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Pavlo HORISHNYI[1], Anastasiia PAVELCHUK[2]

[1] Department of Geography of Ivan Franko National University of Lviv, 41, P. Doroshenko str., Lviv, 79000, Ukraine, e-mail: pavlo.horishnyy@lnu.edu.ua, https://orcid.org/0009-0003-7050-671X
[2] Department of Geography of Ivan Franko National University of Lviv, 41, P. Doroshenko str., Lviv, 79000, Ukraine, e-mail: anastasiia.pavelchuk@lnu.edu.ua, https://orcid.org/0009-0001-1396-5317

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MODERN MORPHODYNAMICS IN QUARRIES OF CRYSTALLINE ROCKS OF THE MIDDLE POBUZHZHIA

The study aims to characterize the modern morphodynamics in the quarries of crystalline rocks of the Middle Pobuzhzhia (Hnivanskyi, Sabarivskyi, and Novosyniavskyi quarries). General geographical and geomorphological research methods were used. General geographical methods include cartographic and remote sensing, while geomorphological methods involve morphographics, morphometrics, and morphodynamics. In the granite quarries of Middle Pobuzhzhia, we can identify both major and minor anthropogenic processes. The major processes shape the primary elements and forms of the relief in the quarries and dumps, while the minor processes add complexity to the structure of the anthropogenic relief. The main anthropogenic processes include: 1) blasting operations in quarries; 2) selection of crushed rock by excavators; 3) formation of overburden ledges; 4) formation of hydraulic dumps and dams; 5) filling of overburden dumps; 6) dumping within processing plants; 7) formation and modification of quarry roads. Anthropogenic processes are mainly represented by two groups of processes: gravity and water erosion. Gravity processes are common on quarry walls and embankment slopes. These processes include collapses, landslides, and slumps, primarily on hard crystalline rock layer, and landslides on loose bedrock layer. Water erosion processes are represented by linear and planar erosion. They are common in the upper parts of quarry walls, where the ledges of loose overburden are exposed, and on the slopes of overburden dumps and processing plants. Planar erosion can be in the form of total and small-scale flushing and accumulation at the foot of ledges and slopes of embankments. Linear erosion consists of the formation of gullies and small ravines, rather short with a significant slope of the longitudinal profile. For the first time, the main and secondary anthropogenic geomorphological processes for mining areas are identified and characterized. Anthropogenic processes in crystalline rock quarries were studied based on our field research, . For the first time, modern geomorphological processes in the quarries of the Middle Pobuzhzhia were examined from a regional perspective. The practical significance of the research is that its results can serve as a basis for predicting anthropogenic and anthropogenically determined processes within quarries.

Keywords: modern morphodynamics, anthropogenic processes, anthropogenically determined processes, anthropogenic relief, crystalline rock quarries, Middle Pobuzhzhia.

Introduction

Modern morphodynamics (modern geomorphological processes) in quarries is a part of the study of anthropogenic geomorphology, namely, anthropogenic morphodynamics. Their main feature is the full or partial anthropogenic determination of processes. Processes in crystalline rock quarries are characterized by a greater role of gravitational processes, such as collapse and slumping, primarily related to the lithology of the extracted raw materials.

The direct anthropogenic factor results in anthropogenic processes, which can be denudational or accumulative. They form the main positive and negative anthropogenic landformsIn the process of quarrying, anthropogenic landforms become increasingly complex due to various human-induced processes. As a result, smaller landforms are also created. These processes can be classified by their origins into several categories: gravity-induced (such as landslides and slumps), water erosion (which includes linear and planar erosion), karst and suffosion phenomena, aeolian processes, abrasion, and others. Human activity leads to the formation of specific relief features, including erosion furrows, ravines, deposition cones, diluvial plumes, landslide cones, breakaway walls, and landslide bodies. Their sizes are small, especially compared to anthropogenic forms, but their distribution is very significant. It should be noted that in granite quarries, the variety of anthropogenic processes, and thus the forms they create, increase towards the surface. This is due to the presence of loose cover rocks in the upper horizons of quarries, which are largely exposed to various relief-forming factors.

Analysis of recent publications. The modern morphodynamics of quarries has been studied relatively recently, since the 70s and 80s of the twentieth century. Publications on this topic can be divided into separate groups: 1) concepts and types of anthropogenic and natural anthropogenic processes [Kovalchuk & Koltun, 2012; Horishnyi, 2018; Horishnyj & Halaiko, 2019; Denysyk & Zadorozhna, 2013]; 2) processes in quarry and dump complexes in geomorphological and other geographical scientific works [Denysyk & Voyna, 2013; Dávid, 2008, 2012; Boengiu et al., 2016; Horishnyi & Pavelchuk, 2019; Ivanov, 2007, 2017; Pavelchuk, 2021, 2023a, b; Horishnyj & Halaiko, 2018; Duchnowska, 2022; Zarychta R., Zarychta A. & Bzdega K., 2020]; 3) anthropogenic geomorphological processes in technical sciences as technological processes during open pit mining [Open pit mining, 2020; Dryzhenko, 2014; Korobiychuk, 2019].

Among these works, it is worth noting the monograph by S. Horshkov [Horishnyj & Halaiko, 2019], which, in particular, proposes the concepts of anthropogenic denudation and anthropogenic accumulation. V. Firsenkova made a significant contribution to the development of scientific thought on the morphodynamics of mining areas [Horishnyi, 2018]. She proposed a wide range of forms created by various geomorphological processes (water-erosion, landslide, aeolian, etc.), identified the main stages of intensity of landslide and erosion processes, and for the first time constructed morphodynamic maps of quarry and dump complexes on a large scale (1:5,000).

The vast majority of publications are devoted to the study of modern morphodynamics in sand, limestone, and clay quarries. Modern geomorphological processes in crystalline rock quarries have been studied in a few publications [Pavelchuk, 2021, 2023a, b; Horishnyi and Pavelchuk, 2019], partially [Dávid, 2008, 2012].

The objects of our research were the Hnivanskyi granite quarry, the Western Sabarivskyi granite quarry, the Eastern Sabarivskyi quarry (all in the region of Vinnytsia), and Novosyniavskyi granite quarry (Khmelnytskyi region) (Fig. 1).

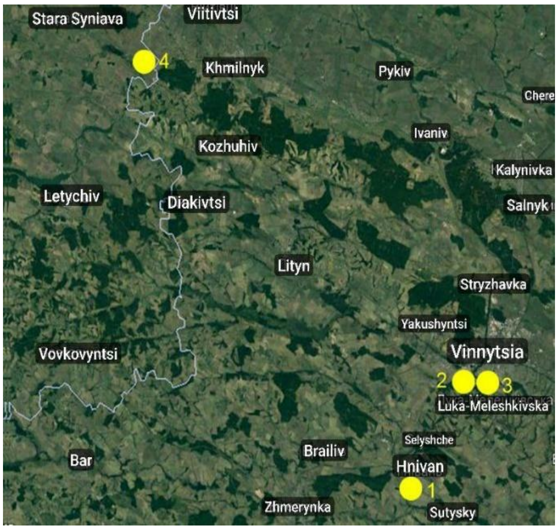

Fig. 1. Location of the studied quarries in the Middle Pobuzhzhia
Numbers on the map indicate quarries:
1 – Hnivanskyi; 2 – Western Sabarivskyi (active quarry); 3 – Eastern Sabarivskyi (disused quarry); 4 – Novosyniavskyi.

The aim of the research is to characterize the modern morphodynamics of the relief in the crystalline rock quarries of the Middle Pobuzhzhia.

Methods

The source materials for this article were field geomorphological surveys of the Hnivanskyi, Novosyniavskyi, and Sabarivskyi quarries in 2014–2016, 2021, and 2023, mining development plans and reclamation plans for individual quarries, surveying materials, and Google Earth Pro satellite images.

The article employs a variety of general geographical and geomorphological research methods. The general geographic methods include cartographic and remote sensing techniques. The cartographic method entails the processing of surveying materials from individual quarries at a scale of 1:2,000–1:5,000. The remote sensing method involves the analysis of high-resolution, multi-temporal Google Earth Pro satellite images to identify elements and forms of the quarries' relief and to track the dynamics of anthropogenic processes.

Geomorphological methods include morphographic, morphometric and morphodynamic methods. The morphographic method consisted in describing individual elements and forms of relief created by anthropogenic and natural anthropogenic processes. The morphometric method was used to determine the quantitative (metric and angular) characteristics of the quarry relief in the field and as a result of processing topographic maps and space images. The objectives of the morphodynamic method were to study the distribution, types, development of anthropogenic and anthropogenically determined processes and forms created by these processes in quarry and dumping complexes.

Results

General characteristics of the study area. Middle Pobuzhzhia occupies the central (middle) part of the Southern Buh River basin [Denysyk, 2002]. Tectonically, it is part of the Southern Buh River basin, which lies within the Ukrainian Shield, stretching from Kostiantynivka in the Khmelnytskyi region to Oleksandrivka in the Mykolaiv region. Geomorphologically, as defined by L. Stefankov) [Horishnyi, Pavelchuk, 2019], it extends from Vinnytsia to Oleksandrivka in Mykolaiv region. In terms of landscape,according to H. Denysyk [Denysyk, 2014], it runs from the northern outskirts of Vinnytsia to Pervomaisk. L. Stefankov [Horishnyi, Pavelchuk, 2019] proposed another interpretation of the boundaries of Middle Pobuzhzhia. According to this interpretation, the region encompasses a section of the Southern Buh River basin, extending from the village of Kostiantyniv (located on the border of Khmelnytskyi and Vinnytsia regions) to the town of Haivoron (bordering Vinnytsia and Kirovohrad regions). In our article, Middle Pobuzhzhia is distinguished on the basis of the physical and geographical zoning of Ukraine [Marynych et al., 2009]. The study area belongs to the Middle Buh Upland Region (from the mouth of the Vovk River to the mouth of the Dokhna River).

The geological structure of the area includes Precambrian crystalline rocks, products of their destruction (weathering crust), Neogene sediments and Quaternary rocks. The Archean formations include a series of gneisses, basic and ultrabasic rocks, as well as rocks of the Podilsk charnockite complex. The weathering crust of crystalline rocks consists ofprimary kaolins and disturbed weakly kaolinized gastropelite. The Neogene rocks are extensively developed and includecolored clays from the undivided Middle and Upper Sarmatian sub-stage, as well as rocks of the Baltic Suite (Baltic Formations), which are represented by sands, clays, sandstones and loams. Quaternary sediments cover almost the entire territory. They consist of fluvioglacial, alluvial, aeolian, deluvial and eluvial formations, which are lithologically represented by loams, clays and sands. Their thickness ranges from 1–3 m to 10–15 m [Peikre, 1984].

According to the geomorphological zoning [Palienko and Barshchevskyi, 2009], the Middle Pobuzhzhia area is located within two geomorphological regions: Volhynian-Podolian region of stratigraphic and denudation uplands and Dnieper-Azov region of stratigraphic and denudation basement uplands and lowlands. Volhynian-Podolian region is represented by one geomorphological sub-areathe Baltska accumulative-denudation plain, which is an old delta formed on Neogene sediments. In contrast, thePrydniprovska-Pryazovska region is characterized by two sub-areas: the Western Prydniprovska stratified-denudation plain, which is comprised of Paleogene and Neogene sediments, and the Central Prydniprovska denudation upland, which is formed on Neogene and Paleogene sediments, as well as Precambrian rocks.

Quarry topography. The Hnivanskyi granite quarry is located on the left bank of the Southern Buh River, 0.5 km west of the town of Hnivan, Vinnytsia district, Vinnytsia region. In 1957, the Vytavske crystalline rock deposit was explored in detail, and two years later, the development of the Hnivanskyi quarry began on its basis, which continues to this day. According to the morphological classification of granite quarries [Pavelchuk, 2021], the Hnivanskyi quarry is deep, polygonal in plan, trapezoidal, and multi-step in profile. Morphometric characteristics of the quarry and dump complex are as follows: the maximum length from north to south, including overburden dumps, is 1,800 m. The maximum length of the quarry excavation from north to south is 1,400 m. The maximum width from west to east is 900 m, and the current depth is approximately 105 m [Pavelchuk, Hnivan, 2023]. Mining operations are carried out in two overburden and six mining ledges. The height of the mining ledges is 15 m. The developed relief is represented by the bottom and walls. The bottom has a complex geometric shape of a polygon stretched from north to south. The bottom surface is flat and there are no internal dumps. The bottom of the Hnivanskyi open pit has a drainage channel and a drainage sump. The walls are characterized by a stepped shape in the profile. They are approximately equal in height and steepness. The biggest differences in the structure of the walls are in the upper parts, represented by the overburden ledges. The open pit's bulk relief is represented by overburden dumps and processing plant dumps. All of them are located outside the open pit and, accordingly, are external dumps. The overburden dumps are reclaimed (stable and artificially forested).

The Sabarivskyi granite quarry (western part) is located on the southern outskirts of Vinnytsia on the right bank of the Southern Buh River. The quarry is operational and has been producing granite since 1958. The Sabarivskyi quarry is a deep rectangular trapezoidal quarry with a low profile. The maximum length of the open pit is 620 m, the width is 370 m and the depth is 54 m. Mining operations are conducted in one overburden and three mining ledges. The height of the mining ledges is 14 meters. The developed relief consists of the pit bottom, berms, overburden ledges, and working ledges [Horishnyi, Pavelchuk, 2019]. The bottom has a shape close to a rectangle. The shape of the bottom surface is generally level. The bottom is defined by the minimally altered worked-out north, west, and east walls, the western part of the southern wall of the pit, and the significantly altered eastern part of the southern wall. The minimally altered walls are formed by one overburden and three mining ledges. The berms are located between the ledges of different levels. Their maximum width is 50 meters. The Sabarivskyi open-pit mine's bulk relief is represented mainly by the outer dumps of the overburden. They do not have a single location. The shape of the dumps is terraced and swale-like. The overburden dumps have been reclaimed, with continuous forest reclamation. The internal dumps are located in the bottom of the quarry and are not widespread and not very large.

The disused Sabarivskyi granite quarry (eastern part) is located on the left bank of the Southern Buh River (Sabarivske Reservoir) above the Sabarivska HPP dam. It is an open pit, shallow and single-stage quarry. Crystalline rocks were quarried in the quarry during the construction of the Sabarivska hydroelectric power plant (1950s). The quarry is adjacent to the Sabarivskyi forest, and its bottom is in contact with the shoreline of the Sabarivskyi reservoir. It has the shape of an amphitheater. The quarry bottom is lined with single granite blocks. The maximum width of the bottom is 70 meters. The walls are steep, almost vertical, and 12–17 m high [Kizyun, 2019]. At the foot of the walls, there are high-powered landslide plumes, which are sodded and sometimes forested.

The Novosyniavskyi granite quarry is located 1 km southeast of Nova Syniavka village, Khmelnytskyi district, Khmelnytskyi region, on the right bank of the Southern Buh River. The Novosyniavske deposit was developed in 1958–2012. Since 2012, Novosyniavske granite quarry has been temporarily inactive, and since 2019, after being decommissioned, it has continued to operate. The Novosyniavskyi quarry is shallow, rectangular in plan, trapezoidal and slightly sloping in profile. The dimensions of the open pit are 270 m long and 235 m wide. In 2021, the pit bottom had a complex structure. It consists of the bottom of an ancient pit with lower absolute elevations (southern part), the northeastern part of the bottom is represented by the first working horizon of minerals from the bottom surface that was uncovered before mothballing, and the northwestern part is uncovered during modern development. The pit walls are up to 20 meters high. The walls are most clearly visible in the southwestern part of the open pit, with their height gradually decreasing towards the north. In the upper part of the highest wall there are two ledges of overburden. The accumulative landforms of the Novosyniavskyi quarry and dumping complex consist of bothancient and modern overburden dumps, as well as mounds of crushed granite from various periods. The modern overburden dump is formed to the north of the excavation site and has an elongated shape, measuring approximately 200 m in length and 100 m in width. The remains of the ancient mounds of sorting and grinding plants are located to the west of the quarry, have a table-like shape, and are mostly elongated. The dumps in the southwestern part of the quarry and dumping complex have been almost completely removed, and the area is being sodded [Pavelchuk, 2023].

Modern geomorphological processes in the granite quarries of the Middle Pobuzhzhia can be categorized into two groups: anthropogenic and anthropogenically determined processes. Among the anthropogenic processes, we can distinguish between major and minor ones, or macro- and mesoprocesses. Major processes create the largest (main) elements and forms of the quarry and dump relief, while minor processes add complexity to the structure of the anthropogenic landscape. In terms of their formation, these processes can be divided into denudational processes (anthropogenic denudation) and accumulative processes (anthropogenic accumulation).

The main anthropogenic processes include: 1) blasting operations in quarries; 2) selection of crushed rock by excavators; 3) formation of overburden ledges; 4) formation of hydraulic dumps and dams; 5) filling of overburden dumps; 6) dumping within processing plants; 7) formation and modification of quarry roads.

Blasting operations are the initial anthropogenic processes in quarries. They are planned in accordance with the technical specifications for the development of the deposit using loosening charges [Korobiychuk et al.] In granite quarries, borehole charges are used for ledge cutting. Traces of borehole charges in the form of long vertical narrow depressions are visible on the walls of the Sabarivskyi and Hnivanskyi quarries (Fig. 2). As a result of blasting operations, a blasted mass is formed in the form of a debris slope with a natural slope angle (Fig. 3).

Formation of overburden ledges. Overburden ledges are formed by excavators and other quarrying equipment. In the studied quarries, these strata are mainly represented by loams (sometimes with carbonate rocks), sands, clays with a total thickness of up to 10–13 m [Peikre, 1984; Syvak and Koval, 2015; Kradozhon, 2019]. The overburden ledges are usually the oldest elements of the quarries' relief, as their formation was most active at the beginning of the deposit's development. With the expansion of the Sabarivskyi, Hnivanskyi and Novosyniavskyi open pits, new overburden ledges were formed. The height of the ledges ranges from 7 to 9 meters. These ledgescan sometimes consist of two smaller ledges separated by a horizontal or slightly inclined berm surface. In profile view, the shape of the overburden ledges is mostly concave, although it can occasionally appear nearly straight. The slopes vary in steepness from slightly inclined surfaces (up to 15°) to distinct ledges (50–70°). These morphological features of the ledges are caused by subsequent changes in gravity and erosion by natural and anthropogenic processes, as will be discussed later. Sometimes the overburden ledges are destroyed by the advancement of the underlying working ledges. This results in the formation of ledges consisting of overburden and mining rocks.

Fig. 2. Traces of borehole charges on the ledge of the Sabarivskyi quarry.

Fig. 3. Blasted rock mass removed by excavators in the Hnivanskyi quarry.

The formation of hydraulicmine dumps and dams is an ancient anthropogenic process. In the Hnivanskyi quarry, the dump was dredged in 1959–1964 and 1976. It is located on the first floodplain terrace of the Southern Buh River, 100–120 m south of the quarry. The area occupied by the dump has the shape of a rectangle with sides of 800 by 400 meters. The absolute surface elevation of the dump is 239.5–238.0 m. The thickness of the alluvial rocks' ranges from 0.5–1.0 m to 4.0–6.0 m. The average amount of rock stored in the dump was 150–400 thousand cubic meters per year. The 1976 alluvium is located near the dumping dam in the northeastern part of the site. The dumps are composed of sandy loam, sand, loam, and clay. Dusty light and heavy sandy loams predominate in the dumps, accounting for 32 % of the total mass of the dumps, fine and dusty sands account for 28 %, and loams and clays account for 20 % each. The rocks of the dump have a lenticular occurrence and a distinct thin-layered structure [Velikin, Petlichenko & Kilizhevskyi, 1977].

An enclosing dam was partially constructed around the hydraulicmine dumps to increase their storage capacity. The dam was built to the elevation of 243.0–245.0 m. The width of the dam was 25–40 m at the top and 40–60 m at the bottom, with external slope angles of 30–40°. The embankment dam was constructed by bulldozers. In the lower parts (to a height of 2–5 m), the dam is composed of alluvium from 1959–1964, consisting of sandy loam, loam, clay, and sand. In the upper parts, the dam is filled with imported soil and overburden - loams, micaceous clay, crushed micaceous kaolin, and fragments of crushed granite. There is a dry dump of overburden on the dumping grounds [Velikin et al., 1977].

Overburden dumps are filled outside the open pits. They extend parallel to the pit slopes or are localized in separate places. In the first case, elongated shaft-shaped embankments are formed, while in the second case, plateau and cone-shaped complex forms of various heights are formed.

At the Hnivanskyi quarry, overburden dumps are located along the southern and western boundaries. The dry overburden dumps are mostly plateau-shaped, with a height of 15–22 m. A unique shaft-like formation is characterized by a dump stretching along the Southern Buh River located beyond the western boundary of the open pit. The slopes of this formation were created byby free rock falls, occurring in a single layer. The profileof the slopes is nearly straight. The mineral composition of the overburden is characterized by heterogeneity (primary kaolin, kaolinized grus, crushed stone, weathered granite, loams, and clays). The structure of the dump is layered. The slopes of the dump with free fall have slope angles of 35–38°, and where the dump mass is dominated by crushed stone, grus, and fragments of weathered granite, the angles reach 40–43° [Velikin et al., 1977].

In the Sabarivskyi quarry, overburden dumps stretch in an intermittent strip along the Southern Buh River, locatedoutside the southern wall of the quarry. These dumps cover a large area beyond the western boundary of the open pit. The dumps are terraced and swale-shaped. The terraced dumps are located to the west of the open pit and partially extend ontoits eastern side. All other overburden dumps have an elongated shaft shape. The height of the dry dump is 10–15 m. The shape of the slopes in the profile is close to rectilinear. The mineral composition of the overburden is characterized by heterogeneity: loams with carbonate rocks, brown clays, and weathered granite. The dump structure is layered. The slopes of the waste heap have a steepness of 35–38° in free fall.In some places they reach 40–45°, if the waste heap is dominated by crushed stone, grus and fragments of weathered granite.

Formation of waste heaps at processing plants. Processing (crushing and screening) plants are built near quarries or at a short distance from them. A small processing plant producing granite crushed stone is located beyond the eastern boundary of the Sabarivskyi quarry. Its operations result in conical and plateau-shaped dumps. Some shapes are stable, while others grow, change, or disappear completely as a result of secondary anthropogenic denudation of the mounds. The dimensions of the forms, as of 2022, are small: length – 60–85 m, width – 20–40 m.

To the north of the Hnivanskyi quarry, at a distance of 1 km, there is a processing plant with a railroad line for the export of crushed stone. It is located near the disused and flooded (in 1975–1980) quarry. The dimensions of this quarry are 320 by 180 m. In recent years, it has been almost filled with production waste. Before that, however, it was a deep pond. The slopes of the dump are not sodded at all but are dismembered by small furrows formed as a result of linear erosion and in-plane flushing. The shape of the processing plant dumps is plateau-like.

The formation and modification of quarry roads is an anthropogenic process that has both denudational and accumulative components. There are various methods to remove rock and connect different levels within a quarry, specifically the berms and the bottom. These man-made formations can be classified as either denudation-accumulative or denudational based on their origin. Quarry roads, which serve as transportation berms, are horizontal surfaces of varying widths that are bordered by quarry ledges. As deposits are extracted, the quarry roads adapt according to the direction of development. The Hnivanskyi quarry features the most intricate network of quarry roads. We can single out the main road that runs from the entrance to the quarry and connects all the mining horizons with two exits to the bottom of the quarry (Fig. 4).

Fig. 4. The main quarry road connecting different horizons and the bottom (Hnivanskyi quarry).

Secondary anthropogenic processes include: 1) cutting (leveling) in the pit floor and on the berms; 2) formation of embankments in the pit floor and on wide berms; 3) terracing and leveling (grading) of embankments; 4) creation of safety berms on quarry roads; 5) construction of drainage channels in the pit floor.

Cutting in the bottom and on the berms is one of the processes of anthropogenic denudation. Special equipment, such as bulldozers, scrapers, etc., is used to level the uneven denudation surfaces found in subhorizontal areas of quarries, including the bottom, berms, which are created after blasting and rock extraction by excavators. Although the depth of the cuts is relatively small (up to few dozen centimeters), the area affected can be quite substantial, particularly in the bottoms of the pits.*Formation of embankments in the bottom and on the berms.* The formations resulting from these processes are referred to as internal dumps. Overall, there are very few such forms in the studied quarries, which is largely due to the mining technology employed. These dumpstemporary in nature and are either removed from the quarry or relocated after a certain period. There are very few such mounds present at the bottom of the quarries. During the field research conducted in July 2023, no internal dumps were observed at the bottom of the Hnivanskyi quarry. In contrast, the Sabarivskyi quarry had four mounds, each rising up to 2 m in height.More mound forms are found on the berms. In the Hnivanskyi quarry, they are concentrated in the southern part of the quarry on the wide berms of the upper horizons. In the southwestern part of the quarry, several mounds were found on the surface of the fifth horizon. There are two mounds of coarse fragmentary material: a smaller one at the foot of an ancient ledge, and a larger one opposite the first one, which extends along the road. Some fragments are up to 1.5 meters in diameter. There is a mound of overburden rocks, consisting of sand, loam, and migmatite veins, located 60 meters from the large debris piles, with a height of up to 7 meters (Fig. 5).

Fig. 5. Formation of embankments on the berm of the Hnivanskyi open pit (in the foreground – a large debris dump, in the background – a dump of overburden).

Terracing and embankment planning occur after the external dumps, such as overburden and materials from processing plants, have been filled. These anthropogenic processes were frequently undertaken, particularly during the early stages of quarry operations when the overburden layer was initially removed. Such activities are directly related to the reclamation of the dumps during the technical reclamation stage. To the south of the Hnivanskyi quarry, substantial areas of external dumps have been successfully reclaimed [Pavelchuk, 2023]. When reclaiming the areas occupied by the dump, their slope angles should have been no more than 25°.

Building safety berms on quarry roads. To ensure the safety of vehicular traffic in quarries, safety berms are built on roads that run along berms or connect different horizons. In the Hnivanskyi quarry, they are made up mainly of large migmatite fragments. The safety berms are located on the outer edge of the quarry roads and are up to 2 meters high (Fig. 6).

Fig. 6. Safety shaft on the quarry road (southern part of the Hnivanskyi quarry).

The construction of drainage channels at the bottom of the pit is designed to collect and drain surface and groundwater that comes to the surface. To address this need, a large-capacity sump was constructed at each open pit: the Sabarivskyi quarry with a capacity of 400 m³ and the Hnivanskyi quarry with a capacity of 600 m³. In the Hnivanskyi quarry, the drainage channel is situated in the northern section and directed towards the northwestern corner of the pit. This channel is bordered by a small embankment, primarily on the southern side.

Anthropogenic processes are mainly represented by two groups of processes: gravitational and water-erosion.

Gravity processes are common on the walls of quarries and embankment slopes. The thickness of crystalline rocks in the studied quarries has significant fractures. These fractures, along with the influencet of anthropogenic activities, such asblasting to crush rocksand transporting them using machinery, as well as the physical, chemical and biological weathering, play a crucial role in facilitating gravity-driven processes. Anthropogenic gravity processes include collapses, screes and rockfalls, which primarily occur in hard crystalline rock formations, as well as landslides that happen in areas withloose bedrock. These processes lead to the formation of various landforms, such aslandslide cones and plumes, isolated blocks of granite (migmatite), niches of landslides and cornices along quarry ledges. Additionally, they result in landslide detachment walls and landslide bodies. Collapses and rockfalls in granite quarries can be considered separately and in combination as landslide processes, in which rock fragments of different fractions are transported down steep, unreinforced quarry walls. These processes form landslide cones and plumes at the foot of ledges, on berms, and at the bottom of quarries. Such landforms in granite quarries can be composed of fragments of granite of different fractions, crushed granite, grus, and loose rocks from layers of overlying rocks. The rate of formation and spread of landslide features varies depending on several factors, including the rock composition, the steepness and height of the walls, the presence of rock fractures (particularly in crystalline rock formations), the age of the walls, and human activities. Over time, the activity related to the formation of these landslide features diminishes. This decrease occurs because the number of unstable rock fragments exposed to gravitational processes on the walls declines, and the slopes become covered with grass and forests.

However, landslide formation does not cease entirely, even in longabandoned quarries. Weathering continues to create new unstable areas of exposed rock, which are then subject to gravitational processes that lead to the formation of landslide cones and plumes. Landslide plumes, which can vary in thickness, develop on walls of different shapes–such as straight, convex, or concave–and are commonly found throughout the open pit. These formations can create landslide slopes that are several meters high and stretch for tens of meters. Landslide cones are formed on the zigzag walls between the stone pillars.

Fresh and relatively fresh walls of granite quarries are characterized by active development of landslide processes, observed in the operating Hnivanskyi, Sabarivskyi, and Novosyniavskyi quarries. For example, landslide and slump forms are being formed in the northern part of the western wall of the Hnivanskyi quarry (Fig. 7). The sediments that make up these landforms are located at several levels: the upper level, the middle level below the transportation berm, and the lower level at the foot of the wall. These processes are caused by both natural collapse and crumbling of granites due to loss of rock stability and weathering, as well as by the accumulation ofcrushed rock in the middle part of the slope. This accumulation occurred as a result of material being extracted from the upper part of the wall to expand and strengthen the transport berm, which is then dumped downthe slope. Consequently, under the influence of various factors, different debris materials are moved from higher elevations to lower ones, leading to the active formation of landslide and slump features in the landscape. Fresh landslide cones and plumes are composed of unsorted loose material, unstable and undermined. Fresh landslide cones and plumes are composed of poorly sorted loose material, unstable and undermined.

Fig. 7. Current active development of landslide processes in the northern part of the western wall of the Hnivanskyi quarry.

Heavily weathered fractured rocks on the walls of quarries are massively exposed to landslide processes. The zigzag shape of the ledges with protrusions and depressions contributes to a certain localization of landslide cones, which are confined to the depressions (Fig. 8). The cutting of berms frequently occurs in granite quarries and exacerbates landslide processes. This reduces their width or even destroys them. As a result, the debris material, moving down the wall, has few, if any, areas for retention and storage. This lack of containment causes it to continue advancing towards the bottom, capturing other rock fragments along the way. Over time, the material in the landslide cones and plumes becomes sorted and compacted, eventually leading to the initiation of sodding.

Fig. 8. Landslide cones on a zigzag ledge (the Hnivanskyi quarry).

The single-ledged walls of granite quarries are characterized by the presence of a several-meter-high landslide plume at the foot. These plumes have the following structure: they are based on fragments of crystalline quarry rocks of various sizes and crushed granites, which are densely covered with loose rocks from overburden horizons (loams, clays, kaolins, etc.). Depending on the time these forms exist, the rocks they are composed of are compacted and sodden, with single trees sprouting on the slopes.Over time, as gravitational processes decay and there is no direct anthropogenic impact, the angle of inclination of landslide cones and plumes decreases and they stabilize. Ancient cones and plumes are dense in texture, mostly sodden and, in some places, forested.

Such types of anthropogenically caused gravitational processes as *rockfalls* are widely represented in the studied granite quarries. This is one of the types of landslide processes. As a result of this process, niches and cornices are formed on the walls of quarries (Fig. 9).

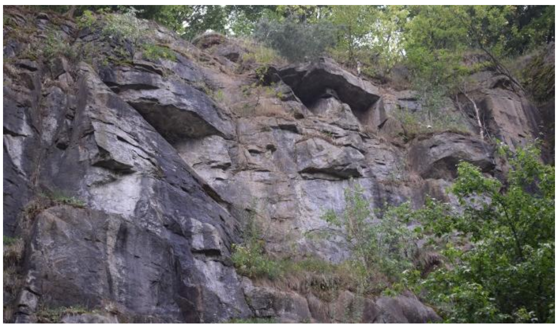

Fig. 9. Niches and cornices on the wall of the disused Sabarivskyi quarry.

Single blocks of crystalline rocks up to several meters in size are formed in the bottom and on the berms of quarries. The removal of large granite blocks, known as migmatites, is aided by the presence of significant vertical and horizontal fractures in crystalline rocks, as well as blasting techniques used in quarries (Fig. 10). After an explosion, an uncrushed solid block of rock that remains on the wall can initially be separated by small cracks. Due to the undercutting and loss of support, the cracks expand under the influence of weathering and gravitational processes, and the block falls out. This process is observed in both active and abandoned quarries and is quite unpredictable and, accordingly, dangerous.

Fig. 10. The place of a possible rockfall on the wall of the disused Sabarivskyi quarry.

Landslide processes in granite quarries can be observed on the ledges of loose overburden, along the granite rock surfaces, and in the upper sections of the mining ledges. These landslide processes result in the formation of various landforms, such as breakaway walls and landslide bodies. In contrast to collapse processes, landslides do not result in an absolute loss of contact between the displaced landslide body and the fixed breakaway wall. Landslide deformations are characterized by slow development with possible rapid displacement of the rock mass in the future. Man-made factors that contribute to landslide processes in quarries include undercutting (mining) of rock horizons, which causes loss of stability; drilling and blasting operations; vibrations during operation of engines, equipment and transportation of rock by dump trucks. Natural factors include excessive wetting of loose rocks by rain and meltwater, as well as fracturing of underlying hard crystalline rocks.

In the Hnivanskyi quarry, landslides occurred in the upper parts of the northeastern and western walls. They have different shapes and sizes. In the eastern part of the northern wall of the pit, on the highest mining ledge, there are two cirque-like shapes - the walls of landslide detachment (Fig. 11). Their width in a straight line is approximately 20 m and 30 m. Small and medium-sized fragments of crystalline rocks, as well as yellowish loams, are common on the landslide walls. Below, in the rock wall, a vertical plane can be traced, which is the surface of the crack along which the landslide occurred. The landslide bodies are represented by heavily weathered rock with some fragments of migmatites and rocks of the covering horizons. Due to the absence of berms (caused by their undercutting) between the first and second, and occasionally between the first, second and third mining ledges in the eastern part of the northern wall of the pit, the material from the landslide bodies is carried downhill by gravitational processes, forming a scree. The walls of the landslide detachment are partially sodded and overgrown with grass and small trees, which indicates that these forms are several years old.

Fig. 11. Walls of cirque-shaped landslide detachment (the Hnivanskyi quarry).

In the southern part of the western wall of the Hnivanskyi quarry, there is a large landslide body composed of sand and loam (Fig. 12). Its width is about 60 m and its height is over 30 m. This landslide captured the overburden sediments, covering the first and second mining ledges and terminating at the natural support of the third mining ledge's berm.The landslide process was active until 2014 for several years, and now the movement has been suspended, with significant sodification of the surface.

Landslide processes are also observed in the Sabarivskyi granite quarry. The upper ledge of the quarry is composed of yellow-brown and pale-yellow loams and brown clays, weathered granites, and grus [Horishnyi and Pavelchuk, 2019]. It is fully represented on the northern wall of the quarry. In the eastern part of the northern wall of the Sabarivskyi quarry, the ledge is 2/3 composed of heavily weathered granites. Its upper part is loess-like loams, where a landslide breakaway wall is visible. The slope has a considerable steepness and a general convex shape, which served as auxiliary factors of the landslide process.

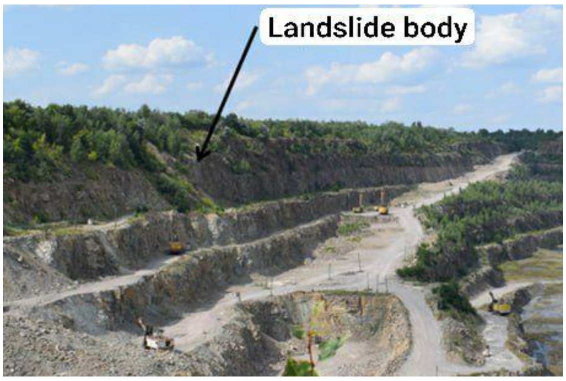

Fig. 12. Significant landslide covering several horizons (the Hnivanskyi quarry).

During the field surveys, no active landslides were observed, however, examples of ancient landslides allow us to conclude that this process occurs both in active granite quarries and in disused ones. This is evidenced by the landslide activity observed in the old Sabarivskyi quarry. A landslide occurred in the upper part of the wall near the sidewall, dislodging loose overburden. As a result, there is a landslide body at the foot of the vertical wall, primarily consistingof loams with small fragments of crystalline rocks. Its soddenness is insignificant, suggesting that this formation is relatively recent, occurring after the quarry was no longer in use. ***Water-erosion processes*** are represented by linear and planar erosion. They are commonly found in the upper parts of quarry walls, where ledges of loose overburden are exposed. They can also be seen on the slopes of overburden dumps and processing plant dumps. The overburden in the study area consists of loams, clays, sands, and kaolins. Linear erosion in the studied quarries forms relatively small landforms – ravines and gullies, which in their lower parts, form small cones of deposition. Surface erosion is represented by small-scale jet washout, which forms an extensive network of micro-furrows and larger furrows on the slopes of ledges. The extent of this erosion depends on factors such as the lithology and particle size distribution of the rocks on the overburden ledges and the working walls of quarries, the steepness of the slopes, the intensity of precipitation, and the moisture content of slopes and berms. As rain and meltwater flow down the walls, they carry away loose debris, forming deluvial plumes that can accumulate to a significant thickness at the base.*Linear erosion* in the studied quarries has the greatest impact on kaolin deposits exposed in the middle part of the southeastern wall of the Hnivanskyi quarry. The slope, composed of kaolin, has a convex-concave shape in plan and is densely dissected by gully-like forms. For example, consider the ravine on this slope, which was formed by the merger of three erosion gullies (Fig. 13). It is characterized by a significant slope of the longitudinal profile.

Fig. 13. Gully-like formations on a kaolin slope (southeastern wall of the Hnivanskyi quarry)

The gully has a wide catchment area that tapers downward and turns into a drainage channel. Its upper part is complicated by small shifts of sod, up to several tens of centimeters thick. The depth of the gully is insignificant, reaching a maximum of 2–3 m in the middle part. Down the slope, the sides of the gully are not actually fixed, but a drainage channel is visible. This is an active erosion form, practically undermined, which is largely eroded during rainsGully-like forms in the Hnivanskyi quarry are also found on the ledges of overburden composed of loose rocks with weathered granite and grit. For example, in the eastern part of the northeastern wall of the quarry, a small gully cuts through the side of the overburden ledge. Its width reaches 10 m in the upper part, slightly narrowing to 8 m below, and its depth is approximately 4 m. Its cross-sectional shape is U-shaped with rather steep sides at the top. The top of the gully is amphitheater-shaped with a clear top threshold, but without a clear growth point. The overall shape of the longitudinal profile is concave, while it becomes convex in the lower reaches due to the presence of a cone of deposition. The sides of the gully are partially sodded, the bottom is fully sodded, and there are a few scattered trees.Planar erosion occurs on low- and no-graded overburden ledges, slopes of external dumps and embankments of processing plants. This process mainly involves jet washout, leading to the formation of micro-furrows in primary relief depressions or creating such forms independently. The shape of the furrows is rectilinear or sinuous, and their network is parallel or prefabricated. Mostly, in the areas affected by small-scale erosion in the studied quarries, the width of erosion furrows was 1–6 cm, the depth was 2–5 cm, and the shape of the cross-sectional profile was U-shaped. In particular, a system of furrows was recorded on the ledge of the overburden in the northeastern part of the Sabarivskyi quarry (Fig. 14).

Fig. 14. Parallel network of erosion micro-furrows on the ledge of overburden of the Sabarivskyi quarry.

Fig. 15. Prefabricated furrows on the slopes of overburden dumps (Hnivanskyi quarry).

On the northern wall of the Hnivanskyi quarry, a parallel network of winding erosion micro-furrows, several centimeters deep, formed on the ledge of overburden composed of loams. There are examples of such forms of relief on the slopes of the dumps, which are prefabricated in nature (Fig. 15).

The landscape of granite quarries is shaped by a combination of geomorphological processes, both natural and anthropogenic, that occur simultaneously or sequentially. One process can trigger the emergence or activation of another. For instance, weathering, water erosion, and gravitational forces work together to create deluvial plumes in granite quarries.

The overburden ledge in the central part of the northern wall of the Sabarivskyi quarry consists of loose sediments. The upper part of the ledge is almost straight, undrained with signs of slumping. In the lower part, a large deluvial-sedimentary plume has formed, partially sodded with distinct erosion furrows. The previously mentioned northern part of the western wall of the Hnivanskyi quarry, where landslide and alluvial relief formations are actively occurring, is also marked by the paragenesis of anthropogenic processes. In addition to gravitational processes, water-erosion and weathering are also at work here. There are manifestations of water flows on the slope, which, together with collapse and slumping, carry away material down the slope, forming deluvial-slump cones.

Weathering processes are an important prerequisite for the development of landslide processes on quarry ledges composed of crystalline rocks (granites, migmatites, etc.). Changes in air temperature, along with the freezing and melting of water in the cracks of rocks, cause these rocks to gradually break down. Moisture and drying also contribute to this process. As a result, rocks can lose their stability on slopes, leading to collapses or crumbling. Another significant effect of weathering that happens after landslides is the peeling of granite blocks from the surface at the base of quarry walls. This is especially typical for the disused Sabarivskyi quarry.

Scientific novelty. For the first time, the main and secondary anthropogenic geomorphological processes have been identified and characterized for mining areas. Based on our field research, we studied anthropogenic processes in crystalline rock quarries. In regional terms, the modern geomorphological processes in the quarries of the Middle Pobuzhzhia (Hnivanskyi, Novosyniavskyi, Sabarivskyi quarries) were studied for the first time.

In our opinion, **the practical value** of the conducted research is that its results can serve as a basis for predicting anthropogenic and anthropogenically determined processes within future quarrying operations in the Middle Pobuzhzhia. In other words, when conducting surveying works outlined in the Order of the Ministry for Development of Economy, Trade and Agriculture of Ukraine No. 669 dated 31.03.2021 “On

Approval of the Rules for Performing Surveying Works during the Development of Ore and Nonmetallic Minerals", the surveying service can utilize the findings from our research, even at the initial stage of studying the potential development of nonmetallic mineral deposits through open-pit mining.This, in turn, will help to avoid unpredictable consequences of anthropogenic and anthropogenically caused processes in operating and disused quarry and dumping complexes.

Conclusion

Modern geomorphological processes in the crystalline rock quarries of the Middle Pobuzhzhia are divided into two types according to the degree of anthropogenic impact: anthropogenic and anthropogenically determined (natural-anthropogenic). Anthropogenic geomorphic processes are fully determined by a certain type of quarrying. The main and secondary anthropogenic processes are distinguished. The main processes create and transform the largest (main) elements and forms of the relief of quarries and dumps, while the secondary processes complicate the structure of the anthropogenic relief. The main anthropogenic processes include: 1) blasting operations in quarries; 2) selection of crushed rock by excavators; 3) formation of overburden ledges; 4) formation of hydraulic dumps and dams; 5) filling of overburden dumps; 6) dumping within processing plants; 7) formation and modification of quarry roads. Secondary anthropogenic processes create smaller anthropogenic landforms that occur locally.

Anthropogenic processes in the studied quarries are mainly represented by two groups: gravitational and water-erosion. Gravity processes are common on quarry walls and embankment slopes. These processes occur under the influence of anthropogenic (blasting, rock movement by machinery) and natural factors (physical, chemical and biological weathering). Anthropogenic gravity processes include collapses, rockfalls and slumps – primarily occurringon the horizons of hard crystalline rocks, which take place on loose bedrock. These processes lead to the formation of various landformssuch as landslide cones and plumes, single blocks of granite (migmatite), niches of landslides and cornices, landslide detachment walls, and landslide bodies.

The water-erosion processes of the studied quarries include planar and linear erosion. They are common on the ledges of loose overburden and on the slopes of overburden dumps and processing plant dumps. In this area, overburden rocks are represented by loams, clays, sands, and kaolins. The overburden rocks are soil mixtures composed of various loose rocks and fragments of granites and migmatites. Planar erosion is represented by total and small-scale flushing and accumulation at the foot of ledges and slopes of embankments. Linear erosion consists in the formation of gullies and small ravines, rather short with a significant slope of the longitudinal profile. The cones of deposition are almost not preserved. Planar and linear erosion are genetically related. Under certain conditions, furrows of small-scale flushing can develop into larger forms, such as gullies and even ravines.

Anthropogenic processes are characterized by an increase in both the area and depth of quarries, including the growth in the number of horizons and, consequently, the number of benches. The dynamics of human-induced processes are multidirectional: on one hand, new centers of activity appear on newly-formed quarry benches and embankment slopes, while on the other hand, processes gradually subside on long-established anthropogenic landforms.

In the future, it is planned to study other active and disused quarries in the Middle Pobuzhzhia and other types of anthropogenic processes (weathering, coastal processes in flooded quarries, etc.). Also, the lithological factors of the processes, their stages of development and activity should be studied in more detail.

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Павло ГОРІШНИЙ[1] Анастасія ПАВЕЛЬЧУК[2]

[1] Львівський національний університет імені Івана Франка, вул. П. Дорошенка, 41, Львів, 79000, Україна
pavlo.horishnyy@lnu.edu.ua, https://orcid.org/0009-0003-7050-671X
[2] Львівський національний університет імені Івана Франка, вул. П. Дорошенка, 41, Львів, 79000, Україна
anastasiia.pavelchuk@lnu.edu.ua, https://orcid.org/0009-0001-1396-5317

СУЧАСНА МОРФОДИНАМІКА У КАР'ЄРАХ КРИСТАЛІЧНИХ ПОРІД СЕРЕДНЬОГО ПОБУЖЖЯ

Мета дослідження – охарактеризувати сучасну морфодинаміку в кар'єрах кристалічних порід Середнього Побужжя (Гніванський, Сабарівські, Новосинявський кар'єри). Використано загальногеографічні й геоморфологічні методи досліджень. До загальногеографічних належать картографічний і дистанційний, до геоморфологічних – морфографічний, морфометричний і морфодинамічний методи. Серед антропогенних процесів у гранітних кар'єрах Середнього Побужжя можна виокремити головні та другорядні (головні створюють головні елементи і форми рельєфу кар'єрів і відвалів; другорядні ускладнюють структуру антропогенного рельєфу). До головних антропогенних процесів належать: 1) вибухові роботи у кар'єрах; 2) вибір подрібненої породи екскаваторами; 3) утворення розкривних уступів; 4) утворення гідровідвалів та дамби обвалування; 5) насипання відвалів розкривних товщ; 6) відвалоутворення у межах переробних заводів; 7) утворення і зміна кар'єрних доріг. Антропогенно зумовлені процеси представлені здебільшого двома групами процесів: гравітаційними й водно-ерозійними. Гравітаційні процеси поширені на стінках кар'єрів і схилах насипів. До цих процесів належать обвали, осипи та вивали – передусім на горизонтах твердих кристалічних порід, а також зсуви – на горизонтах пухких покривних порід. Водно-ерозійні процеси представлені лінійною та площинною ерозією. Вони поширені у верхніх частинах стінок кар'єрів, де розкрито уступи пухких покривних порід, та на схилах відвалів розкривних порід і переробних заводів. Площинна ерозія має вигляд тотального і дрібноструменевого змиву та акумуляції біля підніжжя уступів і схилів насипів. Лінійна ерозія полягає в утворенні вимоїн і невеликих ярів, достатньо коротких, зі значним ухилом поздовжнього профілю. Вперше виокремлено й охарактеризовано головні та другорядні антропогенні геоморфологічні процеси для гірничопромислових територій. На основі власних польових досліджень вивчено антропогенно зумовлені процеси у кар'єрах кристалічних порід. У регіональному плані вперше досліджено сучасні геоморфологічні процеси у кар'єрах Середнього Побужжя. Практична значущість виконаних досліджень полягає у тому, що їх результати можуть слугувати основою для прогнозування антропогенних та антропогенно зумовлених процесів у межах кар'єрів.

Ключові слова: сучасна морфодинаміка, антропогенні процеси, антропогенно зумовлені процеси, антропогенний рельєф, кар'єри кристалічних порід, Середнє Побужжя.