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Limitations of Drawdown Doline Development on Mountainous Glaciokarst

Márton Veress

Department of Geography, Savaria University Centre, Eötvös Lóránd University, H-1053 Budapest, Hungary; veress.marton@sek.elte.hu

Abstract: In this study, we look for a relationship between the lack of drawdown dolines and the karren formation taking place on the bare surfaces of glaciokarsts. Along the profiles, the specific width and density of the most common karren such as rinnenkarren, grikes, and pits were studied, while in three mapped areas, the depth and depth change in rinnenkarren were investigated in various environments. Mainly, carbonate dissolution of a low degree takes place at atmospheric CO_2. Therefore, in the case of carbonate dissolution taking place on the bare surfaces of glaciokarsts, the chance of cavity formation in the epikarst is analysed at karren of percolation origin (grike, pit) and at karren of flow origin (rinnenkarren). Vertical infiltration and local cavity formation are only possible at pits (the CO_2 quantity increases due to the soil effect in them). Therefore, below the bare surfaces of glaciokarsts, as a result of low dissolution capacity and infiltration of low degree, there is no cavity formation, or it is weakly developed. The piezometric surface is absent or it is local, its surface is not deflected. Drainage is not heterogeneous, but it is local, which does not favour drawdown doline development since drawdown dolines develop in the case of epikarst with well-developed, heterogeneous cavitation and deflected piezometric surface.

Keywords: glaciokarst; epikarst; drawdown doline; karren; laminar flow; turbulent flow

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1. Introduction

In this study, it is investigated why there are no solution (drawdown) dolines on the bare surfaces of high mountains (glaciokarsts). Glaciokarst, the high mountainous variety of which is mountainous glaciokarst, is karst being subject to glacial erosion. In the area of high mountains (glaciokarsts) fluviokarstic, glaciokarstic, and karsti-glacial as well as karstic and periglacial features are distinguished [1].

1.1. The Epikarst

In karst areas, epikarst constituted by surface features (karren) and epikarst built up of subsurface cavities are distinguished [2,3]. The thickness of the cavernous part of the epikarst is 10–30 m [4–6]. Its lower boundary is the saturation level, below which the degree of secondary porosity decreases therefore, the water arriving at the karst flows back at this level. The surface of backwater is the piezometric surface [3], the level of which may fluctuate. The water of the epikarst may flow laterally [7].

1.2. Karst Features of Glaciokarst

Dolines are closed depressions of karst areas [8,9]. On soil-covered karsts, solution dolines are formed, while on covered karsts, subsidence dolines develop [10–12]. Among solution dolines, drawdown dolines, point recharge dolines and inception dolines are distinguished [5,13]. Drawdown dolines are large depressions with gentle slopes, below which the piezometric surface is deflected in the bedrock [5,6,14], which can be traced back to horizontally different, heterogeneous cavity formation and therefore, to different vertical drainage below the doline. In high mountains, another solution doline variety, the schachtdoline is differentiated [15]. These features are depressions with steep slopes, small diameter, and relatively great depth, their floor is plain and covered with rock debris, but they may also continue in grikes [15,16].

In high mountains (and on mountainous glaciokarsts), due to the vertical zonality of vegetation and soil, the surface karst landscape also has a zonal development (Figure 1), but with altitude increase, especially because of the diversity of karren features, the diversity of karst features first increases and then decreases, but with altitude change, the density of karst features also changes (Figure 1).

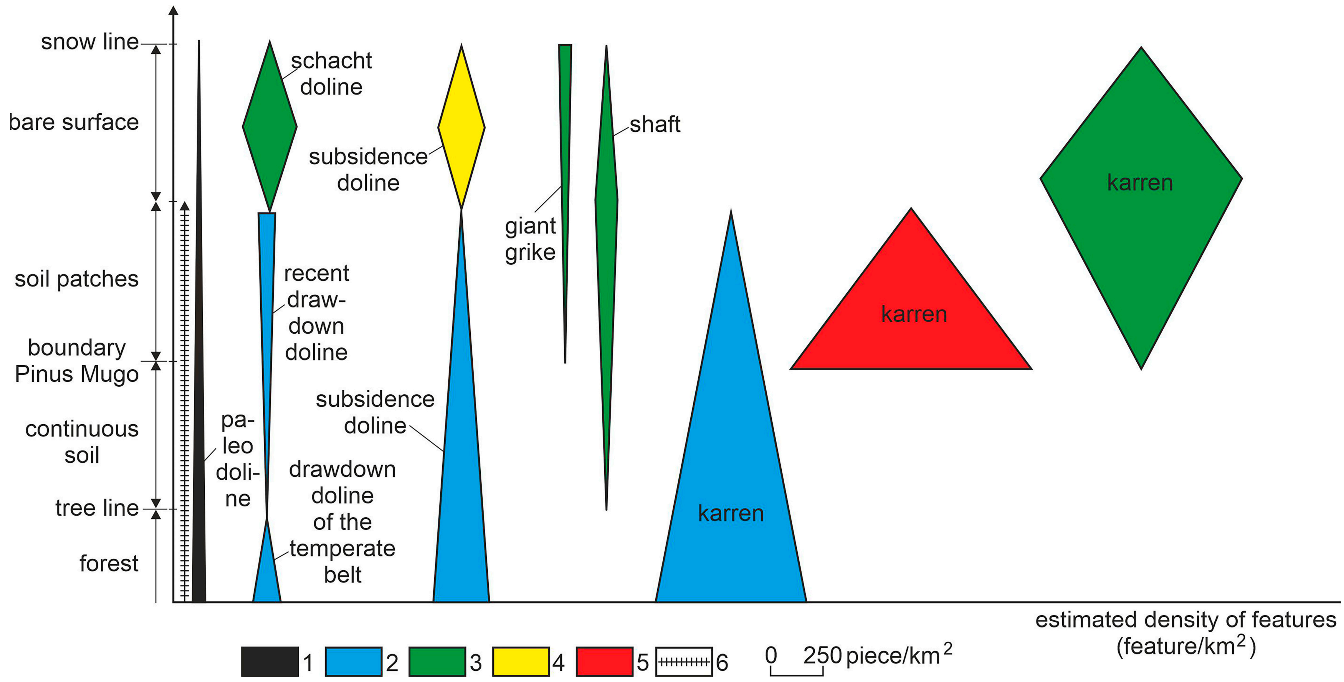

Figure 1. Zonality of karst features on glaciokarst. Legend: 1. in any environment, 2. only below soil or in soil-patch environment, 3. on bare surface, 4. at cover with debris, 5. receives water from soil patch, 6. soil cover.

In high mountains, Pleistocene climate changes resulted in the shift of geomorphological and vegetation zones. In the interglacials, the boundaries of vegetation belts shifted upwards, which resulted in the development of drawdown dolines with an altitude more elevated than the current one. In the glacials, these terrains were covered with ice and drawdown dolines were transformed by glacial erosion. Nowadays, due to the repeated retreat of ice, the drawdown dolines of interglacials became exposed. These are large (solution) dolines and paleokarst features.

On glaciokarst, karst and glacial features influence and promote each other's formation and development [16]. Thus, for example, former drawdown dolines are the sites of ice accumulation and thus, of glacier development. However, glacial features affect karstification. For instance, surfaces with bedding planes that developed by ice are important sites of karren formation.

Above the tree line, in the zone of alpine fields more and more bare surfaces of larger and larger expansion appear with altitude increase. In addition to karren, schachtdolines, shafts, and giant grikes also occur on these surfaces. Some bare surface patches do not receive water from soil patches, while others do, and thus, increase the quantity of CO_2 in the water.

In the forest belt, drawdown dolines being characteristic of temperate soil-covered karsts are widespread. On glaciokarsts, drawdown dolines are also present. Their paleokarstic, inactive variety is widespread in the area of former ice cover. Their active varieties also occur, but at a lower altitude in the tree belt. They also occur on soil-covered surfaces above the tree line (Figure 2A). The latter may only have developed after ice retreat therefore, the term "recent drawdown doline" is used for these features since they are distinguished from older, greater, but active drawdown dolines of these areas with forests [17,18]. In size and morphology, this doline type shows a transition towards schachtdolines.

Figure 2. Karst features: (**A**). recent drawdown dolines (Maglič Mountains), (**B**). paleo drawdown doline with subsidence dolines (Totes Gebirge), (**C**). schachtdolines (Totes Gebirge), (**D**). giant grike (Julian-Alps). Legend: 1. interglacial giant doline, 2. floor remnant of glacier trough, 3. suffosion doline.

Schachtdolines (Figure 2C) already occur on bare surfaces, in the Pinus Mugo belt they occur especially at places where soil and vegetation develop in patches. Schachtdolines can be observed with recent drawdown dolines together, but with altitude increase, only schachtdolines are widespread. It can be generally stated that the lower the degree of soil cover on a surface section, the more common the occurrence of schachtdolines.

Above the tree line, on terrains with higher and higher altitude, shafts are more and more common, and their size also increases with altitude increase. In their environs, giant grikes also occur. Their length is several hundred metres and their depth may be several metres (Figure 2D).

Giant dolines (Figure 2B) and uvalas are large, their diameter may even exceed 1000 m [15,18]; they are lined with till and frost weathering debris, and they are mostly complex. There are subsidence dolines on their cover and ponors at the termination of the cover [16]. They are paleokarst features, which are of preglacial or interglacial age, but of polygenic genetics [15]. This is proved by the fact that they are lined with till and they are dissected by glacial erosion features (roche moutonnée). These features are no longer active, but recent karstification takes place inside them [16]. They are drawdown dolines, in the development of which glacial erosion, snow erosion, and periglacial processes also played a role [19–21]. They may occur at any altitude from cirques downwards in the area of glaciokarsts [22]. On glaciokarsts, subsidence dolines are widespread at every site where there is cover, which is often limestone debris [16]. Their number is large and their size is small.

With altitude increase, karren (Figure 3), both karren of percolation origin (kamenitza, grike, Schichtfugenkarren) and of flow origin (rillenkarren, rinnenkarren, or channel, meanderkarren, wandkarren and trittkarren) are more and more dominant on bare surfaces [16,23,24]. Karren of flow origin may develop by laminar or turbulent flow [25].

Rillenkarren are channels with a width and depth of some centimetres which wedge out and are aligned densely (continuously) [26], their length is 5–15 cm in the Alps [23], but Sauro [27] states that rillenkarren with a length of 10–50 cm (Val Lagarina), and according to Mazari [28], rillenkarren with a length of 50–200 cm (Himalaya) also occur.

Veress [23] differentiated two types of rinnenkarren. Type A rinnenkarren have no tributary channels, are of smaller width and depth, and they do not have a pit inside them. Type B rinnenkarren often constitute channel systems and have several tributary channels, a significant width and depth. They develop on slopes of lower inclination, pits also occur on their floors. Rinnenkarren already develop on slopes with an inclination of 5–10°. The density of type A rinnenkarren increases with the increase in slope inclination (until a slope inclination of 60–70°), while the density of type B rinnenkarren decreases and they are no longer present on slopes with an inclination larger than 50° [23].

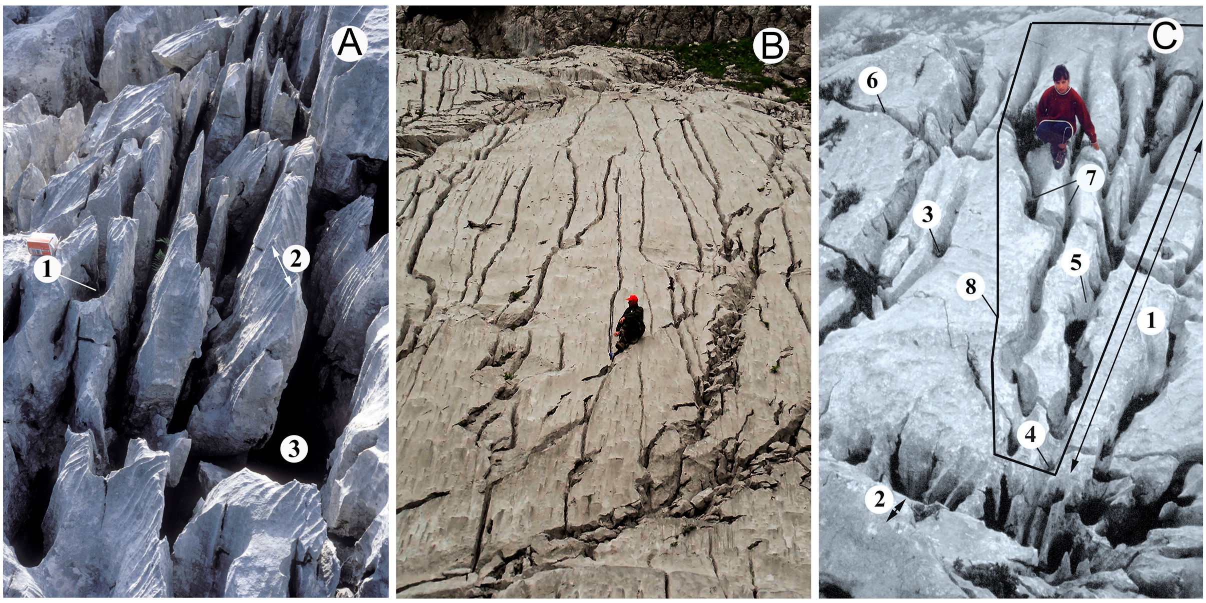

Figure 3. *Cont.*

Figure 3. Karren features. (**A**). grike (Totes Gebirge) Legend: 1. pit, 2. rillenkarren, 3. grike, (**B**). type A rinnenkarren (Totes Gebirge), (**C**). karren features of terrain with bedding planes. Legend: 1. bedding plane, 2. head of bed, 3. channel bottom pit, 4. channel end pit, 5. main channel, 6. grike, 7. tributary channel, 8. channel system, or type B rinnenkarren system (Totes Gebirge), (**D**). rinnenkarren that developed along bedding plane between beds (Julian Alps).

1.3. Dissolution on the Bare Surfaces of Glaciokarst

During its dissolution, the rock is dissolved and then the material that reached the water is transported away during its flow. Carbonate and hydrocarbonate dissolution is distinguished [29]. During carbonate dissolution only a little quantity of material enters the water (according to Bögli [30], Czájlik [31]). In the case of water saturated with atmospheric pCo_2, the degree of dissolution depends on the type of the limestone and the duration of dissolution thus, the duration of the interaction between the water and the rock. Its value may reach 50 mg/L [32].

In the case of both types of flow (laminar and turbulent), dissolution efficiency increases if unsaturated water arrives at the place of dissolution. While in the case of hydrocarbonate dissolution, the quantity of dissolved material increases during the increase in flow rate (see below), in the case of carbonate dissolution, it decreases since the duration of interaction between the unsaturated water and the rock decreases. Indirect evidence for this is the fact that on rocks with high primary porosity, where there is intensive water motion (chalk, coral limestone), no epikarst develops because the dissolution of percolation origin is of a low degree.

The dissolved material may reach the flowing water by molecular diffusion or by eddy diffusion [33]. In the case of turbulent flow, the material is transported into the boundary layer by molecular diffusion [10]. If the rate increases, the boundary layer thins out [25], the vorticity reaches the rock, which increases dissolution because unsaturated water interacts with the rock. Dissolution is 10^4 times larger than in the case of molecular diffusion [34]. In the case of carbonate dissolution, at low slope inclination (about 0–5°) a surface water flow of low rate is not able to transport away the material by molecular diffusion. No karren features of flow origin develop on such slopes. In the case of medium slope angle (about 5–20°), especially at long slopes, the flow is turbulent because of the larger quantity of water since more water flows in the channels due to lower channel density. Eddy diffusion is able to transport the ions of the boundary layer away, if the vortexes reach the rock wall, they even increase dissolution capacity by eddy diffusion. In this domain large karren of flow origin develop, mainly type B channel systems. In the case of higher slope angle (about 20–65°) due to the great number of channels, the water output is lower in the channels, the duration of turbulent flow is even shorter and thus, eddy diffusion is also. However, there is not enough dissolved material for eddy diffusion if vorticity does not reach the rock wall during carbonate dissolution. Karren features of flow origin (type A channels) are formed, but these are of small size.

The CO_2 supply of bare surface parts is very diverse. There are slope parts which obtain water from soil patches and thus, CO_2 while others do not obtain water. At former sites, carbonate dissolution is dominant under current atmospheric CO_2 level, while at the latter hydrocarbonate dissolution also takes place temporarily.

The above-described features primarily occur in the glacier valleys of the karst, mainly in troughs. The slopes of troughs are constituted by cuesta surfaces of glacial erosion origin (Schichttreppenkarst). The bedding planes of cuestas of Schichttreppenkarst are separated from each other by surfaces of head of bed of different height and inclination (Figures 4 and 5) [16,35–37]. There are reasons for the development and karren formation of surfaces of bedding planes. Thus, the rock is well-bedded (1), glacial erosion created surfaces of bedding planes (2), the layers of the nappes constituting the mountains and thus, their bedding planes are of different inclination due to tectonic reasons (3), dissolution conserves the plain surfaces of bedding planes (4), and the meteoric water arriving here flows unhindered and fast on these plain, but well-inclined surfaces (5). Conditions 1 and 2 are for bedding plane development, while conditions 3, 4, 5 are for their intensive karren formation. Bedding plane surfaces are the main distribution areas of karren features of flow origin (within this rinnenkarren, Figure 2B).

Figure 4. Cuestas (Dachstein, Austria).

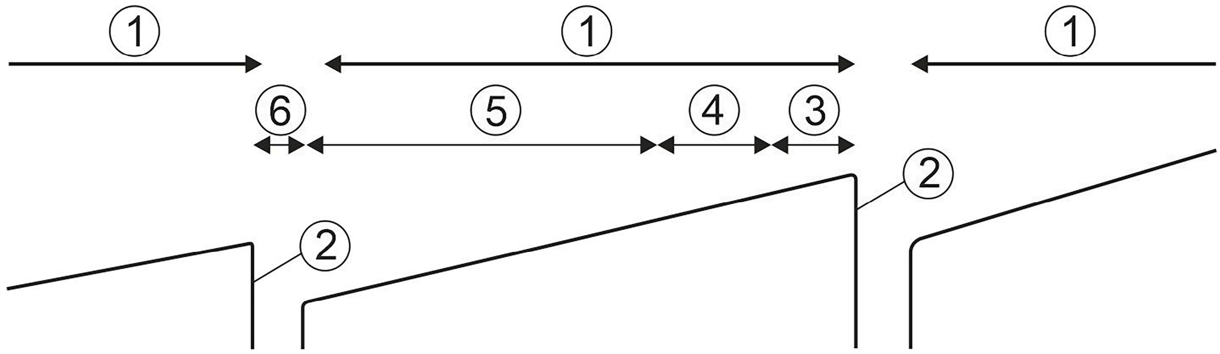

Figure 5. Cuesta units of troughs. Legend: 1. bedding plane part of cuesta, 2. part of cuesta with head of bed, 3. rillenkarren, 4. Ausgleichsfläche, 5. rinnenkarren, 6. pit.

2. Methods

The total width and density of rinnenkarren, grikes, and pits along a 1-metre distance of the profile was measured along the profiles on the bedding planes of bare, cuesta surfaces affected by glacial erosion (This is called specific width). These features are in the focus of our study because these are the most common on these surfaces [23]. The data for the calculation of specific width values were obtained from the sample sites of Totes Gebirge, Dachstein (Austria), and Julian Alps (Slovenia). A line was marked with a string (at about a distance of 5–20 m) and the width and the number of karren features occurring along the line were measured, taking into consideration their type.

The number of different karren features was collected from three bare surface sections. Two of them are described from the maps of these areas in Figures 6 and 7. From the maps, the number of rinnenkarren, grikes, and pits and the depth values of some rinnenkarren were also collected. The measurements and mappings were made in a glacier valley below Tagl Peak in Totes Gebirge (However, further measurements were made in other sample sites of Totes Gebirge and the figures and pictures of this article also include sample sites of Dachstein and Julian Alps). The above-mentioned glacier valley was selected for our study since it was relatively easily and quickly accessible from our accommodation, and there were a number of bedding plane surfaces at this section of the glacier valley with many karren features. The maps were made using the following method:

- Contour line maps of the studied area were made with theodolite.
- A net was stretched (it was oriented and put into a horizontal position, the intervals of the net had an expansion of 50 × 50 cm) in the area to be measured. The opposite edges of karren features were fixed in the intervals and their sites were connected. At these sites, the depth of karren features, as well as inner, smaller karren features occurring in them was measured and marked on the maps. Sample sites marked 1/9XIX/1 and1/9/XIX/3 were mapped with this method.
- In the case of a rinnenkarren system, the site of the edge of features, the width and depth of the features were measured along profiles being perpendicular to the main channel (the measurement sites were marked at a 1 m distance). (If there were smaller karren features in the channel, they were also measured), then the features were drawn by connecting the edges. The rinnenkarren system marked 4 was measured by this method.

The fact that the data concerning which studied sample site was used in our study does not influence the conclusions. The reason for that is that the sample sites were not selected by a certain concept, but by accident. However, the studied sample sites can also be regarded specifically because there are many karren areas in the mountains which are similar to the selected areas. Therefore, the results and the consequences can be regarded as typical.

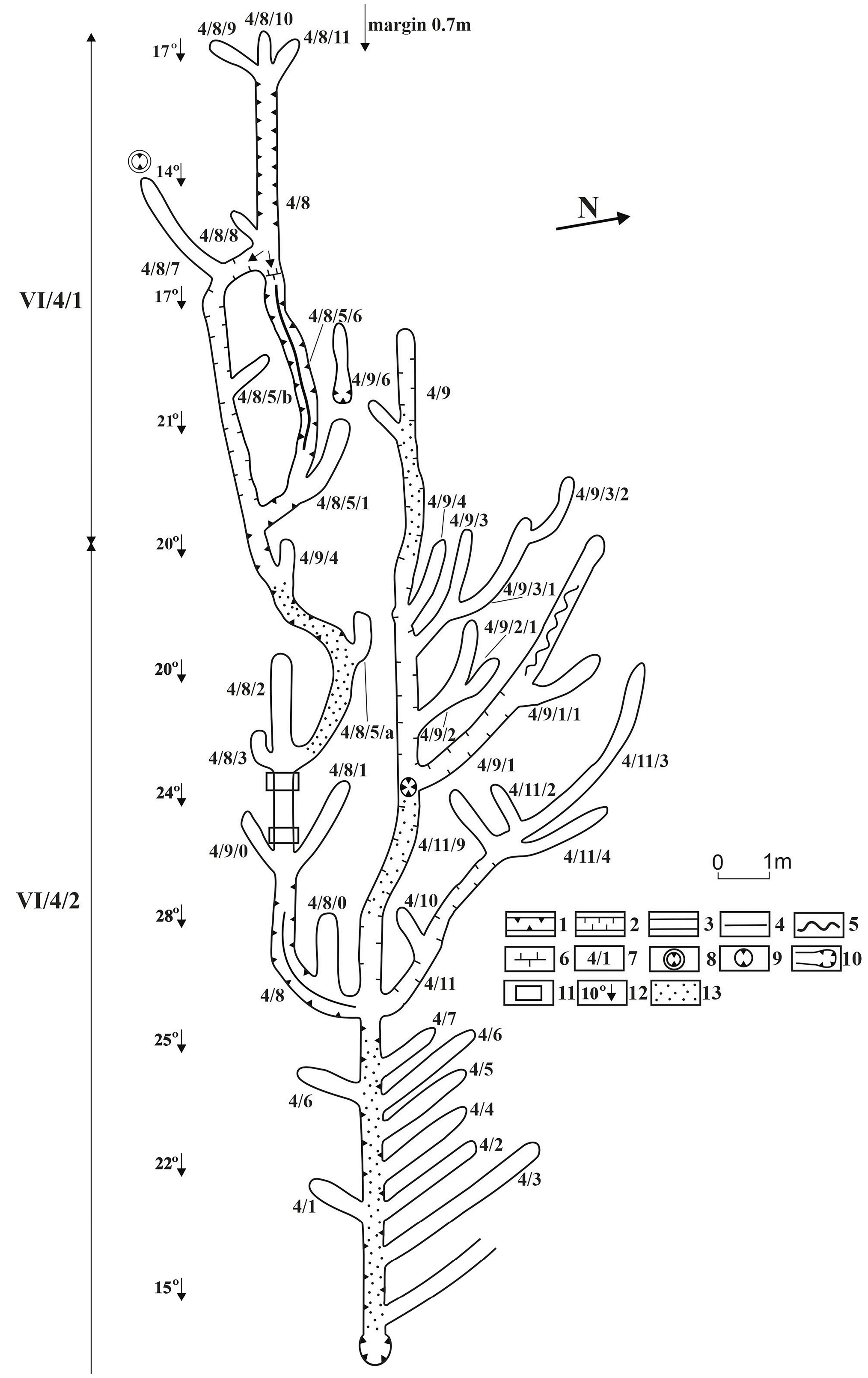

Figure 6. Map (with mark V/4) of one of the channel systems of the bedding plane of a cuesta. Legend: 1. type B main channel, 2. type B tributary channel, 3. type A channel, 4. inner channel (of type III), 5. meandering, type III channel, 6. floor divide, 7. identification code of channel, 8. pit in general, 9. basin of channel floor, 10. pit of channel end, 11. rock block, 12. slope direction and slope angle, 13. soil and vegetation on channel floor.

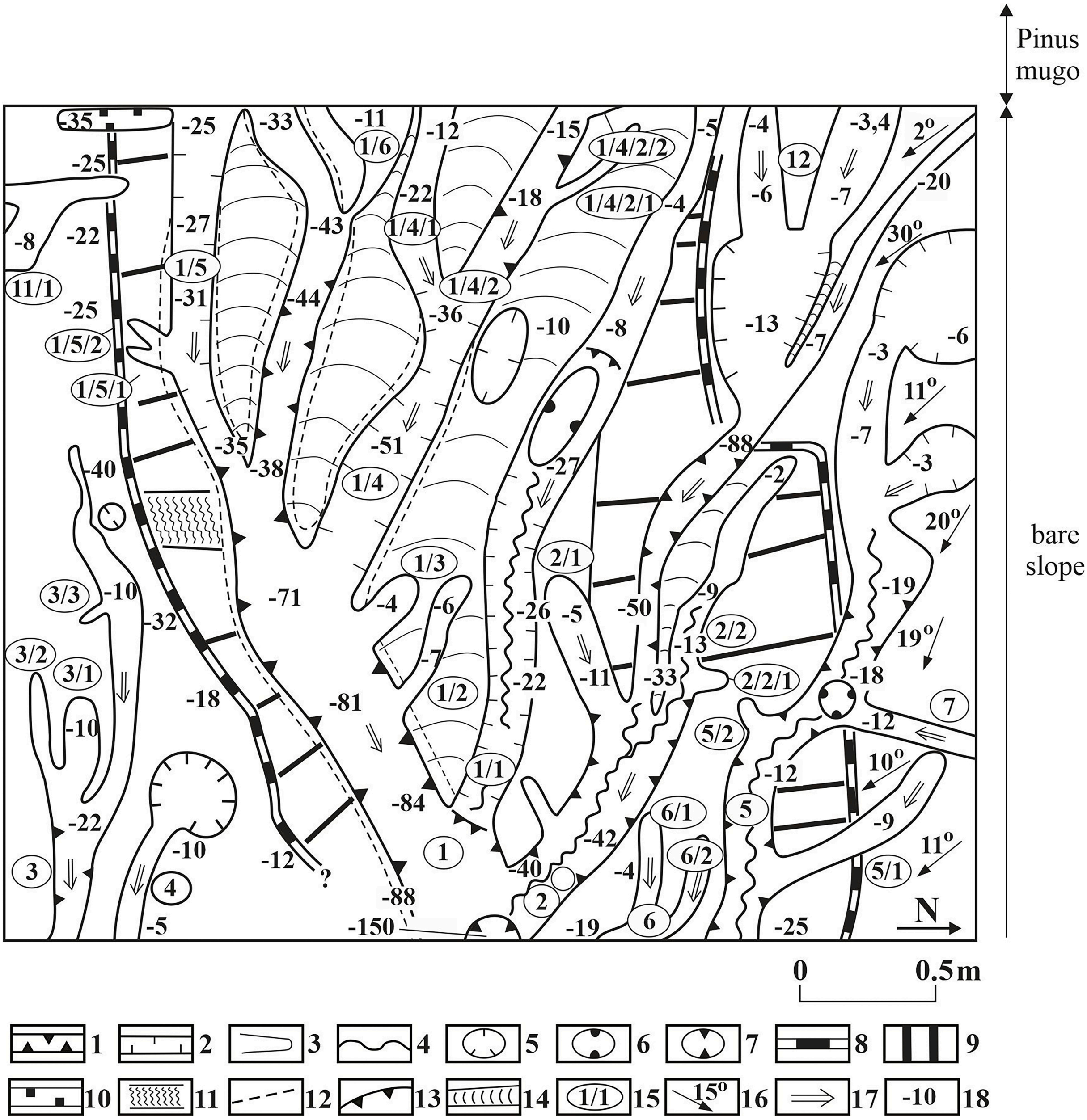

Figure 7. Map of rinnenkarren situated below Pinus Mugo patch [36]. Legend: 1. type B main channel, 2. type B tributary channel, 3. type A channel, 4. inner, type III (channel floor) meander, 5. kamenitza, 6. floor kamenitza, 7. pit of channel end, 8. margin of basin bearing rinnenkarren, 9. side slope of basin, 10. grike, 11. semi-circular indentation, 12. overhanging wall, 13. step, 14. interchannel ridge, 15. identification code of channel, 16. slope direction and slope angle, 17. direction of channel floor inclination, 18. depth of karren feature (in cm).

3. Results

On bare terrains, rinnenkarren are the most widespread. The number of grikes is more considerable at sites where the slope angle is low. Thus, their density is 0.83 in a 1-metre distance on a slope with an angle of 4°. However, it is nowhere higher than 1 within 1 metre. The density of pits is even lower, and they do not occur along every profile. The density of rinnenkarren may also be above 1, but at sites where it is lower, this value is almost 1 (Table 1). The data of Table 1 already show that both the specific width and the density of rinnenkarren increase with the increase in the inclination of the bearing slope, but these values decrease in the case of grikes and pits.

Table 1. Specific width value and density of some karren features on vegetation-free terrain. Based on the data of Veress [23].

Profile Code	Bearing Terrain			Grike		Pit		Rinnenkarren	
	Altitude	Slope Angle	Number of Karren Features	f.sz. [cm/m]	d. [Grike/m]	f.sz. [cm/m]	d. [Pit/m]	fsz. [cm/m]	d. [Rinnenkarren/m]
T-1/1999	1859	31°	27	4.93	0.64	5.0	0.29	15.64	1.0
D-2/1999	1820	17°	31	1.85	0.2	2.75	0.2	20.75	1.15
D-3/1999	2051	21°	35	4.44	0.4	-	-	15.85	0.77
HIII-2/1999	2090	4°	16	19.67	0.83	7.22	0.06	-	-
HIII-1/1999	2098	8°	20	-	-	-	-	14.90	0.97

Notice: without kamenitza, trittkarren, gratekarren. T: Totes Gebirge. D: Dachstein. HIII: Julian Alps. f.sz. specific width; the quotient of the total width and profile length of karren feature occurring along the profile. d: density in a 1 m distance.

In the mapped areas, two of which are shown in Figures 6 and 7, if the number of the three karren features (rinnenkarren, grike, pit) is taken into consideration, it can be stated that rinnenkarren are predominant (Table 2). It can also be established that on the slope which obtains water from a soil patch, the depth of rinnenkarren is larger than at sites where it does not. The depth of rinnenkarren increases in slope direction both on slopes with soil patches and on bare slopes.

Table 2. Karren features of two mapped areas and of a mapped channel system (marked V4) (Totes Gebirge).

Slope Type	Rinnenkarren	Meanderkarren	Grike	Kamenitza	Trittkarren	Pipe	Area [m^2]
Slope (part) fed from Pinus mugo patch	19	1	-	3	1	1	4.96
bare slope C1/9/XIX13 [1]	42	3	2	3	24	0	17.17
bare slope (V) [1]	44	1	-	1	-	2	66

Notice: their detailed map is in the work of Veress [35]. [1] its water is originated from bare slope part.

It can also be established that the depth of rinnenkarren which also receive water from soil patches is larger than the depth of those which do not obtain water from soil patches. The depth of rinnenkarren increases from their upper end to their lower end (Table 3).

Table 3. Depth data of some rinnenkarren of a slope enclosed by Pinus Mugo and a bare slope.

Mapped Area	Code of the Selected and Measured Rinnenkarren	Depth (cm)	Average of Depth [cm]
Slope (part) fed from Pinus Mugo patch (1/9/XIX/1)	1	25(13.15), 27(52.61), 31(65.75), 71(137.56), 81(220.92), 84(255.11), 88(304.45)	45.57
	2	4(7.89), 6(31.50), 13(78.9), 88(118.35), 50(184.1), 35(210.4), 42(263.3), 40(254.50), 88(315.6)	40.67
	5 [1]	6(0.0), 3(39.45), 7(78.9), 19(131.5), 18(170.95), 12(210.4), 25(270.89)	12.85
bare C1/9/XIX/3	5	13(18.72), 106(78.00), 9(124.8), 286(202.8), 20(249.6)	16
	7	6(7), 15(18.72), 12(140.4), 27(171.6), 52(296.4), 42(343.2)	25.67

Notice: The number in brackets is the distance of the measured depth of a given site of the rinnenkarren from the upper end of the feature. [1] its water is originated from bare slope part.

4. Discussion

Williams [5,6,14] claims that drawdown dolines and the epikarst are interdependent. The water of drawdown dolines ensures the development of the epikarst, which does not only mean cavity formation, but it also means the development of its heterogeneity and thus, heterogenous vertical drainage. The main drainage is below the doline centre. The doline centre deepens the fastest here because surface streams converge here and thus, dissolution is also of the highest degree at this site. The piezometric surface reflects heterogeneous vertical drainage. Thus, its surface forms an indentation.

In the Bakony Mountains, where no drawdown dolines occur, on covered karsts, the electric resistivity values of the epikarst are low. The reason for this is that the epikarst is weakly developed (partly because of the lack of drawdown dolines) and thus, the piezometric surface is of high position thus, the VES measurements penetrated below this level, triggering low resistivities due to the presence of wet cavities. However, the VES measurements show that below drawdown dolines, bedrock resistivities are high because there are a lot of waterless cavities above the piezometric level which is of deep position. A possibility for the development of the cavernous part of the epikarst is overviewed below, taken into consideration the most specific karren features.

The depth of rinnenkarren (although there are decreasing sections) increases in slope direction. Their large depth and depth increase can only be explained by turbulent flow, while rillenkarren are at most 1–2 cm deep and wide and their length is only some centimetres (Figure 3A). Based on literary data, at atmospheric CO_2, the rock is of carbonate dissolution, and it becomes of hydrocarbonate dissolution if this value is six times larger [30].

If small rillenkarren develop due to the dissolution effect of sheet water with meteoric water origin in the case of laminar water flow [26], it takes place by carbonate dissolution and molecular diffusion. However, their development is also traced back to partial turbulent flow where eddy diffusion has an impact. Thus, according to Horton [38], on convex slope, where the sheet water thins out, the flow is laminar, while on concave slope, where the sheet water thickens out, the flow is turbulent. Glew and Ford [39] state that the slamming raindrops result in turbulence at places where the sheet water is thin, but at sites where it thickens out, the raindrops are no longer able to trigger turbulence. Since the width and depth of rinnenkarren may be 50 or 100 times larger than those of rillenkarren, and as they receive their water from rillenkarren or from karren-free surfaces, eddy diffusion takes place at rinnenkarren, in their rivulets, while rillenkarren are regarded to have been developed by laminar flow.

The great depth of rinnenkarren can be explained by the eddy diffusion that takes place during turbulent flow in their rivulet [25]. Their depth increase can be explained by increasing water quantity (junction of tributary channels) and by faster and faster water motion towards the lower part of the slope. Rinnenkarren which do not obtain water from soil patches may have different depths because the duration of eddy diffusion is different as a result of turbulence of changing duration which is due to changing water quantity or because different rinnenkarren receive water of different quantity.

On slopes with soil patches (Figure 7), the larger depth of rinnenkarren is the result of biogenic CO_2. Therefore, in addition to turbulent flow, the extra CO_2 also contributes to the deepening of rinnenkarren (hydrocarbonate dissolution). Evidence for this is the fact that the rinnenkarren (Figure 7 feature marked 5) which despite being on the slope with Pinus Mugo, receives no water from soil patch, its depth relations are similar to the depth of the rinnenkarren with bare slopes.

At the upper part of slopes where flow is still laminar, turbulent flow is present at most in a limited way and for a short duration, as a result of carbonate dissolution and molecular diffusion, the degree of dissolution is low. Because of this and fast saturation, the here developed rillenkarren are of small depth and the rillenkarren belt is also of small width (its width is approximately 5–10 cm). Cavity formation can be excluded both in the case of rillenkarren zone and Ausgleichsfläche since saturation takes place fast in the case of the former, while in the area of the latter, the water is already saturated. No infiltration is possible at rillenkarren because of their short length either. The water is separated into rivulets below Ausgleichsfläche (Figure 8), at which turbulent flow causes dissolution and thus, the development of rinnenkarren [25]. On steeper and steeper slopes and on a lower and lower part of the same slope, in rinnenkarren, the flow is faster and faster, and turbulence exists for a longer and longer time in the rivulet of the rinnenkarren. The more water arrives at the rinnenkarren (in case of intensive rainfall and large catchment area), of the longer duration the turbulent flow during water flow. As the duration of eddy periods increases, eddy diffusion dissolution may take place, during which the rock is dissolved and the dissolved material may be transported away.

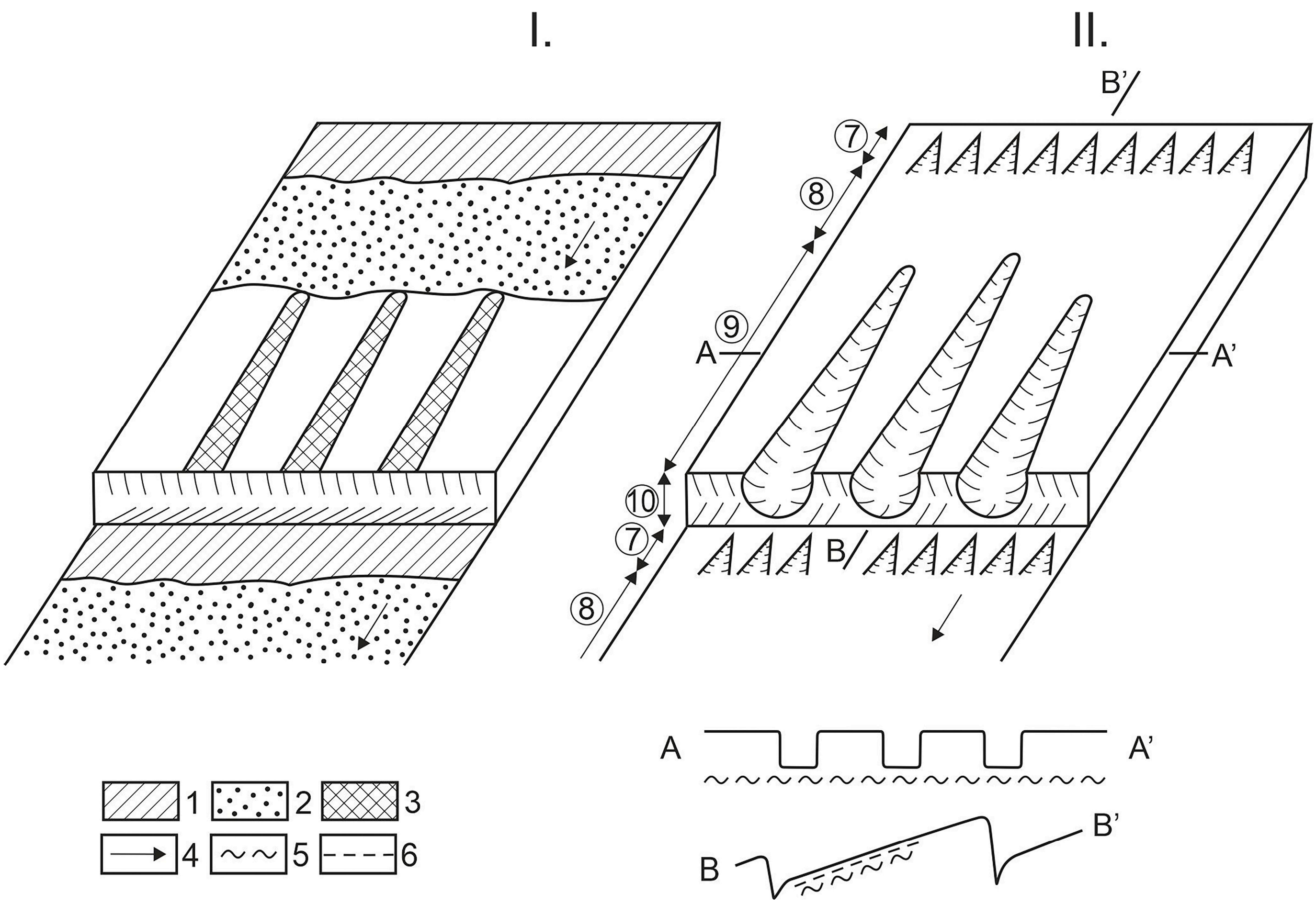

Figure 8. Karren belts of slope with cuestas and development of rinnenkarren. Legend: (**I**). state preceding karren formation, (**II**). slope affected by karren formation, 1. sheet water with dissolution capacity, 2. saturated sheet water, 3. rivulet, 4. slope direction and water flow, 5. saturation level, 6. piezometric level, 7. rillenkarren, 8. Ausgleichsfläche, 9. rinnenkarren, 10. pit.

Fast water motion does not favour infiltration. If it does occur, no turbulent flow is possible, only of percolation origin, which does not result in cavity formation in the rock because of saturated water or of becoming saturated in the case of short infiltration distance. The lack of cavities further decreases the chance of infiltration. Pits may develop in the rinnenkarren where dissolution increases locally because the rivulet entering from the tributary channels generates intensive turbulence 10. At these over-sinking sites and at channel ends, soil, and vegetation development may begin, which results in the increase in CO_2 quantity and thus, in pit development.

Basically, rinnenkarren floors are balance surfaces at which deepening only occurs if the duration of turbulent flow increases. Thus, the saturation level is at the floors. All this results in the fact that the cavernous part of the epikarst is absent below a surface dissected exclusively by rinnenkarren (Figure 9a). However, in the rock below the floors there is no saturated water either because rinnenkarren do not develop along fractures [23]. If there is no infiltration and cavity formation, there is no piezometric level either.

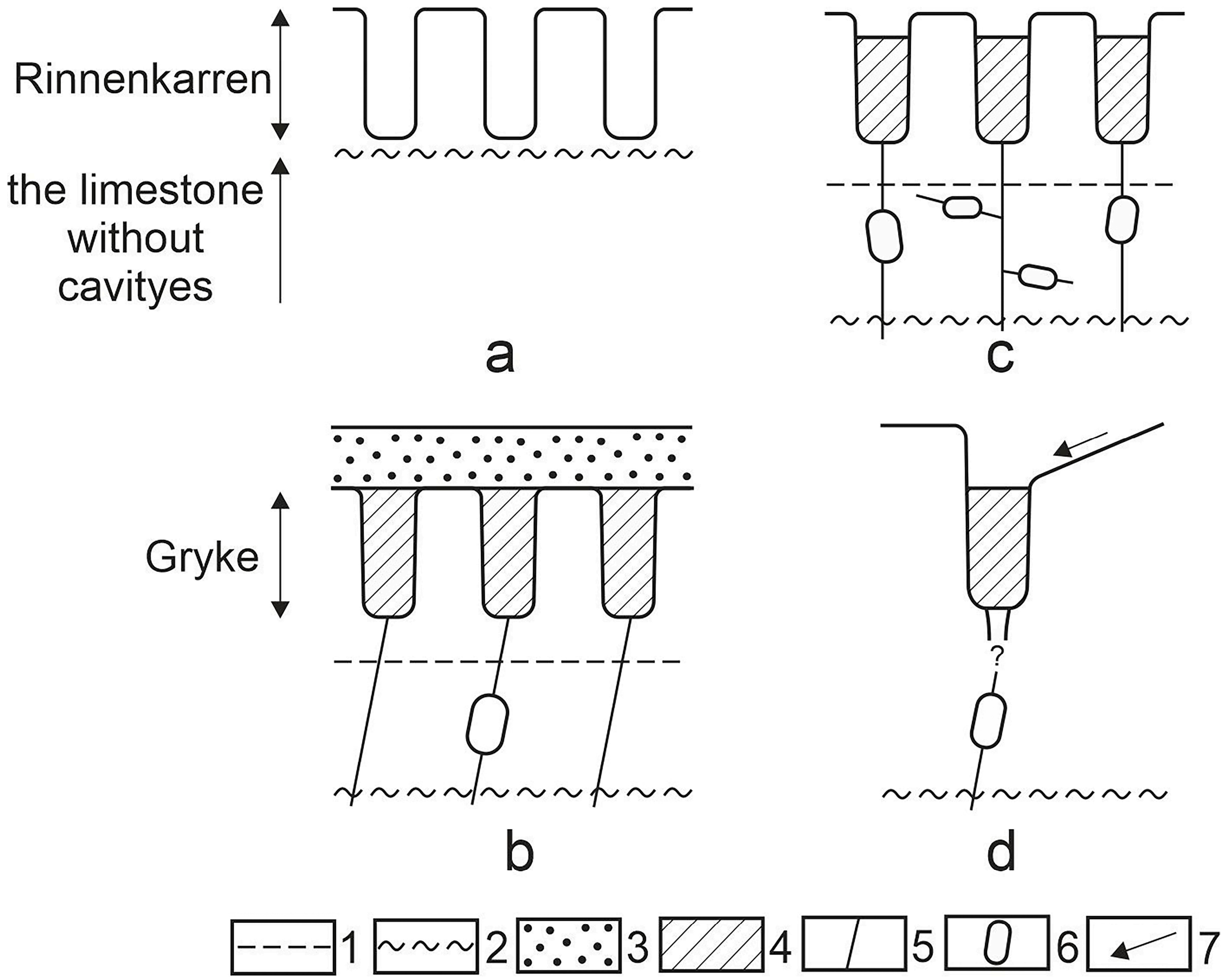

Figure 9. Saturation level at different karren features. Legend: (**a**). at rinnenkarren, (**b**). at grikes, (**c**). at pit group, (**d**). at channel end pit, 1. piezometric level, 2. saturation level, 3. soil, 4. fill in karren feature, 5. fracture, 6. cavity, 7. water flow in rinnenkarren.

The depth and width of grikes may even approach 1 m, during the development of which, the rock is detached into blocks [40]. Their floor does not always terminate in the rock, but they gradually go into the fracture along which they were formed. As a result of percolation, since molecular diffusion is responsible for dissolution on bare surfaces, it results in the fast saturation of the water in the case of dissolution by rainwater. As they may also have snow fill during snow melt, the dissolution process is of long duration therefore, dissolution may penetrate to a great depth, which can be intensified by soil formation on their floor since in this case the CO_2 quantity increases. Therefore, below grikes the water may have a greater expansion in the rock, but since the water becomes saturated before it seeps into the fracture, no extended cavity formation can be expected, at most limited cavity formation is possible (Figure 9b).

Pits are water inlets into the karst. However, in the case of solitary pit (on the floor and at the end of rinnenkarren), the epikarst is local; therefore, neither the water nor the piezometric level can exist in the rock (Figure 9d). However, in the case of pits with cluster development, cavity formation is more expanded and even a piezometric level may develop in a limited way (Figure 9c).

The water budget of karren surfaces can be put into the following varieties:

- On the surface with bedding planes, if exclusively rinnenkarren is present, the water of the bedding plane flows down completely from the bedding plane. There is no cavity formation, and there is no water in the rock. This situation occurs at type A rinnenkarren where pits are absent.
- On the surface with bedding planes, on the floor of rinnenkarren (if they are of type B and constitute channel systems), pits occur. The water of the bedding plane flows into the pits. A limited cavity formation may take place below the pits after soil formation. Local cavity formation (with water in the cavities) may develop in the environment of pits, but they became separated from each other.
- Similar circumstances occur if the rinnenkarren of bedding planes terminate in pits. The water of rinnenkarren flows into these. Local cavity formation takes place in this case too, with water fill.
- At larger patches of grikes there is no cavity formation, but water has a widespread presence below the patch in the rock.
- At pit patch, there is cavity formation and water fill is possible in the rock below the karren, with piezometric level.

On the bare surfaces of glaciokarsts, the cavernous part of the epikarst does not develop (rillenkarren, rinnenkarren, grike); if it does, it is only formed in small expansion and it is underdeveloped (pit). The epikarst cavities of glaciokarst that were exposed by glacial erosion are paleoepikarsts and they did not develop in bare surface environment. Although recent cavity formation may rarely occur, it is due to the fact that to the effect of a specific circumstance, karren formation was placed below the surface, on the bedding plane that separates the beds [23]. Limited cavity formation may develop in the rock, along the bedding plane where rinnenkarren is formed (Figure 3D), or in karren caves (Figures 10 and 11). In the beginning, at percolation by laminar flow, and then more and more by turbulent flow. However, at these sites, the karren caves open onto the surface (Figure 12) and do not take part in the development of the cavernous part of the epikarst. Below the floor of rinnenkarren, the degree of cavity formation increases if there are many pits on the floor (Figure 13). However, the above-mentioned processes and their related features are rare.

Surface dissolution conditions (steep, bare slopes, and thus, fast flow) favour widespread surface dissolution and they do not favour depression development. In the lack of this, neither the cavernous part of the epikarst nor the vertical drainage show heterogeneity.

On surfaces without bedding planes (for example on the slopes of paleodepressions) where soil or soil patches can be found in larger and smaller expansion, the rate of surface flow is lower. This favours infiltration and hydrocarbonate dissolution. In limited expansion, heterogeneous cavity formation with piezometric level develops. Recent drawdown dolines may be formed at these sites.

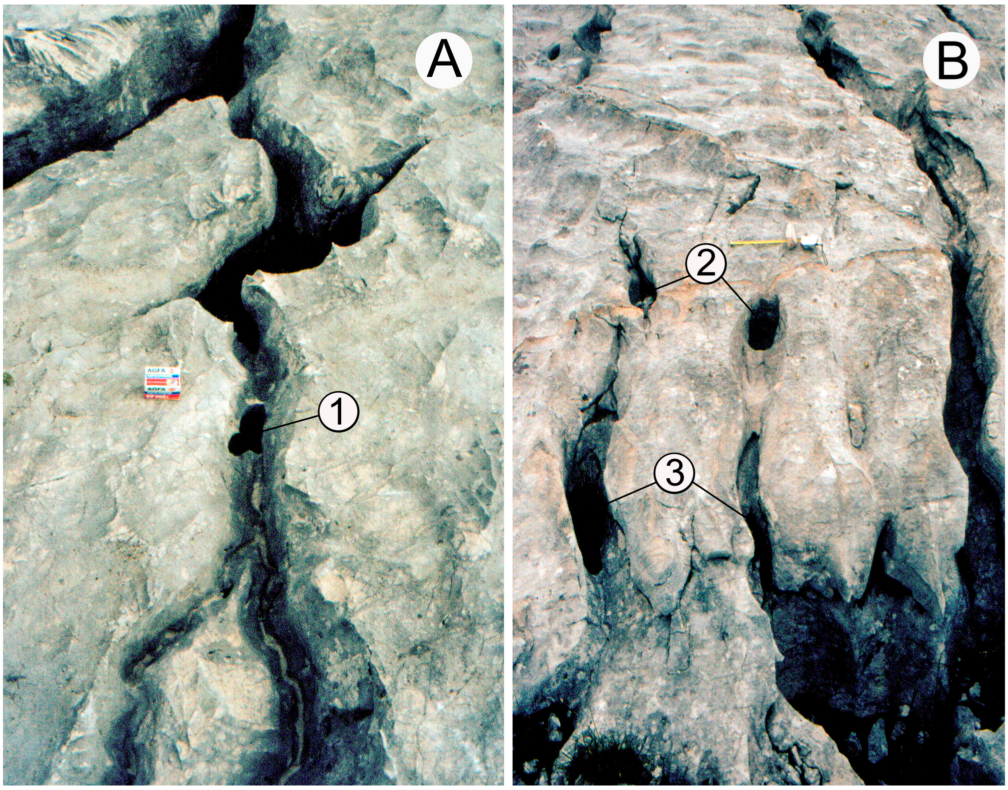

Figure 10. Karren caves (Totes Gebirge) (**A**) at their inlet, (**B**) outlets of storeyed karren cave. Legend: 1. floor pit (ponor of karren cave), 2. outlet of upper karren cave (spring mouth which is temporarily active), 3. outlet of lower karren cave.

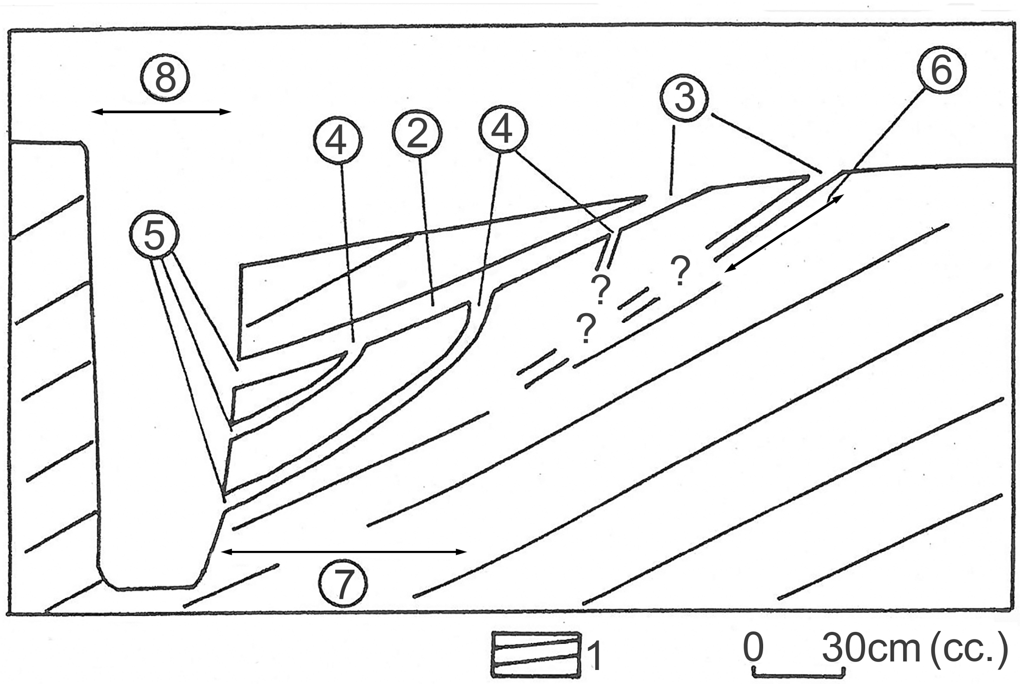

Figure 11. Karren cave system (Totes Gebirge) based on photos of Figure 10 [23]. Legend: 1. bedding plane, 2. through karren cave, 3. channel floor pit, 4. pit inside karren cave, 5. outlets (spring mouth), 6. karren cave that developed in the continuation of floor pit, 7. karren cave belonging to outlet, 8. giant grike. ?: probably, passage development is not continuous.

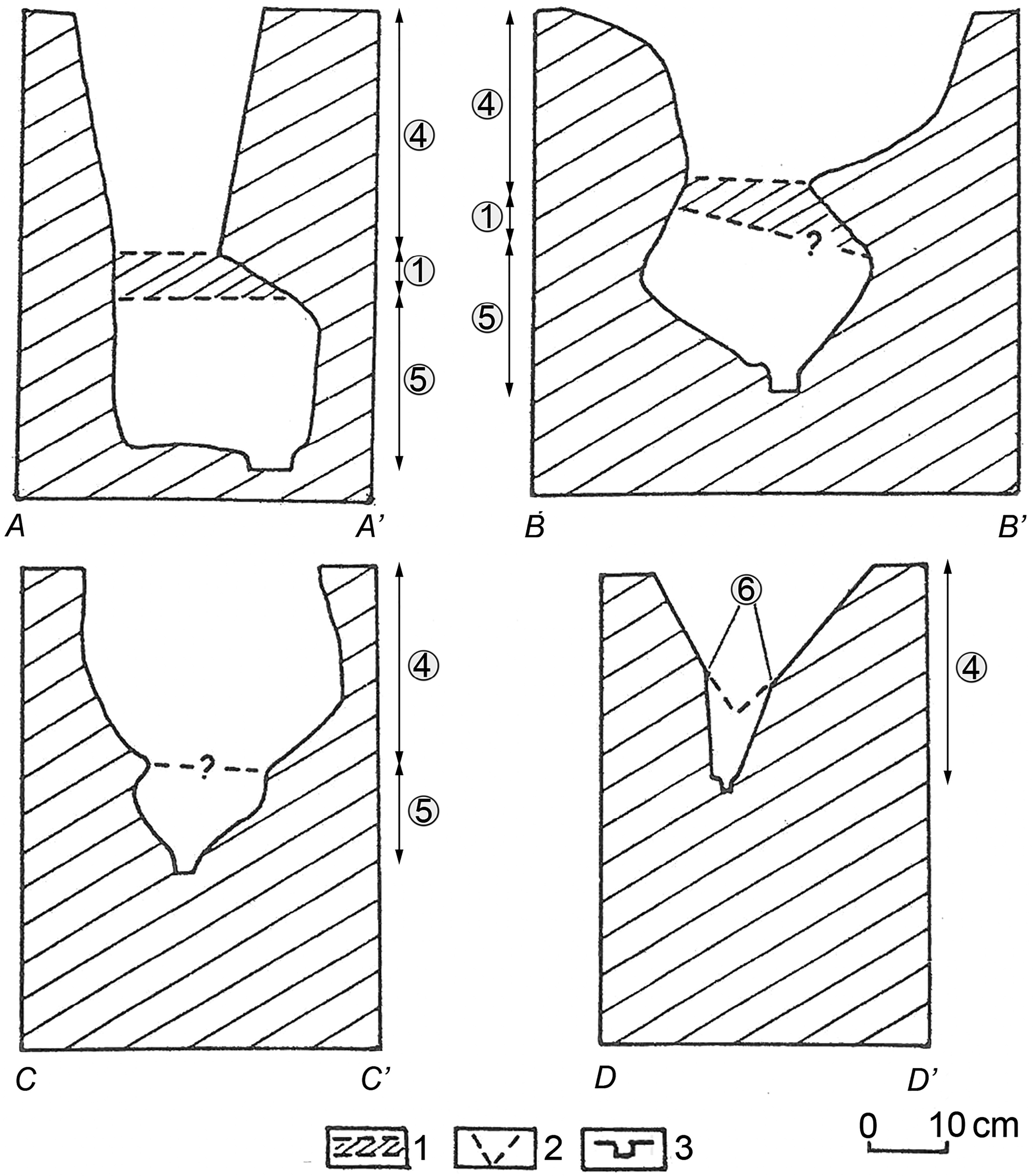

Figure 12. Coalescence of rinnenkarren and karren cave [23]. Legend: 1. former ceiling, 2. previous, now missing part of surface channel part, 3. inner, floor rinnenkarren, 4. channel part that developed by the deepening of the rinnenkarren, 5. channel part that developed by dissolution below surface, the profiles were made from different parts of a rinnenkarren that developed by coalescence: between profiles A–A′ and B–B′ coalescence took place by the collapse of the ceiling of a former karren cave, at profile C–C′ the rinnenkarren dissolved through the ceiling of the karren cave, between profiles C—C′ and D–D′ a channel floor pit developed from which the karren cave was formed.

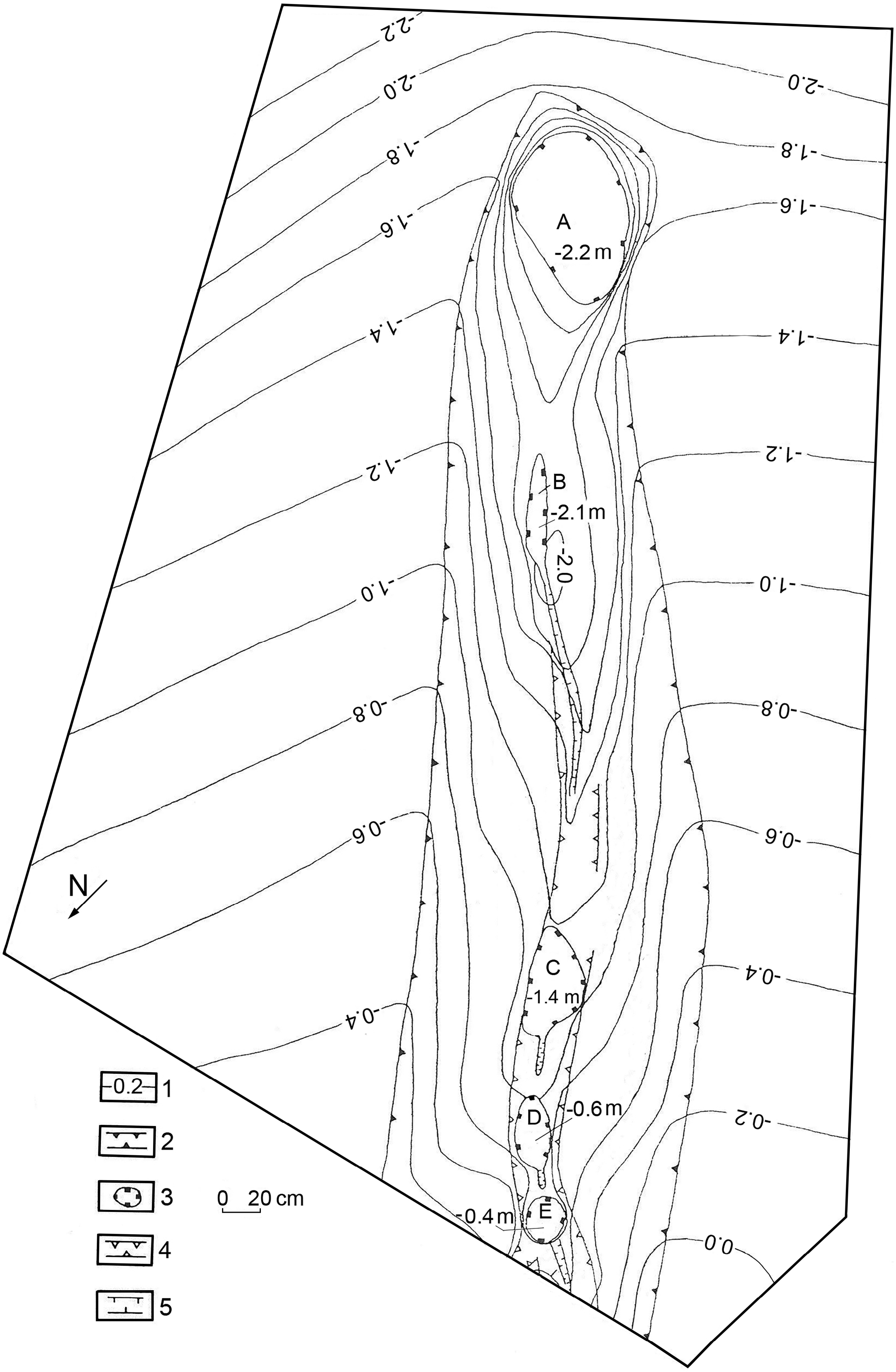

Figure 13. Pits of a large rinnenkarren (Totes Gebirge) [23]. Legend: 1. contour line, 2. margin of large channel, 3. valley floor pit, 4. inner, floor channel, 5. further inner floor channel of a floor channel.

5. Conclusions

In the lack of continuous cavity formation, instead of drawdown dolines, vertical features, pits, shafts, and schachtdolines are widespread on the bare surfaces of glaciokarsts. On glaciokarst, the epikarst is constituted by well-developed karren features, but cavity formation is absent in the rock or it is rudimentary.

On glaciokarsts, as a result of low CO_2 content and intensive surface runoff (it is well manifested on bare surfaces with large inclination), cavity formation in the epikarst is local and vertical. These circumstances do not favour horizontal water motion and heterogeneous cavity formation in the rock. As a result of the above facts, no continuous cavity formation develops in the epikarst. However, water supplies being concentrated to fractures also strengthen verticality and they do not contribute to the development of primitive drawdown dolines, which is also expressed in surface feature development (shaft, schachtdoline). Vertical dissolution tendency is promoted by the coarse-grained sediments of depressions and the snow fills in them which accumulated by the wind.

In the lack of uniform epikarst, no piezometric level develops (or it only develops in a limited way). The lack of local water supply and heterogeneous cavity formation do not favour the development of surface depressions with a relatively large diameter thus, the formation of drawdown dolines. The development of drawdown dolines is possible at sites where the surface is without bedding planes and there is soil or soil patch. No drawdown dolines develop on the bare surfaces of glaciokarsts with bedding planes.

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