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APPLICATION OF SENTINEL-2 SPECTRAL INDICES FOR REMOTE MAPPING OF ORE MINERALIZATION IN THE DEPOSITS OF EAST KAZAKHSTAN

Abstract. The paper discusses the application of Sentinel-2 multispectral data for remote mapping of ore mineralization within the open pit and waste dumps of the Nikolaevsk deposit, the underground workings and dumps of the Artemyevsk deposit, and the tailings facility of the Nikolaevsk processing plant. The aim is to assess the potential of integrated spectral index analysis for identifying mineralization within surface and underground mining areas of the largest polymetallic deposits in the Shemonaikha ore zone. A median composite for 2022–2023 was generated, and NDVI, Clay, Ferrous, Alunite, Brightness, and BSI indices were calculated. After normalization, a spectral anomaly map was produced and compared with mining contours and technogenic formations. High Clay, Alunite, and Ferrous values correspond to hydrothermal–metasomatic alteration zones.

Key words: Sentinel-2, spectral indices, remote sensing, polymetallic deposits, spectral anomaly mapping.

Шығыс Қазақстан кен орындарының минералдануын қашықтықтан картографиялау үшін Sentinel-2 спектрлік индекстерін қолдану

Аннотация. Мақалада Sentinel-2 мультиспектрлік деректерін пайдалану арқылы Николаев кен орнының карьері мен үйінділері, Артемьев кен орнының шахталары мен үйінділері және Николаев байыту фабрикасының хвостохранилищесі аумағында рудалы минералдануды қашықтықтан картографиялау қарастырылды. Зерттеудің мақсаты – Шемонаиха кенді аймағындағы ірі полиметалл кен орындарының жерүсті және жерасты тау-кен жұмыстары шегінде минералдануды анықтау үшін спектралдық индекстердің интегралды талдау әлеуетін бағалау. 2022–2023 жж. медианалық композит құрастырылып, NDVI, Clay, Ferrous, Alunite, Brightness және BSI индекстері есептелді. Нормализация негізінде спектралдық аномалиялар картасы жасалып, ол тау-кен қазбалары мен техногендік түзілімдермен салыстырылды. Clay, Alunite және Ferrous жоғары мәндері гидротермалдық-метасоматикалық өзгерістерге сәйкес келетіні көрсетілді.

Түйінді сөздер: Sentinel-2, спектралдық индекстер, қашықтықтан зондау, полиметалл кен орындары, спектралдық аномалияларды картографиялау.

Применение спектральных индексов Sentinel-2 для дистанционного картографирования рудной минерализации месторождений Восточного Казахстана

Аннотация. В статье рассматривается применение мультиспектральных данных Sentinel-2 для дистанционного картографирования рудной минерализации в пределах карьера и отвалов Николаевского месторождения, шахт и отвалов Артемьевского месторождения, а также хвостохранилища Николаевской обогатительной фабрики. Цель – оценка потенциала интегрального анализа спектральных индексов для выявления минерализации в зонах поверхностных и подземных горных работ крупнейших полиметаллических объектов Шемонаихинской рудной зоны. Построен медианный композит за 2022–2023 гг., рассчитаны индексы NDVI, Clay, Ferrous, Alunite, Brightness и BSI. На основе нормализации создана карта спектральных аномалий, сопоставленная с горными выработками и техногенными образованиями. Показано соответствие высоких значений Clay, Alunite и Ferrous зонам гидротермально-метасоматических изменений.

Ключевые слова: Sentinel-2, спектральные индексы, дистанционное зондирование, полиметаллические месторождения, картографирование спектральных аномалий.

Introduction and literature review

With the growing need for rapid and cost-effective exploration, the use of remotely sensed Earth observation (RSE) data for the initial identification of potentially mineralised zones is of particular relevance [1]. In traditional practice, mapping hydrothermal alteration and oxidised weathering zones requires extensive fieldwork and expensive spectral analysis techniques, which limits coverage of areas, especially in hard-to-reach areas.

Remote sensing, especially using Sentinel-2 multispectral data (10–60 m, VNIR and SWIR bands), has proven to be an effective tool for initial assessment of spectral-mineralogical anomalies associated with mineralisation due to free access to data and high spatial and temporal resolution [2]. Recent studies have demonstrated that Sentinel-2 is suitable for mapping iron oxides (hematite, goethite) and hydroxylated minerals due to the presence of narrow-focus VNIR and red-edge bands sensitive to iron and hydroxyl [3].

Anifadi et al. used Sentinel-2 together with ASTER and Hyperion to delineate hydrothermal alteration zones (clay and aluminosilicate minerals) on the Tibetan Plateau [4]. Ge et al. conducted a study in the Cuprite area (Nevada), showing that Sentinel-2-based indices (Ferrous, Ferric oxides) reliably identify iron-bearing minerals [5]. In Indonesia, Purwadi et al. successfully detected rare earth minerals in mining tailings using Sentinel-2 MSI [6].

In 2024, Abdelkader et al. integrated Sentinel-2 and ASTER data to improve lithological mapping in the shortwave infrared [7]. In addition, a review by Shirmard et al. emphasises that smart processing techniques, including machine learning, enhance the potential of satellite data to build mineralisation prospectivity maps [8]. In parallel, recent studies emphasise the digitalisation of mining operations and the integration of geoinformation systems as part of the overall technological transformation of the sector [9].

Thus, recent literature confirms that Sentinel-2 is capable of detecting spectral signatures of hydrothermal alteration, iron oxides and clay minerals – using indices similar to those applied in this study (NDVI, Ferrous, Alunite, Clay, Brightness, BSI). These approaches effectively complement traditional field methods, especially at the early stages of geological exploration and in remote regions [10].

The Shemonaikha ore zone is characterized by a complex geological structure, a variety of ore types, and a high level of geological exploration, making this region an optimal testing ground for satellite-based mineralization detection. It comprises four ore fields, comprising over 80 ore bodies. The largest of these are the Artemyevsk and Nikolaevsk polymetallic deposits (copper, lead, zinc, gold, and silver), whose ores are processed at the Nikolaevsk processing plant.

The Nikolaevsk deposit is a pyrite-polymetallic (volcanic-sedimentary) deposit of the Altai ore type (similar to the Kuroko type). It is confined to the Nikolaevsk volcano-tectonic depression. The ore bodies occur in rocks of the Nikolaevsk suite (Middle Devonian), represented by acidic effusive rocks (rhyolites). The ore bodies are represented by huge lenses of massive pyrite ores with high copper content and associated lead and zinc. Gold, silver, selenium, and tellurium are also present. The deposit was initially mined using open-pit mining (the famous Nikolaevsk quarry); later, underground mining of the remaining reserves was adopted.

The Artemyevsk deposit is located in a deeply buried block of the same structure. Mineralization is confined to the contact of felsic and basic volcanics, often controlled by shear zones and faults. The deposit is characterized by more complex metasomatic transformation of the ores and belongs to the gold-copper-polymetallic type. The ores at the deposit are complex (*Cu, Zn, Pb, Au, Ag*). It differs from the ores of the Nikolaevsk deposit in having higher gold and zinc grades, as well as a significant proportion of cuprous ores in the lower horizons. The deposit is currently mined exclusively using underground mining. Development is carried out through vertical shafts using modern systems with goaf backfill. However, space maps near the deposit show a significant number of waste dumps.

The objective of the study is to evaluate the capability of Sentinel-2 integral analysis of spectral indices for mapping mineralisation features and to develop an approach to quantitative validation and filtering of false positive anomalies.

Research Objectives:

1. Calculate diagnostic spectral indices (NDVI, Clay, Ferrous, Alunite, Brightness, BSI) for selected deposits;
2. Construct an integral map of spectral anomalies and compare it with known contours of ore bodies;
3. Quantify the coincidence of anomalies with ore contours and the proportion of false positives;
4. Develop and test rules for filtering out false anomalies.

Methods and materials

Satellite data. Multispectral Sentinel-2 satellite images provided by the European Space Agency through the USGS Earth Explorer platform were used as input data. To improve the reliability of interpretation and minimise the influence of cloud cover and atmospheric distortions, a median composite scene was generated for the period 2022–2023, providing a stable representation of the spectral characteristics of the Earth's surface.

Pre-processing. Processing included atmospheric correction, calculation of spectral indices and visualisation of the results using QGIS and ENVI. All indices were normalised to the range [0, 1] using formula (7) to ensure comparability of values.

Diagnostic spectral indices. In the present study, diagnostic spectral indices were used to identify mineralogical anomalies, which is consistent with modern approaches to spectral mapping. Within the framework of this study, six Sentinel-2-based spectral indices were calculated:

1. NDVI (Normalised Difference Vegetation Index) – vegetation cover indicator;

2. Clay Index – sensitive to clay minerals;
3. Ferrous Index – reflects the content of iron-containing minerals;
4. Alunite Index – reveals hydrothermal minerals (alunite, sericite);
5. Brightness Index – characterises the overall reflectivity of the surface;
6. Bare Soil Index (BSI) – identifies exposed soils and rocks.

Formulas and spectral channels follow ESA recommendations for Sentinel-2 and are given in subsections NDVI, Clay, Ferrous, Alunite, Brightness, BSI.

NDVI (Normalised Vegetation Index). One of the most widely used indices designed to estimate vegetation density and soil moisture. It is calculated using the formula:

$$NDVI = \frac{NIR - Red}{NIR + Red}, \quad (1)$$

where Band 8 (*NIR*, 842 nm) and Band 4 (*Red*, 665 nm) channels are used for Sentinel-2.

NDVI values range from -1 to +1, where positive values indicate the presence of vegetation and near zero or negative values indicate exposed surfaces or water bodies. In this study, NDVI was used to exclude vegetated areas and to highlight exposed bedrock.

Clay Index. This index is used to identify areas with high content of clay minerals such as kaolinite, illite and smectite. The index is calculated as the ratio of near and mid-infrared reflectivity:

$$Clay\ Index = \frac{SWIR_1}{SWIR_2}, \quad (2)$$

where Band 11 (*SWIR₁*, 1610 nm) and Band 12 (*SWIR₂*, 2190 nm) channels are used for Sentinel-2.

Clay minerals have a characteristic absorption around 2.2 μm, making this index effective in delineating zones of hydrothermal alteration.

Ferrous Index. The index is designed to identify areas with increased content of secondary ironbearing minerals such as hematite and goethite. These minerals are characterised by high reflectivity in the shortwave infrared range and reduced reflectivity in the near infrared. The index formula is:

$$Ferrous\ Index = \frac{SWIR_1}{NIR}, \quad (3)$$

where Band 11 (*SWIR₁*, 1610 nm) and Band 8 (*NIR*, 842 nm) channels are used for Sentinel-2.

Elevated index values may indicate zones of oxidation, weathering with accumulation of ferruginous compounds and tectonic disturbances. In the study, this index was used to highlight oxidised weathering zones and potential ferruginous anomalies.

Alunite Index. The index is used to map minerals of hydrothermal origin such as alunite, sericite and kaolinite (Yamaguchi, 2003). These minerals show pronounced spectral absorption in the range of about 2.2 μm.

The index is calculated using the formula:

$$\text{Alunite Index} = \frac{\text{SWIR}_2}{\text{SWIR}_1}, \quad (4)$$

where Band 12 (SWIR_2 , 2190 nm) and Band 11 (SWIR_1 , 1610 nm) channels correspond to Sentinel-2.

Elevated index values may be indicators of zones of advanced argillisation, often associated with epithermal and porphyry systems. In the study, this index was used to highlight zones of hydrothermal alteration.

Brightness Index. The index reflects the overall brightness of the surface and is used to identify areas with highly reflective light-coloured rocks such as quartz, salts and carbonates (Qiu, 2017). One formula is the square root of the sum of the squares of the reflectance squares in the visible range:

$$\text{Brightness Index} = \sqrt{\text{Red}^2 + \text{Green}^2 + \text{Blue}^2}, \quad (5)$$

where Band 4 (**Red**, 665 nm), Band 3 (**Green**, 560 nm) and Band 2 (**Blue**, 490 nm) channels were used for Sentinel-2.

Elevated brightness values may indicate light-coloured quartz-sericite alteration, leach zones or exposed salts. In the context of this study, the index was used to highlight highly reflective zones with possible lithochemical anomalies.

Bare Soil Index. The index aims to highlight areas with minimal vegetation cover and maximum soil or rock exposure (Mzid, 2021). The formula used takes into account the difference between $\text{SWIR} + \text{Red}$ and $\text{NIR} + \text{Blue}$ components:

$$\text{BSI} = \frac{(\text{SWIR}_1 + \text{Red}) - (\text{NIR} + \text{Blue})}{(\text{SWIR}_1 + \text{Red}) + (\text{NIR} + \text{Blue})}, \quad (6)$$

where Band 11 (SWIR_1 , 1610 nm), Band 4 (**Red**, 665 nm), Band 8 (**NIR**, 842 nm) and Band 2 (**Blue**, 490 nm) were used for Sentinel-2.

BSI values above zero correspond to bare surfaces not covered by vegetation. In the study, the index was used to highlight exposed areas suitable for further geospectral analysis.

Integral spectral anomaly map. For a comprehensive assessment of spectral anomalies potentially associated with zones of mineralisation, an integral approach based on the summation of normalised values of spectral indices has been implemented as part of this study. This method allows to aggregate the information obtained on various geologically significant features (vegetation, exposed rocks, clay and ferruginous minerals, hydrothermal alteration, etc.) and reflect it in the form of a single integral map of anomalies.

At the first stage, all calculated spectral indices were brought to a single scale (from 0 to 1) by linear normalisation using the formula:

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}}, \quad (7)$$

where X is the initial index value;

X_{min} and X_{max} are the minimum and maximum index values within the whole scene.

The normalised values for each index were then summed pixel by pixel to construct an integral spectral anomaly map reflecting the cumulative intensity of occurrences associated with the ore occurrences.

The final step involved grading the anomalous values to interpret the results. Based on the statistical distribution of pixel values of the integral map (using quantiles), three classes were identified:

1. *Background value* – values lying within the lower 60% of the distribution;
2. *Weak anomaly* – values between the 60th and 85th percentile;
3. *Strong anomaly* – values above the 85th percentile.

This approach allows us not only to localise potentially promising areas, but also to quantify the severity of anomalies. In the future, the results can be compared with geological data, field observations or geophysical surveys to refine the forecast.

Quantitative validation. In order to objectively assess the quality of the identified anomalies, validation was performed using spatial intersection of known ore occurrence points (and non-ore control points) with the classified anomaly map. The following metrics were calculated: Precision – the proportion of anomalous points correctly corresponding to ore occurrences; Recall – the proportion of ore occurrences captured by anomalies; and F1-score – the harmonic mean of Precision and Recall.

This allowed us to quantify both the ability of the method to capture known zones of mineralisation and the level of false positives.

Study area. The quarry and mine dumps of the Nikolaevsk deposit, the mines and mine dumps of the Artemyevsk deposit, and the tailings of the Nikolaevsk processing plant, located within the Shemonaikha ore zone, which is a large mineragenic taxon of Rudny Altai, were selected as the objects of study (Figure 1).

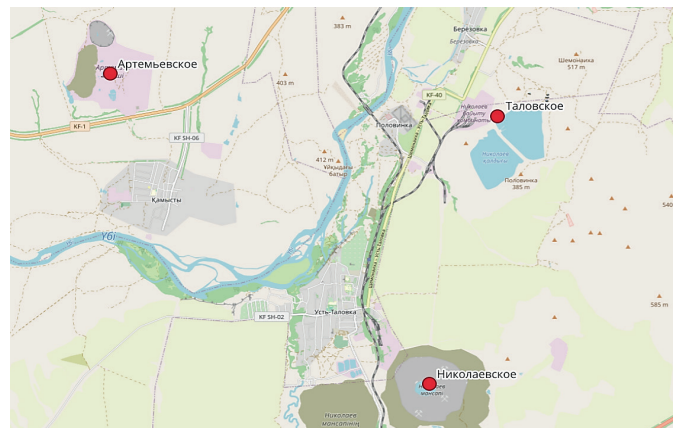


Figure 1. The study area with the location of the quarry and mine dumps of the Nikolaevsk deposit, mines and mine dumps of the Artemyevsk deposit, and the tailings storage facility of the Nikolaevsk processing plant.
Сурет 1. Николаев кен орны карьері мен үйінділері, Артемьев кен орны жерасты қазбалары мен үйінділері және Николаев байыту фабрикасының хвостохранилищесі орналасқан зерттеу аумағы.
Рис. 1. Район исследования с расположением карьера и отвалов Николаевского месторождения, шахт и отвалов Артемьевского месторождения, а также хвостохранилища Николаевской обогатительной фабрики.

Results and Discussion

A study of six Sentinel-2 spectral indices was conducted to identify spectral signatures of mineralized zones within the quarry and waste dumps of the Nikolaevsk deposit, the mines and waste dumps of the Artemyevsk deposit, and the tailings storage facility of the Nikolaevsk processing plant. The value ranges reported below refer to the original (non-normalised) index values; normalisation to [0, 1] was applied only for the integral anomaly map. Whilst these areas have been studied, the objective of the study was to establish the extent to which remote sensing can capture geologically significant anomalies by spectral characteristics without the use of additional geological and structural data.

The results obtained showed that spectral indices allow differentiating areas with pronounced signs of hydrothermal alteration, outcrops of sulphide mineralisation and anthropogenic impact. Interpretations for each of the indices are summarised below and also there are maps of the distribution of each of the indices reflecting various aspects of vegetation, mineralisation and surface geological features (Figure 2–7).

NDVI (vegetation index). NDVI values range from -0.31 to 0.60, reflecting the contrast between anthropogenically disturbed areas and areas of stable vegetation cover. The minimum values reliably indicate areas of open-pit mining and mineral processing, including the quarry and mine dumps of the Nikolaevsk deposit, the mines and mine dumps of the Artemyevsk deposit, as well as the tailings storage facilities of the Nikolaevsk processing plant. The highest values are observed along floodplains and pastures, confirming the sensitivity of NDVI to the extent of vegetation degradation. The index, although not specific to ore occurrences, allows differentiating technogenic objects within the deposits.

Clay Index (Clay Index). The index range (0.80 to 1.73) is characterized by localized maxima forming concentric halos around the quarry and man-made formations of the Nikolaevsk deposit, the mines and waste dumps of the Artemyevsk deposit, and especially the tailings ponds of the Nikolaevsk processing plant. These halos correspond to kaolinite-hydromica mineral associations accumulating in waste dumps and

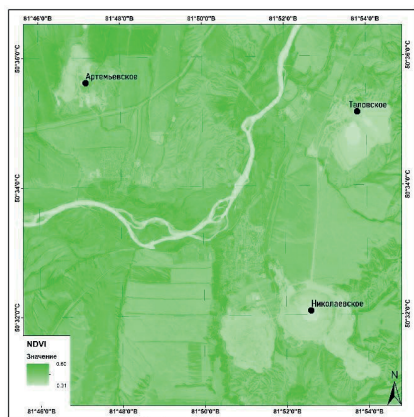


Figure 2. NDVI map.
Сурет 2. NDVI индексінің картасы.
Рис. 2. Карта индекса NDVI.

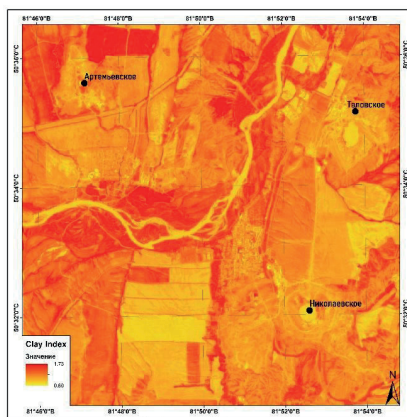


Figure 3. Clay Index map.
Сурет 3. Clay Index индексінің картасы.
Рис. 3. Карта индекса Clay Index.

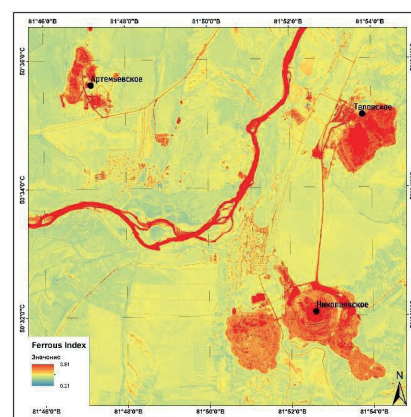


Figure 4. Map of Ferrous Index.
Сурет 4. Ferrous индексінің картасы.
Рис. 4. Карта индекса Ferrous.

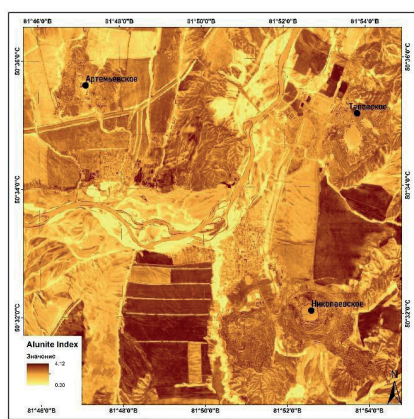


Figure 5. Alunite Index map.
Сурет 5. Alunite индексінің картасы.
Рис. 5. Карта индекса Alunite.

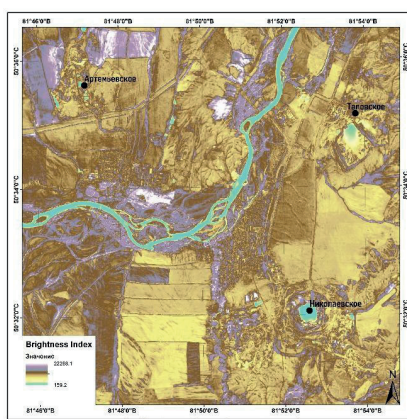


Figure 6. Brightness Index map.
Сурет 6. Brightness индексінің картасы.
Рис. 6. Карта индекса Brightness.

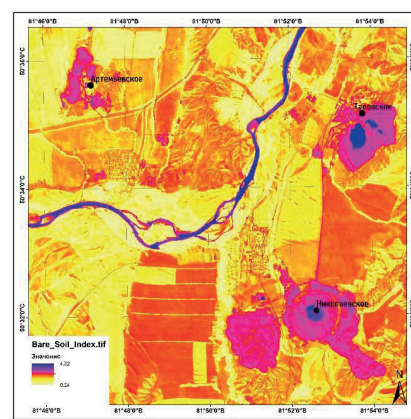


Figure 7. BSI (Bare Soil Index) map.
Сурет 7. Жалаң топырақ индексі (BSI) картасы.
Рис. 7. Карта индекса голый почвы (BSI).

tailings, as well as being localized within the quarry walls that expose «iron hat» zones formed by the weathering of sulfide ores. High clay index values are also typical of agrolandscapes and river valleys, where a thick cover of Cenozoic loose deposits of eluvial and alluvial origin is developed.

Ferrous Index (Ferrous Mineral Index). Index values range from 0.21 to 3.91 and spatially coincide with mine waste dumps and quarries, as well as the tailings of all three man-made sites. The highest values are recorded within the quarries, due to the presence of oxidation products of iron-containing sulfides (hematite, limonite) exposed during mining operations. The sublatitudinal strike of the linear anomalies correlates with the direction of tectonic and mineralised zones of the sulphide-polymetallic formation. It should be noted that the index is sensitive mainly to oxidation products, but not to sulphides themselves, which imposes restrictions on its application in poorly penetrated areas.

Alunite Index (Alunite Index). Alunite index values reach 4.12, with the highest intensity observed in agricultural landscapes. These values correspond to quartz-sericite-alunite mineralization, typical of high-sulfate eluvial systems formed by metasomatically altered volcanic rocks rich in potassium feldspars (such as rhyolites, dacites, and andesites) widely distributed around deposits. In the quarry of the Nikolaevsk deposit and within its waste dumps, the mines and waste dumps of the Artemyevsk deposit, and the tailings ponds of the Nikolaevsk processing plant, this index attains moderate values (~1.32), which may be related to the less intense development of alunite mineralization in the oxidation zones of pyrite-polymetallic deposits. High sensitivity of the index to the presence of secondary aluminosilicates is noted, but the reliability of the estimation depends on the degree of rock exposure.

Brightness Index. The Brightness Index shows a wide range of values (159.2 to 22,268.1), with extreme peaks within quarries, dumps and other anthropogenic sites. This magnitude is expected because the index was computed from scaled surface reflectance values ($\times 10,000$), rather than from 0–1 reflectance. This index serves as a reliable marker of open disturbed surfaces, including oxidation zones associated with «iron hats». High correlation with anthropogenic load maps confirms the index's effectiveness in identifying areas disturbed by mining.

BSI (Bare Soil Index). The Bare Soil Index ranges from 0.73–3.03 and shows similar patterns to the Brightness Index. The main anomalies are concentrated within the quarries where there is no vegetation cover and rock is exposed. The combined use of BSI and Brightness Index can reliably highlight anthropogenic objects, however these indices are not specific to mineralisation.

Integral analysis and anomalous zones. An integral spectral anomaly map (Figure 8) and the corresponding classified spectral anomaly map (Figure 9) were constructed from the normalised values of the six indices.

The integral spectral anomaly map (range of values: 0.73–3.04), constructed by summing the normalised values of the six spectral indices, showed high sensitivity to different types of alteration associated with natural mineralisation and anthropogenic sites.

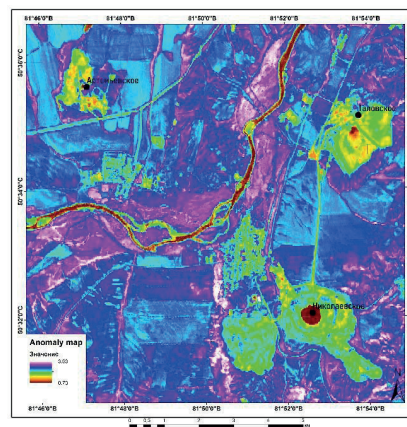


Figure 8. Integral spectral anomaly map.

Сурет 8. Интегралдық спектралдық аномалиялар картасы.

Рис. 8. Карта интегральных спектральных аномалий.

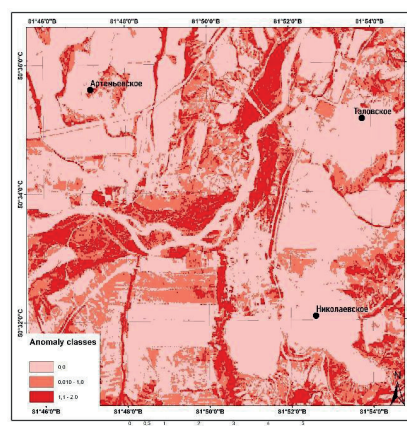


Figure 9. Classified spectral anomaly map.

Сурет 9. Классификацияланған спектралдық аномалиялар картасы.

Рис. 9. Карта классифицированных спектральных аномалий.

Anomalies corresponding to known man-made features were identified:

1. Tailings ponds of the Nikolaevsk processing plant (**Cu-Pb-Zn-Au-Ag**) – pronounced Clay + Alunite + Iron triad, with a maximum integral value of 3.04;

2. Mine dumps and shafts of the Artemyevsk deposit (**Au-Cu-Pb-Zn**) – predominance of the Iron and Brightness indices (3.01), indicating exposed oxidized sulfide zones;

3. Mine dumps and quarry of the Nikolaevsk deposit (**Cu-Pb-Zn-Ag**) – moderate manifestation of the Iron + BSI anomaly (2.63), likely due to weak erosive collapse of the ore bodies.

Also, false signals have also been localised:

1. Anomalies of fluvial genesis (up to 2.8) are interpreted to be the result of redeposition of clay and *ferrous* fractions (*Clay*↑, *Ferrous*↑) leached from primary sources;

2. Technogenic objects (road network, settlements) are characterised by a combination of high *Brightness* and *BSI* values with no *Alunite* signal, which allows their effective screening.

3. Agricultural landscapes around pyrite-polymetallic deposits are distinguished by high values of the alunite index, which indicates the accumulation of alunite mineralization here.

Validation of the above-described methods for identifying pyrite-polymetallic deposits within Rudny Altai deserves special attention. For this purpose, the area near the Nikolaevsk and Artemyevsk deposits was surveyed using Sentinel-2 multispectral imagery. This revealed an area with iron values of 3.5 and alunite values of 1.6, along with lower BSI values of < 0.3 , indicating a potentially promising target. This area coincides with the Kamyshensk pyrite-polymetallic deposit, whose mineralization is confined to the vent of a Middle and Late Devonian paleovolcano composed of rhyolites and basalts. The ores of this deposit are complex, including copper, lead, and zinc. The deposit is characterized by vertical zoning: from top to bottom, barite-galena-sphalerite ores give way to pyrite-chalcopyrite-sphalerite ores, and then pyrite-chalcopyrite (copper) ores. The ores also contain gold, silver, bismuth, and rare minerals. The deposit was mined underground and is currently considered depleted. The extracted ore was sent for processing to the Nikolaevsk processing plant. Therefore, there are no quarries or significant waste dumps nearby.

It is important to emphasise that the results demonstrate predominantly the ability of the method to capture already manifested and erosionally cut features of mineralisation. Nevertheless, the technique can be effectively adapted for screening analysis of areas with limited accessibility, especially when combined with geophysical or geochemical data.

Thus, the method of integral analysis of normalised spectral indices has confirmed its applicability for remote screening of polymetallic prospectivity in the Ore Altai area. The optimal diagnostic combination, allowing to identify ore objects even with limited erosional stripping (for example, in the area of Kamyshensk deposit), was the triad: *Ferrous* > 3.7 , *Alunite* > 1.4 , *Clay* > 1.5 .

It should be noted that the main limitation of the method remains the dependence of the anomalous signal expression on the degree of erosion opening of mineral bodies. Also an important element in improving the accuracy of interpretation is the application of filtering of anthropogenic interferences by using thresholds on *BSI* and *Brightness* indices.

Assessment of classification accuracy. To quantify the effectiveness of the integral anomaly map, validation was performed by spatial intersection of known field points with the classification results. (Table 1) Three categories were analysed – «background» (0), «weak anomaly» (1) and «strong anomaly» (2).

Table 1

Results of validation of the integrated anomaly map for known ore points

Кесте 1

Белгілі кен нүктелері бойынша интегралдық аномалиялар картасын валидациялау нәтижелері

Таблица 1

Результаты валидации интегральной карты аномалий по известным рудным точкам

Class / Actual	Ore Point (True)	Non-ore point (False)
Strong anomaly (2)	7	2
Weak anomaly (1)	2	3
Background (0)	1	12

Calculation of metrics showed: Precision = 0.78, Recall (completeness) = 0.70, F1-measure = 0.74. The high precision values confirm the good correspondence of the «strong» anomalies to the actual ore bodies, with the moderate completeness value explained by the fact that some of the mineralised areas only show up in the «weak anomaly» class due to partial overlap with vegetation cover or spectral response features.

Conclusion

Integrated analysis of Sentinel-2 spectral indices proved effective for mapping hydrothermal alteration and oxidation zones within the Shemonaikha ore zone. The method identified ore anomalies consistent with known mineralization types and distinguished them from anthropogenic and fluvial features. Validation confirmed a good correspondence between «strong» anomalies and ore bodies (F1 = 0.74). Notably, the verification feature showed diagnostic features of iron-alunite consistent with hydrothermal alteration. These results demonstrate that Sentinel-2 multispectral data, which enables the use of integrated spectral indices, can serve as a practical tool for prospecting for ore features in Rudny Altai.

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