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RESULTS DERIVED FROM AUTOMATED AND VISUAL INTERPRETATION OF SATELLITE IMAGERY (EXAMPLE OF THE KUMBOGUT PROSPECTIVE AREA)

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Abstract. *This paper presents the results of automated interpretation of multispectral satellite imagery using the Kumbogut prospective area (Uzbekistan) as a case study. Advanced techniques of digital image processing, atmospheric correction, multispectral classification, and automated linear-structure analysis were applied to identify concealed geological features and zones of potential mineralization. Special emphasis was placed on constructing a lineament-density map and ranking domains according to the intensity of tectonic disruption. The most prospective classes - those characterized by moderate and below-moderate densities of tectonic disturbances - spatially coincide with the majority of known mineral occurrences and sampling points exhibiting elevated concentrations of ore-bearing components. The remotely delineated mineralization zones were further corroborated by spectral signatures acquired in the field using a Spectral Evolution PSM-3500 portable spectrometer. The study demonstrates that automated satellite-data interpretation, when combined with minimal ground verification, significantly enhances the efficiency of identifying ore-controlling structural frameworks in poorly exposed terrains.*

Keywords: *automated interpretation, satellite imagery, lineament analysis, tectonic-disruption density, multispectral classification, atmospheric correction, spectral signatures, mineral exploration, Kumbogut prospective area, remote sensing in geology.*

РЕЗУЛЬТАТЫ АВТОМАТИЧЕСКОГО И ВИЗУАЛЬНОГО ДЕШИФРИРОВАНИЯ КОСМИЧЕСКИХ СНИМКОВ (НА ПРИМЕРЕ ПЕРСПЕКТИВНОГО КУНБУГУТСКОГО УЧАСТКА)

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Аннотация. *В статье приведены результаты автоматизированного дешифрирования мультиспектральных космических снимков на примере Кумбогутского перспективного площади (Узбекистан). Применены современные методы цифровой обработки, атмосферной коррекции, многозональной классификации и автоматизированного анализа линейных структур для выявления скрытых геологических объектов и зон потенциального оруденения. Особое внимание уделено построению карты плотности линеаментов и ранжированию зон плотности тектонической нарушенности. Наиболее перспективные классы (средняя и ниже средней плотность тектонических нарушений) пространственно совпадают с большинством известных рудопроявлений и точками с высокими содержаниями полезных компонентов. Выделенные дистанционными методами зоны минерализации дополнительно подтверждены спектральными*

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сигнатурами, полученными в полевых условиях с помощью портативного спектрометра Spectral Evolution PSM-3500. Исследование показывает, что автоматизированное дешифрирование космических данных в сочетании с минимальной наземной верификацией существенно повышает эффективность выявления рудоконцентрирующих структур на слабораскрытых территориях.

Ключевые слова: *автоматизированное дешифрирование, космические снимки, анализ линеаментов, плотность тектонических нарушений, мультиспектральная классификация, атмосферная коррекция, спектральные сигнатуры, поиск оруденения, Кумбогутская перспективная площадь, дистанционные методы в геологии.*

KOSMIK SURATLARNI AVTOMATIK VA VIZUAL DESHIFRLASHDAN OLINGAN NATIJALARI (KUMBOGUT ISTIQBOLLI MAYDONI MISOLIDA)

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Annotatsiya. *Maqolada Kumbogut istiqbolli maydonida (O‘zbekiston) kosmik multispektral tasvirlarni avtomatlashtirilgan deşifrovkalash natijalari keltirilgan. Raqamli qayta ishlashning zamonaviy usullari, atmosfera tuzatmasi, ko‘p zonali tasniflash va lineamentlarning avtomatlashtirilgan tahlili yashirin geologik tuzilmalar va potensial minerallashuv zonalarni aniqlash uchun qo‘llanilgan. Alohida e'tibor tektonik buzilishlar zichligi kartasini tuzish va zichlik zonalarni ranjirlashga qaratilgan. Eng yuqori istiqbolli sinflar (o‘rta va o‘rtadan past tektonik buzilish zichligi) ma'lum rudoprojavleniyalarning ko‘pchiligi va yuqori ko‘rsatkichli dala namunalarining joylashuvi bilan fazoviy ravishda mos tushgan. Masofaviy usullar bilan aniqlangan minerallashuv zonalari dala sharoitida portativ spektrometr (Spectral Evolution PSM-3500) yordamida olingan spektral signaturalar bilan qo‘shimcha tasdiqlangan. Tadqiqot shuni ko‘rsatadiki, kosmik ma'lumotlarning avtomatlashtirilgan deşifrovkasi minimal dala tekshiruvlari bilan birgalikda ochiq bo‘lmagan hududlarda rudalar to‘planishi mumkin bo‘lgan tuzilmalarni aniqlash samaradorligini sezilarli darajada oshiradi.*

Kalit so‘zlar: *avtomatlashtirilgan deşifrovkalash, kosmik tasvirlar, lineament tahlili, tektonik buzilishlar zichligi, multispektral tasniflash, atmosfera tuzatmasi, spektral signaturalar, minerallashuvni aniqlash, Kumbogut istiqbolli maydoni, geologiyada masofaviy zondlash.*

Introduction. Over the past 30 years, global experience in developed countries has shown that the use of remote sensing methods in geology is regarded as a primary and economically highly efficient information source. Of particular importance are the automated processing techniques applied to multispectral satellite imagery obtained in various spectral ranges from Earth remote sensing (ERS) data [1,7].

Unlike multispectral sensors installed on remote sensing instruments, the human eye cannot perceive the full range of electromagnetic radiation present in nature, as its visible spectral range is limited to wavelengths between 0.36 and 0.78 micrometres [2,7].

Methods. In recent years, interest has significantly increased in the use of satellite spectrometry for mapping the distribution areas of minerals possessing indicator features of favourable geological settings for the identification of mineral deposits. It should be emphasised that the majority of such studies have traditionally relied on data acquired by airborne video-spectrometers. However, currently the most abundant material available comes from investigations conducted using the ASTER spectroradiometer. Consequently, analysing the capabilities of ASTER spectroradiometer data remains a highly relevant and promising task [3,18].

The classification of satellite imagery is currently also referred to as automated interpretation (deciphering) methods. The fact that modern multispectral images are in digital format has created extensive opportunities for developing automated interpretation techniques. With the rapid growth of aerospace data volume and increasing demands for the speed of analysis and interpretation, the automation of image deciphering

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has become a critically important issue. Most methods related to the general problem of pattern recognition are ultimately transferred to the classification of objects on electronic computing machines (computers) based on deciphering features of specific objects.

According to L.A. Bogomolov, deciphering means obtaining information about objects in a given area (or, in a broader sense, about objects and geographically manifested phenomena). In his view, deciphering is the process of extracting information about terrestrial objects (or, more broadly, objects and phenomena of the geographic environment) from their photographic images, based on knowledge of the laws governing the multiplication of their optical and geometric properties in the photograph, as well as on identifying the intrinsic spatial relationships of the objects. The above definitions reflect the general interpretation of the term “deciphering” [4,12].

Numerous methods for processing multispectral imagery utilise spectral brightness characteristics. Therefore, during the implementation of automated interpretation techniques, the task of establishing quantitative relationships between spectral brightness and the properties of objects is solved. The distribution of pixels into classes occurs in spectral feature space.

The task of classifying terrestrial landscapes and water bodies consists of dividing a certain group of objects into classes according to specified criteria. In this case, objects possessing objectively common characteristics (particularly reflectance properties) belong to the same class:

- soils and rock outcrops;
- grasslands and forests;
- agricultural lands and vegetation;
- water surfaces;
- anthropogenic objects, etc.

To solve this problem, various algorithms from pattern recognition theory, mathematical statistics, and cluster analysis are employed. It should be emphasised that, in order to obtain high-quality thematic information, it is necessary to compare classification methods performed on computers with visual interpretation techniques.

Thus, in computer-based classification, any object under study is described by a set of quantitative attributes of its image that form either the image itself or the spectral reflectance curve of the object. During processing, the aerospace image is divided into elements (pixels), numerical values of characteristics are determined for each, and multidimensional vectors (corresponding to the number of characteristics) are formed. The classification task is to isolate regions of feature space in local areas that correspond to a particular object class. This process is also known as image segmentation. Computer classification provides reliable results due to the precise correspondence between the characteristics and the object [5,24].

Linear objects in satellite imagery are called lineaments (from Latin *lineamentum* – line, contour). This term was introduced into geological literature at the beginning of the 20th century by the American researcher W. Hobbs to designate straight linear landforms on the Earth’s surface not associated with tectonic faults or displacements along them. Subsequently, the term became nearly synonymous with deep crustal fractures, but only with the advent of satellite imagery did it acquire an independent meaning [5,138].

Through the interpretation of remote sensing photographic materials of varying generalisation levels and different spectral ranges within the study area, a large number of linear structures have been identified. In the modern relief, these structures mark:

1) tectonic faults with clearly expressed fault-plane lines; 2) zones of micro-fracturing; 3) buried linear structures and zones of fracturing; 4) linear boundaries of landscape elements and components; 5) straight-line boundaries between two geological bodies; 6) straightened boundaries of structural-facies subzones (Fig.1).

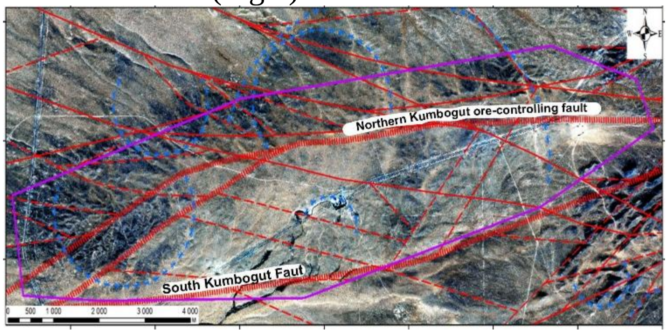

Fig.1. Results of preliminary space-structural interpretation of satellite imagery.

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The forms in which lineaments manifest on the Earth's surface – which constitute the primary criteria for their identification – include the following features:

- straight segments and sharp bends in watershed ridges, river valleys, and dry valleys (sai);
- angular (knee-shaped) bends in the outlines of relief types along the same contour line;
- differences in photographic tone between adjacent terrain areas;
- characteristic linear zones of seasonal vegetation aligned along a specific strike;
- linearly arranged chains of springs.

In many cases, the resulting interpreted data coincide with real objects only probabilistically; therefore, the performed classification cannot yet be regarded as highly accurate. At present, researchers and software developers in this field are actively working to increase the reliability of automated interpretation methods by expanding both the number of algorithms and the set of diagnostic features used. To this end, it is recommended that automated classification of multizonal imagery should utilise a greater number of spectral channels or incorporate images acquired at different times (multi-temporal data). In addition to spectral properties, texture characteristics that take into account the shape, spatial arrangement, and contextual information of surrounding objects are also employed. These additional characteristics significantly improve classification reliability beyond what spectral data alone can achieve.

Results. The products of interpretation (vector layers, thematic maps) can serve as the basis for deriving secondary information about the studied objects through geoinformation analysis methods. Geoinformation analysis, in its general form, involves examining the spatial distribution, structure, and interrelationships of objects and phenomena by means of spatial analysis and geomodelling. The principal tools for such analysis are provided by geographic information systems (e.g., ArcGIS) and include: creation of buffer zones, calculation of density, delineation of tectonic disturbance zones, identification of lineament intersection nodes, evaluation of the accessibility of ore-concentrating structures, etc. Fig.2 presents the results of satellite-image interpretation with a constructed lineament density map.

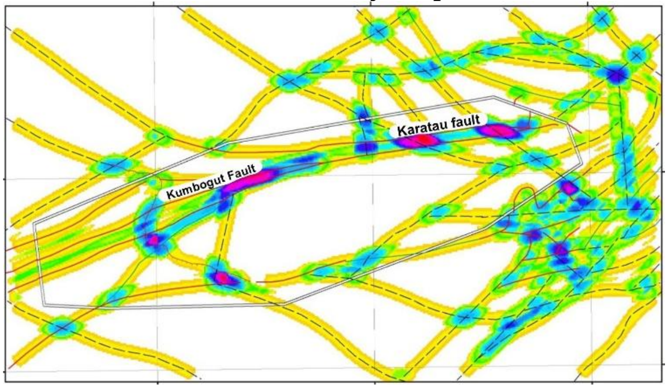

Fig.2. Lineament-density map combined with nodes of lineament and space-structural intersections, constructed using the line-distance method.

Direct geostatistical ranking of linear geological structure density values (i.e., maps of tectonic-disruption density) represents a more complex technical task. This complexity arises because tectonic-disruption density data are expressed numerically in the form of grid (raster) coverage. The main objective was to select optimal value ranges for this grid coverage to enable quantitative sampling of known mineral occurrences. In practice, the inverse problem was solved: for each known mineral occurrence (represented as vector points), the corresponding grid-cell value of tectonic-disruption density was extracted, after which the entire range of grid values was reverse-ranked into 10 intervals according to the quantitative distribution of known deposits and mineral occurrences.

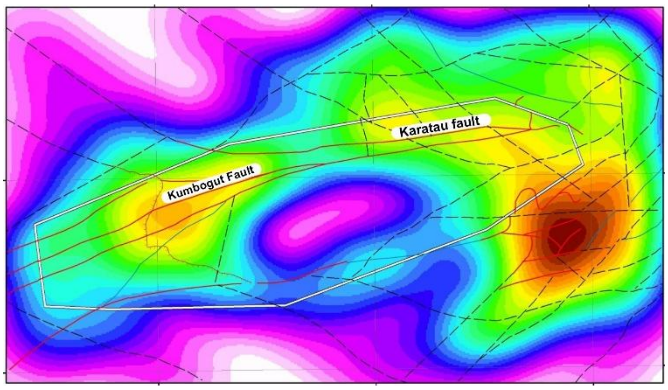

Fig.3. Ranked data of tectonic-disruption density.

The highest concentration of points representing known mineral occurrences and sampling points with the highest contents of valuable metals is observed in zones of medium and below-medium tectonic-disruption density values. This pattern is clearly reflected on the ranked map by gradations ranging from darker to lighter tones. Ranked map of tectonic-disruption density showing the spatial relationship between zones of varying density and known mineral occurrences (Fig.3).

Discussion. One of the key stages of image interpretation is the creation of composite images from different spectral channels of the satellite data or the generation of derived remote-sensing products that characterise the territory and highlight particular aspects of the phenomenon or process under study. First of all, the original satellite imagery undergoes preprocessing because the direct use of brightness characteristics of raw space-acquired material does not always yield satisfactory results for solving most geological problems. To improve outcomes, the relative brightness of the satellite image is directly enhanced, pixel-value variability is reduced, and spectral brightness is converted by normalising solar illumination (i.e. atmospheric correction is performed). All these steps are computed using algorithms embedded in standard remote-sensing software packages (ENVI, ERDAS, QGIS, SNAP, etc.). At present, the majority of satellite data available to cosmogeological researchers are already atmospherically corrected. However, because the correction of large data volumes is fully automated, the algorithms employed are based on average parameters and do not take into account the specific acquisition conditions of each individual scene.

A widespread problem when working with satellite imagery is cloud cover. Several commercial and open-source processing packages successfully minimise the influence of clouds, but this usually incurs additional cost, is not applied in all cases, and sometimes requires supplementary atmospheric data at the time of acquisition. To adapt and apply a correction model to a specific scene, the following basic steps must be performed: (1) acquisition of metadata, (2) analysis of the data, (3) model adjustment, and (4) execution of the model.

As a result of automated interpretation carried out over the Kumbogut prospective area, numerous linear structures were identified, and promising mineralised zones were automatically delineated using reference (training) objects. Within the study area and adjacent territories, the following statistical parameters were regarded as principal: count, maximum, mean, median, minimum, range, standard deviation, sum, and the number of high-magnitude values. By mathematically comparing the anomalies obtained from thermal anomaly data with the zones of mineralisation revealed through the above statistical analysis, potentially ore-concentrating areas were identified (Fig. 4).

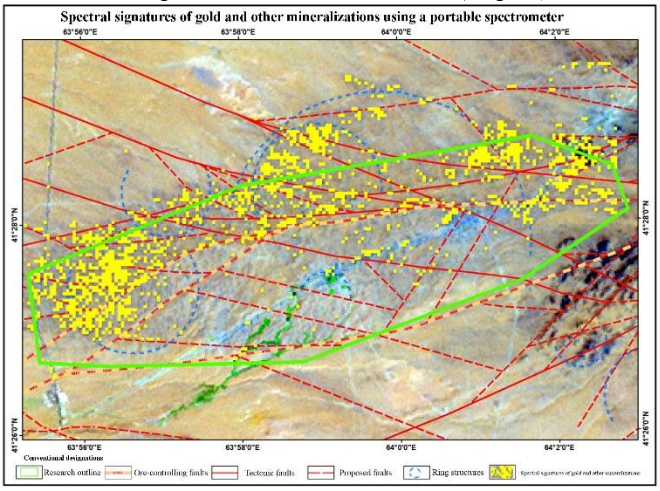

Fig.4. Spectral signatures of gold and associated mineralisation identified in the Kumbogut prospective area on the basis of field measurements using a portable spectrometer (Spectral Evolution PSM-3500).

Conclusions. Automated interpretation of satellite imagery makes it possible to solve a wide range of tasks. Even a simple atmospheric correction significantly increases the clarity of features in the satellite image – that is, it enhances the distinctiveness of pixel photo-tones – thereby enabling much more precise delineation of geological outcrops, lithological boundaries, and other objects.

Moreover, the mineralisation revealed at the intersection nodes of lineaments identified by automated interpretation has been further confirmed and refined by field spectrometer measurements. These ground-truth data provide conclusive evidence of the presence of mineralisation in the zones highlighted by the remote-sensing analysis.

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