; 2 – lines of maximum values; 3 – lines of minimum values*

***Рис. 2. Карта аномалий магнитного поля с линеаментами:***
*1 – линии максимальных градиентов; 2 – линии максимальных значений; 3 – линии минимальных значений*

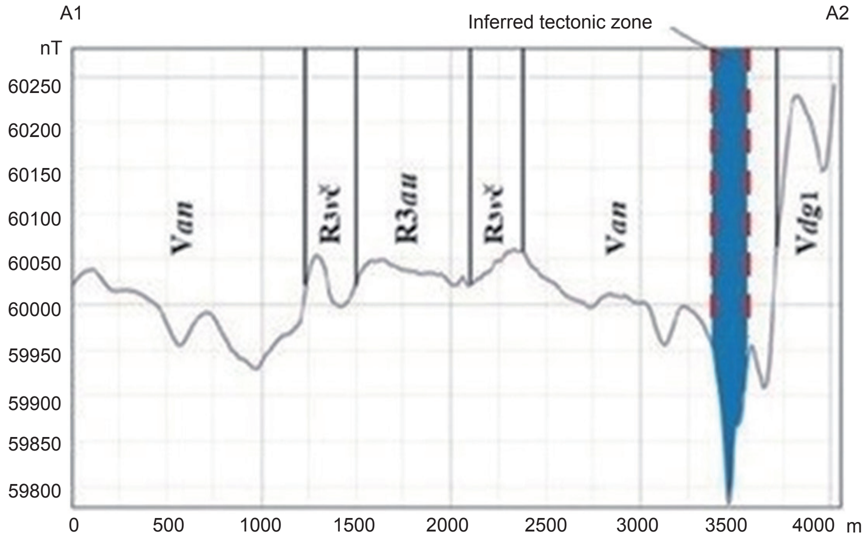


***Fig. 3. Graph of the magnetic total field modulus along the profile A1–A2 with preselected value ranges***
***Рис. 3. График модуля напряженности магнитного поля по профилю A1–A2 с предварительно выделенными диапазонами значений***

Other important sources of information were the profiles of the magnetic pseudo-relief across the structures (Fig. 3) and the map of magnetic field gradients.

As a result of comparative analysis of the available geological map and objective magnetic survey data, the vector layers of the geological map were transformed. The interpretation was based on a set of previously obtained data both on geological and petrographic parameters of formations of the area and on the results of interpretation of magnetic and radiometric survey data [1, 8–11, 14].

First of all, all lines of the largest field gradients and extremals of the largest and smallest values were drawn. According to the greatest readability, contrast and mutual complementation of these three types of lineaments, new inferred geologic boundaries were constructed. Between them, a number of lines, consistent with the assumed boundaries and, apparently, reflecting the internal structure of the folded rock layers, horizons of separate, relatively contrasting in magnetic field rock differences, were identified (Fig. 4).

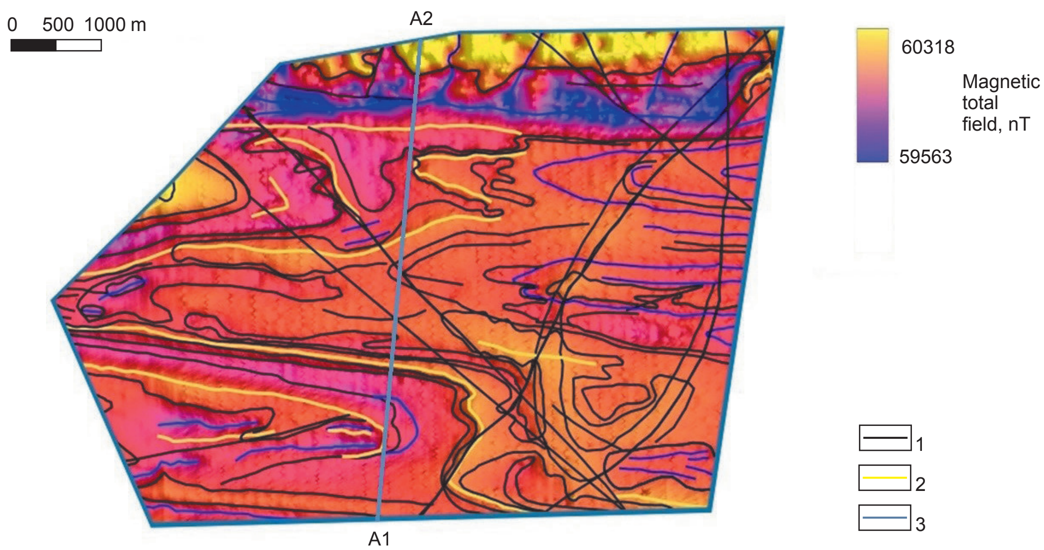


***Fig. 4. Map of magnetic field anomalies with lineaments of the maximum magnetic total field gradients and extrema lines of the highest and lowest values:***
*1 – lines of maximum gradients; 2 – lines of maximum values; 3 – lines of minimum values*
***Рис. 4. Карта аномалий магнитного поля с линеаментами наибольших градиентов напряженности поля и линиями экстремумов наибольших и наименьших значений:***
*1 – линии максимальных градиентов; 2 – линии максимальных значений; 3 – линии минимальных значений*

In the course of the study, four lines of change in values (mostly downward), gradients, and shapes of field structures partially distinguished in the relief were traced. Presumably, these are faults with displacement amplitudes that are insignificant on the map scale (when crossed, these structures do not cause visible displacements either for each other or for the selected folds). The disturbed belts, fracturing and disjunctive dislocations indicated on the map by predecessors (mostly parallel to the strike of the formations) are not detected in the magnetic field.

The magnetometric profile was used to determine the boundary values of the ranges and amplitudes of magnetic field variations (see Fig. 3) characteristic of the most reliably mapped geologic formations. The southwestern fragment of the geologic map was chosen as a reference area of this type, where, unlike other fragments, the boundaries best corresponded to the structures observed in the magnetic field and identified at the previous stage. The number of areas with a relatively monotonous field coincided with the number of mapped units, and the boundaries of the former and the latter were at a distance of up to 250 m, so the areas of the previously mapped and newly identified by magnetic data bedrock outcrops showed an overlap of 50 % or more. Based on this correspondence, the magnetic geological boundaries were delineated in the reference southwestern section and then extended to the north-northeast, where another sub-formation not observed in the south was delineated on the basis of unique values. The results of the analysis showed that the rocks of the Dogaldyn Formation are brightest in terms of the maximum values of the magnetic total field, and the rocks of the Anangra Formation are brightest in terms of the minimum values. The Aunakit and Vacha formations are distinguished by two transitional ranges.

It is important to note that this approach allows us to solve the issue of correcting the existing map, but not the problem of compiling a fundamentally new map, which is impossible, since the data that would allow us to directly reliably link the physical properties of rocks with their material composition are currently unavailable, so it is necessary to use at least the basic materials based on the results of predecessors. Such a task is also complicated by the integral character of the magnetic field, where the absolute measured value is influenced by the underlying rocks within the survey depth, which does not allow us to identify strict parameters close to petrophysical parameters [19].

The scheme of stratification was further modified. Figs 1–4 show that the width of outcrops of the Vacha Formation in the a priori map does not correspond to its proportions with the thicknesses of the overlying and underlying formations. As a result, the lower subformation of the Vacha Formation, which was identified by the predecessors as more monotonic in the magnetic field, was taken as the outcrops of the Vacha Formation proper. The upper subformation is attached to the Anangra Formation, composed of molassoids, unsorted and unconfined along strike metamorphosed clastic rocks, which in the magnetic field can also be distinguished by the greatest variability of properties: magnitudes and amplitude of changes in  magnetic total field both in thickness and along strike. The upper sub-formation of the Vacha Formation, which was identified earlier, is more likely to be related to the Anangra Formation, and its subdivision has been abolished due to insufficient data to substantiate it. The ages of a number of objects marked as Lower Vendian on the existing map were also corrected: the Aunakit and Vacha formations belong to the Upper Riphean, while the Anangra and Dogaldyn formations belong to the Lower Vendian [17, 20].

The gamma-field map (Fig. 5) was compared with the geological map of the predecessors, made on the basis of magnetic data of the new map of pre-Quaternary formations, as well as with a satellite image of the license area to identify and verify the formations defined in the gamma-field.

Among the pre-Quaternary formations, the Aunakit Formation of the Upper Riphean, which is promising for the target type of mineralization and which rocks are rich in potassium-bearing mica that determines its increased radioactivity due to the $^{40}K$ isotope [14], stands out most clearly in the gamma field due to its higher exposure than in other units (Fig. 6).

According to the minimum gamma-field values, the distribution fields of the most powerful Quaternary lake-glacial sediments, which overlap the bedrock and shield ionizing radiation from them, were determined. The other formations are not contrasted in the gamma field due to overlapping of different genetic types of Quaternary sediments and lower content of radioactive elements. Also, due to imaging at altitude, local gamma-activity anomalies from very thin (tens to first meters or less in thickness) structures – complications of folding of multiple orders characteristic of the regional geological situation – are smoothed out, which does not allow their reliable mapping.

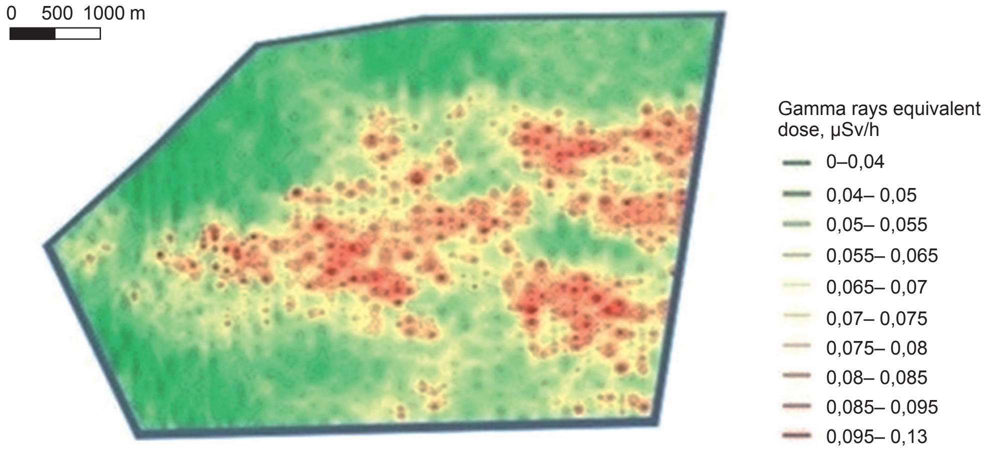


***Fig. 5. Gamma field map***
***Рис. 5. Карта гамма-поля***

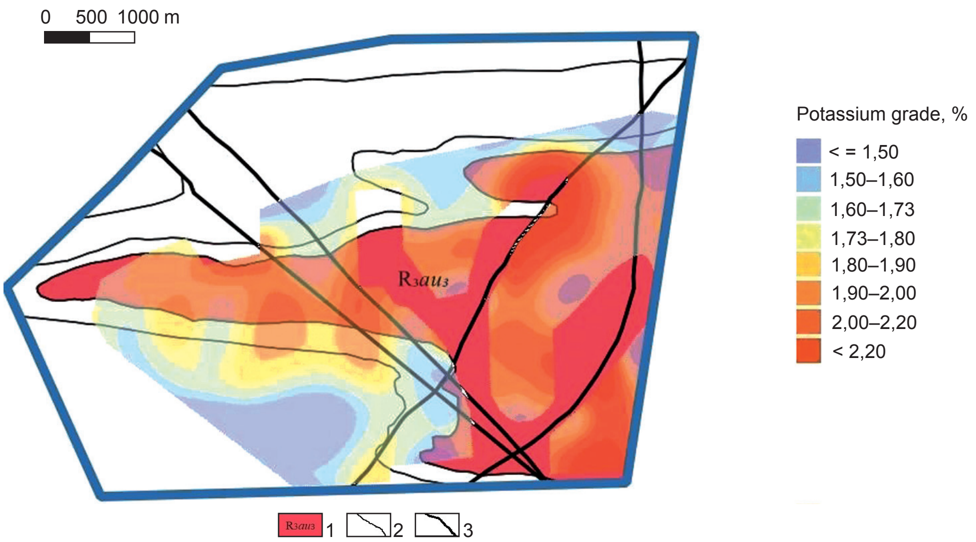


***Fig. 6. Potassium anomalies in comparison with the newly identified boundary of the Aunakit formation:***
*1 – Aunakit formation, upper subformation: sandstones, beds of silty shales;*
*2 – geological boundaries of other units; 3 – suspected faults*
***Рис. 6. Аномалии калия в сравнении со вновь выделенной границей аунакитской свиты:***
*1 – аунакитская свита, верхняя подсвита: песчаники, прослои алевритовых сланцев;*
*2 – геологические границы других подразделений; 3 – предполагаемые разрывные нарушения*

## Results and discussion

Based on the identification of outcrops of magnetically contrasting and monotonic rocks, comparison of geophysical data with each other and with the geological map of the predecessors, bringing the areas with certain ranges of magnetic properties in accordance with specific rock differences in the area with the best convergence of magnetic and previously mapped geological formations, new geological boundaries were drawn over the entire study area. As a result of the interpretation, a map of pre-Quaternary formations with inferred faults and a geologic map of the daylight surface were constructed.

The new geologic model agrees better than the previous one with the ideas about the structural geology of the area – the relationships between the geologic boundaries of the rocks of the conformable sequence have been corrected, the width of outcrops has been corrected taking into account the known maximum thicknesses of the observed layers [17]. In addition, smaller magnetically contrasting structures (packs) were identified within the mapped formations, which provides additional information on the internal structure of folded metasedimentary ore-bearing strata in case of the transition to the next stage of geological exploration. The Sukhoi Log-style of gold mineralization is characterized by confinement to the contacts of not only formations, but also their sub-formations and separate packs, so that geometrization of smaller geological bodies significantly increases the efficiency of detailed prospecting and evaluation.

Fig. 7 shows the comparison of the geologic map of the predecessors and the geologic map corrected during the presented research. The green rectangle indicates the reference area where the magnetic field lineaments and the boundaries of stratigraphic units were compared

a

b

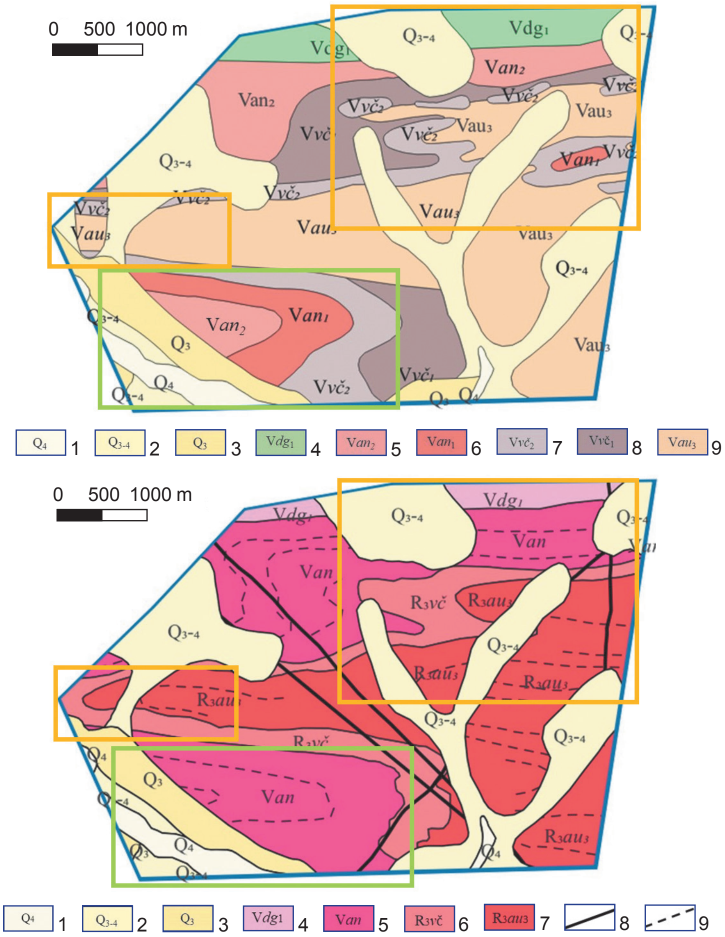


***Fig. 7. Comparison of geological maps based on the interpretation results of unmanned aerial surveys (with the lines of the largest magnetic field gradients):***

*a – predecessors map: 1 – modern alluvial sediments, 2 – glaciolacustrine sediments, 3 – glacial, aqueoglacial sediments, 4 – Dogaldyn formation, lower subformation: sandstones, beds of siltstones and shales, 5 – Anangra formation, upper subformation: sandstones, beds of shales, 6 – Anangra formation, lower subformation: interbedding of shales and sandstones, 7 – Vacha formation, upper subformation: shales, interbedded sandstones, 8 – Vacha formation, lower subformation: shales, 9 – Aunakit formation, upper subformation: sandstones, interbedded silty shales; b – final map: 1 – modern alluvial sediments, 2 – glaciolacustrine sediments, 3 – glacial, aqueoglacial sediments, 4 – Dogaldyn formation, lower subformation:sandstones, beds of siltstones and shales, 5 – Anangra formation: interbedding of shales and sandstones, 6 – Vacha formation: shales, interbedded sandstones, 7 – Aunakit formation, upper subformation: sandstones, interbedded silty shales, 8 – suspected faults, 9 – lines of the greatest magnetic field gradients*

***Рис. 7. Сопоставление геологических карт по результатам интерпретации беспилотной съемки (с линиями наибольших градиентов магнитного поля):***

*a – карта предшественников: 1 – современные аллювиальные отложения, 2 – озерно-ледниковые отложения, 3 – ледниковые, водно-ледниковые отложения, 4 – догалдынская свита, нижняя подсвита: песчаники, прослои алевролитов и сланцев, 5 – ананграская свита, верхняя подсвита: песчаники, прослои сланцев; 6 – ананграская свита, нижняя подсвита: переслаивание сланцев и песчаников, 7 – вачская свита, верхняя подсвита: сланцы, прослои песчаников, 8 – вачская свита, нижняя подсвита: сланцы, 9 – аунакитская свита, верхняя подсвита: песчаники, прослои алевритовых сланцев; b – итоговая карта: 1 – современные аллювиальные отложения, 2 – озерно-ледниковые отложения, 3 – ледниковые, водно-ледниковые отложения, 4 – догалдынская свита, нижняя подсвита: песчаники, прослои алевролитов и сланцев, 5 – ананграская свита: переслаивание сланцев и песчаников, 6 – вачская свита: сланцы, прослои песчаников, 7 – аунакитская свита, верхняя подсвита: песчаники, прослои алевритовых сланцев, 8 – предполагаемые разрывные нарушения, 9 – линии наибольших градиентов магнитного поля* in priority. The discrepancies between the original and corrected boundaries here are minimal compared to the rest of the area, the distances between them are from 0 to 240 m, on average – 100 m. The orange rectangles show the areas where the new boundaries were shifted most significantly, from 100 to 1400 m, with an average of 300 m. The importance of this reassessment is supplemented by the fact that these map fragments meet both stratigraphic and structural exploration criteria for the target type of mineralization, and their location was shifted by up to 1 km, which is critical for the planning of further prospecting.

## Conclusion

The results obtained in the course of the study show the possibility and expediency of using express and inexpensive methods of UAV-geophysics at the early stage of geological exploration. Based on the comparison of available medium-scale geological materials and objective UAV magnetic and gamma-ray data, it was possible to map pre-Quaternary rocks, faults, and Quaternary sediments. The detailed UAV magnetic aerial survey made it possible to correct the geologic map and the position of prospective structural and compositional complexes, and the UAV gamma survey made it possible to identify the distribution fields of the most thick Quaternary sediments and the boundaries of outcrops of the promising Aunakit Formation.

Thus, low-altitude UAV geophysical methods make it possible to quickly and inexpensively obtain detailed objective data about the site, which can be used to clarify the geological structure of the area, identify prospective zones and make decisions about moving to the next stage of exploration. The features used for this purpose are universal for the regional geological situation and are applicable to other license areas within the Bodaibo synclinorium. The importance of this type of work is confirmed by the fact that the location of actual geological boundaries may differ from their cartographic representation on 1:50000 scale maps by a distance of up to 1–1.5 km, in connection with which the planning of expensive ground surveys without preliminary objectivization of geological maps would definitely lead to significant costs or even the failure of the prospecting project due to the omission of prospective settings.

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## Conflict of interests / Конфликт интересов

The author declares no conflicts of interests.

Автор заявляет об отсутствии конфликта интересов.

*The final manuscript has been read and approved by the author.*

*Автор прочитал и одобрил окончательный вариант рукописи.*

## Information about the article / Информация о статье

The article was submitted 06.03.2024; approved after reviewing 20.11.2024; accepted for publication 12.12.2024.

Статья поступила в редакцию 06.03.2024; одобрена после рецензирования 20.11.2024; принята к публикации 12.12.2024.