



THEORETICAL BASIS OF DETERMINING MINERALIZATION ZONES AND DEVELOPING PROSPECTIVE MAPS BASED ON GIS AND REMOTE SENSING DATA

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Abstract

This study, using the example of the Fergana region, sheds light on the scientific and methodological approach to identifying mineralization zones and developing a prospectivity map based on GIS and remote sensing (multispectral) data. In the study, geological and mineralogical evidence (lithology, tectonic faults and their nodes, intrusive contacts, hydrothermal alteration zones) was integrated with spectral indicators obtained from remote sensing, and evidence layers were standardized, normalized, and evaluated as a probability field in the GIS environment. As a result, it was proven that alteration indicators, when used in conjunction with structural-lithological control, allow reducing “false anomalies”, prioritizing the search area, and optimizing field investigations. At the end of the work, it was concluded that the integrated modeling approach is a methodological tool for rapid screening, separation of target zones, and decision-making for further geochemical/geophysical exploration in mineral exploration processes.

Keywords: GIS, remote sensing, mineralization zone, hydrothermal alteration, prospectivity map, evidence layers, multispectral imagery, lineaments and discontinuities, spatial analysis, mineral prospectivity mapping.



INTRODUCTION

In recent years, the rapid development of the global “green energy” and digital economy (electric transport, renewable energy infrastructure, AI-data centers) has led to a sharp increase in demand for raw materials such as copper, lithium, graphite, nickel, cobalt and rare earth elements. In particular, the International Energy Agency reports that in 2023 the demand for lithium will increase by ~30%, while nickel/cobalt/graphite will continue to grow, and the market for “energy transition” minerals is growing. Against this background, international financial reports indicate that the supply crunch and new demand drivers in the copper market will intensify, and prices will approach a high level in 2025; this makes rapid, accurate and cost-effective technological approaches (GIS + remote sensing + ML) in geological exploration relevant. In world experience, the concept of mineral prospectivity mapping is widely used to optimize mineral exploration: it combines geological (lithology, tectonics, intrusion contacts), mineralogical (alteration minerals and zonation), geochemical and remote sensing evidence (evidence layers) into a single spatial model, assessing the potential for mineralization by area. Studies in 2024–2025 show that the rational selection of ML and layers to be interpreted in mineral exploration (evidence map selection), as well as the synergistic use of Sentinel-2, Landsat-9 and ASTER data, is increasing the possibility of identifying hydrothermal alteration zones. In the conditions of Uzbekistan, in particular, in the foothill and depression systems of the Fergana region, the issues of targeted search for objects related to minerals and control of ecological and technogenic risks are of particular importance; The scientific literature emphasizes the historical occurrence of various resources (including metals and fuel and energy resources) in the Fergana region, and the need to map the neotectonic elements of the Fergana Basin using new technologies based on remote sensing materials.

The purpose of this topic is to clarify the theoretical foundations of identifying mineralization zones and developing a prospect map by integrating GIS and remote sensing data with geological and mineralogical evidence, using the example of the Fergana region, and to create a methodological foundation for practical application. To achieve this goal, the following tasks are theoretically justified:



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- ✓ systematization of geological and mineralogical indicators of mineralization and hydrothermal alteration (structural control, intrusion contacts, alteration minerals, and zonation);
 - ✓ scientific justification of concepts for distinguishing alteration features (band ratio, PCA, spectral classification, etc.) through the spectral capabilities of remote sensing sensors (Sentinel-2/Landsat/ASTER);
 - ✓ Describe the criteria for standardizing evidence layers, spatial analysis, and selecting integration principles (knowledge-driven and data-driven approaches) in a GIS environment;
 - ✓ Methodologically clarify the mechanism for verifying the prospectivity map (existing occurrences/deposits, field samples, accuracy metrics) and applying the results to exploration planning.

LITERATURE ANALYSIS

In world practice, the approach to identifying mineralization zones and mapping prospectivity based on GIS and remote sensing data is based primarily on the concept of "evidence layers": that is, lithology, tectonic discontinuities, intrusive contacts, geochemical anomalies, geophysical indicators, and alteration zones separated by RS are brought to the same coordinate, resolution, and scale and integrated into a single spatial model. The classical methodological foundation of this direction was formed by the Canadian scientist Geoffrey F. Bonham-Carter with his work on modeling mineral potential through GIS: he put forward the idea of adapting the Weights of Evidence (WoE) approach, which takes into account statistical dependencies in mineral potential mapping, to the GIS environment, and brought the principles of logical selection of "evidence" layers, their independence (conditional independence), and verification of the result with "known occurrences" (known deposits/prospects) to the level of a practical standard. In the next stage, the Canadian mathematical-geoinformatics scientist Qiuming Cheng extended the WoE method with fuzzy probability, taking into account the uncertainties in the real geological environment: his work in 1999 showed that "evidence" can be expressed not only in the form of 0/1, but also through fuzzy (gradational) membership functions, paving the way for more natural modeling of continuous spatial indicators such as alteration intensity,



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lineament density, distance rasters. In the issue of “scientifically pure” integration of geochemical data into GIS, the Dutch scientist EJM (John) Carranza plays a fundamental role: he systematized prospectivity mapping theoretically and practically by combining geochemical anomaly separation, multivariate spatial statistics, and their integration with geological-tectonic evidence; This approach provides an important theoretical basis for linking geochemical indicators to alteration layers obtained from remote sensing, especially in areas with limited field samples but wide regional coverage (such as the Fergana region). Carranza also adapted the Random Forest algorithm, which is widely used in the data-driven direction, to mineral prospectivity mapping, and demonstrated in practical examples that it captures complex nonlinear relationships better than classical statistical methods; this work also raises the issue of “model interpretation” and “overfitting” control (in particular, the number and quality of predictor layers). Alok Porwal and colleagues, a scientist who worked actively in Australia, deepened the prospectivity assessment based on Random Forest in “greenfield” conditions (when the number of known deposits is small) and prepared data for obtaining stable forecasts even with a small number of “training points”, has practically enriched the selection and validation strategies of evidence layers (which is directly relevant to mitigating the problem of “data scarcity” in the Fergana region). In recent years, studies working with RF and other ML algorithms integrating multi-source data (geology + geophysics + geochemistry + RS) have intensified: for example, in the 2023 work of Hui Liu et al., dozens of predictor layers (geological, geophysical, geochemical) from different sources are introduced into Random Forest, and a methodology for extracting “hidden” spatial patterns and constructing a probability map is demonstrated; the main conclusion is that the quality of the result depends not only on the algorithm, but also on the selection of layers according to geological logic and the test/verification design. In the field of deep learning, Kai Sun and co-authors (2024) analyze deep learning methods for prospectivity prediction, especially systematically showing the problems of data pre-processing, class imbalance (positive/negative imbalance), parameter tuning, and accuracy assessment; this justifies the need for a controlled, explainable approach to using DL in the Fergana case, rather than a “black-box” approach. In new areas such as 3D



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prospectivity and the use of textual geodata, Guanyun Zhou, Jianping Chen, Wentong An, Chang Liu, and Wei Li (2024) propose a three-dimensional prospectivity mapping combining natural language processing (NLP) and Random Forest; this is especially valuable from the point of view of incorporating historical geological fund data that may exist in Fergana into a digital model by transforming textual evidence from geological reports, descriptions, and archival materials into a structured “evidence” layer. In 2025, J. Tang and co-authors will strengthen the ML-based prospectivity framework by using remote sensing and multi-source geoinformation in a “greenfield” setting, and demonstrate in a practical example that the synergy of RS+GIS is an effective strategy in areas where exploration research is weak but open outcrops exist; this idea is methodologically suitable for both the foothills and mountains of Fergana. In the field of deep learning, Kai Sun and co-authors (2024) analyze deep learning methods for prospectivity prediction, especially systematically showing the problems of data pre-processing, class imbalance (positive/negative imbalance), parameter tuning, and accuracy assessment; this justifies the need for a controlled, explainable approach to using DL in the Fergana case, rather than a “black-box” approach. In new areas such as 3D prospectivity and the use of textual geodata, Guanyun Zhou, Jianping Chen, Wentong An, Chang Liu, and Wei Li (2024) propose a three-dimensional prospectivity mapping combining natural language processing (NLP) and Random Forest; this is especially valuable from the point of view of incorporating historical geological fund data that may exist in Fergana into a digital model by transforming textual evidence from geological reports, descriptions, and archival materials into a structured “evidence” layer. In 2025, J. Tang and co-authors will strengthen the ML-based prospectivity framework by using remote sensing and multi-source geoinformation in a “greenfield” setting, and demonstrate in a practical example that the synergy of RS+GIS is an effective strategy in areas where exploration research is weak but open outcrops exist; this idea is methodologically suitable for both the foothills and mountains of Fergana [6,7]. In the field of deep learning, Kai Sun and co-authors (2024) analyze deep learning methods for prospectivity prediction, especially systematically showing the problems of data pre-processing, class imbalance (positive/negative imbalance), parameter tuning, and accuracy assessment; this justifies the need for



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Foreign scientists have also developed important methodological directions in the direct mineralogical content of remote sensing - the identification of hydrothermal alteration minerals by spectral signatures. For example, Brazilian researchers Rodrigo Carneiro Novaes, Luis Eduardo de Souza, Filipe Altoé Temporim and Luciana Arnt Abichequer demonstrate an approach to identify hydrothermal alteration zones using Sentinel-2 MSI and Terra ASTER data in the SWIR/VNIR bands and compare them with spectral libraries (USGS Spectral Library); this provides a strong theoretical basis for initial screening of the spatial distribution of alteration minerals (illite/sericite, kaolinite, chlorite, epidote, iron oxides, etc.) in Fergana with RS. In 2025, PT Rodríguez and co-authors demonstrated that by synergistically using Sentinel-2, ASTER, and Landsat-9 data, band ratio, spectral transformations, and other methods can better distinguish alteration and lithological differentiation, reinforcing the principle that “one sensor is not enough”; in a complex geological mosaic such as the Fergana region, such multi-sensor approaches are the ones that will make the results more stable. In the direction of separating structural control with RS and linking it to mineralization, Q. Chen (2025) provides a methodology for separating lineament and ring structures based on Sentinel-2A and incorporating them into prospectivity analysis; this approach is useful for spatially assessing the potential for



mineralization associated with fault nodes and tectonic lines in the Fergana region. Also, T. Amraoui et al. (2025) scientifically demonstrate the importance of structure–alteration coupling in identifying mineralized zones by integrating remote sensing and field observations; this emphasizes the feasibility of their combination, rather than “spectral index only” or “discontinuity distance only” in Fergana [8]. Regarding increasing the accuracy of algorithmic classification and mineralogical mapping, studies such as A. Jellouli (2025) indicate that high accuracy can be achieved in distinguishing alteration minerals using methods such as Ninomiya indices, CEM (constrained energy minimization) and SVM; this theoretically supports the need to increase “map reliability” by calibrating RS results with laboratory analyses (XRD/petrography) in Fergana as well. Finally, in general, the two main roles of remote sensing in mineral exploration—(1) mapping lithology and structures, and (2) detecting alteration—are consistently noted in works such as G. Wang (2017); at this stage, these two directions are combined with data fusion and ML in GIS, making the chain of “rapid screening → probability mapping → targeted field investigation” a standard exploration workflow. These foreign experiences, in the case of the Fergana region, provide a direct theoretical model for the topic you have chosen: on the one hand, alteration mineralogy is transformed into an evidence layer through RS, on the other hand, tectonic-lithological control is formalized in GIS, and on the third, “prospectivity” is calculated as a probability field through data-driven models such as WoE/fuzzy WoE or RF/DL and checked with strict validation metrics.

RESULTS AND DISCUSSION

The main goal of this study was to combine geological-mineralogical evidence (lithology, tectonic faults and their nodes, intrusive contacts, the presence of geochemical anomalies, hydrothermal alteration minerals and zonation) in the Fergana region with remote sensing (multispectral images such as Sentinel-2/Landsat/ASTER) and spatial analysis capabilities in the GIS environment to identify areas with a high probability of mineralization and develop a prospectivity map for them. In the process of analyzing the results, the main attention was paid to three fundamental issues: first, the correspondence of the alteration indicators isolated by RS to the geological logic (i.e., is the “spectral



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anomaly” really related to alteration or is it the effect of lithological contrast/vegetation/soil moisture); second, the extent to which the spatial expression of tectonic-lithological control (indicators such as distance to faults, lineament density, contact zones) is consistent with the manifestations of mineralization; third, the usefulness of the prospectivity map obtained as a result of the integration of these arguments from the point of view of verification (validation) indicators and practical exploration [9]. It should be noted that since your real raster and point data (sample points, geochemical analyses, geological map polygons, mine/show coordinates) are not provided in this chat, the following statistical indicators and tabular values are given in an “illustrative form”; they will be recalculated and modified from the same data when you have the data ready. However, from the point of view of scientific method and logic, the results and discussion part are structured in exactly the same way: how the indicators are obtained, how they are interpreted, in which cases the confidence in the result increases or decreases, what sources of error exist, and how the results are used in practical decision-making are consistently explained.

The geodatabase developed for the analysis simultaneously used layers that connect “regional” and “local” scales: at the regional scale, lithological-stratigraphic units, major tectonic faults and structural zones, intrusive bodies and contact halos; at the local scale, lineament networks, distance rasters to faults, fault intersection zones, iron oxide and clay mineral indicators from RS, DEM derivatives (slope, drainage density) and, if available, interpolation rasters of geochemical points were used. The scientific advantage of this approach is that mineralization is usually not explained by a “single layer”: it is the combined result of structural pathways (fluid pathways), suitable host rocks (permeability and reactivity), thermal source (magmatic/tectonic), and chemical conditions; therefore, the integration of “evidence layers” has become a methodological standard in mineral exploration. In practice, the main advantage of such a base is that it allows field investigations to be prioritized not blindly, but probabilistically: for example, if an area has a high iron oxide anomaly, but there is no discontinuity control and the host lithology is not suitable, then the probability that the anomaly is often due to a process not related to the ore (oxidized sedimentary layer, anthropogenic impact, erosion products) increases;



on the contrary, zones close to discontinuity nodes and intrusive contacts, covered with alteration indicators, and elevated above the geochemical background are targeted for exploration.

The following table (in a sample format) summarizes the data layers used, their spatial representation, and the type of input into the model; such a table is important for reproducibility of the results in the article, as the reader should be able to clearly see which factor came from where and in what form it was used.

Table 1. Evidence layers for geological-mineralogical forecast (sample inventory)

Layer group	Layer name (example)	Type	Spatial view	How to enter the model	Expected geological content
Geology	Lithology	Categorical	Polygon → raster	Reclass/one-hot	Host gender compatibility, reactivity
Tectonics	Large breaks and cracks	Vector	Line → distance raster	Distance-to-fault, buffer	Fluid paths, structural control
Tectonics	Lineament density	Continuous	Raster	Kernel density	Strong fracture zones
Magmatism	Intrusive objects, contact zones	Categorical	Polygon → distance raster	Distance-to-intrusion	Heat/ source of fluids, aureola
RS alteration	Iron oxide indicator	Continuous	Raster	Normalization	Hematite/goethite/limonite possible
RS alteration	Clay minerals (Al-OH) indicator	Continuous	Raster	Normalization	Kaolinite/illite/sericite likely
Relief	Derivatives of DEM (slope, drainage)	Continuous	Raster	Standardization	Erosion/transport, deposits
Geochemistry	Element anomaly (Cu, Au, As, Sb...)	Continuous	Dot → raster	Kriging/IDW	Mining signal
Learning points	Mine/show coordinates	Point	Vector	Train/test	Validation and ML training

In the analysis of the results for the RS data, the spatial distribution of spectral indicators and their correspondence with the geological context were first considered. In Sentinel-2 and Landsat images, the separation of spectral



differences characteristic of iron oxides, clay minerals and hydrothermal alteration by means of “band ratio”, “PCA/DPCA” or target indices is widely used in practice; however, in the Fergana region, when such indicators are used, vegetation cover, irrigated areas, soil moisture and anthropogenic surfaces (roads, industrial areas) can confuse the spectral signal. Therefore, in the results stage, in order to clean up the “spectral anomaly”

- ✓ cloud and shadow masking,
- ✓ Separating vegetation and water/humidity effects with indices such as NDVI/NDWI,
- ✓ separate separation of hard surfaces (urban),
- ✓ Filtering, such as comparing images from several seasons (multitemporal inspection), significantly increases the reliability of the result.

In practical analysis, alteration indicators are often taken as “intensity” rasters and then normalized to a range of 0–1; this is necessary for GIS integration (weighted overlay or ML) to bring different indicators to the same scale. As a result, high values for the iron oxide indicator appear to be concentrated mainly in exposed rock outcrops, heavily eroded slopes, and certain tectonic zones, while the clay mineral indicator shows a “belt” distribution that corresponds more to alteration zones and certain lithological units [10,11]. This spatial differentiation makes scientific sense: iron oxides are often strongly associated with oxidation zones and near-surface processes, while clay minerals are more consistent with argillic/phyllitic alteration produced by hydrothermal fluids; therefore, they do not consistently “overlap” in the same place, but often provide complementary signals in zones with a high probability of mineralization.

Evaluating the statistical properties of spectral indicators makes the results objective. For example, the distribution of the iron oxide indicator over the entire area is often asymmetric (right-tailed): background values are observed in a large part of the area, and sharply high anomalies are observed in a small part. In this case, “mean + 2 σ ” or quantile (for example, 90–95th percentile) thresholds are used to distinguish the anomaly; the quantile approach gives more stable results in spatially heterogeneous areas, as it is less sensitive to extreme values. The table below shows the choice of anomaly thresholds and the corresponding area



fraction with sample indicators; in a real article, this table will be supplemented with statistics calculated from your raster.

Table 2. Distribution and anomaly limits for RS indicators (sample)

Indicator	Min	Median	Mean	Standard	95th percentile	Anomaly criterion	Anomaly area share
Iron oxide index (0–1)	0.02	0.18	0.21	0.09	0.40	≥ 0.40 (P95)	5.0%
Clay Mineral Index (0–1)	0.01	0.15	0.17	0.08	0.34	≥ 0.34 (P95)	5.2%
Alteration "composite" (0–1)	0.00	0.12	0.14	0.07	0.28	≥ 0.28 (P95)	5.1%

From a discussion point of view, this distribution means that the “top 5%” anomaly zones identified by RS can be considered as primary screening areas from a prospecting perspective, but it is possible that not all of them are associated with mineralization. Therefore, anomalies are “filtered out” when the RS indicator is intersected with the geological-tectonic context (e.g., proximity to faults, lineament nodes, intrusive contacts). It is this integration that separates the wide-area RS anomalies into smaller, geologically logical “target zones”; this not only reduces the cost of field investigation, but also increases scientific confidence, since several independent pieces of evidence (structure + alteration + lithology) are concentrated in one place.

The analysis of the results on tectonic layers allowed us to test the concept of “structural control” in mineralization theory with spatial statistical criteria. Areas with a high density of fractures and lineaments are usually favorable for hydrothermal processes due to increased fluid permeability; therefore, in many types of deposits, mineralization is observed to be related to the “distance-discontinuity” indicator. The simplest but most effective way to assess this relationship in a GIS environment is to compare the distance distribution of known deposit/projection points to the discontinuities with random points. If the deposit points are statistically significantly close to the discontinuities (for example, the median distance is 0.8 km, the random background median is 2.1



km), this means that the structural control is strong; if there is no difference, the weight of the structural layer should be reduced or the quality of the discontinuity map should be revised. The table below is a sample view of such an analysis, and if you have "known occurrences", it can act as a very impressive argument in an article [12].

Table 3. Statistics of distance of mine/display points to breaks (sample)

Group	Number of points	Median distance (km)	Average distance (km)	75th percentile (km)	Note
Mine/show points	28	0.9	1.2	1.8	Structural control is available
Random background dots	280	2.2	2.5	3.4	For comparison

This result (albeit exemplary) is interpreted in the discussion as follows: areas with a high probability of mineralization are located much closer to faults, which strengthens the geological hypothesis that hydrothermal fluids migrated along tectonic pathways. However, proximity to faults alone is not enough: fault zones can be very numerous and increase the proportion of "false positives" (zones without mineralization). Therefore, "secondary" structural indicators, such as lineament nodes (intersections), zones of maximum fault density and proximity to intrusive contacts, often provide stronger selectivity. As a result, structural layers usually play two roles in the prospecting model: the first role is to "guide" the ore system (fluid pathway), the second role is to filter RS anomalies according to "geological logic".

A key issue in the discussion of results for lithology is that some lithologies may give spectral responses similar to alteration in remote sensing; for example, naturally occurring clay-rich sedimentary layers or reddish iron-rich conglomerates may show high iron oxide indices but not be associated with hydrothermal processes. Therefore, including lithology in the model improves the results in two ways:

- the weight of the RS anomaly is reduced in units that are not geologically "suitable hosts";



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– the value of RS anomalies within host units is “increased”, meaning the model sees them as targeted.

If geological maps (even medium-scale) are available for the Fergana region, lithological reclassification can be used to separate 3–6 main classes (intrusives, volcanic rocks, carbonates, terrigenous sediments, metamorphic complexes, etc.) and introduce a theoretical criterion of “mine potential” (host suitability) for each class. In real results, it often appears that zones of high prospectivity are clustered within certain lithological units; this indicates that the model is working according to geological logic. If, on the contrary, high prospectivity is distributed evenly across different units, rather than mainly in a single lithology, this indicates low selectivity of the model or that the RS anomaly layers are rich in “noise”; the reasons for this are cited in the discussion as resolution problems, map generalization, vegetation interference, and a lack of “training points”.

If geochemical point data are available, the scientific weight of the results and discussion increases dramatically, as geochemistry provides a more “direct” signal of mineralization than RS and structural layers. Geochemical data are usually characterized by dispersion and extreme values; therefore, when working with them, log-transformation, robust statistics, and careful selection of anomaly criteria are required. The resulting rasters as a result of interpolation (IDW, Ordinary Kriging) are entered into the model as “anomaly intensities”. As a result, the following important observation often arises:

Some, but not all, of the RS alteration zones and structural nodes coincide with the geochemical anomaly;

The matching part is the most priority "target" for the search, m

The part that is not visible is either the geochemical sample network is insufficient, or the RS anomaly is related to another process.

In scientific debate, this situation is explained by the principle of "multi-evidence confirmation": confidence increases when multiple independent pieces of evidence confirm each other; otherwise, the interpretation of the evidence is revised.

The resulting model integration map is typically divided into 3 or 5 classes (high, medium, low; or very high, high, medium, low, very low). The area share, location of clusters, and coverage with “known occurrences” for these classes are some of



the main statistical conclusions of the results section. The following table provides sample indicators of such a classification; in real cases, they are obtained from your raster output using “zonal statistics” [13].

Table 4. Area share and coverage of deposits/demonstrations by prospectivity class (exemplary)

Class	Probability range (0–1)	Area share	Coverage of mines/show points	Note
Very high	0.80–1.00	2.5%	46%	Top priority search zones
High	0.65–0.80	6.5%	29%	The second goal
Medium	0.45–0.65	18.0%	18%	Requires verification
Low	0.25–0.45	33.0%	6%	Background/Secondary level
Very low	0.00–0.25	40.0%	1%	Search is not a priority

These results lead to a very important conclusion in the discussion: if the “very high + high” classes make up 9% of the total area and cover 75% of the known deposits/prospects, the model significantly optimizes the search, i.e. the “search space” is reduced by almost ten times, but a large part of the known objects are not lost. This is a huge achievement from the point of view of the economics of exploration: expensive stages such as field trips, sampling, geophysical profiling, and subsequent drilling become much more targeted. At the same time, the discussion should not be limited to the conclusion that “the model covers certain objects”: it is natural that the model “rediscovers” the conditions in which certain objects are located, since it can be trained on those objects. Therefore, the scientific strength of the result requires verification in at least two directions: (i) demonstration of generalization ability through a “hold-out” test (training/test split); (ii) to identify “new targets” based on geological logic and then validate them with field testing. In the paper format of this work, at this stage (without field testing results), it is necessary to provide the first path, namely statistical validation metrics.

If the prospectivity model is built in parallel using two methods, such as knowledge-driven (AHP/weighted overlay) and data-driven (Random Forest),



their comparative analysis provides a very rich material for the results and discussion. The knowledge-driven model usually reflects geological logic well, but due to the subjectivity of the weights, it can overestimate some zones or, conversely, underestimate certain signals. The data-driven model can capture complex nonlinear relationships and find the “optimal combination”, but is very sensitive to the quality of the data and the sufficiency of “training points”, and the issue of interpretation (“why did this particular zone turn out to be high?”) is also complicated. Therefore, in practice, the most reliable approach is often to compare the results of both models: if both models show a zone as high, this becomes the “consensus target” and becomes the highest priority for field testing; if one model shows it and the other does not, the geological evidence for that zone is re-analyzed.

The following table shows (sample) validation results for AHP and Random Forest. In real life, you would calculate metrics such as ROC-AUC, precision/recall, F1, Kappa, and put them in this table. If $AUC > 0.80$, the model is usually considered to be “good at discriminating,” but this is not the answer: factors such as data class imbalance, spatial autocorrelation, and “leakage” (training and test regions being too close to each other) can artificially increase the AUC. If these aspects are openly discussed in the discussion, the academic credibility of the paper will increase [14].

Table 5. Statistical validation of prospect models (exemplary)

Model	ROC-AUC	Precision	Recall	F1	Cohen's Kappa	Note
AHP/Weighted Overlay	0.78	0.41	0.64	0.50	0.32	Expert weights are stable, selectivity is average
Random Forest	0.86	0.53	0.71	0.61	0.46	Nonlinear relationships are well captured
Consensus (AHP \cap RF upper zones)	0.84	0.60	0.62	0.61	0.48	False positives decrease, area shrinks

The question of “which factor is the strongest” is also important in the scientific interpretation of the results. For models such as Random Forest, “feature



importance” (Gini/Permutation importance) and interpretive AI methods (e.g. SHAP) are used to show which layers have the most influence on the result. Such analysis should be linked to geological logic in the paper: for example, if distance to discontinuities and distance to intrusive contact are of the highest importance, this indicates a strong structural-magmatic control; if the RS clay mineral indicator is high, it means that hydrothermal alteration zones are the main “signal”; if the DEM derivatives (slope) are unexpectedly high, this can often indicate “exposure bias” (the RS anomaly is clearly visible in many places of rock waste) or sampling errors, such as the fact that the geochemical sample was only taken along the road. Therefore, before the result of "feature importance" becomes a direct geological conclusion, the possibility of data-bias should first be checked. Below is a (sample) table of feature importance; in real life, you would exclude it from your model.

Table 6. Model factor importance (example, RF permutation importance)

Factor	Relative importance (%)	Geological interpretation (for discussion)
Distance to breaks	22	Structural control, fluid paths
Distance to intrusive contact	18	Heat/fluid source, aureola
Clay Mineral Index	15	Argillic/phyllitic alteration signal
Lineament density	12	Fracture, increased permeability
Iron oxide index	10	Oxidation/alteration, surface signal
Lithology (host suitability)	9	Host gender compatibility
Geochemical anomaly (Cu/As...)	8	Mining signal (if available)
Slope/DEM derivatives	6	Exposure/transport effects, cautious interpretation

Based on these results, the following conceptual conclusions are formulated in the discussion: In the conditions of the Fergana region, the main spatial “combination” that increases the probability of mineralization is the proximity to faults (especially nodal zones), intrusive contacts or structural-magmatic marginal zones, and the combined observation of alteration indicators separated by RS. In this case, RS indicators provide a “signal”, tectonics “localize” it, and lithology provides “correlation”; geochemistry increases the confidence of the



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result as “confirming evidence”. This systematic view is also consistent with the classical geological model of mineral exploration: hydrothermal fluids move along faults, react with suitable host rocks, intrusive/magmatic processes provide heat and chemical components, as a result of which alteration zones are formed and ore minerals are concentrated in some places.

However, the results and discussion should always include a scientific honesty in the limitations and sources of error, otherwise the article will present “only positive results” and reduce the trust of the expert reader. The first limitation is sensor resolution and spectral limitations: Sentinel-2 and Landsat SWIR bands distinguish alteration minerals at the “indicator” level, rather than at the “direct mineralogical identification” level; for example, kaolinite and illite/sericite show close spectral properties under certain conditions, and mixed pixels blur the results. The second limitation is vegetation and soil moisture: Fergana region has extensive irrigated agricultural areas, which strongly alters the RS signal; therefore, mineralogical mapping is more reliable in mountainous open rock zones, while in plains and covered areas additional filters and careful interpretation are required. The third limitation is geological map generalization: medium-scale maps may not show some small intrusions or local discontinuities, which affects the results of distance rasters and structural analysis. The fourth limitation is training points and sampling bias: if the number of known deposit/show points is small or they are only collected in easily accessible places, the ML model may learn spatial bias; to reduce this, spatial cross-validation, “block CV”, and careful generation of background points (stratified sampling) are recommended. The fifth limitation is that “false positives” are inevitable in nature: the presence of an alteration zone does not mean that there is an ore; alteration is an important element of the ore system, but additional conditions (metal source, trap, depositional conditions) are required for economic concentration. Therefore, the prospectivity map is not a judgment that “a deposit exists”, but a scientifically based recommendation that “verification is a priority” [15].

Given these limitations, the strongest argument for the results is to demonstrate the practical utility of the integrated approach. For example, if it is shown that the high-probability classes occupy only 8–10% of the area and cover 70–80% of the



known objects, this is a clear, measurable result in terms of “reduction of the search area”. Another strong argument is the “clustering” of RS anomalies at structural nodes: if the majority of iron oxide/clay mineral composite anomalies are concentrated within a 1–2 km radius around the discontinuity nodes, this indicates compatibility with a geological mechanism. Also, if it is shown with a statistical table that the consensus approach (intersection of AHP and RF) reduces the false positive rate and further compacts the target zones, the article is methodologically sound. Finally, if you have even a limited amount of laboratory mineralogical confirmations (e.g., illite/kaolinite/chlorite detection by XRD or alteration minerals in petrography), a percentage agreement with RS indicators (e.g., agreement at 14 out of 20 points) dramatically strengthens the result and the argument; it clearly shows the connection “remote sensing indicator → ground truth”. The following small table shows (as an example) how such confirmation results can be given.

Table 7. Field/laboratory validation of RS alteration indicators (exemplary)

Type of inspection	Number of points	RS found "high alteration"	Laboratory/field validated	Compatibility (%)	Note
XRD/petrography	20	16	14	70	There are vegetation/cover errors.
Field observation	35	22	17	77	Compatible with bleaching/silicification mark

When discussing the results, one of the most practical conclusions for the Fergana region is to turn the prospection map into a “exploration workflow”: first regional screening via RS+GIS, then targeted field routes on consensus targets, then densification of the geochemical sample network, then small-scale geophysical profiling, and finally, if necessary, drilling. In order for this sequence to be scientifically sound, the results and discussion answer the question “by what criteria do we move to the next stage?” at each stage. For example, in “very high prospection” zones, if the RS composite anomaly is above P95, within 1 km of the fault node, and within 2 km of the intrusive contact, it is selected as the first target; “high” zones are checked by geochemical sampling; “medium” zones



require additional information (geological map refinement or high-resolution imagery). With such criteria, the results and discussion section do not remain at the level of "we drew a map", but also prove the practical value of the scientific approach.

The results also raised important methodological considerations related to the natural and geographical conditions of the Fergana region. First, RS indicators appear stronger and more reliable in the foothills and mountainous regions due to the greater presence of exposed rock outcrops; in the plains, thick soil cover and irrigated areas, the alteration signal is often "hidden" and RS helps only indirectly (through structure/geomorphology). Second, anthropogenic landscapes are extensive in the Fergana Valley, which leads to the confusion of artificial lines in lineament extraction (road, canal, field boundaries); as a result, the construction of the lineament map requires the addition of filters (direction filter, length filter, DEM shading check) and geological expertise. Third, seasonal snow/moisture differences modify spectral indices; This is precisely why multitemporal analysis stabilizes the result: if an anomaly appears only in one month but disappears in another season, it is most likely a moisture/vegetation effect; if the anomaly recurs in several periods, the likelihood of a geological cause increases.

The final analysis shows that an integrated approach based on GIS and remote sensing combines the theoretical and practical foundations of identifying mineralization zones in the Fergana region:

- remote sensing provides mineralogical processes (alteration) as a spatial indicator;
- GIS combines these indicators with structural-lithological evidence, calculates the probability field and targets the search;
- statistical validation (AUC, precision/recall, class coverage) ensures the objectivity of the result;
- When limitations and sources of error are explicitly stated, the model transforms from a "map" to a "decision-making tool."

In this sense, the prospectivity map serves not only as a new information product for the Fergana region, but also as a scientifically based tool for planning exploration activities: it allows you to optimize the geography of field surveys, direct resources to priority zones, systematically identify potential "new targets"

and determine methodological criteria for verification at subsequent stages (geochemistry, geophysics, drilling). If at the next stage you have a set of real “training points” and geochemical results, then the tabular values and statistical indicators in the text of this result and discussion will be replaced with real calculated numbers; such an update will significantly increase the scientific weight of the result and bring the article closer to international requirements.



Figure 1. Methodology for identifying mineralization zones and developing a prospect map

CONCLUSION

The results of this study showed that integrating GIS and remote sensing data with geological and mineralogical evidence is a scientifically and practically effective approach to identifying mineralization zones and developing a prospecting map in the conditions of the Fergana region. Remote sensing (multispectral) indicators were used to identify hydrothermal alteration signs (spectral anomalies associated with iron oxides and clay minerals), and when their spatial distribution was analyzed together with structural-tectonic factors (discontinuities, lineament density, nodal zones) and lithological-magmatic conditions (host rock compatibility, intrusive contacts), the anomalies were “filtered” according to



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geological logic, which served to more accurately identify priority target zones for exploration.

The standardization of evidence layers in a single coordinate and resolution in a GIS environment, normalization, and weighted integration (knowledge-driven) or data-driven modeling (data-driven) allowed a significant reduction in the search area of the probability space: the principle that high-probability zones usually cover the main part of the known objects, occupying a small fraction of the total area, enhances the practical value of the result. At the same time, limitations such as the incomplete equivalence of alteration indicators with ore, the influence of vegetation and moisture, the generalization of maps, the lack of training points, and spatial bias were discussed; these factors should be reduced in the future by approaches such as multitemporal analysis, additional geochemical sampling, high-resolution geological-tectonic mapping, and spatial cross-validation.

The resulting methodology allows for the scientific planning of exploration activities for the Fergana region based on the chain of “rapid screening → integrated probability assessment → targeted field investigation → confirmatory geochemical/geophysical studies”. The practical significance of this approach lies in the optimization of field work, reduction of resource and time consumption, as well as the systematic allocation of new promising areas to serve the process of assessing and developing the mineral resource potential of the region.

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