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ARTICLE

A Comparison of the Genetic Shaft Types of Some Karst Areas Based on Their Specific Shaft Lengths

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ABSTRACT

Shaft development can be documented on the basis of comparative studies of specific shaft lengths and shaft patterns. We calculated the specific length of shafts and the average specific shaft length of the shafts in some karst areas and we investigated the relation between the altitude of shaft floors and the specific shaft length. Taking the registered specific shaft lengths and the shaft patterns into consideration, it can be stated that some parts of the shafts developed paragenetically in the studied karst areas. In the Bakony Region, this was caused by surface water influx, rise of karst water level, and their simultaneous effect. As a result, shaft systems, bifurcating shafts and storeyed shafts developed. On glaciokarst areas, shafts may constitute a system with phreatic passages: either because a phreatic environment developed in the vadose zone due to the permanent impoundment of karst water or because a phreatic passage got into the vadose zone since the karst became elevated. On the studied karst areas, the following shaft development types are distinguished: glacial-high mountain surface flood development type (1), glacial-high mountain karst water and surface flood development type (2), glacial karst water and surface flood later phreatic development type (3), shaft with a passage that got into the vadose zone (4).

1. Introduction

In this study, a genetic classification and a comparison of the genetic types of the shafts of some glaciokarst areas (high mountains) and of the Bakony Region are described based on specific shaft lengths and shaft patterns.

With the help of cave morphometry, caves can be characterised quantitatively for which morphometric parameters are calculated and statistically analysed. Klimchouk [1] used the following morphometric parameters to distinguish caves with different settings (confined and unconfined setting): areal coverage (an area occupied by caves in percentage as compared to the area surrounded by the polygon surrounding the cave map which is called cave field) specific volume (the ratio of cave volume and cave length), cave porosity (the ratio of cave volume and the volume bearing the cave, the latter can be given if cave field is multiplied by the vertical expansion of the cave). Verticality index (Vi), horizontality index (Hi), linearity index (Li), and horizontal complexity index (Hci) can be given [2]. For example, Vi

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can be calculated by the quotient of the maximum vertical expansion of cave and the total length of the cave.

Ballesteros et al [3] determined the geometry of a cave (Torca La Texa) by calculating Vi, Li and Hci parameters regarding the cave. Jouves et al [4] created a 3D numerical data base based on the data of caves. Based on the calculation of morphometric parameters such as conduit cross-section shape (ratio of width and height), sinuosity and verticality index (the vertical vs. cumulative development of the cave passages), four cave pattern groups can be created which are the following: vadose branchwork, water-table cave, looping cave and angular maze.

Epigene caves are the caves of the vadose zone which are more or less vertical caves. An overall description of vertical caves and within them, of shafts was given by Audra and Palmer [5]. Their development is due to surface waters. (In this study we refer to the fact that karst water may also have played a role in the development of some sections in case of the presence of certain conditions.) Among vertical caves, shafts are the most common or their majority is partially constituted by shafts. Complex systems may also occur where shafts and shaft sections occur with inclined, horizontal or nearly horizontal sections together. In this case the whole system can be regarded a shaft. Therefore, focusing on a more simple description, complex vertical caves are also called shafts in this study. Shafts can develop by dissolution or erosion [6]. Shafts of solution origin are called primary vadose shafts [6]. These shafts develop along discontinuities of rocks by drainage water since the waters of the walls preserve their dissolution capacity in great depths too [7]. Shafts of erosion origin are formed by the further development of phreatic passages [6].

Mihevc [8] distinguished stepped shafts, fissure zone shafts and independent shafts among the shafts of the plateau of Trnovski gozd. Veress [9,10] distinguished the following shaft types taking into consideration the maps of the shafts of the Bakony Mountains: simple shafts, complex shafts, shaft systems, bifurcating shafts, storeyed shafts and shafts with a phreatic passage part. Simple shafts are constituted by one passage only which can be of vertical or different position. Complex shafts are built up of sections with various inclination which developed along fissures, along bedding planes (connecting those formed along fissures) and tributary shafts with blind termination. Shafts systems have a similar pattern than complex shafts, but tributary shafts reach the surface. Bifurcating shafts fork in bunches downwards, while in case of storeyed shafts there are shaft sections in several levels above each other. As regards shafts with a phreatic passage part, the shaft is connected to a passage with phreatic origin.

Dissolution in caves may also happen by paragenesis. In this case an upward dissolution takes place at the upper part of the water-filled cavity since the accumulating sediment lifts the level of water-fill [11,12,13]. Paragenesis may take place in the vadose zone [13], in the phreatic zone [6] and in the epiphreatic zone [14].

According to Veress, [9,10] in the Bakony Mountains (Hungary) the lengthening of shafts is also caused by the upward growth of tributary shafts that branch out of main shafts (these are called blind shafts that terminate at their upper part). Blind shafts lengthen by an upward growth by paragenesis. This is possible because the already existing shafts became filled with water. The shafts with a closed upper part (blind shafts) can only develop paragenetically since the water infiltrating from the surface does not dissolve the rock above the termination of the shafts. If surface waters had a dissolution capacity, the shafts would reach the surface. A possible explanation of this contradiction is that the dissolution capacity originates from below. During its upward development, the blind shaft may grow until an elevation to which the level of the water-fill of the main shaft may expand.

The state of water-fill is proved by the fact that veneers of sediment and vegetation residue can often be seen on shaft walls. Flooding with water may be caused by surface water inflow, the rise of the karst water level and their simultaneous effect too. Surface flooding is referred by the fact that intermittent lakes may develop in the karst depressions of the shafts of the mountains by impoundment since the shaft is filled with water. The development of lakes is caused by the influx of surface waters into the karst depressions which waters originate from the catchment area of depressions during rainy season.

Fill (or partial fill) with karst water is possible since in case of some shafts of the Bakony Mountains, shaft floors are close to the standstill karst water level. Thus, for example the floor of the Alba-Regia Cave is only more elevated by 52,8m as compared to the karst water level. However, in the mountains, the rise of the karst water level may exceed 100 m during wet seasons according to the data of karst water detecting wells [15].

In the Bakony Region, we studied shaft development related to floods with the analysis of their specific shaft lengths and considering potential floods of surface and karst water origin [9,10]. Surface flood development type and karst water-surface flood development type were distinguished (the shafts of the Keszthely Mountains are mainly shafts of tectonic origin which developed partly independently of flood and are only partially of dissolution origin which were formed during the shift of blocks as compared to each other surrounding fractures and fault).

2. Materials and Methods

(1) From the studied karst areas (Bakony Region, Lovčen-Njegusi-polje, Caucasus, Orjen Mountains), the total lengths and depths of 138 shafts were collected. Based on these data, the specific shaft lengths of the shafts were calculated in the following way:

$$L = \frac{l}{v}$$

where L is the specific shaft length, *l* is the total length of the shaft and *v* is the total depth of the shaft.

The calculated value gives the average length to a 1-m depth of the shaft. It can be concluded from the above mentioned calculation that the specific shaft length can be potential, actual and explored. Potential specific shaft length is the value that is calculated from the possible greatest total length of the shaft. The potential shaft length depends on the thickness of the vadose zone, the possible spatial position of the shaft and the degree of its complexity. When calculating the explored specific shaft length, the mapped (measured) shaft length was taken into consideration. The actual specific shaft length is calculated based on the actual length of the shaft. Actual shaft lengths may be larger than explored shaft lengths thus, actual specific shaft lengths may exceed explored specific shaft lengths. However, the two lengths may be the same and in this case the two specific shaft lengths are also the same. At calculations, explored shaft lengths could be taken into consideration (in the following, this value is meant by specific shaft length).

(2) The average values of specific shaft lengths of the above mentioned areas were calculated, but the average specific shaft lengths of their part areas were also given. (Part areas will be described in the next chapters.)

(3) In the area of the Lovčen-Njegusi polje, the relation between the shaft lengths and the elevation of shaft floors was studied.

Studied Areas

The sample sites are shown in Figure 1. The area of the Bakony Region is separated into geologically different blocks [16,17]. These are mainly built up of Triassic carbonates and with some portions of Jurassic, Cretaceous, and Eocene limestones [18]. The Carboniferous rocks of some blocks (Kab Mountain) are overlain by basalts. The elevation of its surface is 150-700 m, while its area is 4300 km^2 (the area of the Bakony Mountains is 2200 km^2 out of this), the annual precipitation is 650-800 mm. It is a karst of medium height where the specific length of 83 shafts was calculated from these localities (the number of the studied shafts is given in brackets): the Tési Plateau (46 shafts), the Hárskút Basin (7 shafts), the Kab Mountain (11 shafts), the area between the Som Mountain and Száraz-Gerence, Eleven-Förtés doline group, the vicinities of the Márvány valley (altogether 12 shafts) (these latter three are mentioned as the vicinities of the Kőris Mountain below), and the Keszthely Mountains (7 shafts). Shaft patterns distinguished in the Bakony Region are the following [9]. Simple shafts developed along a fracture or a bedding plane (Figure 2). Shaft systems were formed along fractures and bedding planes of various position (Figure 3). Besides their main shafts, complex shafts have tributary shafts reaching the surface (Figure 4). Bifurcating shafts are separated into several parts downwards from their entrance (Figure 5), while storeyed shafts are separated into several levels (Figure 6).

Figure 1. Sample areas

Legend: 1. Bakony Region, 2. Lovčen-Njegusi-polje, 3. Greater Caucasus, 4. Orjen Mountains

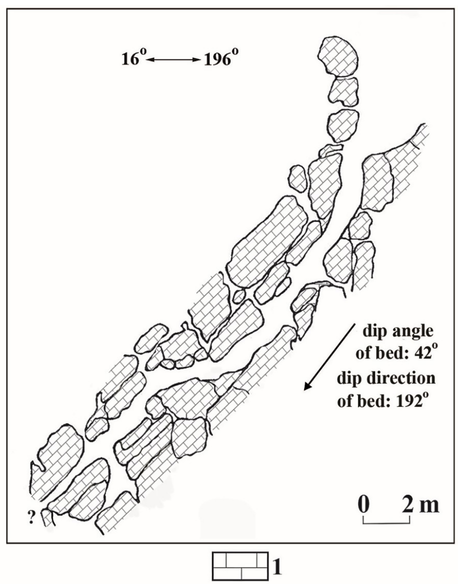

Figure 2. Simple shaft that developed along bedding plane: the shaft of the depression marked G-5/a (Hárskút basin) [9]

Legend: 1. host rock

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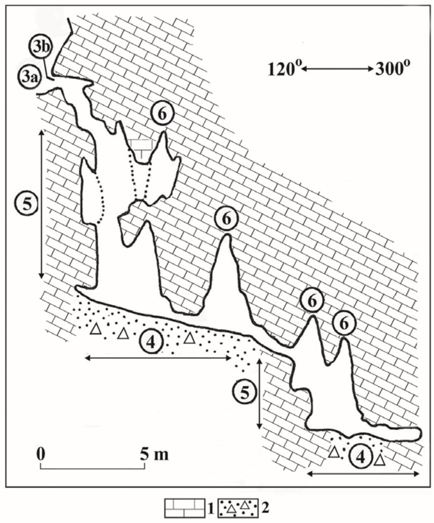

Figure 3. Complex shaft that developed along fracture and bedding plane: longitudinal profile of Ereszes shaft, Hárskút basin [9]

Legend: 1. host rock, 2. washed-in soil and debris, 3a. subsidence doline, 3b. entrance, 4. section that developed along bedding plane, 5. section that developed along fracture, 6. paragenetic blind shaft

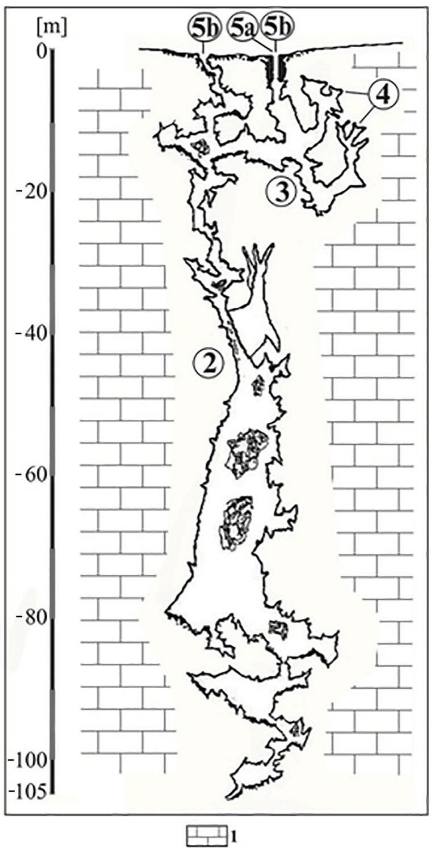

Figure 4. Shaft system: the longitudinal profile of Háromkürtő shaft (Tési Plateau) [9]

Legend: 1. host rock, 2. main shaft, 3. tributary shaft, 4. paragenetic blind shaft, 5a. subsidence doline, 5b. entrance

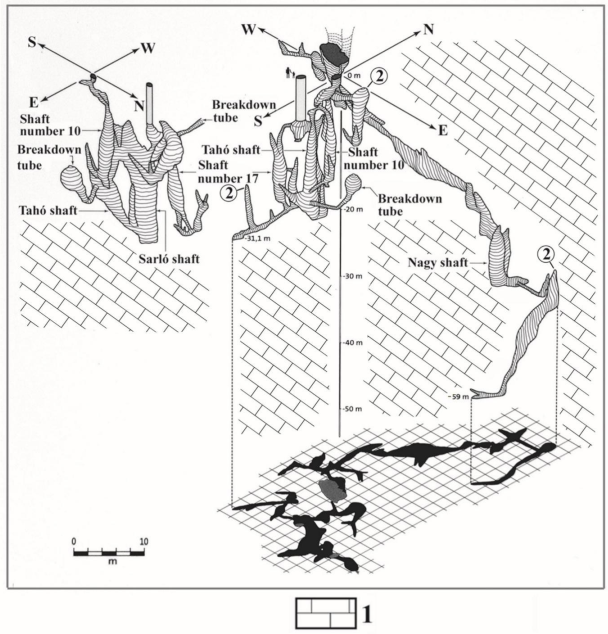

Figure 5. Bifurcating shaft: the shaft of Öreg-Köves ponor (Kab Mountain) [9]

Legend: 1. host rock, 2. paragenetic blind shaft

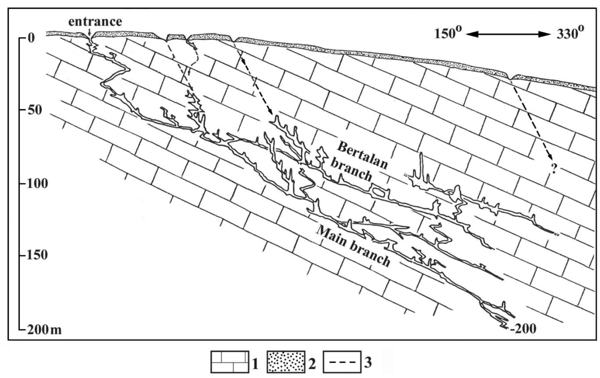

Figure 6. Storeyed shaft: Alba Regia Cave (Tési Plateau) [9]

Legend: 1. host rock, 2. superficial deposit, 3. fracture

The area of the Lovčen-Njegusi polje is situated in the coastal range of the Dinarides along the Bay of Kotor (Montenegro) at an altitude of 870-1700 m. According to cave cadastre, it can be separated into four part areas, namely the Njegusi-polje, the Lovčen Mountains, the Northern Zone and the Middle Zone. Its karst water level is near the level of the Adriatic Sea. The amount of precipitation may reach 4000 mm in some parts of Lovčen. Hungarian speleologists have been dealing with the exploration of its shafts and with the documentation of the explored section for more than a decade [19,20]. From this sample site 21 shafts were involved into our study.

The area of the Njegusi-polje has the size of 6.2 km^2, its elevation is 870-1200 m. The rocks of the polje floor are Upper Triassic and Lower Jurassic limestones with chert, and Middle Jurassic limestones [21]. The glaciers of Lovčen terminated in the polje, leaving fluvioglacial sediment behind thus, it is a polje of piedmont type according to its development. The specific lengths of its 6 caves (these are numbered from 1 to 6) were calculated. Among them, the Njegusi cave (its specific shaft length is 16.32) is a complex system. Vertical (or nearly vertical) shafts alternate with horizontal, phreatic [20] passage parts (Figure 7), similarly to the case of the Kétlyukú-Jeges cave system of Lovčen (Figure 8). The vertical (vadose) shafts may surround the phreatic passage both from above and below. In case of the Njegusi cave, we can also see that the vadose shafts go transversely phreatic passages and cut them and the phreatic passages continued their development in a vadose way [20]. However, the Duboki do cave has an assemblage of flow origin (and not phreatic) [20], which refers to the flow origin of the cave in addition to its water fill. Lovčen is situated between the Njegusi polje and the Bay of Kotor which is built up of Mesozoic carbonates overthrusted over Eocene flysch (but there is a similar structure in the other part areas), its area is 21.8 km^2. It is separated into two ridges trending NW-SE and transformed glacially [22]. Its elevation is 1300-1400 m. In this area, 6 shafts were studied (they are numbered from 7 to 12). Among them, the Kétlyukú-Jeges cave system is a complex system (Figure 8). The Northern Zone is an area north from the Njegusi-polje, which is surrounded by the Bay of Kotor from the west. Its expansion is 30 km^2 and its elevation is 900-1400 m. There was no ice cover in this part [23]. The specific lengths of 5 shafts (they are numbered from 13 to 17) were calculated from the area of the unit. The expansion of the Middle Zone is 25 km^2 and its elevation is 1300-1400 m. The area of the unit was covered by ice in the past, the specific lengths of 4 shafts (they were numbered from 18 to 21) were calculated here.

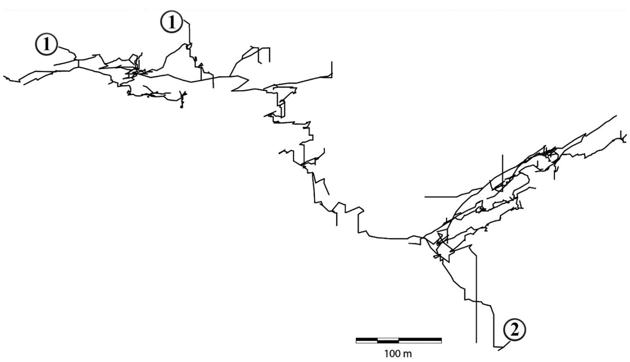

Figure 7. The longitudinal profile of Njegusi Cave (Njegusi-polje) (measured by Börcsök, Hegedűs, Palocsek, Takácsné Bolner, Zih, Kunisch, Szabó, 2003-2019)

Legend: 1. entrance, 2. siphon

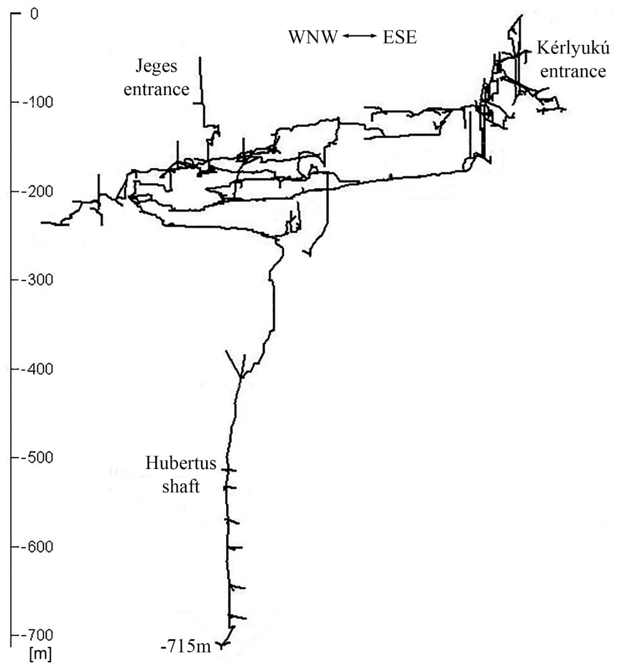

Figure 8. The longitudinal profile of the Kétlyukú-Jeges cave system (Lovčen) (mapped by Nagy, Hegedűs, Kunisch, Nyerges 2009-2019)

The Greater Caucasus is a mountain system of great expansion and diverse structure. Its geology and tectonics have been investigated in several works [24,25,26]. Here, we only describe the bearing areas of the studied shafts (see below). The description of the areas and their shafts is based on the data of [27,28,29]. Twenty-two shafts were investigated from here. The part sample sites of the shafts being included into the study are the Lagonaki Highland, the Sary-Tala Massif, the Dzehntu Range, the Abishira-Akhuba Range, the Sochi area and the Arabika Massif.

The Lagonaki Highland is the most elevated (the elevation of its surface is 1500-2800 m) part of the Western Caucasus (western part of the Greater Caucasus). It is built up of Upper Jurassic limestones. The area of the highland was glaciated in the Pleistocene, and now it hosts snowfield and small glaciers, the amount of precipitation may reach 3000 mm. The specific shaft lengths of 9 shafts is examined (Figures 9, 10).

The Sary-Tala Massif is situated in the central part of the Greater Caucasus. The elevation of its surface is over 1500 m. It is built up of Lower Cretaceous limestones. Its surface is dissected by cuesta-like ranges, the amount of precipitation is over 1000 mm. Apparently, there was no ice cover in the area of the massif. Here, 2 shafts were involved into the study.

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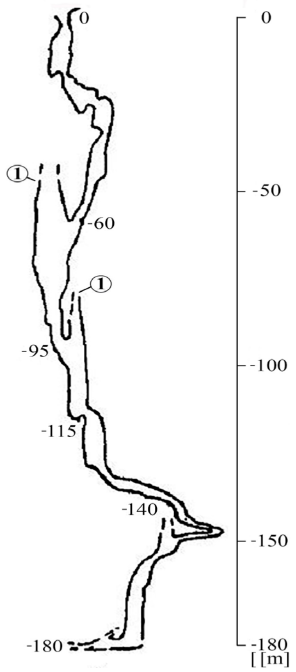

Figure 9. The longitudinal profile of Kuntsev Cave (Lagonaki Highland, Greater Caucasus) [27]

Legend: 1. paragenetic blind shaft

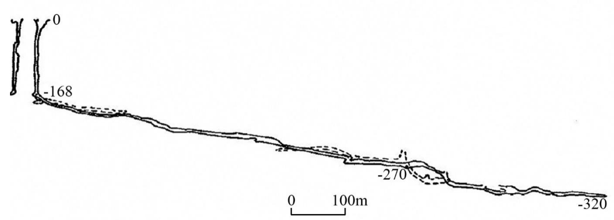

Figure 10. The longitudinal profile of Absolute Cave (Lagonaki Highland, Greater Caucasus) [27]

The Dzehntu Range belongs to the central part of the Greater Caucasus. The elevation of its surface is over 2000 m. It is built up of Upper Devonian-Lower Carboniferous marble-like limestones with shale intercalations. The amount of precipitation is over 1500 m. In this area, the existence of a former ice cover is uncertain. One shaft was included into the present investigation.

The Abishira-Akhuba Range is part of the Middle Caucasus. The elevation of its surface is 2400-2700 m. It is built up of Lower Carboniferous limestones. Former ice cover is probable. The amount of precipitation is more than 1500 mm. The specific lengths of 2 shafts were calculated.

The Sochi area is located in the southwestern part of the Greater Caucasus. The elevation of its surface is 300-1000 m. It is built up of Upper Jurassic and Upper Cretaceous limestones. The amount of precipitation is 1500-2000 mm. There was no ice cover. The specific lengths of 3 shafts were calculated here.

The Arabika Massif can be found in the southern part of the Greater Caucasus. The elevation of its surface is 1900-2300 m. It is built up of Upper Jurassic limestones. The amount of precipitation is more than 1500 mm. Former ice cover is probable. The specific lengths of 5 shafts were calculated here.

The Orjen Mountains is in the coastal range of the Dinarides at the border of Montenegro, Croatia and Bosnia-Hercegovina. The area has a size of 400 km^2, the elevation is 1300-1800 m. These mountains are built of Jurassic, Cretaceous, and Eocene limestones [30]. Their more elevated parts are constituted by ridge-like ranges which separate plateaus and valleys [22]. The amount of precipitation may also reach 5000 mm [31]. The specific lengths of 12 shafts were calculated from the Orjen Mountains. The longitudinal profile of one of the shafts can be seen in Figure 11.

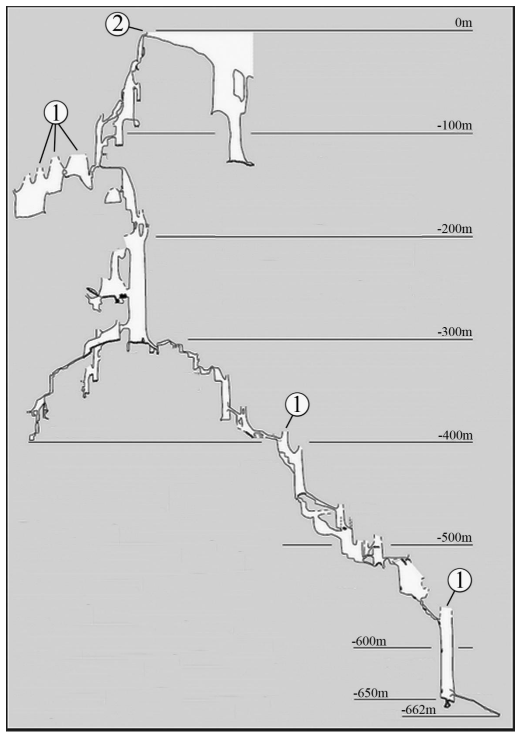

Figure 11. The longitudinal profile of Jeskyně Kozi dira Cave (Orjen Mountains) (https://www.suchy-zleb.cz/cs/cerna-hora-2010/kd-mapa)

Legend: 1. blind shaft

3. Results

A function relation between the elevation of the shaft floors (where the shaft terminates) and the specific lengths of the shafts is established in the area of the Lovčen-Njegusi polje if we disregard the shafts of the Northern Zone (where there was no ice) and the Pipás cave, the Miloseva cave and the Duboki do cave (Figure 12). The former are ignored because these were transformed by collapses, while the Dubo-

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ki do cave is omitted because of its assemblage referring to a specific, intensive water influx [20]. This cave will be dealt with later. The function relation shows that the less elevated the shaft floor, the bigger its specific length (thus, the greater its length is as compared to its depth). Since the specific length of the caves with a less and less elevated floor (e.g. Njegusi cave and Kétlyukú-Jeges cave) becomes larger and these caves have a longer phreatic sections in spite of being situated in a vadose environment. During the initial elevation of the karst water level, there was a greater chance for the development of phreatic sections at shaft floors with a lower elevation than at caves with a more elevated floor (e.g. the Ötórai-tea cave). As a result of this, in case of these caves, vadose and inactive phreatic sections alternate or there may be even vadose sections below the phreatic sections. However, any similar function relation does not exist between the shaft floors and specific lengths in other glaciokarstic sample sites.

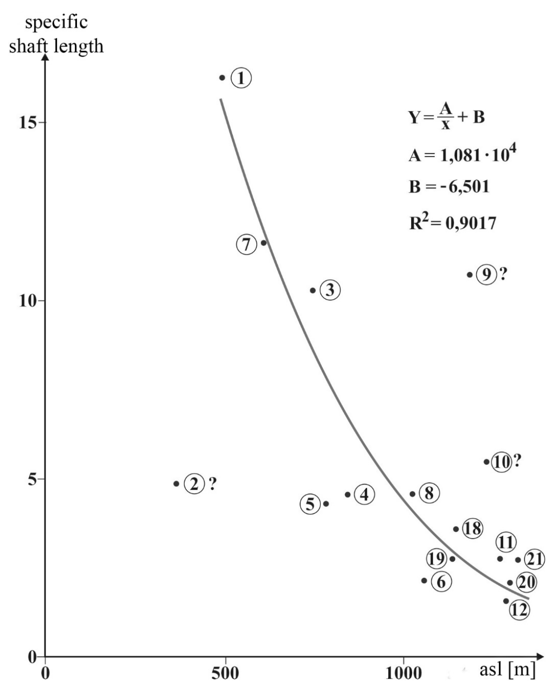

Figure 12. The relation between the altitude of shaft floors and their specific shaft length in the area of the Lovčen-Njegusi-polje

Legend: 1. Njegusi cave, 2. Duboki do, 3. Dögös cave (Zestoka pecina), 4. Szamaras cave (Bojanovica), 5. Meander cave, 6. Sólyom cave, 7. Kétlyukú-Jeges cave system (Dvorupa-Ledena jama), 8. Lahner cave (jama Lahner), 9. Pipás cave (jama Koje pusi lulu), 10. Miloševa pećina, 11. Anna cave (pećina Ana), 12. Ötórai-tea cave (jama JN-1), 18. Jama Golubišnica, 19. Panoráma cave, 20. Bence-lika (jama Du-2), 21. Szamócás cave (Durdevacka jama)

Notice: question mark can be find at caves, the specific shaft length of which was not taken into consideration when making the function

Shafts with large and small specific lengths occur in all sample sites. Shafts with a large specific length are the Alba cave (Tési Plateau), the Njegusi cave (Njegusi polje), the Vilina cave (Orjen), the Absolute cave (Greater Caucasus, Lagonaki Highland). The specific length of the shafts in the above mentioned order are: 17.96, 16.32, 11.00, 7.56, respectively The Bezimena cave (Orjen), the Csengő shaft (Tési Plateau), the Ötórai-tea cave (Lovčen), and the Kuntsev cave (Greater Caucasus) are characterised by small specific shaft length. The specific shaft lengths in the above mentioned order are: 1.79, 1.75, 1.70, 1.53, respectively The differences within the same area can be explained by the various steepness and complexity of the shafts.

If we consider the relation between the specific shaft length and the present thickness of the vadose zone (on glaciokarsts this thickness is great), we can state that both shafts with a large specific shaft length and shafts with a small specific shaft length may occur in case of a thick vadose zone. Examples for a thick vadose zone and a large specific shaft length may be the already mentioned Absolute cave (the present thickness of the vadose zone is about 2000 m) and the Njegusi cave (the present thickness of the vadose zone is 870 m). However, in glaciokarsts caves with a small specific length this phenomenon also occur. Thus, the specific shaft length of the Hippopotamus cave is 1.14, the thickness of the bearing vadose zone is 1700-2000 m. In mountains with a lower elevation such as in the Bakony Region, the thickness of the vadose zone is small as compared to the vadose zones of glaciokarsts, though, as it can be seen below, these may be significantly different within the mountains. Thus, the specific shaft length of the Bujó-lik (Kab Mountain) is 5.27, while the thickness of the bearing vadose zone is 50-100 m. In the Bakony Region, the specific shaft length decreases with a larger and larger thickness of the vadose zone. Thus, in the vicinities of the Kőris Mountain, the thickness of the vadose zone is larger (230-445 m), while the average specific shaft length of the shafts is smaller (1.23) than in case of the Kab Mountain where the thickness of the vadose zone is 50-100 m as we have mentioned and the average specific length is 3.89 [9].

The reported relationship between the specific shaft length and the thickness of the bearing vadose zone permits inferences which are as follows:

(1) In the case of thicker vadose zones there is a greater chance for development of deeper (and thus, longer) shafts, but the increase in thickness of the vadose zone does not result directly in the increase in specific shaft length.

(2) In the case of an extremely thin vadose zone, the value of the specific shaft length is significantly affected by the change of the thickness of the vadose zone.

(3) However, in the area of the Lovčen-Njegusi polje, the shaft floors are closer to the karst water level, which results in the increase in specific length of the shafts.

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We also compared the average specific shaft lengths of the shafts of the various areas and subareas (Table I). It can be seen that these values are smaller in the Bakony Region than in the studied glaciokarstic areas. The average specific shaft lengths of the shafts of the various glaciokarstic areas are also different (Orjen - 2.85, Greater Caucasus - 3.47, Lovčen -Njegusi polje - 5,13). The evidence from the greater Caucasus implies the shafts of the Sary - Tala Massif and the Dzehntu Range are characterized by large specific shaft length (11.85 and 6.22, respectively; however, the number of shafts is small), while smaller specific lengths are characteristic of the Arabika Plateau (1.62). There are various specific shaft lengths in the area of the Lagonaki Highland. Here, the average specific length of the Absolute shaft, the Canyon shaft, the Tourist shaft, and the shaft marked CSS-75-55 is large (5,00). These shafts have mainly phreatic parts. However, the inactive phreatic parts are connected by a (vertical) shaft of vadose type from above only (Figure 10). At the same time, the average specific shaft length of the Soaring Bird cave, the Dniepr cave, the Golden Key cave, the Kuntsev cave and the Hippopotamus cave is small (1.48). These shafts do not have inactive phreatic passage parts. It can be stated that on glaciokarst areas, the specific shaft lengths are not only affected by the shaft pattern, but also presence/ absence of inactive phreatic passages.

Table 1. Average specific shaft lengths according to different areas

Area	Shaft number	Average specific shaft length	Part area	Shaft number	Average specific shaft length
Lovčen-Njegusi polje	21	5.71	1	16	5.71
			2	13	5.36
Orjen	12	2.85			
Caucasus	22	3.47	3	4	5.00
			4	5	1.48
			5	2	11.85
			6	1	6.22
			7	2	2.31
			8	3	2.11
			9	5	1.62
Bakony Region	83	2.05[1]	10	11	3.89
			11	46	2.73
			12	7	2.04
			13	12	1.23
			14	7	42.64

Note: [1]With the Keszthely Mountains the average specific shaft length is 7.85

1. without the Northern zone, 2. without the Northern zone, Duboki do, Pipás cave and the Miloseva-Pecina cave, 3. from the area of the Lagonaki Highland: Absolute cave, Canyon cave, Tourist cave, CSS-75-55 cave, 4. from the area of the Lagonaki Highland: Soaring Bird cave, Dniepr cave, Golden Key cave, Kuntsev cave, Hippopotamus cave, 5. Sari-Tala Massif, 6. Dzehntu range, 7. Abishira-Akhuba range, 8. Sochi area, 9. Arabica Massif, 10. Kab Mountain, 11. Tési Plateau, 12. Hárskút basin, 13. Kőris Mountain and its vicinities, 14. Keszthelyi Mountains

4. Discussion

On glaciokarst areas (and partially in the Bakony Region), shaft patterns and specific shaft lengths can be characterized as follows:

(1) Shafts of a small or relatively small specific shaft length with or without half tubes (blind shafts). Such shafts occur in the Bakony Mountains, e.g., the Ereszes shaft (Figure 3), but also on glaciokarsts, such as the Kuntsev cave (Figure 9). In case of these shafts a paragenetic shaft development may take place and as a result of this, half tubes are formed. The flooding takes place during surface water influx. As a result of a flood of surface origin, the water fill is probably of short duration. Therefore, no half tubes develop (or with a smaller chance), or if they are formed, they do not develop to the surface. Thus, no complex shaft systems develop. However, according to our observations, shafts (the shaft of the depression marked G-5/a, Hárskút basin) also occur where a flood was directly observable, but no half tubes developed (Figure 2). Simple shafts (Figures 2, 13a) and complex shafts (Figures 3, 13b) develop by surface flooding (or without flooding). According to the average specific shaft lengths, shaft development of such type characterizes the Arabika Plateau in the Greater Caucasus, a part (or some shafts) of the Lagonaki Highland and the areas surrounding the Kőris Mountain. Such a shaft development is called glacial-high mountain surface flood type (on glaciokarst) and surface flood type (in mountains of medium height).

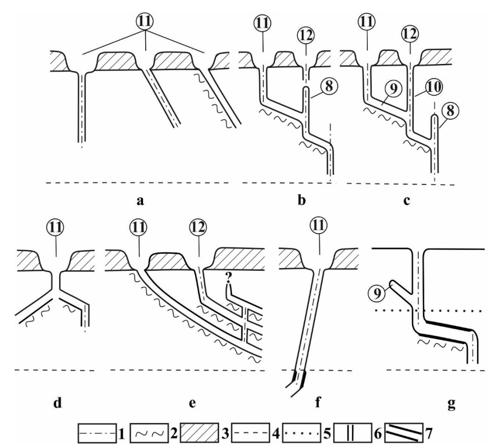

Figure 13. Shaft types according to their pattern based on examples from the Bakony Region [10]

Legend: 1. fracture, 2. bedding plane, 3. superficial deposit, 4. karst water level, 5. former karst water level, 6. shaft section that developed in vadose environment, 7. shaft section that developed in phreatic environment, 8. paragenetic blind shaft, 9. main shaft, 10. tributary shaft, 11. main depression, 12. tributary depression, a. simple shaft, b. shaft system, c. complex shaft, d. bifurcating shaft, e. storeyed shaft, f. shaft with

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active phreatic passage section, g. shaft with inactive phreatic passage section, a-e: shaft with vadose environment, f. shaft with partly vadose and partly phreatic environment, g. the inactive phreatic passage section may develop by the former rise of karst water level or by the former rise of the area

(2) Shafts with a large, but diverse specific shaft length (for instance regarding two shafts of the Tési Plateau, the specific shaft length of the Háromkürtő shaft is 3.43, while that of the Alba-Regia cave is 17.98) and with a varied pattern develop if the flooding can also be connected to surface water influx and a rising karst water level. The duration of karstwater flooding is longer than the flooding of surface origin, which favours the transformation of blind shafts into tributary shafts. Particularly, this is so when there is also a surface water influx above the half tube (Figure 6). Shafts may be complex shafts (Figure 4, 13c), bifurcating shafts (Figures 5, 11, 13d), and storeyed shafts (Figures 6, 13e). The pattern of the shafts is also affected by local morphology and geological conditions (for instance shaft passages are formed above each other to the effect of water influxes developing at newer and newer sites). According to the average specific shaft lengths, the shafts of the Orjen Mountains, the Northern Zone of the Lovčen-Njegusi polje, the Sochi area of the Greater Caucasus, and from the area of the Bakony Region, the shafts of the Kab Mountain, the Tési Plateau and the Hárskúti basin belong to this shaft development type. The Duboki do with a large specific shaft length (4.9) can also be attributed to this group; this developed by an extreme, long-lasting surface flooding. According to Takácsné Bolner [20], the cave does not have any passages of phreatic origin. However, its assemblage developed during an intensively flowing water fill. This can be well interpreted by the long-lasting water fill triggered by the meltwaters of the glacier entering the Njegusi polje. Shafts of this origin belong to the glacial-high mountain karst water and surface flood development type and to the karst water and surface flood development type (Bakony Region, mountain karst of medium height).

(3) Shafts of a large specific length with a phreatic part (Figure 13g) may develop, and these have two varieties. In the first case, inactive phreatic and vadose sections alternate and there are shafts of vadose type below and above the phreatic passages (Figures 7, 8). The second variety is, when the phreatic section is connected by the shaft part of vadose origin from the direction of the surface (Figure 10). The former shaft development type is called glacial karst water and surface flood development type and then phreatic development type. At this time, the karst water occupies the vadose zone. This occurs if the ice covers the karst springs and as a result of this, the karst water is impounded [32]. In this case, a phreatic cavity development takes place in the vadose zone [33]. The shafts of the area of the Lovčen-Njegusi polje (Figure 12) are characterized by such a shaft development, where the specific lengths of the shafts with a less and less elevated floor are larger and larger since the shaft with a less and less elevated floor were flooded by the impounding karst water in glacials with an increasingly greater chance. However, it is without doubt that although there was no ice cover here, the values of specific shaft lengths are great in case of the shafts of the Northern Zone. A possible explanation for this is that the distance between Lovčen and the Northern Zone is small thus, the impoundment of the karst water could have expanded here from the area of ice cover. There is a chance of the impoundment of the karst water on karsts with a lower elevation too such as in case of the shafts of the Kab Mountain and the Tési Plateau in the Bakony Mountains [9,10]. However, this occurs in wet season and it is of short duration. The impoundment of short duration in the vadose zone is not able to create individual phreatic passages, but it contributes to the development of tributary shafts, as already mentioned, in the already existing vadose shaft parts.

In the second case, when the vadose zone is connected to a phreatic passage, a shaft develops with a phreatic passage getting into the vadose zone. For instance the Stirovača cave (Croatia), [34] got from a phreatic environment into a vadose environment. This phenomenon is possible because the glaciokarst becomes elevated to a large extent, and thus, the environment of the phreatic passage is transformed into a vadose environment. A shaft with a vadose environment developing during the uplift is connected to the inactive phreatic passage. Such shafts can be found in the Greater Caucasus (some of the already mentioned shafts of the Lagonaki Highland, e.g. the Absolute cave, the shafts of the area of the Sary-Tala massif, where the specific shaft length of the shaft marked NSS-53 is 12.63, while this value is 11.09 in case of the Su-Akan cave). During the uplift of the Greater Caucasus with a speed of 1-3 mm/year [35], at least 1-2 million years were necessary for the shafts and their phreatic passages to reach their present elevation. Thus, these shafts probably developed preceding the appearance of glaciers in the mountains. The development of their phreatic passages could not have happened below the impounding karst water level since it can be precluded that the glaciers (if they existed) fitting to the level of the Black Sea would have covered the karst springs of the mountains. Thus, the phreatic passages got into a vadose environment as a result of the uplift of the bearing area.

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5. Conclusions

Specific shaft lengths are different for various shafts and karst areas. These are usually larger on glaciokarst areas than on karsts of medium height mountains (Bakony Region). The larger specific shaft length of glaciokarsts can be explained by the greater chance of more intensive surface water supplies (a lot of precipitation, meltwaters of glacial and snow origin) and by the possible existence of phreatic passage parts. The value of the specific shaft length refers to the development trajectory of a shaft and to the karst evolution of the area. The pattern (and development) of the shafts changes radically when they become flooded. In the case of flooding of surface origin or a discontinuous karst water flooding of short duration, the shafts become more complex. In the case of a continuous flooding with a long duration, (the shaft gets into a phreatic environment), parts of vadose origin become complemented by section(s) of phreatic origin.

Factors determining the specific shaft length are the spatial position of the preforming surface, the intensity, degree and duration of the water flow, the closeness of the shaft floor to the karst water level, the impoundment of the karst water, its extent and duration, the possibility of the coalescence with paleophreatic passages.

The shaft development types of glaciokarst (high mountains) are glacial-high mountain surface flood development type (1), glacial-high mountain karst water and surface flood development type (2), where an extreme flood variety can be distinguished (see Duboki do), glacial karst water and surface flood later phreatic development type (3), and shaft with a phreatic passage that got into the vadose zone (4). Among the studied areas formerly covered by ice, the karst water level could have impounded to the surface of the karst in some parts of the Lovčen Njegusi polje.

Three types that can be distinguished on karst of medium-height mountains, namely surface flood shaft development type (Kőris Mountain and its vicinities), karst water and surface flood development type (Kab Mountain, Tési Plateau, Hárskút basin) and tectonic shaft development type (Keszthely Mountains).

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