UDC 551.4; DOI 10.30970/gpc.2024.1.4430

MORPHOLOGY AND EVOLUTION OF ALVEOLAR WEATHERING CAVITIES ON SANDSTONE TORS OF THE UKRAINIAN BESKIDS

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Abstract. The paper systematizes morphological forms of alveolar weathering cavities and presents patterns of their evolution. We have studied the forms of tafoni (cavities 2–10 cm in size), which are found in the crags in the Ukrainian Beskydy. The factors that caused the formation of tafoni in our latitudes are humidity and the inherent specificity of selective weathering in sandstones due to structural and textural features formed during the formation of sediments. In winter periods, the role of frost weathering increases. The crags are composed of sandstones of the Yamna suite of the Palaeocene of the Lower Paleogene age. The lithological composition of the sandstones is represented by quartz and feldspar, which allows us to classify them as typical feldspar-quartz sandstones. The cement is clay-siliceous, sometimes with chlorite, of the basal or contact cementation type. In research region tafoni are distributed on rock surfaces in two ways: locally in small areas or covering large areas e.g. whole crag surface of particular aspect. In the first case, the forms are located in small groups of 10–30 pieces in separate parts of a tor wall. In the second case, they occupy the entire plane of the tor surface or half of the surface of particular exposure. Local groups of tafoni can be divided into three shape varieties: 1) vertical bands, 2) horizontal bands, and 3) lenticular bands. Tafoni concentrations that occupy the entire one plane of the tor can be located on it: a) chaotically, b) in a chain-like manner. The following shapes of particular cavities can be distinguished in the Ukrainian Beskydy: 1) rounded, 2) ellipsoid, 3) vertically elongated, and 4) subtriangular. In the Beskyds, the largest length of ellipsoidal cavities is 20–30 cm, the diameter of rounded cavities reaches 10 cm, and the greatest depth is 15 cm. Investigating the morphology of tafoni in the Beskydy, we distinguished the following stages of their evolution: emergence – deepening – expansion – merging – degradation – re-emergence. On the walls of the Beskydy tors, one can observe tafonic forms at various stages of evolution. We identified morpho-evolutionary varieties of tafoni: A) with all four clear edges, B) with three clear and one leveled wall, C) with all unclear walls. The confinement of cavities to slope exposures was also investigated. Cavities in the Carpathians develop more actively on walls of warm exposures than on cold ones. Tafoni forms on tors, their morphology, evolution and formation factors can be the subject of expert interpretations during geotourism excursions.

Key words: cavities, tafoni; morphology, evolution, alveolar weathering; tors; Beskydy, Ukrainian Carpathians.

МОРФОЛОГІЯ ТА ЕВОЛЮЦІЯ ПОРОЖНИН СОТОВОГО ВИВІТРЮВАННЯ НА ПІСКОВИКОВИХ СКЕЛЯХ УКРАЇНСЬКИХ БЕСКИДІВ

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Анотація. У статті систематизовано морфологічні форми порожнин альвеолового вивітрювання та подано схеми їхньої еволюції. Ми досліджували тафоні – порожнини величиною 2–10 см, які зустрічаються на скелях Українських Бескидів. Загальний процес, який зумовив утворення тафоні в наших широтах – це вологість і притаманна пісковикам специфіка вибіркового вивітрювання, зумовлена структурно-текстурними особливостями, сформованими під час формування осадів. У зимові періоди зростає роль морозного вивітрювання. Скелі складені пісковиками ямненської світи палеоцену нижнього палеогену. Літологічний склад пісковиків представлений кварцом і польовим шпатом, що дозволяє віднести їх до типових польовошпатово-кварцових пісковиків. Цемент глинисто-кременистий, іноді з хлоритом, базального або контактового типу цементації. Нами було з’ясовано, що у досліджуваному регіоні тафоні поширені на поверхні скель двома способами: локально на невеликих ділянках або охоплюючи великі площі, наприклад, всю поверхню скелі певної експозиції. У першому випадку форми розташовуються невеликими групами по 10–30 штук в окремих частинах стінок скель. У другому випадку вони займають всю площину або половину стінки скелі. Локальні групи порожнин можна розділити на три різновиди форм: 1) вертикальні, 2) горизонтальні смуги і 3) лінзоподібні угруповання. Скупчення тафоні, що займають одну стінку скелі, можуть розташовуватися на ній: а) хаотично, б) ланцюгоподібно. В Українських Бескидах можна виділити такі форми окремих порожнин: 1) округлу, 2) еліпсоїдну, 3) вертикально витягнуту, 4) трикутноподібну. У Бескидах найбільша довжина еліпсоїдних порожнин 20–30 см, діаметр округлих порожнин сягає 10 см, найбільша глибина 15 см. Досліджуючи морфологію тафоні у Бескидах, ми виділили такі стадії їхньої еволюції: поява – поглиблення – розширення – злиття – деградація – повторне виникнення. На стінках скель Бескидів можна спостерігати тафонні форми на різних стадіях еволюції. Нами виділені морфоеволюційні різновиди тафоні: А) з усіма чотирма чіткими ребрами, В) з трьома чіткими і однією нівельованою стінкою, С) з усіма невиразними стінками. Було досліджено також приуроченість порожнин до експозицій схилів. На стінках теплих експозицій порожнини у Карпатах розвиваються активніше, ніж на холодних. Тафонні форми на скелях, їхня морфологія, еволюція та чинники формування можуть виступати предметом фахових інтерпретацій під час геотуристичних екскурсій.

Ключові слова: порожнини, тафоні; морфологія, еволюція, сотове (коміркове) вивітрювання; скелі; Бескиди, Українські Карпати.

International experience shows that scientists studying crag landforms are interested in micro- and mesoforms formed on their walls. These include cracks of various genesis, grottoes, crag cornices, as well as a number of forms of honeycomb weathering. The tafoni forms are of considerable scientific, educational and tourist interest. In the Ukrainian Carpathians, the forms of honeycomb weathering mainly on sandstone crags are still insufficiently studied. The relevance of their study is due to the fact that these are forms of modern morphogenesis, which model tor walls. The study of morphology and evolutionary patterns of development is important to elucidate the mechanism of development of tor surfaces and interpret them during excursions.

Forms of alveolar weathering are honeycombs, alveoles, tafoni, which develop on the vertical walls of tors. "Alveolus" come from the term "little cavity" in Latin. Cavities on horizontal surfaces are designated as gnamma. Honeycombs – small forms, 1–2 cm in diameter; alveoles – medium-sized negative microforms, 3–10 cm in size; tafoni – large forms up to 50 cm in diameter; gnammas – the largest forms that can reach from one to several tens of meters. The term "tafoni" comes from the Italian dialect and means "to perforate", as it was used to refer to windows' across in Corsica, Sicily and Sardinia. It was first used by De Prado (1864) to describe the corresponding weathering forms in Spain (De Prado, 1864; Groom et al., 2015). Tafoni (singular tafone) – small (1 cm) to large (41 m) cave-like features generally occurring in granular rock (i.e., granite, sandstone) with smooth concave cavities, and often round rims and openings (Paradise, 2015, p. 16). Turkington and Phillips (2004) describe tafoni as meso-micro-forms 2–10 cm in size in the classification of cavernous forms. Some of the authors also distinguish "arcades" – loops of cavities coalesced into “trains” along the discontinuities, and separated from each other by hourglass-shaped pillars (Filippi et al., 2018). Since the 19th century and to date, more than 100 articles on alveolar weathering have been published in Western literature (Hejl, 2005), in which the question of morphology, genesis and evolution of these forms was considered.

Alveolar weathering forms were discovered and described in different regions of the world: Central Europe (from Spain and Luxembourg to the Czech Republic and Poland); in the Middle East; in the southwest and south of the USA; on the southern coasts and foothill deserts of Australia; the southeastern coast of China; Southeast Asia; South Africa; Patagonia, etc. (Adamovič, 2002; Chen, 2019; Paradise, 2002; Turkington & Philips, 2004). Initially, the main distribution regions of tafoni were thought to be hot and humid coastal environments and/or cold deserts (Blackwelder, 1929), but later these forms were found in all climatic zones, in arid and humid, in cold, such as Antarctica, Scandinavia, and hot, such as the deserts of Arabia and Africa. In coastal environments where moisture is more evenly distributed, tafoni extents tend to be larger, whereas the individual cavities are smaller. Although in arid regions where the moisture is restricted to shaded alcoves and northern faces, tafoni may develop into larger cavities, however occupying a smaller extent (Paradise, 2015).

The influence of climate is not as important as the structure of the rock. All cavities of alveolar weathering develop in granular rocks, such as sandstones, granites, granitoid schists, limestones, conglomerates. Rocks should possess the properties of lithological heterogeneity, permeability, increased porosity and microcracks, which determine the tendency to weathering and the active development of negative forms in them (Migon, 2006; Smith, 1982; Turkington & Paradise, 2005; Young, 1987).

During the 150-year history of studying the forms of alveolar weathering, scientists actively discuss the conditions of their formation and factors of development. The main factors of the formation and development of cavities are considered to be the lithological variability of rocks, climate and weathering processes, and the geographical latitude and location on the surface of the rocks are secondary. Filippi, Bruthans et al. (2018) identify such tafoni formation factors as the influence of raindrops, capillary water effect, frost and salt weathering, and the influence of biota (Filippi et al., 2018). 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, 2021). The moisture flowing down the rock walls after rain is retained in the cavities, causing their development in the form of vertical stripes (Mol & Viles, 2012). Paradise (2002) investigated the dependence of tafoni frequency, location, and size on exposure and pointed out that insolation and temperature are important factors of their occurrence. He also found that southern walls tend to exhibit the largest cavities in arid climates, because that's where the wetting-drying and/or heating-cooling cycles are increased (Paradise, 2002). Cavities both develop best in conditions where an ideal balance between wetting and drying exists. Too much water or too little moisture can arrest their progression, which controls their size, shape, and distribution. Research has indicated that it is the availability of moisture, and it is distribution that is paramount to the development of tafoni and gnammas (Huinink et al., 2004; Mol & Viles, 2012). In arid and coastal areas, pore expansion is strongly influenced by pitting, stagnation and dissolution of salts, and wind removal of weathering products (Rodriguez-Navarro et al., 1999; Young, 1987). In cold and humid latitudes, the development of cavities is more affected by frost weathering (Walder & Hallet, 1986).

Together with cavities of alveolar weathering, rounded and oval cavities of concretions origin can be observed on the tors. Such cavities are located alone, some forms are filled with material that is significantly different from the geological substrate of the base (Adamovič et al., 2010; Havryshkiv, 2008).

Paradise (2015) distinguishes the following morphological varieties of tafoni: honeycomb, sidewall tafoni, basal tafoni, nested tafoni, iconic tafoni, which can bear a resemblance to an animal's head, face, mushrooms, structures, and writing. By default, they are elliptical or rounded in shape – this is the minimum volume that a certain body can occupy. Some authors also highlight subtriangular shapes as a result from remodelling of spherical/ellipsoidal cavities (Adamovič, Mikulaš & Navratil, 2015).

Regarding the issue of tafoni evolution in morphological terms, the criteria of change in shape, change in the width-depth and height-depth ratio are used. First, small pits and cavities develop. Then the cavities and cells widen, deepen, and enlarge. The cells begin to develop orthogonal walls and bases. Then the cells enlarge, the walls thin, and the bases (backwalls) of the cavities flatten. Finally, as the cavities enlarge, some of the walls may collapse, causing cavities to merge creating larger cavities (Paradise, 2015).

The history of cavities study in the Carpathian region as dynamic microforms on tors is several decades old (J. Adamovič – Tatras (Ironstones…, 2002); Z. Alexandrowicz – Western Carpathians (Alexandrowicz, 2008), Y. Urban – Świętokrzyskie (Holy Cross) mountains (Urban & Górnik, 2017); B. Ridush, G. Bayrak i Y. Zinko – Ukrainian Carpathians (Bayrak & Zinko, 2023; Ridush, 2012; Zinko, 2008). In these studies, cavities of the alveolar weathering were not the main subject of research, but appeared as one of the features in the characterization of rock forms.

The purpose of the presented research is: to systematize the morphology of cavities on the sandstone tors of the Ukrainian Beskyds, to establish the stages of evolution for the needs of geotourism interpretations.

The following objectives were addressed in this paper: classification of cavity forms and their combinations on tor walls; analysis of evolutionary patterns of development; and evaluation of morphological and morphoevolutionary constructions for use in geotourism interpretation.

The following **research methods are used**: morphographic and morphometric inventory, relationships between morphological types of tafoni groups with lithological and climate-exposure factors, comparative-geographical, comparative-ecological, and spatial structure analysis.

There are about ten rock groups in the Ukrainian Beskydy, in particular, west to east: Urytskyi, Yamelnytskyi, Komarnytskyi, Kniazhi Rocks, Kliucha-Kamianky, Rozhirche, Bubnyskyi, Tserkovianskyi (Bayrak & Teodorovych 2020) (Fig. 1). There are dozens of rock formations in a research area. Rock formations include the exposure of rocks as upright walls on the slopes of beams or shores of the rivers; gorges in places of gaps of solid rocks; erosion and denudation residual hills – tors. Groups of tors consist of several (5–8) shapes. The highest tor peaks amounts 30–45 m and are located in the Urytskyi, Bubnyskyi and Tserkovianskyi rock groups.

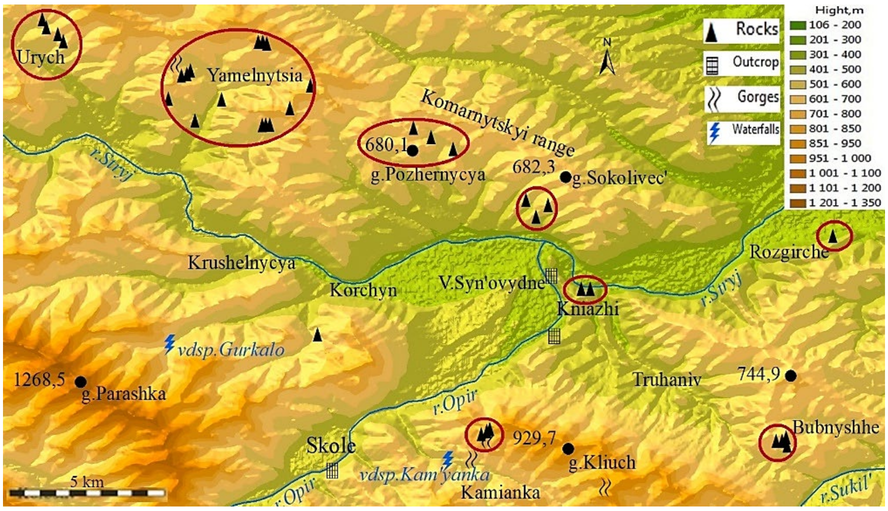


Fig. 1. The location of the rock groups in the Ukrainian Beskydy.
Ovals are marked tor groups

The *crags are composed of sandstones of the Yamna suite* of the Palaeocene of the Lower Paleogene age (56–66 million years), with the exception of the Rozgirche rocks, which are formed by sandstones of the Vyhoda suite of Eocene (average Paleogene, 34–56 million years). The rocks were formed at a depth of 3000–5000 m during the existence of the ancient Tethys Ocean here; that is evidenced by coral remnants and sea turtles in the sandstones. Sandstones are massive thick-bedded, light grey and yellowish with interlayers and lenses of gritstone and fine-grained conglomerates. Single sandstone layers are separated by thin interlayers of grey or greenish grey argillites. Occasionally, the lower part of the sandstone contains cobs of black-colored quartzite, which is probably a product of the destruction of metamorphic complexes. The lithological composition of the sandstones is represented by quartz (85–95%) and feldspar (5–15%), which allows us to classify them as typical feldspar-quartz sandstones. Grains of different degrees of roundness. The cement is clay-siliceous, sometimes with chlorite, of the basal or contact cementation type (Voloshyn, 2012).

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., 2022).

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. 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. There are broken zones in the rocks formed during sedimentation where geomorphological processes occur. All factors together determine the development of external processes that model the tor walls.

We have studied the forms of tafoni themselves, which are found on the tors in the Ukrainian Beskydy. In this region tafoni are distributed on tor surfaces in two ways: *locally in small areas or covering large areas* e.g. whole tor surfaces of particular aspect. In the first case, the forms are located in small groups of 10–30 pieces in separate parts of a tor wall. In the second case, they occupy the entire plane of the rock surface or half of the surface of particular exposure. Local groups of tafoni can be divided into three shape varieties: *1) vertical bands, 2) horizontal bands, and 3) lenticular bands.* Tafoni concentrations that occupy the entire one plane of the tor can be located on it: a) chaotically, b) in a chain-like manner (Fig. 2).

The following shapes of particular cavities can be distinguished in the Ukrainian Beskydy: *1) rounded, 2) ellipsoid, 3) vertically elongated*, and *4) subtriangular*. According to the nature of the walls between them, we distinguish: *A) with all four edges clear, B) with three clear and one levelled wall, C) with all unclear walls*. In the Beskydy, the first type of forms – with distinct edges – prevails.

The size of the cavities was also evaluated during the research. In ellipsoid and vertically elongated forms, the following parameters were investigated: length, width and depth, and in rounded ones – diameter and depth. The largest length is 20–30 cm, while the diameter reaches 10 cm, and the largest depth ranges 15 cm. Holes of large sizes are not common in the Beskydy, they are found only in the Komarnytski crag group and on the Mala crag of the Urytskyi complex. Medium and small-sized tafoni are more common. There are isolated large forms up to 30 cm across, as well as small, closely spaced ones.

In each morphological crag groups different tafoni occur. In the vertical local groupings, vertically elongated and rounded tafoni with distinct four walls or three distinct walls and a lower blurred edge are common. Medium to large (15 cm) sizes prevail. In local groups, tafoni are very densely located next to each other. In horizontal and lenticular local groups, ellipsoid tafoni with distinct edges are widespread. The sizes are medium and small. Subtriangular cavity shapes are also characteristic of horizontal groups (Fig. 3). They can reach large sizes, as in the Uritsky complex (up to 20 cm in diameter), but small tafoni are more common. Rounded, somewhere vertically elongated shapes with indistinct blurred edges are common in chaotic groupings of tafoni. They are mostly small in size and deep, occupy tor wall.

Chain-like continuous groupings are unique, found on the Sokolivets crags groups in the Komarnytskyi complex and on the crags in the Tserkovianskyi complex. Rounded small of tafoni shapes are common here, arranged in elongated cavities resembling chains. The depth of the cavities varies from 1–2 cm on the western side of the tor wall to 10–13 cm on the eastern side.

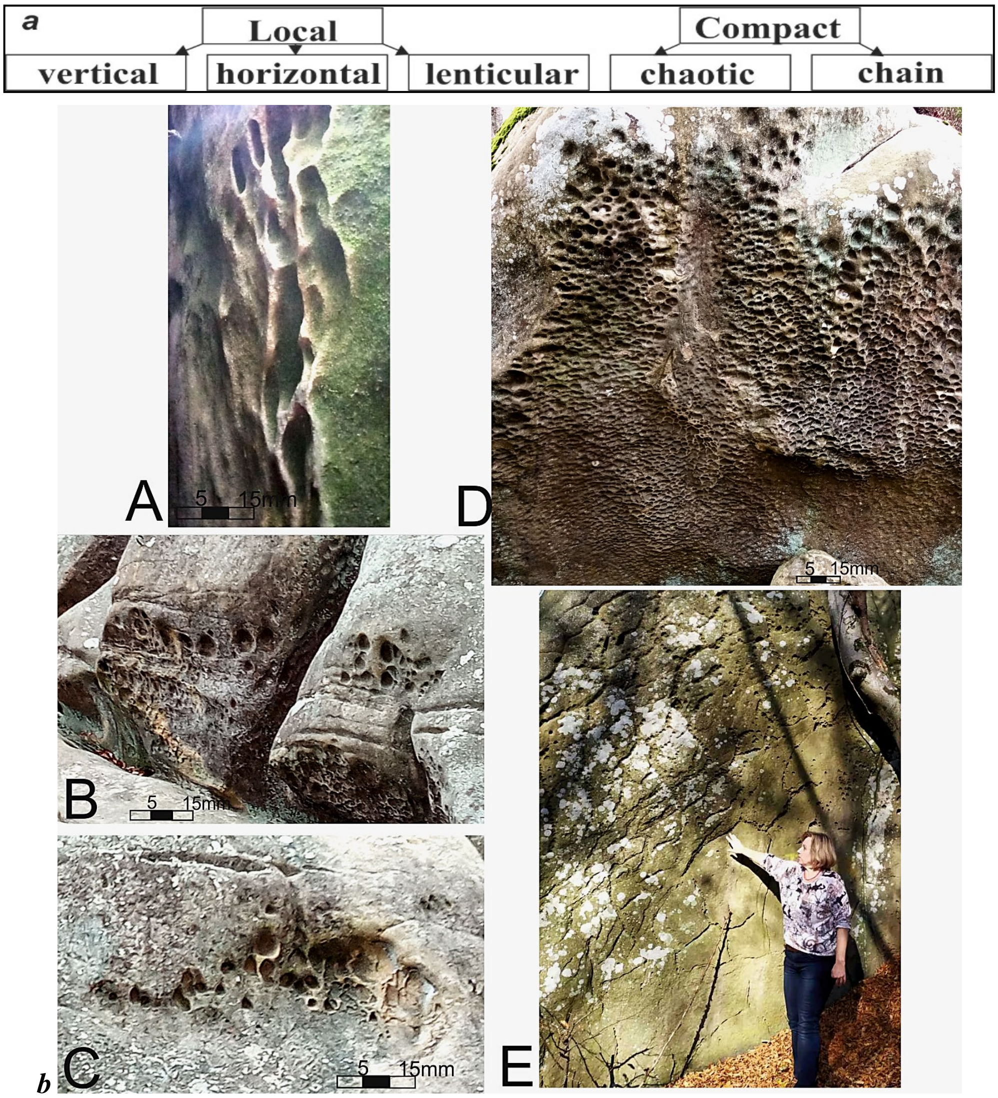
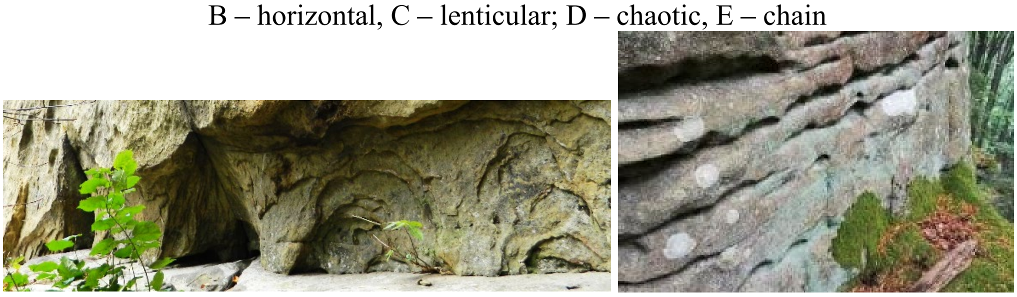


Fig. 2. Types of tafoni groups: ***a*** – scheme; ***b*** – photographs: A – vertical, B – horizontal, C – lenticular; D – chaotic, E – chain



a *b*

Fig. 3. Subtriangular (*a*) and ellipsoid (*b*) shapes in horizontal tafoni groups

There is no doubt that the general process that caused the formation of tafoni in our latitudes are humidity and the inherent specificity of selective weathering in sandstones due to structural and textural features formed during the formation of sediments. At high humidity, typical for mountains, water gets into the pores of the rock and stays for a long time on the shaded areas of the tor walls. The clay-silica cement, which binds the sandstone grains with short-term contacts, is weathered and partially washed away. Sandstone grains get separated, peel and crumble, and various kinds of indentations form on the surface. During winter periods, the role of frost weathering increases, when freezing moisture presses and expands the voids between the rock grains.

However, in each case, weathering was influenced by additional factors, such as runoff water – for vertical formations, widening of stratification cracks – for horizontally formed formations, moisture retention and steam condensation – for lenticular formations. Triangular tafoni forms are often confined to fractures in the strata and, as they develop, encompass elements of the sedimentary textures of the Baum-Sweet sequence. We believe that these shapes expanded only with their tops, while the bases were unchanged. This runs counter to the arguments of some authors that triangular shapes are the next stage of the development of rounded shapes (Adamovič et al., 2015).

According to our research, the formation of all types of tafoni is largely influenced by the shading of their locations. In shaded areas, aggressive atmospheric moisture stays longer in the near-surface pores of unevenly cemented sandstones (contact type cement), causing the dissolution of minerals. We also observe that on walls not covered by weathering crusts, tafoni are more widespread and densely arranged than on mineralized surfaces which indicates the activation of processes on the unweathered tor walls. The intensity of the processes is enhanced by the primary unevenness of the tor surface, such as depressions, niches, protrusions and steps. Tafoni are also often found in niches under horizontal ledges and rock ledges.

The relationship between morphology and climatic factors was also investigated. Studies were conducted on the number and expression of shapes on vertical tor walls of different exposures/aspects. In temperate latitudes climatic conditions (temperature and humidity fluctuations) are important factors in intensifying the degradation of tor walls. The contrast between the intensity of morphodynamic processes on warm and cold exposures is reorded. As a rule, the microrelief of the walls of warm exposures is structurally more complicated; various micro- and mesoprocesses such as weathering, erosion, blowing, fracturing, including the development of alveolar weathering forms, are manifested here.

It was found that on “warm exposures”, i.e. walls exposed toward southeast, south, southwest and west the total number of cavities and expression of microforms is greater and better than on “cold exposures” of north, northeast, east and northwest aspects (Table). Cold exposures act more as "conservators" of micro-relief evolution, while warm exposures act as "stimulators" of active microforms development. It can be argued that tafoni in the Carpathians develop more actively on the walls of warm exposures than on cold exposures, as indicated by T. Paradise (2002), investigating cavities on architectural surfaces in Petra, Jordan (Paradise, 2002). On cold exposures, tafoni are less morphologically distinct, and their number and density are smaller compared to warm exposures. Often, northern exposures are favored by moss-lichen vegetation, which "preserves" the walls of the tors, under which weathering processes are not active, so cavities do not develop.

Studies show that cavities are confined to the middle and lower walls of the tors. They are also more concentrated on unweathered surfaces, which are shaded from the sun and remain in a waterlogged state longer, but are exposed to sunlight for quite a long time. The balance between heating and wetting affects the shape, size, and number of tafoni: less moisture or excessive heat stops the development of cavities.

Table. The location of the taphoni groups studied on the walls of different tores expositions

Cold exposures				**Warm exposures**			
Northwest	North	Northeast	East	Southeast	South	Southwest	West
+	+	+	+	+	+	+	+
+	+	+	+	+	+	+	+
	+	+	+	+	+	+	+
	+		+	+	+	+	+
	+		+		+	+	+
	+				+		+
	+				+		
					+		
					+		
17				24			

Investigating the forms of alveolus weathering on the crags of the Ukrainian Beskydy, we confirmed the evolutionary patterns of tafoni development (Paradise, 2015; Turkington & Paradise, 2005) (Fig. 4).

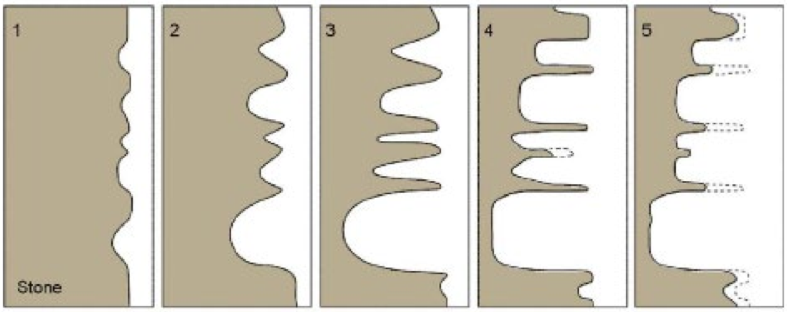


Fig. 4. Stages of Tafone Development (Paradise, 2015) : 1. Small depressions and pits develop due to lithologic weakness or irregularity; 2. Pits and depressions enlarge and deepen, and cells and cavities develop. Ribs and walls become defined and regular; 3. Cavity backwalls, rib and walls and wall intersections develop a more orthogonal and geometric configuration from rounded form; 4. Walls between cavities and cells begin to breach. Overall deepening and enlargement continue until walls are fully breached. 5. Walls erode into recessed ribs within the cavity voids. Many cavities and cells coalesce to create relatively smooth, void surfaces.

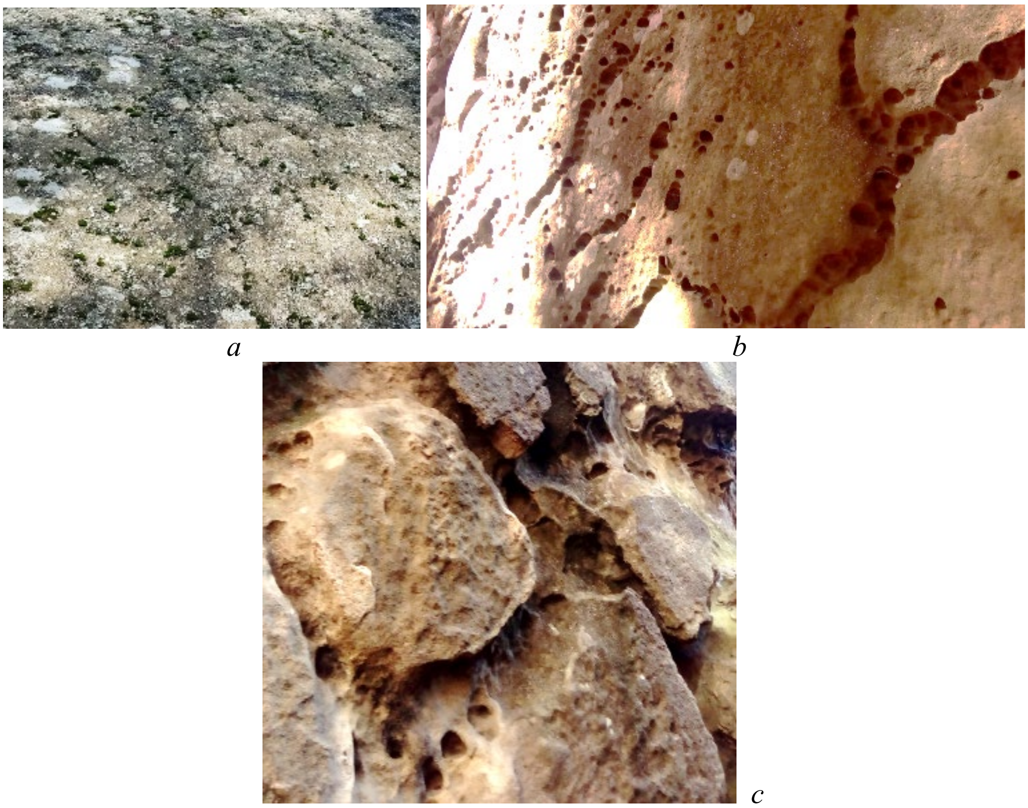
Observing the morphological forms of tafoni in the Beskydy, we distinguished the following *stages of their evolution: emergence - deepening - expansion - merging - degradation - re-emergence*.

On the walls of the Beskydy tors, one can observe tafonic forms at various stages of evolution. The morphological varieties of tafoni forms highlighted by us - *A) with all four clear edges, B) with three clear and one leveled wall, C) with all unclear walls*, - indicate a certain stage of evolution of cavities, when they are at the stage of "youth", "maturity" or "deterioration". The degraded walls are predominantly not lateral, but the lower, or inner walls, see Fig. 4 (5). In all ten groups of Beskydy crags, a single wall most often presents tafoni at a common (one) stage of evolution. These are most often of type A) or B). However, there are sites where tafoni at different stages of evolution can be observed on one wall (Fig. 5). In this case, the tafoni that are located closer to the top are better morphologically expressed, while those closer to the foot are more degraded. This suggests that on the lower parts of the tors they started to develop faster and degraded earlier.

Fig. 5. Stages of morphoevolution of cavities on the tor wall: the stage of "maturity" in the upper part, the stage of rib separation in the middle part, and the stage of degradation in the lower part of the wall

Areas of degraded tafoni forms often have processes of crumbling or washout of weathered material, due to which the walls are constantly "renewed", they lack a weathering crust. These planes often serve as a basis for the formation of new generations of tafoni with corresponding stages.

For the chain-like morphological type of tafoni, the evolution looks somewhat different. Here, along with the weathering processes that modify the cavities, there is linear erosion along the subvertical rows of tafoni. Weathering products are carried away by rain streams flowing down the walls of the tors. Not only the cavities themselves, but also the rows-depressions in which they are embedded undergo deepening (Fig. 6). The evolution for this morphological type is as follows: *emergence - deepening - expansion - deepening* of rows of forms.



a *b* *c*

Fig. 6. Evolution of chain-like groups of cavities: *a* – emergence; *b* – stage of "maturity"; *c* – the stage of expansion and deepening of rows

So, the studies have shown that in the Ukrainian Beskydy, tafoni of various morphology are common. Local groups of tafoni are the most widespread. There are also quite a lot of chaotic tafoni groups. There have more rounded shapes than elongated ones among particular tafone cavities. And we also observe greater number of cavities with distinct edges than with blurred ones, which indicates the relative young age of these forms.

Conclusion. Tafoni forms on tors, their morphology, evolution and formation factors can be the subject of geotourism interests. As evidenced by the experience of organizing geotourist excursions, which have a distinct cognitive nature, the interpretation of these objects becomes an important component of stories about geotourist attractions. Geotourist guidebooks are often amateurish in nature; the scientific and cognitive information in them is insufficient or does not apply to tafoni forms. Therefore, this article complements the research on the problems of development of morphodynamic processes on tor walls and modification of their microrelief. The results obtained concerning the types of morphology, peculiarities of spatial location and evolution of alveolus weathering cavities on the tors of the Ukrainian Beskydy will supplement scientific and educational provisions in the content of educational and scientific geotourism excursions.

REFERENCES

Adamovič, J., Mikulaš, R., Navratil, T., 2015. Spherical and ellipsoidal cavities in European sandstones: a product of sinking carbonate dissolution front. In *Zeitschrift für Geomorphologie,* 59, Suppl. 1, 123–149.

Adamovič, J., Ruckl, P., Langrova, A., 2010. Spherical feruuginous concretions in Cretaceous sandstones of N. Bohemia: genesis and forms of occurrence. In *Geoscience Research Reports for 2009*. Czech Geological Survey. 12–16. ISSN 0514-8057. (In Czech).

Alexandrowicz, Z., 2008. Sandstone rocky forms in Polish Carpathians attractive for education and tourism. In *Przegląd Geologiczny*, 56, 8/1: 680–687.

Bayrak, G., 2019. Morphologic classification of the Beskids rocks in the Ukrainian Carpathians. In *Problems of geomorphology and paleogeography of the Ukrainian Carpathians and adjacent territories: collection of scientific papers*, 1 (9): 117–132. https://doi.org/10.30970/gpc.2019.1.2806.

Bayrak, G., Teodorovych, L., 2020. Geological and geomorphological objects of the Ukrainian Carpathians' Beskid Mountains and their tourist attractiveness. In *Journ. Geology, Geography and Geoecology*, 29, 1, 16–29. https://doi.org/10.15421/112002

Bayrak, G., Zinko, J., 2023. Tafoni on rock surfaces in the Ukrainian Beskydy Mountains: morphological observations. In *14th International Symposium on Pseudokarst* (Sudetes, Southwestern Poland, Karływ 24–27th May 2023). Wrocław: Institute of Geography and Regional Development, University of Wrocław, 10–15. ISBN 978−83−62673−85−8

Blackwelder, E., 1929. Cavernous rock surfaces of the desert. In *American Journal of Science,* 217, 393–399.

Chen, L. et al., 2019. Origin of tafoni in the Late Cretaceous aeolian sandstones, Danxiashan UNESCO Global Geopark, South China. In *Acta Geologica Sinica* (English Edition), 93(2), 451–463. https://doi.org/10.1111/1755-6724.13810.

De Prado, C., 1864. Descripciorn fısica y geolorgica de la provincia de Madrid. In *Col. Ciencias, umanidades e Ingenierıka*, 2, 60–76.

Filippi, M., Bruthans, J., Řihošek, J., Slavik, M., Adamovič, J., Mašin, D., 2018. Arcades: Products of stress-controlled and discontinuity-related weathering. In *Earth-Science Reviews*, 180, 159–184. https://doi.org/10.1016/j. earscirev. 2018.03.012.

Groom, K. M., Allen, C. D., Mol, L., Paradise, T. R., Hall, K., 2015. Defining tafoni: Re-examining terminological ambiguity for cavernous rock decay phenomena. In *Progress in Physical Geography*. 1–9. https://doi.org/10.1177/0309133315605037.

Havryshkiv, G. Y., 2008. The petrography of paleocene deposits of the Skyba unit of the Ukrainian Carpathians. In: *Institute of Geology and Geochemistry of Combustible Minerals NAS Ukraine: collection of scientific papers*, 1, 67–69. (In Ukrainian).

Hejl, E., 2005. A pictorial study of tafoni development from the 2nd millennium BC. In *Geomorphology*, 64, 87–95.

Hnylko, O., Andreeva-Gryhorovych, A., Hnylko, S., 2022. Age and conditions of accumulation of Paleogene deposits of the Skyba Nappe of the Carpathians based on micropaleontological and sedimentological data. In *Geology and geochemistry of fossil fuels*. 1–2 (187–188), 36–47. https://doi.org/10.15407/ggcm2022.01-02.036.

Huinink, H.P., Pel, L., Kopinga, K., 2004. Simulating the growth of tafoni. In *Earth Surf. Proc. Land.* 29, 1225–1233.

Ironstones of the Bohemian Cretaceous basin. 2002. Catalogue of selected prominent geosites of sandstone landscapes. Ed. Adamovic J., Cilek V. Library of the Czech Speleological Society, Praha, 38. 172 p. (In Czech).

Migon, P., 2021. Sandstone geomorphology – Recent advances. Geomorphology, 373(Suppl. 1) https://doi.org/10.1016/j.geomorph.2020.107484

Migoń, P., 2006. Granite landscapes of the world. Oxford University Press. New York, 417 p.

Mol, L., Viles, H.A. 2012. The role of rock surface hardness and internal moisture in tafoni development in sandstone. Earth Surface Processes and Landforms 37, 3: 301–314.

Paradise, T. R., 2002. Sandstone weathering and aspect in Petra, Jordan. In *Zeitschrift für Geomorphologie*, 46, 1–17.

Paradise, T. R., 2015. Tafoni and other rock basins. In: *Reference module in earth systems and environmental sciences*, Elsevier. https://doi.org/10.1016/B978-0-12-409548-9.09570-1.

Ridush, B. T., 2012. Taphonomy of rock art of the Carpathians and Transdnistria. In *Fortress: collection of the nature reserve "Tustan"*, 2, 74–81.

Rodriguez-Navarro, C., Doehne, E., Sebastian, E., 1999. Origins of honeycomb weathering: The role of salts and wind. In *Geological Society of America Bulletin* 111–8, 1250–1255.

Smith, P. J., 1982. Why honeycomb weathering? In *Nature,* 298, 121–122.

Turkington, A., Philips, J., 2004. Cavernous weathering, dynamical instability and self-organization. In *Earth Surface Processes and Landforms*, 29, 665–675. https://doi.org/10.1002/esp.1060.

Turkington, A. V., Paradise, T. R., 2005. Sandstone weathering: A century of research and innovation. In *Geomorphology,* 67(1), 229–253.

Urban, J., Górnik, M., 2017. Some aspects of lithological and exogenic control of sandstone morphology, the Świętokrzyskie (Holy Cross) Mts. case study, Poland. In *Geomorphology*, 295, 773–789.

Voloshyn, P., 2012. Engineering and geomorphological characteristics of the Urytsky rocks. In *Problems of geomorphology and paleogeography of the Ukrainian Carpathians and adjacent t areas*: *collection of scientific papers*, 172–180. https://geography.lnu.edu.ua/research/problemy-heomorfolohiji-i-paleoheohrafiji-ukrajinskyh-karpat-i-prylehlyh-terytorij-zbirnyk-naukovyh-prats (In Ukrainian).

Walder, J. S, Hallet, B., 1986. The physical basis of frost weathering: toward a more fundamental and unified perspective. In *Arctic Alpine Res*. 18(1), 27–32.

Young, A. R. M., 1987. Salt as an agent in the development of cavernous weathering. In *Geology*, 15(10), 962–966.

Zinko, Y. V., 2008. Creation of a didactic geotourist trail "Uritski rocks". In: *Problems of geomorphology and paleogeography of the Ukrainian Carpathians and adjacent territories: collection of scientific papers*, 247–258.

Стаття надійшла в редакцію 14.04.2024
Прийнято до друку 29.05.2024
Дата публікації 20.06.2024