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Liudmyla SHTOHRYN[1a], Sergiy ANIKEYEV[1b], Eduard KUZMENKO[1c], Sergiy BAGRIY[1d]

[1] Ivano-Frankivsk National Technical University of Oil and Gas, 15, Karpatska Str., Ivano-Frankivsk, 76019, Ukraine, phone, fax (0342) 54-67-25, e-mail: gbg@nung.edu.ua, [1a] https://orcid.org/0000-0001-8381-1236, [1b] https://orcid.org/0000-0002-7377-7326, [1c] https://orcid.org/0000-0002-1994-0970, [1d] https://orcid.org/0000-0003-1190-6222

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REFLECTION OF THE ACTIVITY OF LANDSLIDE PROCESSES IN THE REGIONAL GRAVITATIONAL AND MAGNETIC FIELDS (ON THE EXAMPLE OF THE TRANSCARPATHIAN REGION)

Purpose. The aim of the research presented in this article is to analyze the features of the reflection of the damage to the territory of the Transcarpathian region by landslide processes based on the anomalies in the magnetic and gravitational fields, taking into account tectonic zoning. The study is an important stage in predicting the landslide processes and it is aimed at reducing their negative effects on the environment. The relevance of the research is due to the growing intensification of landslides in the Carpathian region of Ukraine. Methodology. The development of landslides in each structural-tectonic zone is associated with its tectonic structure, and therefore these processes can have different intensity, dynamics, tendencies for further development and distribution area. Lithological-facies composition and bedding conditions of rocks form the physical and mechanical properties of rocks, determining the rate and mechanism of the development of landslides. The spatial confinedness of landslide processes in the fault zones is reflected in the gravitational and magnetic fields. Results. With the help of GIS MapInfo tools, a number of landslides in each tectonic zone, anomalies in the gravitational and magnetic fields, areas affected by landslides, the distance to the fault zones were calculated. The important result of the research is to prove a direct correlation between the spatial distribution of landslides and fault zones, tectonic structure, the lithological composition of rocks, which are reflected in gravimagnetic anomalies. Scientific novelty. The peculiarities of the reflection of the tectonic structure, zones of decompression, fragmentation of rocks and lithological composition in gravimagnetic fields on a regional scale are examined, and their association with landslide processes is evaluated for the first time. Practical significance. The theoretical substantiation of the peculiarities of the behaviour of gravimagnetic fields in the zones of distribution of landslide processes makes it possible to assess the natural conditions for the formation and development of landslides in a given region. The connection between the impact of the fault zones on landslide processes by their reflection in gravimagnetic fields is established, which can be used in the future for spatial forecasting of the development of landslides in territories with related structural-tectonic conditions.

Key words: landslide, tectonic zone, faults, lithological-facies composition, local anomalies of gravitational and magnetic fields.

Introduction

For the time being, the effectiveness of the application of geophysical methods in the study of landslides is considered proven. In our opinion, first of all, it is necessary to mention the fundamental research of VSEGINGEO (All-Union Research Institute of Hydrogeology and Engineering Geology), the results of which are described in many reports and published works, in particular, in the classical monograph [Sheko, et al., 1982]. In Ukraine, large-scale geophysical studies of landslides were performed in the Carpathian region, in the Crimea, on the Dnipro slopes; they are associated with the names of such scientists as M. G. Demchyshyn, G. I. Rudko, A. F. Bezsmertnyy, O. M. Ivanik, E. D. Kuzmenko, V. D. Cheban, D. N. Liaschuk, M. I. Maiko, O. K. Tiapkin [Demchyshyn, 1992; Rudko, 1991; Kuzmenko, et al., 2009; Cheban, 2002; Tiapkin, 2002; Ivanik, 2008; et al.].

The use of geophysical methods for the study of landslide processes has the following advantages: 1) determining a comprehensive picture of the structure of the landslide area in space by identifying the features of geophysical fields that carry information about its entire structure; 2) obtaining information without violating the integrity of the geological environment; 3) possibility to carry out, in a relatively short time, geophysical research of the surface with a fairly dense network of observations; 4) detecting abnormal changes in geophysical fields in time under the condition that a short observation period is provided with each of the methods used; 5) ensuring high accuracy and reliable interpretation of geophysical anomalies; 6) insignificant, in comparison with other methods, costs for solving the same problems.

In the study of landslides in different areas, various geophysical methods were tried out: seismic method of refracted waves, method of vertical electric sounding, georadar sounding, method of natural pulsed electromagnetic field of the Earth, method of the natural electric field, gravimetry, magnetometry, emanation method. Common to all these methods was the fact that they were applied on separate landslide areas. At the regional level, in the study of a large number of landslides, there were no attempts to connect the features of geophysical fields with the damage of territories by landslides processes. In this publication, for the first time, such an attempt is made for gravitational and magnetic fields.

As it is known, the territory of Ukraine suffers greatly from the occurrences of landslides and their consequences. Thus, according to the Information

Yearbook report on the activation of hazardous exogenous geological processes (EGP) at the beginning of 2020 in Ukraine, there are 22.,937 landslides with a total area of 2140.9 km^2. One of the most dangerous within the Carpathian region is the territory of the Transcarpathian region, where 3288 landslide instances with an area of 385.21 km^2 have been registered, which accounts for 18 % of the total area of landslides in Ukraine.

The specific objective of the research presented in the article is the analysis of the association of landslide processes with tectonic faults, which are reflected in the gravitational and magnetic fields. The research area is the Transcarpathian region, which structurally and tectonically is divided into the Transcarpathian inner depression and the Folded Carpathians.

Aim

The aim of the research presented in this article is to analyze the reflection of the impact of landslide processes based on the tectonic zoning in the local anomalies of the magnetic and gravitational fields. The relevance of the research is associated with the growing intensification of landslide processes in the Carpathian region of Ukraine. Therefore, the study of conditions of their development is an important stage in developing a forecasting methodology to reduce the negative consequences of landslides on the environment.

Initial Source Data

The spatial database of landslides (by State Research and Production Centre "Geoinform of Ukraine") for the period from 1980 to 2001 in the Transcarpathian region and the State Geological Map of Ukraine, scale 1: 200000, were examined and processed. Carpathian series. Uzhhorod set of sheets M-34-XXXV (Uzhhorod); L-34-V (Satu Mare) [State ..., 2003].

In order to analyze the connection between the spread of landslide processes and tectonic faults reflected in gravimagnetic fields [Scheme…, 2002; Map…, 2002], local anomalies of the gravitational field and magnetic field of the Ukrainian Carpathians and adjacent troughs, calculated by S. G. Anikeyev [Monchak, 2017], were used.

Methodology

Characteristics of the impact caused by landslides, taking into account tectonic zoning and reflection of spreading of landslide processes in gravimagnetic fields.

The development of landslides within each structural-tectonic zone is related to its tectonic structure, where landslide occurrences have different intensity, dynamics, tendency to further development and area of distribution (see Fig. 1).

Tectonic zones are established according to the lithological-facies composition of rocks, since it is this composition that forms the physical and mechanical properties of rocks, determining the speed and mechanism of landslide development. With the help of GIS MapInfo tools, a map featuring tectonic zoning with contours of structural-tectonic zones was constructed and within the tectonic zones, it was calculated: 1) the impact by landslide processes; 2) areas of local gravitational and magnetic anomalies; 3) the total length of tectonic faultsdistance from landslides to the nearest tectonic fault; 5) distance from landslides to the nearest river.

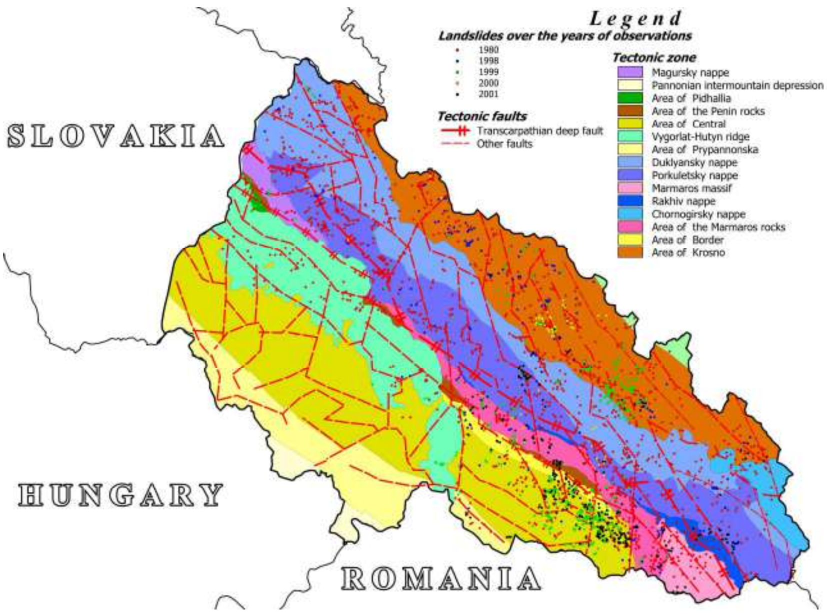

Fig. 1. Scheme of tectonic zoning of the Transcarpathian region with landslides and tectonic faults.

In addition, geomorphological characteristics, such as absolute marks and the angle of inclination of the daylight surface of the "head" of the landslide, were considered independent factors. All these parameters allow us to comprehensively analyze the patterns of spatial spreading of landslides.

From a physical point of view, the connection between the impact of territories by landslide processes with the peculiarities of the morphology and intensity of local anomalies of potential geophysical fields is mainly explained by the reflection of lithological and tectonic factors in the geophysical fields.

The lithofacies type of bedrock should be considered as one of the most significant natural factors in the development of landslides. Moving masses, formed on the surface of the underlying rocks, are genetically related to them. The individual mineral, physical and lithological characteristics of surface sediments, which directly create the potential for the formation of landslides, are determined by geological and facies features of the bedrock.

From a theoretical point of view, this factor is explained by the differentiation of strength characteristics that determine the stability of the slope for different types of rocks. The general coefficient of the slope stability is calculated by the formula

$$\eta = \frac{N \cdot tg\varphi + C \cdot L}{T}, \quad (1)$$

in which: η – coefficient of landslide stability, N – component of gravity that keeps the landslide in balance, $N = P \cdot \cos\alpha$; $\mathrm{tg}\varphi = f$ – coefficient of internal friction of rocks forming a sliding surface or attenuation zone (the main deforming horizon); C – adhesion of rocks forming a sliding surface or adjacent surfaces; L – the length of the sliding surface; α – the angle of the sliding surface; T – component of gravity (total weight of rocks P that forms a displacement) [Lomtadze, 1977]. Parameters $\mathrm{tg}\varphi$ and C are related to lithofacies here. Differentiation of the parameters is established experimentally. Table 1 illustrates the parameters, which are typical for the main types of some rocks [Clark, et al., 1969].

Analysis of the table shows that the lowest values of C and $\mathrm{tg}\varphi$ have rocks containing clay fractions. This fact is also confirmed by other researchers, some of whom are more categorical in their conclusions and believe that landslides are inherent only in clay rocks [Goshovsky, et al., 2004, Küntzel, 1980]. In the publication [Jarg, 1974] clays, argillites, shales and marls are mentioned as capable of forming landslides.

The gravitational field reflects the deep structures, dividing them by density. The environment for the development of landslide processes in the study area is sedimentary rocks, in which clay and sand-clay fractions take an important place. Since the density of these rocks in the lithological series is minimal, therefore, this factor is expected to result in reduced gravity field values. Meanwhile, the different depth of landslides (respectively, associated with them lithological varieties) and rocks, which correspond to the gravitational field anomalies, should be taken into account. That is, a weak inverse correlation is to be expected.

Table 1

Strength characteristics of the main types of rocks

Types of rocks	Rock Resistance limit, bar	C, bar	tgφ
Phyllite	55	20	1.1
Sandstone	480	120	1.1
Clayey shale	30	80	2.1
Clayey shale silicic	700	240	1.0
Siltstone	115	28	1.3
Tuff	15	5	0.9
Argillite	18	3,5	0.9
Conglomerate	210	180	1.4
Granodiorite	1200	170	1.5
Basalt	680	320	1.2
Gneiss	630	110	1.3
Granite	500	135	1.6
Limestone	810	200	1.3

As for the Earth's magnetic field, its positive local anomalies must correlate with the landslide activity. Positive anomalies in the magnetic field are generally caused by the influence of the raised blocks of the foundation, which are lined by thicknesses of sedimentary rocks, that is, the structures formed in this way. The geometry of the slope of these structures contributes to the formation of dangerous zones for landslide processes.

Transformations of geophysical fields make it possible to identify local anomalies caused by various deep-laid structures. The methodology for analysing local anomalies involves comparing the features of their distribution with drilling data and structural-tectonic maps. Local anomalies are calculated as the difference between the observed and averaged fields and are displayed as isometric or elongated anomalies of a certain direction. At the same time, the depth (h) of the sources of anomalies of the same shape and size in gravitational and magnetic fields differs. Regarding gravitational anomalies, the depth of research is approximately equal to the radius (R) of the averaging of the gravitational field. The depth of sources of magnetic anomalies is approximately 1.2–1.4 of the depth of occurrence of the sources of gravitational anomalies [Anikeiev, 2019].

A qualitative interpretation of gravitational and magnetic fields on maps in the relief-shadow image consists in detecting the reflection of geological structures and faults in the form of anomalous zones of different shapes, intensities, and signs. In the publication [Mayevsky, et al., 2012], a list of features of geological-tectonic structures was drawn up: 1) the axes of the folds of anticlinal (synclinal) structures are represented by narrow strips of positive (negative) anomalies (structures) with clear boundaries of the areas; 2) groups of the folds of the cover, which come out to the surface, are displayed in an anomalous field in the form of a complex combination of gradient zones and axial lines; 3) discharge-thrust faults in the sediments are reflected by complex forms of branching strips (zones of delimitation of anomalies of the same sign); 4) raised (lowered) blocks of the foundation and groups of folds (or their wings) with a calm subhorizontal occurrence of rock layers are distinguished by light (dark) isometric or irregularly shaped areas of a relatively calm field; 5) deep faults with significant subvertical amplitude are displayed as lengthy darkened strips (gradient zones); a chain of dark (light) elongated areas-strips, and transverse strips reflect transverse faults of any origin.

Let's consider the characteristic features of the mapping of tectonic faults, fracture zones, the lithological composition of rocks in the gravitational (see Fig. 2) and magnetic (see Fig. 3) fields of the study area.

The Carpathians are a complex mountain system, the structure of which is dominated by flysch deposits, usually divided into Inner, formed in the Late Cretaceous period, and Outer (flysch), which are the product of the final Cretaceous-Paleogene stage of the Carpathian geosyncline.

In the Outer Carpathians, only Cretaceous-Lower Miocene deposits of flysch formations with a total thickness of up to 10 km come to the surface. They are divided into separate blocks (scales) by tectonic faults, which played a major role in forming the present-day relief, the orientation of slopes as well as determining the direction of the hydrographic network, and geomorphology of valleys.

Fine-rhythmic Cretaceous-terrigenous flysch rock mass with folded-scale structure and increased fracture contributed to the intensive development of weathering processes and the formation of thick masses of eluvial-diluvial deposits, which constitute the environment for the development of exogenous geological processes, in particular landslides [Rudko, 1991, 2002].

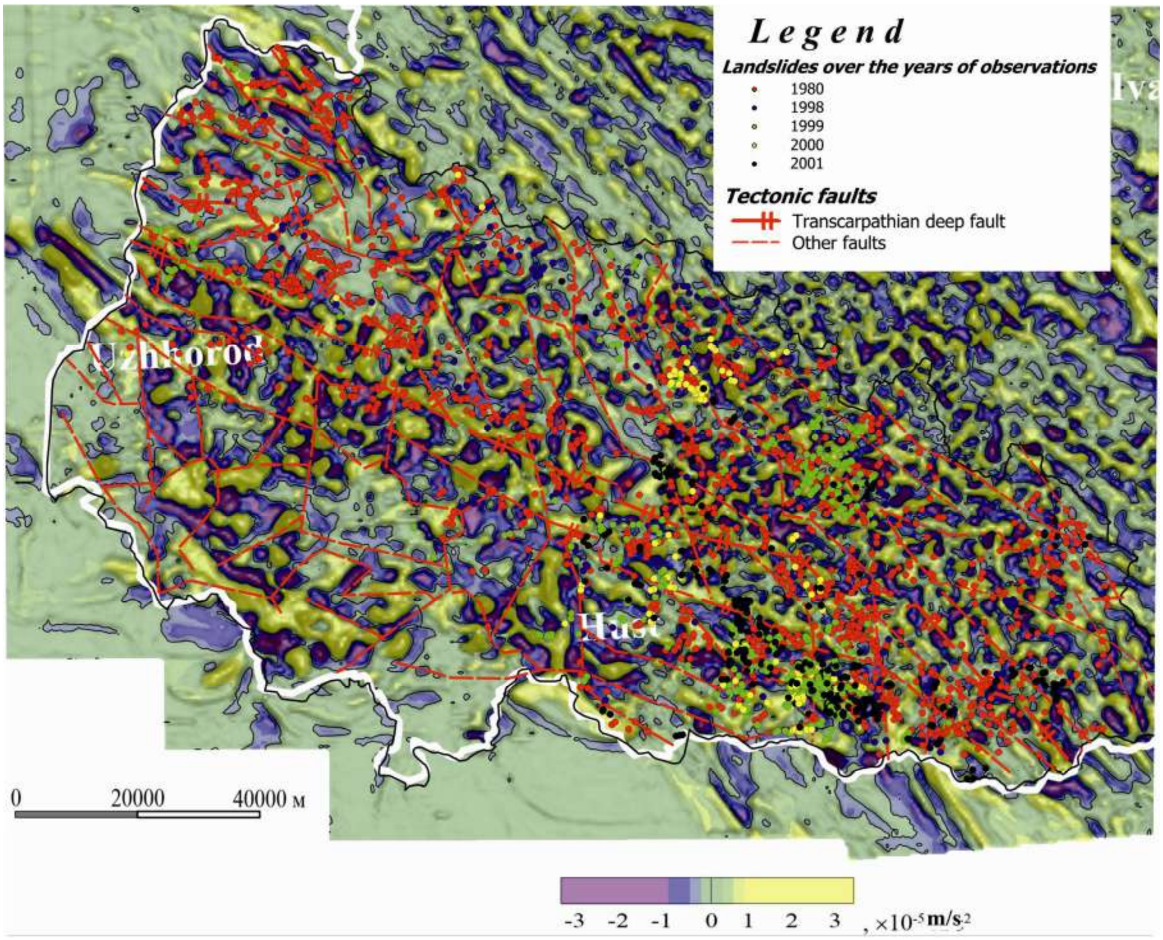

Fig. 2. Map of local anomalies of the gravitational field (averaging radius 2500 m) (S. G. Anikeiev, 2017) taking into account the spread of landslides within the Transcarpathian region.

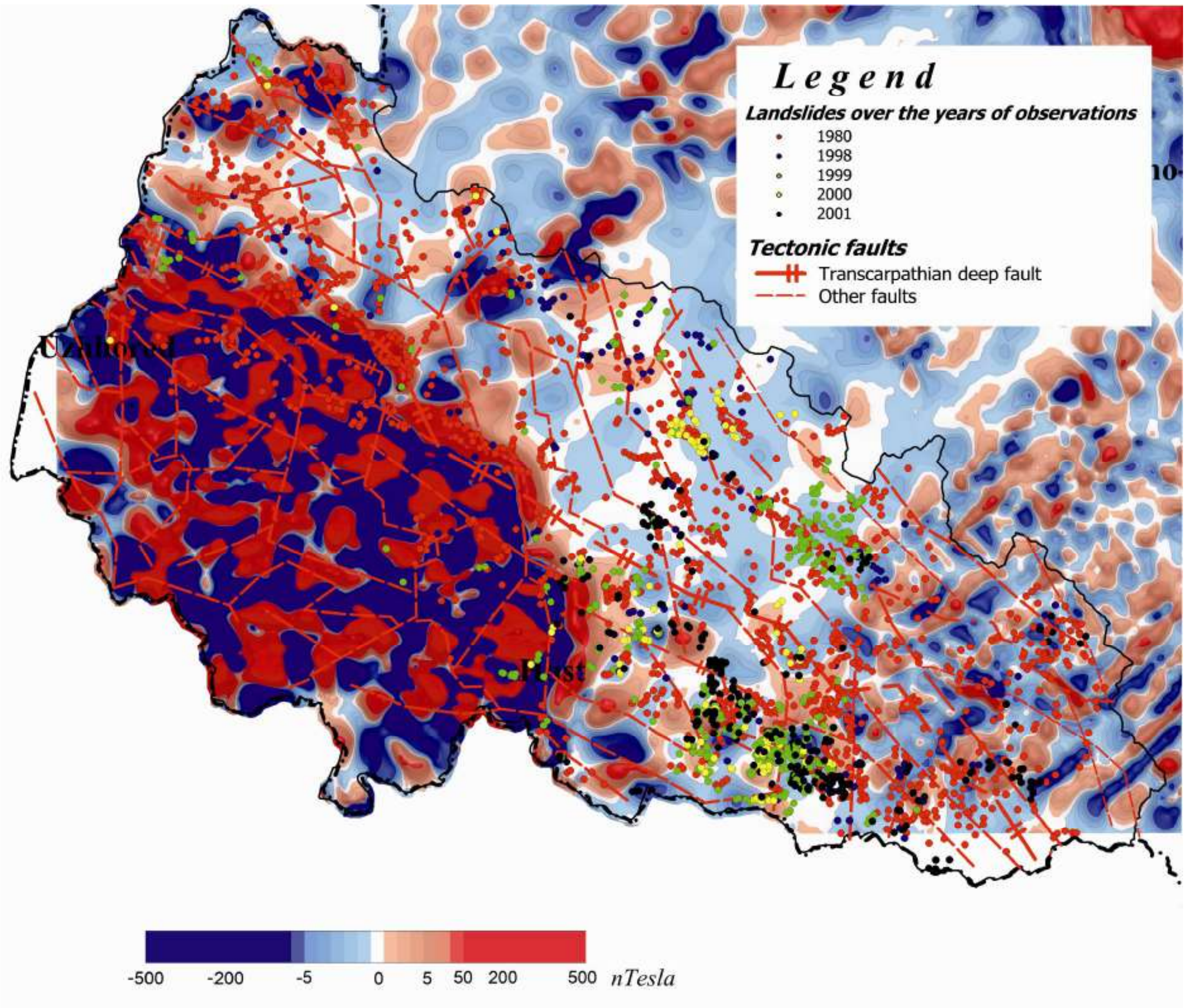

Fig. 3. Map of local anomalies of the magnetic field of the Ukrainian Carpathians (averaging radius 5000 m) (S. G. Anikeiev, 2019) taking into account the spread of landslides within the Transcarpathian region.

Within the Transcarpathian region, the Outer Carpathians are divided into the following tectonic units according to tectonic zoning: Krosno zone, Duklyansky nappe, Porkuletsky nappe, Chornohirsky nappe, Magursky nappe and Rakhiv nappe.

In order to determine the extent of coverage of the tectonic zone by the landslide processes, the 'impact coefficient' was used, which is a characteristic of the inclination of the territory to develop these processes:

$$K_i = S_i / \sum S_i , \qquad (2)$$

in which S_i – the area of landslides within the tectonic zone; $\sum S_i$ – area of the tectonic zone.

Let's analyze the impact of landslides within individual structural and tectonic units, taking into account the distribution of local anomalies of gravimagnetic fields, as well as the geological structure of the region [State ..., 2003].

The Krosno area has no cover style; it is associated with its depressive development in the Oligocene and Early Miocene. The synclinal structures of the north-western part of the Krosno zone are much wider than the anticline ones and their central parts are filled with the youngest Oligocene deposits lying flat. The southwest wings of the synclinals are characterized by quite steep bedding. The Krosno zone is composed of a thick layer of sandy-clay flysch with layers of sandstones, marls, limestones; common horizons of olistolites are common there and in the west of the zone there are layers of variegated clays. It is mainly characterized by a positive gravitational field with an intensity of up to $2 \cdot 10^5$ m/s^2 and a negative magnetic field with an average intensity of 5 to 15 nT. The style of tectonics is integumentary-scaly, the width of the scales ranges from 0.5 to 4–5 km and they extend in the north-eastern direction, the bedding of scales is quite steep on the surface (45–80°). The internal structure of the scales is dominated by steep anticlines; there are monoclinal scales, the wings of which are complicated by folds and longitudinal fractures and this contributes to increased fracturing. The anticlinal internal structure of the scales, the steep bedding of the scales, the distribution of olistolite horizons indicate a lithological contact of rocks and is well displayed in negative anomalies of gravity of isometric form with intensity up to -3·10 m^5/s^2. Most of the landslides develop on the slopes and by the mechanism of displacement refer to blocking and landslides of the current with such characteristics. There have been 588 landslides registered, with an impact coefficient of 0.03. The average characteristics of landslides: absolute values of 632.5 m, the thickness of landslides 11.8 m, average dimensions 302.7×268 m, steepness of slopes 26.8°.

Further to the southwest, the Duklyansky nappe extends, which belongs to the most complex ones in its internal structure and has a multi-layered folded-scale structure. The internal structure of the scales is complex; there is fine folding and crumpled rocks. In the front part, the most ancient rocks of the Cretaceous age come to the surface; the wings and rear parts of the scales make up Paleogene-Neogene sediments. In the fine-rhythmic Oligocene sand-clay flysch, there are often acute fragments of sandstones, variegated argillites ranging in size from decimeters to a kilometer, the number of fragments accounts for 40–60% of the rock, which indicates a significant dismemberment of rocks. The flysch is represented by alternating sandstones with thin layers of argillites with a subordinate value of marls. Compared to other elements of the flysch Carpathians, it has reverse vergence of individual thrusts. Against the overall gravitational field of a positive sign, negative anomalies of the isometric shape of a different direction with intensity up to -$3 \cdot 10^5$ m/s^2 are displayed, which reflects significant dismemberment and fracturing of rocks. The biggest number of landslides were registered in the northwest and east of the nappe, which are mostly covered by tectonic faults of the Carpathian stretch. There have been 296 cases registered with the following average characteristics: absolute marks 576 m, the thickness of landslides 14 m, average dimensions of landslides 461×355 m, slope steepness 25°. The impact coefficient is 0.03.

Porkuletsky nappe is also characterized by an integumentary-scale style of tectonics. The fine-rhythmic Eocene sand-clay and sand flysch prevail there. Flysch rock masses are immersed in the opposite direction in relation to the Krosno zone from the southeast to northwest, that is, if in the southeast the nappe is composed of rocks of exclusively Lower Cretaceous age, the Paleogene deposits prevail in the northwestern part. Small folds, complicated by rupture, are widespread, which contributes to the processes of cracking and fracturing of the rocks. The scaly structure and fault zones are displayed by sharp gradient zones of the gravitational field with an intensity range from $-3 \cdot 10^5$ m/s^2 to $3 \cdot 10^5$ m/s^2; magnetic field anomalies reduce their intensity from 20 nT in the north-west direction (contact zone with effusive rocks Vygorlat - Gutynsky ridge) to the south-east up to 10 nT (contact with Rakhiv nappe). There have been 431 landslides registered, mostly of block sliding, with the following characteristics: absolute marks 512.7 m, sediment thickness 14 m, average dimension of landslides 426.5×321.3 m, slope steepness 24.7°. The coefficient of impact is 0.035.

The Chornogirsky nappe only partially occupies a small area of Transcarpathia in its south-eastern part. The extension of the scales coincides with the total extension of the zone. The densely distributed Cretaceous sediments prevail there and they form a wide gentle area, complicated by small folds of synclines and formed by fine-rhythmic argillite-sandy flysch with alternating layers of powerful sandstone units. Most of flysch deposits are thin-layered tiled non-limestone argillites. The Chornogirsky nappe is the highest mountain range within the Ukrainian Carpathians, its slopes are steep. The gravitational field is dominated by positive anomalies that characterize the high-altitude massive, while the magnetic field is dominated by negative anomalies. On its territory, 24 block landslides have been registered with the following characteristics: absolute marks 991.8 m, sediment thickness 22 m, average landslides 692×517 m, slope steepness 26.7°. The impact coefficient is 0.023.

The Magursky nappe within the Transcarpathian region is a wedge-shaped protrusion, which is separated from the Dukliansky nappe by a fault zone and is composed of Paleocene and Eocene sand-clay flysch rocks. The general style of tectonics is longitudinal scales, separated by steep thrusts in the north-eastern direction. The internal structure is folded and scale with the predominant Paleocene and Eocene deposits forming anticlinal and synclinal folds with the fall of rocks 20-70°. It is characterized mainly by a positive gravitational field up to $3 \cdot 10^5$ m/s^2 and a negative magnetic field of 20 nT. The vast majority of landslides by the mechanism of displacement belong to the ductile ones and are characterized by the following parameters: absolute marks 323.3 m, sediment thickness 233×199 m, the average size of landslides 233×199 m, slope steepness 25.2°.

The Rakhiv nappe stretches between the Marmarosky and Chornohirsky nappes in the shape of a strip and is gently pushed onto the more external elements of the flysch Carpathians. Thick flysch strata of dark terrigenous-carbonate formations and separate small lenses of basaltoids and limestones, collected in small strongly dislocated folds, are widespread there. It is characterized by mountainous terrain with a network of tectonic faults, which are reflected by the gradient zone of the gravitational field of linear extension with a field intensity from $-3 \cdot 10^5$ m/s^2 to $2 \cdot 10^5$ m/s^2 and magnetic anomaly up to 15 nT. The damage coefficient for the area of landslides is 0.07. There have been 27 landslides registered, mainly of a block sliding type, with the following characteristics: absolute marks 649.2 m, sediment thickness 15 m, average landslides 646×496 m, slope steepness 30°.

The inner Carpathians on the territory of Ukraine are almost completely covered with young rocks of the Transcarpathian Neogene trough and only their outer elements emerge on the daylight surface: the Marmaros rocks zone, the Marmaros massif and the Penin rocks zone.

The area of Marmaros rocks is small in its area but has a very complex structure. Its characteristic feature is the development of sedimentary olistolites in the stratum of sandy-clay rocks, which is a result of the destruction of catastrophic landslides and landslides of large blocks of pre-Apt sediments that, before denudation, occupied the position between the modern area of their distribution and the Flysch Carpathians. The zone is composed of Paleogene sediments in the form of conglomerates, sandstones and variegated marl-clay rocks, black argillites and marls. In general, the zone of Marmaros rocks is reflected by a positive gravitational field, against which a strip of intermittent isometric anomalies of the negative sign up to $–3·10^5$ m/s^2 is displayed, which is the evidence of zones of increased fracturing caused by olistolites and tectonic faults. The territory is very affected by landslides – the coefficient of impact is 0.05. There have been 220 landslides registered: absolute marks 486.6 m, sediment thickness 10 m, average landslides 398.5×228.6 m, slope steepness 23.3°.

The Marmaros massif is thrust to the north, to the Flysch Carpathians. In the area of its junction with flysch complexes, there is a narrow contact zone of tectonic blocks, which are characterized by the autonomy of developed, metamorphic and sedimentary rocks, composed mainly of shales, quartzites, limestones and sandstones. Carbonate-terrigenous strata with powerful Upper Jurassic effusives lie on top with a sharp inconsistency. This structure is clearly reflected in a positive gravitational field up to $3·10^5$ m/s^{2}and magnetic fields with an intensity of up to 15 nT. The impact coefficient is 0.08. There have been 55 block-type landslides registered with the following characteristics: absolute marks 679.3 m, sediment thickness 17.4 m, average landslides 398.5×228.6 m, slope steepness 28.9°.

The area of the Penin rocks is a narrow natural boundary between the Cretaceous and Paleogene flysch of the Outer Carpathians and the molasses of the Transcarpathian trough. The most important feature of the Penin rocks is a great fragmentation of all sedimentary complexes without exception. This is a zone of giant breccia, which is also in the tectonic relationship with neighbouring structural units. It is characterized by an extremely wide development of small-amplitude faults and a dense system of crushing zones, which can be observed in sharp gradient zones of the gravitational field up to $-3·10^5$ m/s^2. Paleogene flysch strata, which lie on Cretaceous sediments with blocks of more ancient rocks, form large structures of multi-storey coverings, and lie one above the other on the sloping surfaces of thrusts. There have been 22 landslides registered: absolute marks 529.2 m, sediment thickness 5.7 m, average landslides 217.8×160.8 m, slope steepness 24.6°. The damage coefficient is 0.08.

The Transcarpathian inner depression is limited by deep faults: in the northeast – Transcarpathian, in the southwest – Prypannonsky, which are reflected by sharp gradient zones of the gravitational field. The lithological contact of rocks is distinguished by a transition zone between anomalies of different signs (the amplitude of the gravitational gradient in the studied zone varies from –3 to $3·10^5$ m/s^2) and it reflects the boundary between the Outer Carpathians (Marmara and Penin rocks) and Inner Carpathians (Transcarpathian). In the field of local magnetic anomalies, the faults are reflected by negative anomalies.

The trough is composed of a powerful complex of Neogene molasses, dislocated in gentle folds and complicated in some places with salt stocks and volcanic formations. According to the structure of the sedimentary nappe from the northeast to the southwest, the following zones are distinguished: Border (monoclinal), Central (salt-diapir with brachy folds) and Prypannonska.

An overlay element of the trough is the Vygorlat–Hutyn ridge (20–25 km wide), which is composed of a thick layer of rocks of volcanic formations of Neogene age, effusives, andesites, andesite-basalts, liparites and their tuffs and covered with a stratum (up to 10 m) of eluvial yellowish-brown sediments, containing a significant portion of crushed and redeposited volcanic material. The stratum is intensively fragmented by variously oriented rupture faults and complicated by secondary folding in the submeridial direction [Rudko et al., 1999]. The Vyhorlat-Hutyn ridge divides the central zone of the Transcarpathian Trough into the Mukachevo and Solotvyno depressions by its section of the meridional direction. The latter is characterized by the fact that on its surface there are mainly Baden and partly Sarmatian deposits, and in its section saline rocks are widespread.

The volcanic rocks (andesites, basalts and their tuffs) of the ridge are reflected by strong anomalous zones of positive sign both in gravitational (up to $3·10^{-5}$ m/s^2) and in magnetic fields (up to 20 nT). Negative gravitational anomalies of isometric shape indicate the contact of rocks of different lithological composition and are concentrated in the troughs (240–360 m) that are associated with alluvial sediments (pebbles with gravel, sand and clay) of river valleys. Most landslides develop on river slopes and in the area affected by tectonic faults. There have been 91 landslides of mainly block type registered: absolute marks 407.8 m, sediment thickness 16.5 m, average landslides 402×361 m, slope steepness 19.6°. The damage coefficient is 0.014.

The Border zone is located in the northeast of the trough. The basement consists of metamorphic shales, Triassic, Jurassic and Cretaceous sediments, as well as flysch deposits. The depth of the basement increases in the direction from west to the south-east – from 53 m to 1000 m. The Prypannonsky fault is distinguished by a sharp gradient of gravity and separates the Border Zone and Prypannon. In the Border trough zone, the gravitational field of the positive sign predominates, which is explained by the presence of a number of buried stratovolcanoes in the structure of which there are stocks of andesitic porphyrites or domes of andesites. There are positive gravitational anomalies of isometric shape, the central part of which is formed by a chain of more intense to $3\cdot10^{-5}$ m/s^2 oval anomalies with a diameter of 5-10 km. The presence of volcanic rocks is also reflected in a positive field of magnetic anomalies with an intensity of up to 15 nT. There have been 80 landslides registered: absolute marks 462.5 m, sediment thickness 6.75 m, average landslide sizes 80×221 m, slope steepness 24°. The impact coefficient is 0.04.

In the Central zone, the foundation is composed of metamorphosed volcanic and Cretaceous-terrigenous deposits and lowered along faults to a depth of 2200 to 3400 m. The overall structure of the basement is block. Salty diapir and brachyanticlinal folds are also widespread and they are associated with effusive and intrusive Neogene volcanic formations. The size of the folds is proportioned with the volcanic structures, and the extension is close to the Carpathian and only in some riparian structures – anti-Carpathian. The stratovolcano stretch is reflected in the gravitational field by positive isometric anomalies, in the centre of which more intense values of $2\cdot10^{-5}$ m/s^2 are displayed; similarly, they are reflected in anomalies of the magnetic field up to 20 nT. The anticlinal folds around the volcano structures are distinguished by isometric anomalies of the Carpathian extension with a reduced gravitational field to $-2\cdot10^{-5}$ m/s^2 and magnetic anomalies –20 nT. There have been 470 landslides registered, which mainly develop on mountain slopes and river valleys: absolute marks 464.5 m, thickness of landslides 5.6 m, average landslides 238×181 m, slope steepness 25.3°. The impact coefficient is 0.012.

The Pidhallia zone is composed of Paleogene flysch rocks, overlain by volcanic sediments of the Vygorlat-Hutyn ridge, and it emerges on the daylight surface within a small area in the northwestern part of the trough. In the middle, in the direction from the west to east, the zone is crossed by the Prypannonsky fault, which is reflected by sharp gradient zones of the gravitational field (from $-3\cdot10^{5}$ m/s^2 to $3\cdot10^{5}$ m/s^2) and negative anomalies of the magnetic field. Single landslides have been registered there: absolute marks 380 m, sediment thickness 3.8 m, average landslides 93,8×65 m, slope steepness 16.3°.

Confinedness of landslide processes to the fault zones.

The tectonic factor in the literature sources devoted to the study of landslides is mentioned as one of the most influential [Emelyanova, 1978; Sheko et al., 1999].

From our point of view, the tendency for the correlation of spatial distribution of landslides with tectonic faults is explained, first of all, by the development of fracture zones, which, when activated by landslides, are realized due to two main factors: 1) weakening of stability of the upper layer of the geological environment due to a decrease in the angle of internal friction and adhesion of rocks; 2) formation of aquifers and intensification of groundwater filtration along the slopes.

Fault zones are geodynamic systems that are constantly in a tension state (a combination of compression and tension). Overlapping structures can be formed above them, but they still remain zones of fracturing, intensive rock fragmentation, increased permeability, which reduces the stability of rocks in the upper layers of the geological environment.

As it is mentioned in [Mikhailov, 2002], "in contrast to the surface structures, deep faults form powerful zones with a width of kilometers to tens of kilometers". Such zones are called zones of "dynamic impact of faults" [Sherman et al., 1983]; in such zones the distribution of cracks has a wide range of sizes and directions and their formation depends on depth, rock properties, hydrological and tectonic conditions (compression, tension), size of accumulated tensions that exceed the strength of rocks in the vicinity of the fault [Guiju, et al., 2015; Castro, et al., 2012; Nurwidyanto et al., 2019; Sungchan et al., 2020].

The overall geodynamic model of the region is compression in the anti-Carpathian (southwest – northeast) direction with a rise of 1–2 mm/year of the daylight surface. [Nazarevich, et al., 2013]. The peculiarity of this region is the intensive displacement and the presence of faults of different directions and order. The main fault is Transcarpathian, which is characterized by a block structure, high mobility and contrast of oscillatory movements; the width of the impact zone ranges from several hundred meters to 5–5.5 km [Maksymchuk, et al., 2014].

Table 2 shows the proportion between the number of landslides and the distance to the nearest fault within the structural-tectonic units. As you can see, there is a direct relationship: most landslide processes develop within a radius of 2.5 km – primarily, this is typical of the Chornogirsky nappe, Rakhiv nappe, and such zones as Penin rocks, Pidhallia, Prypannonska (90–100 % of landslides). For other zones, the share of landslides is from 65 to 87 %.

Table 2

Confinedness of landslide processes to fault zones taking into account tectonic zoning

Tectonic zone	Number / of landslides	Distance from landslides to fault zones		
		1.5 km	2.5 km	3.5 km
		number of landslides / percentage of the total number of landslides in the tectonic zone		
Outer Carpathians				
Area of Krosno	588	250/42.5 %	385/65.5 %	495/84.2 %
Duklyansky nappe	296	120/40.5 %	189/63.9 %	252/85.1 %
Chornogirsky nappe	24	16/66.7 %	23/95.8 %	24/100 %
Porkuletsky nappe	431	196/45.5 %	287/66.6 %	367/85.2 %
Magursky nappe	18	9/50 %	12/66.6 %	15/83.3 %
Rakhiv nappe	27	17/40.7 %	25/92.6 %	27/100 %
Inner Carpathians				
Area of the Marmaros rocks	220	118/53.6 %	158/71.8 %	184/83.6 %
Area of the Penin rocks	22	19/86.4 %	22/100 %	
Marmaros massif	55	37/67.3 %	48/87.3 %	52/94.5 %
Area of Pidhallia	4	3/75 %	4/100 %	
Vygorlat-Hutyn ridge	91	54/61,5 %	79/72.5 %	83/80.2 %
Area of Central	470	179/39.8 %	287/62.8 %	386/80.2 %
Area of Border	80	35/41.7 %	65/77.4 %	74/88.1 %
Area of Prypannonska	18	14/77.8 %	18/100 %	

Since geological and geophysical information is probabilistic, statistical methods are used for data analysis and processing and they are divided into parametric and nonparametric. One of the conditions for using the parametric methods is the normal distribution of the studied data; for non-parametric methods, this condition is not required. The check for the normal distribution was carried out using the Shapiro-Wilk test and showed that the normal law is characteristic for the parameters: “absolute mark”, “angle of inclination of the daylight surface” of the landslide “head”, “distance to the river”; the other parameters – “total fault length”, “distance to faults”, “areas of gravimagnetic anomalies” are distributed according to the lognormal law or Weibull's law. If the sample is not described by the normal distribution law, it is incorrect to use the average values because they are strongly affected by the extreme values of the sample elements. In such cases, the sample is best characterized by the median (the value of the parameter, to the right and left of which there is an equal number of observations); for normally distributed values, the values of the median and the average are close (see Table 3).

In order to determine the structure of the spatial relationships between landslides spreading and the considered parameters, let’s use the factor analysis, with the help of which it’s possible to identify the groups of independent factors which are in fact their own correlation vectors, and investigate their effect and intensity on landslides.

The factor analysis was carried out with the rotation of the coordinate axes by the method of varimax, which allows obtaining a matrix of loads on each factor in such a way that they differ as much as possible from each other.

The analysis of the obtained results showed that four parameters are characterized by the highest intensity – “total length of fault zones”, “distance to faults”, “negative gravitational areas” and “positive magnetic anomalies”, which directly correlate with factor 1 and have the largest share of total dispersion – 0.42 (see Table 4). This indicates that they reflect a single process, in this case, we can assume that factor 1 is the spread of landslide processes. These four parameters play an important role because they characterize the general fracture and fragmentation of rocks within the radius of influence of tectonic faults.

Table 3

Median values of the studied parameters according to tectonic zoning

Tectonic zone	Area of the zone, km^2	Area of landslides, km^2	Number of landslides	Total length of faults, km	Distance to the river, km	Distance to faults, km	Absolute. mark of the "head" of the landslides, m	angle of the surface of the landslides' "head" , deg.	Area of negative gravitational anomalies, km^2	Area of positive magnetic anomalies, km^2
Outer Carpathians										
Area of Krosno	2500.4	72.72	588	337.6	0.22	1.73	637.5	26.9	31.51	42.61
Duklyansky nappe	1938	59.11	296	296.5	0.28	1.8	575	25.8	28.36	33.13
Chornogirsky nappe	505.6	12.11	24	59.3	0.29	1	880	26.7	6.7	5.8
Porkuletsky nappe	1885.9	68.36	431	332.3	0.3	1.67	445	24.7	27.6	43.24
Magursky nappe	158.2	0.77	18	31.3	0.22	1.48	280	25.2	0.37	0.45
Rakhiv nappe	138	9.79	27	24.6	0.42	0.91	665	30	3.15	5.83
Inner Carpathians										
Area of the Marmaros rocks	521.5	28.12	220	90.3	0.27	1.67	460	29.1	10.33	19.7
Area of the Penin rocks	97.3	1.66	22	20.4	0.25	0.72	472.5	24.6	0.36	0.8
Marmaros massif	279.9	22.48	55	53.2	0.46	1.12	675	28.9	19.1	12.8
Area of Pidhallia	15.6	0.08	4	4.5	0.33	0.80	458.6	16	0.03	0.02
Vygorlat-Hutyn ridge	1429.3	14.85	91	240.5	1.04	0.38	350	19.6	9.99	10.62
Area of Central	2558.9	31.21	470	414.4	0.31	1.96	420	25.3	16	20.2
Area of Border	171.2	7.87	80	4.2	1.69	0.29	421.3	24	4.1	4.37
Area of Prypannonska	910.2	2.78	18	120.4	0.27	0.77	447.5	20.4	2.4	1.38

Table 4

Matrix of factor loads on the studied parameters

Factor characteristics	Factor 1	Factor 2
Total length of faults, km	0.862	-0.138
Distance to the river, km	-0.222	-0.728
Distance to faults, km	0.720	0.535
Absolute mark of landslide, m	-0.075	0.635
The angle of the surface of landslide, deg	0.023	0.853
Area of negative gravitational anomalies,km^2	0.922	0.088
Area of positive magnetic anomalies, km^2	0.889	0.095
The proportion of total variance	0.42	0.28

Factor 2 shows the influence of relief on the development of landslides and is determined by the connection of the parameters "absolute mark" of the landslide "head", "angle of inclination of the daylight surface" of the landslide "head" and "distance to the river". The inverse correlation of the parameter "distance to the river" with the spread of landslides indicates that they develop far from rivers and not only under the influence of spatial conditions: geological, tectonic structure, lithological composition, type of relief, degree of destruction of the upper layer of rocks, but to a large extent, they are also caused by external influences – anomalous values of precipitation [Shtohryn et al., 2020]. As we can see, the geomorphological parameters have a much smaller share of the total dispersion (0.28), so their influence is not determining. Therefore, two factors explain 70 % of the total dispersion.

Thus, the direct spatial connection between landslide occurrences and the location of zones of tectonic faults, which are uniquely reflected in gravimagnetic fields, is confirmed. This is due to the influence of the nappe-scale tectonic style, when the rocks are separated by steep thrusts and complicated by longitudinal ruptures and faults.

Scientific novelty

The peculiarities of the reflection of the tectonic structure, zones of decompression, fragmentation of rocks and lithological composition in gravimagnetic fields on a regional scale are examined, and their connection with landslide processes is evaluated for the first time.

Practical significance

The theoretical substantiation of the peculiarities of the behaviour of gravimagnetic fields in the zones of occurrence of landslide processes makes it possible to assess the natural conditions for the formation and development of landslides in a given region. The connection between the impact of the fault zones on landslide processes by their reflection in gravimagnetic fields is established, which can be used in the future for spatial forecasting of the development of landslides in territories with related structural-tectonic conditions.

Conclusions

Thus, as a result of the studies performed, the following conclusions can be singled out:

1) associated impact of landslides to the fault zones and anomalies reflecting the fracture zones of rocks indicates the usefulness of gravimagnetic techniques for mapping weakened zones of rocks;

2) the gravitational anomalies correlate well with the geological structure of the region; increased values of intensity in mountain areas are due to high-density rocks, such as Neogene volcanic rocks and metamorphic rocks. Negative anomalies reflect Neogene and Quaternary sediments; high gradient zones reflect tectonic faults;

3) sedimentary and metamorphic rocks have small magnetization, which is reflected in the reduced values of the intensity of magnetic field anomalies. Intense anomalies of the magnetic field of the Transcarpathian internal trough are explained by the influence of volcanic rocks of high magnetization. On the contrary, sedimentary and metamorphic rocks are mapped by anomalies of different signs due to low magnetization and contrast in rock density.

The necessity for analysis of gravitational and magnetic fields in the analysis and prediction of landslides activity can be considered proven.

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Людмила ШТОГРИН[1], Сергій АНІКЕЄВ[2], Едуард КУЗЬМЕНКО[1], Сергій БАГРІЙ[1]

[1] Каф. геотехногенної безпеки та геоінформатики, Івано-Франківський національний технічний університет нафти і газу, вул. Карпатська 15, Івано-Франківськ, 76019, Україна, тел. +38(0342)504761, ел. пошта: gbg@nung.edu.ua

[2] Каф. нафтогазової геофізики, Івано-Франківський національний технічний університет нафти і газу, вул. Карпатська 15, Івано-Франківськ, 76019, Україна.

ВІДОБРАЖЕННЯ АКТИВНОСТІ ЗСУВНИХ ПРОЦЕСІВ У РЕГІОНАЛЬНИХ ГРАВІТАЦІЙНОМУ ТА МАГНІТНОМУ ПОЛЯХ (НА ПРИКЛАДІ ЗАКАРПАТСЬКОЇ ОБЛАСТІ)

Метою досліджень, представлених у цій статті, є аналіз особливостей відображення ураженості території Закарпатської області зсувними процесами в аномаліях магнітного та гравітаційного полів з урахуванням тектонічного районування. Дослідження є важливим етапом у прогнозуванні зсувних процесів, який спрямовано на зменшення їхніх негативних наслідків на довкілля. Актуальність досліджень зумовлена зростаючою активізацією зсувних процесів у Карпатському регіоні України. Методика. Розвиток зсувів у кожній структурно-тектонічній зоні має зв'язок із її тектонічною будовою, і тому зазначені процеси можуть мати різну інтенсивність, динаміку, тенденцію до подальшого розвитку та площу поширення. Літолого-фаціальний склад та умови залягання порід формують фізико-механічні властивості порід, визначаючи швидкість і механізм розвитку зсувів. Просторова приуроченість зсувних процесів до розломних зон знаходить своє відображення у гравітаційному та магнітному полях. Результати. За допомогою засобів ГІС MapInfo виконано розрахунок кількості зсувів у кожній тектонічній зоні, аномалій гравітаційного та магнітного полів, площ, що уражені зсувами, відстані до зон простягання розломів. Важливим результатом досліджень є доведення прямого зв'язку між просторовим розподілом зсувів і розломними зонами, тектонічною будовою, літологічним складом порід, які відображаються у гравімагнітних аномаліях. Наукова новизна. Розглянуто особливості відображення тектонічної будови, зон розущільнення, подрібненості порід та літологічного складу в гравімагнітних полях регіонального масштабу, а також вперше оцінено їхній зв'язок із зсувними процесами. Практична значущість. Теоретичне обґрунтування особливостей поведінки гравімагнітних полів у зонах поширення зсувних процесів дозволяє оцінити природні умови формування та розвитку зсувів у даному регіоні. Виявлені зв'язки між впливом розломних зон на зсувні процеси за їхнім відображенням у гравімагнітних полях, які можуть у майбутньому застосовуватись під час просторового прогнозування розвитку зсувів на територіях зі спорідненими структурно-тектонічними умовами.

Ключові слова: зсув, тектонічна зона, розломи, літолого-фаціальний склад, локальні аномалії гравітаційних і магнітних полів.

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