ABSTRACT

PhD thesis, Degree in Geology and Exploration of Mineral Deposits (Code 8D07201)

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"METHODOLOGY FOR PROSPECTING GOLD-BEARING DEPOSITS USING MODERN SATELLITE TECHNOLOGIES, CASE STUDY OF THE WEST KALBA GOLD BELT"

General characteristics of the research: The thesis examines the application of satellite remote sensing methods, specifically Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) multispectral data and EnMAP hyperspectral data, for mapping hydrothermal alteration zones and developing exploration criteria for gold deposits in the West Kalba gold belt of Eastern Kazakhstan. As part of the study, a comprehensive geology-driven mineral targeting framework was developed, integrating regional geological data, mineralogical-petrographic characteristics of deposits, and hydrothermal alteration models with laboratory reference spectra (USGS spectral library). A reproducible processing pipeline for ASTER multispectral data was established, including co-registration, atmospheric correction, NDVI masking, band ratio calculations, false color composite generation, and multi-scene mosaicking. The study demonstrates that the use of diagnostic spectral features of Al–OH, Mg/Fe–OH, carbonate, and Fe^{3+} oxide minerals, and their properties of absorption and reflection of electromagnetic radiation, provides a reproducible relationship between satellite spectral responses and the zonality of hydrothermal alterations genetically associated with gold mineralization. The methodology was validated through spatial correlation analysis with known deposits and exploration footprints, as well as hyperspectral EnMAP spectral confirmation, demonstrating strong spatial correspondence: over 80 documented deposit and exploration locations spatially coincide with ASTER-derived alteration zones.

Relevance of the research. In recent decades, global demand for gold and the scale of gold mining have continued to grow, while discovery and development have become more difficult due to depletion of the richest deposits, declining ore grades, and increasing environmental constraints. East Kazakhstan contains numerous gold deposits of different genetic types, with a major concentration in the West Kalba gold belt, which has long been a key contributor to the country's mineral resource base. At the same time, the potential for discovering new large objects using only traditional exploration approaches is

decreasing, creating a need for scalable and reproducible screening methods. Satellite remote sensing provides such capability by mapping surface alteration footprints and structural controls at regional scale, but its application in Kazakhstan remains limited and requires a consistent workflow and clear validation.

The object of research: gold deposits and ore occurrences of the West Kalba metallogenic zone, specifically the Bakyrchik and Akzhal-Vasilyevskoye ore fields (Eastern Kazakhstan).

The subject of research: hydrothermal alteration zones associated with gold mineralization, their spectral signatures detectable by satellite remote sensing, and the relationship between alteration mineralogy and gold ore formation.

Aim of the research: To develop a consistent remote sensing methodology for gold exploration in the West Kalba gold belt (East Kazakhstan) that maps hydrothermal alteration footprints and supports delineation of prospective zones.

Research objectives:

1) Identify and justify a set of key indicators of hydrothermal alteration in the gold-ore systems of the West Kalba gold belt that reflect the staged nature of ore formation and are suitable for interpreting Earth remote sensing data; then assess their diagnostic value and limitations for prospective delineation of promising gold-ore sites.

2) Build a mineral targeting framework that maps alteration minerals and diagnostic absorbers using regional geological sources and reference laboratory spectra.

3) Develop a reproducible processing pipeline for ASTER multispectral data, including alignment, NDVI masking, band ratios, false color composite generation, and multi-scene mosaicking.

4) Validate alteration mapping results using independent object-based comparison and hyperspectral EnMAP spectra where coverage is available.

5) Produce regional selection of hydrothermal alteration composites and identify prospective zones for follow-up work.

Main research methods: Review and analysis of research on gold deposits of the West Kalba belt and global analogues; detailed analysis of deposit mineral composition and creation of a catalog compiled from laboratory spectral measurements of minerals from multi- and hyperspectral images; comprehensive analytical studies, including processing of satellite remote sensing data (ASTER multispectral and EnMAP hyperspectral data), spectral analysis, spectral index calculations, false color composite generation, spatial correlation analysis, and integration with geological and mineralogical data.

Main defended statements:

1) For the first time for the West-Kalba gold belt, a geologically justified spectral data catalog has been developed, based on integrating regional geological data, mineralogical-petrographic characteristics of deposits, and hydrothermal alteration models with laboratory reference spectra (USGS library). It is demonstrated that using diagnostic spectral features of Al–OH, Mg/Fe–OH, carbonate, and Fe^{3+} oxide minerals, along with their electromagnetic absorption and reflection properties, establishes a reproducible relationship between satellite spectral responses and the zonality of hydrothermal alterations genetically linked to gold mineralization.

2) An integrated multi- and hyperspectral methodology for gold exploration with mineralogical verification has been developed, combining ASTER multispectral analysis with hyperspectral mineralogical verification using EnMAP data. It is shown that the combination of multispectral ratios targeting diagnostic absorption bands of Al–OH, Mg/Fe–OH, carbonates, and Fe^{3+} oxides, with high-resolution spectral matching, enables the transition from regional exploration mapping to local mineralogical identification and enhances the geological justification of remotely detected anomalies.

3) The high effectiveness of remote mapping of hydrothermal alterations for identifying prospective gold-bearing zones within the West Kalba belt has been demonstrated. Over an area of approximately 30,750 km², a stable spatial correlation has been established between alteration zones identified from ASTER data and more than 80 known gold deposits and occurrences. Based on comprehensive validation, the district-scale zonality of hydrothermal alterations has been reproduced, and three perspective zones (B1, B2, and A1) have been identified, confirming the possibility of detecting concealed and previously unidentified mineralization targets.

Scientific novelty. The scientific novelty of this work lies in integrating a geology-driven mineral targeting framework for the West Kalba belt with a reproducible multi-scene ASTER processing pipeline that produces comparable merged products across the study area, combined with a two-level validation strategy that merges object-based spatial correspondence with deposits and exploration footprints together with hyperspectral EnMAP spectral confirmation in the area of coverage overlap, thereby strengthening minerals interpretation and uncertainty assessment. At the gold-ore sites, these works are being carried out in Kazakhstan for the first time, which will undoubtedly make a significant contribution to the development of the use of remote technologies for prospecting and exploration of deposits of various genetic types.

Practical significance. The practical significance consists in the creation of a methodology for using remote methods for the preliminary forecasting of

promising areas of possible gold-ore occurrences and deposits, which will significantly increase the efficiency of geological exploration works

The research outcomes have also been implemented in the production activities of LLP “GEOSAT” and are used in the educational process of NJSC «D. Serikbayev East Kazakhstan State University» under the educational program 7M07302 “Geodesy” for the discipline “Automated systems for collecting and processing the results of remote sensing”.

Factual material and personal contribution of the author.

The core research data consist of information, that is collected by author during educational and participation in following projects:

1. Project IRN BR24992854 “Development and implementation of competitive scientifically substantiated technologies to ensure the sustainable development of mining and metallurgical industry East Kazakhstan region”.

2. Project IRN AP25795761 “Development of a combined method for forecasting gold-bearing deposits using satellite technology, GIS and deep learning AI”.

Author has participated in two research internships to Technical University Berlin (Germany), where the learning program was fully aligned with methodology and analytical approaches, used in this dissertation.

The dissertation uses the results of an analysis of monographic, reauthor analyzed monographic, reference, and scientific publications on gold deposits of the West Kalba belt, as well as relevant international analogues. The dissertation draws on regional geological materials and datasets compiled and interpreted by the author, together with the results of satellite remote sensing analysis and related thematic products. In addition, the study uses information from known deposits and exploration sites within the study area, including data provided through prior investigations and, where available, supplementary materials obtained in collaboration with colleagues who conducted field work on the examined objects.

Satellite-based data processing was as a part of the project AP25795761 “Development of a combined method for forecasting gold mineral deposits based on satellite technology, geoinformation science and deep learning AI”, which was completely done by author. Based on results of which, author has developed a combined methodology for prospecting gold-bearing mineral deposits, highlighting remote sensing as a powerful tool enabling to enhance the traditional geological exploration.

Approbation of the work and publications

The results of the work have been published in 7 articles, including 3 in publications recommended by the Committee for Quality Assurance in Science and Higher Education of the Republic of Kazakhstan (Proceedings of the

University, Mining Journal of Kazakhstan), and 1 in a journal indexed in Scopus / Web of Science (Minerals).

The research results were reported in following contributions:

The open source peer-reviewed journal, included in Scopus and Web of Science:

1. D'yachkov B.A., Mizernaya M.A., Khromykh S.V., Bissatova A.Y., Oitseva T.A., Miroshnikova A.P., Frolova O.V., Kuzmina O.N., Zimanovskaya N.A., Pyatkova A.P., Zikirova K.T., Ageyeva O.V., Yeskaliyev Y.T. Geological history of Great Altai: Implications of Mineral Exploration. Minerals 12 (6), 744, 2022. https://doi.org/10.3390/min12060744

Scientific journals, recommended by SHEQAC of MSHE of Republic of Kazakhstan:

1. Zikirova K.T., Mizernaya M.A., Yeskaliev Y.T., Aitkazyyev T., JoyaShish T. The Scientific Basis of the Investment Attractiveness of Geological Structures on the Example of Rudny Altai. Universitet Enbekteri – University Proceedings. №1 (90), 2023, P. 146-152.

2. Mizernaya M.A., D'yachkov B.A., Miroshnikova A.P., Zikirova K.T., Yeskaliyev Y.T. Features of Geological Structure, Magmatism and Ore Formation of Bakyrchik ore Field Deposits. Universitet Enbekteri – University Proceedings. №3 (84), 2021. P. 94-99.

3. Mizernaya M.A. Agaliyeva B.B., Shayakhmetova Z.A., Yeskaliyev Y.T. Features of the microelement composition of ore of the Artemyevskoye deposit (Rudny Altai). Mining journal. № 1, 2026. P. 25-30.

Presentation in international conferences:

1. Methodology of scientific forecasting based on GIS of precious metal deposits in Eastern Kazakhstan. 20 International Conference Geoinformatics: Theoretical and Applied Aspects, 11- 14 May, 2021. Kiev, Ukraine.

2. Structural position, magmatism and mineralization of Bakyrchik ore field (Kazakhstan). 22nd International Multidisciplinary Scientific GeoConference SGEM 2022. 4-10 July, 2022, Albena, Bulgaria.

3. WeedsGalore: A Multispectral and Multitemporal UAV-Based Dataset for Crop and Weed Segmentation in Agricultural Maize Fields. IEEE/CVF Winter Conference on Applications of Computer Vision (WACV), Feb. 28 – Mar. 4, 2025, Tucson, Arizona, USA.

Thesis volume and structure. The dissertation content is represented by 161 pages, which include introduction, 6 chapters, conclusions and bibliography of 94 references, 56 figures, 14 tables, 2 appendixes.

The first section describes the position of the West Kalba gold belt in Kazakhstan as the country's largest area hosting gold deposits, and summarizes the studies carried out over the past century.

The second section explains West Kalba in terms of its geological structure, tectonics, and magmatism.

The third section provides a detailed description of the research methodology used.

The fourth section describes the relationship between the ore bodies of the study objects and the elements in the mineral composition that control absorption features of electromagnetic radiation.

The fifth section presents mineral-by-mineral results of applying the methodology at the reference deposits of the Bakyrchik and Akzhal-Vasilyevskoye ore fields.

The sixth section describes the identification of three prospective zones with sulfides and oxides within the Bakyrchik and Akzhal-Vasilyevskoye ore fields.

The concluding section summarizes the main findings of the research.