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ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ

ХАБАРЛАРЫ

ИЗВЕСТИЯ

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НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

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APPLICATION OF REMOTE SENSING METHODS FOR THE IDENTIFICATION OF IRON OXIDE ZONES AT THE KYZYLKIYA DEPOSIT

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Abstract. The paper focuses on the identification of iron oxides in oxide ores using remote sensing methods, with the Kyzylkiya copper deposit in Abay Province, Kazakhstan, serving as a case study. Remote sensing accelerates the process of identifying and mapping minerals, reducing the need for costly and time-consuming fieldwork.

The study utilizes data from Landsat 8 OLI/TIRS, ASTER satellites, and UAVs equipped with advanced cameras. These tools provide detailed, high-resolution images critical for identifying iron oxide-containing minerals. Spectral ratios, such as Landsat 8's B4/B2 and ASTER's B2/B1, are employed to establish thresholds that enable precise mineral identification. These thresholds facilitate the delineation of zones rich in copper and iron minerals.

Modern software solutions like ArcGIS Pro, ENVI, and Agisoft Photoscan are used to process the data, allowing for the creation of accurate mineral distribution maps. Aerial photographs, emphasizing the brown rust-like appearance typical of iron oxides, are instrumental in confirming the surface presence of these minerals.

Field surveys and laboratory tests support the reliability of these remote sensing methods, demonstrating the effective integration of ground-based techniques with satellite data. This integration enhances the accuracy of mineral zone mapping, potentially reducing exploration costs and improving the efficiency of geological studies.

Keywords: remote sensing, iron oxides, Kyzylkiya deposit, spectral indices, Landsat 8, ASTER, ENVI, unmanned aerial vehicles (UAVs).

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ҚЫЗЫЛҚИЯ КЕН ОРНЫНДА ТЕМІР ОКСИДТЕРІНІҢ АЙМАҚТАРЫН АНЫҚТАУ ҮШІН ҚАШЫҚТЫҚТАН ЗОНДТАУ ӘДІСТЕРІН ҚОЛДАНУ

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Аннотация. Мақалада Қазақстан, Абай ауданындағы Қызылқия мыс кен орны мысалында қашықтықтан зондтау әдістерін қолдана отырып, кен орындарындағы темір оксидтерін анықтау қарастырылады. Қашықтықтан зондтау әдістері пайдалы қазбаларды анықтау және картаға түсіру процесін жылдамдатады, шығынды және көп уақытты қажет ететін дала жұмыстарына қажеттілікті азайтады.

Зерттеуде Landsat 8 OLI/TIRS, ASTER спутниктері және жетілдірілген камералармен жабдықталған ұшқышсыз ұшатын аппараттар (ҰАО) деректері

пайдаланылады. Бұл құралдар құрамында темір оксидтері бар минералдарды анықтауға қажетті егжей-тегжейлі, жоғары дәлдіктегі кескіндерді береді. Landsat 8 үшін B4/B2 және ASTER үшін B2/B1 сияқты спектрлік индекстер берілген минералдарды дәл анықтауға мүмкіндік беретін шектерді белгілеу үшін пайдаланылады. Бұл табалдырықтар мыс пен темірге бай аймақтарды бөліп көрсетуге көмектеседі.

Деректерді өңдеу үшін ArcGIS Pro, ENVI және Agisoft Photoscan сияқты заманауи бағдарламалық шешімдер пайдаланылады, бұл пайдалы қазбалардың таралуының нақты карталарын жасауға мүмкіндік береді. Бетінде темір оксидтерінің болуын растау үшін тән қоңыр, тот тәрізді түсті көрсететін аэрофотосуреттер маңызды. Далалық зерттеулер мен зертханалық сынақтар жердегі әдістердің спутниктік деректермен тиімді интеграциясын көрсете отырып, осы қашықтықтан зондтау әдістерінің сенімділігін растайды. Бұл интеграция пайдалы қазбалар аймақтарының картасын жасаудың дәлдігін жақсартады және геологиялық барлаудың тиімділігін арттыра отырып, барлау шығындарын әлеуетті түрде азайтады.

Түйін сөздер: қашықтықтан зондтау, темір оксидтері, Қызылқия кен орны, спектрлік индекстер, Landsat 8, ASTER, ENVI, ұшқышсыз ұшатын аппараттар (ҰАО).

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ПРИМЕНЕНИЕ МЕТОДОВ ДИСТАНЦИОННОГО ЗОНДИРОВАНИЯ ДЛЯ ИДЕНТИФИКАЦИИ ЗОН ОКСИДОВ ЖЕЛЕЗА НА МЕСТОРОЖДЕНИИ КЫЗЫЛКИЯ

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Аннотация. В статье рассматривается идентификация оксидов железа в рудных месторождениях с использованием методов дистанционного зондирования на примере Кызылкийского медного месторождения в Абайской области, Казахстан. Методы дистанционного зондирования ускоряют процесс идентификации и картирования минералов, снижая необходимость в дорогостоящих и трудоемких полевых работах.

В исследовании используются данные спутников Landsat 8 OLI/TIRS, ASTER и беспилотных летательных аппаратов (БПЛА), оснащенных современными камерами. Эти инструменты предоставляют детализированные и высокоточные изображения, необходимые для обнаружения минералов, содержащих оксиды железа. Спектральные индексы, такие как B4/B2 для Landsat 8 и B2/B1 для ASTER, используются для установления пороговых значений, которые позволяют точно идентифицировать данные минералы. Эти пороговые значения помогают выделить зоны, богатые медью и железом.

Современные программные решения, такие как ArcGIS Pro, ENVI и Agisoft Photoscan, используются для обработки данных, что позволяет создавать точные карты распределения минералов. Аэрофотоснимки, подчеркивающие характерный коричневый цвет, напоминающий ржавчину, играют важную роль в подтверждении наличия оксидов железа на поверхности. Полевые исследования и лабораторные тесты подтверждают надежность этих методов дистанционного зондирования, демонстрируя эффективную интеграцию наземных методов с данными спутников. Такая интеграция улучшает точность картирования зон с минералами и, возможно, снижает затраты на геологоразведку, повышая эффективность геологических исследований.

Ключевые слова: дистанционное зондирование, оксиды железа, месторождение Кызылкия, спектральные индексы, Landsat 8, ASTER, ENVI, беспилотные летательные аппараты (БПЛА)

Introduction. Remote sensing, one of the most far-reaching fields, plays a crucial role in exploring the Earth's intricate composition without the need for physical presence. This revolutionary technology offers a faster, more resource-efficient alternative to traditional exploration methods, particularly when searching for mineral deposits such as iron oxides. These territories of iron oxides are essential for mining, as their discovery enhances efficiency and exposes valuable Earth materials. Geological mapping accuracy is significantly improved by employing remote sensing techniques like aerial surveys and hyperspectral imaging, which offer more comprehensive insights than conventional ground surveys.

The study demonstrates how the integration of remote sensing, geophysics, and geology data using fuzzy logic models and the multi-class overlap index method enables efficient and cost-effective identification of zones with high potential for polymetallic mineralization, confirmed by field surveys and drilling in the Chakchak region, Yazd Province, Iran (Aali, et al. 2022). This research utilized Landsat-7 and ASTER satellite imagery, as well as advanced analytical methods, to map hydrothermal alteration zones and geological structures associated with iron skarn mineralization in the Galali region of northwestern Iran. High-potential zones for further exploration projects were delineated and confirmed through field surveys and laboratory analysis (Moradpour, et al. 2022). The study used Landsat-8/OLI and EO-1/Hyperion imagery, integrated with aerogeophysical data, to map iron oxides and clay minerals in the Serra Norte region, Carajás, Brazil. This allowed for the successful identification of zones with high iron ore content and improved geological characterization of mineralized areas. The multi-resource classification proved effective for mapping in areas with vegetation and open-pit mines (Ducart, et al. 2016). In (Mansouri, et al. 2018) work, multivariate regression was applied to create a mathematical model for iron skarn mineralization prospectivity in the Sarvian region, Central Iran, with the aim of mapping iron outcrops and searching for new deposits. The model, based on ASTER data and multivariate regression, demonstrated high accuracy in identifying prospective zones, which were confirmed by field observations at the contact between limestone and intrusive rocks (skarn type) (Mansouri, et al. 2018).

This approach to rock detection also offers many advantages compared to field exploration because it allows for rapid examination of large areas without the need for physical sampling. Advanced image acquisition technologies can detect specific light signals associated with iron oxide. Numerous examples from the literature show that hyperspectral imaging works effectively for detecting iron oxides in various geological settings. For instance, image science data has been used in geological exploration (Tempfli, et al. 2001).

Object of study. Administratively, the Kyzylkiya copper deposit is located in the Ayagoz district of Abay Province, Republic of Kazakhstan (Figure-1). Its coordinates are 46°57’ N and 80°02’ E. The deposit area is part of the northern margin of the Balkhash-Alakol depression and represents an extensive plain with the development of low hills and small salt lakes and takyrs (clay flats) between them. Surface exposure is weak. The absolute elevations range from 390 to 470 meters, with relative heights of 5 to 80 meters. Climatically, this is an arid semi-desert area with sparse dune and salt-tolerant vegetation. The nearest river, the Ayagoz, flows 35 km southwest of the deposit. In this section, the river does not have a permanent flow and breaks into specific pools. Smaller streams, such as the Ay, Bakanas, and Tansyk, are also intermittent and low-water, making them unsuitable as water supply sources.

Structurally, the Kyzylkiya deposit is located within the eastern part of the Koldar intrusive massif, near the junction of the large Ikbas and South Koldar fault zones, and is characterized by the following main geological features (Sergiyko, et al. 1980).

The Kyzylkiya deposit was discovered by the Almaty team of the «Yuzhkazgeologiya» geological exploration company using the induced polarization method and secondary copper and molybdenum dispersion halos, which were identified in 1974 as a result of 1:50,000 scale surveying. During that same period, senior geologist Krasnikov A.M. discovered a series of small ancient quarries with copper mineralization in the spoil heaps, as well as isolated ore outcrops (Miroshnikov, et al. 1980).

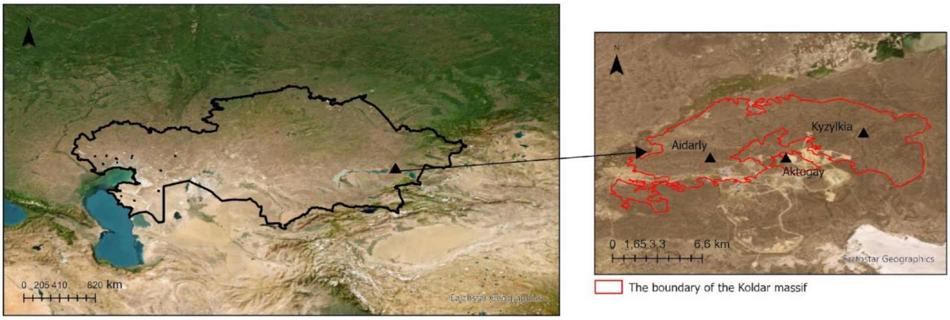

Figure 1 – The object of the study

Lithogeochemical surveying has revealed extensive secondary dispersion halos of copper, molybdenum, lead, zinc, and other metals. The highest concentrations of these metals are found in an anomalous belt that curves southward. This belt extends almost continuously for about 14 km with a width of 1.5 to 2.0 km.

The entire anomalous zone of secondary metal dispersion halos is accompanied by an induced polarization (IP) anomaly covering approximately 26 km², with the most intense part located in its western half. The intensity reaches 20-24%. In the central part of this belt, at the junction of the northwestern and northeastern trending zones, is the Aktogay deposit, while in the northwest lies the Aidarly deposit, and in the northeast is the Kyzylkiya deposit. The Kyzylkiya deposit is characterized by contrasting copper and molybdenum dispersion halos and IP anomalies, which allow for an initial approximation of the molybdenum-copper mineralization area. The identified secondary copper and molybdenum halos spatially coincide with an IP anomaly of up to 6% intensity, with a slight decrease in the magnetic field (Krasnikov, et al. 1977).

The ores at the Kyzylkiya deposit are complex, comprising molybdenum and copper. The primary ore minerals are pyrite, chalcopyrite, bornite, molybdenite, sphalerite, magnetite, and galena. Among the vein minerals, quartz, chlorite, and carbonates are the most common. Secondary copper minerals are represented by chalcocite. In the oxidation zone, which extends to a depth of 60.0-66.0 m, the main minerals are malachite, azurite, and chrysocolla (Kydyrbekov, et al. 1976).

Materials and Methods. This research utilized multispectral information gathered from various remote sensing platforms, including satellite imagery and data from unmanned aerial vehicles (UAVs), to examine and identify areas with high iron concentrations and the spread of iron oxides. The primary data sources included ASTER and Landsat 8 satellites, along with a UAV equipped with a SenseFly camera (Table-1).

Table 1 – Spectral Band Ratios for Iron Oxide Mineralization and Detection

№	Minerals/Groups of Minerals	Definition	Source
1	Fe^{3}+ (hematite, goethite)	Band Ratio [ASTER B2/B1] – [0.63-0.69 μm / 0.52-0.6 μm]	(Rowan, et al. 2003)
2	Iron mineralization index for identifying areas with high iron content	Band Ratio [UAV SenseFly] – [735/790 nm or 660/550 nm]	(Jackisch, et al. 2021)
3	Iron oxides, which are common minerals in oxidation zones	Band Ratio [Landsat 8 4/2] – [0.630-0.680 μm / 0.450-0.515 μm]	(Osinowo, et al. 2021)

The spectral ratio technique was employed to detect Fe^{3+} minerals, such as hematite and goethite, by analyzing their reflectivity within specific wavelength ranges. A key indicator used reflectivity in the 0.63-0.69 μm and 0.52-0.6 μm spectral ranges, corresponding to the Band Ratio [ASTER B2/B1], which enabled the identification of iron-bearing minerals in the study areas. In addition, the spectral ratio [Landsat 8 4/2] was applied to investigate the distribution of iron oxides, which are prevalent in oxidation zones. This ratio encompassed wavelength ranges from 0.630-0.680 μm and 0.450-0.515 μm, effectively identifying oxide minerals through their unique spectral signatures (Table-1).

To achieve comprehensive mapping of regions with unusually high levels of iron, data collected from the UAV was used. The SenseFly UAV's camera captured spectral signatures in the near-infrared and red wavelengths. An iron mineralization index, derived from the ratios of the 735/790 nm or 660/550 nm ranges, was employed to pinpoint areas with elevated iron concentrations (Table-1). This approach provided significant precision in detecting zones that required further geological investigation.

The data processing consisted of several phases. Initially, satellite imagery and UAV data underwent pre-processing, including radiometric and atmospheric corrections to remove noise and improve the accuracy of subsequent analyses. Following this, spectral ratios were calculated for each study region, and areas with elevated iron oxide levels and iron mineralization were identified. In the final phase, the results were interpreted, and the derived indices were used to generate maps of anomalous regions, highlighting sites for additional field investigation.

The data was processed and analyzed using ArcGIS Pro, ENVI 5.3, and Agisoft Metashape Professional software. These tools enabled the computation of spectral indices and the visualization of maps for the study areas, facilitating a more effective interpretation of the findings related to mineralization and iron oxides.

In this method, a comprehensive approach was applied to the processing of multispectral data, involving two software solutions: ENVI version 5.3 for satellite remote sensing data processing and Agisoft Metashape for UAV data processing. Both tools were used for additional analysis of the territory using high-resolution data.

Processing of Multispectral Data in ENVI Version 5.3. The preliminary processing of data in ENVI was focused on preparing satellite imagery for further analysis. One of the primary steps was radiometric calibration, which converts the digital numbers in each image pixel into physically meaningful measurements, such as surface reflectance. This is critical for accurately measuring the spectral characteristics of objects in the image.

The next step was atmospheric correction, aimed at minimizing atmospheric distortion factors, such as aerosols, water vapor, and other atmospheric components that affect the spectral signals of Earth's surface objects (Nazeer, et al. 2021). This correction makes the data more accurate and converts it into real physical surface data, ensuring higher quality analysis.

To enhance the accuracy of the analysis and identify the objects of interest, MDWI (Modified Difference Water Index) (Ali, et al. 2019) and NDVI (Normalized Difference Vegetation Index) (Huang, et al. 2021) masks were created. These indices focus on key surface characteristics: MDWI is used to identify moist areas, while NDVI detects vegetation cover, allowing for a detailed analysis of the study area.

The final step of the preliminary data processing was to crop the image to the boundaries of the target area. This was necessary to exclude unnecessary regions from the analysis and improve the efficiency of data processing by focusing only on the study area.

Processing of Multispectral UAV Data in Agisoft Metashape Software. The UAV-collected data was processed in Agisoft Metashape, which allows the creation of highly accurate 3D models and orthophotos based on aerial photography.

The first step of data processing was reflection adjustment. A special sensor mounted on the UAV measured the level of electromagnetic radiation during the capture, ensuring accurate spectral analysis by adjusting the reflectivity of objects in the images. The «use sun sensor» function in Agisoft Metashape significantly improved the lighting adjustments depending on the shooting conditions, which is especially important when working with multispectral data.

Then, the exact shooting centers were calculated using the Post-Processing Kinematic (PPK) method (Zhang, et al. 2019). PPK data helped determine the coordinates of each shot at a high accuracy level, which is crucial for creating precise geo-referenced images and orthophotos.

In the final stage, the frame assembly and orthophoto generation were completed. This process involved merging individual sections into a single image, a fundamental requirement for representing the territory. An orthophotomap is a highly accurate contour image of the area, which can be used for further spatial data analysis.

Thus, the combination of satellite data processing in ENVI and UAV data processing in Agisoft Metashape offers a comprehensive approach to the study of the area, providing accurate data for subsequent geological and environmental analysis.

Results and discussion. The iron hydroxides found in the study area include hydrogoethite and goethite, which are widespread in the oxidized ores. The replacement of goethite by limonite was noted in sulfide minerals such as pyrite and chalcopyrite. An important feature of the process is the pseudomorphic replacement of primary iron and copper sulfides. Iron hydroxides also fill cracks and leaching voids in the host rocks, either independently or in combination with hypergene copper minerals such as malachite, azurite, and chrysocolla.

The analysis of the textures and structures of the iron hydroxides revealed their colloform and crystalline granular structures. These minerals are present as disseminations, veins, and nests. Additionally, they form fine mixtures with hypergene copper minerals, which often contain relics of primary sulfides. This indicates complex oxidation and leaching processes that occurred in the ore bodies and the surrounding rocks.

On aerial photographs, the area is distinguished by a brown hue resembling rust, which is a clear indicator of the presence of iron oxides, confirming the oxidation processes in this zone. These visual indicators are also supported by spectral remote sensing data, which show a concentration of iron-bearing minerals on the surface (Figure-2).

Figure 2 – Results of UAV Data Processing Highlighting the Area with Iron Oxide Concentration

By utilizing various remote sensing methods, such as Landsat 8 OLI/TIRS, ASTER, World View 3, and UAV data (P4M), significant results were obtained for the analysis of mineral distribution. A color orthophotomap with a spatial resolution of 5.66 cm/pixel, a dense point cloud, and a digital elevation model (DEM) with a resolution of 11.3 cm/pixel enabled more accurate mapping of mineral distribution and the identification of key ore body features.

Threshold values were determined for each data source. For example, for Landsat 8 OLI/TIRS, the threshold value $B4/B2 > 1.378$ was used, for ASTER — $B2/B1 > 1.27$, for World View 3 — $B3/B2 > 1.35$, and for P4M — $B3/B2 > 1.165$. These values allowed the identification of areas with high mineral concentrations. The trial-and-error method for determining thresholds made it possible to isolate «pure pixels,» which were then exported in .shp format for further analysis.

The data were processed in ArcGIS Pro, ENVI, and Agisoft Photoscan, with each data source assigned a specific color: ASTER in yellow, Landsat 8 OLI/

TIRS in blue, World View 3 in purple, and P4M in green (Figure-3). A black-and-white UAV orthophotomap was used as the base layer, along with ground-based geological points. The analysis identified two areas with a high pixel density, where data from different sources overlapped, indicating potential zones for further geological investigation.

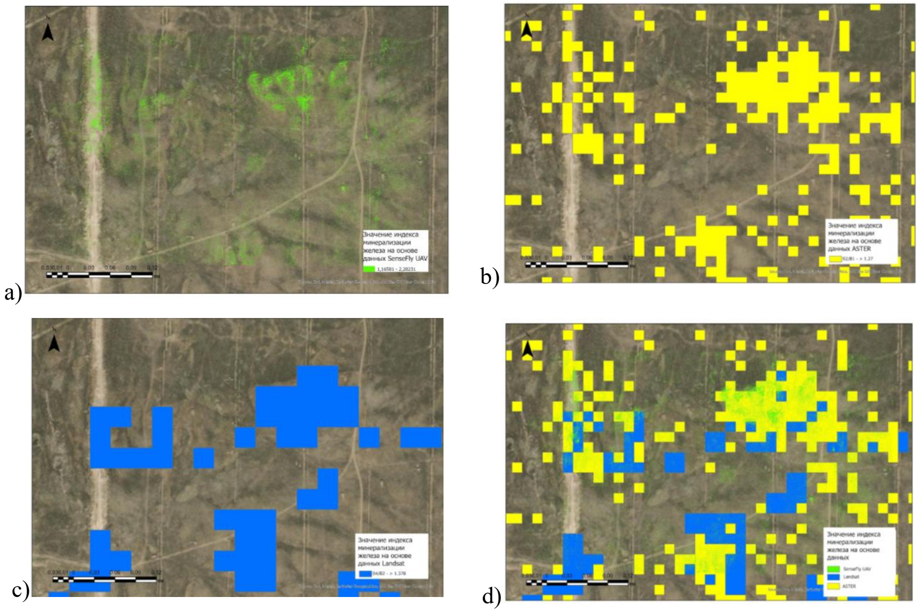

Figure 3 – Remote sensing data processing results: a) SenseFly UAV, b) ASTER, c) Landsat, d) combined results

The figures present the results of data processing from Landsat 8, ASTER, and UAV, where one clearly distinguishable area is visible across all images. This confirms the presence of minerals identified through remote sensing data and emphasizes the importance of a comprehensive approach to the investigation of geological objects using multiple remote sensing methods.

When comparing the obtained data with a simplified geological map of the study area, modified from the RGF Report 45219 by V. M. Mertenov, «Geological Reassessment of the Bakanas Syncline Territory (Sheets L-44-I, II, III)» at a scale of 1:200,000, published in Almaty in 1997, it was established that granodiorites are present in the study area (Figure-4). Igneous rocks have a notable influence on the geological structure of the region and are likely associated with mineralization processes involving iron oxides.

Granodiorites are often associated with hydrothermal activity, which promotes the formation of iron-bearing minerals such as hematite and goethite. Hydrothermal fluids interacting with granodioritic rocks could have caused the leaching of iron and its deposition as oxides in oxidized zones. This is supported by remote sensing results, where zones with iron oxides are clearly distinguishable, as well as by field research data. Thus, granodiorites, being an essential component of the region's geological structure, play a key role in the formation of mineralization zones enriched with iron oxides. This emphasizes the need to consider them in future geological exploration activities.

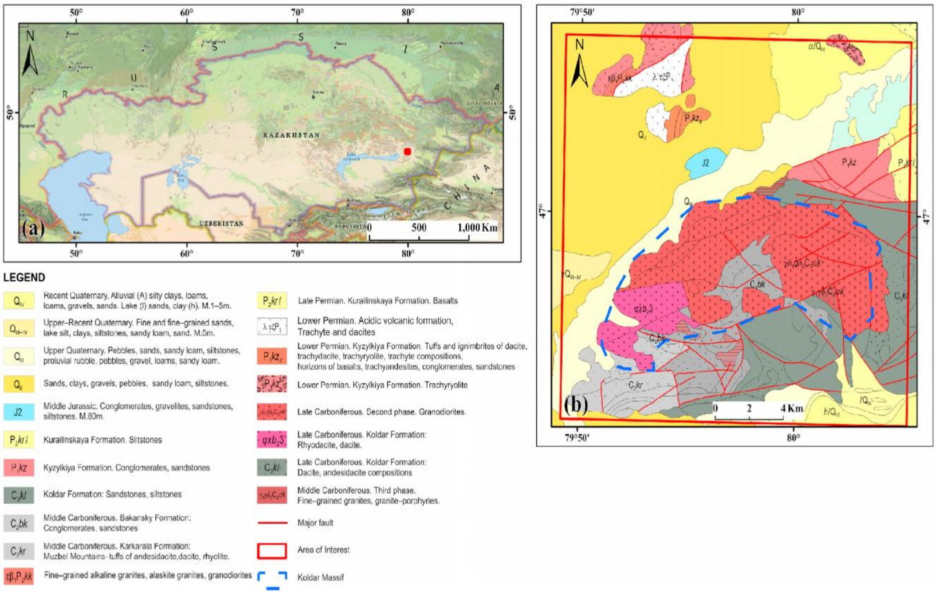

Figure 4 – (a) Geographical location of the study area and surroundings regions. (b) Simplified geological map of study area (modified from RGF Report 45219 by V. M. Mertenov (sheets L-44-I, II, III), Almaty, 1997).

Conclusion. The conducted study demonstrated the high efficiency of applying remote sensing methods for mapping iron oxides and associated copper minerals in the Kyzylkiya copper deposit area. The use of satellite data from Landsat 8, ASTER, and UAVs allowed for detailed mapping of mineral zones, significantly enhancing the geological characterization of the region. The identified areas with elevated concentrations of iron-bearing minerals, visualized on aerial photographs, aligned with the results of spectral analysis, confirming the reliability of the obtained data. The combination of tools such as ArcGIS Pro, ENVI, and Agisoft Photoscan provided comprehensive data processing and visualization, leading to the identification of two promising zones for further field exploration and drilling. This approach opens new opportunities for cost-effective and rapid mineral exploration, especially in remote and hard-to-reach areas.

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