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GEOLOGICAL CONDITIONS OF DEVELOPMENT AND LANDSCAPE DIFFERENTIATION OF MODERN GEOLOGICAL AND GEOMORPHOLOGICAL PROCESSES IN THE HIGHLANDS OF THE CHORNOHORA MASSIF (UKRAINIAN CARPATHIANS)

The aim of the research is to analyze the factors of development, distribution and landscape differentiation of geological and geomorphological processes in the subalpine and alpine highlands of Chornohora, as well as to determine the influence of geological structure and morphometric features on the intensity of their development. The methodological basis of the study is a combination of methods of field research and geoinformation analysis using GIS, which allowed to identify the main centers of the highlands of Chornohora of rockfalls, screes, landslides and linear erosion. On the basis of the landscape approach the spatial differentiation of geological and geomorphological processes in high altitude terrains and landscape structures is analyzed and their complex analysis is carried out, and with the help of geoinformation and statistical data processing on location and number of cells the intensity of negative processes is calculated. The main result of the study is a map of the distribution of negative geological and geomorphological processes (rockfalls, screes, landslides and linear erosion) in the landscape complexes of the subalpine and alpine highlands of Chornohora, as well as a map of a key area near Smotrych Mountain, which expresses landscape processes at the level of landscape striyas and tracts. As a result of the research the structure and specifics of development of geological-geomorphological processes in geocomplexes of different origin and with different morphological and morphometric parameters are analyzed. The influence of geological structure on the development of processes is manifested in the dominance of massive sandstones and sandstone flysch, which contributed to the development of large and steep landforms with inherent intense rockfalls, screes and linear erosion. The analysis of the intensity of the manifestation of these processes testifies to their greatest development in the geocomplexes of ancient-glacial-exarational genesis – corries, cirques, glacial troughs, nival niches, etc. The development, nature and intensity of the manifestation of negative geological and geomorphological processes in landscape complexes of nival erosion and denudation genesis differ significantly. The peculiarity of the differentiation of processes here is their clear dependence on the composition and peculiarities of the occurrence of bedrock stratum, relief morphometry and so on. An important result of the study is the above-mentioned map of the highlands in the vicinity of Smotrych Mountain, which expresses the previously little-studied landslides to the narrow bands of argillites and argillite flysch. **Originality.** The relationship between the diversity and distribution of negative geological and geomorphological processes with the genesis of landscape complexes of the Chornohora highlands, their structure, structural-lithological and morphometric features is determined. Landscape differentiation and intensity of rockfalls, screes, landslides and linear erosion in the highlands of the studied massif are analyzed and described. **Practical significance.** The results of the study contribute to the further study of the dynamics and properties of highlands landscape complexes of Chornohora, as well as provide an opportunity to predict the peculiarities of the geological situation and optimize the nature management system, in particular – organizational features of recreational and tourist activities.

Key words: high-mountain landscape tier; screes; rockfalls; landslides; linear erosion; Chornohora Landscape; Ukrainian Carpathian.

Introduction

Studying of the development and functioning of natural territorial complexes (NTC) is an important task of landscape analysis of the Ukrainian Carpathians and mountain areas in general. One of the main external manifestations of their functioning is modern physical and geographical processes and phenomena which development is influenced not only by natural (landscape) properties of the territory, but also the degree of anthropogenic impact [Melnyk, 1999; Kara-

biniuk, 2020]. The variety of modern physical and geographical processes determines the primary ecological state of the territory, affects the specifics and possibilities of its use and so on.

Chornohora landscape occupies a central and hypsometrically highest position in the Ukrainian Carpathians landscape system. Its special feature is the significant spread of valuable NTCs of denudation, glacial-exaration and nival-erosion origin, which together at altitudes above 1450–1500 m a.s.l. form a high-mountain landscape tier [Melnyk & Karabiniuk, 2018; Melnyk et al., 2018; Karabiniuk, 2020].

The natural territorial complexes of the subalpine and alpine highlands of Chornohora and other Ukrainian Carpathians mountain landscapes are characterized by high lithomorphic, dynamics and unique set of modern physical and geographical processes. Geological and geomorphological processes such as rockfalls, screes, landslides, etc. occupy a special place among them. Their intensive development in the highlands of Chornohora has a negative impact on the environmental situation, economic activity and also is potentially dangerous to human life. Therefore, a comprehensive analysis of geological and geomorphological processes and factors of their development in the highlands of Chornohora landscape contributes to the development of measures to optimize management, as well as the possibility of further forecasting in other mountain landscapes of the Ukrainian Carpathian.

Features of geological structure, as well as related morphometric features of the territory, are a determining factor in the development of rockfalls, landslides and other processes in the high-mountain landscape tier of Chornohora. Features of geological structure, as well as related morphometric features of the territory, are a determining factor in the development of rockfalls, landslides and other processes in the high-mountain landscape tier of Chornohora. The composition and lithological features of rocks, the nature of the occurrence and deformation of strata directly determine the location of the main centers and the intensity of geological and geomorphological processes. Therefore, in addition to studying the landscape features of rockfalls, screes and other modern negative geological and geomorphological processes in the highlands of Chornohora, it is also important to determine the geological preconditions for their development. Also, the study of the peculiarities of processes development in the highlands and their landscape differentiation is important to determine the main trends in the morphological structure of the territory, which occurs through the formation of new NTCs and accompanied by active manifestations – modern physical and geographical processes.

Purpose

The aim of the research is to analyze the peculiarities of the main modern negative geological and geomorphological processes development (rockfalls, screes, landslides and linear erosion) in the subalpine and alpine highlands of Chornohora, as well as to determine the impact of geological structure on their distribution and to establish patterns of landscape differentiation.

Methodology

The study of the impact of geological structure and modern geological and geomorphological the landscape differentiation processes in the highlands of Chornohora was conducted using a set of field and geoinformation methods used at different stages of research tasks. From the organizational point of view, our study was implemented in three stages, which methodologically differed from each other:

- *The first* – the analysis of literary and cartographic sources of information, modeling of the research area (geological structure, relief, etc.) and identification of potential places for the development of processes based on GIS analysis;
- *The second* – field expeditionary research and mapping of geological and geomorphological processes development centers, clarification of bedrock distribution and geological stratum boundaries;
- *The third* – geoinformation analysis of distribution features and landscape differentiation of geological and geomorphological processes, determining the relationship between the processes centers location with the territory geological structure, calculating the intensity of their manifestation in landscape complexes of different hierarchical levels.

During the first stage of the study there was an analysis of scientific papers and publications on geological and geomorphological structures, relief genesis and morphometry, development and distribution of processes in the highlands of Chornohora ([Świderski, 1937; Kravchuk et al., 1966; Kravchuk, 1982, 2008; Bolyukh & Kravchuk, 1967; Gofshtejn, & Carnenko, 1982; Gofshtejn, 1995; Melnyk, 1999; Mukha, 2003; Shushnyak, 2006, 2007; Klapyta, 2006, 2008; Rogoziński & Krobicki, 2006; Klapchuk, 2012; Rinterknecht et al., 2012; Karabiniuk et al., 2017a, 2017b; Karabiniuk, 2019, 2020; Kłapyta et al., 2021], etc.). Important information about the geological structure and a number of large-scale centers location of negative processes in the highlands of Chornohora is presented in cartographic materials and reports fonds of SE “Zahidukrgeologiya” ([Voloshyn et al., 1971; Vashchenko et al., 1985]; etc.).

Modern GIS technologies play an important role in the study of negative geological and geomorphological processes and are used to identify and map the centers of their development, monitoring, etc., [Karabiniuk et al., 2020]. A comprehensive geoinformation analysis of the territory was conducted and a database on the properties of natural components and landscape complexes, the landscape structure of the highlands, etc. was formed to study these processes in

the highlands of Chornohora. With the help of specialized software environment ArcGIS morphometric analysis of the terrain on the basis of digital topographic basis of SE "Zakarpatheodezcentr" scale 1:25 000 with a cross section of 5 m was performed, which allowed to build high quality DEM and TIN-relief model. Other elements of the topographic basis – points of vertices and their heights, points of water streams and their heights, thalweg lines etc. were also vectorized for their development.

Since the development of negative geological and geomorphological processes is closely related to the slope of the surface, we have compiled a map of the steepness of the slopes throughout the highlands of Chornohora. Based on it, the manifestation potential places of these processes were determined. We also analyzed the exposure of slopes which allowed us to determine the exposure affiliation of development centers of modern geological and geomorphological processes and predict potential places of their development with similar morphometric parameters. A number of Spatial Analyst module functions were used to construct these maps. After that, in order to identify the centers of negative geological and geomorphological processes development space images and aerial photographs of high resolution 0.4×0.4 were analyzed and deciphered in detail [Aerial…, 2017]. The coordinate system of the Pulkovo 1942 (GK Zone 5N) projection was used by us in the processing of geoinformation data.

Geological map layers of the highlands of Chornohora were vectorized and created in the ArcGIS software environment and a database on the composition and properties of bedrocks was formed. Geoinformation data processing on geological structure is important for the preliminary identification of potential areas geological and geomorphological processes development in the high-altitude landscape tier of the massif and further establishment of development conditions in places of actual identification of these processes. Thus, with the help of modern GIS analysis methods of the highlands of Chornohora numerous screes, rockfalls, landslides and linear erosion foci have been identified.

The main stage of studying the peculiarities of geological and geomorphological processes distribution in the highlands of Chornohora was the field (third) stage. Field surveys of the territory were carried out in expeditionary form, which lasted during the warm periods from 2014 to 2020. During this period, 789 centers of rockfalls, screes, landslides and other modern negative geological and geomorphological processes were identified in the highlands of the landscape. During the field survey of the territory, direct mapping of development centers of processes and their boundaries was carried out, the main parameters were recorded, etc. Garmin eTrex10 GPS receivers Garmin eTrex10, Sndway SW-S100 rangefinders, etc. were used in the research process. Field studies of the development of geological and geomorphological processes peculiarities in the highlands of Chornohora were conducted on a landscape basis according to the method of G. P. Miller (1974). The main survey results were entered in special data recording forms, as well as recorded on a field landscape map, a number of photographs and so on.

Further processing of field research results and survey points spatial reference of negative processes centers in the NTCs of highlands of Chornohora was also carried out using the above-mentioned geographic information systems. The filling of the previously formed database with information on the location of development centers of geological and geomorphological processes allowed to determine the relationships with the geological structure of the territory and its landscape organization. The analysis of landscape differentiation of the above-mentioned processes was mainly carried out in terms of high altitude terrains and landscape striyas according to our previously tested method (Karabiniuk, 2019; Karabiniuk et al., 2020). This technique also involves determining the intensity of processes manifestation (I_{pm}), which is calculated by the ratio of centers total number of negative physical and geographical processes to the NTC area within which they occur (centers/km^2) [Karabiniuk, 2019].

At the final stage of our study, the percentage distribution of each type of geological and geomorphological processes in high-altitude areas and landscape streams is calculated. It is based on the quantitative ratio of recorded centers of processes development in the highlands of landscape. This expresses manifestation dependence of these processes on the landscape structure of the study area. The analysis of landscape differentiation and intensity of geological and geomorphological processes manifestation in the high mountain NTC of Chornohora was conducted entirely on the basis of GIS-analysis methods.

Results

Conditions of processes development

The subalpine and alpine highlands of Chornohora are confined to the central watershed of the massif in the form of two sections of complex configuration with a total area of 80,5 km^2 (Fig. 1). These areas are torn between the peaks of Hoverla and Petros, where there is a decline in the watershed and the spread of spruce forests. The territory of the highlands is represented by massive domed peaks and wavy ridges of the main ridge with a number of spurs, in which deep glacier corries, circuses, firn fields, etc. are deeply incised [Kravchuk, 2008; Karabiniuk, 2020]. Significant landscape diversity and the formation of unique natural conditions have contributed to the development of a complex of physical and geographical processes, the manifestations of which in different origins and properties of NTC differ significantly.

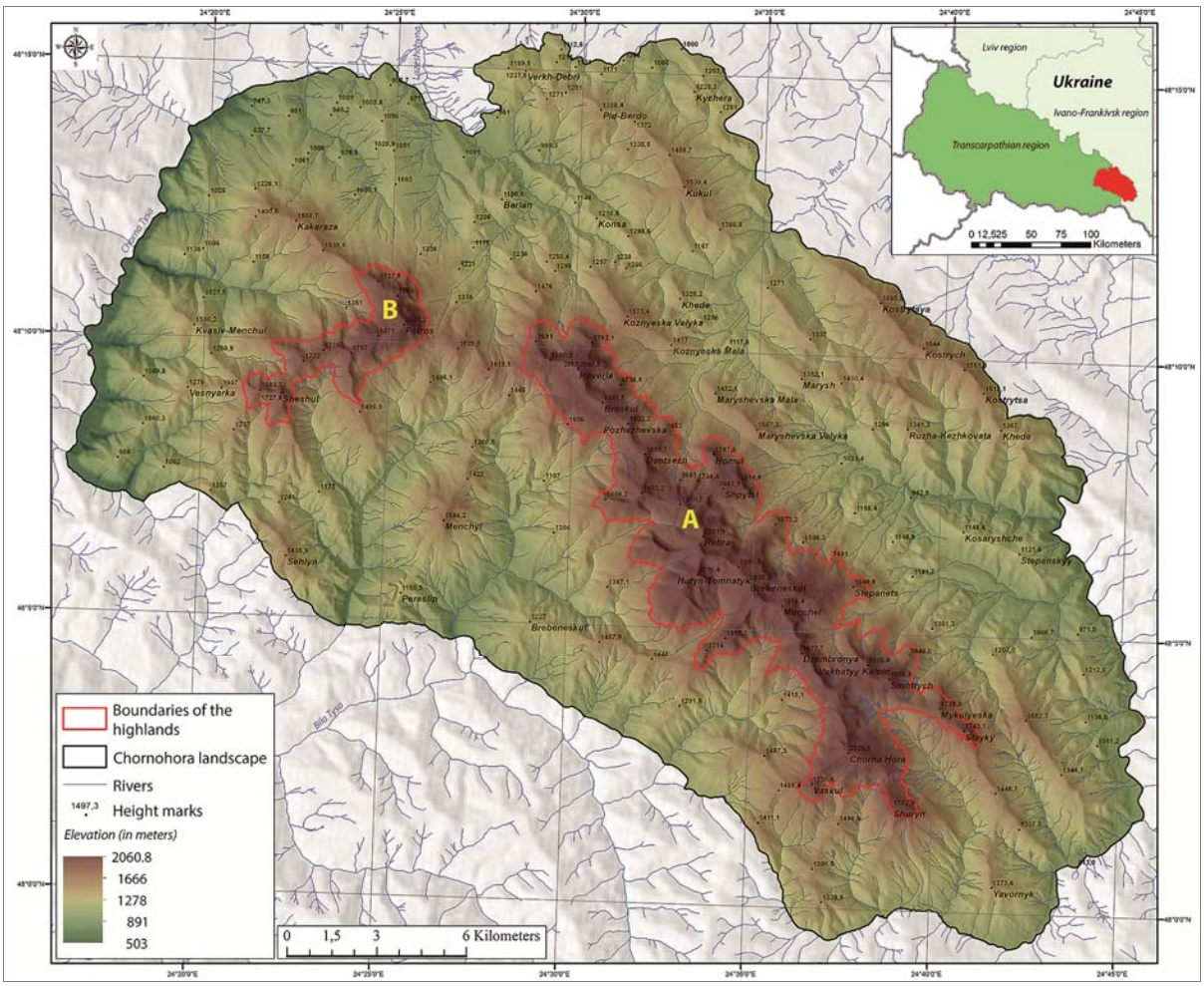

Fig. 1. Geographical position of the subalpine and alpine highlands within the Chornohora landscape (A – "Hoverla-Shuryn" highlands section; B – "Sheshul-Petros" highlands section).

The lithogenic basis, namely the peculiarities of the geological structure, has a decisive influence on the development of geological and geomorphological processes in the highlands of Chornohora. It also significantly affects the main morphological features of the relief, its morphometric parameters and so on. Thus, the subalpine and alpine highlands of Chornohora were formed within three structural-facies tectonic units. More than 90 % of the territory of the Hoverla-Shuryn highlands is located within the flysch Hoverla subzone of the Chornohora cover Cretaceous period [Vashchenko et al., 1985]. Its defining feature here is the fine-grained structure and dominance of mica massive gray sandstones and conglomerates of the Chornohora stratum (K_2cr_a). This contributed to the formation of massive landforms, the presence of numerous outcrops of native rocks on the day surface and the intensive landslides development [Vashchenko et al., 1985; Kravchuk, 2008].

Within the above-mentioned structural-facies unit, a significant complication of the geological structure in the highlands of Chornohora is observed in the south-eastern part of the "Hoverla-Shuryn" section, namely in the upper basin of the Dzembronya River and Pohorilets Stream (Fig. 2). Here are concentrated strips of argillites of the upper (K_1jl_2) and lower (K_1jl_1) substratum of the Yalovetsky stratum and black argillites and quartzite sandstones of the Shypotsky stratum (K_1sp_2) [Vashchenko et al., 1985]. A characteristic feature of these geological stratums is the high content in the flysch strata of argillites and their dominance in some areas, which significantly affects the nature of the development of geological and geomorphological processes.

A small southwestern spur of the central watershed of Chornohora with the Vaskul Mountain is formed by rocks of another structural-facies unit – the Blyznytska subzone of the Dukliansky cover Cretaceous period [Vashchenko et al., 1985]. It is composed of flysch strata of quartzite sandstones of the upper (K_1sp_2) and argillites of the lower (K_1sp_1) substratum of the Shypotsky stratum, which form stepped slopes and cause significant gravelly surface of tracts.

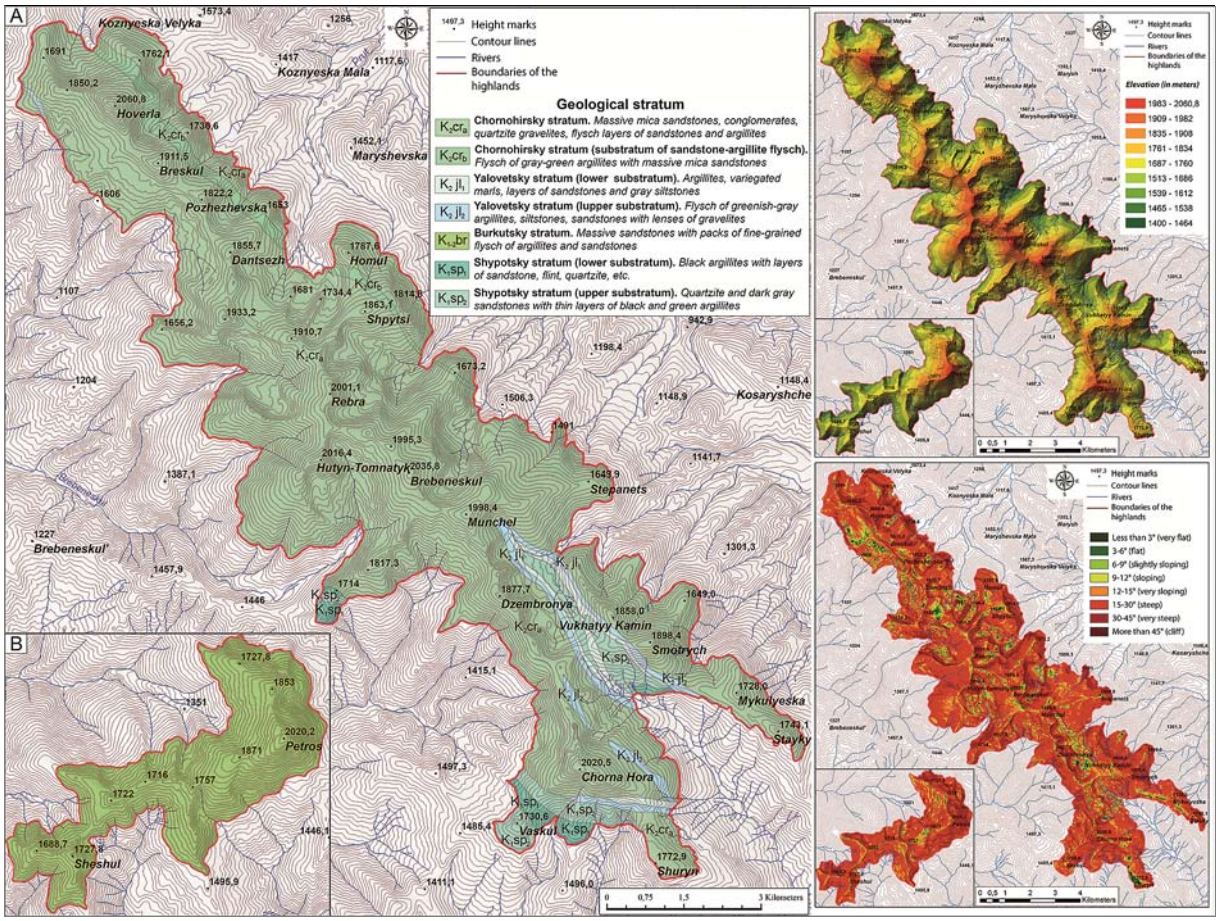

Fig. 2. Geological structure and morphometric features of the relief of the subalpine and alpine highlands of Chornohora
(concluded for [Vashchenko et al., 1985; Karabiniuk, 2020] with the author's addition)
(A – "Hoverla-Shuryn" highlands section; B – "Sheshul-Petros" highlands section).

The Sheshul-Petros highlands section is located within the Bilotysenska subzone of the Porkuletsky cover, in the geological basis of which there is an exclusively homogeneous stratum of coarse-grained sandstone flysch of the Burkutsky stratum ($K_{1\text{-}2}br$) made of mica massive coarse-grained gray sandstones [Voloshyn et al., 1971; Vashchenko et al., 1985]. Important for the development of geological and geomorphological processes here is the presence of a well-defined in relief thrust of the Porkuletsky cover on Chornohirsky, the frontal zone of which is located in the basin of the Lazeshchyna River in the northeast from Petros Mountain [Karabiniuk et al., 2017b].

Thus, the geological structure of the subalpine and alpine highlands of Chornohora is dominated by massive sandstones and sandstone flysch, the dismemberment and denudation of strata of which contribute to the formation of a complex of coarse deluvium and colluvium. The latter are best expressed on the steep northeastern slopes of the main ridge. The north-eastern vergence of the bedrock strata, which caused the asymmetry of the slopes of the central watershed, also has a significant impact on the development and spread of rockfalls, screes, landslides and other geological and geomorphological processes in the highlands of the massif.

Thus, mainly the south-western incline of the strata and the consistency with it of the south-western slopes led to a decrease in the steepness of their surface and contribute to the development of landslides and exfoliation processes of geological strata [Shushnyak, 2007; Klapyta, 2008; Karabiniuk et al., 2017a; Karabiniuk, 2020]. Such processes are best expressed on the southwestern macroslope of the main ridge in the upper Hoverla River basin. Instead, the vergence of the bedrock layers led to a significant increase in the steepness of the surface of the north-eastern macroslope of the Chornohora landscape, which is favorable for the development of mainly rockfalls and screes processes and linear erosion in places of argillite strata. Such structural and lithological factors of development of geological and geomorphological processes in the highlands of Chornohora determine their differentiation and differences in the intensity of manifestation in different landscape complexes.

Also, the peculiarities of the geological structure of the territory significantly influenced the formation

of the relief, its main features and morphometric parameters. An important factor in the development of rockfalls, screes and other processes is the steepness of the slopes. For example, the steepness of the surface above 35–50° is an important condition for the development of rockfalls, and therefore their development in the highlands is possible only in NTCs with appropriate morphometric parameters. Morphometric analysis of the relief shows the absolute dominance in the subalpine and alpine highlands of Chornohora of steep slopes with a steepness of 15–30°, which occupy 58.9 % of the total area of the landscape tier. These are mainly ridge slopes and slopes of water catchments, which slowly cut into the spurs of the main ridge. The predominance of steep slopes promotes the development of screes in the highlands and linear erosion, the active development of which is inherent in the current stage of development of highland natural territorial complexes of Chornohora.

Glacier corries, cirques and ridge slopes of the north-eastern exposition of the mainly north-eastern macroslope of the Chornohora massif are characterized by very steep slopes (30–45°). They occupy 21.6 % of the highlands of the massif and are the centers of increased activity of rockfalls and screes. However, the most active development of these processes is observed on the cliff walls of cirques, the surface steepness of which exceeds 45° (1.1 % of the territory). The minimum possibility of development of geological and geomorphological processes is characteristic of very gentle and gentle slopes, the steepness of which does not exceed 9–12°. In the high-mountain landscape tier, they are characteristic of the tracts of undulating surfaces of ridges and their spurs, as well as stepped bottoms of glacial corries and cirques, filled with moraines of Pleistocene glaciation.

Thus, the determining factor in the development and differentiation of geological and geomorphological processes (rockfalls, screes, landslides, linear erosion) in the highlands of Chornohora is the geological structure. It is characterized by an exceptional predominance of strong massive sandstones and sandstone flysch, the specificity of which determines the general orographic nature of the territory and led to the formation of steep and very steep slopes, which together are favorable for the development of rockfalls, screes and linear erosion processes. Landslide activity is inherent in highland areas with significantly different structural and lithological conditions. In particular, the determining factor in the development of landslides in the highlands of Chornohora is the presence of indigenous rocks of argillites and fine-layered argillite flysch, as well as the peculiarity of the strata of the bedrock. The latter contributes to the formation of a system of block-cascade landslides on the slopes of the southwestern and southern exposures. The pronounced belonging of intensive landslide processes to the strip of argillite flysch of the Shypotsky stratum is recorded in the upper basin of the Pohorilets stream, which forms the stepped slopes of the southern exposure here (Fig. 3). These landslide slopes are coordinated with the direction of slope of the rock layers and are divided by a cascade of landslide bodies south of Smotrych Mountain.

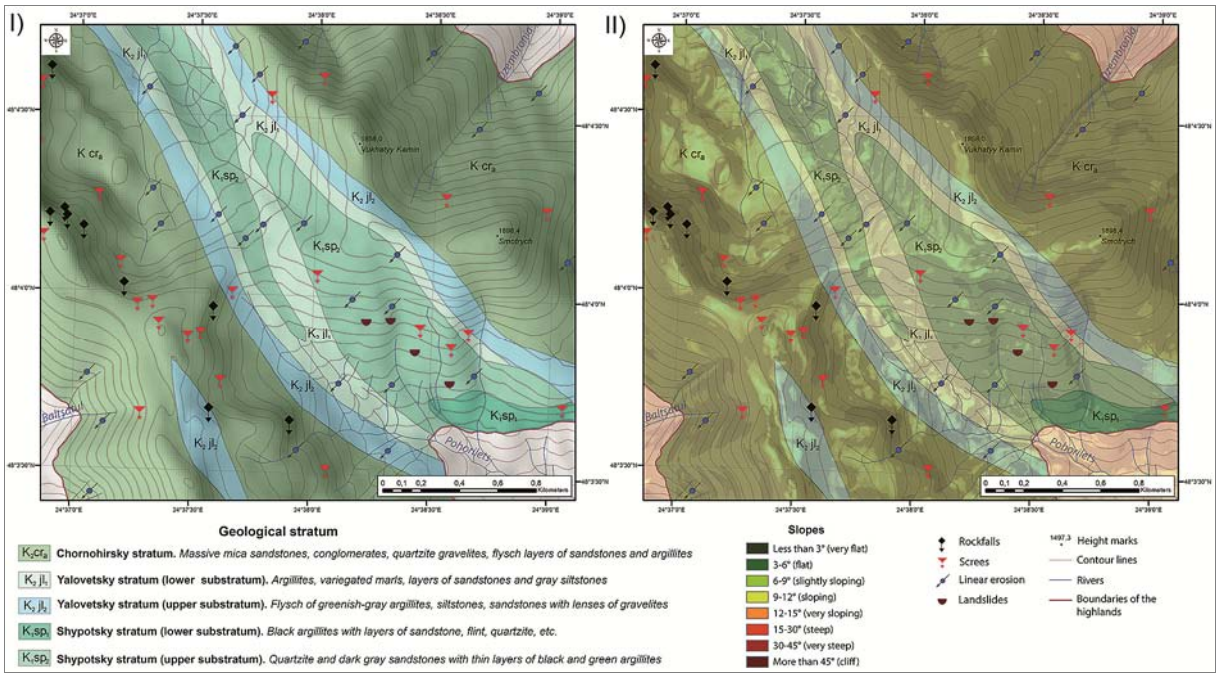

Fig. 3. Negative geological and geomorphological processes in the subalpine and alpine highlands of Chornohora (area near Smotrych Mountain)
(I – on the geological structure map; II – on the steepness of the slopes map with the boundaries of the geological stratum).

Features of development and processes spread

Significant spread and differentiation of geological and geomorphological processes (rockfalls, screes, landslides and linear erosion) in the high-mountain landscape tier of Chornohora due to the properties of landscape complexes and the development history of the lithogenic basis of the landscape. High landscape diversity and sharp differences in the genesis and morphometric parameters of alpine NTCs contribute to the spatial differentiation of processes.

Rockfalls in the highlands of Chornohora are confined to natural territorial complexes of glacial-exaration genesis, which are characterized by the highest surface steepness (Fig. 4). Numerous landslides are formed in all tracts of corries, walls of glacial troughs and some amphitheaters of ancient firn fields [Karabiniuk et al., 2017a, 2017b].

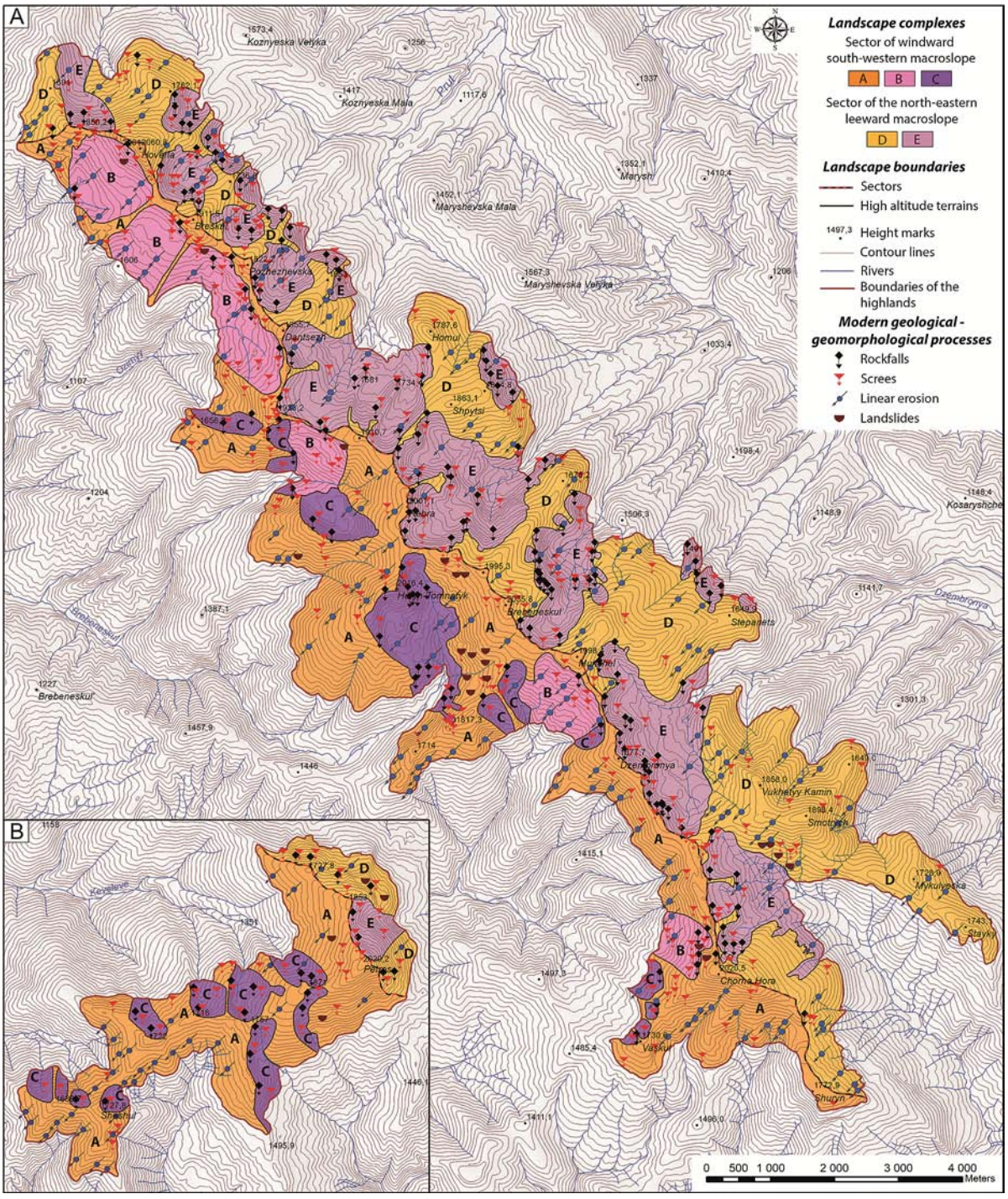

Fig. 4. Negative geological and geomorphological processes in the natural territorial complexes of the subalpine and alpine highlands of Chornohora
(A – "Hoverla-Shuryn" highlands section; B – "Sheshul-Petros" highlands section).

The largest rockfalls in the highlands of Chornohora are observed in complex tracts of corries and glacial troughs of high-altitude sharply concave glacial-exarational subalpine highlands within the leeward sector of the north-eastern macroslope. This is due to the north-eastern vergence of coarse-grained sandstones with admixtures of conglomerates and gravelites of the Chornohirsky and Burkutsky stratum, as well as massive size and deep incision of corries, circuses and other glacial tracts in the ridge slopes. Particularly intensive development of rockfalls is observed in the presence of a high rear wall in the corries tracts, because in its cliff part much more exposed outcrop strata.

In the high-mountain landscape tier of Chornohora, rockfalls are characteristic for tracts of steep and very steep slopes of the amphitheaters of the ancient firn fields of high-altitude terrain of the nival-erosion subalpine highlands [Karabiniuk, 2020]. They are located in the upper reaches of the Hoverla River basin and coincide with the direction of the fall of the bedrock of the powerful sandstones Chornohisky stratum, which are exposed in the upper part of the amphitheaters and crack and collapse under the influence of frost weathering. They are located in the upper reaches of the Hoverla River basin and coincide with the direction of the fall of the bedrock of the powerful sandstones Chornohisky stratum, which are exposed in the upper part of the amphitheaters and under the influence of frost weathering crack and collapse. Such rockfalls are well traced on the southwestern slopes of the Hoverla, Breskul, and other peaks. Particularly well-defined landslide wall in the tract of tectonic landslide on the northeastern slope of Petros Mountain within the basin of the Lazeshchyna River [Melnyk & Karabiniuk, 2018].

Among the geological and geomorphological negative physical and geographical processes in the high-mountain tier of Chornohora are also widespread scree, which is closely related to rockfalls. In particular, under each rockfalls wall of the corries there are srees located hypsometrically lower. They are also inherent in most nival niches that are concentrated on the walls of corries. Their scree walls are actively developing due to the degradation of hypsometrically higher rockfalls.

The screes are also characteristic of the upper parts of the tracts of the amphitheaters of the ancient firn fields, forming large accumulations of fragmentary coarse-grained material at the contact of steep talus slopes and leveled wet steps of the amphitheaters. Such screes are territorially limited by the amphitheaters of ancient firn fields, and their accumulative shafts are particularly large. Active scree processes are also characteristic of tracts formed on sandstone-argillite and argillite flysch, in particular – on the ridge slopes of the southern exposition of Smotrych Mountain. The screes are also manifested in the tracts of convex slopes of domed peaks and ridge slopes of various exposures in the form of stone accumulations.

Manifestations of screes processes have been recorded in the relict catchment funnels of the north-eastern exposition, which are located in the upper reaches of the Bystrets and Dzembronya rivers [Karabiniuk, 2020]. At the highest hypsometric levels of the high-mountain landscape tier of Chornohora, stone placers in the form of stone rivers over 50–100 m long are also common. They are confined to the convex areas of the ridge slopes in places of gravitational tectonics and steep slopes of the peaks of Turkul, Breskul, Shpytsi, Pozhezhevska and others (Fig. 5).

Fig. 5. Stone placers in the tract of convex slopes of the south-western exposition of the Pozhezhevska Mountain (Photo – M. Karabiniuk).

Landslides occupy an important place among the geological and geomorphological processes in the high mountain NTC of Chornohora. The largest landslide processes are characteristic of the tracts of stepped landslide slopes in the upper reaches of the Brebeneskul stream, which mainly determined the general development of the southwestern macroslope of the landscape and are directly related to its structural and lithological features. Intensification of such landslides in the tracts of the southwestern macroslope sector is due to the clear agreement of most of the ridge slopes with the soles of massive layers of the Chornohirsky stratum with the characteristic processes of exfoliation and formation of landslides [Vashchenko et al., 1985; Shushnyak, 2007; Klapyta, 2008].

Intensive nival-erosional pruning of coastal slopes during the Pleistocene glaciations and degradation of snow-firn masses in the amphitheaters of ancient firn fields in the Holocene caused the intensification in the Northgrippian and Meghalay of landslides in the upper parts of amphitheaters tracts and the formation of massive landslides, which remain active to this day. Such landslides are characteristic of most tracts of nival-erosion genesis. Large-scale landslides are also manifested in the upper reaches of the Lazeshchyna River basin in the tract of tectonic

landslides on the slopes of the north-eastern exposure. Here they are accompanied by rockfalls and screes processes.

Significant steepness of the surfaces of the landscape complexes of the highlands of Chornohora and frequent heavy rains and downpours determine the intensification of linear erosion processes here. During heavy rains on the slopes of the highlands, numerous temporary channel flows are formed, which gradually merge into larger streams with higher water content, leading to the development of erosion and intensive dismemberment of the surface of the tracts. This process is especially active in areas with weak grass turf or damaged turf due to avalanche activity or anthropogenic impact. Such erosional activity of temporary water flows contributes to the formation of numerous furrows, washes, and other linear NTCs of the facias level. Particularly large furrows and ravines, which have acquired contrasting features, and within them formed a relatively complex internal facies inhomogeneity, in the landscape structure are presented as links. Examples of such links are the furrows on the northern slopes of Hoverla Mountain and the ridge slopes of the north-western exposure, which are the result of linear erosion.

The processes of linear erosion are mainly characteristic of complex tracts of steep and very steep ridge slopes, in the morphological structure of which there is a significant number of catchment funnels. The greatest development in the high-mountain landscape tier of Chornohora linear erosion was in the tracts of undulating ridge slopes of the southern and northwestern exposures, as well as the slopes of the spurs of the ridges, which formed on the sandstone-argillite flysch. The vulnerability of the bedrocks to linear erosion was caused by the formation of numerous furrows and ravines up to 2–3 m deep within these tracts. Significant influence on the depth of incision of furrows in the tracts of slopes and the intensity of the development of linear erosion has the power and composition of the deluvial cover, which is directly involved in this process.

Landscape processes differentiation

The study of modern geological and geomorphological processes in the subalpine and alpine highlands of Chornohora and their landscape analysis shows their significant diversity and dynamism. This is mainly due to the complex landscape structure formed by different-aged and different-genetic high-mountain NTCs with significantly different morphometric characteristics, peculiarities of development, complexity of internal structure, etc. Therefore, the intensity of their manifestation and the nature of distribution within the highlands depends on the landscape organization of the territory, as negative physical and geographical processes are characterized by their confinement to a certain type of landscape complexes.

As a result of field research and in-house geoinformation analysis of the territory in the highlands of Chornohora identified 789 centers (c.) of negative geological and geomorphological processes, which is about 63 % of the total centers of all physical and geographical processes in the landscape tier [Karabiniuk, 2020]. Among them, the most common are screes, which are characterized by the highest intensity of manifestation (4.3 c./km^2) and recorded in 338 centers. The intensity of linear erosion and rockfalls here is 2.9 and 2.4 c./km^2. Among the geological and geomorphological processes analyzed by us, localized distribution is characteristic of landslides. There are 24 landslide centers throughout the highlands of Chornohora, and the intensity of their manifestation is 0.3 c./km^2.

Significant differences in the intensity of manifestation and nature of the development of geological and geomorphological processes in the highlands of Chornohora are observed between high altitude terrain, due to their genesis and lithological features (Fig. 6). Thus, the most intensive development of the previously mentioned processes over 13–14 c./km^2 is characteristic of the genetic type of altitude terrain of *ancient-glacial-exarational high-mountain* (C, E), which are represented by tracts of deep-cut corries, circuses, glacial troughs, nival niches, etc. In addition to the significant spread of scree processes and erosion, their main feature is the intensive development of rockfalls in the tracts of landslides and back walls of corries, very steep walls of crossbars, nival niches and others (Fig. 7). More than 85 % of all centers of rockfalls in the highlands of Chornohora are concentrated within the ancient-glacial-exarational type of high-mountains. Also, its feature is the actual absence of landslides, which is directly related to the peculiarities of the genesis of NTCs, their confinement to hard sandstone rocks and modern morphometric features (Table 1).

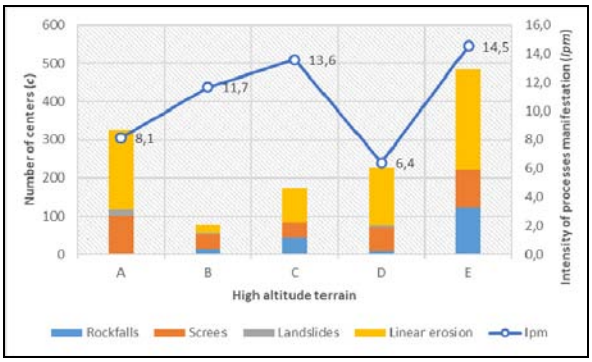

Fig. 6. Landscape differentiation of negative geological and geomorphological processes in the high altitude terrains of the highlands of Chornohora.

Table 1

Landscape differentiation of centers of negative geological and geomorphological processes in the subalpine and alpine highlands of Chornohora

Sectors	High altitude terrains	Striyas	Rockfalls			Screes			Landslides			Linear erosion		
			Num. c.	I_{pm}*, c./km^2	%	Num. c.	I_{pm}, c./km^2	%	Num. c.	I_{pm}, c./km^2	%	Num. c.	I_{pm}, c./km^2	%
Sector of windward southwestern macroslope	A	I	1	0.1	0.5	81	5.1	23.4	12	0.8	47.8	47	2.9	19.9
		II	–	–	–	–	–	–	–	–	–	2	6.7	0.8
		III	–	–	–	5	5.5	1.5	–	–	–	4	4.4	1.7
		IV	–	–	–	1	1.3	0.3	–	–	–	6	7.5	2.5
		V	–	–	–	15	2.0	4.5	2	0.3	8.7	32	4.2	13.6
		sum	***1***	***0.1***	***0.5***	***102***	***4.0***	***29.7***	***14***	***0.5***	***56.5***	***91***	***3.6***	***38.5***
	B	VI	14	2.2	7.6	38	5.9	11.3	4	0.6	17.4	21	3.3	8.9
		VII	–	–	–	–	–	–	–	–	–	–	–	–
		sum	***14***	***2.1***	***7.6***	***38***	***5.7***	***11.3***	***4***	***0.6***	***17.4***	***21***	***3.3***	***8.9***
	C	VIII	26	11.3	13.7	15	6.5	4.5	–	–	–	1	0.4	0.4
		IX	1	5.0	0.5	3	15.0	0.9	–	–	–	1	5.0	0.4
		X	1	10.0	0.5	2	20.0	0.6	–	–	–	–	–	–
		XI	16	6.7	8.7	19	7.9	5.7	–	–	–	1	0.4	0.4
		XII	–		–	–	–	–	–	–	–	5	2.9	2.1
		sum	***44***	***10***	***23.4***	***39***	***5.8***	***11.7***	–	–	–	***8***	***1.2***	***3.3***
Sector of leeward northeastern macroslope	D	XIII	2	0.1	1.1	44	2.2	13.1	–	–	–	59	2.9	24.7
		XIV	1	1.2	0.5	3	3.7	0.9	–	–	–	5	6.2	2.1
		XV	–	–	–	5	4.5	1.5	4	3.6	17.4	8	7.2	3.4
		XVI	6	4.0	3.3	8	5.3	2.4	2	1.3	8.7	3	2.0	1.3
		sum	***9***	***0.4***	***4.9***	***60***	***2.6***	***17.9***	***6***	***0.3***	***26.1***	***75***	***3.2***	***31.5***
	E	XVII	118	11.0	61.4	87	8.1	25.8	–	–	–	30	2.8	12.7
		XVIII	2	5.0	1.1	7	17.5	2.1	–	–	–	3	7.5	1.3
		XIX	2	4.0	1.1	4	8.0	1.2	–	–	–	–	–	–
		XX	–	–	–	1	0.2	0.3	–	–	–	9	1.4	3.8
		sum	***122***	***6.7***	***63.6***	***99***	***5.5***	***29.4***	–	–	–	***42***	***2.3***	***17.8***
Total			**190**	**2,4**	**100**	**338**	**4.2**	**100**	**24**	**0.3**	**100**	**237**	**2.9**	**100**

* I_{pm} – indicator of the intensity of process manifestation, which is expressed by the ratio of the number of centers of development of a particular type of physical-geographical process to the area of the tract within which this process is manifested [Karabiniuk, 2020]

Fig. 7. Stone placers in the tract of the nival niche of the Hoverliansky corrie (upper reaches of the Prut River basin) (Photo – M. Karabiniuk).

Glacial glaciation of the Pleistocene period in the highlands of Chornohora also contributed to the formation on the southwestern macroslope of an array of unique natural territorial complexes of nival-erosion genesis – amphitheaters of ancient firn fields, nival corries, etc. [Miller, 1963; Melnyk & Karabiniuk, 2018]. In the modern landscape structure of the study area, they form a high-mountain terrain of the *nival-erosive subalpine highlands* (B), within which 77 centers of modern negative geological and geomorphological processes have been identified (see Fig. 6). It is characterized by a significant variety of processes associated with the imposition of a complex structural and lithological basis, the presence of a number of tectonic faults and a combination of peculiar nival-erosion NTCs. For example, in Hoverlansky, Ozirny and other amphitheaters of ancient firn fields of the upper Hoverla river basin, screes and landslides are observed mainly on steep and very steep slopes of amphitheaters with outcrop of bedrocks. In the upper part of the tracts of a number of amphitheaters, landslides in the form of hilly landslides with accumulative shafts, which are in contact with the exposed stepped bottoms, have also been formed. Here, on steep interstage slopes and very steep lower ledges of the tract, linear erosion is actively developing, which has led to the formation of a complex system of hollows and ravines. The total intensity of geological and geomorphological processes here is 11.7 c./km^2, which is the average among high-mountain terrains (see Fig. 6).

The largest area (49.1 km^2) in the subalpine and alpine highlands of Chornohora is occupied by the genetic type of high-mountain terrains of *denudation alpine-subalpine highlands* (A, D), which are the oldest and hypsometrically highest in the Ukrainian Carpathians [Melnyk et al., 2018; Karabiniuk, 2020]. According to field research, 358 centers of geological and geomorphological processes have been recorded within the localities, the most common of which is linear erosion. In particular, about 70 % of all centers of linear erosion in the highlands of the massif are concentrated here.

The intensity of linear erosion in denudation NTCs of the highlands of the massif is the highest and depends on the features of the morphological structure of landscape striyas, the main identifying feature of which is the lithological homogeneity of geo-complexes of lower ranks.

Thus, in the highlands of Chornohora, landscape striyas formed on argillite flysch are characterized by maximum indicators of the intensity of the linear erosion process of more than 7 c./km^2 (see Table). The spread of linear erosion in the high-mountain landscape tier is also facilitated by the dominance of steep and long slopes with massive deluvial cover, significant precipitation, mainly in the form of heavy and heavy rains, poor soil and vegetation cover at the highest hypsometric levels.

A characteristic feature of the denudation type of high-mountains in the highlands of Chornohora is also the screes significant development of various nature and origin. The intensity of their manifestation reaches 3–4 c./km^2. Most of the screes in high-mountains NTCs develop in the form of plumes and are composed of large fragments of massive mica gray sandstones, which are mainly covered with moss-lichen and shrub vegetation. Within the type of localities analyzed by us, the largest number of them is confined to the tracts of ridge slopes and catchment funnels of northeastern and eastern exposures, which are characterized by a greater slope of the surface. A significant number of screes in the high-mountain landscape tier in the tracts of the ridge slopes and convex surfaces of the spurs of the ridges are ancient and have periglacial origin.

The development of screes in the subalpine and alpine highlands of Chornohora is also influenced by other physical and geographical processes, including avalanches and snow erosion (exaration), which are much more active in the sector of the northeastern macroslope of the massif [Karabiniuk, 2019; Melnyk et al., 2019]. Avalanches in tracts of steep slopes and nival-erosion niches contribute to soil and vegetation damage, compaction of snow in depressions and formation of snowfields, which significantly delay the vegetative development of vegetation and increase the likelihood of further development of erosion and screes processes in the warm seasons.

The lowest indicators of the intensity of manifestation (0.1–0.4 c./km^2) among the processes in the highlands of Chornohora are characteristic of landslides, which are limited in territorial distribution and due to structural and lithological factors. The development of landslides in this area is territorially limited by the spread of argillites and argillite flysch strata, which formed a kind of landscape striyas at the upper basins of the Baltsatul, Vypchyna, Gropynets, Pohorilets, etc. streams. In Fig. 8 presents a map of the distribution of geological and geomorphological processes for the vicinity of Smotrych Mountain, which

shows the inherency of landslides exclusively to the landscape striya of steep hilly ridge slopes composed of thin-layered black argillites and quartzite-like dark gray sandstones. Blueberries (*Vaccinium myrtillus* L.), junipers (*Juniperus sibirica* Burgsd.) and mountain pine (*Pinus mugo* Turra) are common in the vegetation.

Small landslides have caused the undulating nature of the surface of the tracts of the southern exposure slopes, which due to the presence of argillites in the geological base retain a significant amount of moisture and are most vulnerable to landslides during periods of prolonged precipitation.

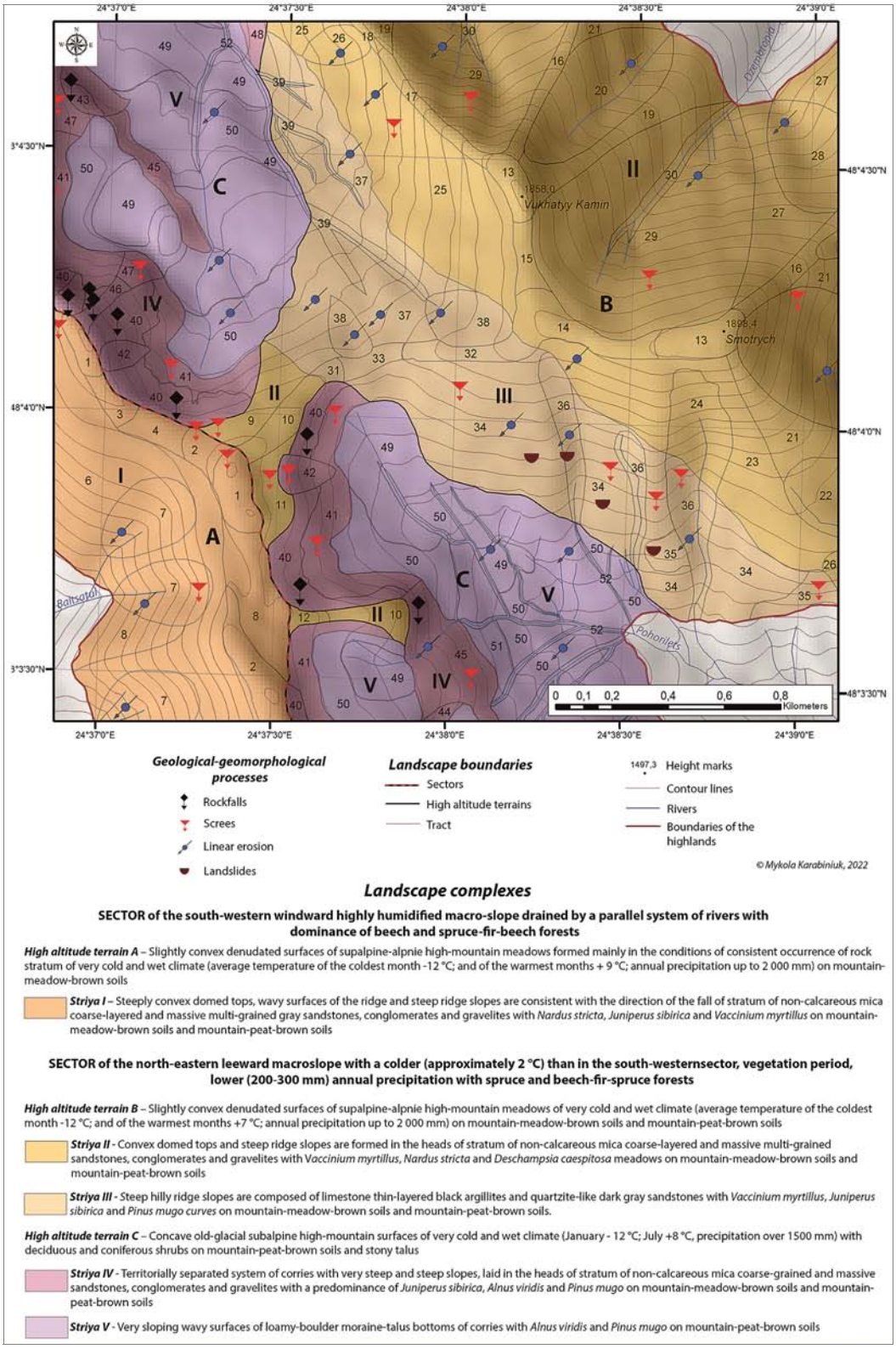

Fig. 8. Map of the distribution of geological and geomorphological processes in the landscape complexes of the subalpine and alpine highlands of Chornohora (area near Smotrych Mountain).

Originality

For the first time are held a comprehensive analysis of factors and features of modern negative geological and geomorphological processes in the subalpine and alpine highlands of Chornohora and the impact of geological structure on the distribution of the largest centers of their development. Peculiarities of landscape differentiation of rockfalls, screes, landslides and linear erosion in the high-mountain landscape tier of Chornohora in terms of high-mountain areas and landscape structures are specified. For the first time, the influence of landscape structure is described in detail and the relationship between the diversity of geological and geomophrological processes with the genesis and mophrological structure of the territory, in particular – tracts.

Based on the results of our own field research and geoinformation analysis data, we clarified and detailed information on the intensity of negative geological and geomophrological processes in the Chornohora highlands and their landscape differentiation, taking into account structural and lithological features of the territory, relief morphometry, etc. For the first time, a map of the distribution of negative geological and geomorphological processes in high- mountain natural territorial complexes in the area near Smotrych Mountain was developed and the impact of striyas landscape structure on the development of landslides was recorded.

Practical significance

The results of the study of the peculiarities of development and distribution of modern geological and geomorphological processes in the highlands of Chornohora provide an opportunity for further landscape analysis of the territory, study the dynamics and properties of highland natural territorial complexes, as well as to substantiate constructive recommendations for optimizing the system of nature management, taking into account the patterns of manifestation of negative processes and phenomena.

Today, the territory of the high-mountain landscape tier of Chornohora is actively used for recreational and tourist activities. The centers of rockfalls, screes, landslides and other dangerous processes identified by us allow us to develop new and improve the existing tourist routes and ways to ensure the safety of tourists and vacationers. Analysis of geological and geomorphological processes in the highlands of Chornohora is important to determine the overall geological situation in the Ukrainian Carpathians and ensure sustainable development in the region.

Conclusions

The subalpine and alpine highlands of Chornohora are characterized by a significant development of negative physical and geographical processes, the most common and most dangerous of which are geological and geomorphological like rockfalls, screes, landslides and linear erosion. As a result of the study, 789 centers of these processes were identified in the high-mountain landscape tier of the massif, the main factors of development and differentiation of which are the geological structure nature, its structural and lithological features and high level of landscape organization.

Based on our own field research and the results of geoinformation analysis, a map of the spread of negative geological and geomorphological processes in the natural territorial complexes of the subalpine and alpine highlands of Chornohora at a scale of 1:25 000 at the level of high altitude terrains are developed, which indicates the uneven distribution of these processes in geocomplexes of different origins and properties. It is determined that the highest intensity of geological-geomorphological processes is characteristic of landscape complexes of ancient glacial-exaration genesis, which in the north-western landscape sector reaches 14.5 c./km^2. Also, high indicators of intensity (11.7 c./km^2) and a significant variety of geological and geomorphological processes are characteristic of the high-mountain terrain of the nival-erosive subalpine highlands of Chornohora, within which large-scale centers of rockfalls, landslides and other processes. In general, in the highlands of the massif, the highest intensity of manifestation is characteristic of screes (4.2 c./km^2), linear erosion (2.9 c./km^2) and rockfalls (42.4 c./km^2). This is the result of the predominance in the geological structure of the study area of massive sandstones and sandstone flysch of the Cretaceous period, a complex combination of geocomplexes of different genesis, the predominance of steep slopes and others.

Particular attention is paid to the study of landslides in the highlands of Chornohora, which to this day have remained out of the attention of researchers and scientists. As a result of the research, 24 landslides were recorded here, which are directly related to the structural and lithological features of the territory – the distribution of argillites and argillite flysch in the geological structure, southwestern inclination of strata bedrock and consistency with them southwestern slopes, the presence of tectonic faults, etc. The inherency of landslides in the highlands of Chornohora to the landscapes striyas formed on argillites and argillite flysch, demonstrated by the example of a key research site in the vicinity of Mount Smotrych, which crowns the north-eastern spur of the main ridge interfluve the basins of the river Dzembronya and the stream Pogorilets. In total, large-scale landslides were recorded in 4 landscape striyas, and their total intensity of manifestation is 0.3 c./km^2.

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ГЕОЛОГІЧНІ УМОВИ РОЗВИТКУ ТА ЛАНДШАФТНА ДИФЕРЕНЦІАЦІЯ СУЧАСНИХ ГЕОЛОГО-ГЕОМОРФОЛОГІЧНИХ ПРОЦЕСІВ У ВИСОКОГІР'Ї ЧОРНОГІРСЬКОГО МАСИВУ (УКРАЇНСЬКІ КАРПАТИ)

Мета цього дослідження – проаналізувати фактори розвитку, особливості поширення та ландшафтну диференціацію геолого-геоморфологічних процесів у субальпійському й альпійському високогір'ї Чорногори, а також визначити вплив геологічної будови та морфометричних особливостей на інтенсивність їхнього розвитку. Методичною основою дослідження є комбінація методів польових досліджень та геоінформаційного аналізу засобами ГІС, що дало змогу визначити у високогір'ї Чорногори основні осередки розвитку обвалів, осипів, зсувів та лінійної ерозії. На основі ландшафтного підходу проаналізовано просторову диференціацію геолого-геоморфологічних процесів у розрізі висотних місцевостей та ландшафтних стрій і виконано їх комплексний аналіз, а за допомогою геоінформаційної та статистичної обробки даних про розміщення та чисельність осередків розраховано інтенсивність прояву негативних процесів. Основним результатом дослідження є укладена карта поширення негативних геолого-геоморфологічних процесів (обвалів, осипів, зсувів, лінійної ерозії) у ландшафтних комплексах субальпійського й альпійського високогір'я Чорногори, а також карта на ключову ділянку в околицях г. Смотрич, яка відображає ландшафтну диференціацію цих процесів на рівні ландшафтних стрій та урочищ. У результаті дослідження проаналізовано структуру та специфіку розвитку геолого-геоморфологічних процесів у геокомплексах різного походження та з різними морфологічними і морфометричними параметрами. Вплив геологічної будови на розвиток процесів проявляється у домінуванні масивних пісковиків та пісковикового флішу, які сприяли розвитку великих та крутосхилих форм рельєфу із притаманними їм інтенсивними обвально-осипними процесами та лінійною ерозією. Аналіз інтенсивності прояву

цих процесів свідчить про найбільший їх розвиток у геокомплексах давньольодовиково-екзараційного походження – карах, цирках, трогових долинах, нівальних нішах тощо. Розвиток, характер та інтенсивність прояву негативних геолого-геоморфологічних процесів у ландшафтних комплексах нівально-ерозійного та денудаційного походження суттєво відрізняються. Особливістю диференціації процесів тут є чітка залежність їх від складу та особливостей залягання пластів корінних порід, морфометрії рельєфу тощо. Важливим результатом дослідження є укладена згадана вище карта на ділянку високогір'я в околицях г. Смотрич, яка відображає приурочення раніше малодосліджених зсувних процесів до вузьких смуг поширення аргілітів та аргілітового флішу. **Наукова новизна.** Визначено взаємозв'язок різноманіття та поширення негативних геолого-геоморфологічних процесів з генезисом ландшафтних комплеків високогір'я Чорногори, їхньою структурою, структурно-літологічними та морфометричними особливостями. Проаналізовано та описано ландшафтну диференцію та інтенсивність прояву обвалів, осипів, зсувів та лінійної ерозії у високогір'ї досліджуваного масиву. **Практична значущість.** Результати дослідження сприяють подальшому вивченню динаміки та властивостей високогірних ландшафтних комплексів Чорногори, а також дають можливість пронозувати особливості розвитку тут геоекологічної ситуації та оптимізувати систему природокористування, зокрема організаційні особливості рекреаційно-туристичної діяльності.

Ключові слова: високогірний ландшафтний ярус; осипи; обвали; зсуви; лінійна ерозія; ландшафт Чорногори; Українські Карпати.

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