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SATELLITE IMAGERY APPLICATION FOR SEARCHING BURIED INTRUSIVE STRUCTURES

Introduction. *At the current stage of information technology development, methods for remote sensing have been increasingly used for mineral exploration.*

Problem Statement. *Significant capital intensity of geological works for intrusive bodies search when the crystalline basement is overlapped by a thin sedimentary cover requires the implementation of advanced methods that, on the one hand, allow reducing the costs of exploration and, on the other hand, enable increasing the accuracy of objects identification.*

Purpose. *The development of methodological framework for the application of remote sensing data to identify prospective areas in search of buried intrusive bodies.*

Materials and Methods. *Medium (Landsat, Sentinel) and high (WorldView) resolution optical satellite imagery data in the thermal infrared and visible ranges of the electromagnetic radiation spectrum; radar satellite data (SRTM), multispectral aerial survey data obtained by unmanned aerial vehicles; methods for structural interpretation, digital terrain model analysis, results of field thermometry have been used in this research.*

Results. *A few prospective sites for the search for buried intrusions within the Hubkivska and Anastasivsko-Bolyarska squares of the Novohrad-Volynskyi block of the Ukrainian Shield, regardless of the geophysical data, have been identified. These objects were later confirmed by detailed geomagnetic surveying and drilling. Within the detected thermal anomalies, several small (60—120 m long and 30—50 m wide) dikes have been detected. Four of the 5 wells drilled have confirmed the presence of dike bodies, and 1 well enters the fracture zone. In other areas, where detailed geophysical survey was carried out within the detected thermal anomalies, new dike bodies have been discovered*

Conclusions. *The developed technique may be used as an additional tool in geological prospecting.*

Keywords: thermal satellite imagery, thermal anomaly, structural interpretation, unmanned aerial vehicle, buried intrusions, and diamond content.

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The use of modern satellite data in combination with obtained by UAV multispectral aerial imagery in forecasting and search for buried intrusive structures as possible containers of kimberlite (lamproite) rocks is an extremely promising area of modern technological process of mineral prospecting in Ukraine. The development of new advanced and the improvement of the existing methods and approaches for remote sensing data analysis in combination with the conventional geological and geophysical survey significantly increase the efficiency and cost-effectiveness of exploration works aimed at identifying prospective sites with manifestations of buried intrusive bodies.

The main source of remote sensing data, in this research, are as follows: satellite images obtained in the thermal infrared range of the electromagnetic radiation spectrum by sensors TM (satellites *Landsat 4*, *Landsat 5*), ETM + (*Landsat 7*) and TIRS (*Landsat 8*), multispectral images of high (*WorldView 1—3*) and medium (*Sentinel 2*) resolution, digital elevation models (DEM) obtained through processing of radar satellite data (SRTM) and aerial imagery from UAV. The study also includes structural interpretation by processing of multispectral satellite data in visible range, analysis of digital elevation models with ground truth measuments (including field profile thermometry). A detailed technological diagram for the use of remote sensing data in the search for buried intrusive structures is presented in Fig. 1.

The technique is mainly based on thermal infrared data processing with futher analysis of land surface temperature distribution, the theoretical foundations of which for the search for minerals were laid in the 1970—1980s. In Ukraine, the theoretical and methodological foundations of using infrared, mainly aerial imagery in geological mapping and mineral prospecting, in particular geothermal water, oil and gas, were developed by V.I. Lialko, L.D. Vulfson, M. M. Mytnik, Z.M. Shportiuk and others [1—5]. Due to different thermophysical properties, the temperature of rocks in intrusions will be different from host rocks, which allows them to detect and contour the body of the intrusion on the land surface. In addition, this method allows to identify tectonic faults of different rank with active fluid flow.

S**urface temperature analysis.** Long wavelength infrared satellite data is provided in integral digital values called digital numbers (DN) that shall be recalculated into radiance value. To perform surface temperature estimation per pixel (T) of mapped area, the inverse Planck radiation formula is used [6—7]:

$$T = \frac{c_2}{\lambda \ln\left(\frac{\varepsilon \cdot c_1}{\lambda^5 \cdot L_s} + 1\right)},$$

where $c_1 = 1.191 \cdot 10^{-16}$ W per m^2, $c_2 = 1.439 \cdot 10^{-2}$ m $\cdot$ K are radiation constants, ε is land surface emissivity, λ is electromagnetic radiation wavelength, and Ls is surface radiance.

Except the actual thermodynamic temperature, Planck's equation contains another unknown variable — emissivity, which can be derived from visible and near-infrared (NIR) satellite imagery by calculating normalized vegetation difference index (NDVI) and vegetation projective cover. Thus, in order to increase spatial resolution of the resulting image of surface temperature distribution, two different satellite dataset can be used (visible and NIR data from the first one and long-wavelength data from the second one), while both of them shall be obtained in similar weather conditions and the time period between two dates of scanning shall very short [8].

The temperature of the Earth`s daylight surface depends on a number of factors, including landscape features, weather, relief, etc., thus to identify the probable endogenous thermal impact on it, we analyzed long-term time series of remote sensing data to determine constant in time and space temperature anomalies. The RXD algorithm (RX anomaly detector) and the sliding window method were used for calculation of anomaly values per pixel. The first one is based on the detection of spectral differences between the region to be tested and the entire image and the magnitude of the anomaly calculated in the RXD algorithm is the Mahalanobis distance to the mean value of the whole image spectral signa-

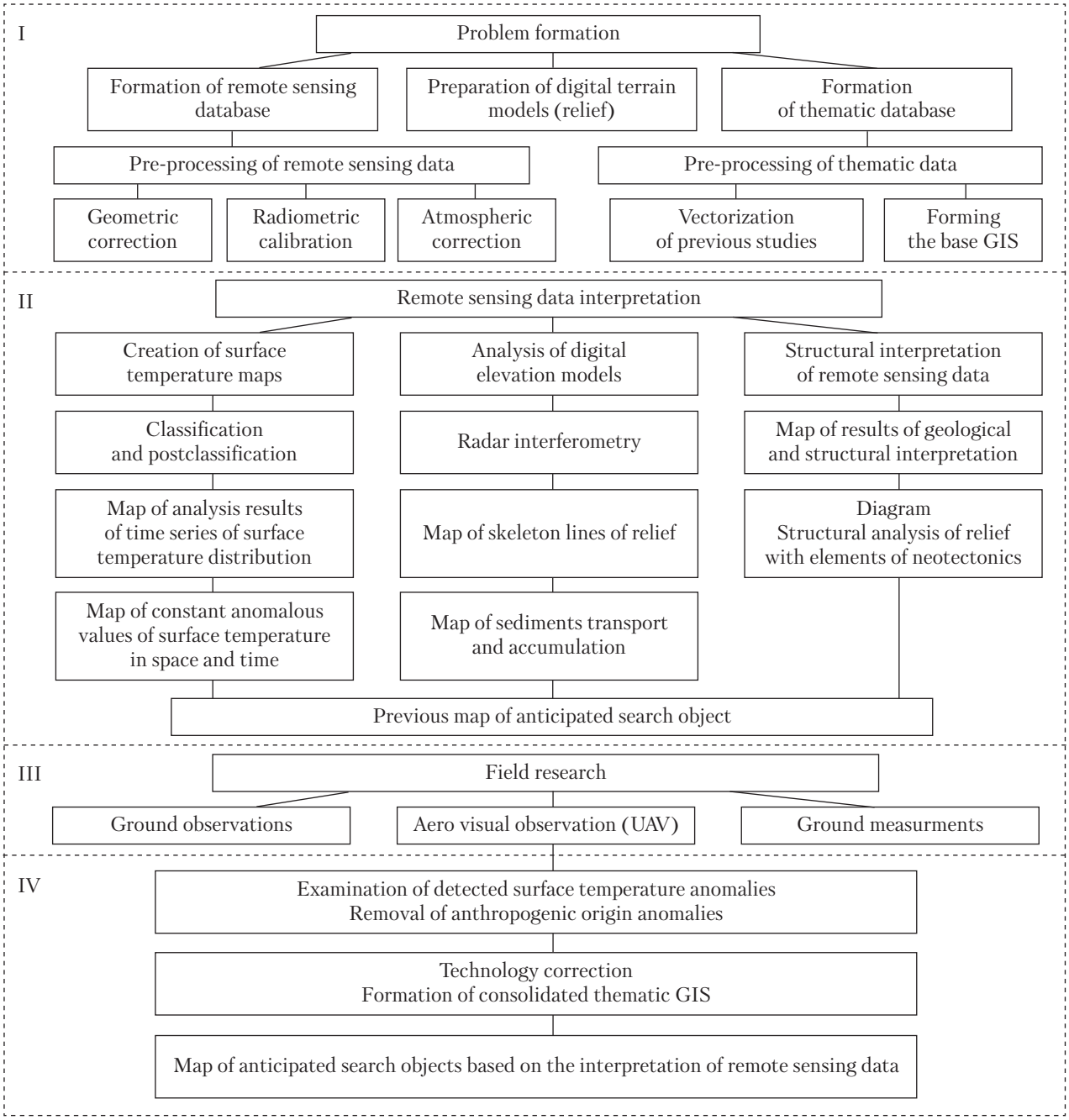

Fig. 1. Process flowchart for satellite data application in searching buried intrusive structures

tures. That is, the anomalies are most distant values from the mean value with taking into account the correlations between the spectral bands, which in our case are multitemporal thermal images. The result of the calculations is an image with integer values of anomalies in each pixel. The standard RXD algorithm implements a filter specified by:

$$\delta_{RXD}(r) = (r - \mu)^{\mathrm{T}} \; K^{-1}_{LxL} (r - \mu),$$

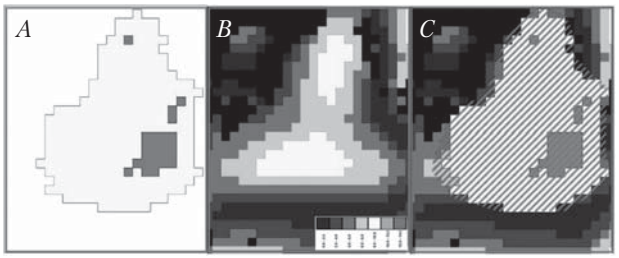

Fig. 2. An example of comparing surface temperature anomalies detected in different ways and creating a final cartographic model. The Bolyarka site constant in space and time anomalies of surface temperatures detected: *A* — by RX anomaly detection algorithm, *B* — by sliding window method, *C* — definition of anomaly contour

where r is the sample vector, μ is the sample mean, and K_{LxL} is the sample covariance matrix [9—10].

The second method involves determination the difference of pixel brightness within the defined subset of data from given array — the sliding window. The size of the window is set manually in pixels and shall match the size of the search object, i.e. the intrusive body. In our case, it was 5 pixels by 5 pixels, which corresponds to 150 m by 150 m on the land surface — the approximate size of the search object — diatreme or dike. The end result of processing is an image that displays the ratio between the brightness of pixel groups of the given window size and the background.

The results of the temperature anomalies identification by both methods on the example of Bolyarka area are presented in Fig. 2.

As additional information to detect anomalous areas of land surface temperature, a time series for a period of 34 years has been analyzed. This time series is a linear trend of increasing temperature based on temperature values for each year image included in. The trend is built separately for each pixel, which allows one to track in detail the dynamics of temperatures for individual small areas over a certain period of time.

Structural interpretation, DEM analysis (morphodynamics analysis). The main purpose of structural interpretation is to identify structural and tectonic units: faults, rock-fracture zones, folds and block structures with which geodynamic zones can be associated. In satellite images, the units of the structural framework can be reflected in the form of spectrometric and textural anomalies, linearly extended or arcuate (lineaments) and oval or round with central symmetry (ring structures) [11]. Interpretation is carried out visually on the basis of landscape-indication and contrast-analogue approaches or automatically with the subsequent manual adjustment of machine processing result. The most difficult part in the process of interpretation is to identify probable areas of manifestation of blocks tectonic displacement and magmatism. The areas of the intersection of subregional (2 km wide and several hundred km long) lineaments, which also coincide with the detected temperature anomalies of the land surface, are particularly interesting. These areas are a priority for further ground truth works.

Morphodynamics analysis of the relief allows distinguishing its' elementary surfaces with relatively stable characteristics (slope, hill aspect), watershed lines, thalwegs, contours of erosion basins, which makes it possible to model the features of lithomasses lateral flows and their direction [12]. The results of morphodynamics analysis, on the one hand, serve as additional information for the structural interpretation, as crystalline basement relief is partially reflected in the daylight surface relief because of the thin sedimentary cover and on the other hand allows locating the most suitable sites for further heavy mineral concentrate sampling. The lines of terrain framework are obtained automatically by machine processing of the already mentioned digital elevation models.

Field inspection, ground truth measurements. The main purpose of field measurements is to study landscape physical parameters within the detected anomalies of land surface temperature. This stage includes ground measurements of the land surface temperature and rejection of those areas where it is significantly affected by anthropogenic activity and natural exogenous processes, in particular microrelief with a predominance

of south-facing slopes, soil moisture, saturation with organic residues etc. The measurement is carried out with a digital probe thermometer, pyrometers, and a professional thermal image device from 6 00 to 9 00 a.m., when the sun elevation angle is small as compared with other daylight period, which decreases the effect of the solar radiation on land surface temperature. For that aim, profiles were built — straight lines on the land surface, which are a set of measurement points with geographical coordinates taken by GPS device. The measurement profile shall exceed the boundaries of remotely detected anomaly, and the temperature values obtained outside them are considered as the background values. If the temperature within the anomaly increases, in comparison with the background or trend line, the anomaly is considered confirmed.

As a result of the study, on the basis of the developed technique, the new original information on tectonic structure of particular areas and sites of the north-western part of the Ukrainian shield has been received. According to the results of a comprehensive analysis of geological, geophysical and remote sensing data, several areas with abnormally high and constant in time values of land surface temperature have been identified. They have been interpreted as areas within which the development of buried intrusions is predicted. In particular, within the Hubkivska and Anastasivsko-Bolyarska squares, regardless of geophysical data, a few objects (Bolyarka, Korda, Mala Hlumcha, and Paranino) have been detected. Later, these results have been confirmed by detailed geomagnetic surveying and drilling. Within the detected thermal anomalies, several small (60—120 m long and 30—50 m wide) dikes have been confirmed. Four of the 5 wells drilled have confirmed the presence of dike bodies, and 1 well enters the fracture zone (Fig. 3). In other areas, where detailed geophysical survey was carried out within the detected thermal anomalies, new dike bodies have been discovered (Fig. 4). Detailing of geophysical data in other areas, in particular in Marynin square, is expected.

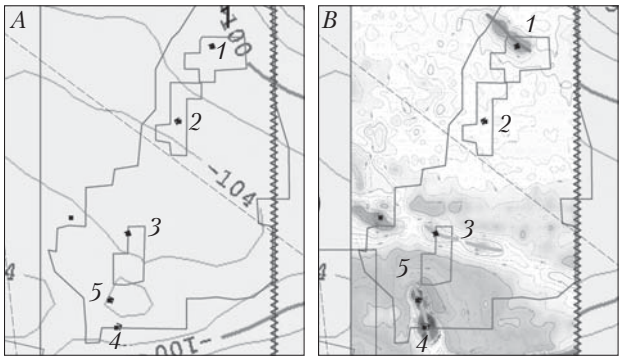

Fig. 3. Identification of new intrusive bodies within temperature anomalies. The Bolyarka site: *A* — Thermal anomalies (green contour corresponds to medium intensity; red contour corresponds to maximum intensity) on the background of the previous geomagnetic survey map; *B* — New dike bodies detected within the contour of surface temperature anomalies. The numbers on the maps are wells that have entered the dike bodies and the fracture zone

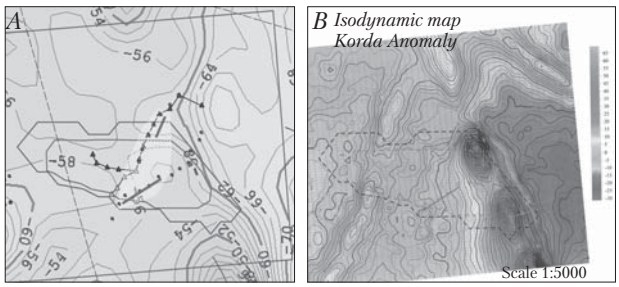

Fig. 4. Detection of new intrusive bodies within thermal anomalies. The Korda site: *A* — Thermal anomalies (green contour corresponds to medium intensity; red contour corresponds to maximum intensity) on the background of the previous geomagnetic survey map; *B* — New dike bodies detected within the contour of surface temperature anomalies

According to the results of the research, it can be stated that the classic methods of geological and geophysical survey, which are widely used in the search of primary sources of diamond content, have received another additional methodological tool in form of the study of land surface temperature distribution and terrain structural features, based on remote sensing data analysis. Of course, the proposed technique of satellite imagery application in the search for buried intrusive structures and its methods, in particular field thermometry, require further improvements. This includes justification for choosing the optimal

season and time for temperature measurements, improvement of procedure of soil temperature measurement (depth, time interval, resolution enhancement, corrections for soil moisture, etc. However, this technique can be used as a basis for similar studies in other promising areas and sites of the Ukrainian Shield, to search for both diamond-bearing rocks of kimberlite-lamproite composition, and other minerals associated with igneous rocks of buried intrusions.

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МЕТОДИКА ЗАСТОСУВАННЯ МАТЕРІАЛІВ КОСМІЧНОЇ ЗЙОМКИ ПРИ ПОШУКАХ ПОХОВАНИХ ІНТРУЗИВНИХ СТРУКТУР

Вступ. На сучасному етапі розвитку інформаційних технологій методи дистанційного зондування Землі (ДДЗ) все частіше знаходять своє застосування в комплексі пошукових геологічних робіт.

Проблематика. Значна капіталоємність геологічних робіт для пошуку інтрузивних тіл в умовах перекриття кристалічного фундаменту малопотужним осадовим чохлом вимагає впровадження нових методів, що, з одного боку, дозволили б знизити вартість пошукових робіт, а з іншого — підвищити точність ідентифікації пошукових об'єктів.

Мета. Розробка методичних принципів застосування даних ДЗЗ для виявлення перспективних ділянок на пошуки похованих інтрузивних тіл.

Матеріали та методи. Для проведення досліджень використано дані оптичної супутникової зйомки в тепловому (інфрачервоному) і видимому діапазонах електромагнітного спектру середнього (Landsat, Sentinel) та високого (WorldView) розрізнення, дані радарної супутникової зйомки (SRTM), дані багатоспектральної аерозйомки з безпілотних літальних апаратів, методи структурного дешифрування, цифрового аналізу рельєфу, результати польової профільної теплометрії.

Результати. Виділено ряд перспективних ділянок для пошуку похованих інтрузій в межах Губківської та Анастасівсько-Болярської площ Новоград-Волинського блоку Українського щита (УЩ), незалежно від даних геофізичних досліджень. Ці об'єкти в подальшому підтверджено детальними магнітометричними роботами й бурінням. У межах виявлених теплових аномалій підтверджено низку невеликих (60—120 м завдовжки та 30—50 м завширшки) дайок. З пробурених п'яти свердловин чотири підтвердили дайкові тіла, а одна свердловина увійшла у зону тріщинуватості. На інших ділянках, де в межах виявлених теплових аномалій було проведено детальні геофізичні дослідження, виявлено нові дайкові тіла.

Висновки. Розроблену методику можна використовуватися як додатковий інструмент при геолого-пошукових роботах.

Ключові слова: теплові супутникові знімки, теплова аномалія, структурна інтерпретація, безпілотний літальний апарат, заховані вторгнення, вміст алмазів.