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SEDIMENTARY MARKERS OF MODERN MORPHODYNAMIC PROCESSES ON THE SANDSTONE TOR "KAMIN`" (VILLAGE URYCH, EASTERN BESKYDY, UKRAINIAN CARPATHIANS)

The paper studies the types of modern morphodynamic processes on the sandstone tor "Kamin`" ("Stone") in the village Urych (Eastern Beskydy, Ukrainian Carpathians) as a nature monument and historical and cultural reserve. It reveals interrelationships between the modern manifestations of the processes and the sedimentological facies of the Paleogene rocks of the Yamna Formation. During the formation of the Carpathian trust fault structure, they were created in the geodynamic conditions of the Outer Carpathian deep-water oceanic paleobasin and deformed during the stages of accretion and orogeny. The main research methods were morphological, morphodynamic, sedimentological, and lithological. Modern morphodynamic processes on the tor walls are classified by their origin, localization within the studied object, and the amount of tor wall coverage. Morphodynamic processes can be classified into different types such as soaking and very small pits; destruction; flaking; spalling; dimples weathering; alveolar weathering; corrasion and washing away the grains; linear underground erosion; biogenic superficial weathering; biogenic linear weathering; block collapses; joint-guided weathering: along tectonic, tensile, weathering, lithological cracks; gravity cascade folds. According to the amount of coverage of the tor walls, the following are distinguished: microprocesses (local manifestations), medium-scale and large-scale processes, with a destruction depth of 1-10 cm. Medium-scale processes that occur on tor superficials are related to primary sedimentary structural-textural features of rocks and their lithological composition. Fractured paragenesis of the Sub-Carpathian and Anti-Carpathian directions dominate large-scale processes. Studies of the tor destruction processes are important to determine the preservation methods of the sandstone tor "Kamin`" as a valuable object of historical, cultural, and geotourism heritage. The obtained results indicate that individual tor blocks are strongly affected by superficial processes, on which deep polygenetic cracks are superimposed. This provides a basis to implement measures for strengthening the stability of the tor.

Key words: modern morphodynamic processes; geodynamic paleoconditions; sedimentary features; sandstone tor "Kamin`" ("Stone"); Eastern Beskydy; Ukrainian Carpathians.

Introduction

Sandstone tors are common in the Eastern Beskydy of the Ukrainian Carpathians. In the Paleogene flysh, there are approximately ten tor groups linked with outcrops of massive sandstones from the Yamna and Vygoda suits. The Urytskyi Complex of Tors is the most famous among scientists, local historians, and tourists. This confirms its attracttiveness and attendance [Bayrak & Teodorovych, 2023]. There are four large tors in the Urytskyi complex, including the "Kamin`" tor, on which the medieval fortress "Tustan" was built. In 1994, it was assigned the status of a State historical and cultural reserve.

The tor as an object of geotourism was presented as a part of the project to create the Tors Beskydy geopark ("Skelyasti Beskydy") [Zinko, 2022]. It was also included in the Geo-Carpathian geotouristic path developed as part of the International Program for Cross-Border Cooperation Poland – Belarus – Ukraine (Geo-Carpathians) [Geotouristic…, 2013]. The Skole Beskydy geo-tourism routes highlight the captivating morphology and historical significance of the tor. [Bayrak & Teodorovuch, 2020]. During detailed engineering and geological studies of the "Kamin`" tor, various authors clarified the mineral-petrographical composition of the rocks, physical and mechanical properties, structural and textural features, lithogenetic types, and the nature of the tor fracturing [Voloshyn, 2012; Havryshkiv, 2008; Havryshkiv & Radkovets, 2020; Kulish and Koretskaya, 2018]. In particular, the rocks were characterized by variable granulometric composition, specific cementation-type compression, high closed porosity, low water absorption, and different degrees of polygenetic fracturing. This was established by engineering research [Voloshyn, 2012].

In general, tor formations are a result of tectonic uplifts, and their uneven forms are caused by weathering and denudation [Jahn, 1962]. After being exposed, tors gradually formed due to the effects of selective weathering, both above and below the ground. This weathering process was guided by the presence of joints and was also influenced by larger-scale processes of erosion and denudation [Migon, 2021; Migon & Duszynski, 2021].

High-energy turbidite flows influenced the formation of the tor macrostructure. The micromorphology of the tor superficial was formed due to rock lithology and external factors such as solar radiation, rainwater infiltration, and wind [Urban & Gornik, 2017]. It is believed that the resistance of rocks to weathering and erosion is due to the compressed rock strength. It depends primarily on porosity, as well as on the amount of cement, the packing density of grains, and their skeleton [Urban, 2020]. Over time, a layer of weathering crust develops on the surface of sandstone rock walls. This crust protects the shape and texture of the rock from natural erosion and degradation, which happens gradually. This allows for a new protective layer to develop sequentially, ensuring the longevity of the rock walls [Alexandrovicz, 2012]. We examine the external processes that shaped the tor's surface and caused gradual modifications to its modern form.

The goal of the article is to investigate the different types of morphodynamic processes that have modified the tor "Kamin`". Additionally, it aims to identify the relationship between surface landforms and rock structures that have formed in the geodynamic conditions of the Outer Carpathians deep-water sedimentary basin.

Research methods

The main research methods were morphological, morphodynamic, sedimentological, and lithological. Monitoring of the tor "Kamin`" started in 2011 and was conducted by one of the article's authors. Periodically, every two years, we performed detailed photo-recording of tor sections. As part of the research project, detailed mapping of the tor was carried out using aerial surveys conducted from the YH-19G Explorers model UAVs in 2019.

The Yamna Formation was studied using sedimentological analysis. This involved examining natural outcrops to identify the structural and textural features of the rocks, as well as the processes involved in their transportation and accumulation. Through this analysis, certain sedimentary dynamic types were identified. These types belong to specific deep-water facies of the Middle Paleocene Carpathian flysch basin, as determined by biostratigraphic studies conducted by O. Hnylko [Hnylko et al., 2022].

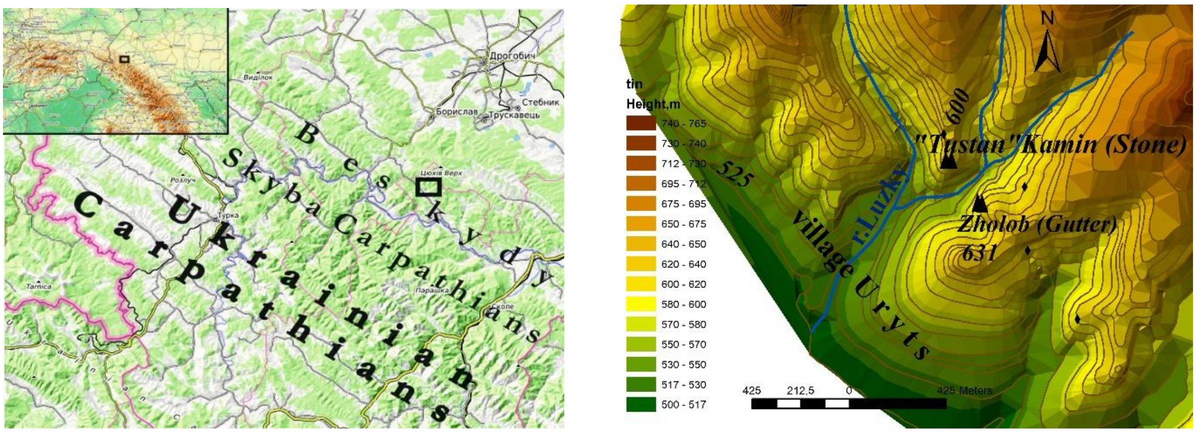
Typical deposits in deep-water oceanic environments include pelagites and hemipelagites from vertical sedimentation flows, as well as gravitites, such as turbidites and gravitites of debris, from gravitational flows of liquefied sediments [Leszczynski, 1981; Sedimentary…, 1986; Stadnik & Waśkowska, 2015]. In the deposits of the Yamna Formation, the predominant part of the thickness of the sections belongs to gravitites. The structural features of gravitites, a type of clastic rock, were studied in laboratory conditions. We analyzed their grain size distribution, shape, and degree of sorting of terrigenous components. The composition of the framework and cement in psammite petrotypes was studied for petrographic analysis. Results are presented on classification diagrams.

General characteristics

Tors, precipices, and waterfall steps represent Natural rock outcrops in the Eastern Beskydy. Outcroped rocks, which come to the surface, stretch from the northwest to the southeast in discontinuous narrow strips along the Skyba Carpathians. The total thickness of the sandstone rocks is 200–350 m [Derzhavna, 2007; Hnylko et al., 2020]. According to our observations, the outcrops of layers at the Earth's surface are 50–100 m wide and 7–45m high in the Eastern Beskydy.

The studied area belongs to the Skyba Nappe, one of the largest tectonic units of the Carpathian cover-fold structure [Krupskyi, 2001]. Skyba Nappe is the structural unit of the Outer Carpathians, which form a flysch-molasse orogenic prism thrusted over to the northeast on the Precarpathian depression. A characteristic feature of the internal structure of this cover is the presence of structural forms of the sliding type [Kravchuk, 2021]. Cretaceous-Paleocene rocks superimposed on younger sediments lie in the frontal parts of the ridges that form the cover. In the vast majority, the Cretaceous-Paleocene rocks form compressed tectonic slices. The younger Eocene-Neogene complexes are exposed in synclines.

The studied territory is located within a low mountain landscape with the prevailing absolute heights of 820–850 m heer-ridges. The absolute foot height of the tor "Kamin`" is 580 m (Fig. 1). The relative height of the tor at the bottom of the nearest valley of the Urychanka River is 60 m. The height of the rock exposure reaches 37 m. The tor belongs to the morphological class of remnants, which combines the type of rock wall with spire-like peaks [Bayrak, 2019]. The tor consists of two rock walls and resembles the letter "H", turned and elongated in the direction of 330°, between which there is a small platform 18 m high from the foot. It was the basis for the medieval fortress "Tustan". The tor's highest peak, Velykyy Kamin (Great Stone), is located north west of Okremyi Kamin (Separate Stone). Additionally, the longest wall of the tor is called Velyke Krylo (Great Wing) and measures 60 m in length. (Fig. 2 *a*)



a *b*

Fig. 1. The location of the tor "Kamin`" in the Eastern Beskydy of the Ukrainian Carpathians (*a*) and within the neighboring ridges (*b*)

The direction of the sandstone dip is 220°, azimuth of the strike is 310/130°. The dip angle of the strata is 60–70°. The sandstones belong to the Paleocene Yamna Formation (P_1jm). They were formed 56–66 million years ago at a depth of more than 3,000 m in the ancient Tethys Ocean, as evidenced by the remains of deep-water microfauna in sediments. The tor is composed of lithologically heterogeneous rocks. There are three main lithological variations identified which include gravelites, fine-medium-grained quartz sandstones with an admixture of gravel material up to 10%, and relatively homogeneous fine-grained and medium-grained quartz sandstones with almost no impurities [Voloshyn, 2012].

The Skyba Nappe is a geological formation that contains a continuous sequence of rock beds from the Lower Cretaceous to the Lower Miocene periods. The formation consists of three layers, namely the Yamna Formation, the Stryi Formation, and the Manyava Formation. The Stryi Formation lies beneath the Yamna Formation and is made up of a different type of rock called rhythmic flysch, with layers of variegated argillites around 1,000 meters thick. The Manyava Formation lies on top of the Yamna Formation and consists of fine to medium rhythmic green and/or variegated flysch up to 400 m thick. The Manyava Formation corresponds to the Thanet-Ypr period. Stable tectonic conditions result in equal contact between lithofacies, indicating gradual subsidence and sediment accumulation. The Yamna Formation (Zelandian-Tanet) are sandstones, roughly rhythmic flysch (350 m) with the Yaremcha horizon (up to 40 m) of variegated (cherry-red and greenish-gray) argillites at the base [Generalova et al., 2022]. According to biostratigraphic studies, the Yamna, Stryi and Manyava Formations were formed in the Outer Carpathian deep-water conditions [Hnylko et al., 2021].

Sedimentological studies have identified several sedimentary dynamic types within the Yamna Formation. Among these types are hemipelagites and pelagites, which are red and green homogeneous, thinly laminated argillites. Additionally, there are coarse-grained flysch-turbidites with Bouma textures, gravitites, and, sometimes, debrites (Yamna massive psammites). Sedimentary dynamic types reproduce the character of hydrodynamic flows in off-shelf oceanic areas. These types include (hemi) pelagites, which are sediments of vertical flows of the particle-by-particle type, as well as turbidites, granites, debrites (gravitites), sediments resulting from gravitational redeposition [Hnylko et al., 2021; Sedimentary…, 1986].

The study of rock formations in the Outer Carpathian sedimentation basin, including the Skyba sub-basin, showed that during the Cretaceous-Eocene period, deep-water sedimentation occurred in the lower part of the continental slope-foot and part of the abyssal plain. These areas have a bathyal-abyssal depth and were dominated by sedimentation that occurred below the Calcite Compensation Depth (CCD) [Hnylko et al., 2022]. At the end of the Eocene, the sediment basin became shallower, and the region began experiencing tectonic thrusting towards the northeast. Over 10 million years, sedimentary layers composed of sand and clay have accumulated at the bottom of the sea basin. These materials were sourced from both the denudation of rocky archipelagos in the Cordillera Islands and the sedimentation from turbid river flows. Thick strata of sand accumulated due to the activities of episodic turbidite flows, mostly in the deep-water part of the sea basin, and gradually cemented into the stage of diagenesis and catagenesis, turning into strong rocks. During the orogenic stage of mountain formation in the Miocene-Pliocene time, sandstones were uplifted and exposed on the surface [Bayrak & Gavryliv, 2011; Krupsky, 2001; Stupka, 2010].

Thick-layer massive sandstones, with individual layers 1.2-1.7m thick, represent the Yamna Formation of the "Kamin`" tor outcrops. Sandstones on a weathered surface are gray, while on a fresh chip, they are light gray, and yellowish gray. The structure of rocks varies from aleuritic to psammitic and can include fine-sulphitic sandstone with pudding inclusions of larger clastolites. The sandstone can have various textures, such as massive, cross-bedded, normally graded, reverse graded, symmetrically layered (siltstone-coarse-grained sandstone or gravel drill-siltstone), and symmetrically pendulum layered (coarse-grained sandstone or gravel drill-siltstone-coarse-grained sandstone). The study of structural and textural features of the Yamna Formation contributed to the identification of various lithological and genetic types of deposits: claystone, layered sandstones and siltstones, massive sandstones, sandstones with olistholithes, sandstones with nodules (?).

Claystones are cherry-red and greenish-gray thin-laminated. They correspond to dynamic types of hemipelagites and pelagites by sedimentological analysis. Claystones form variegated horizons. The Yaremcha horizon is found in the lower part of the Yamna Formation, while the Overyamna horizon is located in the upper part. Claystones are formed as sediments of vertical slow flows of the "particle by particle" type or suspension between episodes of turbidite flow. They are characterized by thin horizontal bedding, probably due to the composition of sedimentary components.

They demonstrate the formation of background sedimentation, which, according to oceanographers, occurs in ultra-slow mode (speed < 2-0.5 mm/1,000 years). Under conditions of endogenous activity, sedimentation is accompanied by manifestations of hydrothermal fluids. This is expressed in the layers of manganese-ferruginous mineralization (found in the "Tustan" Stone vicinity).

Layered sandstones are middle-thick turbidites with elements of A. Bouma T_{ab} sequence textures. In some cases, elements S_3 or S_2 of D. Lowe sequences with thicknesses up to 1.5-1.7 m are observed (Fig. 2 *b*). High-density turbidite/grain or debris flows, generated by underwater gravitational landslides, result in structural textural elements at the foot of the continental slope due to the gravitational redeposition of terrigenous sediments. The clastic material of sandstones can be represented by quartz (75-95%), feldspar, and mica [Havryshkiv & Radkovets, 2020, p. 118–119].

Various-grained patumaceous (chlidolitic) medium-grained or siltstone with gravel polymict varieties are often found among greenish-gray sandstones. They are poorly sorted and contain non-rounded material. In the classification diagram of sand rocks by the fragment composition, the studied rocks fall into the fields of graywacke and arkose-graywacke (quartz greywackes, feldspar greywackes) (Fig. 3).

Massive sandstones have clear lamination surfaces, several meters thick. There are no gradational or cross-bedding layers and the structure is characterized by poorly sorted cluster material. There is a pudding structure with large fragments among psammite grains, but no clay matrix is present. According to hydrodynamic formation conditions, these formations should be attributed to grain flows (gravitites). In addition, there are deposits of debris (mud-stone) flows (Fig. 4). Debris flows accompany large shifts, the combination of which forms olisthostroms. A detailed survey of the rock outcrops reveals large Yamna-like sandstone olistholithes with "snowball" textures embedded in the matrix.

These data allow us to demonstrate the rich tectonic history of the development of the Outer Carpathian sedimentary basin, which was individualized in the loop-shaped bay. Dark mud piled up in the basin in anaerobic conditions in the early Cretaceous. Since the Late Cretaceous, water circulation has improved significantly.

Fig. 2. *a.* General view of the “Kamin`” tor from the south: on the left is the Great Stone, and on the right is the Great Wing. *b.* A fragment of A. Bouma's sequence of Yamna sandstones with T_{ab} elements. The initial stage of the development of “flaking” and “honeycomb weathering” types of reporting is traced

Fig. 3. The Yamna Formation. Sandstone is multi-grained, poorly sorted, siltstone with gravel, coarsely polymict, and gray. Quartz (up to 50% of the mass of the fragments), glauconite (10–15%), and lithoids (15–20%) prevail in the composition of the detrital material. Clay-silica cement with chlorite, type of cementation is porous. Photo of the cut. Nick. × Incr. 136^x. Photo by O. Kostyuk

Fig. 4. Debrit. Yamna Formation. River Kamianka. Green metamorphic shale of the Lezhai massif (in the center of the foreground).

Since then, episodic gravitational (turbidite) sedimentation has reigned in the basin, alternating with background hemipelagic sedimentation. Biostratigraphic studies suggest that deep-water conditions at the foot of the continental margin led to turbidite, background, and accompanying sedimentation processes [Hnylko et al., 2021]. During the end of the Eocene epoch, the Carpathian Basin began to shallow and the Carpathian Mountains started to form. The processes of active orogenesis continued from the end of the Oligocene and during the Miocene. This caused a gradual rise and change in the gypsometric position of the Yamna sandstone layers. As a result of the tectonic folding and thrusting in the Carpathian region, we assume that the Skyba Nappe as part of the orogenic prism formed a structure. It was prepared for the influence of external exogenous processes on it. According to various authors, sandstones were exposed to the daytime surface and underwent weathering and denudation from the beginning of the Pleistocene. During the last stage of maximum glaciation, known as the Würm glaciation, the tor superficial was highly exposed, resulting in intense conditions [Alexandrovicz, 2008; Urban et al., 2015].

Research results

We investigated the "Tustan" Stone tor and its morphodynamic micro- and mesoscale processes, leading to the modeling of its surface and walls. The walls of the tor are characterized by different degrees of weathering and dissection depending on the types of lithodynamic facies of the rocks and the nature of their exposure at the Earth's surface.

We have identified various geomorphological processes that shape the tor "Kamin`". These processes can be categorized as follows:

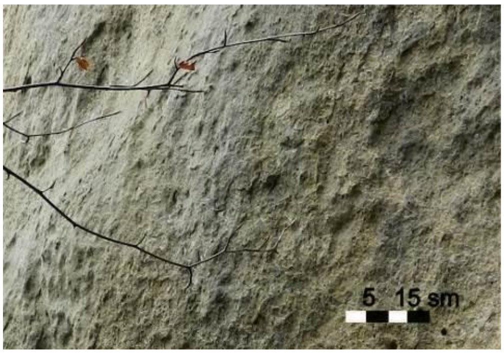
A. *By origin*: soaking and very small pits – separation of individual grains; destruction – finding a part of the material in a semi-separated state of the material; flaking; spalling (fine lamination along lithofacies); dimples weathering; alveolar weathering; corrasion and washing away the grains; linear underground erosion; biogenic surface weathering (corroding with mosses and lichens); biogenic linear weathering (along the roots of plants growing in cracks); block collapses; joint-guided weathering: along tectonic, tensile, weathering and lithological (bedding) cracks; gravity cascade folds (Table 1).

B. *By surface localization*: superficial, linear, point processes.

C. *In terms of coverage of tor walls*: microprocesses (local manifestations), medium-scale processes (cover a smaller part of the tor wall), and large-scale processes (occur on half or more half of the tor wall) (Table 2). In many cases, the destruction depth of the tor superficial is small – 1-10 cm. Various types of cracks have a large penetration depth.

Table 1

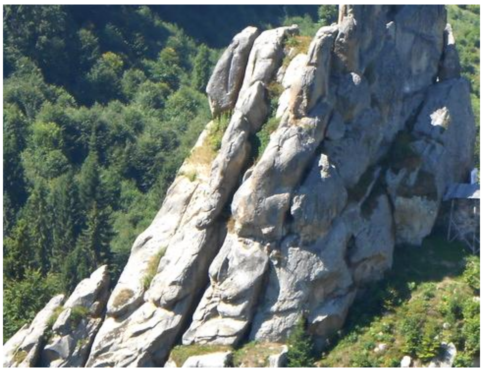
Types of small-scale, medium, and large-scale processes within the tor "Kamin"

	The name of the processes	Image
1	2	3
1.	Soaking and very small pits	
2.	Surface destruction	
3.	Exfoliation (flaking)	

Continuation of Table 1

1	2	3
4.	Spalling	
5.	Dimples weathering	
6.	Alveolar weathering	
7.	Corrasion and washing away the grains	
8.	Linear underground erosion	

Continuation of Table 1

1	2	3
9.	Biogenic superficial weathering	
10.	Biogenic linear weathering	
11.	Block collapses	
12.	Joint-guided weathering along tectonic cracks	
13.	Joint-guided weathering along vertical bedding surfaces	

Continuation of Table 1

1	2	3
14.	Joint-guided weathering along tensile cracks (gravitational displacement of blocks)	
15.	Joint-guided weathering along of weathering cracks	
16.	Joint-guided weathering along of horizontal bedding surfaces	
17.	Gravity cascade folds	

As a result of soaking, sandstone develops deep pits due to the different properties of its framework and cement. We attribute them to a special type of weathering on the tor walls. The tor “Kamin`” is characterized by silicic cement such as compression [Voloshyn, 2012] or touch, or contact, which predetermines the high porosity of rocks. Porosity is favorable for moisture ingress and accumulation as an additional weathering factor. Moisture destroys the rock, contributing to the disintegration of the cementitious substance. The solid minerals of the framework are distinguished on the surface of the tor, forming a granular structure. The sandstone surface is uneven, and resembles "smallpox". Rock grains due to the low degree of cementation, are easily removed. This type of weathering is developed on parts of the tor walls, the surface disintegration is up to 1 cm. Therefore, we attribute it to micro- and mesoscale processes of a medium-scale superficial nature (see Table 2).

Surface destruction processes are characteristic of gravitite lithotypes, formed during the lithification of granular flows. They do not have pronounced Bouma textures. On surfaces of this type, internal hidden texture elements of gravitites become embossed. During weathering, they show an uneven internal structure as a hilly-pitted surface. The disintegration of the rock is stronger than in the previous type of weathering: here a large collection of particles is prepared for removal from the surface. This type of process is characteristic of sun-shaded tor walls. Superficial destruction reaches several centimeters and occurs locally on large sections of the tor. Therefore, we classify them as large, medium-scale, and micro-processes.

Exfoliation process, particularly, *flaking* is characteristic of illuminated areas of the tor. In the daytime, heating of the outer sandstone layers occurs more strongly than the inner sandstone layers. Heat is gradually transferred to the inner layers at night. The outer layers cool quickly when the inner layers are still heated. At various temperature fronts, parts of the layers are peeled off. This is controlled by the texture of sandstone interlayers. Such a weathering process occurs locally as separate spots on the walls on the southern exposure of the tor. Therefore, we classify them as micro- and medium-scale processes.

Table 2

Interdependencies between different types of morphodynamic processes on the tor “Kamin”

	Points	Linear	Superficial
Large-scale processes	Block collapses	Linear underground erosion; joint-guided weathering: tectonic, lithological, tensile, weathering cracks; gravity cascade folds	Destruction; dimples weathering; alveolar weathering; corrasion and washing away the grains; biogenic superficial weathering
Medium-scale processes	Flaking; alveolar weathering; block collapses	Spalling; linear underground erosion; biogenic linear weathering; joint-guided weathering: lithological, tensile, weathering cracks; gravity cascade folds	Soaking and very small pits; destruction; flaking; dimples weathering; alveolar weathering; corrasion and washing away the grains; biogenic superficial weathering
Microprocesses	Flaking; alveolar weathering	Linear underground erosion; spalling; joint-guided weathering: lithological, weathering cracks; biogenic linear weathering	Soaking and very small pits; destruction; flaking; biogenic superficial weathering

Spalling processes develop according to the elements of sedimentation textures of the Bouma sequences. They correspond to either element B – the lower horizontal interval, which consists mostly of medium-grained sandstone interbedded particles (see Fig. 2), or element D – the upper horizontal interval, composed of fine-grained sandstones or siltstones. Being on the daytime surface, contacts between intervals of sequences, which differ in structure and texture, are weathered faster. This type of weathering refers to meso-scale and microprocesses developed locally, and are mainly linear, sometimes point-like.

Dimple weathering develops where gravitational redeposited material is common. Gravitational strike-slip fault of accumulated sediments occurred during the formation of sediments on the seabed. Strike-slip faults were formed with characteristic structural-texture elements as asymmetric folds. During exposure to the daytime surface, this section of sandstone weathers along the contacts of micro-compressions, forming notches - furrows. The depth of the furrows reaches 5-10 cm. Clear chipped ribs are visible at the boundaries of the grooves. This suggests that strong minerals particularly siliceous cement, are involved in the sandstone structure. Such a process occurs on large fragments of tor walls, so we classify them as large and medium-scale processes.

Alveolar weathering is represented by honeycombs and small alveoli. The form size ranges from 2 to 10 cm in diameter with 1-5 cm depth. There are single deep forms (see paragraph 6 of Table 1) and groups of forms whose density reaches 30 pcs/m^2 [Bayrak & Zinko, 2023]. They are located mainly on areas of tor shaded from the sun but are most developed on the wall of the eastern exposition of the Great Wing. The main factors contributing to the formation of alveoli are temperature weathering (i.e., dissolution of siliceous cement), capillary moisture, and raindrops [Adamovic et al., 2015; Mol & Viles, 2012; Paradise, 2015]. In deserts and coasts, growing salt crystals rupture rock grains to form arcades of alveoli or large-sized tafoni [Filippi & Bruthans, 2018; Turkington & Philips, 2004]. Such a formation involves factors of both organization and disintegration of elements that reflect the distribution of stress in the rock mass and hydraulic field [Migon, 2022]. We believe that in our conditions, the main factor in the formation of alveoli is moisture. With the high relative humidity characteristic of the mountains, it falls into the pores of the rock and holds for a long time on the shaded sections of the tor walls. In cold periods, frost weathering is active: moisture freezes/thaws in the pores, expands them and contributes to the formation of caverns. If the primary superficial is uneven due to lithological structural and texture features, then the process of alveolar formation is more intensive. Alveolar weathering is attributed to mesoscale and microprocesses of point location, and local processes of plane propagation. We classify them as a more severe form of weathering compared to “superficial destruction”.

The "*corrasion and washing away the grains*" process occurs on the surface of sandstone, which is not covered with weathering crust. The color of such areas is yellowish-gray and yellowish, which stands out from the gray weathered surface of other sandstone areas. Weathering develops on fresh chippings after the removal of some surface material. The thickness of the weathered layer reaches several millimeters, and dust particles, as well as sandstone grains, are in a semi-separated state so that gusty winds or heavy showers constantly remove them from the superficial. A characteristic feature of such areas is the presence of a plume of weathered material at the foot of tor blocks.

Linear underground erosion processes develop along vertical fractures, the upper part of which is often funnel-shaped. During precipitation, water flows down concentrated runoff, following cracks and avoiding the entire plane of the tor. The water traps the weathered sandstone particles inside the fractures and carries them out. Fresh tearing cones at the base of the cracks confirm the process. In cracks that cover the entire superficial of the tor, the outflow cone is several meters long, and in small areas of cracks such cones reach several tens of centimeters. This suggests that the process of linear erosion began to develop relatively recently. In the Tustan Tor, which covers an area of 6,000 m^2, there are only four locations with intense linear erosion. This differs from the Mesozoic massif of the Table Mountains in Poland, where the cones of debris and sand that form at the foot of the tors due to erosion are tens of times larger [Duszynski et al., 2016].

Biogenic superficial weathering. These are micro- and processes of a large and medium scale. On the tor surfaces, mosses and lichens grow, dominated by *Hypnum cupressiforme* and *Homalothecium sericeum*, with *Lecanora rupicola* and *Phlyctis argena* standing out among the lichens. On the upper parts of the tor, lichens do not yet have a destructive effect, compared to the lower, more humid, and shaded areas, where peeling processes have begun to occur. The growth of the influence of lichens occurs in the areas near the base of the tor (see point 9 of Table 1). The superficial of the tor acquires an uneven character with rounded pits up to 5–6 cm in diameter. The superficial under the mosses has not yet undergone noticeable weathering: the mosses create a shield under which temperature contrasts are weakly felt. The thickness of the weathered layer under the mosses reaches several millimeters. When external conditions change, such a layer will be quickly removed, and disintegration will cover deeper layers.

Biogenic linear weathering occurs along cracks of different genetic types, the root system of plants growing on the cracks deepens and widens them (Fig. 5). As a rule, physical and chemical weathering processes can occur simultaneously, preparing biological weathering. Three years ago, the workers of the historical and cultural reserve removed all woody plants from the walls of the tor. However, a significant amount of bushy and grassy vegetation remains. It has penetrated the cracks and is causing them to widen.

Block collapses. Horizontal and vertical cracks break the tor into irregular boulders. The tor morphology is such that the higher its section is, the narrower and deeper it is dissected by cracks. The tops of the Great Stone, the Great Wing, and the Separate Stone consist of blocks, the individual forms of which have already been separated from the base due to weathering. Small seismic shocks (for the Skole area an earthquake intensity is 6.0 Richter scale) can collapse these blocks. At the top of the tor, we observed 8 blocks that appeared to have been arranged for imminent collapse. Another example is the collapse of the block near the top of the Great Wing, which destroyed part of the medieval stonework. About a dozen large and small fragments are located at the foot of the tor on the eastern and southern sides, and on the tor walls, even areas of detachment superficial remain. Sometimes they have not yet had time to be covered with a crust of weathering and processes of shedding develop over them. Debris of more than 1 m^3 around the tor prove that the collapse process is still active. They are dangerous for visitors to this historical and cultural reserve.

a

b

Fig. 5. Growth of plant cover in the cracks on the wall of the south-eastern exposure of the tor “Kamin`”: *a* – 2011, *b* – 2023

Cracks on the tor were the object of earlier engineering and geological studies to determine the degree of preservation of the "Kamin`" as the basis of a historical and cultural reserve [Voloshyn, 2012; Kulish & Koretska, 2018]. The processes that develop along different genetic types of cracks – tectonic, gravity (side resistance), weathering, and lithological, have similar factors and a similar nature. These processes develop differently and depend on the location of the cracks, their closure, smoothness or roughness of the walls, and the composition and amount of aggregate in the open cracks [Bubniak et al., 2007].

Physical weathering is sensitive to fluctuations in daily and seasonal temperatures. When heated, the minerals that make up the tor change. Different minerals are characterized by excellent coefficients of volumetric and linear expansion, which contributes to the occurrence of local pressure that destroys rocks. The most destructive pressure is fixed at the contact of different minerals and rocks. When rocks experience changes in heating and cooling cycles, cracks form due to differences in minerals and lithology. These cracks allow water to enter and create capillary pressure, destroying the rock. Ruined rock can both pass and retain water, which increases the superficial area in contact with water, gases, and organic substances. The heterogeneity of the structures and textures of the sandstones of the Yamna Formation, characterized by the indicated dynamic types of sedimentation, are favorable complexes for weathering processes of various scales, which are manifested precisely along the cracks.

Characteristic features of *tectonic cracks* are their extension's endurance along the Carpathians' thrust (310–330°), and the formation of mutually perpendicular systems that cut the strata from top to bottom. They mostly have a vertical laying. Open tectonic cracks have dismembered the Great Wing into transverse blocks, along with closed ones. The man-made widening of open tectonic fissures between the strata of the Great and Separate Stone tors has formed grottoes. Fine soil accumulates in open cracks. Tor fragments are in a state of unstable equilibrium. Cracks are also occupied by vegetation, which contributes to the active weathering of their walls.

Tensile cracks along block flexure predetermine the gravitational displacement of blocks and are mainly vertical, as tectonic ones. Despite the morphological similarity to tectonic cracks, wedge-shaped cracks have a different formation process. They occur due to the unloading of rocks when the lower stop is removed, and when the tangential force exceeds the normal force. These cracks narrow down from the upper to the lower section of the tor and vary in width depending on the hypsometric position. They are wider at the foot of the slope than at the lower part. These cracks facilitate the movement of the tor down the slope.

Weathering cracks arise as a result of mechanical and biological destruction of the tor. The Carpathians experience high humidity for most of the year, which along with the effects of moisture, atmospheric precipitation seepage, and plant roots, causes sandstones to crack due to frost weathering. These weathering cracks are relatively short and do not have a continuous trace. They can change from being open to closed and eventually disappear altogether. The cracks are multidirectional: they have vertical, diagonal, and horizontal directions. Horizontal and diagonal cracks are often closed, their development is more affected by increased humidity and frosty weathering. Multidirectional cracks cause the separation and preparation for the collapse of blocks of unstable tors. In general, weathering cracks develop between lithofacies in tors. Water circulates along vertical tectonic, tensile, and weathering cracks during precipitation. Snow accumulates in winter, which is the biggest factor in their expansion and wall destruction.

Joint-guided weathering along horizontal and vertical bedding surfaces. They were formed as a result of the uneven transformation of sand strata in the stage of diagenesis, the separation of the overlying and underlying layers along the cracks. Horizontal cracks between strata are mostly closed. The Great and Separate Stone formations have vertical lithological cracks that were caused by tectonic thrusts during the orogeny. The sandstone layers, which originally lay horizontally, were overturned and now have a dip angle of approximately 70°. Tectonic cracks have been superimposed on these layers, resulting in large areas between rock packs containing different types of aggregate (Fig. 6). The opening width is 0.5–1.3 m. The regolith consists of rock fragments and fine soil. One such crack runs along the Great Wing tor, under the superficial of the tor block, along which processes of disintegration and leaching of material take place. It is evidenced by fresh cones of whitish sand drifting in the southern part of the Wing (under the attraction of the reserve – the mirror). Depressions on the walls of cracks are the places where the processes of weathering and denudation of tors are the most active (Fig. 7). The more densely the tor is dissected by cracks, the less resistant it is to weathering

Gravity cascade folds are caused by sedimentogenic landslide processes. A detailed field study of sandstone occurrence and their structural and textural features allows us to classify them as underwater landslide formations. They form a wedge-shaped body with a chaotic accumulation of fragments of different sizes, which helps to identify them as chaotic landslide masses (and deposits of clastic flows = debris flows). Paleogeographically, this is the facies of the channel of the underwater canyon, probably an element of the normal (clastic) plume of the slope. In the structure of the studied exposure, the shift expressed in the lower part is complicated by blade-like fragments of protrusions emphasized by the accumulation of clastic material and landslide blocks. Based on the researchers' observations, the primary occurrence of sandstone underwent weathering processes in the form of wave-congestive shapes. In some areas, distinct boundaries indicate that the primary sedimentation involved viscous-plastic granular flows (resulting from the primary landslide). They were pushed against each other and eventually cemented to form the sandstone. In the outcrop, it is evident that fracturing is developing behind the gravitational folds, following the textural elements that emphasize various properties of underwater landslide phenomena.

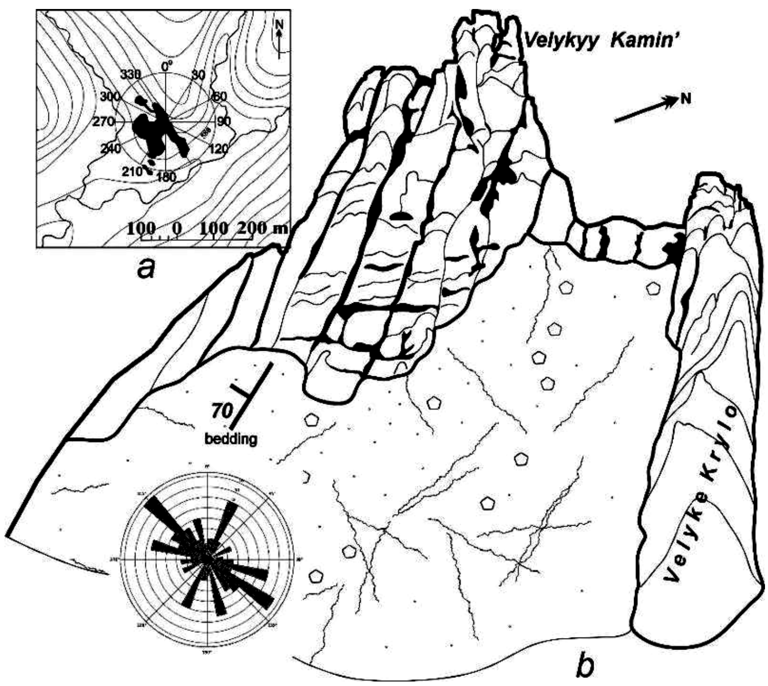


Fig. 6. Tor "Kamin`": *a* – plan view. The darkened element corresponds to the shape of the tor and the direction of the strata; *b* – a morphological diagram showing the cracks of the Transcarpathian extension

Fig. 7. Fragments of argillites in the sole of the sandstone (granite) strata, which indicate the heterogeneity of the layering surface

Discussion

Mesoscale and microprocesses occurring on the tor superficial have a clear condition with primary sedimentation structural-texture features of rocks and their lithological composition.

Microprocesses are due to the structures and textures of the Yamna Formation petrotypes, which contribute to the development of chaotic planar, linear, and point types. Linear types refer to the textures of the elements of a Buma sequence of turbidites (gravitites).

They consider the lithological heterogeneity of bedding rocks, often accentuated by manifestations of biological weathering. Chaotic weathering forms, such as smallpox, destruction processes, and alveolar weathering, are dependent on the structural features of the original rock, the type of cement, its variety, the type of cementation, and differences in the physical characteristics (hardness) of the rocks of the framework, matrix, and cement. Pointed microprocesses of flaking and spalling are subject to primary structural and textural features of rocks.

Texture features of mesoscale processes of gravitational shifts form dimples weathering and gravity cascade folds. The penetration of moisture into the initially heterogeneous surface of the sandstone causes the type of alveolar weathering that develops more in pseudo-psamitic turbidities.

Microprocesses lay the original plan for weathering morphodynamics; mesoscale processes contribute to its development both on an average and a large scale.

The heterogeneity of sedimentation textures contributes to the development of diagenetic and catagenetic textures, and weathering textures, along which fracturing actively develops.

During the formation of the Carpathian orogen, tectonic movements contributed to the development of plicative and disjunctive deformations of the layers of Yamna sandstone. According to our observations of the study area, tectonic fractures of the Transcarpathian strike emphasized diagenetic fracturing, which caused its expansion, and further filling with weathered material and caused an additional factor of tor destruction.

During the orogenic stage, local cracks opposite the Carpathian extension appeared, probably laid earlier [Hnylko et al., 2021]. According to morphokinematic works, they carry a shear component and are accompanied by structural paragenesis of cleft and tear cracks and breaks of higher orders. In field studies, we have described mostly closed chipping cracks, which serve as the basis for the application of non-tectonic chipping processes; in particular, tensile and weathering cracks. In general, latent fracturing (of different genetic groups) contributes to an increased degree of tor destruction and often leads to the separation of blocks ready for collapse.

The observations helped typify morphodynamic processes and individualize their consequences in Table 2 "Interdependencies between different types of morphodynamic processes on the tor “Kamin`”.

The scientific novelty of the work consists in the analysis of the relationships between the morphodynamic types of processes on the tor walls and the lithological structural and textural features of the rocks that were formed in different geodynamic conditions of the oceanic paleobasin and some deformation structures. It was found that it is the lithologic-geodynamic differences that have the greatest influence on the course and direction of external micro- and mesoscale processes on the tor walls. Research complements knowledge in the field of sandstone geomorphology.

Practical meaning. Studies of the processes of the destruction of the tor are important for determining the preservation method of the “Kamin`” as a valuable object of historical, cultural, and geotourism heritage. The obtained results indicate that individual tor blocks are strongly affected by superficial processes, on which deep polygenetic cracks are superimposed. This provides a basis for the implementation of measures on the part of the historical and cultural reserve to strengthen the stability of the sandstone tor.

Conclusions

Sedimentation occurs in various dynamic environments, associated with fast and slow flows, landslides, and calm accumulation conditions. They influenced the formation of specific structures and textures in strata. The rocks were deformed during tectonic thrusts and the formation of the Outer Carpathian orogenic prism. Differences in the rock structures and textures become primary factors in which various morphodynamic processes develop. Peculiarities of the rocks laid down at the early sedimentation stage determine the types of modern processes developing on the tor walls we have established. Other factors are secondary. They include moisture, temperature differences, vegetation, erosion, and gravity. There are broken zones in the rocks formed during sedimentation where geomorphological processes occur. All factors together determine the development of these processes that model the tor walls. We distinguish superficial, linear, and point types of these processes.

Morphodynamic processes of medium scale are formed partially by structural-textural heterogeneity of dynamic types of sedimentary. They frequently develop by sedimentation contacts of dynamic types and their constituent elements. An important role belongs to non-tectonic and latent tectonic fracturing.

Dynamic types of sedimentary or strata exhibit specific cross-sectional textures influenced by tectonic fracturing. They result in structural paragenesis with discontinuous disturbances in the subcarpathian and anticarpathian directions. Our research reveals the prospects of studying the structural and textural characteristics of rocks related to their influence on modern morphodynamic processes developing on the surfaces of sandstone tors.

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СЕДИМЕНТАЦІЙНІ ІНДИКАТОРИ СУЧАСНИХ МОРФОДИНАМІЧНИХ ПРОЦЕСІВ НА СКЕЛЯХ МАСИВУ “КАМІНЬ” (с. УРИЧ, СХІДНІ БЕСКИДИ, УКРАЇНСЬКІ КАРПАТИ)

Досліджено типи сучасних морфодинамічних процесів на скельному масиві “Камінь” у селі Урич (Східні Бескиди, Українські Карпати), який є пам’яткою природи та історико-культурним заповідником. Виявлено взаємозв’язки між сучасними проявами процесів та седиментологічними фаціями палеогенових порід ямненської світи. Вони формувалися у геодинамічних умовах Зовнішньокарпатського глибоководного океанічного палеобасейну і зазнали деформування на етапах акреції та орогенії в процесі становлення Карпатської складчасто-покривної споруди. Головними методами досліджень були морфологічні, морфодинамічні, седиментологічні та літологічні. Сучасні морфодинамічні процеси на стінках скелі класифіковані за походженням, локалізацією в межах досліджуваного об'єкту та величиною покриття стінок скелі. За походженням морфодинамічні процеси представлені видами: розмокання і "віспа"; дезінтеграція; десквамація; лускування; лункування (ямковість); сотове вивітрювання (ураженість формами honeycombs та alveoles); видування та вимивання; лінійна підповерхнева ерозія; біогенне площинне вивітрювання; біогенне лінійне вивітрювання; обвали блоків; руйнування вздовж різних типів тріщинуватості: тектонічної, бортового відпору, вивітрювання, напластувань; тріщинуватість за каскадною гравітаційною складчастістю. За величиною покриття стінок скелі виділено: мікропроцеси (локальні прояви), мезопроцеси середнього масштабу і мезопроцеси великого масштабу, при глибині дезінтеграції від одного до десяти сантиметрів. Мікропроцеси та мезопроцеси середнього масштабу, які відбуваються на поверхнях скель, мають чітку обумовленість із первинними седиментаційними структурно-текстурними рисами порід та їхнім літологічним складом. Для мезопроцесів великого масштабу домінуючу роль відіграють тріщинні парагенези субкарпатського та антикарпатського напрямів. Дослідження процесів руйнування скельного масиву "Камінь" є важливими для визначення його збереженості як цінного об'єкта історичної, культурної і геотуристичної спадщини. Отримані результати свідчать, що окремі блоки скелі сильно уражені поверхневими процесами, на які накладаються глибокі полігенетичні тріщини. Це дає підставу для впровадження заходів щодо посилення стійкості скельного масиву.

Ключові слова: сучасні морфодинамічні процеси; геодинамічні палеоумови; седиментаційні риси порід; скельний масив "Камінь"; Урицькі скелі; Східні Бескиди; Українські Карпати.

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