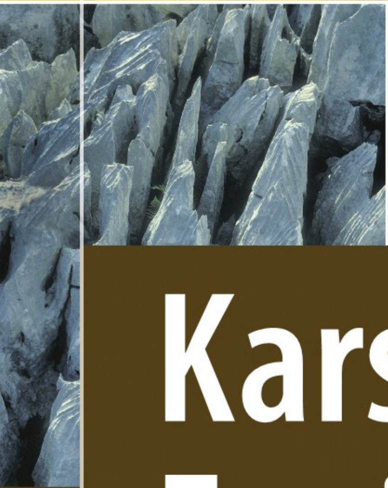
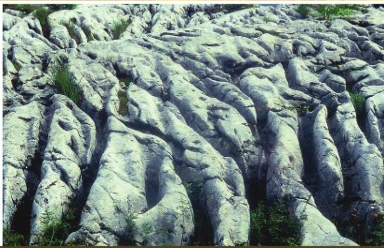
Márton Veress





Karst Environments

Karren Formation in High Mountains

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Márton Veress
Department of Physical Geography
University of West Hungary
Szombathely
Hungary
vmarton@ttmk.nyme.hu

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Preface

The author of this book has been working in different types of karren landscapes for more than fifteen years. The book summarizes the scientific results of systematic observations made during field trips as well as the interpretation of the data collected in the sample localities of the high mountain karren area, and specifically in the European Alps, using modern analytical methods. This book is written for graduate students and university professors of a variety of disciplines such as Physical Geography, Karst Geomorphology, Carbonate Mineralogy, Geology, Environmental Engineering, Forestry, and Soil Science.

The introductory chapter of this book underlines the importance of high mountain karren formation, in addition to charting the history of karren research at high altitude, and describes the major characteristics of high mountain karstification. Chapter 2 provides information regarding the research sites and methods. In Chapter 3, the general characteristics of the karren formation in different vegetation zones are discussed. In Chapter 4, the specific environment, morphology, formation and the development of the different high mountain karren forms are covered. Chapter 5 provides a discussion of those karren assemblages of the karst of the high mountains which were discovered by the author and analyzes the type of denudation observed on karren assemblages. Chapter 6 describes the karren belts of the slopes and the karren forms, and presents the karren formation development happening at the embryonic, young, and mature stage of karren formation. The final chapter on coalescing types and their origin offers the reader a detailed description of karren cells and their characteristic features, and analyzes the relationship between different karren formations.

Márton Veress
Szombathely, Hungary

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Contents

Chapter 1
Introduction

Abstract In this chapter, we underline the importance of high mountain karren formation. For example, the study of the karren process allows us to understand the solution processes that are key to the development of a particular karst area. Furthermore, the karren process is a clear indicator of changing environmental conditions and can be used to establish the value of soil denudation. We also provide an overview of the history of karren research in this chapter. The major stages of this process are the following: the karren was recognized in the late nineteenth century; the terminology of the karren forms has been created in the early and the middle part of the twentieth century; the genetic systematization of the karren forms in the later twentieth century. Moreover, we discuss the main characteristics of the high mountain karstification, the associated karst forms and their belt pattern formation.

Keywords Karren • Terminology • Classification • High Mountain karstification • Glacial valley • Altitudinal zones

1.1 The Importance of High Mountain Karren

Karren are widespread landscape-forming factors in high mountain environments. According to estimates, they occur in half of the mountains of the Alpine system. For instance, they occupy the entire surface of quite a few valley floors – the appearance of karren features, however, is not continuous (e.g. in Totes Gebirge and in Julian Alps). The investigation of karren is important from both conceptual and practical aspects. Some considerationsthat support this statement are as follows:

- The karren provide important data on the karstification process of a mountain range.
- Karren phenomena are small in size. However, there are analogies with some larger-scale phenomena of the Earth's surface. Consequently, we can study the phenomena and processes of the Earth on karren in certain cases. Karren are the 'terrain models' of the Earth processes reduced in scale. Furthermore, karren

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processes are rapid. Therefore, they may assist us to understand larger-scale geomorphic processes, such as surface denudation and meander formation.

- Solution processes are often observed and measured directly on karren surfaces. Therefore, the characteristics of these processes can be studied in detail. The process how water dissolves rocks and erodes the surface can be described, and the experience gathered during the study of karren solution may be used to understand other karstic processes.
- Recognizing the characteristics of karren can contribute to the recognization of paleo karren formation. With this knowledge, we can understand the former karren environment and karst environment better. We can outline the whole karren formation at an area in more detail.
- Karren are sensitive indicators of environmental change. A conclusion for the changing environment can be drawn from the transformation and destruction of karren features. For instance, karren formation begins on surfaces, which had been exposed from below ice cover. By knowing the age of the karren features, we can reconstruct the process of glacier retreat and, indirectly, climatic changes. Certain karren forms develop exclusively under soil. If they occur on bare surfaces, they provide evidence for the denudation of a former soil cover. Karren features of bare surfaces may be buried under soil. This fact proves that the soil and timber line moved to a higher altitude. This is also an evidence of climate change. The *Pinus mugo* belt may also shift to a higher elevation. This process can be detected because karren formation is more intense in the surroundings of the *Pinus mugo* patch than on bare slopes (see below).

Kamenitzas are traps of pollution. Therefore, atmospheric pollution may be presentin their soil fill. For example, high radioactive pollution was detected in a few kamenitzas of Totes Gebirge (Hidasi et al. 1995). The radioactive isotopes of the soils in kamenitzas have a small half-life. Therefore, this kind of pollution must have originated from the Chernobyl accident.

- Instead of slow percolation, the water flows into the karst through some karren features. Therefore, surface pollution spreads inside the karst by the medium of karst water more rapidly over karst areas with karren features than over surfaces without them.
- Certain karren features (such as kamenitzas) are the sites where soil formation begins. At the same time, these features are the habitats of various living organisms.
- Deforestation may cause soil erosion. The density and shape of karren features control the type and characteristics of denudation. If there are linear karren features of downslope alignment under the soil, soil erosion may be more intensive after deforestation than if there are forms that are perpendicular to the dip direction of the slope or circular forms (such as kamenitzas) on the slope. The higher the density of downslope linear karren, the more intensive the soil erosion. The higher the density of linear karren features perpendicular to the slope, the lower the rate of soil erosion. Certain karren forms (such as kamenitzas and grikes perpendicular to slope) are soil traps. Soil removed from the environs accumu-

lates in them. Thus, they may be sites of soil formation. In case of other karren features, such as pits, the soil removed is transported into the karst. Therefore, the soil that surrounds the pits vanishes and is destroyed for good. For this reason, it is important to establish the density of karren features and their (morphological) properties prior to deforestation in a few study areas. If we know such data, we can predict the rate of soil erosion after deforestation. The optimum size of the selected forest clearing area can also be calculated.
- The more karren features are found on a surface (high values for both density and size), the more the formation of a new soil is hindered. We believe that with suitable investigations we can estimate the extent of karren occurrence, which makes soil formation impossible.
- Karren are spectacular features and increase the touristic attraction of the mountains where they occur.
- Karren are extremely useful in education. Karren features and processes can be clearly presented in their full beauty and, thus, are applicable in the education of natural sciences.

1.2 The History of Research on High Mountain Karren

1.2.1 Overview

The recognition and description of karren features began in the late nineteenth century. Mostly geological and geomorphological investigations were carried out in the Dinarids and the Alps. At that time, karren features were not considered as an independent group among karst forms. First, Favre (1867) mentioned karstic microforms using the term ‘lapies’. Some years before Favre, Sachs (1865) carried out experiments on karren. He created karren features in laboratory environment but did not identify them as karren. Eckert (1898, 1902) studied the development of karren features and the role of plants in karren formation. In his studies, Eckert used the German term ‘karren’ along with the French ‘lapiés’. Both terms are used in the terminology to this day. The forms are named in French and German because the majority of the studies in the late nineteenth century were performed in the Swiss Alps. Therefore, authors alternately used the forms in French and German because they respected the two languages of the canton. The use of plural form of the terms is explained by the fact that karren features occur in groups.

The Swiss geologists Chaix Senior and Chaix Junior from (Chaix 1894, 1905 Chaix and Chaix 1907) Geneva significantly contributed to the fact that karren are well known in the world. In their tectonic and tectonic-geomorphological investigations over several generations, they observed karren plateaus in the French and Swiss Alps they were familiar with. They published a series of scientific papers on the morphology of these mountains. Particularly Chaix Junior (1913) published important works on the structure, mass movements and karren plateaus of the Western Alps.

Both father and son published in French and German languages. In the wake of their scientific activities both terms ‘lapies’ and ‘karren’ became widespread.

1.2.2 Development of Terminology

Karren came to be regarded as an independent group of karst features in the early twentieth century. Their independent research only began at that date. The main direction of research was directed at the classification of these features. Jovan Cvijič and Alfred Bögli are the two major representatives of this research direction.

Cvijič is the founder of Serbian geology and geography. He studied and described karren features from many areas as he had an excellent knowledge of the Dinaric Mountains and the Alps (Cvijič 1924). His scientific achievements opened a new chapter in the research history of karren. With a complex approach, he did not restrict his attention to the description of the features but performed their classification and established genetic connections between them. As the terminology changed, it is difficult to identify the features as he mentioned. The ‘channels’ described in his scientific papers may equally be rillenkarren, rinnenkarren or wall karren. He distinguished these features from grikes, which are elongated features developed along cracks. However, in some sentences below, he erroneously claims that rinnekarren are also controlled by cracks. He also described circular forms but failed to distinguish kamenitzas from pits.

Cvijič (1924) described the stages of surface karren development. The stages of the Davisian geomorphological cycle may be recognized in his concept. He distinguished juvenile, mature and senile stages. Surface dissection takes place by rinnenkarren formation. He established that the rate of karren formation may be more rapid than that of karstification. He also established that the process of denudation by karren formation may stop where the limestone is interbedded with sandstones, slates, dolomites or marls.

The most comprehensive classification system of karren features was created by Bögli (1951, 1960, 1961, 1963, 1976, 1980). This system is also used today. Bögli was an outstanding figure of karren research. He is considered to be the first scientist to provide a detailed description of high mountain karren. His papers are the most referred in literature on karren. The German names and terms which were created by Bögli are used universally in every language.

In his classification of karren he combined several criteria. He identified three groups according to the covering of the enclosing surface: karren of covered surfaces, karren of semi-covered surfaces and karren of bare surfaces. He distinguished the forms according to their morphology. He termed the forms by taking morphology into consideration. He created a separated group, karren assemblages, which contain various karren features. He grouped karren according to their geographical environment, too. Apart from the already mentioned groups, he distinguished cave karren and littoral karren. This grouping may be difficult to be used due to the abundance of viewpoints and the application of numerous criteria. But the names he gave the features have become part of the basic vocabulary of karren research. Bögli carried out his research focusing on different karst areas of the Swiss-Alps. German researches described and researched the karren formation of the karst areas of the Austrian Alps at the same time (Fridtjof 1954; Haserodt 1965; Bauer 1962).

1.2.3 Modern Classifications

White's classification (White 1988) has a genetic approach. The criteria in his classification are the following: angle of slope, whether the limestone is covered and or not and rock structure (Table 1.1). We believe that his classification is based on the most important facts. The advantage of this classification is that the features on bare surfaces are grouped according to their relationship to the water flow. The disadvantage of this classification is that only individual forms can be placed in his categories. Nevertheless, his classification systems are simple and easily understood. However, his system cannot be developed to include various coalescing forms and karren cells.

Table 1.1 White's (1988) genetic classification of karren features

		Hydraulic forms		*Etched forms*	
		Sheet flow	*Channel flow*	*Structural weakness*	*Massive bedrock*
Bare bedrock surface		↑ Rill karren (rillenkarren)	↑ Wall runnels (wandkarren)	Solution grooves	Rain pits
		Stepped karren (trittkarren)	Pit and tunnel karren		
		Increasing slope		Cleft karren (kluftkarren) ↓	Pinnacle karren (spitzkarren)
		Kaminitza	Runnels (rinnenkarren) Meandering runnels (meänderkarren)		
Covered surface	Snow pack			Groove karren	Pedistal karren
	Soil		Bag-shaped runnels (hohlkarren)		
			Solution wells		
			Rounded runnels (rundkarren) ↓	Ledge pendants (deckenkarren)	Irregular rounded pinnacles

The important innovation of Ford and Williams's classifications (1989, 2007) is that the forms are ranked into five groups by morphological and genetic criteria. Their groups are the following:

- Circular planforms: micropits and etched surfaces, pits, trittkarren and shafts
- Linear forms – fracture controlled: microfissures, splitkarren and grikes (kluftkarren)
- Linear forms – hydrodynamically controlled: microrills, rillenkarren, solution runnels (Rinnenkarren and Rundkarren), decantation runnels (wall karren, meanderkarren), decantation flutings, fluted scallops or solution ripples
- Polygenetic forms: mixtures of solution channels with pits, wells and splitkarren, hohlkarren, spitzkarren, subsoil pinnacles
- Karren assemblages: karrenfield, limestone, pavement (flachkarren, schichttreppenkarst), pinnacle karst (arête-and-pinnacle, stone forest), ruiniform karst, corridor karst, coastal karren

We would like to mention two conference volumes edited by Paterson and Sweeting (1986) and Fornós and Ginés (1996), which particularly focus on karren research. They present modern research methods and knowledge of karren. Several chapters of this book deal with karren formation in high mountain (Oh 1996; Perna 1996; Perica 1996). The study of Perna (1996) is really outstanding. In his work, the development of different karren forms is derived from the scouring, scratching and polishing work of the glacier. Furthermore, the book entitled *The Encyclopedia of Caves and Karst Sciences*, edited by Gunn (2004), primarily presents the karst regions of the Earth, discusses karren forms of a few karst areas in detail, and also has a chapter on karren (Gines 2004). A similarly huge volume in preparation (Karst Rock Features, Karren Sculpturing), written by 30 authors, will describe karren features.

Finally, it is worth mentioning that comprehensive investigations on karren have been carried out by the Department of Physical Geography of the University of West Hungary in Szombathely. The results of research are presented in a book series entitled *Karst Development* ('Karsztfejlődés'). Volumes I to IV exclusively cover karren research. Forty-nine studies on karren (mainly on karren in high mountains) were published in this series. Sixteen papers were published in other scientific journals summarizing the achievements of research on karren at the Department.

1.3 Major Characteristics of High Mountain Karstification

Karst forms and karstification appears in altitudinal zones in high mountains. The position of the zones where karstification happens in high mountains primarily depends on the distance from the Equator but local and regional facts also have an influence (e.g. exposure, morphology and tectonic structure). The zone of high mountain karstification is located between 1,600 and 2,200 m in the Alps.

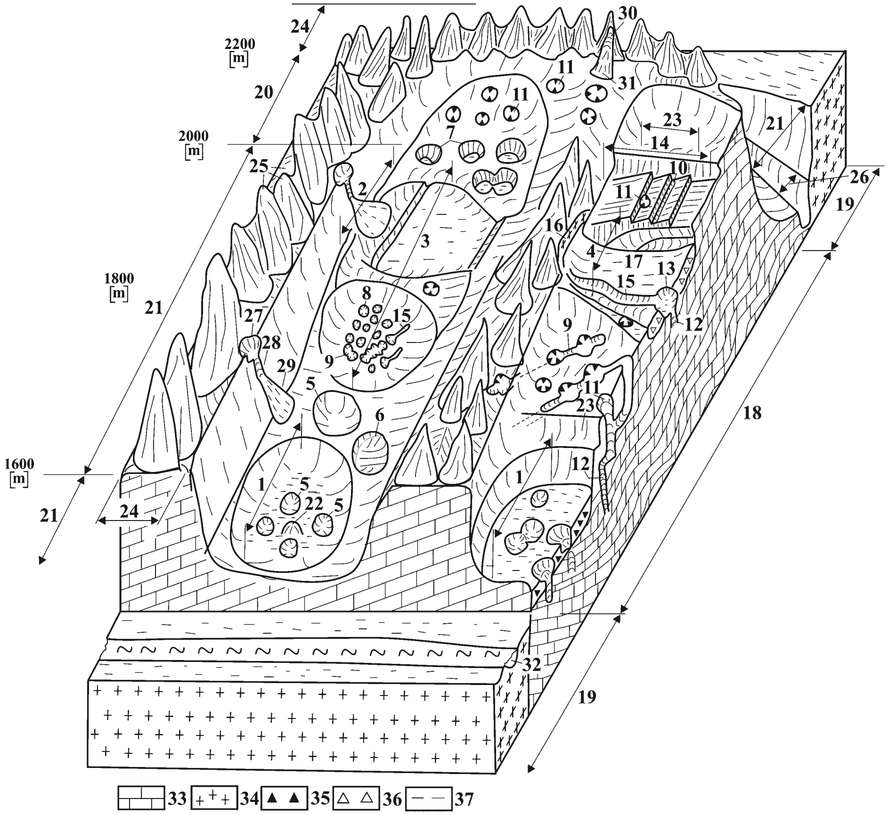

Fig. 1.1 Model of high mountain karst in the Alps (Veress 2004). Legend: 1 – paleodoline, 2 – asymetrical paleodoline, 3 – paleouvala, 4 – paleodoline which is accruing partly, 5 – solution doline, 6 – asymetrical solution doline, 7 – shaft doline, 8 – covered karst doline, 9 – uvala covered karst depression (doline), 10 – solution grike, 11 – aven system, 12 – burrow, pit, cross section of shaft system, 13 – sinkhole, 14 – Schichttrippenkarst, 15 – gulley of the covered karst depression 16 – silica intercalation in the limestone, 17 – cone of dejection which developed from non-carstic rock, 18 – klippe, 19 – window, 20 – amphitheatre, 21 – glacier trough, 22 – roche moutonnée, 23 – step in glacier trough, 24 – combe-ridge, 25 – horn, 26 – river valley, 27 – rock shelter, 28 – gulley of debris avalanche, 29 – blow-out dune, 30 – the way of debris avalanche, 31 – cone of dejection, 32 – river, 33 – limestone, 34 – older metamorphic bottom, 35 – moraine, 36 – the debris of mass movement, and 37 – crack

The karst forms developed on older features created by glaciers (Fig. 1.1). Karstification primarily takes place in former glacial valleys. We would like to emphasize that glaciers often reshaped already existing karstic surfaces. Therefore, there are large-scale (several hundreds of metres in diameter) paleodolinas and paleouvalas on glacial valley floors now ice-free. These forms do not develop further but karstification processes are active on their floors today. Karstic rocks may be covered by till. If till depth is relatively great, it prevents karstification. But if the till cover is shallow, covered karst develops.

When the direction of glacier motion and of the dip of limestone beds are significantly different (their angle is close to 90°), cuestas developed on glacial valley floors, and on valley slopes where the slope of the valley and the dip angle of beds pointed in opposite directions. Slopes on bedding planes show the same direction as the dip angle of beds, while it is the opposite on head scarps. The morphology of escarpments depends on the dip angle and thickness of bedding. The steeper the dip angle is, the greater is the chance for steeper slopes on bedding planes. Naturally, the slope gradient of the bedding plane surface is controlled by the dip angle of bedding. For instance, if the dip angle is 0°, the bedding planes are planar, eroded flat by a glacier. If the dip angle of bedding increases, the steepness of the escarpment slope decreases. The lengths of escarpment slopes depend on the number of the exposed beds, their thickness and on the length of the bedding plane slopes. The length of the escarpment slopes is ever steeper if more and more beds are eroded and these beds are ever thicker and it is also important that these bedding plane slopes are ever longer.

It can also happen that a former glacier did not carve a valley as it could not erode the surface intensely or the already existing karst forms prevented the development of a glacial valley. In this case plateau parts, poljes and gentle and shallow valleys may appear on the karst.

Certain features alone develop on minor forms or steep slopes created by glaciers. For example, only karren forms appear on roche moutonnées, or on the steps of the glacier valleys. Forms belonging to a certain characteristic type can be found on positive forms (elevations). In addition to karren forms, avens also occur on arrêtes.

At various altitudes in the Alps, the following karst forms are present. Between 1,600 and 1,700 m there are solution dolinas and uvalas typical of temperate karst. These forms can often be found inside paleodolinas. They did not develop in paleodolinas and they are of large dimension, it is difficult to distinguish them from paleodolinas.

The bottoms of paleodolina and uvalas may be increasingly covered by sediments with elevation above 1,800 m. The covering sedimentary rock may be weathering residual, transported soil or debris which originates from non-karstic rocks. Streams may flow over the accumulated surfaces to sinkholes developed at junctions. Hence, sinkholes may develop anywhere on karst areas in high mountains, where non-karstic rocks are intercalated into the limestone beds. Covered karstification may happen on the bottom of paleodolinas. Covered karst forms of variable size and morphology occur on these surfaces. It is frequent that erosional forms (drainage channels and gully systems) can be found next to each other. Ground ice can be present in the covering sedimentary rock and influences karstification. It also prevents rainwater from infiltrating. Percolating waters above the ground ice moves into sinkholes and covered karst forms. As ground ice melts, it contributes to the formation of covered karst features. If ground ice melts locally, the covering deposits can break down into the cave or pits. Cave and aven remnants can be seen on the steep cliffs.

Karren forms are more predominant on higher surfaces. Karren forms develop in zones (see below).

Primarily the following karst forms are typical above 1,800 m elevation:

- There are grikes, a few hundred metres long and wide. There is a gradual transition from grikes to grikekarren. Grikes are frequent at the heads of beds (escarpments). The direction of the grikes is the same as that of the strike. Their bottoms are dissected by smaller steep-sided depressions.
- So-called shaft dolina replaces the gentle-sided temperate dolina above this elevation as a typical high mountain form. They primarily occur in high density on surfaces with gently dip angle (as on the bedding planes of cuestas). But they may also occur at the bottom of valleys created by meltwater erosion. In this case, they appear in a row and make the valley floor undrained. The dividing walls of these forms are destroyed by solution and collapse, leading to the development of uvalas. They are absent from dissected surfaces. The forms are a few metres in diameter and their side slopes are steep or subvertical. Their depth is also only a few metres but surpasses their diameter. The debris on their floors derives from collapse or frost weathering. The transition is from ‘aven dolina’ to aven is also gradual.
- Avens are major forms with diameters of several tens of metres and depths of several hundreds of metres. They occur in various geomorphological positions: on arrêtes, glacial valley floors and on bedding planes of escarpments. Karren forms and avens develop at highest elevations in the Alps, at ca. 2,200 m. The avens are commonly connected to the well-developed system caves of the karst.

Chapter 2
Research Sites and Methods

Abstarct In this chapter we provide the characteristics of the research sites, describe the accessibility of these places, their altitude, the morphology of the surroundings and the native vegetation. We also present different measurement methods (for example mapping, profiling, the measurement of the parameters of the bearing slope and the measurement of the cracks of the bearing rock). Using the collected data we calculated the specific width of the karren forms, their frequency distribution and the different parameters of the meanderkarren. We try to find a connection function between different parameters of the channel, taking into account the length of the bearing slope and the dip angle of the bearing slope.

Keywords Research sites • Alps • Methods • Mapping • Profiling

2.1 Research Sites

We made measurements in various parts of the Alps, e.g. in Totes Gebirge in Dachstein, in Julian Alps and on the Assiago Plateau. The investigation areas are built of Dachsteinkalk except Assiago Plateau, which is built up of Triassic dolomitic limestone (Fig. 2.1). We made observations in Karavanken, Tennengebirge and Glarus Alps. We also investigated areas of the Dinaric Mountains (Durmitor and Maglič Mountains) and in Norway in the Jotunheimen Mountains. Although they are not high mountains, the setting is similar to a high mountain environment. We also measured karren on the Diego de Almagro Island, Chile. The conditions on the island are also similar to a high mountain environment. We have not included the results in this work as the belts of the island differ from those in high mountains. Furthermore, high wind velocities make the conditions of karren formation on the island quite different.

Measurements were made at nine sites in Totes Gebirge. (It is to be noted that measurements often affected several smaller terrains of the study areas.) The area marked 1/1 is in a glacial valley of E–W alignment near the tourist track No. 201. There is a lake in a glacial basin near the study area. The study area is on an extensive

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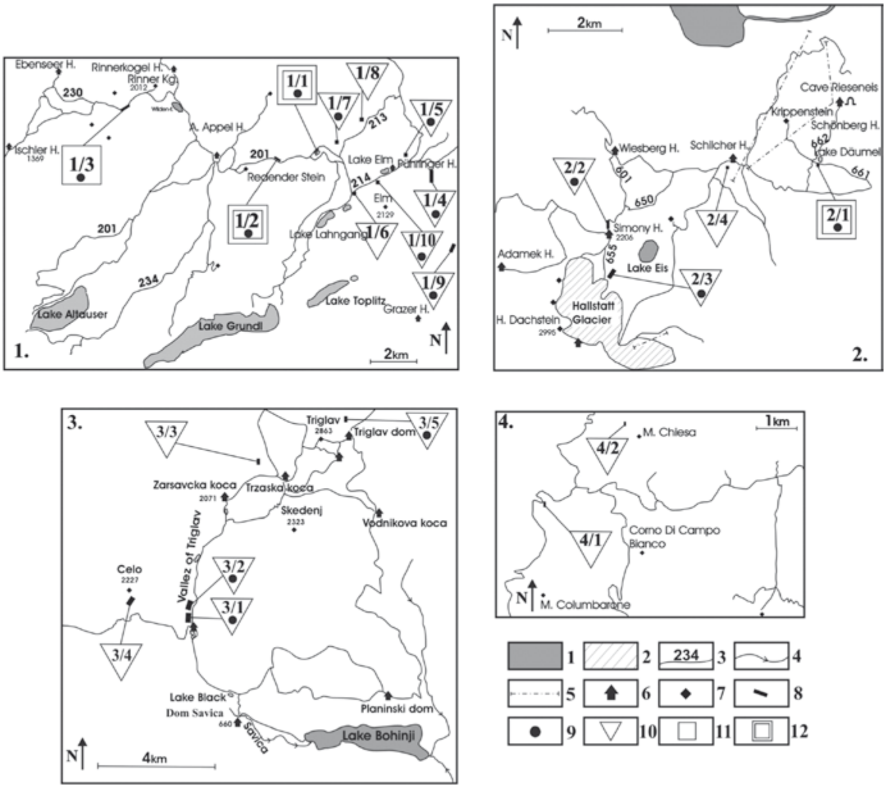

Fig. 2.1 Research areas. Legend: 1 – lake, 2 – glacier, 3 – hiker's track, 4 – brook, 5 – ski-lift, 6 – alpine hut, 7 – peak, 8 – research area, 9 – research area divided into several parts, 10 – profiling, 11 – mapping, and 12 – profiling and mapping

bedding plane, the surface of which tilts towards the lake. This area is a part of the escarpment surface of the valley floor. The study area lies in the *Pinus mugo* belt, but the studied slope section is a bare surface at 1,840–1,860 m elevation.

The area marked 1/2 (it is separated into several partial areas) is in the same glacial valley near the tourist track No. 201. It is also on an extensive bedding plane, which is dissected by the grikes of NE–SW direction. There are shafts along the grikes. The rock is dissected by lenticular and stratiform siliceous rock intercalations. The bedding plane surface is bordered on the south by a steep slope a few metres high. This slope was not created by a glacier, but resulted from karren formation and frost weathering. The area is bordered by a grike, which developed at the escarpment face in the east. The area marked 1/2 tilts to the direction of this grike. It is also located in the *P. mugo* belt at 1,820 m elevation and has a bare surface.

The area marked 1/3 (it is separated into several partial areas) is along the number 230 hiker's track. This study area is on a flat surface eroded by a glacier, in a cirque of a former glacier near Scheibling Peak, in the *P. mugo* belt at 1,842 m elevation.

The area marked 1/4 area is located on a glacial valley floor of N–S alignment (it is separated into several partial areas). This valley is branched out of the glacial valley, which contains the area marked 1/5. There are escarpments at the bottom of the valley, but some roche moutonnées also occur. Shafts and grikes are common on this valley floor. The area marked 1/4 is in the *P. mugo* belt at 1,810 m elevation.

The area marked 1/5 (it is separated into several partial areas) is at the bottom and northern slope of a glacial valley of NE–SW direction near the tourist track No. 214. There are several paleodolinas and covered karst forms on the valley floor. The southern slope of the valley is a steep cliff; there are intercalations of siliceous beds on the limestone. The bank continues in a gentle slope of siliceous and limestone debris. It is in the *P. mugo* belt at 1,700–1,800 m elevation.

The area marked 1/6 (it is separated into several partial areas) is the side slope of the paleodolina, which is at the bottom of the above-mentioned glacial valley. This area is in the *P. mugo* belt at 1,637 m elevation.

The area marked 1/7 (it is separated into several partial areas) is at the bottom and on side slope of an extensive paleouvala. This form is on the floor of the glacial valley, which also contains the area marked 1/2 near the tourist track No. 201. Its bottom is dissected by depressions partially filled with siliceous debris. Smaller watercourses, sinkholes and covered karst features also occur in this depression system. Limestone outcrops are dissected by escarpments. This area also lies in the *P. mugo* belt at 1,720–1,850 m elevation.

The area marked 1/8 is in the eastern part of the glacial valley, which contains the areas marked 1/2 and 1/7 near the tourist track No. 213. This valley is dissected by karst forms (shafts dolinas, shafts, grikes). The study area is on the steep northern slope of the valley. This area is in the barren zone at 1,906 m elevation.

The area marked 1/9 (it is separated into several partial areas) is located in the southern part of the glacial valley, which contains the area marked 1/4. The bottom of the valley is dissected by cuestas, shafts and paleodolinas. The area is in the *P. mugo* zone at an elevation between 1,800 and 1,900 m.

The area marked 1/10 is at the bottom of the glacial valley, which also contains the area marked 1/5. The area marked 1/10 is between the areas 1/5 and 1/6. It is in the *P. mugo* belt. It is separated into several partial sections. Its elevation is between 1,650 and 1,700 m.

Measurements were made at four sites on the Dachstein Plateau. The area marked 2/1 (it is separated into several partial areas) is on a ridge situated on the margin of the plateau near the tourist track No. 666 close to Lake Däumel. Paleodolinas, 'shafts dolinas' and the shafts are common in the neighbourhood. This area belongs to the *P. mugo* belt at 1,820 m elevation. The area marked 2/2 (it is separated into several partial areas) is on a step. This step is near the Simonyi Hut and hotel. It forms one of the steps of the glacier valley, which was created by the Hallstatt Glacier. This area belongs to the bare rock belt at 1,820 m above sea level. The area marked 2/3 occurs at the bottom of this valley, which was also created by the Hallstatt Glacier. We also investigated karren forms at several sites of the study area. This portion of the valley became uncovered and ice-free because the glacier retreated in the last few decades. The various sections lost their ice cover at various dates. This area is in the bare rock belt; the elevation is between 2,040 and 2,050 m. The area marked 2/4 is inside a polje in the *P. mugo* belt at an elevation of ca. 1,700 m near Schiller Hut.

We worked in five study areas in the Julian Alps. The areas marked 3/1 and 3/2 (they are separated into several partial areas) are on the floor of the Valley of the Triglav Lakes. They are in escarpment environments in the pine belt. The measurements took place on bare surfaces at both sites. The elevation of the area marked 3/1 is ca. 1,700 m, and the elevation of 3/2 area is 1,776 m. The slope of the area marked 3/1 borders Lake Dvojno. Its basin was created by a glacier. The area marked 3/3 is also in the Valley of the Triglav. The surface of this area is smooth and almost flat. Probably this area was part of a cirque of the former glacier. Shafts and grikes are frequent in the area marked 3/3. This area is in the bare rock belt. Its altitude is 2,106 m. The area marked 3/4 is in the *P. mugo* belt. Its elevation is between 1,900 and 2,100 m. The area marked 3/5 (it is separated into several partial areas) is in the glacial valley under Triglav Peak, a tributary valley of Vrata Valley. The area belongs to the cirque of the former glacier. This surface is dissected by glacial basins, shafts, ridges, steps and roche moutonnées. This area is covered by till. Ice covered the area 50 years ago (Gams 2002). This area is in the bare rock belt between 2,200 and 2,300 m elevation. We mostly measured microkarren in this area.

The Assiago Plateau is dissected by mounds, paleodolinas, escarpments and shafts. Steep-sided depressions are found at the end of extensive bedding planes, which drain the bedding planes. Both research areas belong to the *P. mugo* belt. Both measurement sites are on bedding planes between scarps. The elevation of the area marked 4/1 is 2,055 m and that of the area marked 4/2 is 2,061 m.

2.2 Methods

We employed the following methods on the investigation areas: mapping, profiling, investigation of the relationship between the cracks of the bearing rock and karren formation, analysis of the age of the various karren features and measurements of meander parameters.

2.2.1 Mapping

We made surveys to produce maps of karren surfaces of variable sizes as well as some individual karren forms. We employed various mapping methods, such as instrumental survey and grid measurements. For instrumental surveying levelling instrument or a tachymeter was applied. By using the data achieved, we constructed large-scale (1:20 and 1:10) contour line maps and planimetric maps. We prepared maps of rinnenkarren, meanderkarren and entire karren terrains with these methods. The grid measurement method is as follows. We placed a grid over the selected karren terrain or on the selected karren forms. Grid size was 2 by 2 m. The grid mesh was 10 or 20 cm. To measure even smaller forms we used a grid with a mesh of 5 cm. We levelled the grids. We also considered the karren surface or the karren form as a system of figure lines. (The figure lines separate slopes of various angles.) We identified such a figure line system on the terrain with the grid. We consider as an element of the figure line systems, for instance, the borderline of a karren form or of the side slope or the bottom of the form. The grid squares provide the coordinates of the points of the figure line system. We drew these points to the squares of the map to be prepared. By connecting these points a planimetric map was drawn. We constructed geomorphological maps of karren from the planimetric maps. We assessed the slopes segments between the figure lines, and also employed a special legend to present the details of the slopes. These maps were made at scales of 1:5 and 1:10. We created mainly planimetric maps and morphological maps of the rinnenkarren and meanderkarren with this grid technique. We measured the vertical distance between the planar dimension of the grid and some points of the figure lines for some forms. Thus, we made contour line maps by the grid method. We also prepared morphological maps of karren from the contour line maps. The maps present the various forms, minor features as well as their development.

These maps can be further developed into solution history maps. Forms and partial forms of a surface of an arbitrarily fixed age are presented on a solution history map. Series of maps can be constructed from the same surface parts. A single map presents the various phases of karren formation. In this way the solution history of the mapped terrain can be shown in detail from the start of karren formation until the present day. Such map series were made possible by the assessment of karren inselbergs and residual hills and runnels. Furthermore, we analysed the joining sequence of runnels in the mapped areas and pointed out channel captures and their sequence.

We made cross sections of channels at several sites. To this end, we measured the widths of the channels every 5 or 10 cm in the horizontal direction.

We also measured the dip angles of channel floors and those of the enclosing surfaces at the same sites. We can analyse the various cross sections shown by the channels at various dip angles.

2.2.2 Profiling

We measured the parameters of karren forms and those of the bearing slopes along a line in the strike direction on selected slopes (further it is termed ‘profile’), see below.

We chose the alignment of profiles in order to represent terrains in the various zones: the pine belt, *P. mugo* belt and bare belt. On the other hand, we selected sites on slopes with different characteristics in the *P. mugo* belt. For example, we measured various parameters on bare slopes, or on slopes with *P. mugo*, or on slopes with herbaceous plants (in patches).

We measured the following parameters along the profiles:

- Width, depth, location and alignment of karren forms
- The inclination and dip angle of the slope
- Direction of the cracks of the bearing rock and the number of cracks along a distance of 50 cm
- Height, geographical coordinates, direction and length of profiles
- The distance between the profiles and the upper margin of the slope (*d*)
- Width of the *P. mugo* patch (*s*) on slopes with *P. mugo* (measured perpendicular to the longitudinal axis of patch)
- Presence or absence of soil or plants in the karren forms
- Type of rinnenkarren according to its situation of the runnel head: the rinnenkarren can be marginally located (the runnel head is at the upper margin of the slope) or internally located (the runnel head is inside the slope)
- The order of the runnel: primary (type A channel) if the channel has no accessory channel and secondary (type B channel) if the channel has (an) accessory channel(s) (distinction also made in the case of meanderkarren)
- The position of the runnel head compared to the *P. mugo* patch (the runnel head may be at the margin of or inside the *P. mugo* patch)

We investigated the rate of karren formation in various belts (pine belt, *P. mugo* belt, bare belt). Then we calculated the following properties of karren forms:

- Specific width (*c*), i.e. the ratio of the total width of the karren forms (which occur along the profile) and the length of the profile
- Density (ρ), i.e. the ratio of the numbers of the karren forms of the profile and its length

By using the above data we compared karren formation in the various belts. We used the specific width of all of the karren forms for comparison. We demonstrated the rate of karren formation with the specific width. Furthermore, we compared the proportion of various karren forms in total karren formation and the density data of karren features for the various belts.

In order to be able to compare the rate of karren formation on slopes with *P. mugo*, herbaceous plants and bare slopes, we measured the following parameters of the slopes in the *P. mugo* belt (Fig. 2.2):

- Specific width of the runnel (*c*)
- The specific cross section area of runnel (*T*), which is the ratio of total cross section area of channels and profile length (the cross section area of a channel may be given as the product of the width and the depth of the channel along the profile)
- Average cross section area of the channel (*t*), which is the ratio of the overall cross section area of the channel and the number of the channel
- Specific shape of runnel or relative width (*f*), which is the ratio of shape index of channel and profile length (the shape index of the channel may be given as the ratio of the width of the rinn and its depth along the profile)

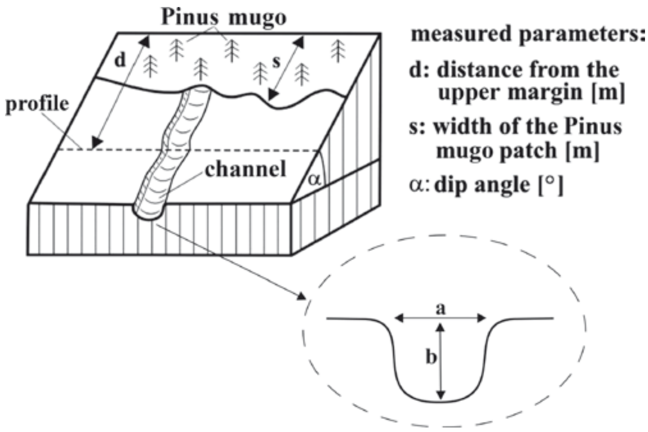

Fig. 2.2 Measured parameters, which were used for calculating the characteristics of the channels (Veress et al. 2008b)

- Average shape of the channel (*l*), which is the ratio of the overall shape of the channel and the number of the channel
- Density of the runnel (ρ)

We looked for a functional relationship between the values *T, c, f* and ρ and between *d, s* and the dip angle. Slope classes were established to obtain a sufficient number of cases to investigate the dip angle and to investigate the relationship between the calculated parameters of runnels (*T*, *c*, *f*, ρ) and *s*, *d* for the various slope classes.

We investigated the specific width, shape index and density of wall karren along the profiles. The shape index is the width to depth ratio as above. We measured the differences between their direction and the direction of their enclosing slopes (direction differences). Grouping the data into various classes, we could give the dispersion of shape index, of width and of direction difference.

In order to characterize the variations in the quantity and quality of karren formation along the bare slopes, the following investigations were performed on three slopes of the research area marked 1/9:

- Parallel profiles were allocated at 3-m intervals on each slope.
- We measured the width, depth and location of karren forms (channels and meanderkarren) along the profiles.
- We also measured the inclination, the dip angle of the bearing slope and the direction of the cracks of the karstic rock and their number within 50 cm distance along the profiles.
- We measured the catchment areas of secondary runnels and meanderkarren, and the number of tributary primary and secondary runnels along the profiles.
- We measured the catchment areas and numbers of tributary channels of type B channels, which occur above the various profiles. (These measurements were carried out in order to investigate the relationship between the parameters of the

channels and the part catchment areas belonging to the various profiles). We can calculate a part catchment area of any channel above a 3-m long profile, if we multiplied the length of part catchment area (it is between profile places and its divide along the channel) by the greatest width of the catchment area taken along the strike of the slope. (We can give the length of part catchment area, which is measured between two profile places if we multiply the distance between two profiles and the width of the part catchment areas. We can calculate the total extension of a catchment area belonging to any channel when we sum up all of the partial catchment areas of a channel.

This value is mostly greater than the effective expansion of the catchment area. We declared the area of a rectangle above, the value of which is greater than the real catchment area. The difference calculated between the catchment area and the real catchment area may change. However, the real catchment area depends on the shape of the catchment area. It is normally not a rectangle, but has an uneven shape.

The specific width, specific and average cross section areas, specific and average shape indexes and density of the various karren forms are represented along profiles. Thus, the variations in the parameters of karren formation on the slope can be revealed. Data on secondary runnels and meanderkarren can be represented separately along individual profiles. Thus, the relationship between runnel parameters and catchment area of the runnel and meanderkarren, and also between runnel parameters and the number of the feeding runnels can be analysed in addition to the d values. We can also analyse the relationship among the cross-section areas (F_0) of a certain type B channel and its shape (f_0) and the values of d.

2.2.3 The Role of Cracks in the Development of Karren Forms

In order to investigate the role of the cracks in the development of the karren forms, we established the frequency distribution of the direction of individual karren forms in a polar coordinate system. We present the percentage of the various karren forms belonging to classes of 20° interval out of the total karren forms (100 %) on a direction–frequency diagram. (The numbers of the karren forms differ from the actual numbers, because we only included rinnenkarren, grikes and pits. Their numbers were doubled, because each strike of karren form can be given with two directions.) We have indicated the inclination of the slope and the directions of its cracks, and their density belonging to a 10-cm distance in a polar coordinate system.

2.2.4 Dating Karren Forms

The concept of dating the development of the karren forms on the floor of a glacial valley is as follows. The Hallstatt Glacier has been retreating in recent decades. The glaciologists marked the glacier terminus at various dates. The development of a certain karren form might begin when the surface is exposed as the glacier retreated. So we had to calculate the date when the locality of a certain karren form became ice-free if the age of the site had not yet been established. For this purpose, we measured the distance (l_1) between the site of karren formation and the former glacier terminus below this site, on the bottom of the valley. Furthermore, we measured the distance (l_2) between the former glacier termini upvalley and downvalley at the site of karren formation. Assuming a uniform glacier retreat, from l_1 and l_2 we can calculate the date (and thus the age of the karren form) when the locality of karren formation became ice-free.

2.2.5 Measuring Meanderkarren

For meanderkarren the parameters of meandering are similar to those of meandering rivers. These parameters are useful for the classification of meanderkarren. The parameters are the following (Fig. 2.3):

- Meander wavelength (λ) is the straight lines distance between two neighbouring inflection points. The inflection points will be where the channel line crosses the channel midline.
- Meander length of the arch (m_i) is the distance that we measure between two neighbouring inflection points along the channel line.
- Sinuosity is the ratio of the channel midline and the axial curve of meanderkarren between neighbouring inflection points.
- Width of meander belt (m_{sz}) is the smallest distance between the boundary line of the meanderkarren. (The boundary lines are straight lines tangential to the loops.)
- According to Laczay (1982) the degree of development of the meander (β) is calculated with the help of the following formula:

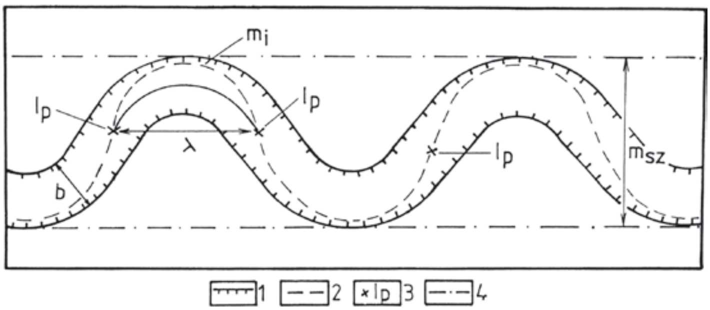

Fig. 2.3 Parameters of a meander (Veress-Tóth 2004). Legend: 1 – margin of meanderkarren, 2 – channel line, 3 – inflection point, 4 – boundary line of meanders, λ: wavelength of the meander, m_i: length of the arch of the meander, m_{sz}: width of the meander zone, b: width of the meanderkarren

$$\beta = \frac{m_i}{\lambda}$$

The above parameters of the meanderkarren can only be calculated if we establish the inflection points and the channel line. The channel line can be original (non-swinging channel line) and swinging. The original channel line coincides with the midline of the stream, which produced the meanderkarren. The swinging channel line moved away from the channel midline. The swinging of channel line is either initial or actual. The initial channel line is defined as the level of the upper margin of the channel. The actual channel line is marked along the bottom of the meanderkarren. We can determine the channel line from the morphology of meanderkarren because water flow rarely occurs in meanderkarren. The actual channel line is located at the bottom of the channel of the meanderkarren and adjusts to the margin of the concave channel wall.[1] If hanging walls are absent, the channel line touches the wall in the middle of the concave margin of the loop. In this way inflection points can be identified for channels of various shapes (Fig. 2.4). The inflection points are located at the following places in meanderkarren with various morphologies:

- Where the midline of meandering karren cuts the smallest width of the channel into two (Fig. 2.4a, d)
- At the midpoint of a line that connects the ends of two opposite overhanging channel margins (Fig. 2.4b, c)
- Where a line constructed from the end of the overhanging wall cuts the original channel line (Fig. 2.4e)
- At the midpoint of the straight line that connects directly opposite 'skirts' (Fig. 2.4f)

The actual channel line can be described with such a curve, which adjusts to the lower margins of hanging walls and crosses the constructed inflection points. If there are no hanging walls, the channel line can be drawn if the inflection points are connected with the points of the channel margin, which touch the boundary lines (Fig. 2.5). The establishment of the channel line can be checked. Its precision is satisfactory if the inflection points lie on the original channel line. (It is seen that the identification was not always correct.)

If we determine the places of inflection points and the channel line, we can establish the meander wavelength and the sinuosity of meandering karren. The width of the meander belt itself is not characteristic because its value depends on meanderkarren width (Zeller 1967). Therefore, we introduce the term of the specific meander belt, calculated as

$$m_f = \frac{m_{sz}}{b}$$

[1]Meanderkarren are asymmetrical. There are overhangs under concave margins, while the walls are gently sloping under convex margins (see below).

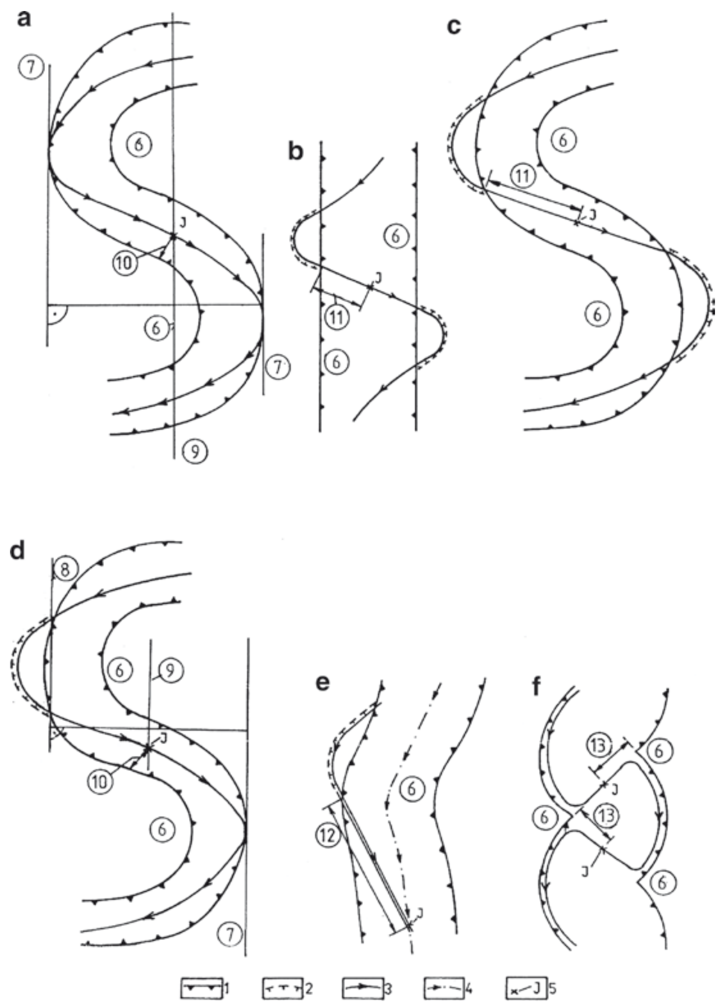

Fig. 2.4 Plotting of inflection points of meanderkarren with various morphology (Veress 2003). (**a**) plotting of inflection points of a meandering river (after Cholnoky 1935), and of a channel that has no overhanging wall, (**b**) in the case of straight or almost straight channel, where there are overhanging walls at both sides (developing meanderkarren), (**c**) at a meanderkarren, where the overhanging wall developed at both loops (loop or meander remnant), (**d**) at a meanderkarren, where the overhanging wall developed only at one loop, (**e**) at false meanderkarren (the channel sections are at about right angle), where there is only one overhanging wall, and (**f**) at a meanderkarren remnant without overhanging walls, 1 – meanderkarren edge, 2 – end of overhanging wall at the plain of meanderkarren bottom, 3 – present channel line, 4 – previous channel line, 5 – inflection point, 6 – skirt, 7 – boundary line, 8 – a straight passing channel at the end of the overhanging wall, which is parallel with the boundary line of the next loop, 9 – middle line, 10 – half width of the meanderkarren at the middle line, 11 – shortest half width between the ends of opposite overhanging walls, 12 – the straight line received as the extension of the original channel line at the end of the overhanging wall where it crosses the original channel line, and 13 – the shortest half width between opposite neighbouring skirt tips

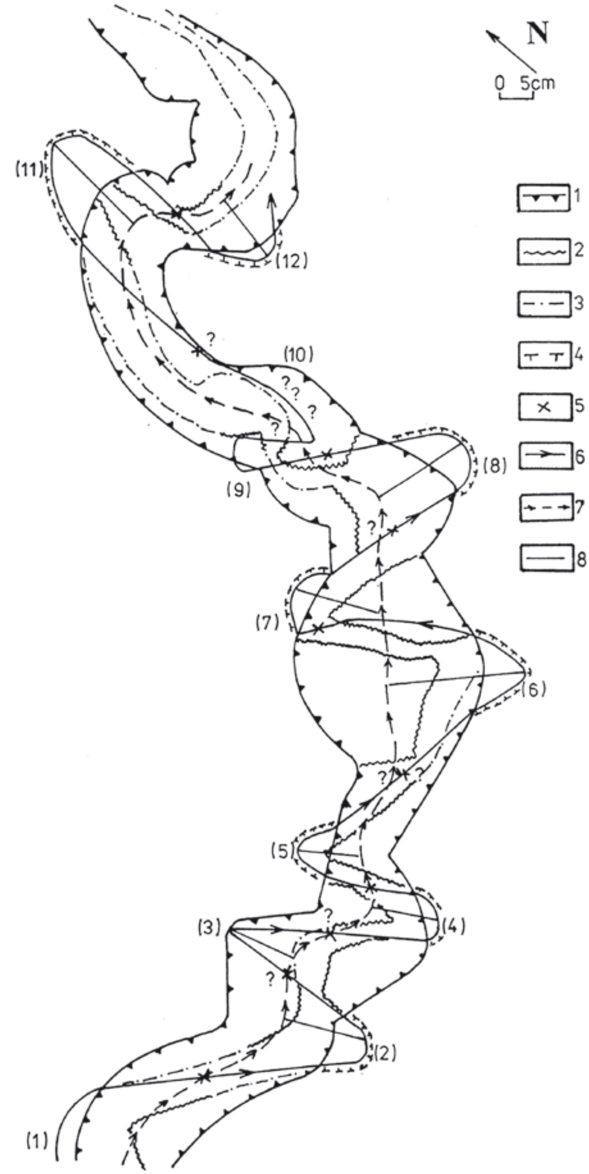

Fig. 2.5 Constructed channel lines of meanderkarren No. 7 (research area marked 1/3, Veress 2000b). Legend: 1 – edge of type I meanderkarren, 2 – lower edge of skirt, 3 – end of gently sloping meanderkarren, 4 – bottom of overhanging wall at the plane of the meanderkarren bottom, 5 – inflection point, 6 – present channel line, 7 – previous channel line, and 8 – accessory straight along which the Sk_k and Sk_j values can be measured (for definition of Sk_k and Sk_j, please see the appropriate chapter and Fig. 2.6a and b) (Note: number in parentheses identifies the loop)

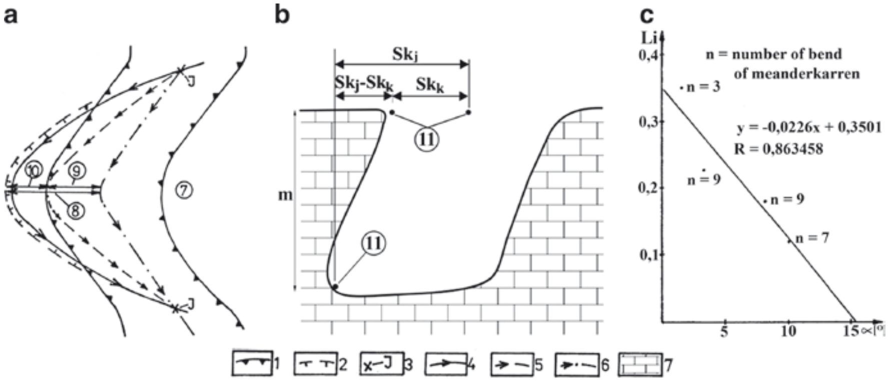

Fig. 2.6 Swinging of the channel line and its components: planimetric representation (**a**), in profile (**b**), relation between the slope angle (α) and slippage intensity (L_i) (**c**), Veress 2000b transformed). Legend: (**a**) 1 – meanderkarren rim, 2 – end of overhanging wall at the meanderkarren bottom plane, 3 – inflection point, 4 – present channel line, 5 – channel line at the start of slippage, 6 – previous channel line, 7 – skirt, 8 – Sk_j 9 – Sk_k 10 – $Sk_j - Sk_k$ (**b**) 11 – channel line m. the depth of the meanderkarren at the loop, Sk_j the biggest distance measured between the former and the present channel lines on the map, Sk_k: the biggest distance measured between the channel line at the beginning of the slippage and the previous channel line on the map, $Sk_j - Sk_k$: the biggest distance measured between the channel line at the beginning of the slippage and the present channel line on the map (the horizontal reflexion of the biggest swinging of the channel line during the deepening of the meanderkarren which equals to the overhanging of the convex channel rim)

where m_f is the width of the specific meander belt
m_{sz} is meander belt width
b is meanderkarren width

To characterize the swinging of the channel line, we introduce the term intensity of slippage (L_i). The channel line moves downward and in lateral direction along the bottom of the incising meanderkarren. This is called channel line slippage. The channel line is swinging and, parallel with channel incision, it is replaced to a lower position. The intensity of slippage in a loop is defined from the measured values (Sk_j) and (Sk_k) using the following formula (Fig. 2.6a, b):

$$L_i = \frac{Sk_j - Sk_k}{m}$$

where Sk_j is the greatest distance between the present and original channel lines measured on the map
Sk_k is the greatest distance between the initial slippage and the original channel lines measured on the map
m is the depth of the channel in the loop

The intensity of slippage represents the rate of swinging of the channel line for a unit measured incision. Its value can be calculated for a meander, averaged out for meanderkarren and also for the types of meandering karren.

We examined the intensity of slippage in function of gradient. To this end, we calculated the values of the intensity of slippage for every loop and the mean values for each of the meanderkarren. We also calculated the mean surface slope. We measured the inclination of the surface at the loops. Thus, we were able to analyse the relationship between the mean intensity of slippage and mean surface slope for four meanderkarren (Fig. 2.6c).

Chapter 3
Age and Characteristics of High Mountain Karren Formation

Abstract In this chapter we present a comprehensive study on high mountain karren forms. We also describe the general characteristics of karren formation in different vegetation zones, the density of all karren forms and their specific width in different vegetation zones as well as the previous results for the different karren form types.

Keywords Absolute age • Relative age • The rate of denudation • Diversity of forms • Karren zonation • Density • Specific width

3.1 Age of Karren and the Rate of Their Development

Karren forms produced prior to glaciation are eliminated by glacial erosion. However, there are exceptions to this rule. For instance, some large grikekarren in North West England were not eroded entirely by ice (Rose and Vincent 1986b). Therefore, the karren forms of high mountains are younger than the late Würmian. The snowline was at an elevation of 1,500 m in the Alps during glacial periods. Thus, karren forms could only develop after the retreat of glaciers. They are getting ever younger upwards from the elevation of 1,500 m to the present-day snowline.

Karren forms may be dated for absolute and relative age. Relative ages can be compared to each other. The relative dating of a karren form relies on the following environmental conditions:

- The karren forms on boulders of rockfall are younger than the rockfall itself (if the boulders acquired their position by the rockfall) (Wagner 1950).
- The grikes, that crossed deep runnels are younger than the runnels (Williams 1966; Louis 1968).
- The karren formsthat enclose another form are always older. For example, the kamenitzas and pits at the bottom of runnels are younger than the runnels itself.

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- The karren forms that consume or merge with other karren forms are younger than the latter. For instance, the decantation runnels of kamenitzas are younger than the kamenitzas. Furthermore, those channels are bordered by trittkarren.
- The karren forms that developed through coalescing and any forms created during this process are younger than the elements of complex forms. For example, those forms that are connected to regressional runnels.
- Remnant forms are younger than the forms from which they developed, for example, karren natural bridges.

Absolute age may be determined in a direct or indirect way. When the rate of the surface solution is measured, it is indirect dating. For direct dating, the rate of growth of the karren form is measured.

The methods proposed by Bögli (1961) and Cucchi et al. (1996) are suitable for measuring the rate of surface denudation. Bögli (1961) measured the length of the legs of the karren tables. The top of the karren tables are moraine boulders carried to their present sites by glaciers in the Würm Age. Therefore, he calculated the date when solution began in the environment of the boulders, which caused the development of the pedestal supports, from the end of the Würm Age. The climate tended to become more humid from the late Würm, and this favoured the solution. He measured the length of the pedestals of the karren table and found it to be 10–15 cm. He regarded 10,000 years as the time period necessary for the development of a pedestal. This means that the solution rate in the Glarus Alps is 0.015 mm/year (Bögli, 1961).

Cucchi et al. (1996) fixed metal bars into the limestone and measured their height above the surrounding surface. They repeated measurements at certain intervals and thus calculated the rate of surface denudation by solution. Using the data measured at various dates, he established the thickness of the layer removed and calculated the rate of denudation.

The rate of denudation by solution may be estimated if we know the dissolved matter content of waters, which leave the karren form. The rate was found to be 0.04–0.004 mm/year for bare limestone surfaces of the British Isles with rainfall of 1,500–2,500 mm/year (Sweeting 1966; High and Hanna 1970; Newson 1970; Thomas 1970). The rate of subsoil solution was 0.43–0.50 mm/year in runnels, which occur in soil with peat and heavy metals (Newson 1970). The rate of denudation by solution was 0.010–0.015 mm/year in runnels, which received their water from soils of heavy metal content and 6.3–11.5 mm/year in rinnenkarren, which received water from peat soils (Sweeting 1966). The development rate of kamenitzas was 0.02 and 0.1–0.2 mm/year for grikes when the intensity of solution was taken into account (Trudgill 1985).

We could determine an absolute age for karren forms on the bottom of the Hallstatt Glacier valley from dating glaciation at various places where karren forms occur (see above). We surveyed karren forms in the year of 2000. According to our data, rillenkarren developed within 1 year, while rinnenkarren, in 14 years, and for trittkarren, it took 23 years (Veress et al. 2001).

We made measurements on karren features along profiles. We measured specific solution at these places. By using these values, we can calculate the velocity of specific solution too as follows: we divide the specific width of a karren formation site with the time period of karren formation. This is the age when the surface became ice-free. The values of the velocity of specific solution scatter between 4.12 and 0.23 cm/m year. The former value belongs to the closest site to the recent glacier end, while the latter one belongs to the farthest place from the present glacier. The data, however, show considerable scattering. Decreasing values suggest that the rate of widening for karren is less today at places where karren formation started earlier.

3.2 General Characteristics of High Mountain Karren Formation

Our observations and examples of karren formation are based on measurements in several areas of the Alps. Therefore, the characteristics, which are specific for Alpine climate (such distance from the Equator, orientation to prevailing wind direction) may be not generalized to karren in other high mountains of the Earth.

3.2.1 Diversity of Forms

Almost all karren forms occur in high mountains though a few may be absent (such as tropical karren forms and cave features). The greatest variety of karren forms can be seen in high mountains of the Earth. Certain karren forms do not occur in any other karst type (schichtfungenkarren, napfkarren). A few karren forms may occur only in extreme surroundings., whereas some may occur not only in high mountains but also on surfaces where conditions characteristic of high mountains occur, such as trittkarren (certain variability of these forms may develop wherein snow covers the surface temporarily), wall karren and meanderkarren.

Karren features are produced by water flowing on slopes or infiltrating into the rock (Fig. 3.1) and by raindrops or of combined origin (e.g. by flowing and dripping water). Karren appear on bare slopes or on uncovered segments of slopes with soil patches. In the latter case, the water which leaves the soil patch contributes to karren development. Seeping water may create karren forms on bare rock surfaces (water infiltrating into the rock from the surface) or on rock surfaces under soil. The direction of the karren forms which were created by water flow is controlled by slope direction, while their size and type by slope angle. Slope exposure controls the direction of run-off, while slope angle controls the velocity of flow and thus the intensity of solution. The karren created by flowing water may be classified into two groups (Table 3.1):

- A group of forms, which were created by a sheet of water: rillenkarren, trittkarren, and scallops, ripplekarren and solution bevels
- Those created by rivulets: rinnenkarren (runnels, channels), wall karren and meanderkarren

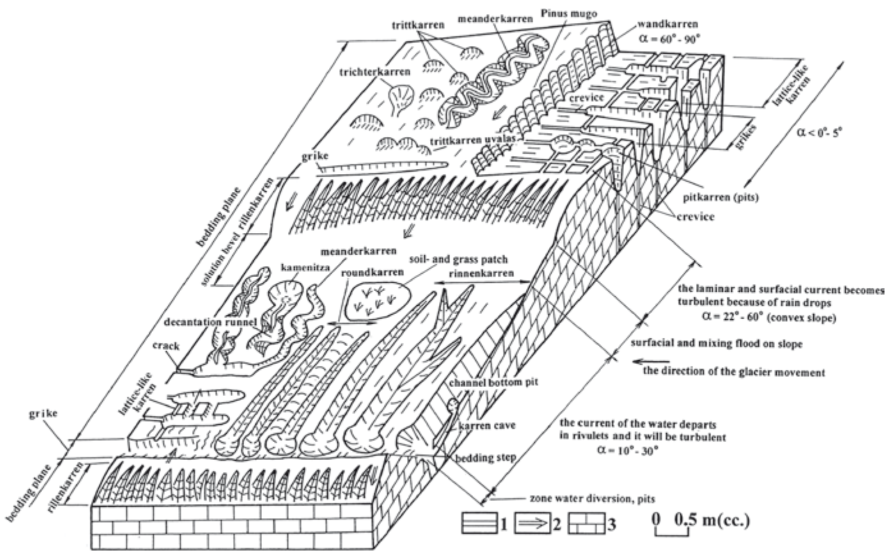

Fig. 3.1 Main karren forms on bedding planes truncated by glacier (Veress and Tóth 2002). Legend: 1 – crack, 2 – line of the dip of the surface, and 3 – limestone

Table 3.1 Classification of karren forms according to their development

Manner of development		Crack and bedding plane: Do not play a role	Crack and bedding plane: Play a role
Water flow	Sheet water is only on bare surface	Rillenkarren Solution level (“Ausgleichsfläche”) Trittkarren Flutes Scallops	
	Rivulet is only on bare surface	Meanderkarren Rinnenkarren Wall karren angle of slope increases ↓	
Seepage water	Those develop subsoil or on bare surface		Pitkarren Kamenitza Grikekarren Schichtfugenkarren angle of slope increases ↓
	Those develop only subsoil	Rundkarren Napfkarren	
Raindrops	Those fall on the surface only	Rainpits	
Forms with complex origin	Those develop subsoil or on bare surfaces	Spitzkarren Karren mounds Remnant forms of coalescing	Karren cavities Bed head karren Karren debris
Organic acids	It happens only subsoil	Phytokarst	Rootkarren

The karren created by seepage on bare surface are schichtfugenkarren. Karren forms, which result from seepage on bare slope or under the soil are grikekarren (kluftkarren), kamenitzas or pits (pitkarren). Rain pits develop by raindrop impact. There are karren forms, which are exclusively due to solution under soil cover: napfkarren and rootkarren. Roundkarren develop when rinnenkarren were covered with soil temporarily. Karren cavities and solution remnants, like basset or scarp karren, spitzkarren and debris accumulated during karren formation and karren mounds (e.g. karren karren monadnocks, karren inselbergs), are of complex origin.

3.2.2 Karren Zonation

Karren are formed in three zones of temperate high mountains: in the pine belt (1,600–1,800 m), *Pinus mugo* belt (1,800–2,000 m) and the bare rock belt (2,000–2,200 m). The elevations of the upper and lower limits of the belts in the Alps show some variation with exposure and partly because we established altitudinal zones based on our measurement sites. Thus, for instance, we indicated 2,200 m as the upper boundary of bare rock because we did not have a measurement site above that. Although karren are also known from elevations between 2,400 and 2,600 m, the phenomena, they are small in dimension and density. (We carried out few measurements above 2,100 m.) We measured, for example, the karren forms on wall karren and other ice-free surfaces from where the glacier retreated.

The boundaries may alter to some extent due to Pleistocene and Holocene climate changes. Therefore, the environments of existing karren forms changed and this involved changes in the nature karren and in the intensity of their evolution. Karren formation began on surfaces, which became ice-free and ceased when they were covered with ice again. Karren may be destroyed by ice or preserved under snow. Finally, deforestation has to be mentioned. The upper limit of pine forest moved lower as deforestation cut up the pine forest into pine groves. The herbaceous plants that replaced pines could not preserve the soil. Therefore, bare spots of variable sizes formed on gentler slopes. Probably, karren formation was modified (for instance, intensified by organic acids) under the soil too.

The lower limit of high mountain karren formation cannot be separated from the upper limit of karren formation in mountains of medium height. The karren formation does not show great variation between the lower regions of high mountains and the upper regions of mountains of medium height neither in elevation nor in character. On the one hand, the lower limit of the pine belt can lie below 1,500 m; on the other, subsoil karren formation is rapid both in the zones of pine and deciduous forest. Karren formation under soil cover is similar in both zones but differ in the following:

- Roof karren may be more common in the deciduous forest zone than in the pine zone.
- The proportion of the bare slope segments decreases with elevation. Therefore, subsoil karren forms are becoming widespread with decreasing elevation.

The zonation of karren forms is due to the following facts: the zonal distribution of land cover, change in rainfall and the period of snowmelt, which depends on elevation. Some karren features can occur anywhere and are called ‘cosmopolitan’ (grikekarren, pits and probably spitzkarren and kamenitzas). Their proportion among karren features, however, varies.

At lower elevations karren mainly occur on steep, short and bare slopes. Rillenkarren, wall karren and schichtfugen karren are also ‘cosmopolitan’ there. The karren types which develop in each of the zones are the following: rinnenkarren, meanderkarren, karren caves and trittkarren. Rinnenkarren occur in the bare rock and the *Pinus mugo* belt, but they may occur on the bare slope section in the upper pine belt. Meanderkarren, trittkarren and karren cavities are also spread in the *Pinus mugo* (mainly in its upper part) or in the bare rock belt. Roundkarren occur at the border of the *Pinus mugo* and pine belts, where soil covered the bare slopes temporarily.

We would like to emphasize that karren forms on bare surfaces are not continuous over the entire belt. Patches of karren forms of various extensions are separated by surfaces without karren. Three facts explain this:

- Karren forms do not develop on unstable slopes or on surfaces under the influence of intense frost. High joint density may prevent karren formation.
- Subsoil karren forms may develop in soil patches only at higher elevation.
- The development of karren forms due to flowing water favours large-sized bare slopes. These slopes develop on forms of discontinuous development. Slopes carved by glaciers cirque walls, floors and walls of glacier troughs, gently sloping structural (bedding planes of low dip) or glacial surfaces, cuestas, backslopes of cuestas and slopes of roche moutonnées. Other forms of local occurrence are karren on the slopes of canyons, on slopes of other karst forms (dolinas or shafts) as well as on rockfall, morainic and frost weathering boulders.

3.2.3 Magnitude, Frequency and Rate of Karren Formation

The size of high mountain karren is predominantly in the range of a few centimetres to a few metres. A few forms, however, show exceptional length: rinnenkarren and grikes may be some tens of metres long but their diameters and their depths rarely exceed 1 m. (The size of karren forms may be one order of magnitude larger on tropical karsts.) The diameter of kamenitzas is the largest in high mountains. The diameter of some kamenitzas may be more than 5 m. The diameter and depth of microkarren, rillenkarren and spitzkarren, common in high mountains, ranges from a few millimetres to a few centimetres.

The average density of karren is 0.35 features/m along our measurement profiles, 0.41 features/m in the pine belt, 0.37 features/m in the *Pinus mugo* belt and 0.26 features/m in the bare rock belt (Veress 2003). The density of the karren features decreases with increasing elevation. Even on bare surfaces of tropical karst the density of karren features is higher. For instance, the average density of karren forms is 28.09–93.33 features/m (Veress et al. 2006a) on the Ankarana Little Tsingy

(Madagascar) although we also counted rillenkarren superimposed on larger karren. When we do not take rillenkarren into account, the density of the karren features is 3.22–3.89 features/m. It is important to mention the last figure as rillenkarren could not be measured in the Alps. Furthermore, the density of karren forms of the high mountain is smaller than the density of subsoil karren in Hungary (0.63–1.56 features/m) or in the Mediterranean areas (0.33–1.4 features/m, Veress 2003). If we investigate the density of single karren forms, the density of some karren forms may be remarkably high. The density of rinnekarren is 1.17 features/m in the *Pinus mugo* belt, while the density of the wall karren is 4.36 features/m in the bare rock belt. Along one measurement profile, the density of the wall karren was found to be 14.55 features/m. We can explain the relatively low density of karren in the Alps with the particularly low density of some karren types (kamenitzas and pits) there. For example, along our profiles, the average density is only 0.05 pits/m and 0.03 kamenitzas/m in the bare rock belt. The total average density is 0.17 pits/m in all the three belts and 0.04 kamenitzas/m.

The specific width shows the intensity of karren formation better than their density. Their average specific width is 30 cm/m in the Alps, not remarkably different from the specific width of subsoil karren outside high mountains (on Mediterranean karsts: 41.00 or 54.49 cm/m, while on Hungarian karsts 42.35 cm/m. The values for the different belts are 32.5 cm/m for the pine belt, 31 cm/m for the *Pinus mugo* belt and 22 cm/m for the bare rock belt (Fig. 3.2a, Veress 2003; Veress et al. 2006b).

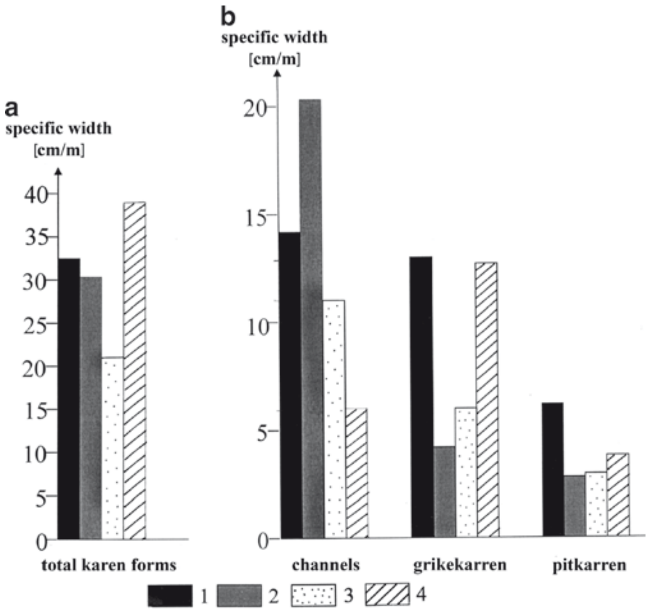

Fig. 3.2 Specific width with total value (**a**) and values belonging to various kinds of karren forms (**b**) in various plant belts (Veress et al. 2006b). Legend: 1– Pine belt, 2 – *Pinus mugo* belt, 3 – bare belt (1–2–3 valley of Lake Triglav Lakes, Totes Gebirge, Dachstein), and 4 – *Pinus mugo* belt (Assiago Plateau)

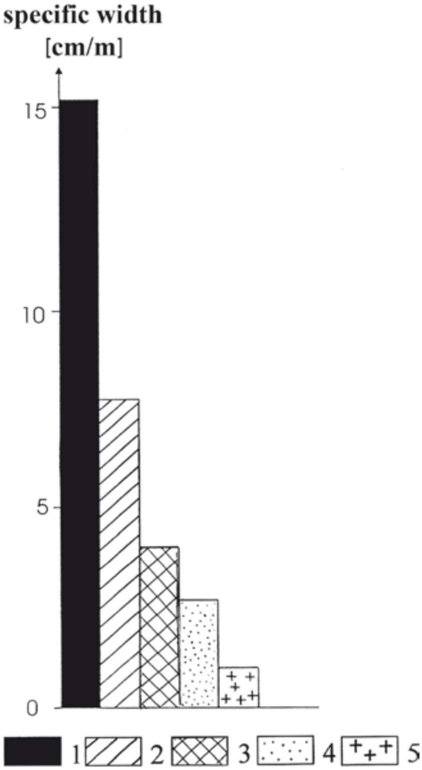

Fig. 3.3 The degree of specific width which are refer to different karren forms by using data of profiles of valley of Triglav Lakes, Totes Gebirge, and Dachstein (Veress et al. 2006b). Legend: 1 – rinnenkarren, 2 – grikekarren, 3 – pitkarren, 4 – trittkarren, and 5 – kamenitzas

The mean specific width by karren types and by altitudinal belts in the Alps is the following. For rinnenkarren it is 15.23 cm/m and for grikekarren 7.75 cm/m (Fig. 3.3) but the values vary with the different belts. While in the pine belt the specific width of grikekarren is 13 cm/m, for rinnenkarren (with roundkarren) it is 14 cm/m. In the *Pinus mugo* belt, the specific width of the grikekarren is 4 cm/m and for rinnenkarren is 20 cm/m. In the bare rock belt, grikekarren have a specific width of 6 cm/m, while rinnenkarren 11 cm/m (Fig. 3.2b, Veress 2006). We can explain the remarkable specific width of the rinnenkarren in the pine belt with three causes. Firstly, rinnenkarren or roundkarren outcrop because their initially bare surfaces were later buried under soil, but they have been exhumated recently. Secondly, rinnenkarren developed on steeper (and consequently, bare) slopes in the pine belt. Thirdly, a new generation of features could develop when the soil eroded after deforestation. We can explain the large specific width of rinnenkarren with two causes in the *Pinus mugo* belt. Firstly, cuesta surfaces predominate in this belt and their common occurrence means abundant steep slopes favouring the development of rinnenkarren. On the other hand the *Pinus mugo* patches effect karren formation. The water, which flows out from the *Pinus mugo* patches promotes the development of rinnenkarren. Consequently, the role of *Pinus mugo* is important in the process as while the specific cross-section of rinnenkarren on bare slopes sections in the *Pinus mugo* belt is 3.85 dm^2/m, the specific cross-section area of rinnenkarren on slopes with *Pinus mugo* patches in the *Pinus mugo* belt is 9.35 dm^2/m (Veress et al. 2007). It is only 6.58 cm^2/m on slopes with herbaceous plants in this belt (Veress et al. 2006c, 2008b).

We can explain the above-mentioned characteristics of karren formation in high mountains with the following:

- There are widespread glacial landscapes with slopes of variable extension and inclination.
- Forms created by ice are bordered by steep slopes. The dissolution intensity is greater on such slopes than on gentle slopes since the ion transport (Ca^{2+}), which is relevant to dissolution, is higher when its difference is great between the bordering layer and flowing water. If the flowing velocity of the flowing water is great, the difference in ion concentration is high, too. As fast flowing contributes to the fact that the layer with small ion concentration reaches the boundary layer above the rock (Nerst 1904; Trudgill 1985; Ford and Williams 2007).
- The plant and soil appearance in patches can be primarily seen between 1,800 and 2,000 m because of high altitude.
- Although the duration and intensity of the soil activities decrease as the altitude increases, CO_2 may accumulate in the snow cover (Mariko et al. 1994; Fig. 3.4). According to the aforementioned authors the reason for this is that life activities in the soil still go on even in the winter months. Measuring the CO_2 content of the snow cover Körner (1999) also found it to be higher than that of the atmosphere. At altitudes where the soil is frozen during winter, CO_2 cannot develop in the soil; therefore, in these areas, for example, the areas at the altitude of 1,980 and 2,200 m investigated by the aforementioned authors, we consider

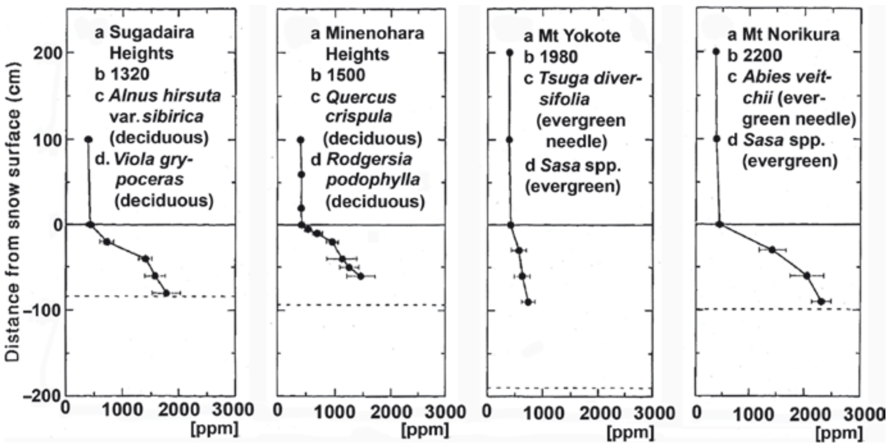

Fig. 3.4 The changing of the CO_2-contretation under the snow on the Alps areas (in Japan) which are covered with vegetation (Mariko et al. 1994): the changing of CO_2-concetration where the thickness of snow is greater than 0.8 m, between March and May, on Honshü Island (between 35°12′ N and 37°02′ N). Legend: (**a**) location, (**b**) altitude (asl), (**c**) tree plant, and (**d**) floor plant

evergreen plants to be the source of the CO_2. Thus, our opinion is that in the Alps the CO_2 content of the snow cover is produced by *Pinus mugo*. This conclusion is also supported by our direct measurements (we measured the CO_2 content of the snow cover, and found it to be higher than that of the atmosphere, near a *Pinus mugo* fully covered by snow in the area of Schneealpe (Austria).

- Precipitation is abundant, amounting to some thousands of millimetres, and adjusted to the diverse morphology and due to snow drifts, has a highly variable distribution.
- As snow remains for an ever longer time at high elevations, the period of melting and thus that of the dissolution will be longer too.

3.2.4 The Role of Slope Direction and Jointing Direction on Karren Formation

Investigating the direction distribution of the karren forms, we claim that the grikes of grikekarren mainly developed along cracks in strike direction but there are some grikes aligned in other directions. On gentle slopes grikes develop exclusively along dip-direction fractures (Fig. 3.5). Grikes and pits develop in the direction(s)

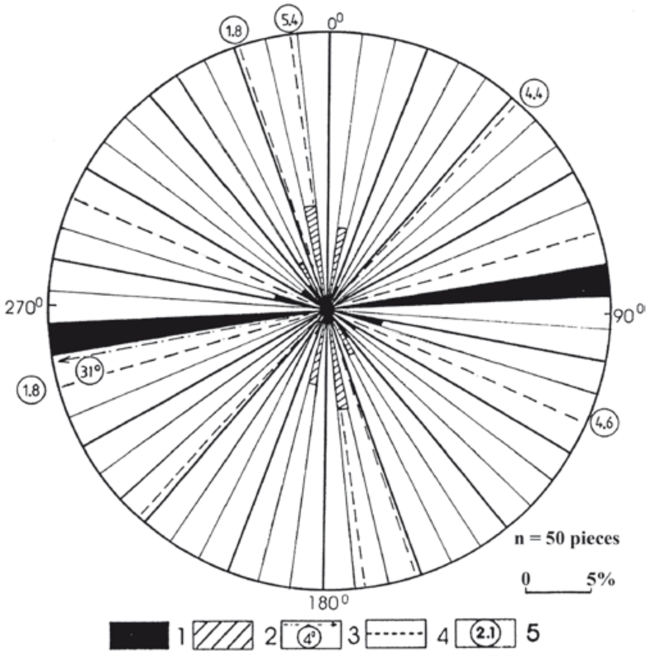

Fig. 3.5 Direction distribution of karren forms, which occur along profile marked T-1/1999 (research area marked 1/1, Veress et al. 2006b). Legend: 1 – rinnenkarren, 2 – grikekarren, 3 – slope direction, with slope angle, 4 – direction of crack, and 5 – frequency of cracks (piece/dm)

along which the density of fractures is higher. Grikes only develop along cracks, which have the same direction as the slope in case of slopes with small inclination. Grikes and pits develop mostly along those directions along, which crack density is bigger. If the directions of cracks are varied, the direction of grikes also shows a higher dispersion. Furthermore, if grikes develop along varied directions, certain grikes may develop independently from cracks.

We claim that the directions of rinnenkarren never coincide with the directions of fractures. Dip direction controls the directions of rinnenkarren (Fig. 3.5), but their direction may show considerable dispersion compared to slope direction. Undoubtedly, the frequency of rinnenkarren is the highest in slope direction. It seems probable that with increasing slope angle the difference between the direction of the rinnenkarren and slope direction reduces. We explain this phenomenon with the fact that with increasing slope, the direction of the rivulets, along which the channel was created, is getting more and more similar to that of the slope.

Bögli (1976) distinguished karren forms and karren assemblages and thus the various levels of karren formation. This classification present different karren assemblages as higher levels of karren formation. Hence karren assemblages do not interpret only with the occurrence expansion of karren forms. We believe that even more levels of karren formation are identified in high mountains than those distinguished by Bögli (1976). Thus, karren formation in high mountains can be described more completely. A higher level of karren formation represents a higher quality. Consequently, we distinguish the following levels of karren formation:

- Karren features
- Karren assemblages (these differ from those form groups which were termed karren assemblages by Bögli)
- Karren belts of slopes and karren forms
- The coalescing karren forms
- Karren cells

We wish to describe karren formation in high mountains by analyzing these levels.

Chapter 4
Karren Features

Abstract In this chapter we describe the specific environment, morphology, formation and the development of the different karren forms. We provide a comprehensive study of the following karren forms: rillenkarren, solution bevel, trittkarren, solution ripples, scallops, rinnenkarren, wandkarren, meanderkarren, grikekarren, kamenitzas, pitkarren, schichtfugenkarren, napfkarren, rainpits, karren cavities, spitzkarren, karren mounds heads of bead karren, clints, clasts, karrennasen and root karren.

Keywords Rillenkarren • Solution bevels • Trittkarren • Rinnenkarren • Wandkarren • Meanderkarren • Grikekarren • Kamenitzas • Pitkarren • Karren cavities

4.1 Karren Features of Flowing Water Origin

4.1.1 Features of Sheet Water Origin

4.1.1.1 Rillenkarren (Solution Grooving)

Rillenkarren (Picture 4.1) consist of series of small troughs (flutes), whose direction is identical with the dip direction of the bearing slope. Their length is a few decimetres and their cross section is mostly parabolic or sometimes V-shaped. Several authors dealt with the characteristics, the development and development surroundings of rillenkarren (Sweeting, 1973; Perna and Sauro, 1978; Dunkerley, 1979; Bögli, 1960, 1976, 1980; Osmaston, 1980; Jennings, 1985; Ford and Williams, 1989; Ford and Williams, 2007; Gines, 1996; Mottershead, 1996; Vincent, 1996). They occur on the upper margin of the slopes, but they wedge out towards the ends (Picture 4.1). All this refers to the fact that the water flowing downwards on the slope becomes saturated quickly. As rillenkarren have high density, there are sharp and crenulate ridges, remnants of the original surface, between them. Their high density value proves that they develop under continuous water cover and thus water sheet (see below). The rillenkarren develop on bare slopes of expansion and is of a few metres high. Thus even though their occurrence is local, they may develop in

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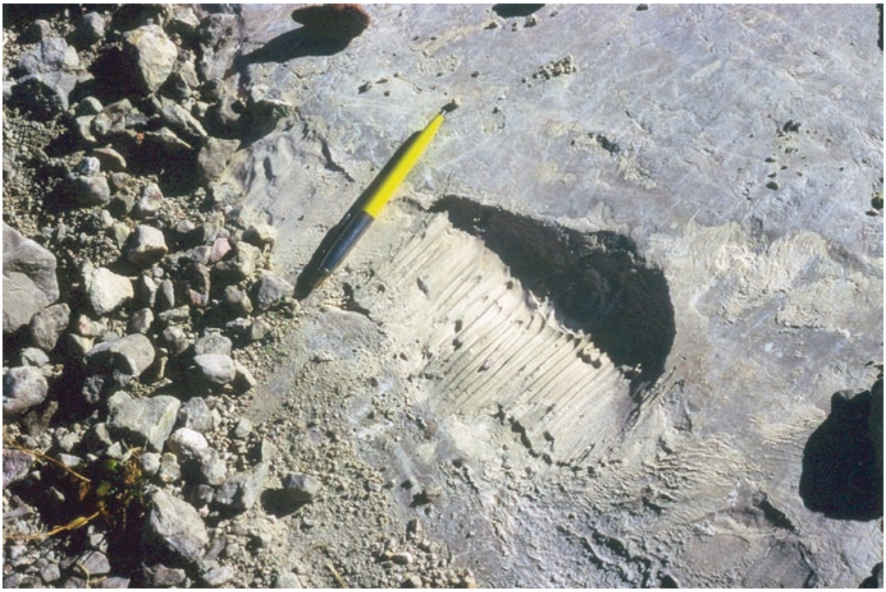
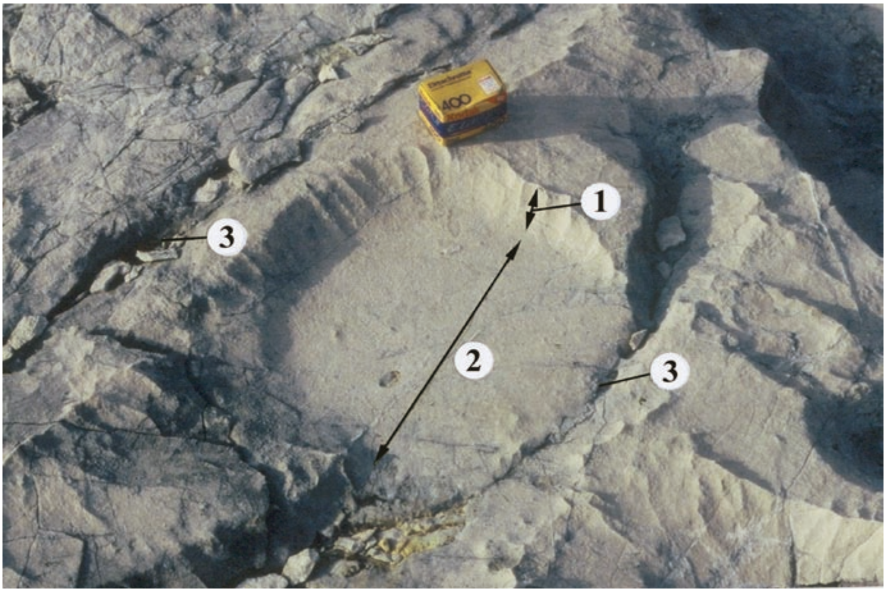
Picture 4.1 Rillenkarren (at Lake Lahngang, Totes Gebirge)



Picture 4.2 Rillenkarren developed on the tread of the trittkarren (area marked 2/3, the valley of the Hallstatt glacier; the environment of the form was covered with glacier 33 years ago)



Picture 4.3 Rillenkarren on the tread of an almost closed trittkarren (Totes Gebirge). Legend: 1 – rillenkarren, 2 – solution bevel, and 3 – joint

a range of geomorphological environment: on the sides of blocks, on slopes of glacier valleys and of karren forms. Rillenkarren, however, may develop on the walls of grikekarren, on the slopes of rinnenkarren, on the treads (Picture 4.2) and risers of trittkarren (Picture 4.3).

The rillenkarren (flutes) have simple patterns and morphology. They may meander (true or falsemeandering) or branch or connect to each other. On steeper slopes, they are mainly straight features. Bögli (1976) distinguished Grossrillenkarren, which are larger flutes with scallops dissecting the bottoms of such forms. One kind of rillenkarren is decantation flutes (rills), which drain small kamenitzas and mostly terminate in kamenitzas of lower position. (Gines, 1996) distinguished between two types of rillenkarren according to their width, the threshold being 2 cm. Rillenstein (rillenstones) is the term for rillenkarren which occur on debris (Laudermilk and Woodford, 1932). Microrillen, 1 mm wide, a few centimetres long and semicircular in cross section (Ford and Williams, 1989; Ford and Williams, 2007), are referred to as a separate group of rillenkarren. Microrillenkarren along with other microkarren (microtrittkarren, micropits, microgrikekarren) occur primarily on slopes exposed from below ice cover recently (in the last decades). Furthermore, they are covered with snow considerably for a longer period of the year (Veress and Zentai, 2004). Such microkarren population is observed between the Triglav Peak, and the Vrata valley (Julianska Alps), where the ice cover melted recently. The sizes of rillenkarren are measured not only in high mountains but mostly in tropical karst (Dunkerley, 1979, 1983; Osmaston, 1980; Veress et al. 2006a).

The length of rillenkarren was investigated thoroughly. According to Bögli (1980), this parameter depends on slope angle, amount of rainfall and temperature. Length increases if temperature, rainfall and slope angle increase and decreases if the elevation of the bearing surface increases. On the contrary, according to (Ginès, 1996), karren length is 50 cm at sea level and 10 cm at 1,000 m (asl) in Mallorca. Their length is between 50 and 200 cm in the Himalayas (Mazari, 1988), while it is around 100 cm in the Mediterranean region (Ginès, 1996). Their length may be different within the same mountains, too. For example, according to Heinemann et al. (1977) rillenkarren are longer on the south-exposed slopes of the Alps than on northern slopes. Glew and Ford (1980) examined the connection between the length of the forms and slope angle using rainfall simulation on gypsum. They established a close correlation between the two parameters up to 60°. The length of the forms increases with increasing slope angle. Average width ranges from 1.2 to 2.1 cm (Ginès, 1996) but extreme dimensions, for example rillenkarren 4 cm wide (Gil, 1989), have also been observed. Their depth is between 2 and 8 cm on average and drops with decreasing elevation in high mountain environments and probably also in Mediterranean environments (Ginès, 1996).

As mentioned above, rillenkarren develop on the upper sections of slopes. They are produced by sheet flow[1] (Lehmann, 1927; Bögli 1961). They are created where the flow is periodically turbulent. The water sheet on the rock is divided into two zones: flowing water and the boundary layer. The flowing water transports the dissolved limestone recharged from the boundary layer (Dubljanszkij 1987). Ca^{2+} ions reach the boundary layer from the rock mass. The boundary layer is stagnant on the rock surface and becomes saturated within a short time. Therefore, solution takes place only if the boundary layer is disrupted by turbulent flow and becomes unsaturated (Curl, 1966; Ford 1980; Trudgill, 1985). Furthermore, dissolution is more intense in turbulent flow driven by turbulent diffusion, while molecular diffusion only happens in laminar flow. The diffusion coefficient is 10^{-4} times higher for turbulent diffusion than for molecular diffusion (Dreybrodt, 1988).

According to Horton (1945), if discharge is the same, water flow is more rapid on the upper convex slope section. Therefore, the water film is shallower than that on the lower convex slope section where the water flow is slower. Therefore water flow is laminar along the upper section, where the shallower water film does not allow the development of turbulent flow. Turbulent flow will occur on the lower slope section, where the water sheet is deeper. There is a transition from laminar to turbulent water flow in the upper slope section in response to some external effect presented below. Woo and Brater (1962) examined the effect of rainfall on water flow on slopes. They found that due to rainfall flow characteristics and dispersion change. The turbulent current may be caused by the unevenness of the surface, but more often by raindrops or snowflakes hitting the water film when the water cover is thin. According to Glew and Ford (1980) turbulent flow develops as a result of raindrop impact on the upper slope section. If the water sheet is deep, raindrops cannot cause turbulent flow since

[1] Water sheet: if water covers the surface of the slope continuously developing and from every direction.

beyond a certain distance from the upper margin of the slope, the quantity of flowing water increases considerably. The intensity of rainfall is the main agent here. According to Glew and Ford (1980), with rainfall intensity above 35–45 mm/h, the thickness of the water flowing on the slope will be 0.15 mm. At such water depth, turbulent flow does not develop even temporarily. Hence solution does not occur where the water sheet is deeper than 0.15 mm and because of the lack of turbulent flow, solution does not happen even temporarily. When it does occur, it leads to rillenkarren development. Rillenkarren wedge out where the depth of the sheet water is more than 0.15 mm. This is caused by increasingly deeper water sheet or water quantity downslope. The upper slope section is affected by solution and, therefore, the rim effect is held responsible for the development of the rillenkarren (Smith and Albritton, 1941; Hoffmeister and Ladd, 1945). Thus, rillenkarren are mostly limited to the upper margin of the slope in high density, which is due to the continuous surface solution under water film. The rillenkarren are basically of uninterrupted distribution. Biogenetic solution also contributes to the development of rillenkarren as it loses rock fabric and increases surface roughness (Fiol et al. 1996). As already mentioned, roughness may cause the turbulent flow in the water sheet and indirectly promote the development of rillenkarren.

Their parabolic cross section is explained by Glew and Ford (1980) as follows: the raindrops, which fall onto inter-rill ridges move towards the axis of the flutes where they exert the strongest solution effect.

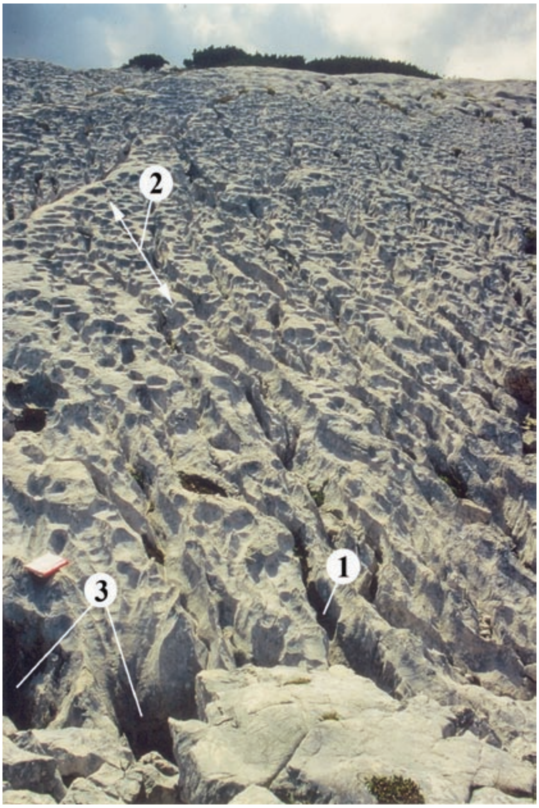
The development of microrillenkarren is explained by Trudgill (1985) with surface water flow. According to other authors, evaporation happens on the surface of the rock. The process causes capillary rise of water from the interior of the rock mass. The solution of seeping waters create these forms (Laudermilk and Woodford, 1932; Ford and Lundberg, 1987).

4.1.1.2 Solution Bevels (Ausgleichsfläche)

These forms are planar surface sections of straight slope segments and of various width (Fig. 3.1). Solution is of limited intensity over such surfaces and, therefore, they retain their ‘planated’ character created by other agents (e.g. glacial erosion). The chances for the development and preservation of such surfaces are better on gentle slopes. They are, however, short-lived: their surfaces are dissected by rinnenkarren regressing towards the upper end of the slope as well as by trittkarren, pits and kamenitzas. But Ausgleichsfläche may extend upwards on the slope at the expense of the rillenkarren belt.

4.1.1.3 Trittkarren

Trittkarren, also called ‘step’ karren (Werner, 1975) and ‘heelprint’ karren (Bögli 1980), are steps that develop on bare slopes (Picture 4.4). Trittkarren consist of a riser, a tread and a foreground (Vincent, 1983; Veress and Lakotár, 1995). The riser is usually curved and surrounds the tread (Fig. 4.1), which is a flat, more or less



Picture 4.4 Trittkarren and rinnenkarren of bedding plane surface (area marked 2/1). Legend: 1 – channel, 2 – trittkarren on the ridge between channels, and 3 – channel end pits

horizontal section. The riser is a vertical surface at the back, while the foreground is the sloping section at the front of the tread, not surrounded by a riser (Fig. 4.2f). Trittkarren are 2–25 cm wide. According to Sweeting (1973), the riser may be about 3–5 cm high, while the tread 20–100 cm wide. According to Haserodt (1965), trittkarren occur at elevations between 1,900 and 2,200 m in the Alps, mostly on gentle slopes. According to Sweeting (1973), they can develop in the initial phases of surface karren formation. Trittkarren occur on marble (Vincent 1983), on gypsum (Callafora, 1996; Macaluso and Sauro, 1996) and on sandstone (Veress 2003).

Types of Trittkarren

We distinguish the following trittkarren types:

- Microtrittkarren are small features. Their treads are 1–2 dm wide. Their heels are 1–2 mm high. The dip of the tread is relatively great. The angle created by the heel and the tread is small.
- Embryonic trittkarren (Picture 4.5) differ from developed trittkarren in their varied shape and smaller dimensions. The angle created by the heel and the tread is small.

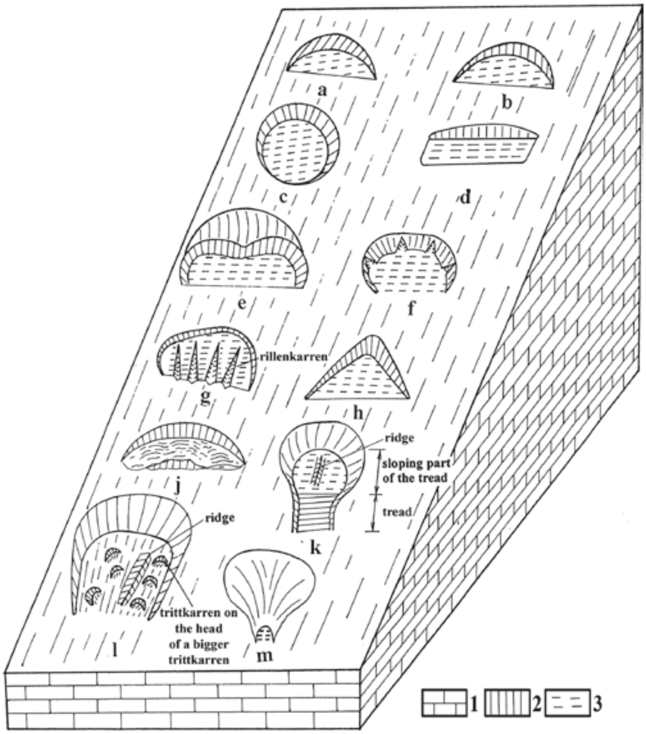


Fig. 4.1 A few simple trittkarren (research area marked 2/1, after Veress and Tóth 2002). Legend: (**a**) trittkarren with gentle and short riser, (**b**) trittkarren, with steep and longer riser, (**c**) trittkarren which has a nearly complete circle-shape riser-arch, (**d**) trittkarren which has a straight riser, (**e**) trittkarren without tread (uvalas trittkarren below it), (**f**) trittkarren, which has rills on its riser, (**g**) trittkarren, which has rills on its tread, (**h**) trittkarren which is arcuate on its riser, gentle on its tread, (**j**) trittkarren, which has a wavy tread, (**k**) trittkarren which has an elongated tread, (**l**) trittkarren with ridges and trittkarren on its tread, and (**m**) trichterkarren: *1* – limestone, *2* – riser, and *3* – tread

- 'Nischenkarren' (Fig. 4.2c; Picture 4.6) are a type of trittkarren with wide and common tread and are surrounded by a small riser-system that is interconnected (Haserodt, 1965).
- Trichterkarren (Picture 4.7; Fig. 4.1m) are a type of trittkarren with no tread (Bögli 1951).
- Uvala trittkarren (Picture 4.7; Fig. 4.2d–g) are a type of trittkarren with coalescing risers and ridges separating the partial risers from each other (Veress, 2000e).
- Semi-circular 'step-trittkarren' develop around or on the margins of grikes and shafts. The treads and risers occur in a row and the risers of individual 'step-trittkarren' can develop parallel to each other (Picture 4.8).
- There are karren forms with treads but with no risers (Picture 4.9). They occur on very steep slopes. These forms are similar to trittkarren but they may also be a special variety of 'spitzkarren'. Choppy (1996) calls them 'tetrahedron' karren.

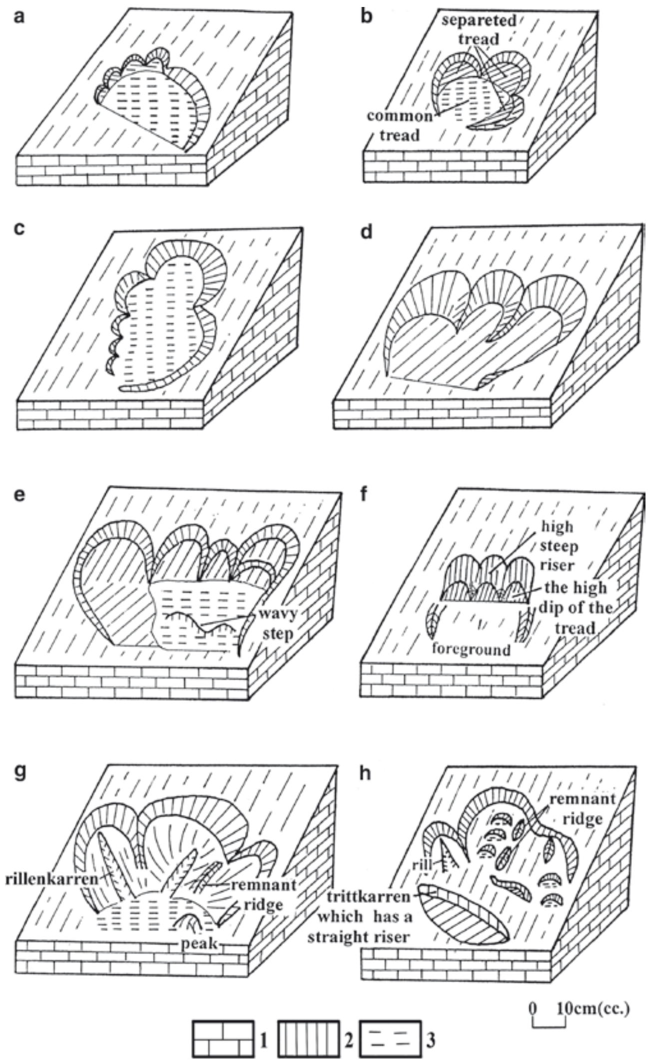
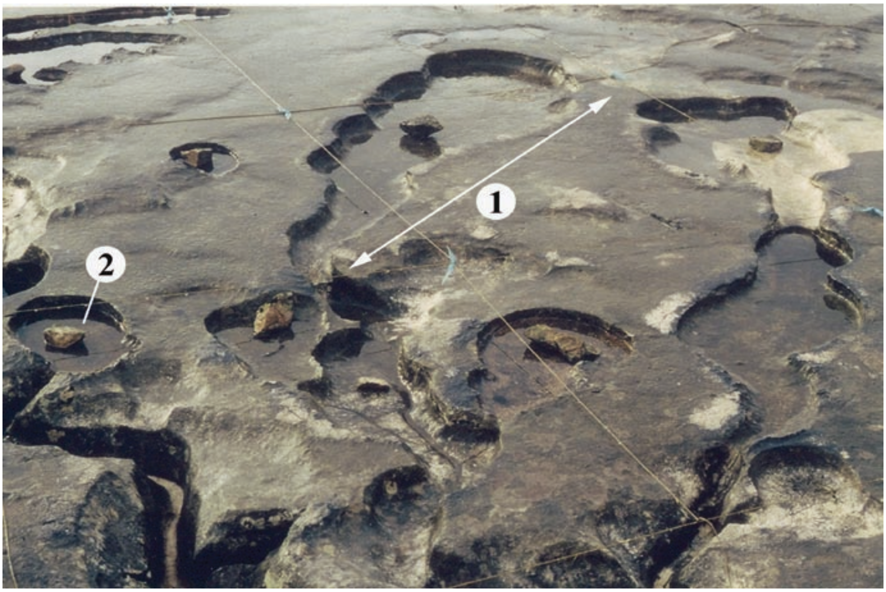


Fig. 4.2 A few uvala trittkarren (research area marked 2/1, after Veress and Tóth, 2002). Legend: (**a**) trittkarren, whose margin is dissected by younger trittkarren, (**b**) nearly closed uvala trittkarren, (**c**) nischenkarren (trittkarren uvala, which borders a planar foreground), (**d**) uvala trittkarren whose independent and common tread parts do not separate from each other, (**e**) uvala trittkarren with step on its tread, (**f**) uvala trittkarren whose independent and common tread parts are separated from each other, (**g**) uvala trittkarren, which are dissected by rills (on steeper separated tread), and conicles (on common planar tread), and (**h**) uvala trittkarren which has rillenkarren on its steeper tread, and smaller trittkarren and remnant ridges on its tread: *1* – limestone, *2* – riser, and *3* – tread

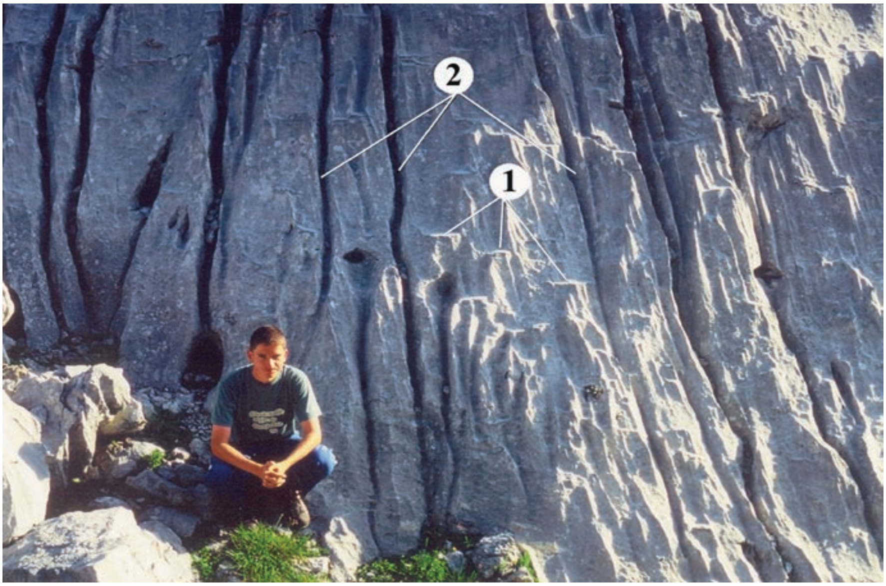
Picture 4.5 Embryonic trittkarren, on a solution bevel under a grike (area marked 1/2)



Picture 4.6 Almost closed nischenkarren (area marked 1/4). Legend: 1 – nischenkarren, and 2 – almost closed trittkarren

Picture 4.7 Trichterkarren (area marked 2/1). Legend: 1 – trichterkarren, and 2 – uvalas trittkarren

Picture 4.8 ‘Step trittkarren’, with narrow steps (area marked 1/4)

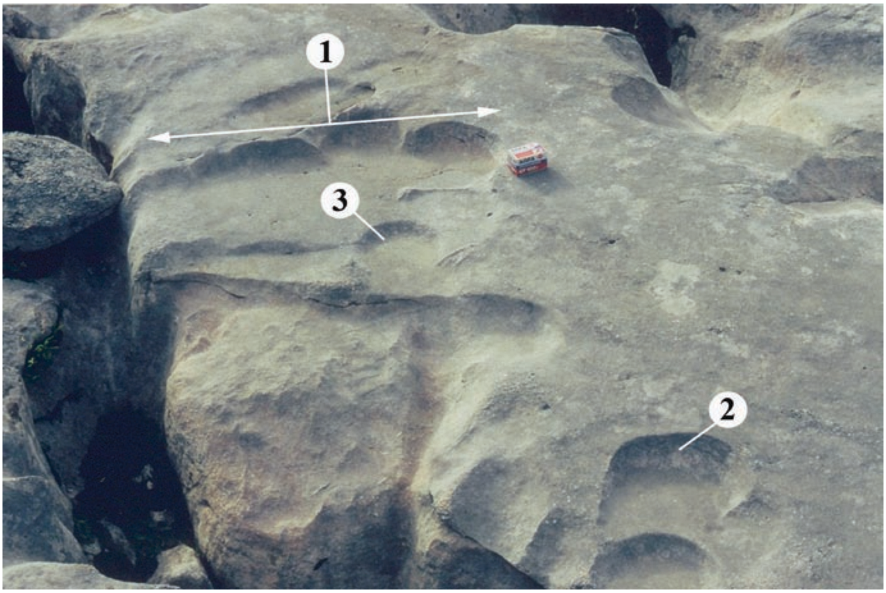


Picture 4.9 Tetrahedral karren (Dachstein). Legend: 1 – tetrahedral karren, 2 – wall karren

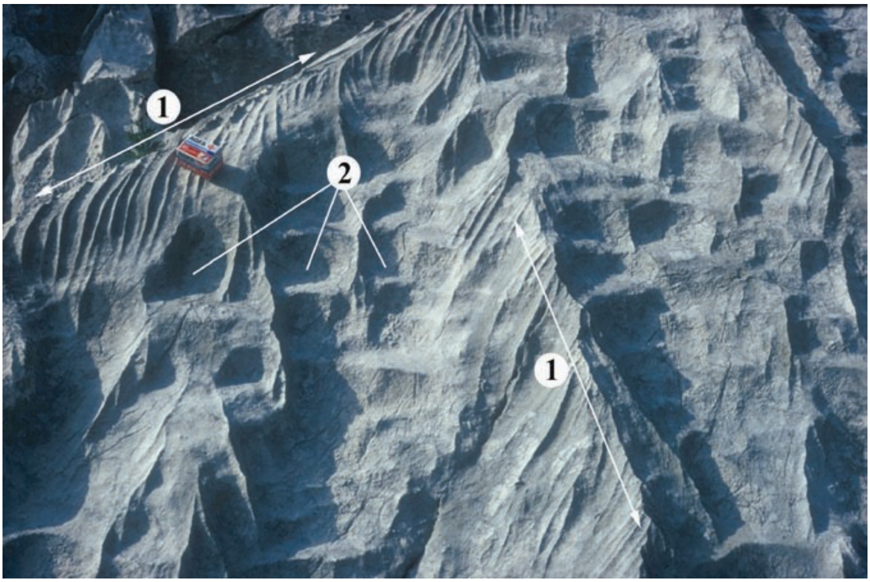
Trittkarren occur in rinnenkarren, in kamenitzas, on 'Ausgleichsfläche' and on ridges between rinnenkarren as well as on exhumed head scarps.

Morphology of Trittkarren

Trittkarren occur in groups. According to Bögli (1951) and Haserodt (1965), the tread of trittkarren is a minor solution bevel. According to Bauer (1962), there is a close relationship between the angle of the enclosing slope and the morphology of trittkarren. If slope angle is gentle (less than 10º), the height of the riser will be 1 or 2 cm, and the width of the tread a few decimetres (Pictures 4.6 and 4.10). If the angle of the slope is between 10º and 30º, the riser and the tread will be larger (the height of the riser will be several centimetres and the width of the tread 1 or 2 dm, Picture 4.7). If the inclination of the slope is high (above 30º), the height of the riser will be several decimetres and the width of the tread will be 1 or 2 cm (Picture 4.11). The riser can have a gentle (Picture 4.12) or a steep slope (Picture 4.11). Viewed from above, the curve of the riser can be short (Fig. 4.1a; Picture 4.12) or long (Fig. 4.1b, f; Pictures 4.6 and 4.7). In the first case, the length of the riser is smaller than a semi-circle arc; in the latter case, its length is longer than a semicircle arc. The riser may also be almost closed (Pictures 4.3 and 4.6; Fig. 4.1c). The curve of the riser can be almost straight (Picture 4.13; Fig. 4.1d) or angular, close to a right



Picture 4.10 Nischenkarren and trittkarren with riser with small height on a slope with small inclination (area marked 1/4). Legend: 1 – nischenkarren, 2 – trittkarren, and 3 – smaller trittkarren on the tread



Picture 4.11 Trittkarren with high risers of a slope great inclination (area marked 1/1). Legend: 1 – rillenkarren, and 2 – trittkarren

Picture 4.12 Trittkarren with high and slanting rise: the dip of the bearing slope is big (area marked 1/1). Picture 4.8: 'step trittkarren', with narrow steps (area marked 1/4)

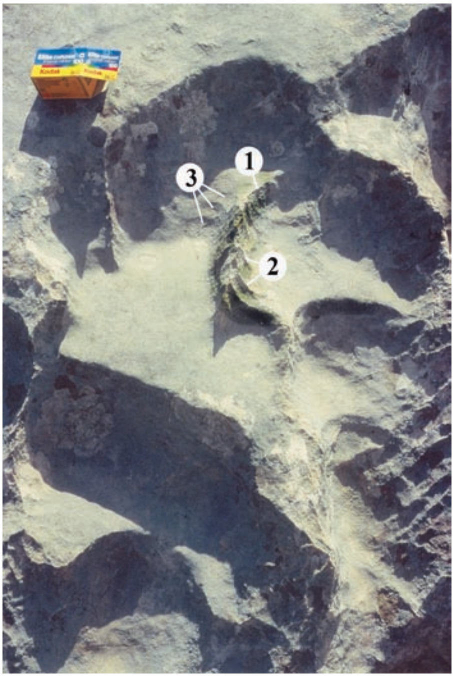
angle (Fig. 4.1h; Picture 4.12). Rillenkarren (Picture 4.3; Fig. 4.1f) or secondary (small sized) trittkarren can occur on a riser (Picture 4.14). The tread may be horizontal and planar (Picture 4.6) or complex. It can be composed of surfaces with various slope angles (Fig. 4.2b). Minor forms, which occur on the surface of a tread are waves (Fig. 4.1j), steps (Fig. 4.2e), ridges (Figs. 4.1k, l, and 4.2g, h; Picture 4.15), 'peaks', secondary trittkarren (Picture 4.15; Figs. 4.1l and 4.2a), rillenkarren (Picture 4.2; Figs. 4.1g and 4.2g, h) and kamenitzas. Trittkarren and rinnenkarren can occur on the tread of 'nischenkarren' (Fig. 4.3) and minor rinnenkarren within trichterkarren.

The characteristics of trichterkarren are the following:

- They are large.
- Their morphology is less diverse.
- They occur isolated, instead of in groups.
- They develop together with other karren forms (such as trittkarren).
- They do not join other karren forms.
- Small rinnenkarren can occur inside them.
- They continue in a rinnenkarren (channels).
- They are connected to rinnenkarren.

Picture 4.13 The trittkarren with a straight riser (area marked 2/1)

Picture 4.14 Riser with small trittkarren (area marked 2/1). Legend: 1 – trittkarren on the riser



Picture 4.15 Tread of trittkarren with ridges (area marked 2/1). Legend: 1 – ridge, 2 – rillenkarren, and 3 – secondary trittkarren

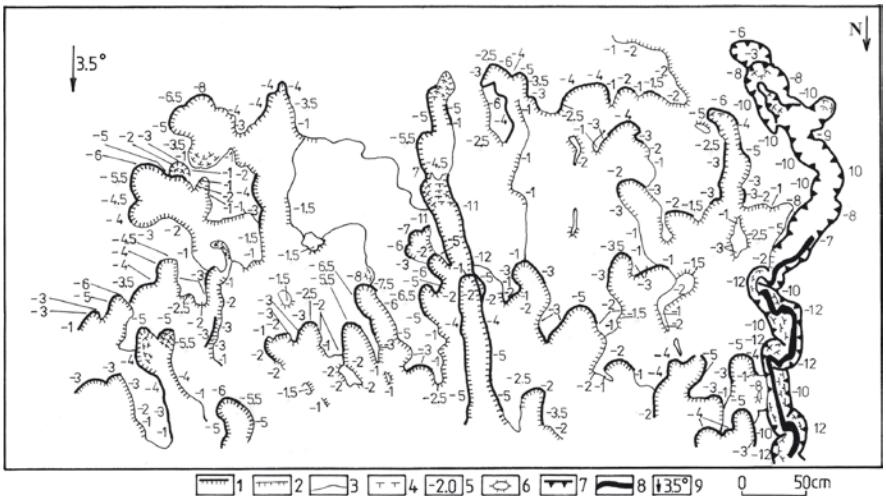


Fig. 4.3 'Nischenkarren' and trittkarren of a gentle surface (research area marked 2/1, Veress, 2003). Legend: 1 – trittkarren and uvala trittkarren which have perpendicular risers, 2 – the height of the gentle riser of the forms is bigger than 1 cm, 3 – gentle step with less than 1 cm height, 4 – scallops, 5 – the height of any slopes boarding a karren form (in cm) 6 – remnant surface, 7 – type I channel, 8 – type III channel, and 9 – line of dip and dip angle (see Picture 6.1)

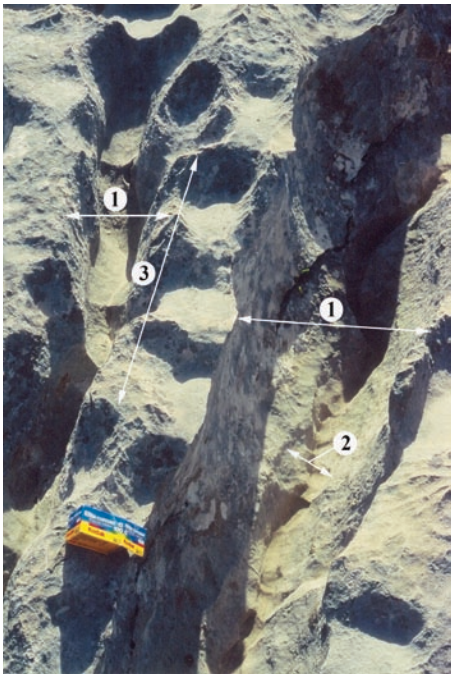
Development of Trittkarren

According to Bögli (1960), trittkarren develop where the intensity of the dissolution is high and the flow of water is shallow. In one of his later papers, Bögli (1976) claimed that these forms developed by dissolution under snow when small drops of melting snow fall into already existing depressions on the limestone surface. Haserodt (1965) thought that trittkarren occur under micro-scale snowdrifts. According to Haserodt (1965), the development of trittkarren occurs due to the melting of snow patches. The melting dissolves limestone through surface corrosion. The process requires the enduring presence of snow patches, which is typical of northern slopes. The rate of dissolution (and thus the dimensions of the forms) depends on the rate of saturation. According to Sweeting (1973), trittkarren develop due to large raindrops (during intense rainfall). She believes there is horizontal dissolution on their areas primarily because two water layers merge on the surface. According to Ford and Williams (1989), trittkarren appear on homogenous fine-grained rock if micro-steps developed earlier on its surface (by erosion). According to Ford and Williams (1989), these forms develop from kamenitzas.

According to several other authors (Vincent, 1983; Trudgill, 1985; Veress and Lakotár, 1995), the development of trittkarren can be caused by turbulent flooding. In that case dissolution can increase due to the above mentioned fact by carbon dioxide entering the water due to turbulence. As turbulence grows, the rock surface becomes uneven and the turbulence of flow increases.

The morphology of trittkarren suggests that they develop through surface dissolution under sheet water fed by snow. The following facts prove this process:

- Trittkarren develop under rillenkarren on a slope. The ‘Ausgleichsfläche’ (solution bevel) are often observed downslope trittkarren. Therefore, the water saturation does not occur at the trittkarren but on the ‘Ausgleichsfläche’.
- Trittkarren that occur on ridges between rinnenkarren (Pictures 4.4 and 4.16) can only develop under snow. If they are not covered with snow, they can only get water from the rain that falls on their surface but this water drains quickly into the adjacent troughs. If the adjacent rinnenkarren are filled with snow, the melt water can flow along the ridges.
- Sheet water develops on areas of trittkarren. The presence of rillenkarren on the riser and on the tread proves the presence of sheet water. The presence of rillenkarren also proves that sheet water dissolution can occur without snow.
- Secondary trittkarren can develop on the perpendicular riser of the primary trittkarren. Secondary trittkarren cannot be created by dropping rainwater since the drops can not touch the surface of the riser.
- Trittkarren occur in high density.
- The width of the tread of ‘nischenkarren’ proves the large surface extension of dissolution.
- Secondary trittkarren develop on the tread of uvala trittkarren.
- Dissolution occurs on the tread. The following facts prove this process:



Picture 4.16 Rows of trittkarren on a ridge between channels (area marked 2/1). Legend: 1 – type I channel, 2 – type III channel, and 3 – trittkarren

- The rills of a riser can continue on the tread.
- The uneven surface of a tread including 'peaks' and ridges is a sign of dissolution on the tread.
- Young trittkarren exist on the ice-free floor of the valley of the Hallstatt Glacier because the environment of the trittkarren was covered with ice only a few decades ago. The risers of the trittkarren are short and the dip of their tread is large. The inclination of the tread of older trittkarren is low and decreases during its development. This can only be explained by the dissolution of the tread.

Trittkarren often occur below one another along a slope. This fact shows that dissolution resumes repeatedly downslope. Given the presence of the tread, dissolution must be local. We believe that trittkarren develop on slopes where sheet flow is turbulent, and at places where local dissolution is remarkable. That local turbulence develops under snow is proven by the fact that trittkarren occur on ridges between rinnenkarren as mentioned. Furthermore, there are no rillenkarren on most trittkarren and therefore the turbulent sheet water cannot be caused by rain. The sheet water is of meltwater origin. According to Glew and Ford (1980) raindrops must hit sheet water to make it turbulent and promote the development of rillenkarren. We claim that trittkarren can develop if dissolution takes place locally and temporarily, which is possible if sheet water flows under snow.

The development of trittkarren has three phases:

- In the first phase, a flat surface develops on a slope due to meltwater. This surface part becomes the tread of the trittkarren.
- If the inclination of the slope is low, in the second phase the tread and the riser form simultaneously, both the riser and the tread retreat and thus the form (trittkarren) can develop probably because there is no or little turbulence on the slope. Because of laminar flow, dissolution has a uniform rate over a larger area (Fig. 4.4a). Trittkarren are stable forms and their tread is ever increasing. On a slope of medium inclination, dissolution is most intense at the junction of the riser and the tread. The inclination of the tread decreases while the riser becomes ever steeper (Fig. 4.4b). On steeper slopes, the riser subsequently becomes less steep because dissolution is more rapid (Fig. 4.4c, d). As a result, trittkarren cannot survive on such slopes for a long time; however, we believe that trittkarren develop again later since their density is also high on such slopes.
- In the third phase, the intensity of the dissolution can vary along the length of the riser in that case the curve of the riser is longer (Fig. 4.4c, d). The shape of the riser does not change if dissolution is similar all over the riser, and the riser becomes longer as it develops (Fig. 4.4a). The risers of the trittkarren with low risers retreat at a rapid rate, thus wide treads develop and the risers coalesce. When the risers coalesce, the trittkarren change into 'nischenkarren'. In the case of trittkarren with higher risers (if the riser is not destroyed), the speed of the

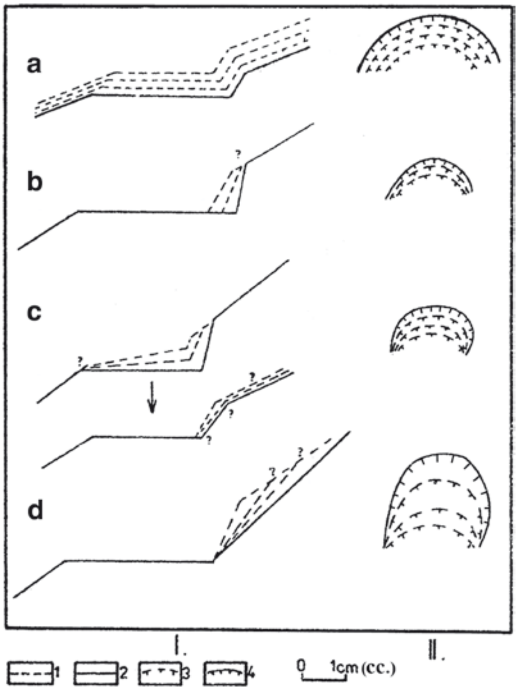


Fig. 4.4 Development of trittkarren on different pitching slopes (after Balogh 1998). Legend: I – profile view, II – view from above (**a**) small pitching slopes, (**b**) 25° pitching slopes, (**c**) 30° pitching slopes, and (**d**) 40° pitching slopes: 1 – original surface parts, 2 – actual surface parts, 3 – former riser arch, and 4 – actual riser arches

backstepping is slower. Uvala trittkarren (with small width of tread) develop if the trittkarren are close to each other.

The absence of treads in the case of trichterkarren suggests that these forms develop from already existing forms such as heads of channels. The slope, which surrounds the head of channel moves backwards at its whole length. Therefore, a tread is not able to develop later either.

4.1.1.4 Solution Ripples

These forms are small ridges which are parallel to each other. Their height is between a few millimetres to a centimetre. Their direction is parallel to the strike direction of the enclosing slope. They develop on steep or hanging walls and have two varieties according their cross section: symmetrical and asymmetrical solution ripples. They occur in small extended patches but they have high density and their appearance is continuous.

4.1.1.5 Scallops

The depth and the diameter of the scallops are a few centimetres (Wall and Willford, 1966). They also occur in patches of various sizes (Picture 4.17). As their density

Picture 4.17 Scallops (Diego de Almagro Island, Chile). Legend: 1 – Scallops (notice: Step channel may see been on the upper part of the picture)

is high, they can be considered minor depressions separated from each other by solution ripples with irregular pattern. Probably the ‘finger’-like depressions (‘fingerkarren’) represent a variety of scallops. Their diameter and depth are 1–2 cm and their sides are steep. Finger-like depressions are described at the bottom of type III rinnenkarren (trough), from the wall of type I rinnekarren with great size (trough), which is of concern, from the Julian Alps (Veress, 1995, Veress, 2000c).

Jennings (1985) explains their development with periodical fluctuation of solution. According to Curl (1974) and Ford and Williams (1989), the cause of their development is the solution by eddies along rock surfaces.

4.1.2 Forms Created by a Rivulet

4.1.2.1 Rinnenkarren (runnels, channels)

Rinnenkarren are solution channels (runnels, flutes) that occur parallel to each other and whose direction coincides with the dip direction of the slope. According to Eckert (1898), Bögli (1976), and Ford and Williams (1989), rinnenkarren are several decimetres wide and deep, and they can be several dozen metres long. They are large forms that cover extensive areas and do not wedge out at the ends without surface water drainage (Picture 4.18). According to Haserodt (1965), rinnenkarren occur between the altitudes of 480 and 2,300 m in the Alps, and according to

Picture 4.18 Rinnenkarren (Valley of Triglav Lakes)

Kunaver (1984), between 1,650 and 1,700 m in the Julian Alps. They can develop parallel on steeper slopes (as mentioned above), but they can also be separated as main channels and subsidiary channels on gentler slopes where they create interlocking systems (Figs. 4.5 and 4.6). We present a theoretical distribution of channel systems on a big slope in Fig. 4.7. According to Wagner (1950), rinnenkarren occur on slopes between 30º and 90º, but we believe rather that wandkarren develop on the steeper slopes (cc. 60–90º).

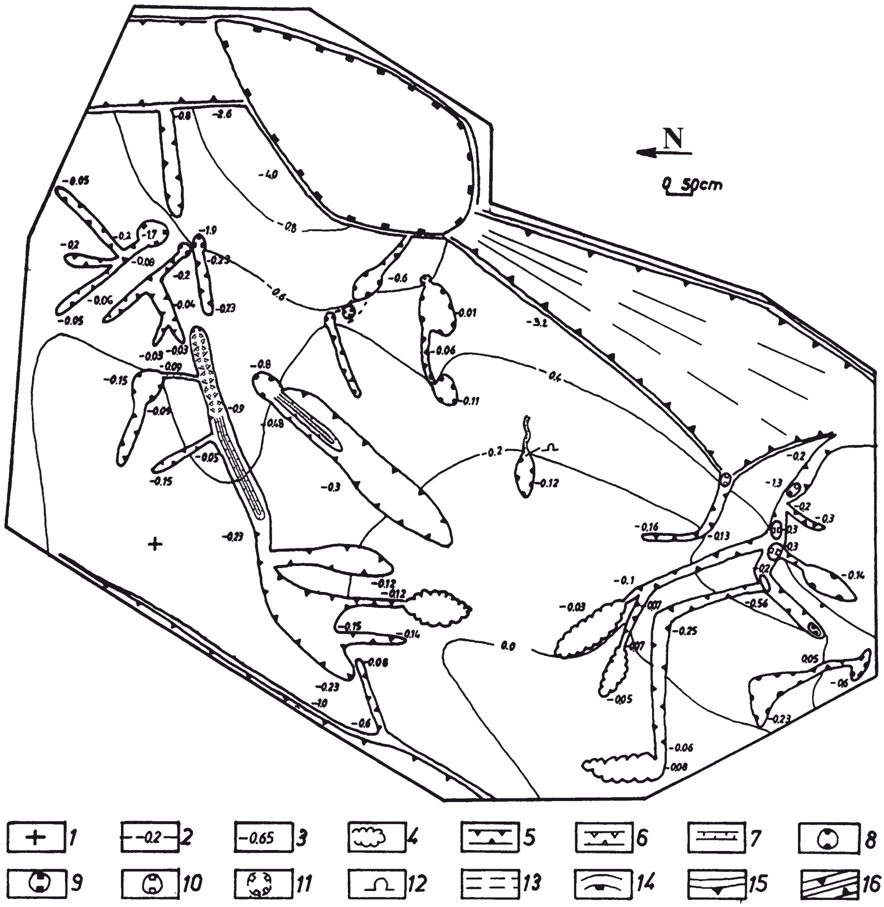


Fig. 4.5 Channels system on a flachkarren (research area marked 1/4, Veress et al. 1995). Legend: 1 – the place of theodolite, 2 – contour line in local system, 3 – the depth of the form (m), 4 – nischenkarren, 5 – type I channel or channel in general, 6 – type II channel, 7 – type III channel, 8 – kamenitza, 9 – pit in general, channel end pit, 10 – channel-bottom pit, 11 – wreck pit at the bottom of a channel, 12 – entrance of spring karren cave, 13 – through karren cave, 14 – schaft, 15 – grike, and 16 – grike system

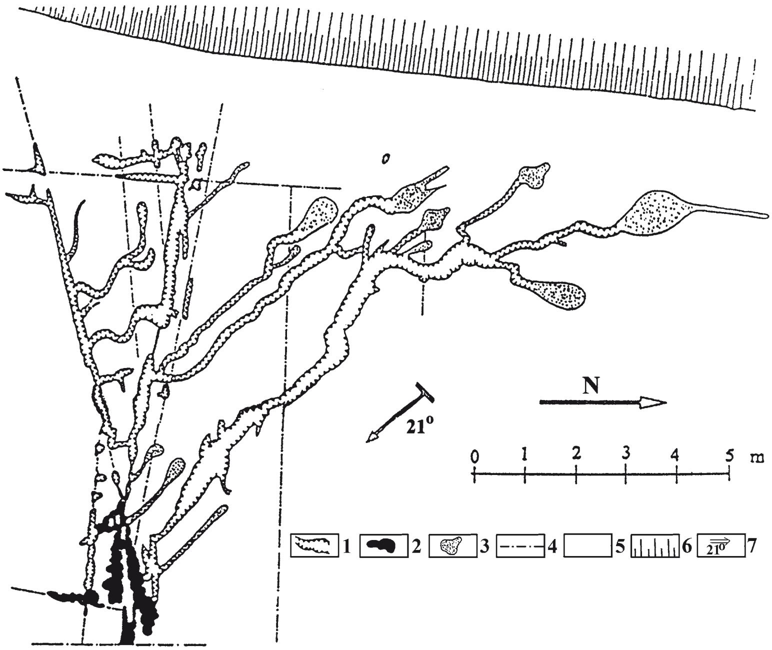


Fig. 4.6 A system channel on a slope with big dip angle (research area marked 1/1, Szunyogh, 1995). Legend: 1 – channel, 2 – pit, 3 – kamenitza, 4 – joint, 5 – bedding plane slope, 6 – bed head slope, and 7 – the dip direction and dip of the surface

Rinnenkarren and Their Types

Rinnenkarren can be divided into several types. Large channels can have depths and widths of about 1 m (Picture 4.19; Fig. 4.8; Veress, 1995, Veress, 2000f). According to Bögli (1976), the surface remnant between the channels, which compose rillenkarren, can be flat or round. Bögli (1976) called the latter karren form 'Rundkarren' or 'rounded solution channels'. Several researchers explain the development of this form by dissolution under soil (Eckert 1902; Bögli 1976; Jennings 1985; Sweeting, 1955). Other researchers think that rundkarren could have developed when rinnenkarren were transformed during their development (Bögli 1960; Haserodt 1965; Louis, 1968; Wagner 1950). The surfaces that are covered with soil today were bare during the glacial period, and therefore rinnenkarren could have developed on such surfaces. These rinnenkarren were covered with soil after the retreat of the ice in the Holocene, and due to dissolution under the soil, the ridges between the channels were rounded off. The side walls of the channels dissolved steeply (resulting in a U profile), depressions could develop at the bottom of channels ('Korrosionshohlkehlen'), and the slope angle of the bottom of the channels became smaller (Bögli 1976; White, 1988).

The side walls of the channels can also be overhanging due to dissolution under the soil. Bögli (1976) called this type 'Hohlkarren' ('bag-shaped'). The soil can erode and the rounded ridges partly or totally protrude (Picture 4.20). Subsoil solution

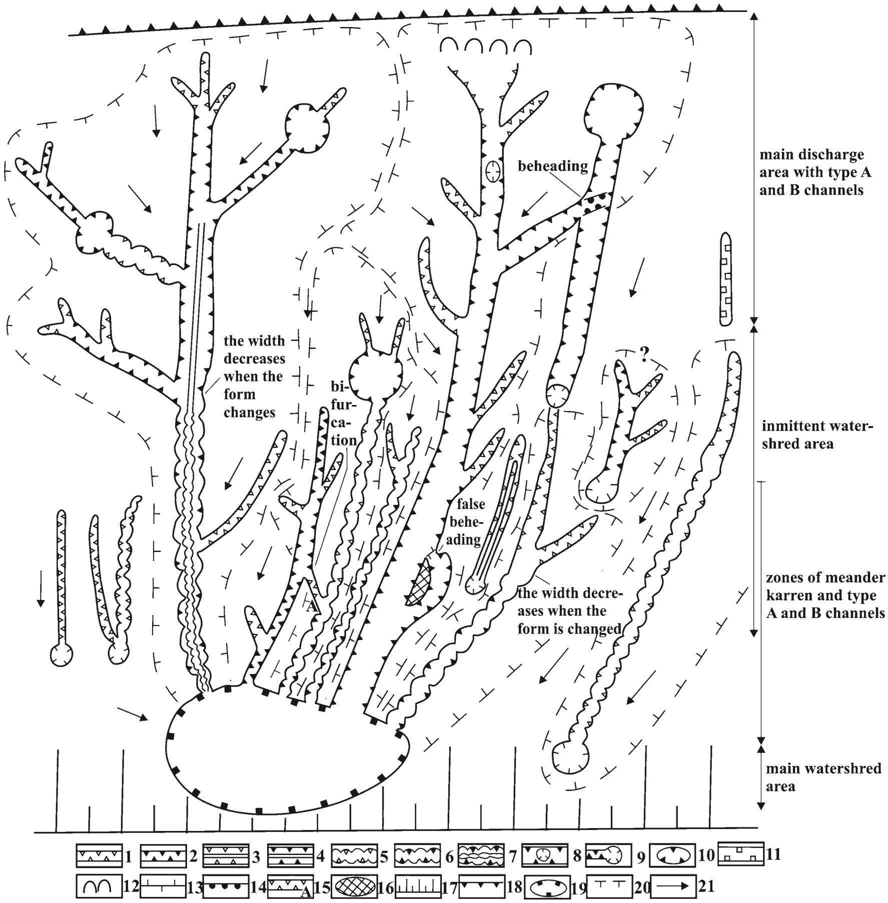


Fig. 4.7 Theoretical figure of channels and channel-systems of great sized slope with small dip angle and the relationship between the channel and other karren features (used cases: part areas marked 1 and 2 of the research area marked 1/9). Legend: 1 – simple type A channel, 2 – simple type B channel, 3 – complex type A channel, 4 – complex type B channel, 5(simple meanderkarren, 6 – simple type B meanderkarren, 7 – complex meanderkarren, 8 – channel-bottom pit, 9 – channel end pit, 10 – kamenitza, 11 – grikekarren, 12 – trittkarren, 13 – watershred on the channel bottom, 14 – step on the channel bottom, 15 – anti-regressional channel, 16 – karren monodock, 17 – front of a cuesta, 18 – grike wall, 19 – shaft, 20 – boundary of catchment area (water divide), and 21 – dip direction (notes: catchment area of some channels, or channel-system may be decreased by the channel-bottom pits, the beheadings and the bifurcations)

forms develop on the side walls of the rinnenkarren such as pockets, ‘ears’ and small cavities (Szunyogh, 1999).

According to Jennings (1985), flutes and smaller channels (‘rain solution channels’) occur on the ridges between channels. We consider the latter to be rillenkarren.

Ford and Williams (1989) describe one rinnenkarren type as Horton-type channels whose forms become larger and more complex downward along the slope, taking a branched form. They are fed from the upper part of the slope (e.g. from an

Picture 4.19 A great channel, which may be seen in Fig. 4.8 (area marked 1/1). Legend: 1 – end of channel, 2 – pit marked A, 3 – pit marked B, 4 – pit marked C, 5 – pit marked D, 6 – remnant of terraces of various elevation, 7 – terrace edges, 8 – terrace in development, and 9 – type II channel of pit marked B

'Ausgleichsfläche' area), but in our opinion they receive further water from their margins on the lower part of the slope. According to Gladysz (1987), they are complex forms from about 3–5 m below their upper ends. There can be pits (karren sinkholes) and grykes on their bottoms, and their development is also complex (complex channel). According to Ford and Williams (1989), there are single rinnenkarren that receive their water directly from rain whose width and depth decrease farther down the slope. There are also decantation channels (Picture 4.21) fed by kamenitzas. The water supply of decantation channels is therefore local, but they can also receive water dropping from leaves and the trunks of trees. According to Sauro (1976), all rinnenkarren developing from a kamenitza are decantation channels. According to Ford and Williams (1989), 'decantation flutes' are forms of large density with narrow dividing ridges between them. These forms are fed by sheet water from the upper part of a slope.

Bögli (1960) described 'regenrinnenkarren', forms that develop on a steep slope due to rainwater. However, this form is a special wandkarren. According to Jennings (1985), this type can develop with the coalescing of neighbouring rills. Crowther (1997) distinguishes different types of rinnenkarren according to their vertical section: those with a planar bottom, with a stepped bottom ('step rinnenkarren' Picture 4.17), and with a changing bottom slope angle ('bevel rinnenkarren').

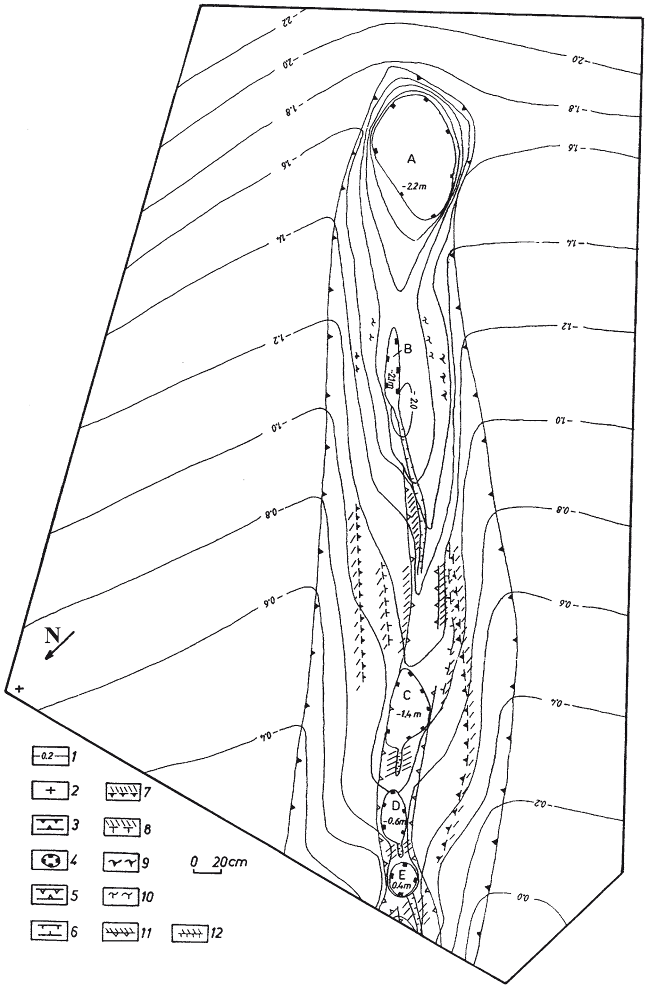
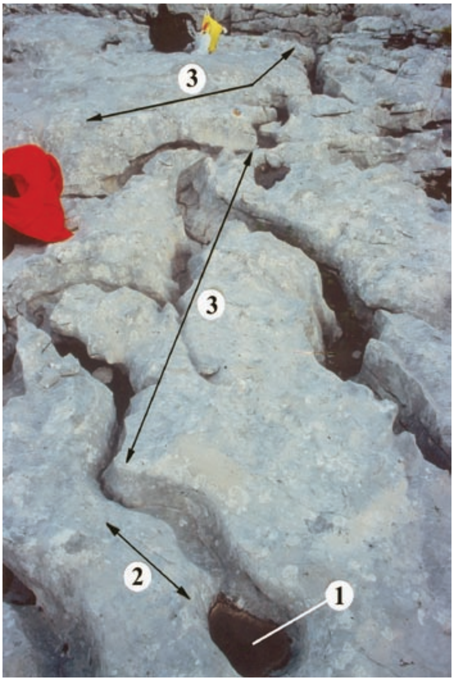


Fig. 4.8 Contour and morphological map of a major channel (see Picture 4.19 research area, marked 1/1, Veress et al., 1995). Legend: 1 – contour line in local system, 2 – position of the surveyor, 3 – rim of the major channel, 4 – channel-bottom pit, 5 – margin of type II channel of the pit marked B, 6 – margin of type III channel, 7–8 – remnants of terraces of various elevation, 9–10 – edges (remnants of terraces) of various elevation, 11 – terrace, and 12 – terrace in development

Rinnenkarren can develop on a variety of rocks. For example, they can occur on marble (Veress et al. 2006d), granite (Rassmusson, 1959), calcareous sandstone, calcareous conglomerate, amorphous silica sandstone (Veress and Kocsis, 1996), gypsum (Calaforra, 1996), basalt (Bartrum and Mason, 1948), quartzite (White et al. 1966; Marker, 1976; White 1988), halite (Macaluso and Sauro, 1996) and calcareous greenschist (Veress and Szabó, 1996; Veress et al. 1996b). Large channels mostly develop on granite and halite.

Picture 4.20 Semi-exhumated rounded rundkarren (Totes Gebirge, at Lahngang Lake)



Picture 4.21 Decantation channel (area marked 1/2). Legend: 1 – kamenitza, 2 – type I channel, and 3 – evolved channel

Morphology of Rinnenkarren

To describe rinnenkarren, we must consider their environment and their morphology. Trittkarren (Figs. 4.5 and 4.9; Picture 4.22), 'leafkarren' (Szunyogh et al. 1998), and kamenitzas (Fig. 4.9; Picture 4.23) can occur near rinnenkarren and at the side of the rinnenkarren or at head of the channel. Hanging kamenitzas (which are at the sides of the rinnenkarren) are often connected to a main channel by a small subsidiary channel (type III channel; Picture 4.23). These forms feed the rinnenkarren.

The morphology of rinnenkarren varies according to sections of the channels (Fig. 4.9). Forms with a water-feeding function such as kamenitzas are characteristic of the upper sections of rinnenkarren, while forms created by water flowing on the channel bottoms (steps, bottom basins) characterize the middle section of the channels. Various types of pits and grikes increasingly dominate the lower section of the channels and can also occur in the middle section (Figs. 4.5 and 4.9). These latter forms lead the water towards and into the rock.

The cross section of a channel can take simple (Figs. 4.10 and 4.11a–d) or complex forms (Figs. 4.11e, and 4.12; Picture 4.24). The shape of the ridges between the channels (if they are not covered with soil) depends on the density and shape of the channels (Fig. 4.13). The cross sections of simple rinnenkarren can be V, U, ⊔ Ʊ, or (Fig. 4.11a–d, Veress, 2000a).

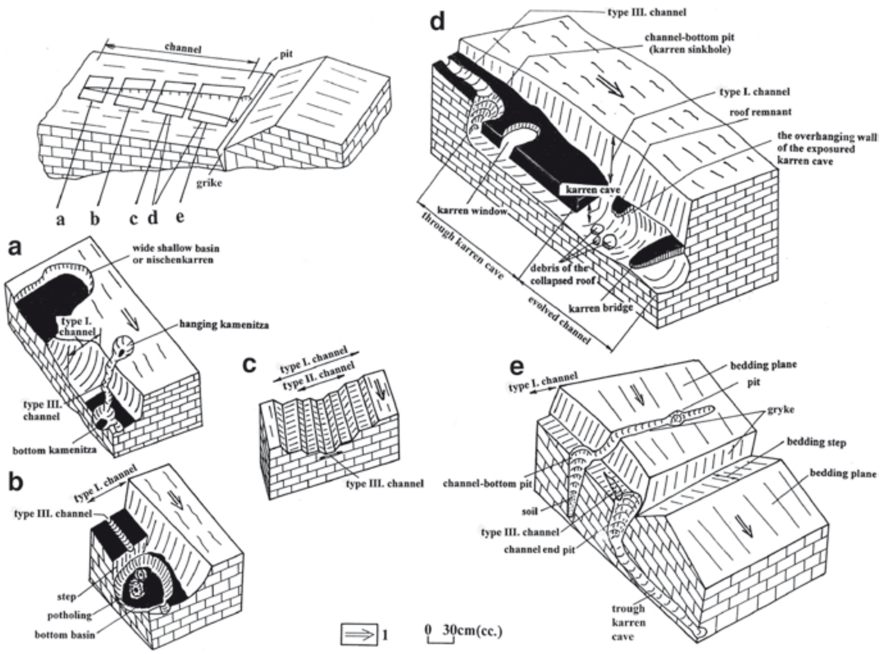
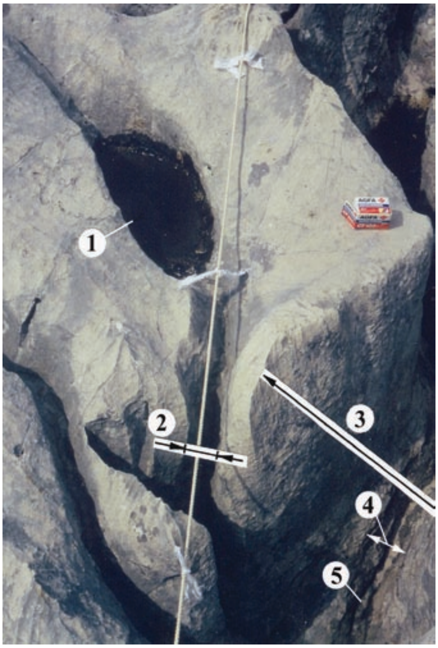


Fig. 4.9 The morphological complexes of different parts of a channel (Veress, 2004). Legend: (**a**, **b**) upper parts of the channel, (**c**, **d**) middle parts of the channel, and (**e**) lower part of the channel 1. line of dip of surface

Picture 4.22 Trittkarren feeding channel (area marked 2/1). Legend: 1 – trittkarren, and 2 – channel



Picture 4.23 Hanging kamenitza (area marked 1/1). Legend: 1 – kamenitza, 2 – decantation runnel of kamenitza, 3 – type I channel, 4 – type II channel, 5 – type III channel

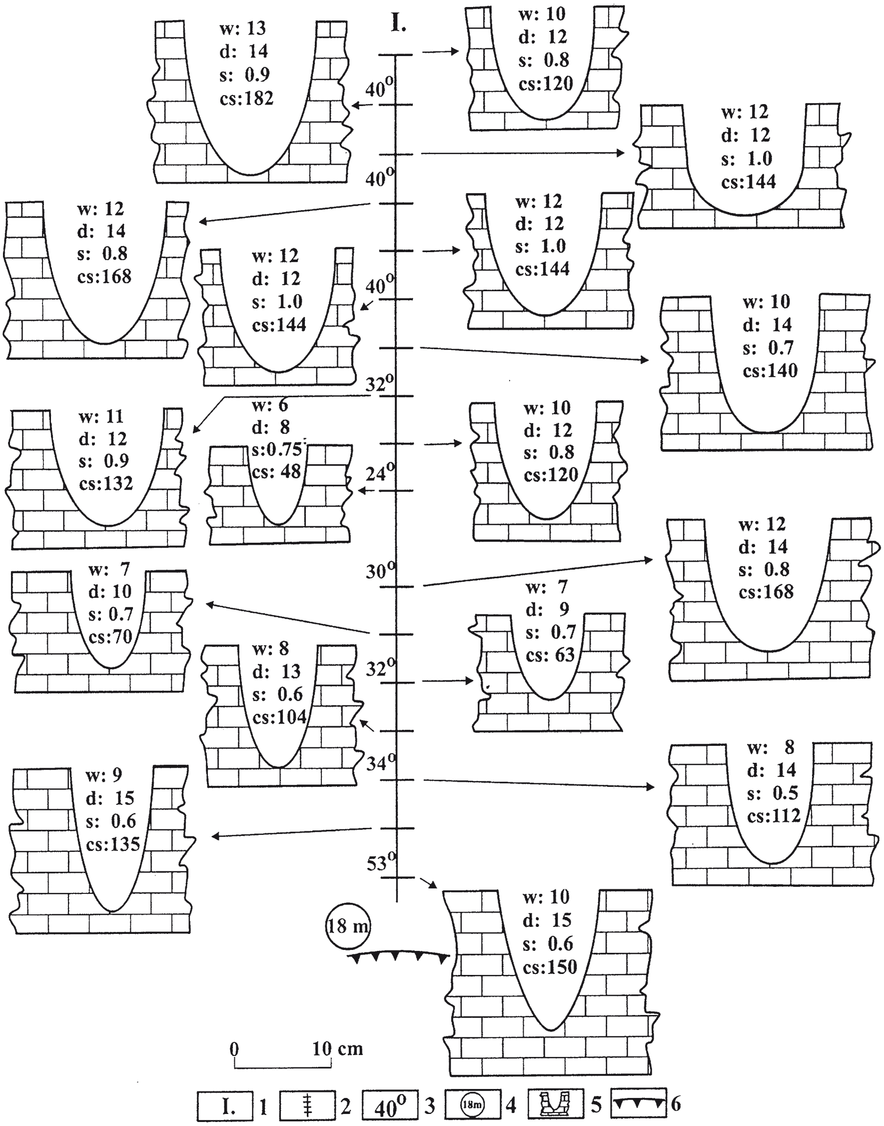


Fig. 4.10 Various cross-sectional data of a channel in the Valley of Lake Triglav (the research area is between areas marked 3/2 and marked 3/3, Zentai, 2000). Legend: 1 – map reference number of the channel, 2 – sites of the cross sections on the channel, 3 – slope angle, 4 – the length of the channel, and 5 – cross section; width of channel in cm (*w*), depth in cm (*d*), shape of channel (*s*, the quotient of its width and its depth), cross sectional area of the channel in square centimeters (*cs*, the product of its width and depth), and (6) grike

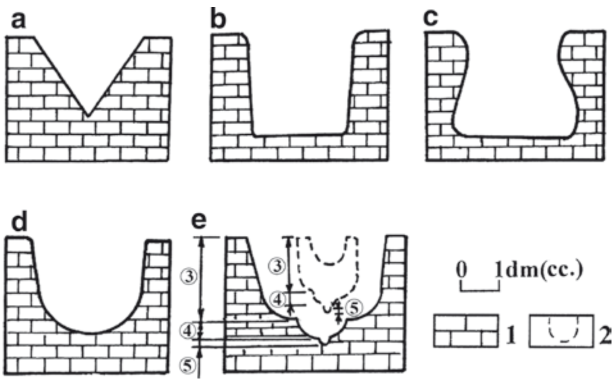


Fig. 4.11 Cross-section types of a channel (Veress, 2000a). Legend: (**a–d**) simple channels, and (**e**) complex channel: 1 – limestone, 2 – former channel, 3 – type I channel, 4 – type II channel, and 5 – type III channel

We group simple rinnenkarren according to the size of the cross section (Veress, 1995, Veress, 2000a, Veress, 2002): type I, type II and type III rinnenkarren.

The widths and depths of type I rinnenkarren are several decimetres, while the widths and depths of type III rinnenkarren are only several centimetres. The widths and depths of type II rinnenkarren lie between the sizes of type I and type III rinnenkarren. Complex rinnenkarren have 'simple complex' and 'manifold complex' forms. In the case of simple complex rinnenkarren, only type III or type II rinnenkarren develop in a type I rinnenkarren (although occasionally two type III rinnenkarren can develop at the bottom of a type I rinnenkarren). The type III rinnenkarren can develop on surfaces without other karren formations. Scallops can occur at the bottom of type III rinnenkarren. A type III rinnenkarren can occur not only in type I rinnenkarren, but also on the inside of other karren forms. Furthermore they can occur on surfaces without other karren formations. The rate of the size increase of the bearing rinnenkarren and the rate of the size increase of the inner rinnenkarren can be congruent or incongruent. In the case of manifold complex rinnenkarren, type II rinnenkarren occur inside type I rinnenkarren, and type III rinnenkarren inside the type II rinnenkarren (Picture 4.24; Figs. 4.11e and 4.12; Veress, 1995, Veress, 2000a, Veress, 2002).

According to their profile channels with planar bottom (their shape may be Ʊ or ⊔) or V-shaped channels are the most frequent. Channels with planar bottom are the most characteristic on the slope with *Pinus mugo*, while channels with planar bottoms and V-shaped channels and channel parts occur on bare slopes, too. We also experienced, simple or simply complex channels can be found on slopes with *Pinus mugo*. In the case of simply complex channel a type III channel can be found in the type I channel. While there are simply complex channels and manifold complex channels on bare slopes. Manifold complex channels develop if a tributary channel is connected to a main channel. But manifold complex channels develop if the channels are connected to the decantation runnels of kamenitzas, furthermore, the catchment areas of the channels are great.

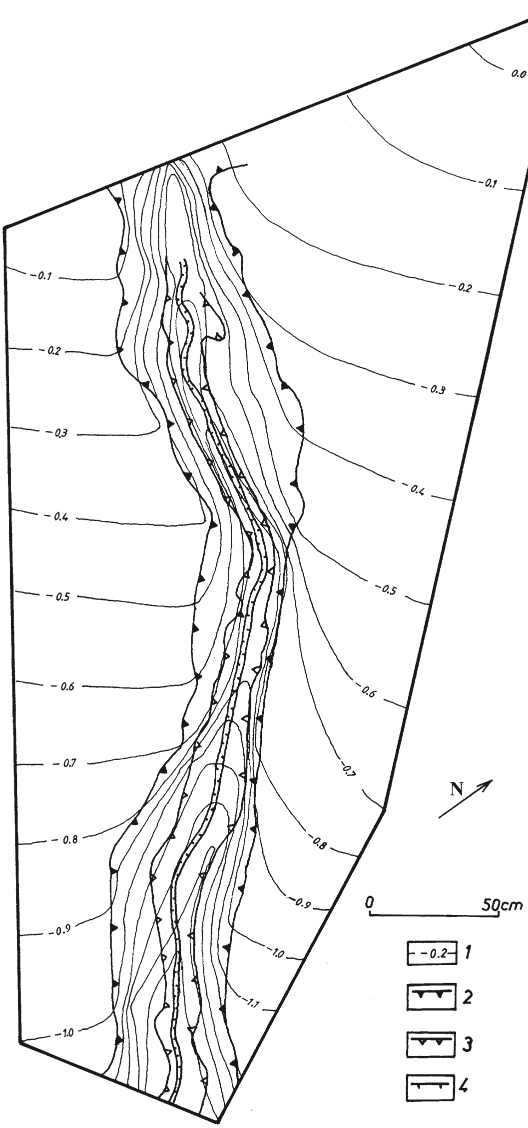
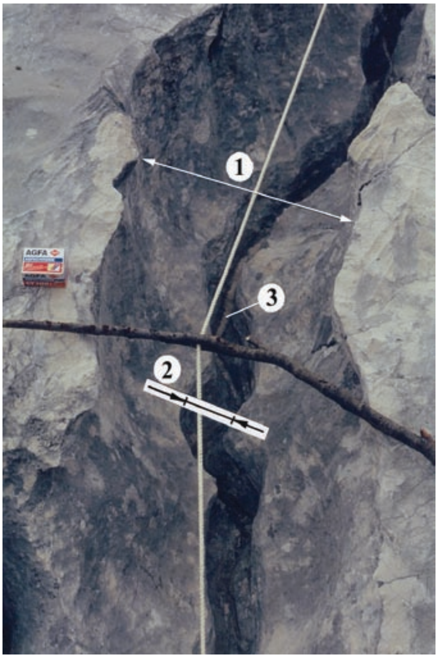


Fig. 4.12 A complex channel (research area marked 1/1, Veress et al. 1995). Legend: (1) contour line in local system, (2) margin of type I channel, (3) margin of type II channel, and (4) margin of type III channel

Karren terraces can develop at the bottom of the channels (Veress, 1995) in wide complex rinnenkarren (Fig. 4.8). Karren terraces are the remnants of former rinnenkarren bottoms. The surface of terraces slopes toward the middle of the channels and to the ends of the channels. The terraces drop in gently concave stages from the edges of the main type I rinnenkarren but have sharp edges where they meet the steeper walls of a lower channel.

Picture 4.24 Complex channel (area marked 1/1). Legend: 1 – type I channel, 2 – type II channel, and 3 – type III channel



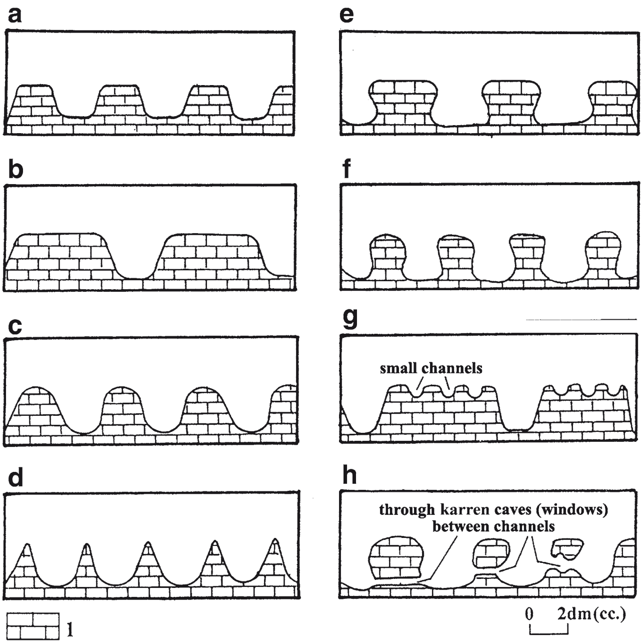


Fig. 4.13 Ridges between channels in profile (Veress, 2003). Legend: (**a**) flat and narrow ridges between channels, (**b**) flat and wide ridges between channels, (**c**) rounded ridges between channels (rundkarren), (**d**) ridges between channels that have become sharp, (**e**) flat ridges between channels that become narrow downwards, (**f**) rounded ridges between channels that become narrow downwards, (**g**) wide ridges between channels with small channels, and (**h**) windows cutting through ridges between channels: *1* – limestone

According to Veress (1995, 2000c, 2002), steps (Figs. 4.9b and 4.14d; Picture 4.25), bottom basins (Figs. 4.9b and 4.14e, f; Picture 4.25), bottom kamenitzas (Figs. 4.9a and 4.14c) and pits (Figs. 4.9d, e and 4.14f; Picture 4.19) occur at the bottom of the channels.

Steps are vertical or overhanging forms whose height ranges from some centimetres to some decimetres and are vertical to the directions of the channels.

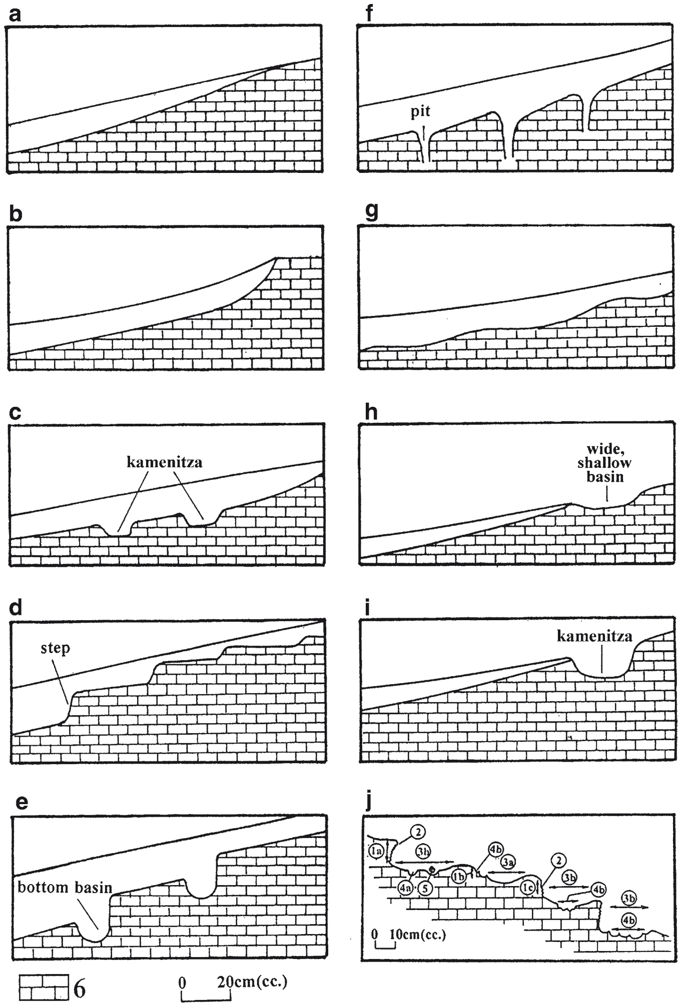
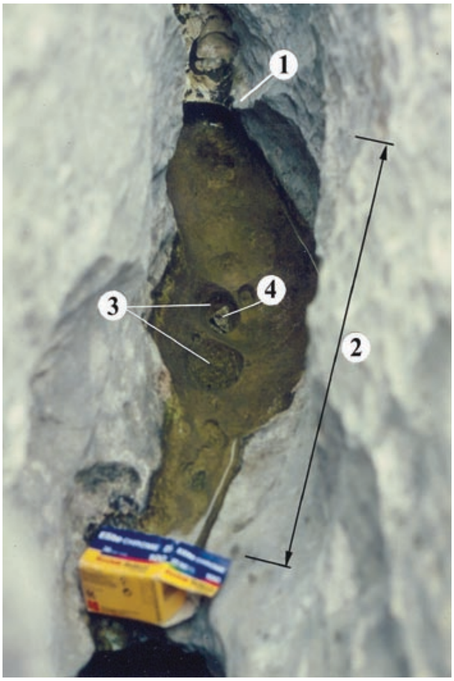


Fig. 4.14 Vertical cross section of the channels (**a–i**) and section of a stepped channel bottom (**j**) (Veress, 2003). Legend: (**a**) gradually wedging channel, (**b**) suddenly wedging channel, (**c**) channel with kamenitzas on its bottom, (**d**) channel with steps, (**e**) channel with basins, (**f**) channel with pits, (**g**) bevel channel, (**h**) channel with 'leafkarren' on its upper part, (**i**) channel with kamenitzas on its upper part, (**j**) channel section with basins: 1a – overhanging step, 1b – gentle step, 1c – perpendicular step, 2 – scallops, 3a – bottom basin without potholes, 3b – bottom basin with potholes, 4a – potholes, 4b – uvala potholes, 5 – debris, and 6 – limestone (the channel section diagrammed in Fig. 4.14j can be seen in Picture 4.25)



Picture 4.25 Channel bottom with basins and steps (area marked 3/4). Legend: 1 – step, 2 – bottom basin, 3 – pothole, and 4 – debris

Scallops divide the heads of the steps and the side walls of the basins. Steps develop at the bottom of bigger channels (their depth is 0.5–1 m), sometimes alone, but mostly in groups. Basins deepen into the bottom of the channel signing the presence or the increase of turbulence. The basins are about some decimetres in diameter and they are about 1 dm deep. The basins are elongated to the strike direction of the channels, but they occupy the whole width of the channel. Potholes, that are some centimetres in diameter and in depth dissect the bottom of the basins. The edges of the potholes are sharp. They sometimes coalesce into each other (uvala-like potholes). Debris pates, which are sharp and edged (originated due to frost weathering) can be found in the potholes (Veress, 2000c). Bottom-channel kamenitzas occur at the non-stepy basin bottoms. These forms also have some decimetres in diameter and in depth. They have gentle side walls, plant-patches (herbaceous plants and moos) and soil patches can often be found inside them. Bottom kamenitzas develop in channels where water flow is absent or secondary.

The Causes of the Development of Rinnenkarren

Rinnenkarren can be formed by rivulets as the limestone dissolves under them (Bögli 1960, 1976; Trudgill, 1985; Ford and Williams, 1989). According to Parry (1960) they could have developed during the ice ages due to abundant meltwater. He theorized that the quantity of CO_2 in the atmosphere was higher than it is today, although this theory has not been confirmed by measurements. According to Smith (1969), the quantity of $CaCO_3$ in the meltwater on Somersat Island was only 60 mg/L. According to Trudgill (1986), rinnenkarren can also develop from subsoil solutional features.

We believe that the following factors (in combination or individually) cause development of rinnenkarren:

- The development of rinnenkarren occurs under turbulently flowing rivulets. The laminar flow becomes unstable and transitions to turbulent flow when the Reynolds number is between 1,500 and 6,000. For our particular problem the Reynolds number is given by Horton (1945) as

$$R_e = \frac{4VD}{r},$$

  where V is the mean fluid velocity
  D is the film thickness of the water layer over the surface
  r is the kinematic viscosity
  From the definition it is clear that the Reynolds number depends on the thickness of the water layer and through that it depends on the surface roughness (Emmett, 1970). In general, however, we can say that the thickness of the surface flow formed on a slope depends on many other factors as well, for example: the water supply, the roughness of the surface or even on the ongoing water flow, therefore even on the Reynolds number (Fig. 4.15a). Thus, if the slope angle decreases (concave slope), the velocity of the flow decreases and the thickness of the water layer increases; thus the chance of the formation of a turbulent flow increases (Fig. 4.15b). On a slope with a steeper angle, however, the mean fluid velocity is the dominating factor in the Reynolds number, thus turbulent flow may arise even in case of smaller water thickness (Fig. 4.15a). The roughness of the bottoms of the channels is considerable (Crowther, 1997), and therefore the development and the maintenance of the turbulent flow can be caused by the roughness of the bottom of the channel as well. Because of the turbulent flow, the boundary layer is broken (Curl, 1966; Ford 1980; Trudgill, 1985). A new boundary layer develops repeatedly and because it is unsaturated, Ca^{2+} ions can enter it from the limestone.
- Plant and soil patches since they produce more CO_2 (Jennings 1985; Ford and Williams, 1989).
- Mixing corrosion: Zentai (2000) showed that the area of the diameter of the main channel below two coalesced rinnenkarren is larger than the diameter lengths of the two subsidiary rinnenkarren added together. Therefore, the solubility of the water increases where the waters of two subsidiary rinnenkarren join each other.
- As we have already mentioned the difference in the ion concentration between the boundary layer and flowing water is greater if the velocity of the current is higher; therefore, the quantity of the ion transport increases from the boundary layer to

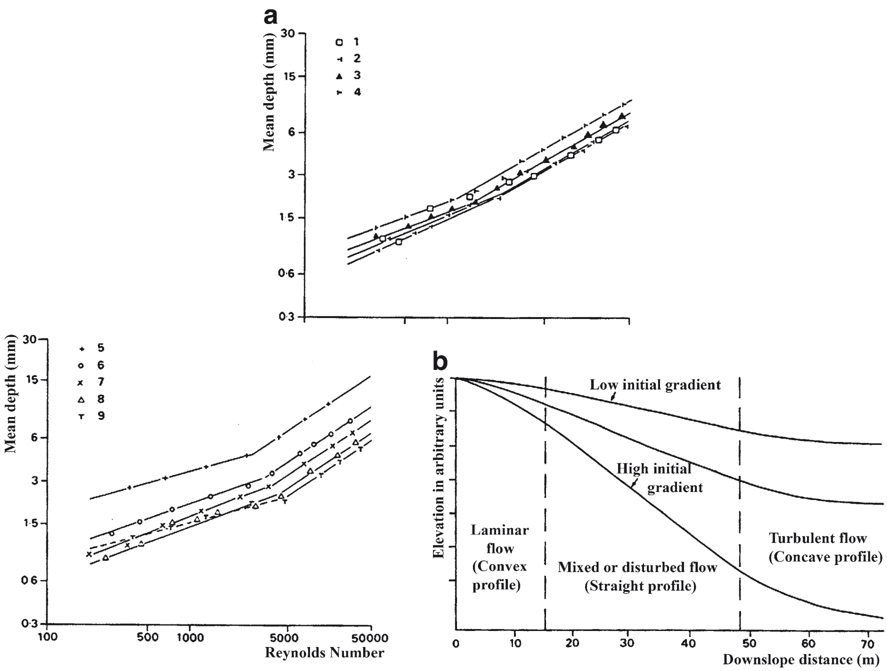


Fig. 4.15 The relationship between depth of uniform flow, Reynolds number, and roughness; (**a**), laminar current changes into turbulent current when the value of the Reynolds number is between 1,500 and 6,000; diagrammatic representation of the changes in flow regime downslope with a transition from laminar flow to turbulent flow, producing a transition from a convex to a concave profile (**b**) (from Emmett, 1970). Legend: slope values: 1 = 0.0775; 2 = 0.0550; 3 = 0.0342; 4 = 0.0170; 5 = 0.0033; 6 = 0.0170; 7 = 0.0342; 8 = 0.0550; 9 = 0.0775

the water current. Therefore, more ions are able to enter the boundary layer from the limestone.

- CO_2 enters the flowing water from the atmosphere (Jennings 1985).
- The quantity of CO_2 is high if the plants (*Pinus mugo*) are covered with snow (and the snow is solid). This phenomenon can be explained by the fact that the plants are unable to photosynthesize but are able to dissimilate under show. For this reason the average diameter area of channels found in a metre distance on bare slopes is 3.65 dm^2/m according to our measurements while this value is 9.35 dm^2/m on slopes covered with *Pinus mugo*.
- The meltwater of the snow filling of the channel dissolves its bottom and walls (see bellow).

The Various Development Types of Rinnenkarren

The different channel shapes can develop in three different ways theoretically. Either the sheet water originating from the boundary surface dissolves the side slopes of the channel. They can be created when the meltwater of the snow filling or the water of the rivulet dissolves the side slopes and its bottom. However, sheet water cannot dissolve the channels under the following conditions:

- The margins of channels (except of roundkarren) are sharp.
- The side walls of some rinnenkarren are unbroken and free from smaller karren forms (Picture 4.24). Rillenkarren occur in the neighbourhood of some rinnenkarren. These rillenkarren cannot continue at the margins of the channels because they wedge out. Hence the water is saturated before it enters the channel.
- The channel wall slopes similarly (except with meanderkarren) along its whole length.
- The dip direction of the bearing surface and the direction of the channel are equal. Therefore, water from the boundary surface cannot flow into the channel. Sometimes we observe that channels can develop on 'ridges' and water cannot flow into the channel because of the ridges.

According to Veress et al. (2007, 2008b) the development of channels may happen independently from rivulets. According to him the development of channels may happen in two phases. At the beginning (embryonic phase), a small channel develops under the rivulet of the slope. Later the development of the channel happens in two ways during the increasing of the channel. The process may also happen under the rivulet or it may proceed due to percolating water.

Channel development due to percolating may occur because the snow (in a form of a show filling) remains in the channel when is not snow on the surface between the channels. Meltwater, which flows laminary, is created between the snow and the wall of the rinn because the snow filling melts. Development originating from seepage can change development due to rivulets at the same channel. Namely, snow filling can remain in channels developed due to rivulets in the spring for a longer time period. Channels, which were created by seepage can grow due to rivulets. Taking into account the fact that channels with small catchment areas can receive water reserve from their surroundings even for a short period of time.

If we analyze the shape of channel and the extension of the cross-section shape of the channel we can see that the development of the channels differs on slopes with *Pinus mugo* and on bare slopes. Namely channels on slopes with *Pinus mugo* have great specific cross-section area and small specific channel shape (specific relative width). While channels of bare slope have small specific cross-section area and relatively great specific channel shape (Veress et al. 2006c). All this can happen because channels of slopes with *Pinus mugo* receive their water from *Pinus mugo* patches, which developed under rivulets. The water of these rivulets can dissolve better than the rivulet of bare slopes. As the rivulets which are on slopes with *Pinus mugo* contain more CO_2. The cross sections of the channel increase considerably because of the more CO_2. But the channel may deepen considerably under the rivulet. The shape of the channel decreases due to the deepening (Veress et al. 2008b).

Channels develop due to water percolating primarily on bare slopes. This development proves that the values of specific cross-section areas of the channel and values of shapes of the channels depend on the values of slope angle in case of slopes with *Pinus mugo* (see below). On the other hand the values of these parameters do not depend on the values of the slope angle on bare slope (Veress et al. 2007, Veress et al. 2008b). The authors explain this with the fact that the flowing velocity of the rivulets increases as the slope angle increases. Therefore, the degree of the cross-section area of channel increases, while the shape of the channel (relative width) decreases as the slope angle increases. Namely the value of the solution depends on flow velocity.

The shape of the cross section of a channel in case of development generated by a rivulet is determined by the quantity of the water present and its changing quantity over a period of time. These characteristics depend on several factors including: the velocity of flow (which depends, e.g. on the angle of the bearing slope) and the quantity of the flowing water (which depends, e.g. on the thickness of the snow and the intensity of the melting). In an active period, the dissolution works in a narrower width because the quantity of water decreases. In this case, the shape of the rinnenkarren takes a V-form in cross section. The wall of a channel is perpendicular (e.g. U cross-section shapes) and their bottoms are wide if the quantity of water does not change over a longer period and the width of the rivulet is also the same for a long period.

Internal channels develop (type II or type III rinnenkarren) in a channel (which could develop earlier, type I rinnenkarren) if the quantity of water decreases considerably and subsequently does not change further for a long period.

A connection can be found between the length of the slope, the slope angle and the density of the channels. According to Veress et al. (2006c) the greater the slope angle is the greater the channel density is (Table 4.1). It can be seen that data show dispersion in a way. It can happen because the channel density depends on the length of the slope too. According to Veress et al. (2007) channel density increases on slopes with smaller slope angles if the distance between the upper margin slope and profile increases while channel density decreases on the slopes with greater slope angle (Fig. 4.16). The data show (Veress et al. 2006c) that there is a less close connection between slope angle and channel density on slope with *Pinus mugo* and on slopes with herbaceous plants.

We can see that channels, which are on bare slopes with small dip (20°) belong to two various types. These types are A-type channels and B-type channels. They are described in Section 2.2.2. The specific cross-section area of A-type channel as well as their average cross-section area are smaller than those of B-type channel.

Table 4.1 Relationship between slope angles and channel density on bare slope (Veress et al., 2006a)

Profile mark	Slope angle	Channel density (pc/m)
T-1	12°	0.71
T-16/c	25°	2.27
T-3	28°	3.17
T-16/A	30°	1.48
T-16/B	35°	2.39
T-11	35°	3.17

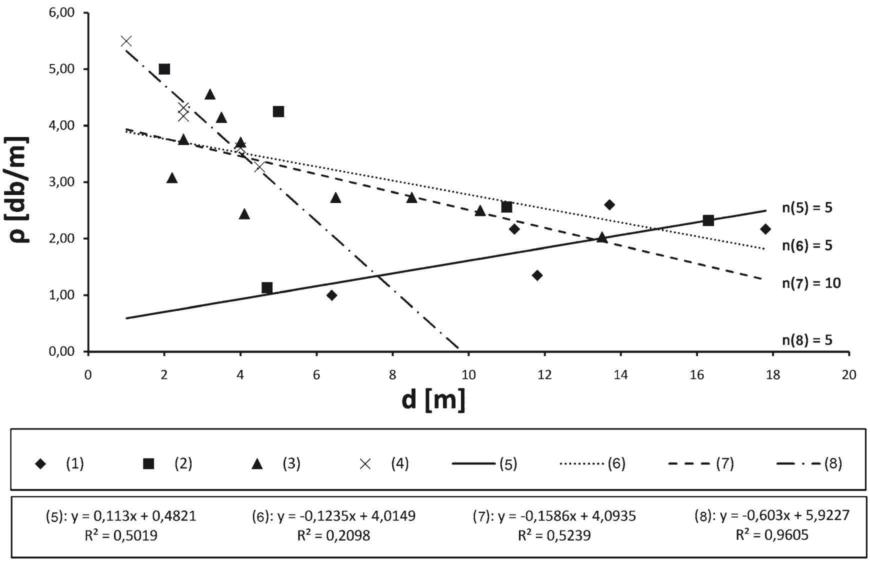


Fig. 4.16 The united *ρ–s* functions of research areas with Pinus mugo (based on data collected along of the profiles in the research areas marked 1/4, 1/5, 1/6, 1/7, 1/8, 1/10, Veress et al. 2008b). Legend: 1 – data points of slopes belonging to the 16–20° slope class, 2 – data points of slopes belonging to the 31–35° slope class, 3 – data points of slopes belonging to the 36–40° slope class, 4 – data points of slopes belonging to the 41–45° slope class, 5 – the explicit form and the graph of the *ρ–s* function of the slopes belonging to 16–20° slope class, 6 – the explicit form and the graph of the *ρ–s* function of slopes belonging to the 31–35° slope class, 7 – the explicit form and the graph of the *ρ–s* function of slopes belonging to the 36–40° slope class, and 8 – the explicit form and the graph of the *ρ–s* function of slopes belonging to the 41–45° slope class

The values of the shapes of A-type channels are greater than those of B-type channels (Table 4.2).

This relationship proves that channels may develop due to percolation, and rivulet too, on bare slopes with small dip values. The A-type channels develop due to percolating only, because their catchment area is small. As channels do not receive water from their surroundings more or less their great shapes prove that their development is due to percolating. Namely due to their development type, the channels grow along their whole shape (side walls and bottoms). There is no functional relationship among *d*, the cross-section area and the shape of the channel. Namely, meltwater is created from the snow fill of the channels and its quantity and solution ability are similar all along the length of the rinnenkarren.

B-type channels developed under rivulets. Their small shape value may prove this development. It can happen because their catchment area is considerably great. A bigger catchment area and more tributary channels belong to the same channel as the length of the slope increases (Figs. 4.7 and 4.17; Table 4.2). Therefore, they may receive considerable meltwater from the snow patches of their catchment areas. Because their development is due to rivulets their cross-section areas increase and the shapes of the channel decrease as the length of the bearing slope increases

Table 4.2 Various channel parameters occurring on three slopes in if the research area

Profile marked 1/9/1													
Type A channel and meanderkarren								Type B channel and meanderkarren					
d (m)	*α*	*n*	*ρ*	*T*	*t*	*f*	*l*	*n*	*ρ*	*T*	*t*	*f*	*L*
0	10°	4.0	0.3	33.7	135.0	0.5	2.1	No data	No data	No data	No data	No data	No data
3	22°	20.0	1.3	4.2	3.3	2.5	2.0	7.0	0.4	438.0	1002.7	0.4	0.9
6	17°	41.0	2.5	185.3	72.3	6.6	2.6	7.0	0.4	415.9	950.7	0.7	1.5
9	15°	43.0	2.6	235.6	87.6	5.6	2.1	5.0	0.3	298.5	955.3	0.3	1.1
12	15°	31.0	1.9	244.1	126.0	3.5	1.8	6.0	0.3	413.0	1101.4	0.4	1.0
15	15°	28.0	2.0	254.7	145.5	2.8	1.6	8.0	0.5	676.9	1353.8	0.5	0.9
18	13°	24.0	1.5	190.6	127.0	2.9	1.9	10.0	0.6	260.5	416.9	0.5	0.7
21	23°	28.0	1.8	180.6	103.2	3.0	1.7	8.0	0.5	389.8	779.6	0.3	0.7
24	18°	8.0	0.5	83.2	166.3	0.7	1.4	6.0	0.3	161.6	431.1	0.4	1.1
27	19°	19.0	1.2	125.0	105.3	2.4	2.0	No data	No data	No data	No data	No data	No data
Average		24.6	1.6	153.7	107.2	3.1	1.9	5.7	0.3	305.4	699.2	0.4	0.8
Profile marked 1/9/2													
Type A channel and meanderkarren								Type B channel and meanderkarren					
d (m)	*α*	*n*	*ρ*	*T*	*t*	*f*	*l*	*n*	*ρ*	*T*	*t*	*f*	*l*
0	18°	7.0	0.8	57.2	73.6	1.6	2.1	3.0	0.3	129.0	387.0	0.5	1.6
3	13°	7.0	0.7	91.9	118.1	1.1	1.5	7.0	0.7	345.8	444.7	0.9	1.2
6	10°	9.0	1.0	69.6	69.6	2.6	2.6	3.0	0.3	201.6	605.0	0.4	1.2
9	14°	9.0	1.0	112.8	112.8	2.6	2.6	2.0	0.2	133.3	600.0	0.2	1.2
12	20°	11.0	1.2	75.8	62.0	3.6	3.0	5.0	0.5	259.0	466.2	0.4	0.8
15	20°	17.0	1.9	114.4	60.5	4.7	2.5	2.0	0.2	26.1	117.5	0.2	0.9
18	20°	13.0	1.4	175.4	121.5	2.6	1.8	3.0	0.3	131.7	395.3	0.3	1.0
21	12°	5.0	0.6	55.0	99.0	0.4	2.2	4.0	0.4	154.4	347.5	0.1	0.8
Average		9.8	1.1	94.0	89.6	2.4	2.3	3.6	0.4	172.6	420.4	0.4	1.1

Profile marked 1/9/3

Type A channel and meanderkarren								Type B channel and meanderkarren					
d (m)	α	*n*	ρ	*T*	*t*	*f*	*l*	*n*	ρ	*T*	*t*	*f*	*l*
0	26°	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data	No data
3	22°	8.0	0.9	67.2	75.6	1.5	1.6	No data	No data	No data	No data	No data	No data
6	16°	21.0	2.3	**81.6**	**35.0**	7.2	3.1	6.0	0.7	250.7	376.1	0.6	1.1
9	16°	19.0	2.1	206.7	97.9	5.7	2.7	4.0	0.4	68.3	17.0	0.6	1.3
12	16°	12.0	1.3	138.5	103.9	2.8	2.1	4.0	0.4	146.6	330.0	0.4	0.8
15	16°	11.0	1.2	110.1	90.0	2.0	1.6	6.0	0.6	632.1	948.1	0.3	0.4
Average		11.8	1.3	100.7	67.1	3.2	1.9	3.3	0.4	183.0	278.5	0.3	0.6

d – distance between the upper margin of the slope and profile place, α – slope angle, *n* – channel number, ρ – channel density, *T* – specific cross-section area of the channel, *t* – average cross-section area of the channel, *f* – specific shape of the channel, *l* – average shape of the channel.

$$T = \frac{\Sigma F_0}{m},\quad t = \frac{\Sigma F_0}{n},\quad F_0 = axb,\quad f = \frac{\Sigma f_0}{m},\quad l = \frac{\Sigma f_0}{n},\quad f_0 = \frac{a}{b},$$

where F_0 cross-section of a channel
m profile length
a width of the channel
b depth of the channel
f_0 shape of a channel

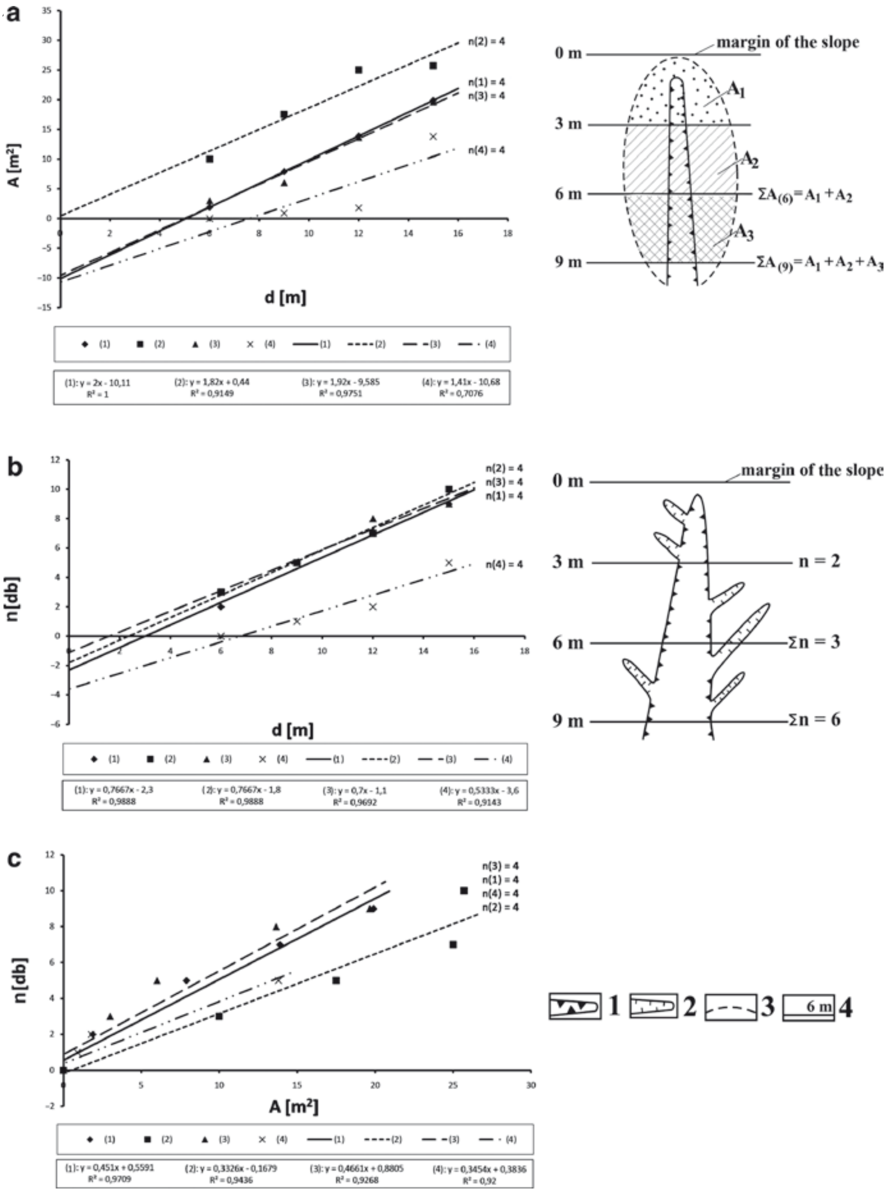


Fig. 4.17 The function relationship between the catchment area of the channels, and the their distance (**a**), between number of the tributary channels and the distance (**b**) between the number and the catchment area of the tributary channels (**c**) on bare and gentle slopes (note: slope marked 1/9/3, Veress et al. 2009). Legend: A catchment area, A_1, …, A_3: catchment area part of a channel above the site of any profile or between two profiles, $\Sigma A_{(6)}$: overall catchment area above the site of the profile with 6 m length, *d* – distance between the upper margin of the slope and profile place, *n* – number of tributary channels, Σ*n* – overall number of tributary channels above any profile: 1 – type B channel, 2 – type A channel, 3 – boundary of the catchment area, 4 – place of profile and its distance from upper margin slope (note: the numbers in the braces are in connection of the various channels of the slope. The some name indicates the data, the function and graph of the same channel)

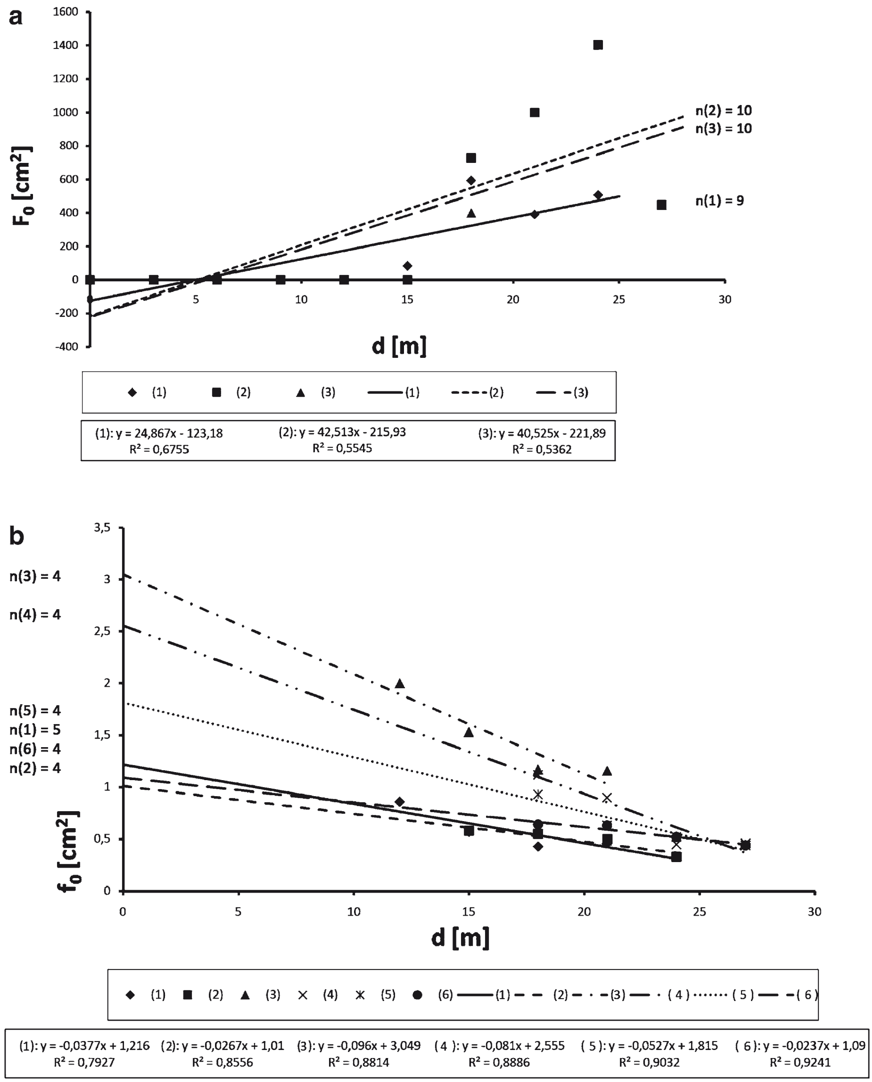


Fig. 4.18 Function relationship between the cross-section area of various channels and the distance (**a**) and between the shape of the channels and the distance (**b**) on bare and gentle slopes on research area marked 1/9/1, (Veress et al. 2009). Legend: F_0 – cross-section area of a channel, f_0 – shape of a channel, d – distance between the upper margin of the slope and the profile place (note: the numbers in the braces are in connection of the various channels of the slope. The some name indicates the data, the function and graph of the same channel)

(Fig. 4.18). Namely, more and more water flows in the channels towards their ends. The rivulets exist for longer and longer time at the lower parts of the channels. Their cross-section area gets bigger and bigger and they get deeper and deeper towards their lower parts.

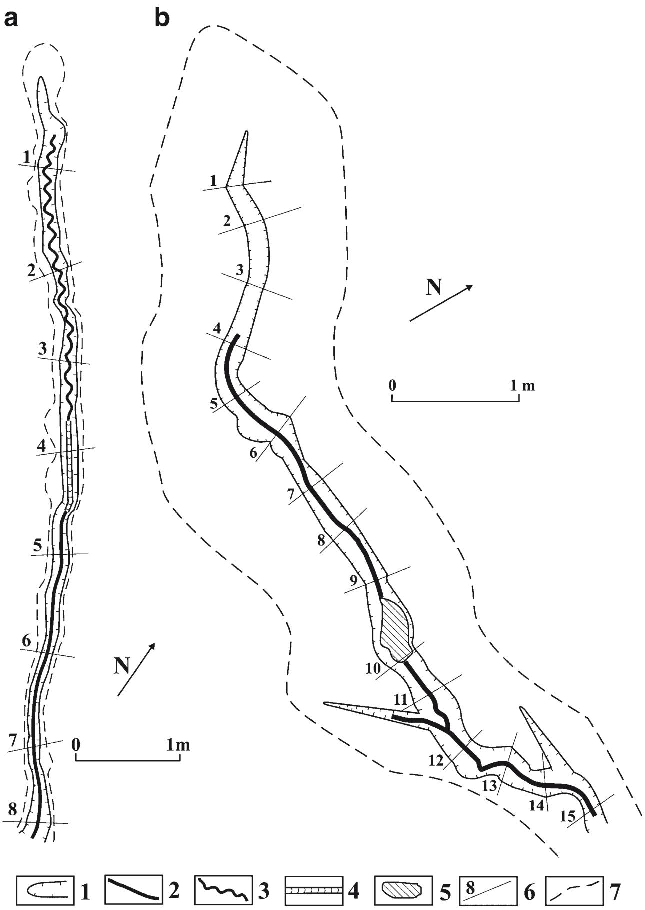


Fig. 4.19 Example of channel with small catchment area (**a**) and channel with great catchment area (**b**). Legend: 1 – type I channel, 2 – type III channel, 3 – type III meanderkarren, 4 – trittkarren, 5 – kamenitza, 6 – profile place and its mark, and 7 – boundary of catchment area

According to our measurements, and employing the above data, the development types of channels may be the following on bare slopes with small dip angles:

- The channels which do not have tributary channels (Figs. 4.7 and 4.19a) and small catchment areas (Table 4.2) have small and V-shaped cross section (A-type channel). These channels are the tributary channels of great channels. The rivulet-generated development is subordinated as their catchment area is small. Their creation and development happen as follows. A V-shape channel is created due to rivulet in the first phase (Fig. 4.20I.a). The cause of V cross section is that the discharge of the rivulets decreases fast. Therefore, the solution happens in a narrower and narrower stripe at the bottom of the deepening channel during the existence of the rivulets. The channel develops due to percolating in the second

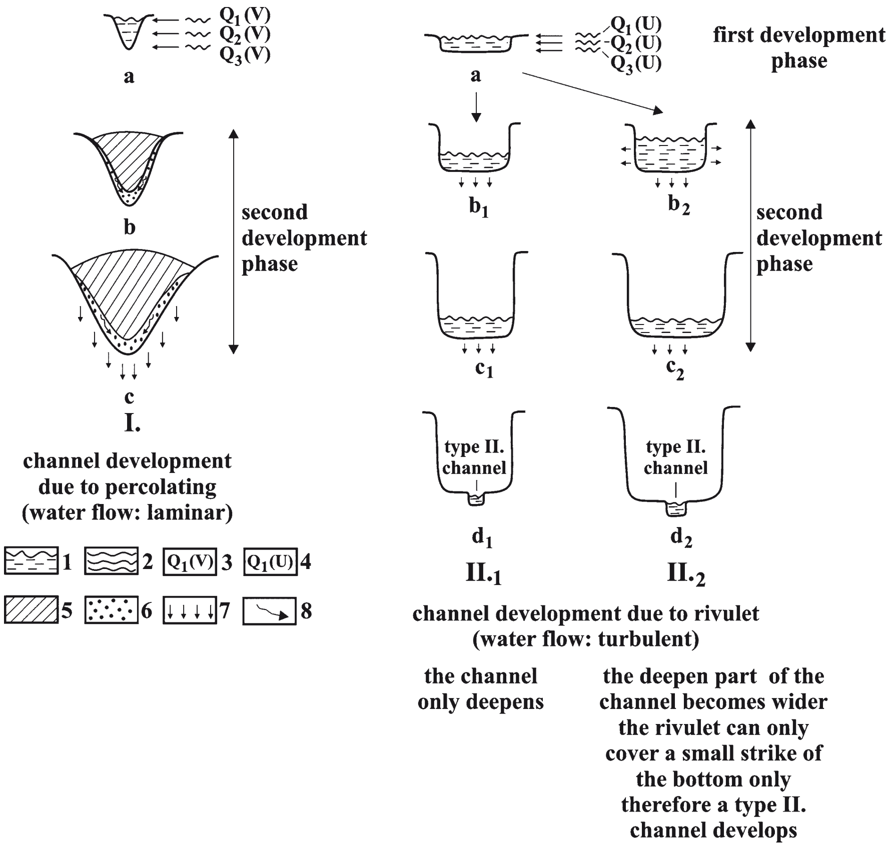


Fig. 4.20 Channel development due to percolating (I) and due to rivulet (II). Legend: 1 – rivulet, 2 – water levels of rivulet, 3 – discharge of shape V channel in various time, 4 – discharge of shape U channel in different time, 5 – snow, 6 – melt water, 7 – solution, 8 – percolating of melt water. I. Channel development due to percolating, II_1 channel development due to rivulet, without the increasing of the channel width, II_2 development due to rivulet with the increasing of the channel width (Veress et al. 2009)

phase (Fig. 4.20.Ib–c). The seepage happens between the snow filling and the wall of the channel. The feeding of water comes from melting snow. The thickness of the water cover (water film) which develops is varied. Its thickness depends on the melting intensity, the temperature and the thickness of the snow. Probably its thickness increases in the direction of the bottom of the channel. Probably the water cover is not continuous at the beginning of the melting period. It is continuously developing gradually only. Probably its flow type is laminar because its velocity and thickness are small. The cross-section area of the channel increases because the walls and the bottom of the channel are dissolved at seepage development. Its shape (relative width) does not change, because the walls and the bottom of the channel denudate in a similar value. Therefore, widening and deepening of the channel are just the same. The cross-section shape of channel does not change either. Namely the walls of the channel are dissolved similarly everywhere.

However, a rivulet may develop in the channels if the snow melts totally. The rivulet dissolves mainly the bottom of the channel. Then the channel deepens mainly. The shape of those channels can decrease during their development. (The shape of the channel does not change when a rivulet is not created or only existed for a very short time.) Various V-shaped channels may be created due to development generated by rivulet even for various sections of the same channel. Namely the deepening of channel may be greater than its widening because of the development generated by rivulet. Therefore, the steepness of the channel walls depends on the length of the time period of rivulet's existence. If the rivulet exists for longer time then the walls of the channel become steeper. Therefore, narrower and narrower V cross-sectioned channels are formed if the rivulets exist for longer and longer period of time. Great slope angle of the bearing slope also contributes to the development of this V shape (Fig. 4.21a). The dip angle of the bottom of the channel (which have V-shaped cross section and are not tributary channels) is 28–45° at 12 cross-profile places and the dip angle was less than 30° only at four sites. The great dip angle causes the decrease of the discharge of the rivulet. Namely the water flow will be faster. Therefore the width of the rivulet will be small.

We may establish a direct connection between the cross section of the channel and its catchment area. There is also a direct connection channel density and slope angle. Thus there is an indirect connection between the dip angle of the channel bottoms and its cross section. Namely water reserve going into the channel will be small because of the channel density on slopes with great slope angles. Channels with V-shaped cross section develop because the water discharge decreases fast or rivulets are absent on slopes with greater dips.

- There are channels with great catchment area and some tributary channels (Figs. 4.7 and 4.19b) and have considerable length (type B channel or secondary channel). These channels have mainly U cross section. They are formed if the dip of their bottoms is small (Fig. 4.21b). Channels which belong to this group have a rivulet-generated development. The development of the channel happens in two phases. A channel with small depth, great width and steep sides develops under the rivulet in the first phase (Fig. 4.20.IIa). This cross-section shape develops because the discharge of the rivulet decreases slowly. Therefore such a rivulet can be wide for over a long period of time during its existence. Therefore, the solution of the bottom happens in a similarly wide stripe during the existence of the rivulet. In the second phase the development of the channel happens due to percolating partly. But the process is generated mainly by a rivulet. The rivulet of the channel gets enough water. Therefore the bottom of the channel deepens in its total width (Fig. 4.20.IIb). On the other hand, the discharge of the rivulet remains great for a long time. Therefore, considerably great snow patches can remain on the catchment area of the channel with great probability. Small slope angle contributes to the greatly lasting discharge of the rivulet. (The velocity of the water flow can be smaller.) We investigated the dip of the bottoms of 52 channels with U cross section. The dip of the bottoms was smaller than 20° at 41 cross sections. And the dip values of the bottoms were between 21° and 30° at 11 cross-section places. Due to the above-mentioned facts the embryonic

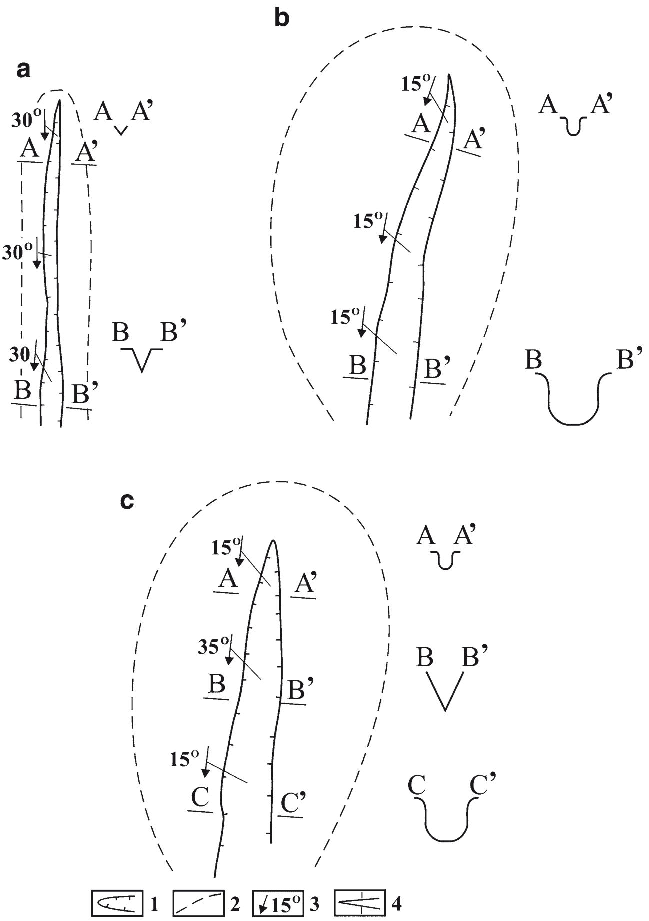


Fig. 4.21 Channels with great bottom dip (**a**), with small bottom dip (**b**), and with changing bottom dip (**c**). Legend: 1 – channel, 2 – boundary of the catchment area of the channel, 3 – dip angle of bottom, and 4 – the place of the cross section

channels deepen in their overall width and they form U shapes (Fig. 4.20.IIc_1, IIc_2). There are such channels which have great catchment areas and tributary channels, but they have U or V cross-section shapes in various parts. The dip of the channel bottom changes with the different cross-section shape channels (Fig. 4.21c). Where the dip of the slope is great the flowing of the rivulet is faster therefore the width of the rivulet decreases rapidly. Therefore the stripe of solution decreases too, causing the development of the V cross-section shape at the bottom of channel parts with greater dip angles. The discharge and the width of the rivulet decrease slowly on those parts where the dip of the channel bottom is small. Therefore, the solution of the bottom of the channel happens in its whole width. U cross-section shape is created on these channel parts during the deepening of the channel.

In this case there is a direct connection between the cross section and the catchment area of the channels. There is also a direct connection between the density of the channels and the dip angle. Therefore, there is an indirect relationship between the cross section and the dip of the channel bottom. Moreover the catchment of the channel can be great. Channels can develop under rivulets, which have lasting discharge.

The following facts prove the tight connections between the discharge and its changing, and the corresponding cross section, in additionto the size of the catchment area:

- Only type III channels occur at the bottom of channels with V cross section. These small channels have U-shaped cross section. Small rivulets can be found in their narrow channels during the summer and in humid season these rivulets fill the channels totally. Due to rainfalls only rivulets with small discharge can develop into those whose discharge is the same for a long period. The cross-section shape of the type III channel proves that the rivulet contributes to the development of U cross sections. It also indicates that rivulets with only a small discharge can develop in channels with V cross sections. Our observations also proved this connection.
- Tributary channels are common at channels with U cross section with great catchment area. Type II channels are repeated in such channels. While there are no type II channels in the type A channels. The type II channels have U cross sections hence they develop under rivulets. It may be because the water which leaves the tributary channels can stabilize the discharges at a smaller value. Hence a rivulet with small width and lasting discharge develop at the bottom of the type I channel. The development of these rivulets causes the development of the type II channels (Fig. 4.20.IId_1).

Hence channel development due to percolation and rivulet may happen alike on bare slopes with small slope angle. Channel development due to percolation has a greater change on bare slopes with growing dip after the initial development generated by a rivulet.

The development type of a channel depends on the size of its catchment area. The values of the latter are determined by the channel density on the slope. The development of the channel is due to a rivulet (the development of type B channel) if channels develop in various times on the slope. Those channels, which are created the earliest, have great catchment areas. Those that develop later in great numbers can only have small catchment areas. Therefore, their development happens due to seepage. Because type A channels dominate such slopes with great slope angle, we can establish that the development of the channels of such slopes happen at almost the same time.

There are function connections among the specific cross-section area of the channel (*T*), the shape of the channel (*f*) and the width of the *Pinnus mugo* patch (*s*), the distance between the profile sites and the upper margin of the slope (*d*) and slope angle (Figs. 4.22 and 4.23). The development of the channel depends primarily on the quantity of the CO_2 and velocity of the flowing water on such slopes. The width of the *Pinus mugo* patch (*s*) regulates the quantity of the CO_2. The slope angle decides

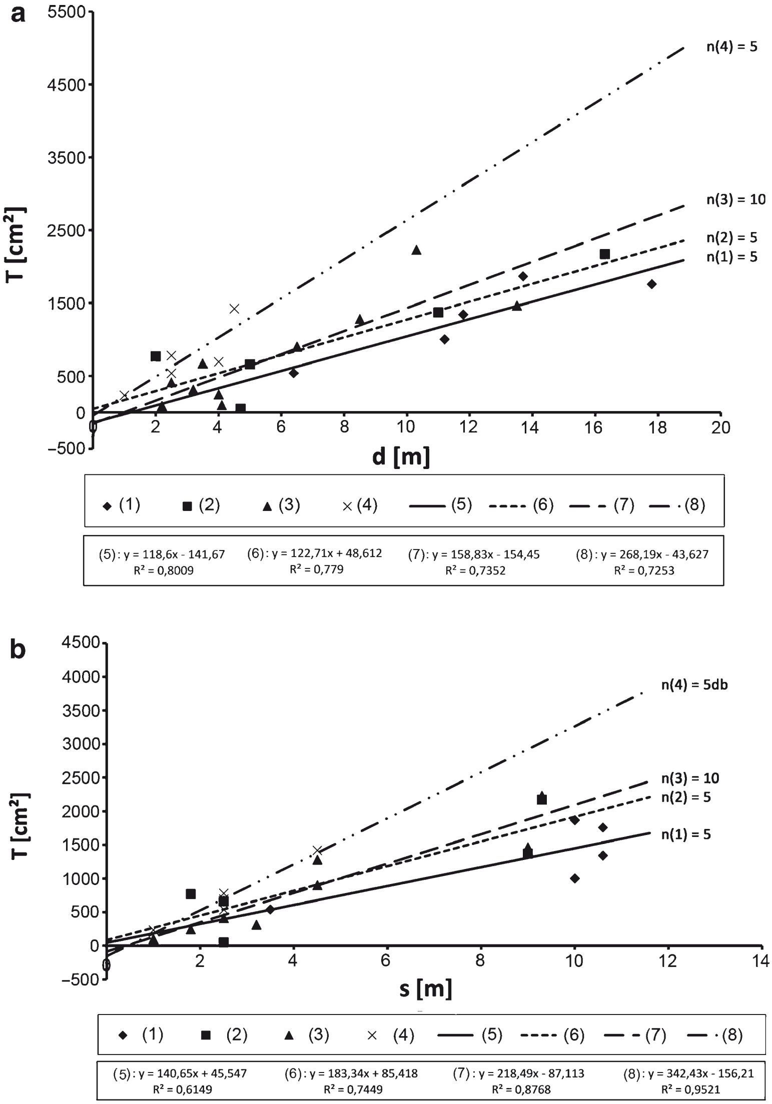


Fig. 4.22 The united *T–d* functions of slopes with areas of *Pinus mugo* coverage (**a**) and the united *T–s* functions (**b**) (based on data collected along the profils in the research areas marked 1/4, 1/5, 1/6, 1/7, 1/8, 1/10, Veress et al. 2008b). Legend: 1 – data points of slopes belonging to the 16–20° slope class, 2 – data points of slopes belonging to the 31–35° slope class, 3 – data points slopes belonging to of the 36–40° slope class, 4 – data points of slopes belonging to the 41–45° slope class, 5 – the explicit forms and the graphs of *T–d* (**a**) and *T–s* (**b**) functions of slopes belonging to the 16–20° slope class, 6 – the explicit forms and the graphs of *T–d* (**a**) and *T–s* (**b**) functions of slopes belonging to the 31–35° slope class, 7 – the explicit forms and the graphs of *T–d* (**a**) and *T–s* (**b**) functions of slopes belonging to slopes of the 36–40° slope class, 8 – the explicit forms and the graphs of *T–d* (**a**) and *T–s* (**b**) functions of slopes belonging to the 41–45° slope class, *T* – specific cross-section area of channel, *d* – distance between the upper margin of the slope and the place of the profile, *s* – the width of the Pinus mugo patch (note: The cause of the weak function relationship is that channels which end at the bare slope parts and thus they do not receive water from the *Pinus mugo* patch were also included in our data processing)

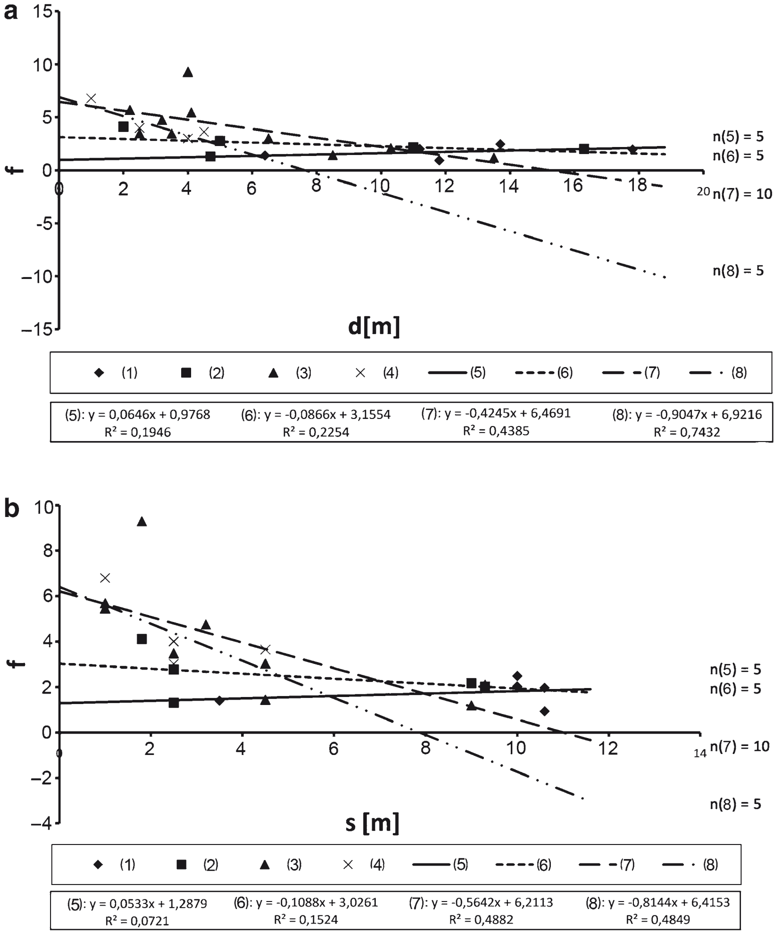


Fig. 4.23 The united *f–d* functions of slopes with areas of *Pinus mugo* coverage (**a**) and the united *f–s* (**b**) functions based on data collected along the profiles in the research areas marked 1/4, 1/5, 1/6, 1/7, 1/8, 1/10, Veress et al. 2008b. Legend: 1 – data points (values) of slopes belonging to the 16–20° slope class, 2 – data points of slopes belonging to the 31–35° slope class, 3 – data points of slopes belonging to the 36–40° slope class, 4 – data points of slopes belonging to the 41–45° slope class, 5 – the explicit forms and the graphs of *f–d* functions (**a**) and *f–s* functions (**b**) of slopes belonging to the 16–20° slope class, 6 – the explicit forms and the graphs of *f–d* functions (**a**) and *f–s* functions (**b**) of slopes belonging to the 31–35° slope class, 7 – the explicit forms and the graphs of *f–d* functions (**a**) and *f–s* functions (**b**) of slopes belonging to the 36–40° slope class, 8 – the explicit forms and the graphs of *f–d* functions (**a**) and *f–s* functions (**b**) of slopes belonging to the 41–45° slope class. *f* – specific shape of a channel, *d* – distance between the upper margin of the slope and the profile, *s* – the width of the Pinus mugo patch (note: The cause of the weak function relationship is that channels, which end at the bare slope parts and thus they do not receive water from the Pinus mugo patch were also included in our data processing)

the flowing velocity of the rivulet, the quantity of the water is dominated by the distance from the upper margin of the slope (*d*). Namely more and more water flows in the channels at greater and greater *d* values. The slope angle decides (Figs. 4.22 and 4.23) the specific cross section of channel (*T*), specific shape of channel or relative width (*f*) and specific width (*c*) if the values of *d* and *s* are given figures.

Therefore, water flow dominates the development of the channel on the slope with *Pinus mugo*. Water flow, which causes the development of channels may be only rivulets. The following channel development types can occur on slopes with *Pinus mugo*:

- If the channel head is on bare slope part and its catchment area is small the development is due to percolating.
- If the catchment area of the channel is big but its head is inside the bare slope the development of the channel is due to rivulets.
- If the heads of the channels are in the *Pinus mugo* patch or at its margins primarily the development of the channels is due to rivulets. The cross-section shapes of the channels create U and ⊔shapes. The changing of the cross-section area and shape can take place as follows:
    - Channels with great cross-section area are created if the width of the *Pinus mugo* patch is great (a lot of CO_2 goes into the water), the slope angle is great (the flow is fast) and the water discharge decreases slowly (the soil can store the melt (snow) water, Fig. 4.24c$_1$). Namely the water, which has great solution ability, can dissolve the wall and the bottom of the channel in a considerable value. The cross-section area of the channel increases but its shape remains. The cross-section areas of the channels increase to the direction of the lower parts of the channels, because more and more water flows at lower parts of the channels.
    - If the width of the *Pinus mugo* patch is small (therefore the solubility is small), the angle slope is small (therefore water discharge decreases slowly), the cross-section area of the channel increases even to a smaller degree. Since the channel is dissolved everywhere due to the large water discharge, the cross-section shape of the channel does not change during its development. Therefore its shape will be relatively great (Fig. 4.24c$_2$).
    - The shape of the channel can be small if the *Pinus mugo* patch is wide, but the slope angle is great if the discharge decreases quickly (Fig. 4.24c$_3$). In this case, the rivulet dissolves the bottom of the channel primarily with intensity and lasting.
    - The shape of the channel is comparatively small (Fig. 4.24c$_4$) if the *Pinus mugo* patch is small and slope angle is great (because the decreasing of the discharge of rivulet is comparatively fast) but the cross-section area of the channel is small, too. As mainly the bottom of the channel is dissolved. Therefore the cross-section area of the channel does not increase considerable, but its shape decreases during its development. Channels with V-shaped cross sections can occur between channels which receive water from *Pinus mugo* patch due to the fast decreasing discharge.

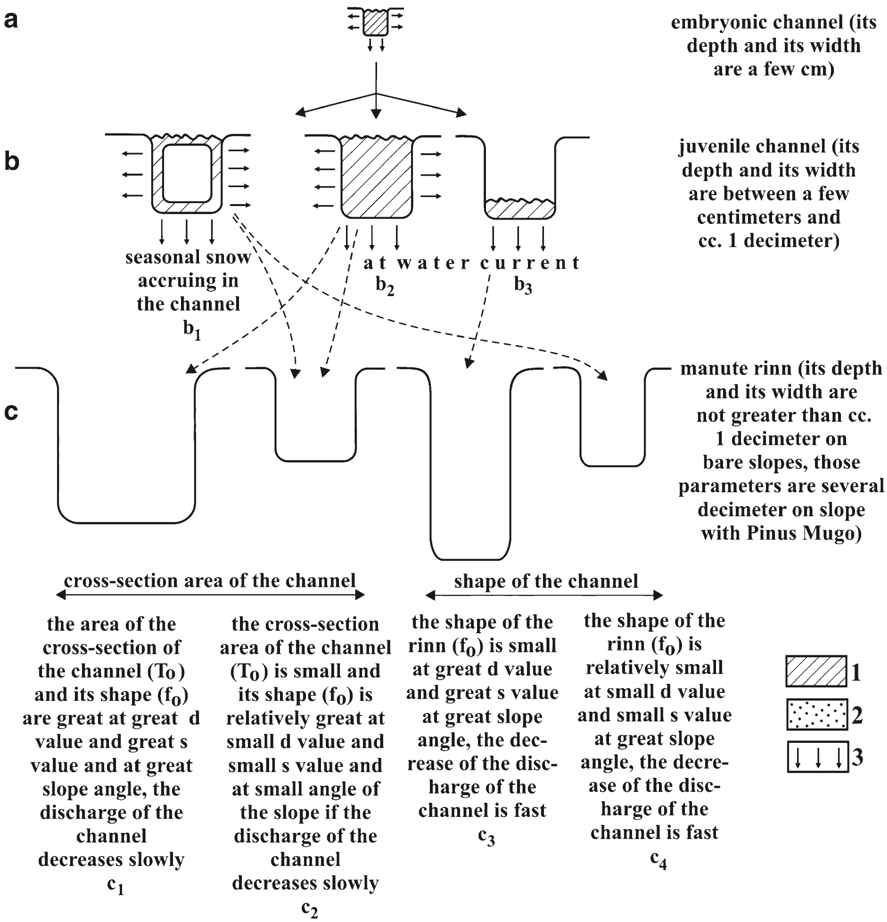


Fig. 4.24 The development of channels on slopes with various characteristics (Veress et al. 2008b, transformed). Legend: 1 – water, 2 – snow, and 3 – solution (the length of the arrow is proportional with the intensity of dissolution), T_0 – cross-section area, d – distance between the upper margin of the slope and the profile, s – width of Pinus mugo patch, and f_0 shape of channel

Hence, channels development due to rivulets is characteristic at those channels which are fed from *Pinus mugo* patch at greater slopes angles too on slope with *Pinus mugo*.

Karren terraces develop if the bottoms of the bearing channels are destroyed partly (Veress, 2000a). A karren terrace develops if the older and greater channel increases in a smaller degree, because the discharge is smaller in the channel. Then the widening of the younger and smaller type II channel is faster. Namely it gets much flowing water compared to its size. During its increasing it destroys partly the bottom of the older channel (Fig. 4.25c). But it may also happen in the case of the second development type, that a type I channel 'over-develops' and becomes wide too. Its water flow cannot fill its bottom. Its widening may be due to

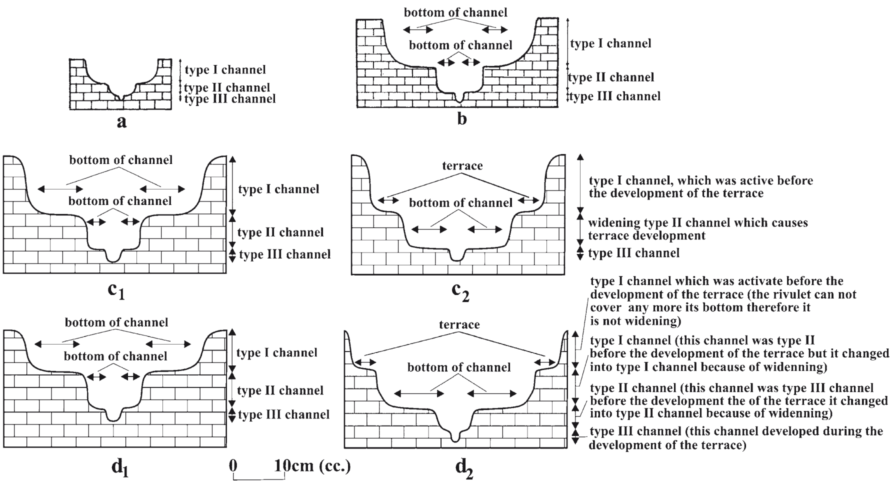


Fig. 4.25 The development of a complex channel without a terrace (**b**) from a complex channel (**a**) and the development of a complex channel with a terrace (**c–d**) from a complex channel (after Veress, 1995 changed). Legend: (**a**) complex channel develops because the development velocity of the various channels is the same (**a**, **b**), a terrace develops because the bearing channel does not grow, but its water discharge decreases (c_1–c_2) or the channel increases but its water discharge is the same (d_1–d_2), a smaller water discharge is dominant on the channel shown in (**c**) therefore the type II channel widens in a greater extend than the type I channel in the case of (**d**) the type I channel becomes too wide to widen further, its role is undertaken by the former type II channel: it is transformed into a type I channel due to the water flowing inside the form and it destroys the bottom of the type I channel which is inactive, and non-widening

sheet water by chance. In that case the type I channel becomes non-active. The type II channel widens fast and it changes to type I channel. The changing channel destroys the bottom of the non-active channel during this process. The remnant bottom of this non-active channel forms the karren terrace (Fig. 4.25d). A terrace also develops if a channel-bottom pit is formed (Veress 2000f). Namely internal channels develop from the channel-bottom pits. These forms also destroy the bottoms of the older channels in which they occur.

The channels can develop in the following ways among their longitudinal directions (Fig. 4.26):

- The channel deepens in the direction of the channel head and becomes longer during its development. The head of the channel extends up the slope. The channel deepens in a greater degree to the direction of the head of the channel than at its lower part if the slope angle increases in the opposite dip direction (Fig. 4.26a).
- The depth of the channel does not increase towards the head of the channel during its development, but its length grows as the head of the channel retreats to the opposite direction of the dip direction (Fig. 4.26b).
- The depth of the channel increases uniformly while its length does not change (Fig. 4.26c).

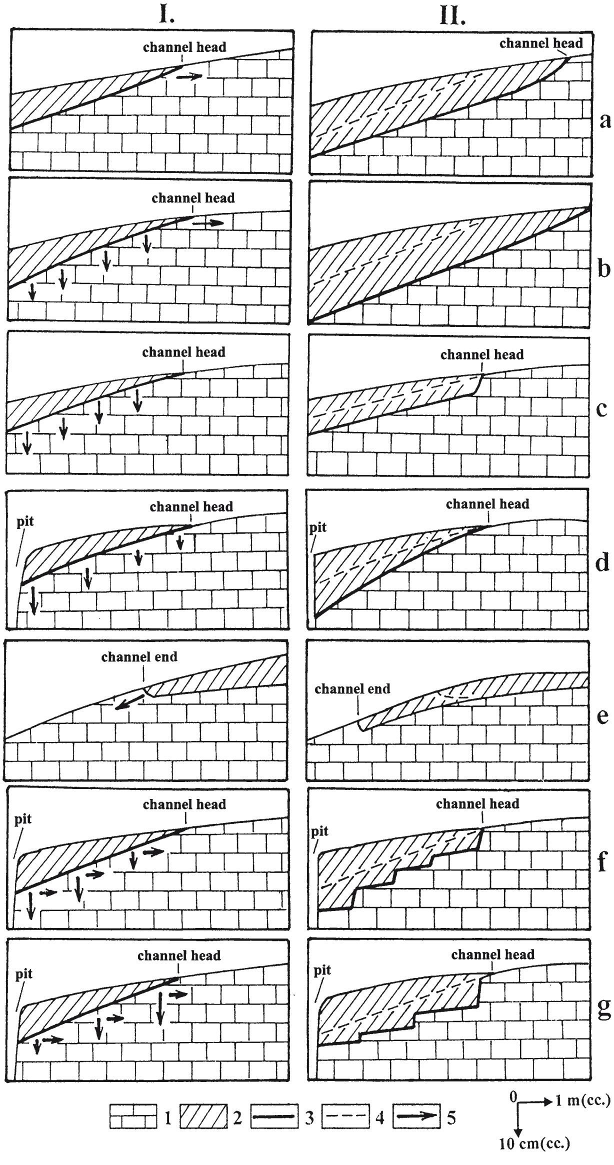


Fig. 4.26 Types of channel development (Veress, 2003). Legend: (I) initial phase, (II) mature phase; (**a**) – regressional developing channel, (**b**) – regressional rain-furrowed developing channel, (**c**) – rain-furrowed developing channel, (**d**) – regressional rain-furrowed developing channel, (**e**) – anti-regressional developing channel, (**f**–**g**) – stepped development of channel bottom. 1 – Limestone, 2 – channel in profile, 3 – bottom of channel, 4 – earlier bottom of channel, 5 – relative velocity of channel development

- The depth of the channel increases downward along the dip of the slope while its length does not change (Fig. 4.26d).
- The depth of the channel decreases away from the channel head as it extends down slope (Fig. 4.26e).
- Some sections of the bottom of the channel are dissolved to varying degrees. In this case the channel takes up various-sized steps (Fig. 4.26f, g).

In the first two cases, the development of the channel is regressional. The causes of this phenomenon are the following. Rivulets develop along the dip direction of the slope, and such currents have the highest velocity. In the first case, the development of the channel is exclusively regressional (Fig. 4.26a); in the second case (Figs. 4.10 and 4.26b), it can be partly rain-furrowed (regressional rain-furrowed channel development).

In the third and fourth cases, the length of the channel does not change and therefore their development is rain-furrowed (Fig. 4.26c, d). In the third case when the velocity of the channel is uniform in the whole length of the channel, the development of the channel is rain-furrowed (Fig. 4.26c).

The rate of deepening can increase toward the lower section of the channel due to the increase of the current velocity. The deepening of the channel results in a horizontal movement. The dissolving of the bottom of the channel is more significant in the lower parts than in the upper section of the form. The development of the channel is – in the fourth case – rain-furrowed and regressional (Fig. 4.26d).

In the fifth case (Fig. 4.26e), the development is anti-regressional, which is characteristic of decantation channels. If anti-regressional channels are created then the bifurcation channels may develop. In case of bifurcation a channel gets a tributary channel. Such channels may coalesce into each other (Fig. 4.7).

Finally the development of the channel is steep (Fig. 4.26f, g).

Channels can develop from other karren forms:

- 'Leafkarren' develop into channels (Szunyogh et al. 1998).
- Trittkarren of trittkarren series coalesce (Veress and Tóth, 2002, Picture 4.26).
- Scallops coalesce (Curl, 1966).
- Karren caves can open-up (Veress, 2000a, Veress, 2002).

4.1.2.2 Wandkarren (Wall Karren, Wall Runnels)

Wandkarren ('wall' karren) are created by water flowing on slopes (Ford and Williams, 1989). Wandkarren develop on vertical slopes (e.g. on the walls of shafts). They are parallel to each other and have a semi-circular cross section (Bögli 1960). According to German researchers, wandkarren can be independent karren forms (Bögli 1960) but in the English research literature, these forms are described as a type of rinnenkarren (Ford and Williams 1989). Jennings (1985), for example, calls wandkarren 'wall solutional runnels'.

Picture 4.26 Embryonic channel developing from trittkarren row (area marked 2/1)

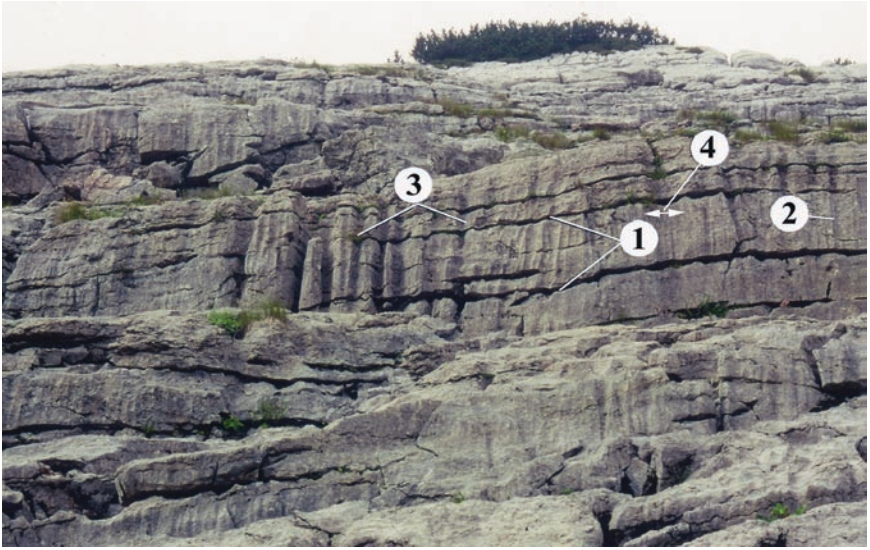
The Spreading of Wandkarren

Wandkarren occur mostly on cuestas (Picture 4.27), in karst forms, on the walls of shafts, on the sides of pits, on the walls of poljes and on the sides of dolines. They can also develop on steep coasts, on the sides of boulders (Picture 4.28), in caves (Choppy, 1996), on slopes shaped by glaciers on cuestas, erosion steps on the sides of roche moutonnée rocks on the slopes of horns and on the slopes of glacier valleys. Their altitude distribution is varied as they can occur near sea level (Diego de Almagro Island) and above the snowline in the Alps. Wandkarren can develop on limestone, on marble (Diego de Almagro), on granite (Corsica, Mongolia) and on halite (Atacama Desert).

Size and Morphology of Wandkarren

The width of wandkarren is between 2.5 and 34 cm in Dachstein. Their most common width is between 4 and 12 cm (Fig. 4.27). The shape of the wandkarren in Dachstein (Fig. 4.28) is between 0.14 and 28 (Table 4.3). The density of wandkarren can range between 1.49 and 14.55 pieces/m, while the value of the specific dissolution is 19.37–39.31 cm/m (Table 4.4; Veress, 2003).

Wandkarren develop mostly along a down-dip, a characteristic shown for the profiles measured in Dachstein. As much as 61.98% of the wandkarren,



Picture 4.27 Wandkarren on cuesta (Totes Gebirge). Legend: 1 – schichtfugenkarren, 2 – wandkarren, which wedge out at schichtfugenkarren, 3 – wandkarren, which cross-section schichtfugenkarren, and 4 – complex wandkarren

Picture 4.28 Half-pipe wandkarren on side of moraine boulder (area marked 2/2)

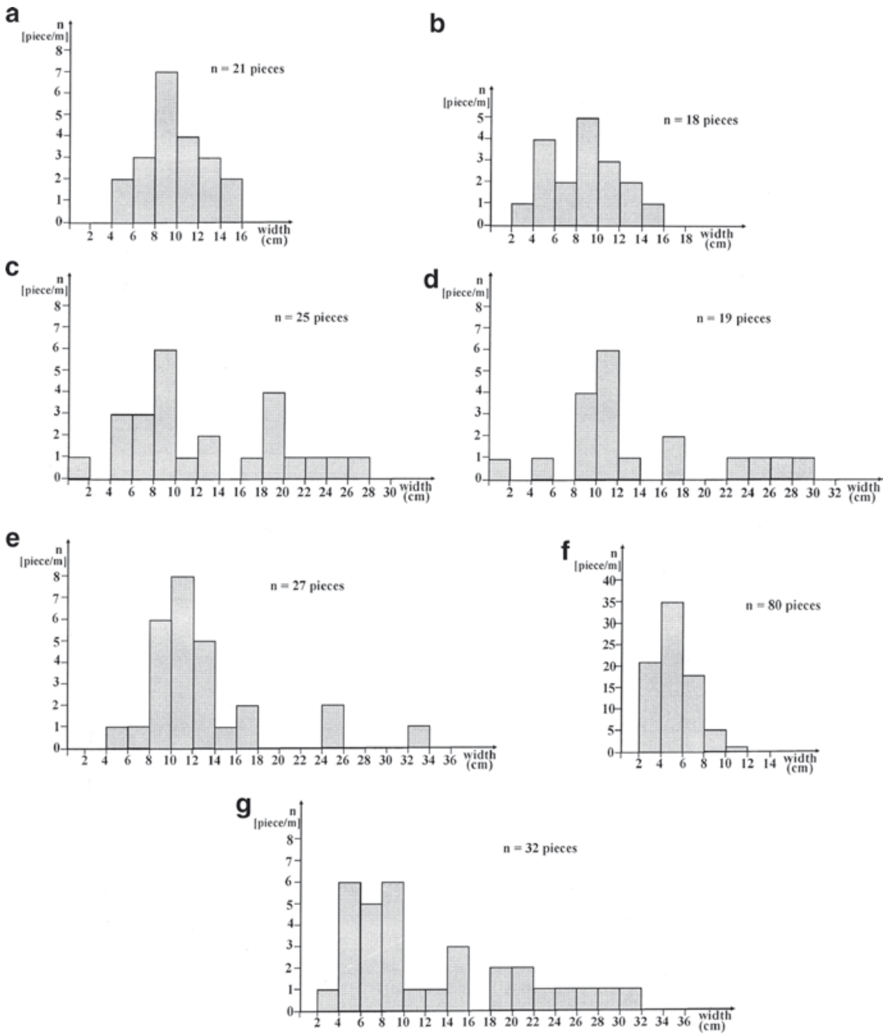


Fig. 4.27 Distribution of wandkarren relative to width (Veress, 2003). Legend: (**a**) site of profile marked D-13/2000 in area 2/2, (**b**) site of profile marked D-14/2000 in area 2/2, (**c**) site of profile marked D-16/2000 in area 2/2, (**d**) site of profile marked D-19/2000 in area 2/2, (**e**) site of profile marked D-20/2000 in area 2/2, (**f**) site of profile marked D-5/2000 in area 2/1, (**g**) site of profile marked D-4/1999 in area 2/4

the D-5/2000 profile, differs less than 20º from the slope direction of the bearing slope, while this value for the D-13/2000 profile is 100% (Fig. 4.29a, b). It can also happen that the difference between the direction of the form and that of the bearing slope is more than 20º. This is the case for 42.3% of the wandkarren of the profile marked D-19/2000 and for 47.36% of the wandkarren of the profile marked D-16/2000 (Fig. 4.29c, d).

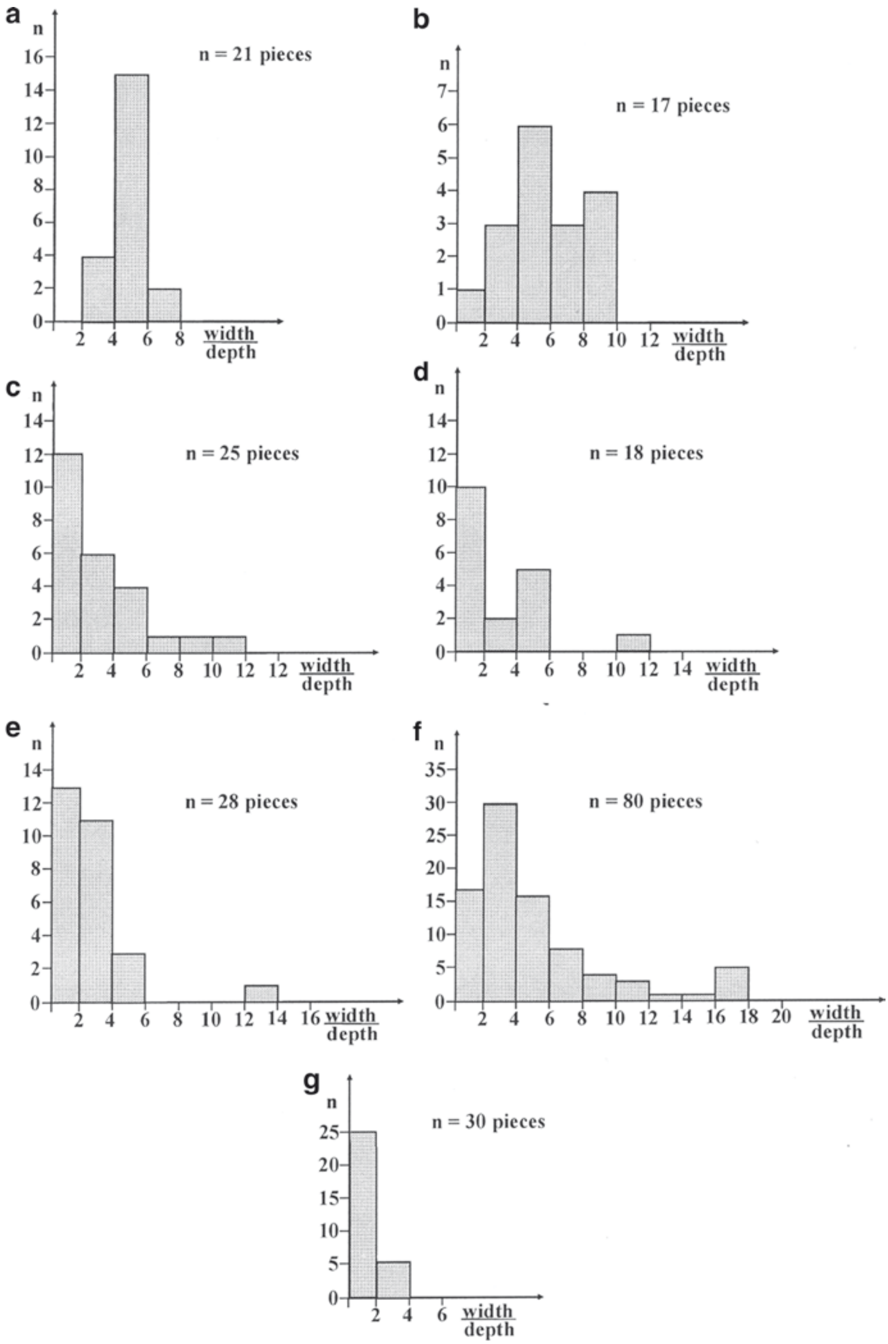


Fig. 4.28 Distribution of wandkarren relative to shape (Veress, 2003). Legend: (**a**) profile marked D-13/2000, (**b**) profile marked D-14/2000, (**c**) profile marked D-16/2000, (**d**) profile marked D-19/2000, (**e**) profile marked D-20/2000, (**f**) profile marked D-5/2000, and (**g**) profile marked D-4/1999

Table 4.3 Distribution of wandkarren along selected profiles from Dachstein relative to width

Profile	Width interval (cm)	Most common interval width	Most common width (%)	Shape interval	Greatest frequency of shapes relative to interval (piece)	Greatest frequency of shapes in interval (%)
D-4/1999	3–50	4–6; 8–10	20; 20	0.14–4	0–2	80
D-5/2000	2.5–11	4–6	43.75	0.75–18	2–4	37.5
D-13/2000	6–16	8–10	33	1.22–5.5	2–4	71.42
D-14/2000	4–16	8–10	29.4	1–10	4–6	35.3
D-16/2000	2–27	8–10	24	0.25–28	0–2	48
D-19/2000	2–61	10–12	31.5	0.19–12	0–2	55.55
D-20/2000	4.3–34	10–12	29.6	0.35–13	0–2	46.42

Intervals are in 2 cm.
Width interval: the width of the smallest and biggest wandkarren that occur along a profile.
Most common width: the width of the wandkarren grouped in an interval (along a profile).
Shape: ratio of width and depth of wandkarren.
Shape interval: ratio of smallest and greatest width and depth along a profile.
The greatest frequency of shapes: the most common shape along a profile from the shapes grouped in an interval.
Last figure of profile number indicates the year when measurements were taken.
Profile D-4/1999 is on side of polje (area 2).
Profile D-5/2000 is near LakeDäummel on the edge of a doline (area 3).
Profile D-13/2000 is on the side of a boulder which is on a moraine.
The sites of profiles D-14/2000, D-16/2000, D-19/2000 and D-20/2000 are on bed-heads of cuestas (area 1).

Table 4.4 Characteristics of selected wandkarren

Name of profile	Altitude (m)	Length of profile (m)	Angle slope of bearing surface	Characteristics of wandkarren ö.sz. (cm)	Number (pc)	f.sz. (cm/m)	s. (pc/m)
D-4/1999	1,700	10.2	51	401	32	39.31	3.14
D-5/2000	1,990	5.5	55	450.5	80	81.91	14.55
D-13/2000	2,180	4.5	75	226	21	50.22	4.67
D-14/2000	2,157	7.0	48	163	18	23.29	2.57
D-16/2000	2,115	17.5	90	339	26	19.37	1.49
D-19/2000	2,106	9.0	75	279	17	31.00	1.89
D-20/2000	2,078	12.5	73	371.3	28	29.70	2.24
average	–	–	–	408	31.71	39.26	4.36
Ch-2/2002	500[a]	20.0	90	804	6	40.2	0.3

D – Dachstein, Ch – Chile, ö.sz. – total of measured widths along a profile, f.sz. – specific width, s – density, last figure of profile name indicates year measurements taken.
[a] Estimated.

The specific dissolution and the density are independent of the altitude or the dip of the bearing surface (Table 4.4), but connections appear between width, shape, density and specific dissolution. For profiles where the value of shapes of the wandkarren is high, the density and specific dissolution are large as well. Such wandkarren occur on the profiles marked D-5/2000 and D-13/2000. The wandkarren of these profiles have a half-pipe shape. On profiles where the value of shapes of the wandkarren

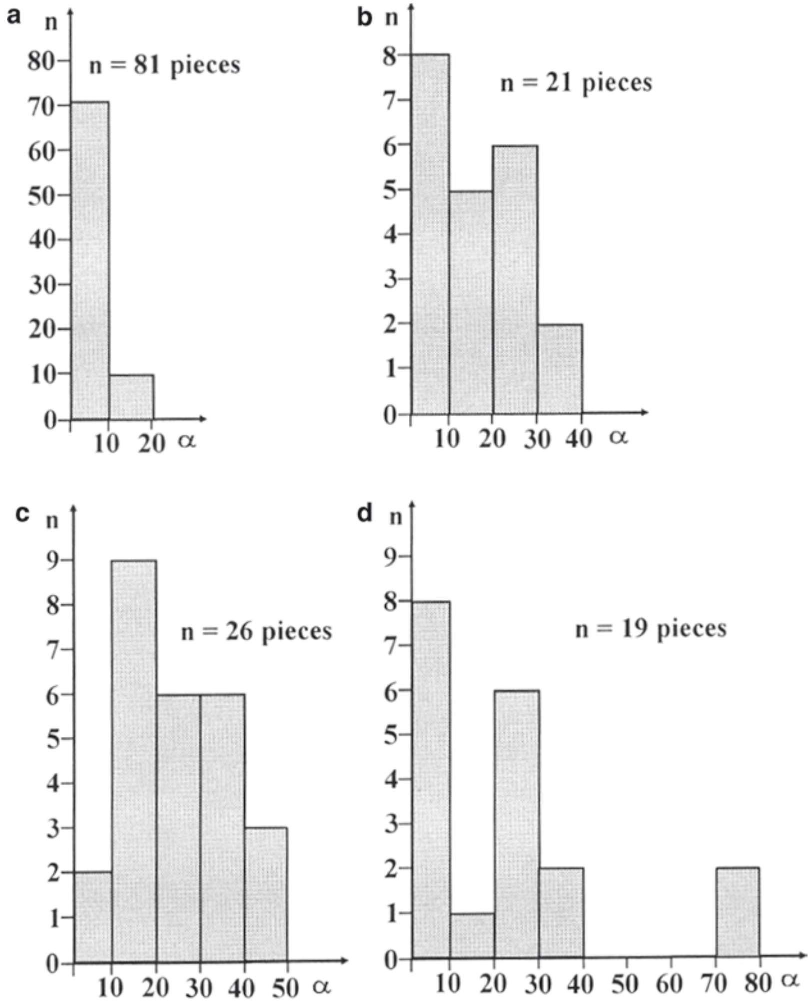


Fig. 4.29 Frequency distribution of differences between the direction of wandkarren and the slope direction of their bearing slopes (we consider the direction of the wandkarren as the direction that follows the direction of the slope downwards, Veress, 2003). Legend: α – direction difference between wandkarren and bearing slope, (**a**) frequency distribution of wandkarren that occur along profile marked D-5/2000, (**b**) frequency distribution of wandkarren that occur along profile marked D-13/2000, (**c**) frequency distribution of wandkarren that occur along profile marked D-16/2000, and (**d**) frequency distribution of wandkarren that occur along profile marked D-19/2000

is small, the density and the specific dissolution are also small. Such wandkarren occur on the profiles marked D-16/2000, D-19/2000, D-20/2000 and D-4/1999 (Tables 4.3 and 4.4). Along these profiles, grike-like wandkarren developed.

There is a difference between the width values of the above-mentioned two various wandkarren types. According to the data, the width of half-pipe wandkarren can show less, deviation while the width of grike-like forms shows a greater deviation. We assume that where wandkarren occur in great density, the adjacent forms do not let each other widen. Since the grike-like forms are far from each other, they can widen freely and can therefore have great width.

Types of Wandkarren

According to cross section, wandkarren can be classified as (Fig. 4.30; Veress, 2003):

- Grike-like wandkarren (Figs. 4.30.1 and 4.31.Ib; Picture 4.29) have sharp edges and flat side walls. We can distinguish different types as well. Their side walls can take different "V" shapes. If the side slopes do not cross each other, the

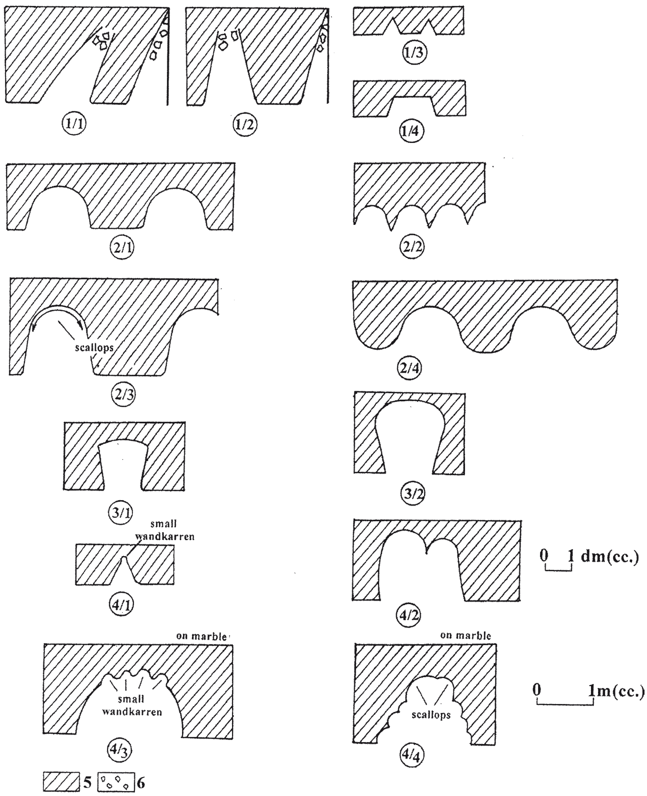


Fig. 4.30 Shapes of wandkarren (cross section, Veress, 2003). Legend: 1 – grike-type wandkarren: 1/1 slanting, 1/2 straight, 1/3 wedging-out, 1/4 flat-bottomed; 2 – half-pipe wandkarren: 2/1 planar surfaces between wandkarren, 2/2 ridges between wandkarren, 2/3 scallops in wandkarren, 2/4 rounded surfaces between wandkarren; 3 – cavernous wandkarren: 3/1 widening with flat bottom, 3/2 widening with curved bottom; 4 – complex wandkarren: 4/1 with one internal channel, 4/2 with internal ridge; 4/3 with smaller wandkarren, 4/4 with scallops; 5 – limestone, marble; and 6 – debris

forms end in a flat surface and the end of the wandkarren can have debris or not. The side wall can be vertical to or slanting relative to the bearing slope. Soil can fill the ends of nearly vertical side-walled forms (Picture 4.30).

- Half-pipe wandkarren (Figs. 4.30.2 and 4.31.Ia; Picture 4.31) have curved side walls. This type also varies. The half-pipe cross section can be similar to a semi-circle or to an ellipse. The bearing slope between these forms is rarely wide (it Alpscan be flat or rounded), and its shape is more often ridge-like. Scallops can occur on their walls (Picture 4.31).
- Cavernous wandkarren can widen at the bottom of the form (Fig. 4.30.3), and the bottoms can be flat or curved.
- Complex wandkarren (Fig. 4.30.4/1, 4/2; Picture 4.27) can be separated into at least two parts. For example, the form can be the coalescing of two smaller wandkarren. More frequently, however, small wandkarren divide the side walls or the bottom of a larger wandkarren (Fig. 4.30.4/3).

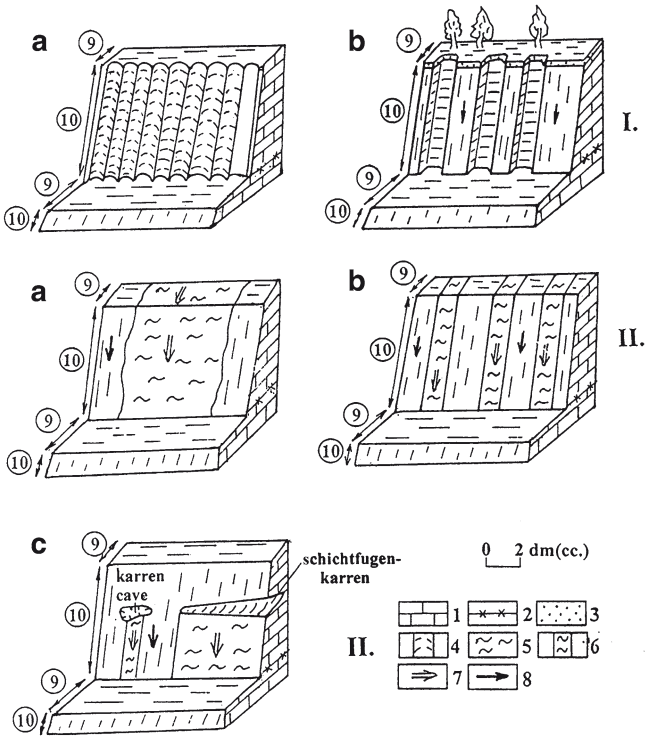


Fig. 4.31 Genetic types of wandkarren (Veress, 2003). Legend: (**Ia**) half-pipe wandkarren, (**Ib**) grike-like wandkarren, (**IIa**) wandkarren developing under sheetwater originating from surface, (**IIb**) wandkarren developing under rivulets originating from surface, (**IIc**) wandkarren developing under water flowing from hollows in head of bed. 1 – Limestone, 2 – bedding plane in profile, 3 – soil, 4 – wandkarren, 5 – sheet water, 6 – rivulet, 7 – water current, 8 – inclination, 9 – bedding plane, and 10 – heads of bed

Picture 4.29 Grike-like wandkarren (Totes Gebirge)

Picture 4.30 Wandkarren formed below soil (area marked 4/2)

Wandkarren can extend over the complete length or only on a part of the bearing slope. In the first case, wandkarren can have a continuous development or the form can be interrupted by schichtfugenkarren or by variously shaped hollows

Picture 4.31 Half-pipe wandkarren (area marked 2/2)

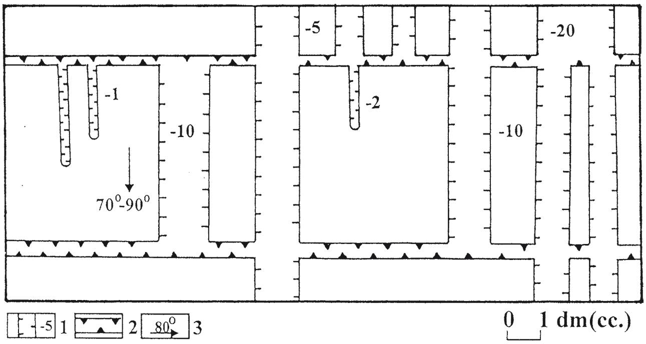
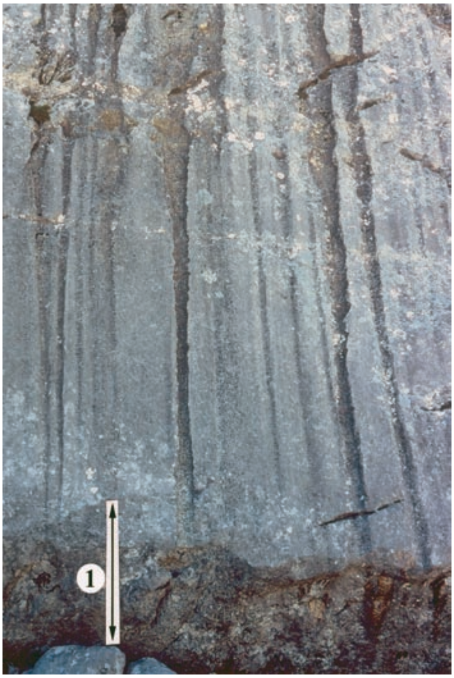


Fig. 4.32 Development types of wandkarren where the bearing surface is crossed by schichtfugenkarren (front view) (Veress, 2003). Legend: 1 – depth of wandkarren (cm), 2 – schichtfugenkarren that developed along bedding plane, and 3 – inclination and angle of bearing surface

(Figs. 4.31c and 4.32; Picture 4.32). The width of the wandkarren can be unchanged or smaller below the schichtfugenkarren, or the wandkarren can also be branched (Fig. 4.32). The upper end of the wandkarren can be at or below the top of the bearing slope. The lower end of the wandkarren can wedge out or end at a schichtfugenkarren (Picture 4.33). When they begin at a schichtfugenkarren, they can

Picture 4.32 Wandkarren that cross schichtfugenkarren and start at it (area marked 2/2). Legend: 1 – schichtfugenkarren



Picture 4.33 Wandkarren that end at schichtfugenkarren (area marked 2/2). Legend: 1 – schichtfugenkarren

extend to the lower edge of the bearing slope or to another schichtfugenkarren, or they can also wedge out (Fig. 4.32; Pictures 4.32 and 4.33). Wandkarren that end at the lower part of the slope can wedge out or join a soil-covered surface or another karren form.

Development of Wandkarren

We distinguish two development types of wandkarren according to their characteristics:

- Half-pipe or rill-type wandkarren (Fig. 4.31.Ia) develops under sheet water that flows down the bearing slope (Fig. 4.31.IIa). Their cross section, the value characterizing their shape and their great density prove this fact. Sheet water can originate from the bedding plane above the slope (Fig. 4.31.IIa) or from a schichtfugenkarren (Fig. 4.31.IIc). When the bedding plane is covered with soil, there is less probability they will develop since soil can store rainwater. Meltwater also plays an important role in the development of this type of wandkarren. There they can also develop on such head of bands above which the surface tilts to the opposite direction that of the bearing slope. As the accumulated snow above this surface changes the sloping relationship, the meltwater flows downwards the forehead of the slope.
- Grike-like or rinnen-type wandkarren (Fig. 4.31.Ib) develop under rivulets (Fig. 4.31.IIb), which their small density proves. Rivulets are fed from bare bedding planes, soil (with numerous source points) or soil patches. Wandkarren can help the development of a soil patch. Rivulets can also flow from a hollow (Fig. 4.31.IIc). Because the distance between rivulets is random, their discharge, the period of their existence, the date of their development and the CO_2 saturation level of their water can differ to a great extent. Neighbouring forms can therefore have different sizes. Forms that are close to each other can have different ages and activity levels. We believe cavernous wandkarren can be included in this type since we believe the cause of their development is an increasing discharge or an increasing dissolution effect.

The direction scattering of the two various types of wandkarren suggest the two different types of water flows generating their development. The direction of those forms that develop under sheet water differs less from the dip line of the bearing slope. On one hand, the flow of water cannot be diverted by the irregularity of the surface, and on the other, the forms do not have space to develop in different directions. Those forms that develop under rivulets have a different dip direction relative to the bearing slope since the direction of the flow is changed by the irregularity of the slope and the development of grike-like wandkarren occurs in various directions.

- Complex wandkarren develop if the rivulet cannot fill the form. If there is only one rivulet, we can see only one internal wandkarren, while if there are several rivulets we can observe several internal wandkarren (Fig. 4.30.4/3).

- Covered wandkarren develop if soil fills the forms. This type of development occurs where the quantity of plants and soil is significant (e.g. the southern slopes of the Southern Alps or on the lower part of a mountain). Because of the soil accumulation, water cannot flow in the forms and dissolution occurs under the soil.

The development of wandkarren is anti-regressional, as demonstrated by the following points:

- If they do not begin at schichtfugenkarren, their upper end is always at the beginning of the upper margin of a slope.
- Their lower ends can wedge out at different altitudes.
- Their width usually decreases in the direction of their lower ends (down slope).
- There are no rillenkarren and rinnenkarren on steep slopes (70–90º).

Several factors contribute to the anti-regressional development of wandkarren, including the following:

- The water flow is faster in already developed wandkarren and therefore saturation of the water occurs over a longer path.
- To the effect at vegetation, the CO_2 saturation value of the water increases at the edge of the bearing slope.

Grike-like wandkarren generally cut across schichtfugenkarren or develop from the site of the schichtfugenkarren (depending on the time of origin of the forms).

We can formulate a genetic model of wandkarren crossing schichtfugenkarren in the case where the schichtfugenkarren is older than the wandkarren. Such cases prove the following characteristics:

- The width of a wandkarren abruptly becomes smaller when the wandkarren crosses a schichtfugenkarren. This can only happen if the schichtfugenkarren developed earlier than the section of wandkarren below it (its width decreases).
- The inner height of schichtfugenkarren does not change. The inner height of schichtfugenkarren can decrease (away from a wandkarren) if the schichtfugenkarren is younger than the wandkarren. In this case, the schichtfugenkarren will have started at the wandkarren so its inner height will be the largest there.

Schichtfugenkarren direct and effect the development of wandkarren with different lengths and widths as follows (Fig. 4.33):

- A wandkarren cuts a schichtfugenkarren without changing its width because only saturated water leaves the schichtfugenkarren (Fig. 4.33a).
- We can observe that the width of a wandkarren decreases after it cuts a schichtfugenkarren. In this case, the water flowing down the wall becomes more or less saturated at the height of the schichtfugenkarren but the water leaving the schichtfugenkarren is unsaturated, therefore there is a wandkarren below it (Fig. 4.33b).
- Wandkarren cut some schichtfugenkarren without a decrease or even an increase in their width. In these cases, the solubility of the water flowing down decreases

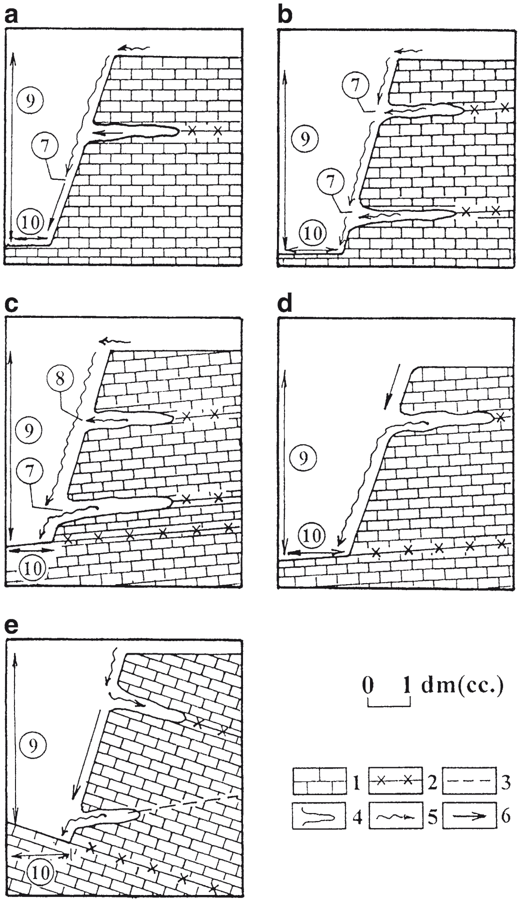


Fig. 4.33 Development of wandkarren with different lengths (Veress, 2003). Legend: 1 – limestone, 2 – bedding plane (in cross section), 3 – joint, 4 – schichtfugenkarren, 5 – unsaturated water, 6 – saturated water, 7 – site of complete saturation of water flowing on head of bed, 8 – dissolution increases because water mixes on head of bed with unsaturated water flowing from schichtfugenkarren, 9 – head of bed, 10 – bedding plane. (**a**) Unsaturated water can dissolve rock anywhere (width of wandkarren is similar above and below schichtfugenkarren), (**b**) water flowing down head of bend becomes saturated at the level of the highest schichtfugenkarren, but the water flowing from schichtfugenkarren is unsaturated (width of wandkarren is smaller below the Schictfugenkarren), (**c**) water from head of bed above schichtfugenkarren can no longer dissolve rock but mixes with unsaturated water flowing from schichtfugenkarren (wandkarren crosses several schichtfugenkarren but its width does not change), (**d**) water is saturated (wandkarren can only develop under schichtfugenkarren if unsaturated water flows from schichtfugenkarren), (**e**) water is unsaturated but flows into upper schichtfugenkarren and water which is unsaturated leaves the lower schichtfugenkarren (wandkarren do not develop between schichtfugenkarren)

minimally since the water leaving the schichtfugenkarren is unsaturated and is able to maintain or even increase solubility as it mixes with the water flowing down the wall (Fig. 4.33c).

- Wandkarren begin at schichtfugenkarren because the water flowing down the bed heads is already saturated. Wandkarren can only start at schichtfugenkarren when unsaturated water leaves the schichtfugenkarren (Fig. 4.33d).
- Wandkarren do not develop between two schichtfugenkarren when the water flowing down the bed head flows into the upper schichtfugenkarren or becomes saturated at this altitude. At the same time, unsaturated water flows out of the lower schichtfugenkarren (Fig. 4.33e).

4.1.2.3 Meanderkarren (Meänderkarren, Meandering Runnels)

Meanderkarren have asymmetrical cross section. They may be sometimes meandering (Veress, 1998, Veress, 2000b; Veress and Tóth, 2004) and mostly occur as isolated features on gentle slopes (less than 10°).

General Characteristics of Meanderkarren

Meanderkarren can be connected to kamenitzas, pits, grikes, shafts and rinnenkarren. Their types can be the following (Fig. 4.7):

- The decantation runnels of kamenitzas always show a meandering feature, too. It is true that the length of the meandering part is a few metres altogether. The meandering channel either wedges out or continues in a non-meandering channel.
- The channels of a long slope turn into meanderkarren towards the lower part of the slope. It can be clearly seen, that the width of the meandering part is smaller compared to their depth than in case of the non-meandering channels.
- The reverse case can occur, too. Hence meanderkarren of the upper slope is transformed into rinnenkarren (channel) on the lower slope part.
- The meanderkarren can lead to pits, kamenitzas, grikes and shafts.
- It can also occur that only the middle part of the channel is a meanderkarren.
- It can also occur that the internal channel of non-meandering complex channel shows meandering (see below). In that case a type III channel may be meandering in a simply complex channel. (It is a type III meanderkarren.) Or a type II channel (type II meanderkarren) or a type III channel may be meandering in manifold complex channels. Or both channels may be meandering. Internal channels do not show meandering mostly along their total length. Hence type II channels or type III channels are interrupted by parts of type II or III meanderkarren.

Meanderkarren are described by Bögli (1976) and others (Jennings 1985; Ford and Williams, 1989) as a special type of rinnenkarren. According to Bögli (1960), the cross section of meanderkarren downslope. The above-mentioned characteristics are not the most important of that of the meanderkarren. We present pictures in this chapter that show their most important characteristics such as typical asymmetrical cross section and the under-detailed morphology of meanderkarren.

Small 'micro-meanderkarren' (decantation micro-meanderkarren) are described by Macaluso and Sauro (1996), who claim these forms are found on halite but not on limestone. We should also mention that various authors describe the morphology of meanderkarren differently. Sauro (1973), for example, regards channels that have non-symmetrical cross sections and changing directions as meanderkarren (for this type we use the term 'false meander'). In his later publication, Bögli (1976) describes these forms emphasizing their small size and that they are created by a solution flow percolating from the soil. According to Ford and Lundberg (1987), the sinuous Horton-type rinnenkarren are associated with meanderkarren, while according to Sweeting (1973) meanderkarren are internal channels of larger channels. We have already mentioned that meanderkarren can develop not only on limestone but also on other rocks, for example, on evaporites (Calaforra 1996; Macaluso and Sauro 1996) and marble (Veress et al. 2006d).

Hutchinson (1996) published a new way of classifying meanderkarren as young and mature types. He distinguishes 'gutters' that have a V cross-section, 'gorges' that have steep sides, and a meandering type of the mature type. This latter type is characterized when a smaller meandering channel occurs inside a large straight channel. According to Hutchinson (1996), meanderkarren have two main characteristics: sinuosity and an asymmetrical cross section. According to Hutchinson (1996), meandering occurs when rinnenkarren become old and when the inclination of the surface is between 7º and 14º. He notes that young channels flatten downwards along the slope while older ones do not and that older channels have less sinuosity than young ones.

According to Ford and Williams (1989), meanderkarren develop where the flow of the water is slow, while according to Zeller (1967) they may be formed where the velocity of the water current is high (Froud-number 1.8–20) and the velocity of the water current is higher than the velocity of the currents of river and meltwater. Hutchinson (1996) describes the development of meanderkarren as a characteristic process when rinnenkarren become older (on slopes between 7° and 14°), while according to Davies and Sutherland (1980) they are forms that adapt to the flow (along the profile of least resistance). According to Zeller (1967), meanderkarren develop during turbulent flow, related as well to when the flow changes from turbulent to laminar. However, Zeller (1967) also suggests that secondary currents can cause the development of meanderkarren as well.

Morphology and Development of Meanderkarren

Veress (1998, 2000b) distinguishes two groups of meanderkarren: false and true. False meanderkarren change direction in such a way that the cross section of the channel is symmetrical, whereas true meanderkarren do not develop during the deepening of the channel (Fig. 4.34a; Picture 4.34). The cross sections of the meanders of true meanderkarren as mentioned earlier become asymmetrical (Figs. 4.34b, 4.35 and 4.36; Picture 4.35).

Picture 4.34 False meanderkarren (Assiago-Plateau)

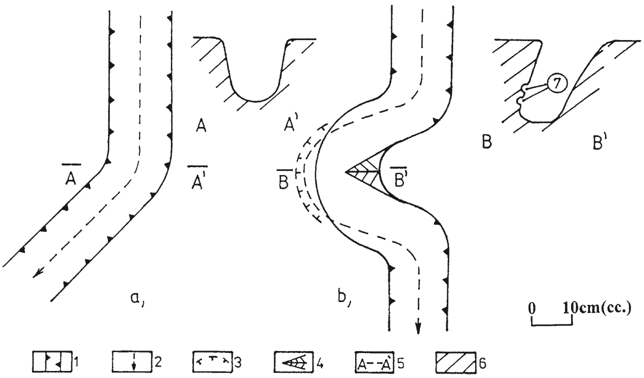


Fig. 4.34 False (**a**) and true meanderkarren (**b**) (Veress and Tóth, 2004). Legend: 1 – vertical channel side, 2 – channel line, 3 – edge of overhanging wall of the concave meanderkarren side, 4 – moderately sloping side of concave meanderkarren side (skirt), 5 – cross section, 6 – limestone, and 7 – meander scour grooves

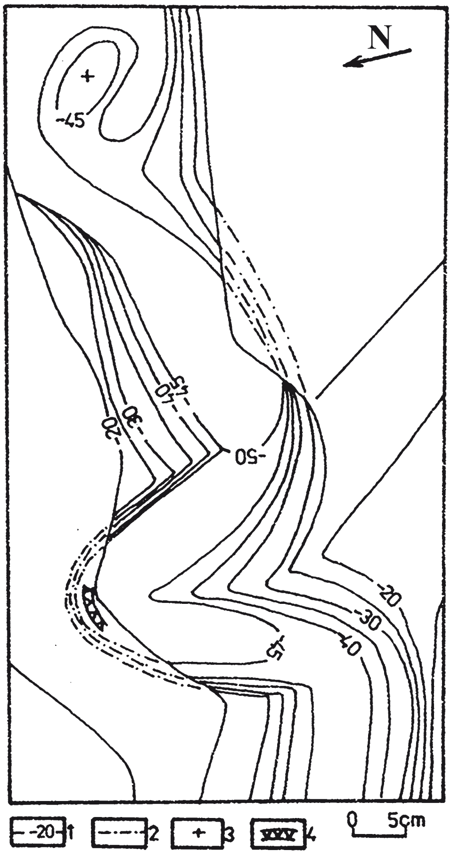


Fig. 4.35 Contour line map of a meanderkarren marked 4 (research area I/3, Barna, 1998). Legend: 1 – contour line in local system, 2 – contour line at overhanging wall, 3 – detached skirt, 4 – meander scour groove

Type III meanderkarren show the most variable meander samples (Fig. 4.37).

The cross sections of meanderkarren are partly identical or similar to those of the beds and valleys of meandering rivers. The beds of the meandering river are steep under the concave river bank and gentle under the convex bed. In case of meanderkarren the side slope is also steep or even overhanging under the concave side and it is gentle under the convex margin. The cross section of meanderkarren can be also similar to those of forced meandered valley cross section which are asymmetrical. Hence these valleys have V-shaped cross sections but asymmetrical and the side of the valley can be steep or even perpendicular under the convex margin, thus the opposite slope is gentle.

The side walls of meanderkarren overhangs under the concave side of a meandering channel while the slope of the wall is gentle on the convex side of the meandering channel (Figs. 4.35 and 4.36). Veress (1998, 2000b) calls this gentle side wall a ‘skirt’. The form of the skirt is very varied both in profile and seen from above (Fig. 4.38). According to the measured data (Veress 1998, 2000b) the projected lateral extension of the opposite sides are different. He established that the size of

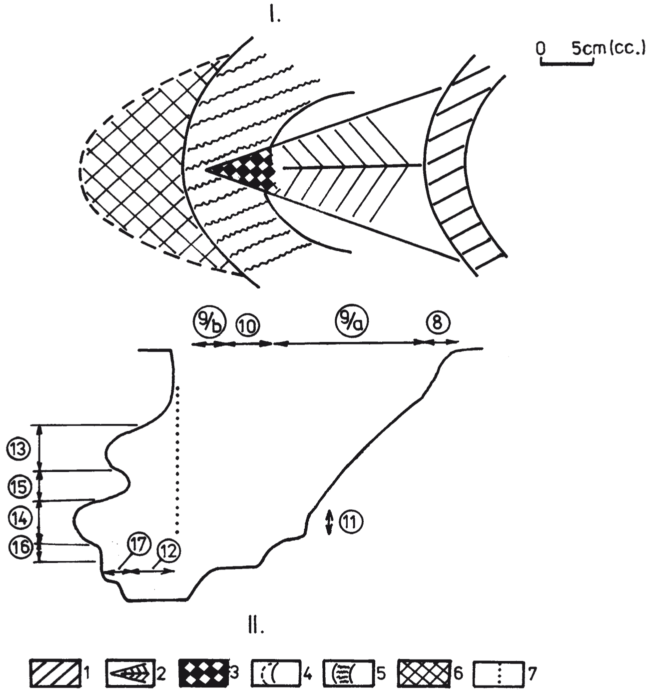
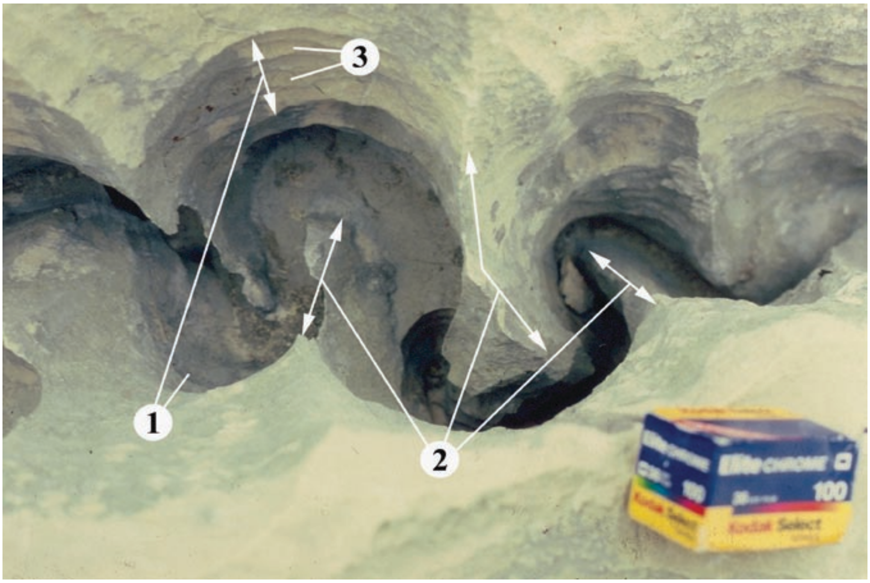


Fig. 4.36 Morphological forms of a meanderkarren (Veress, 2000b). Legend: (**I**) plan, (**II**) cross section, on the plan: 1 – gently sloping meanderkarren side, 2 – skirt, 3 – skirt terrace, 4 – overhanging side wall, 5 – meanderkarren bottom, 6 – meander terrace on the concave side; on the cross section, 7 – projection of the rim of the overhanging wall, 8 – convex meanderkarren side, 9a – skirt remnant at the top, 9b – skirt remnant at the bottom, 10 – meander terrace (on skirt), 11 – meander scour groove, 12 – meander terrace (on overhanging wall), 13 – asymmetric scour groove, 14 – symmetric scour groove, 15 – crest between scour grooves, 16 – eroded crest between scour grooves, 17 – scour groove terrace (scoure groove remnant)

the overhang is less than the lateral extension of the skirt. Skirts sometimes can extend beyond the edge of the overhanging wall. Thus the skirts can 'wedge' under the margin of the overhanging walls. The shape of a skirt is half-conical or half-pyramid when seen from above (Fig. 4.38; Pictures 4.36 and 4.37). In the first case the skirt is rounded, in the latter case it ends in a sharp angle. Asymmetrical skirts can also occur. (Their side walls have various indications.) Half-skirts, the shape of the skirt is a quarter of a circle, thus one of its side slopes is vertical: perishing skirt, decantation channel divides the side slope of the skirts into parts or the rock, which builds up the skirt is broken into debris. If the meandering is complex, the skirt will be complex as well (Picture 4.36). Skirts frequently become detached (budding) and form oxbows and islands (karren 'inselbergs') for many reasons (Tóth and Balogh 2000; Veress, 2000a, b), for example, when the flowing water at the bottom of the channel hits a skirt and dissolves its way through it (Picture 4.37). The roof of the karren cave that develops this way will eventually collapse. The process can



Picture 4.35 True meanderkarren (area marked 3/3). Legend: 1 – overhanging wall, 2 – gently dip wall (skirt), and 3 – scour groove

rough sketches of meanderkarren	type I. meanderkarren		type III. meanderkarren	
	true meander-karren	false meander-karren	true meander-karren	false meander-karren
0 5cm(cc:)		+	+	+
0 5cm(cc.)			+	
0 5cm(cc.)			+	
0 5-20cm(cc.)	+	(+)	+	
0 5cm(cc.)			+	
0 5-20cm(cc.)	+	(+)	+	
0 5-20cm(cc.)	+			

(+) Special case

Fig. 4.37 False and true meanderkarren and their pattern from Totes Gebirge (by using morphology of meanderkarren of research area marked 1/2, Veress, 2000b)

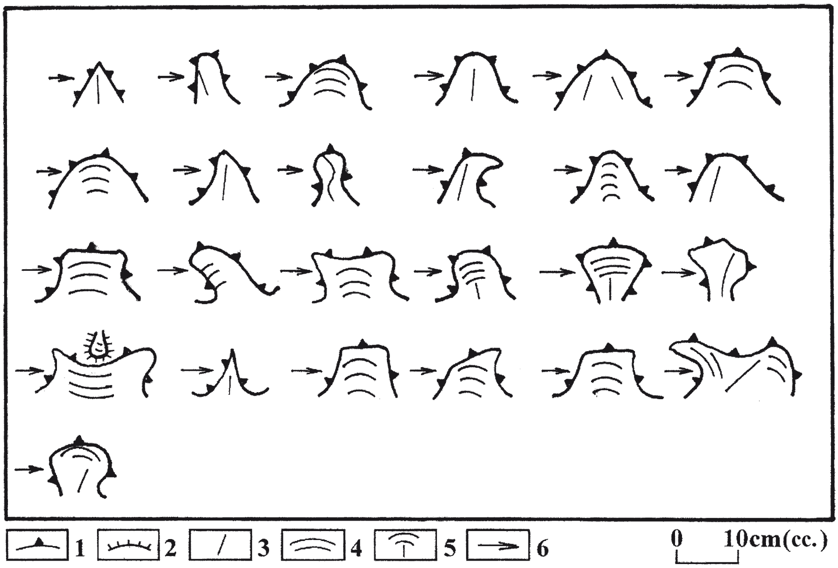
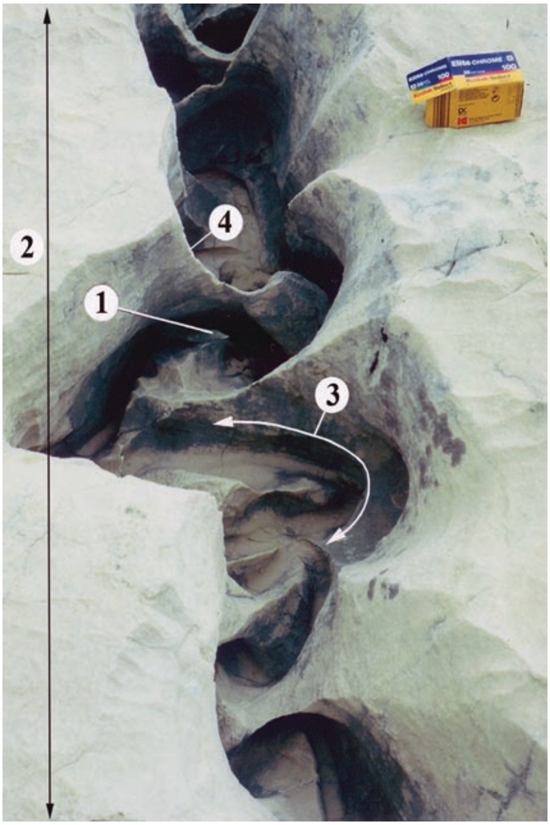


Fig. 4.38 Skirt forms in plan (by using morphology of meanderkarren of research area marked 1/2, Veress, 2000b). Legend: 1 – skirt of type I meanderkarren, 2 – skirt of type III meanderkarren, 3 – skirt ending in edge (half-pyramid) skirt, 4 – round (half-cone) skirt, 5 – skirt ending in edge at top and rounded at the bottom, and 6 – direction of flow

Picture 4.36 Complex skirt (area marked 3/3). Legend: 1 – complex half-cone skirt, 2 – part skirt, 3 – detached skirt, 4 – skirt

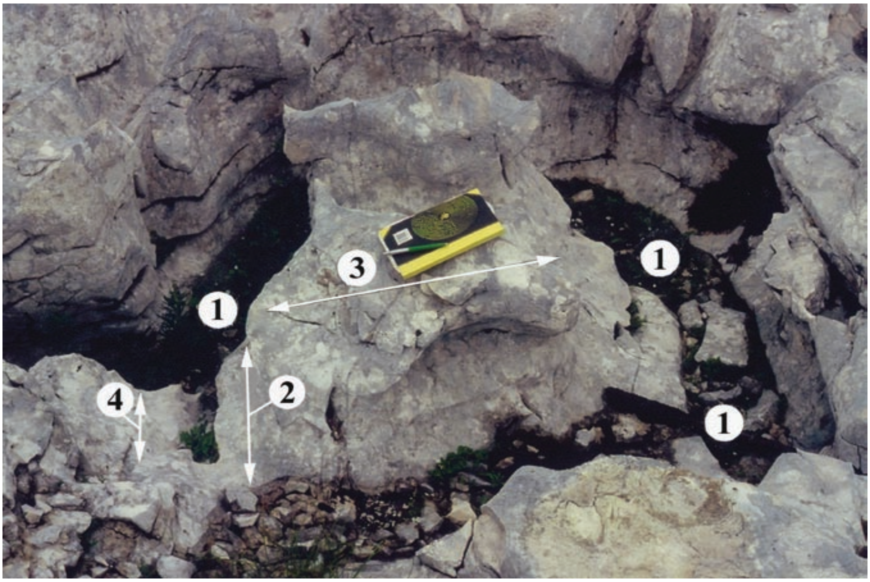


Picture 4.37 Channel with holed skirt (area marked 3/3). Legend: 1 – karren cave at karren neck, 2 – bearing remnant meander, 3 – internal loop meanderkarren, and 4 – half-cone skirt

also occur when some of the water flowing at the bottom of the channel overflows at a karren neck and dissolves the rock, resulting in a detached form (Picture 4.38; Fig. 4.39). Therefore inselberg and oxbow develop at the skirts (Fig. 4.35).

Meanderkarren scour grooves (notch) can develop on the overhanging side walls of meanderkarren. They occur below one another at several levels (Picture 4.35; Fig. 4.36) and are like small horizontal channels on the side walls (Veress, 2000a).

The morphology and the position of scour grooves may be various (Figs. 4.40 and 4.41). According to their cross section they may be asymmetrical, symmetrical, stump scour grooves (they are partly destroyed) and scour grooves terraces (the upper side of the scour grooves is absent). They may occur single or in groups. In the latter case two or three scour grooves may occur above each other. Sharp or rounded ridges can be found between the scour grooves if they developed in groups. The depth and height of the scour grooves are 1–2 cm. They do not occur at every loop. Those scour grooves that belong to one level are along one slanting planar surface. This planar surface part is (nearly) parallel to the bottom of meanderkarren. According to their position they mainly occur on overhanging walls and sometimes on gentle walls (skirts) on one or both walls. They may occur on the bearing meanderkarren or in the internal meanderkarren of a complex meanderkarren.



Picture 4.38 Detached loop (neck, area marked 1/2). Legend: 1 – detached karren oxbow, 2 – karren neck, 3 – karren recess (karren "inselberg"), 4 – anti-regressional channel

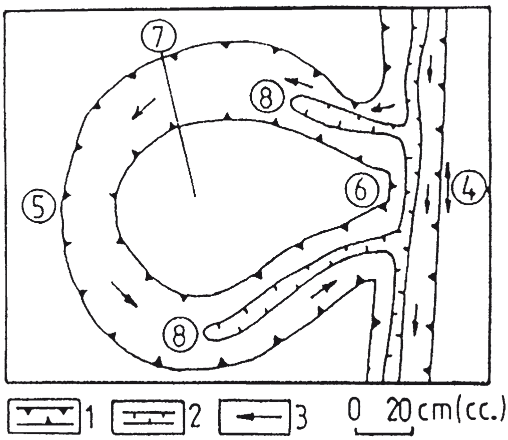


Fig.4.39 The budding of a bend (research area marked 1/2, the form may be seen in Picture 4.38, Veress, 2000a). Legend: 1 – type I meanderkarren, 2 – type III channel, 3 – direction of the indication of the meanderkarren bottom, 4 – location of budding, 5 – karren oxbow, 6 – karren neck, 7 – karren inselberg, and 8 – retreating channels

Two various terraces can occur inside a meanderkarren: karren terraces and meander terraces. Karren terraces, which were described in Chapter Rinnenkarren, also occur on bottom parts of meanderkarren where the form is not asymmetrical. Meander terraces are only characteristics of asymmetrical meanderkarren bottoms. Meanderkarren terraces are embayments of the bottom of the channels on the side walls that are below the concave edges (Fig. 4.36). There are full terraces (the skirt does not extend beyond the rim of the concave side therefore meanderkarren

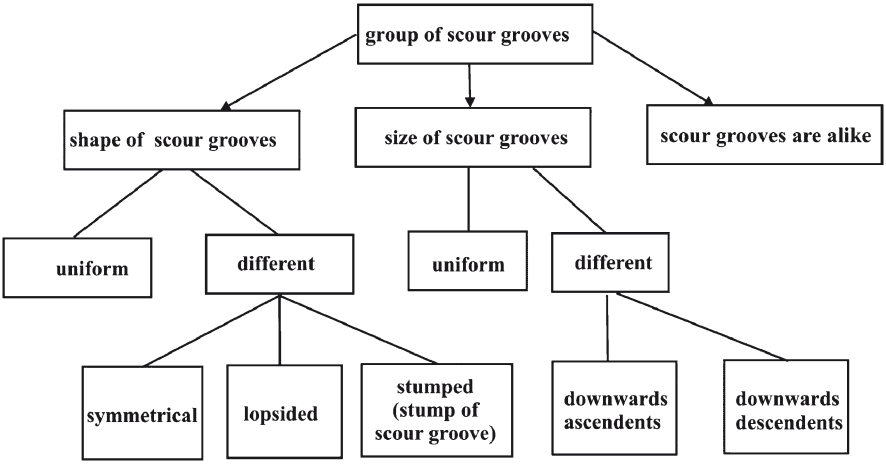


Fig. 4.40 Scour grooves according to shape and size of the scour groups (Veress, 2000b)

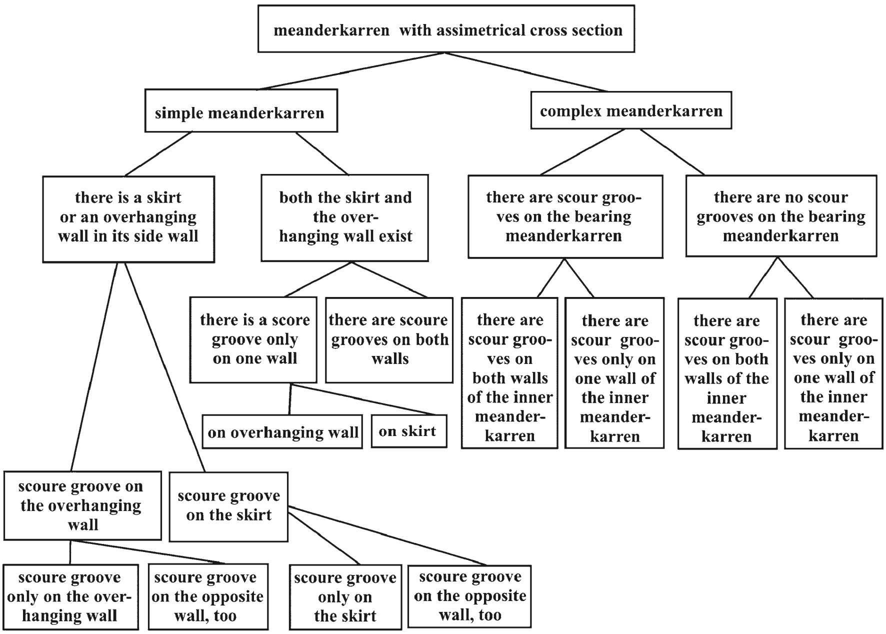


Fig. 4.41 The grouping of the scour grooves according to their occurrence in the meanderkarren (Veress, 1998)

terraces cannot develop to its full length), incomplete terraces (the skirt extends beyond the rim of the concave side) and composite terraces (the meander terrace transforms to karren terrace). They may occur at the bottom of the meanderkarren (bottom meanderkarren terrace) or above the bottom (hanging terrace). We present the types of meander terraces in Fig. 4.42. Hanging terraces develop when the bottom of the channel is able to deepen more intensively (Picture 4.39). Meanderkarren terraces can also develop on parts of the surface of a skirt where the inclination is small (Picture 4.39).

According to Veress (1998, 2000b), the cross sections of channels are asymmetrical because the rate of solution is different on the opposite sides of the meanderkarren. He explains this by the fact that the velocity of the current is different on the opposite sides of a channel.

The difference in the ion concentration between the boundary layer and flowing water is larger if the velocity of the current is higher, and therefore the quantity of the ion transport out of the boundary layer increases (Nerst, 1904; Trudgill, 1985; Dubljanszkij, 1987; Ford and Williams, 2007). Therefore, more ions pass from the

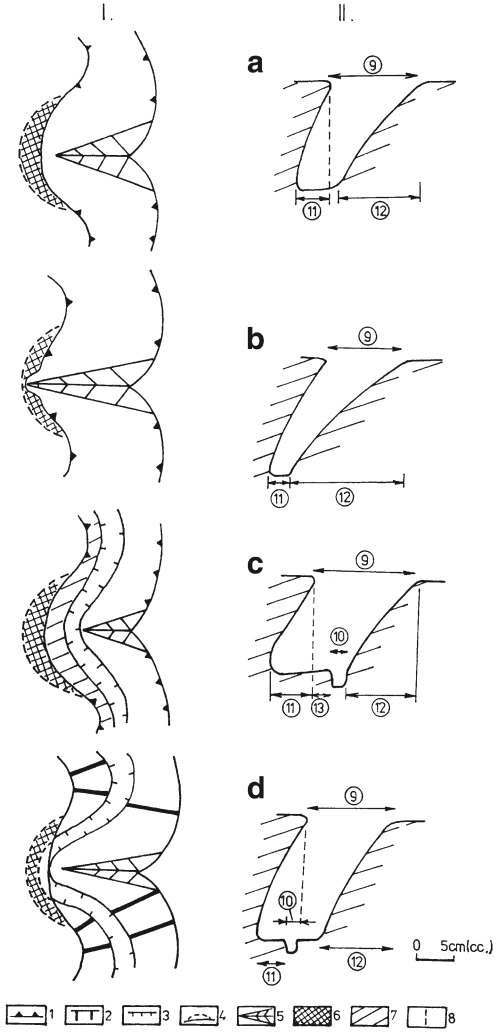
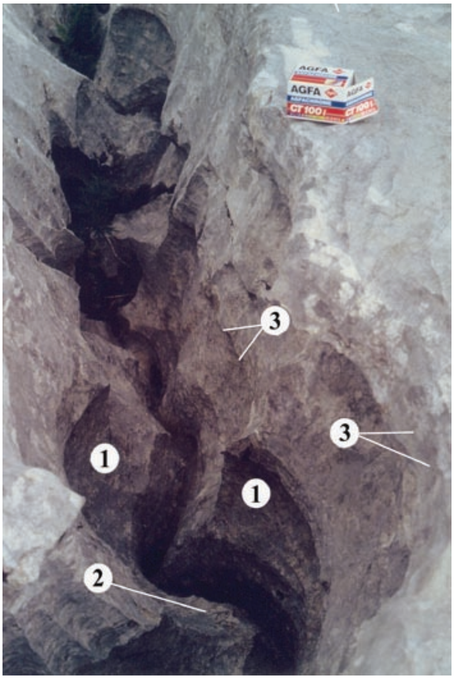


Fig. 4.42 Meander terrace types (Veress, 2000b). Legend: (**a**) full terrace, (**b**) truncated terrace, (**c**) complex terrace, and (**d**) hanging terrace. (I) ground-plan and (II) cross section (profiles near the skirts) top view: 1– boundary of I. type vertical sided meanderkarren, 2 – gently sloping channel side of I type meanderkarren, 3 – edge of III type meanderkarren, 4 – overhanging side wall, 5 – skirt, 6 – meander terrace, 7 – karren terrace, in cross section, 8 – projection of boundary of overhanging wall, 9 – type I meanderkarren, 10 – type III meanderkarren, 11 – meander terrace, 12 – skirt, and 13 – karren terrace



Picture 4.39 Meander terrace (area marked 1/1). Legend: 1 – terrace of overhanging wall, 2 – terrace of skirt, and 3 – meander scour groove

limestone to the boundary layer. A fast current causes turbulence and therefore the boundary layer is interrupted (Curl, 1966; Ford 1980; Trudgill 1985). A new boundary layer will develop repeatedly and because it will be unsaturated, Ca^{2+}-ions can enter it from the limestone. In case of turbulent current, turbulent diffusion changes the molecular diffusion (Dreybroth, 1988). Material transport is bigger and more in quantity in the case of turbulent diffusion. Veress (2000b) and Veress and Tóth (2004) explain the development of the asymmetrical cross sections by the asymmetrical relationships of the currents. The channel line will not stay in the middle of the channel (in the middle of the rivulet flowing down the slope); instead, it will move laterally and at some points will even reach the wall of the meanderkarren (swinging of the channel line, Fig. 4.34). The dissolving of the meanderkarren wall will be more intensive here than on the opposite side of the meanderkarren where the velocity of the flowing water is smaller because the channel line has moved away. The development of meanderkarren as well as the development of meanderkarren types may be explained by the swinging of the channel line with varying quantity and quality (see below). According to Veress (1998, 2000b, 2006) and Veress and Tóth (2004), the swinging of the channel line can be explained with external and internal causes. They regard morphology as an external cause. They observed this in several cases, for example, when water from a tributary channel flows into the main channel (in this case, the main channel meanders locally below the mouth of the tributary channel because the water from the tributary channel deters the swinging line of the main channel). Meandering can also be caused by a false meanderkarren, by a change in the inclination of the bottom of the channel, by calcareous spar lenses (it marks the bottom of the meanderkarren uneven as it is dissolved in a smaller degree) and by an older skirt (Fig. 4.43). The channel line can also often swing in a homogeneous environment. In this case, we explain the process by the changing conditions in the current of the water (internal cause). Probably due to the current of the water, a wave motion develops that can change the swinging of the channel

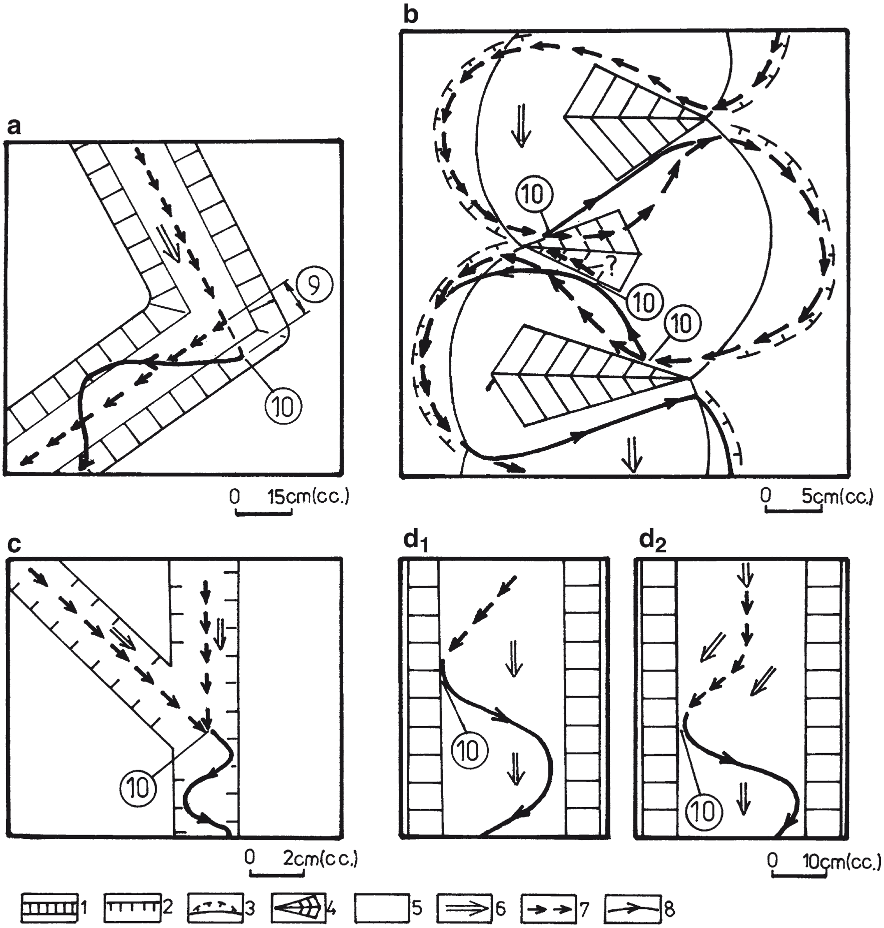


Fig. 4.43 Swinging of the channel line due to external causes (Veress, 2000b). Legend: 1 – gently sloping meanderkarrren and channel side, 2 – vertical meanderkarren side (type III meanderkarren), 3 – overhanging meanderkarren side, 4 – skirt, 5 – meanderkarren and channel bottom, 6 – dip direction of meanderkarren bottom and channel bottom, 7 – channel line, 8 – swinging of channel line due to external causes (suffering further swinging of the channel line), 9 – lengthening of channel line caused by flow inertia, 10 – location of obstacle hit by the channel line, which causes the swinging of channel line caused. (**a**) False meander, (**b**) skirt, (**c**) flowing water from tributary channel, and (**d**) meanderkarren side wall causes the swinging of the channel line (d_1 the already swung channel line hits the meanderkarren side wall, d_2 the channel like is directed by the indication of the channel bottom)

line of the rivulet downstream (it becomes meandering instead of the original straight line).

Meander terraces of the hanging wall develop if the channel line remains near the margins of this wall but does not touch the wall at all for a long lime. The cause of this phenomenon may be the shape of the skirt. Namely the channel line is forced at certain skirt shapes near the hanging wall even if the discharge of the rivulet is smaller. The other cause can be when the meanderkarren becomes narrow as it deepens. Therefore, water covers the bottom of the meanderkarren at smaller discharge too. Thus channel line stays near the hanging wall at smaller discharge but it does not reach it. A skirt terrace develops if the pattern of the channel line changes. Therefore it goes to the skirt. Hanging terrace develops as the changing of channel line takes place too. In this case the channel line does not go near the hanging wall even at maximum discharge either. In this case an inner meanderkarren or channel develops at the margin of the meander terrace. The terrace is transformed into hanging position.

The rivulet and its channel line get deeper and deeper due to the deepening of the channel. Due to the common resultant of the lateral and downward movements the channel line moves to the direction which closes the angel of the horizontal direction (see Section 2.2.5). This phenomenon is called the seepage of the channel line.

The intensity of the slippage causes the asymmetry of the meanderkarren and indirectly its development. The greater its value, the more concave the margin of the overhang wall will be. Partly the development degree of meanderkarren will be greater because its neck becomes narrow due to this process. The development degree of the meanderkarren increases only partly, because the channel does not move to the sides because of the slippage, but the wall overhangs to a greater degree at the concave margin. Figure 2.6c represents the relationship between the intensity of the slippage and the slope angle. We can establish linear function connection between the slope angle and the intensity of the slippage. But we only had few data to create the function. The smaller the slope angle is, the greater the intensity of the slippage will be. As meanderkarren deepen faster on steep slopes they can be the cause of this process. Therefore a short time period is needed for unit deepening and hence a short time is given to lateral solution.

It may be seen (Table 4.5) that the intensity of slippage due to external cause (0.2439) is greater compared to the intensity of the slippage due to internal cause (0.2928). Therefore, external causes the oscillation of the channel line to a greater degree than the internal cause.

Types of Meanderkarren

Using the morphology and the measured parameters of meanderkarren (such as the length of the curve, the wave length, development of meanderkarren width of the specific meanderkarren zone, intensity of seepage), Veress (2000a, b) and Veress and Tóth (2004) classified them into the following types: ‘looping’, ‘remnant’, ‘developing’, and ‘perishing’ (Fig. 4.44).

Table 4.5 Averages of parameters (using data measured in the No. 3, 4, 6 and 7 meanderkarren; from Veress 2000b)

Meander type	Looping	Developing			Remnant			All types	
Cause of swinging	External $n = 3$	Internal $n = 7$	External $n = 13$	All $n = 20$	Internal $n = 2$	External $n = 6$	All $n = 8$	Internal $n = 10$	External 21
Length of bend	45.75	23.5	18.6153	21.0576	27.5 (66.71)[a]	33.5833	30.54	25.5	32.6495
Wavelength	15.125	12.0	10.38	11.19	16.0 (16.87)[a]	13.8333	14.9166	14.0	13.1128
Stage of development	3.0233	2.0210	1.8992	1.9601	1.7239 (4.08)[a]	2.6181	2.171	1.8724	2.5135
Intensity of slippage	0.3336	0.1056	0.2300	0.1678	0.08 (−3.32)[a]	0.1608	0.1204	0.0928	0.2439 0.2966[b]

[a] The number in parenthesis belongs to channel No. 6 ($n = 7$).
[b] With the data of channel No. 3 ($n = 3$).

I present as example the development stages of river bends illustrating the meandering of karren (Table 4.6). We calculated various parameters of the curves of four meanderkarren in Totes Gebirge. It can be clearly seen that the values of the various parameters differ in the case of various meanderkarren type (Table 4.5). The parameters can even be varied in the case of the same types depending on the fact whether internal or external causes contribute to the swinging of the channel lines, which helps the development of these forms. It can also be seen that external cause contributes to a bigger swinging of the channel line and therefore the higher values of the parameters.

It is clear that looping meanderkarren may be distinguished from the other types by using the value of curve-length and the value of the development of the meanderkarren. The average length of the curve of looping meanderkarren is 45.76 cm, and the average value for the development of a looping meanderkarren is about 3.0.

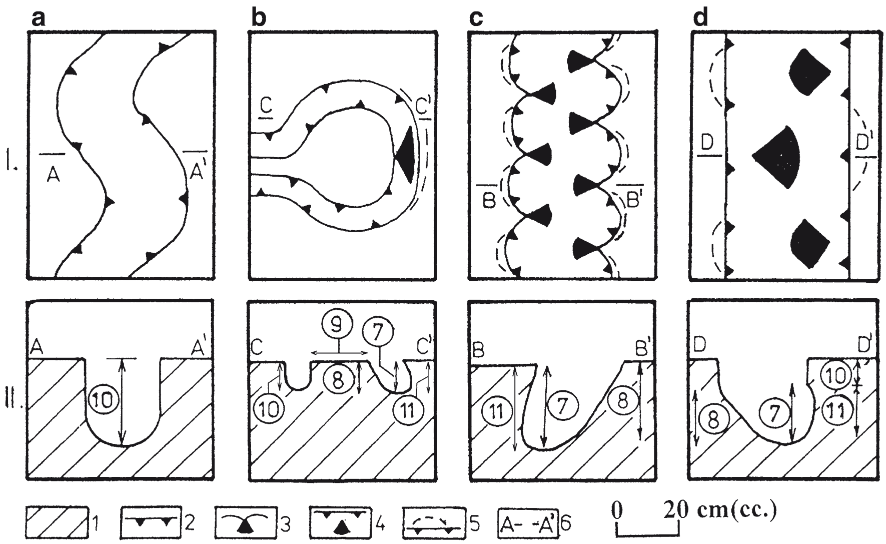


Fig. 4.44 Meanderkarren types (Veress, 2000b). Legend: ground-plan: 1 – limestone, 2 – type I meanderkarren, 3 – skirt at the margin of the meanderkarren, 4 – skirt at the lower part of the slope of the meanderkarren, 5 – overhanging wall, 6 – place of profile in cross section, 7 – overhanging wall, 8 – skirt, 9 – karren recess, 10 – meanderkarren, and meanderkarren part with symmetrical cross section, 11 – asymmetrical meanderkarren and meanderkarren part. (**a**) False meander, (**b**) looping meander, (**c**) remnant meander, and (**d**) developing meander. (I) ground-plan, and (II) cross section

Table 4.6 River bend types specified by their development (Laczay 1982)

Type of river bend	Value of β
Undeveloped bend	< 1.1
Developed bend	1.1–1.4
Well developed bend	1.4–3.5
Fully developed bend	> 3.5

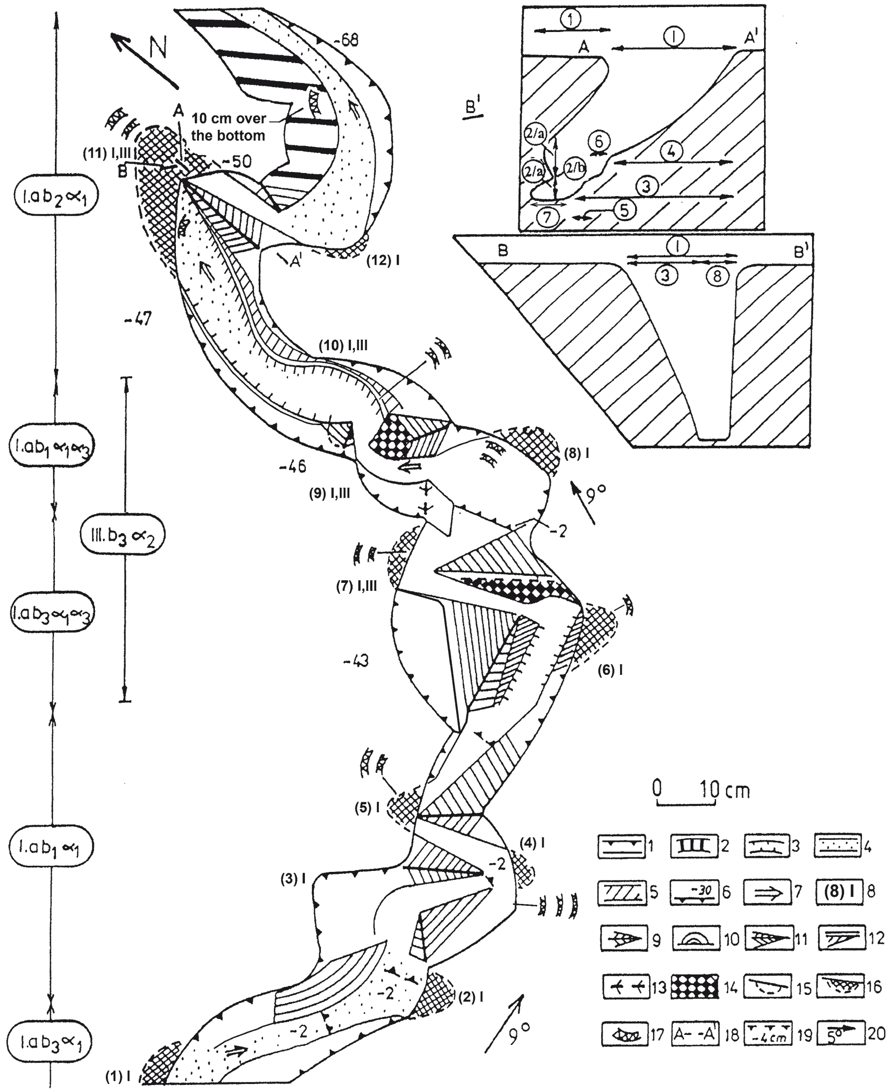


Fig. 4.45 Morphological map of meanderkarren marked 7 (research area marked 1/3, Veress, 2000b). Legend: planimetric representation: 1 – vertical or steep side wall of type I meanderkarren, 2 – gently sloping side of type I meanderkarren, 3 – vertical side wall of type III channel, 4 – plane meanderkarren bottom, 5 – terrace, 6 – depth of meanderkarren (in cm), 7 – slope direction of meanderkarren bottom, 8 – number of bend (the Roman number indicates the meanderkarren type which belongs to that special meandering type), 9 – half-pyramid skirt, 10 – half-cone skirt, 11 – asymmetrical skirt, 12 – half-skirt, 13 – non-active skirt remnant with sharp ridge, 14 – meander terrace on skirt, 15 – overhanging wall, 16 – meander terrace on overhanging wall, 17 – meander scour groove and major meander scour groove (position and size of small scour groove in the bend are not drawn to scale), 18 – position of section, 19 – solution threshold, step with depth (in cm), 20 – gradient and slope direction of surrounding rock surface. (**a**) false meander section, (**b**) true meander section (b_1 remnant meander, b_2 looping meander, b_3 developing meander), the swinging of

The average length of the curve of developing and 'remnant meanderkarren' is 21.06 and 30.54 cm, respectively, and the development value of these meanderkarren is 1.96 and 2.17, respectively (Table 4.5). When the loops that belong to the different types are compared, the difference is especially great. Thus, for example, in the case of the meanderkarren seen in the Picture 4.38 the development value is 4.27. The value of the development is 2.76 in the case of loop number 11 of the looping meanderkarren seen in Figs. 2.5 and 4.45 but this value is only 1.66 in the case of the number 3 remnant meanderkarren in the same meanderkarren.

Meanderkarren can be ranked into the looping meanderkarren type when the average length of their curves is over 30 cm and the average of the meanderkarren development value is above 2.5.

According to Veress (Veress, 2000b), the slippage of the channel line can be best characterized with the morphology of a meanderkarren because it can explain its asymmetry. The average intensity of slippage of the channel line is 0.33 for looping meanderkarren, 0.17 for developing meanderkarren and 0.12 for remnant meanderkarren.

The sinuosity and the width of the meanderkarren zone can be different for various meanderkarren types. For example, the sinuosity is 2.1 for the number 11 and 12 loops of the looping meanderkarren seen in Figs. 2.5 and 4.45 while this value is 1.7 for developing meanderkarren and remnant meanderkarren sections (Fig. 4.46, number 11, 12, 13 loops). The sinuosity values calculated by Zeller (1967) are between 1.1 and 1.7. According to Hutchinson (1996), the value of sinuosity is between 1.0 and 1.6 if the slope inclination is between 25º and 40º.

The specific width of the meanderkarren zone is 2.41 for looping meanderkarren (Fig. 2.5 and 4.45, loops 11 and 12) while it is 1.56 for remnant meanderkarren (loops 2 to 10 in Figs. 2.5 and 4.45). This parameter is considered small for remnant meanderkarren.

Looping meanderkarren will develop if the channel line swings due to a direction change in a false meanderkarren at its curvature (Figs. 4.44b and 4.47d; Pictures 4.36, 4.38 and 4.40). It may be seen that the size and the density of looping meanderkarren depend on the false meanderkarren (Fig. 4.48b, c), while in the case of remnant meanderkarren there is not such a connection (Fig. 4.48a). The length of the curve of a looping meanderkarren is large as is the width of the meanderkarren zone, the sinuosity of the meanderkarren and the intensity of slippage. On the other hand, the wavelength of looping meanderkarren is small. The oscillation of the channel line occurs in part of a false meanderkarren during the deepening of the channel. Thus this meanderkarren type develops from rinnenkarren.

Fig. 4.45 (continued) the channel line is due to an external (α) reason (α_1 false meandering, α_2 the bend or its skirt, α_3 edge of bearing meanderkarren); in cross section: I – type I meanderkarren, 1 – overhanging wall of concave meanderkarren rim, 2a – meander scour groove on side wall of concave meanderkarren margin, 2b – ridge between meander scour grooves, 3 – skirt, 4 – upper skirt remnant, 5 – lower skirt remnant, 6 – meander scour groove on skirt, 7 – meander terrace at overhanging wall, and 8 – meanderkarren bottom

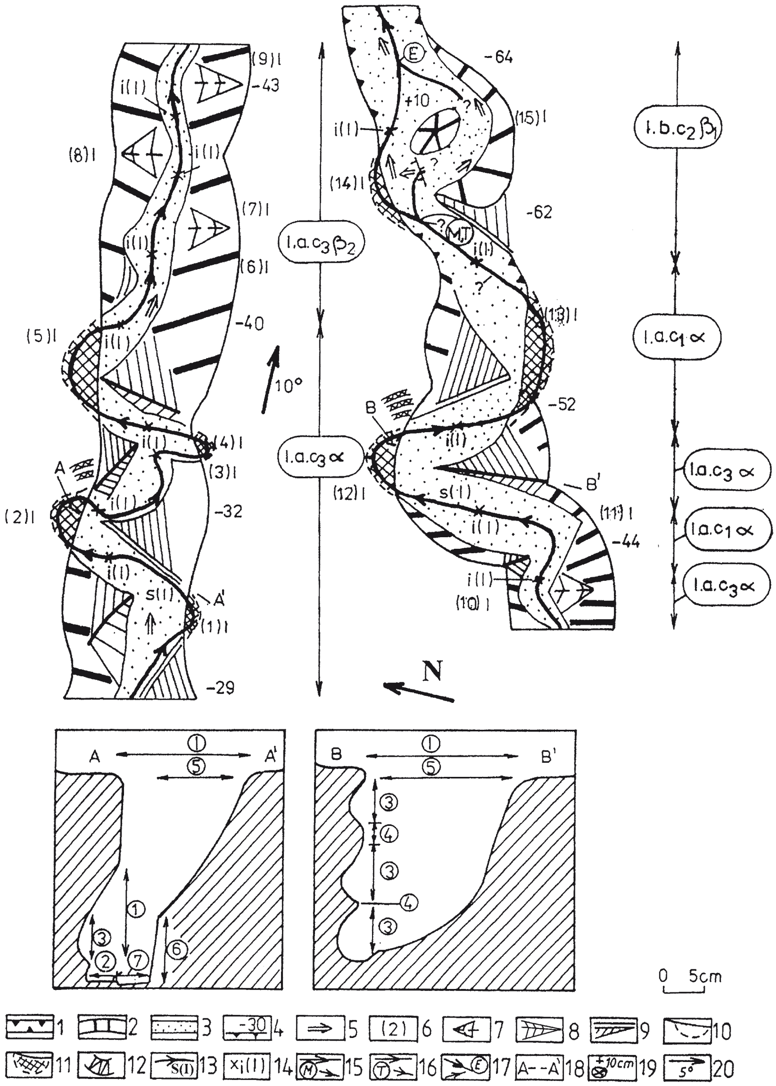


Fig. 4.46 Morphological map of meanderkarren number 4 (research area marked 1/3, Veress and Tóth, 2004). Legend: planimetric representation: 1 – vertical side wall of type I meanderkarren, 2 – gentle side wall of type I meanderkarren, 3 – plane meanderkarren bottom, 4 – depth of meanderkarren (in cm), 5 – slope direction of meanderkarren bottom, 6 – number of meander loop (the Roman number indicates the meanderkarren type which belongs to that special meandering type), 7 – developing skirt, 8 – asymmetrical skirt, 9 – Half-skirt, 10 – overhanging wall, 11 – meander terrace at overhanging wall, 12 – meander scour groove and major meander scour groove (position and size of the small meander scour groove in the bend are not drawn to scale), 13 – estimated channel line, with stream direction (number in brackets indicates type of meanderkarren in which the channel line developed) 14 – estimated inflection point (the number in the brackets indicates the inflection point which belongs to the meanderkarren type of the channel line), 15 – bifurcation of channel line connected to function, 16 – bifurcation of channel line connected

Picture 4.40 Looping meander (Valley of Triglav Lakes)

Remnant meanderkarren may develop in as its sides are dissected by curved sections. The curved sections become the concave sides of the meanderkarren, and where the curved sections meet we can see the peaks that become the convex sides of the meanderkarren where skirts develop. The peaks and skirts occur opposite to the center of the concave sections of remnant meanderkarren (Figs. 4.35, 4.44c and 4.46; Pictures 4.35 and 4.37). The length of the curve of remnant meanderkarren is respectively big and the width of the meanderkarren zone, the intensity of slippage and the development of the meanderkarren are small. For this type of meanderkarren, the swinging of the channel line begins in the rivulet on the surface before the development of the channel begins. Remnant meanderkarren can even be straight (Fig. 4.47c).

Fig. 4.46 (continued) to slippage, 17 – uniting channel lines, 18 – site of cross section, 19 – karren "inselberg" at bottom of channel (with altitude data; in cm), 20 – slope direction and degree of slope of boundary surface. (**a**) Straight meandering segment, (**b**) false meander meandering segment, (**c**) true meander segment (c_1 remnant meander, c_2 looping meander, c_3 developing meander), the swinging of the channel line can occur due to an internal (α) or external (β) cause (β_1 false meandering of channel, β_2 bend and its skirt); in cross section. I – type I meanderkarren, 1 – overhanging side wall of concave meanderkarren margin, 2 – meander terrace under the side wall of concave meanderkarren margin, 3 – meander scour groove under the side wall of a concave meanderkarren margin, 4 – ridge between meander scour grooves, 5 – skirt, 6 – vertical wall of skirt that developed due to solution, 7 – bottom of meanderkarren (note: counter line map of the meanderkarren part between parts No 10 and 15 is shown in Fig. 4.35)

Developing meanderkarren can originate if the swinging of the channel line occurs later than when the channel started deepening. These meanderkarren have symmetrical cross sections in the upper parts and asymmetrical cross sections in the lower parts. In this type of meanderkarren, the vertical side walls will start to overhang at a certain depth below the concave channel rim and begin to slope gently at a similar depth below the convex meanderkarren rim (Fig. 4.44d; Picture 4.41).

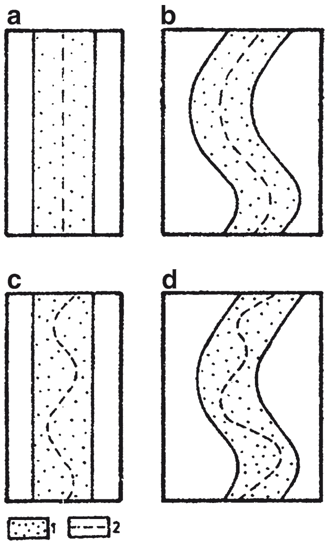


Fig. 4.47 Non oscillation (**a**), pseudo (**b**) and true (**c**, **d**) oscillation of channel lines (Veress, 2000b). Legend: 1 – rivulet, and 2 – channel line

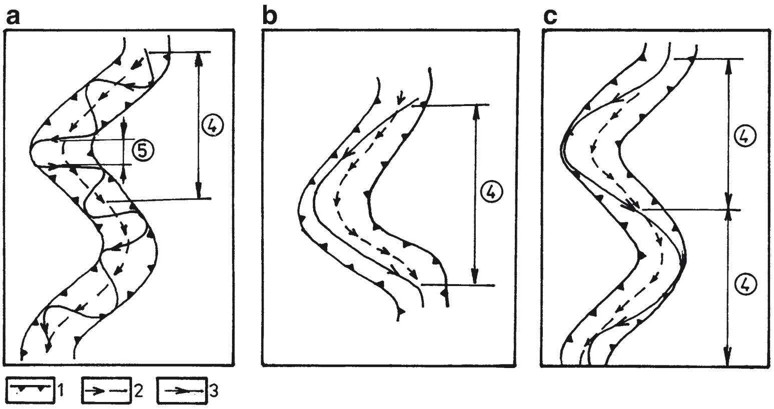


Fig. 4.48 Channel line wave-lengths at different meander types (Veress, 2000b). Legend: (**a**) on false meandering meanderkarren with meander remnant, (**b**) on false meandering meanderkarren with loop meander with simple direction change, and (**c**) on false meandering meanderkarren with loop meander with double direction change, 1 – rivulet or boundary of developing meanderkarren, 2 – original channel line, 3 – swung out channel line, 4 – wavelength of original channel line, 5 – wavelength of swung out channel line

Picture 4.41 Developing meanderkarren (area marked 3/4). Legend: 1 – composite skirt, 2 – partly detached skirt (karren "inselberg"), 3 – symmetrical meanderkarren part (without skirt and overhanging wall), and 4 – asymmetrical meanderkarren part (with skirt and overhanging wall)

Perishing meanderkarren occur rarely. This type will develop if the swinging of the channel line ends during the deepening of the meanderkarren. Therefore at the lower part of the meanderkarren a symmetrical cross section develops (Picture 4.42). On the concave side the wall of the meanderkarren as well as the skirt change from overhanging to vertical.

Meanderkarren can often be complex (Veress, 2000a, b). In this case, a smaller younger channel will develop at the bottom of a larger and older one which can even be and meandering (Fig. 4.49). When the meandering of the internal channel is similar to the meandering of the bearing channel, the process is called 'forced meandering' because the meandering of the internal channel is 'forced' by the bearing channel. This false meandering can be identical (Fig. 4.49a) or non-identical (Fig. 4.49b). It is also possible for the meandering of an internal channel to be independent of the meandering of the bearing channel (it can also be that the bearing channel does not meander). When the bearing channel (meanderkarren) is able to limit the meandering of the internal channel, the meandering of the latter channel will be "strained" (Figs. 4.49c, d, 4.50, and 4.51; Picture 4.37).

The meanderkarren found at the bottom of the channel is freely-meandering, if its curves do not touch the side walls of the bearing channel or the bearing meanderkarren (Fig. 4.49e; Picture 4.43).

Internal meanderkarren of complex meanderkarren may be remnant meanderkarren, or pseudo-forced meandering karren (Fig. 4.50a), or slipped pseudo-forced meandering karren (Fig. 4.50b). Both the bearing meanderkarren and the internal meanderkarren can be remnant meanderkarren. Those may be similarly forced

Picture 4.42 Perishing meander (area marked 3/4). Legend: 1 – gently wall (skirt), 2 – overhanging wall, and 3 – perpendicular meander wall (symmetrical meanderkarren part)

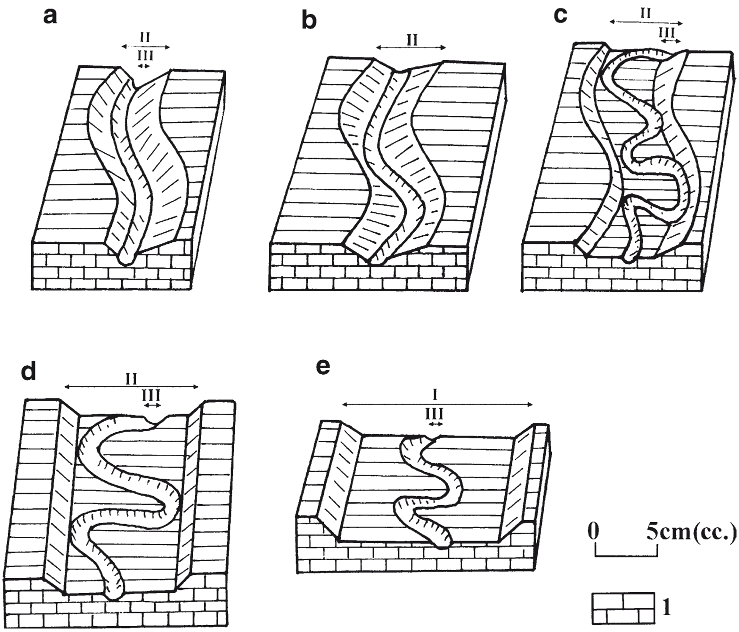


Fig. 4.49 Inherited meanders of false and true complex meanderkarren (Veress, 2000a). Legend: 1 – limestone; I, II, III meanderkarren types. (**a**) Similar from the beginning forced meandering, but similar meanderkarren, (**b**) from the beginning forced meandering; but shifted meanderkarren, (**c–d**) strained meander, and (**e**) free meander

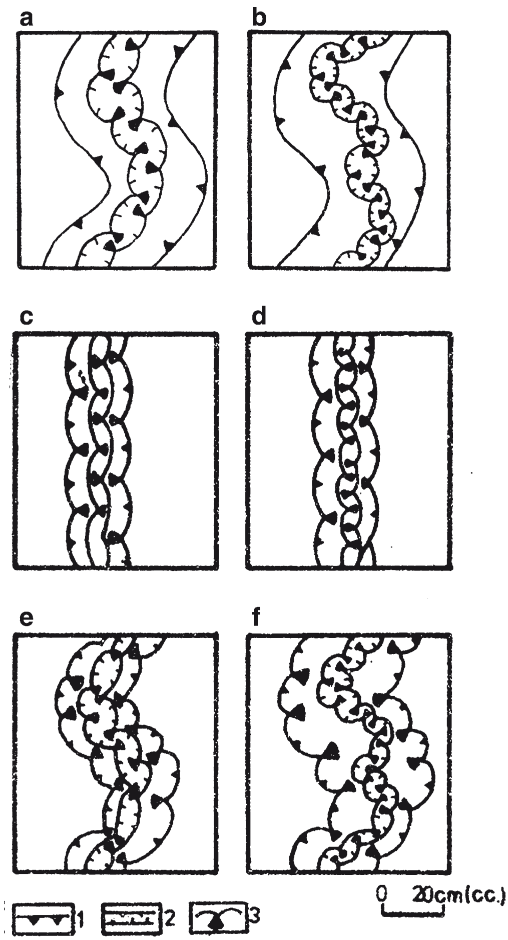


Fig. 4.50 Complex meanderkarren where the internal meanderkarren under go false and true meandering (Veress, 2000b). Legend: 1 – type I meanderkarren, 2 – type III meanderkarren, 3 – remnant meanderkarren. (**a**) Type I meanderkarren and similarly false and forced meandering type III remnant meanderkarren, (**b**) type I meanderkarren and similarly slipping false and forced meandering type III remnant meanderkarren, (**c**) type I meanderkarren with remnant meander, in which a similarly forced meandering type III remnant with meander can be found, (**d**) type I remnant meanderkarren, in which a slipping forced meander type III remnant meanderkarren can be found, (**e**) type I false meanderkarren with remnant meander, in which similarly forced type III remnant meanderkarren can be found, and (**f**) type I false meandering meanderkarren with remnant meander, in which a slipping forced meander type III remnant meanderkarren can be found

meandering remnant meanderkarren (Fig. 4.50c), or furthermore slipped forced meandering remnant meanderkarren (Fig. 4.50d). Complex similarly forced meandering remnant meanderkarren (Fig. 4.50e), or complex slipped forced meandering remnant meanderkarren (Fig. 4.50f) can also appear.

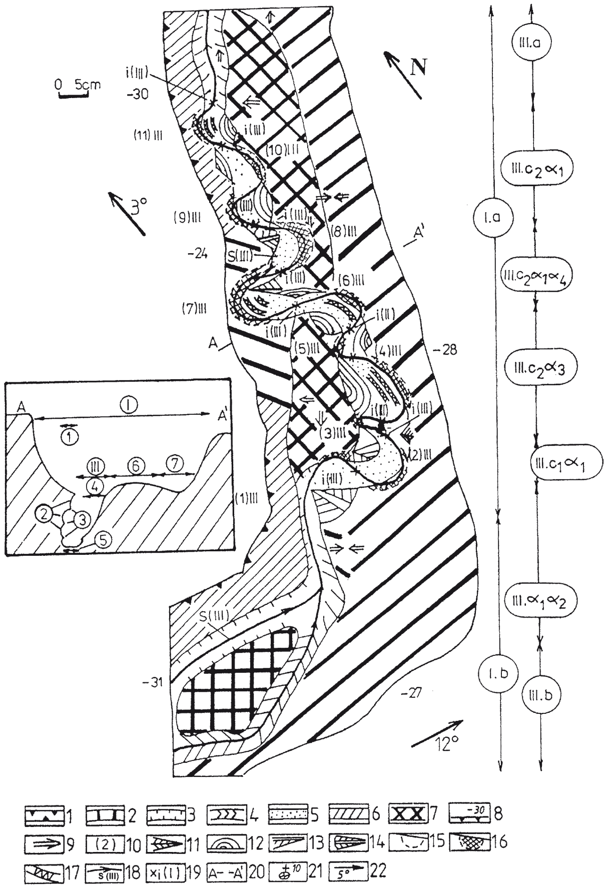
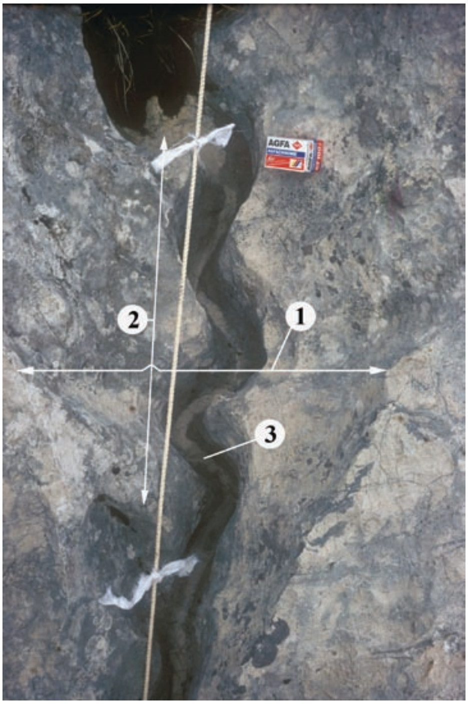


Fig. 4.51 Morphological map of meanderkarren No 3 (strained and complex meanderkarren) (from research area marked 1/3, Veress and Tóth 2004). Legend: planimetric representation: 1 – vertical side wall of type I meanderkarren, 2 – gentle side wall of type I meanderkarren, 3 – vertical side wall of type III channel, 4 – gentle side wall of type III channel, 5 – type III meanderkarren with planar bottom, 6 – karren terrace, 7 – remnant of the bottom, 8 – depth of the meanderkarren (in cm), 9 – indication direction of the meanderkarren bottom, 10 – the number of the bend (the Roman number indicates the type of meanderkarren which was given), 11 – half-pyramid skirt, 12 – half-cone skirt, 13 – Half-skirt, 14 – remnant skirt is destroyed by type III meanderkarren, 15 – overhanging wall, 16 – meander terrace at the bottom of the overhanging wall, 17 – scour groove, and major meander scour groove (the position and the size of the small scour groove in the bend is not drawn to scale), 18 – estimated channel line with current direction (the number in the brackets indicate the type of the meanderkarren in which the channel line developed) 19 – estimated inflection point (the number in the brackets indicates the infection point of the channel line which belong to a certain type of meanderkarren), 20 – site of the cross section, 21 – karren inselberg at the bottom (with altitude data; in cm), 22 – slope direction and the degree of the slope of the boundary surface. (**a**) straight meanderkarren segment, (**b**) false meander segment, (**c**) true meander segment (c_1 looping meander, c_2 developing meander) the cause of the swinging of the channel line is exterior (α) (α_1 false meander of the bearing meanderkarren, α_2 water stream of the accessory channel, α_3 bend and its skirt, α_4 margin of bearing meanderkarren), cross section: I – type I meanderkarren, III type III meanderkarren', 1 – overhanging side wall of concave meanderkarren margin, 2 – scour groove on the wall under concave meanderkarren margin, 3 – ridge between scour grooves, 4 – skirt, 5 – meanderkarren bottom, 6 – remnant of meanderkarren bottom, and 7 – older, inactive meanderkarren bottom

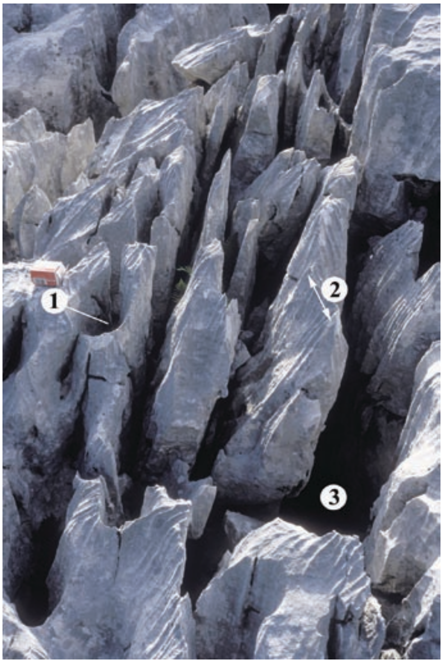


Picture 4.43 Free meandering in a bearing channel (area marked 1/1). Legend: 1 – type I. channel, 2 – type II. free meandering, and 3 – type III. channel

4.2 Karren Forms Originated by Seepage

4.2.1 Grikekarren (Kluftkarren, Cleftkarren)

In general, grikes develop along cracks and faults. Their direction is mostly the same as the strike of the bearing slope. Their length is a few metres, their depth and width are a few decimetres. There are grike systems, where few grikes are parallel to each other (Picture 4.44; Bögli 1976; Jennings 1985; Ford and Williams 1989, Ford and Williams, 2007). Ford and Williams (1989, 2007)) consider the structure of the rock (cracks) as the main cause for the lineal structure of the grikes. According to our measurements their directions are the same as the direction of the cracks of the bearing surface (Fig. 3.5; Veress et al. 2006b). According to Haserodt (1965) the development of these forms only slightly depends (if at all) on the altitude of the bearing surface. The lower altitude of their occurrences is below the elevation limit of high mountains. While the upper altitude of their occurrences can be 2,400 m, too. The grikekarren may develop on bare, or on soil-covered surfaces (Bögli 1976). According to Haserodt (1965) these grikekarren can develop when snow occurred in embryonic grikes. However, they can also develop the following way: the water seeping through the soil and non-karstic cover forms grikes. Following this, soil and non-karstic deposits are denude completely. Later



Picture 4.44 Grikekarren (area marked 1/1). Legend: 1 – destroying pit, 2 – rillenkarren, and 3 – grike

secondary soil may develop in the surroundings of the grikes and plants begin to populate the area (Feeney, 1996). According to Wagner (1950) the development of grikekarren begin where the cracks intersect to each other. Later star-like forms develop because the grikes are getting longer along the cracks with different direction. The neighbouring star forms may coalesce due to solution. The rock may be cut up totally between the grikes.

The development of grikes with soil happens as follows: the soil deepens again in the sinking grike and therefore the bottom of the grike deepens intensively (Fig. 4.52a; Trudgill, 1985).

Plant and soil may occur in the increasing grikes even on bare surfaces. In that case notches may develop at the soil level and the grike walls will be overhanging. The above-mentioned forms such as potholes, 'rock ears' and holes may develop on the grike walls under the soil level. Grikes often develop where pits grow together (see Chapter 7.2).

The grikes of bare slopes may change the characteristics of flowing water of the bearing slope particularly if the direction of the grikes and the strike of the slope are the same. The development of rinnekarren below grikes is interrupted. Those rinnenkarren parts, which are between the grikes, develop independently. Additional runnels may begin from the grikes.

Grikes are distinguished in various categories according to their width such as, narrow (a few centimetres wide), wider (a few decimetres wide) and even much wider (a few metres wide, Bögli 1976). These latter grikes are termed

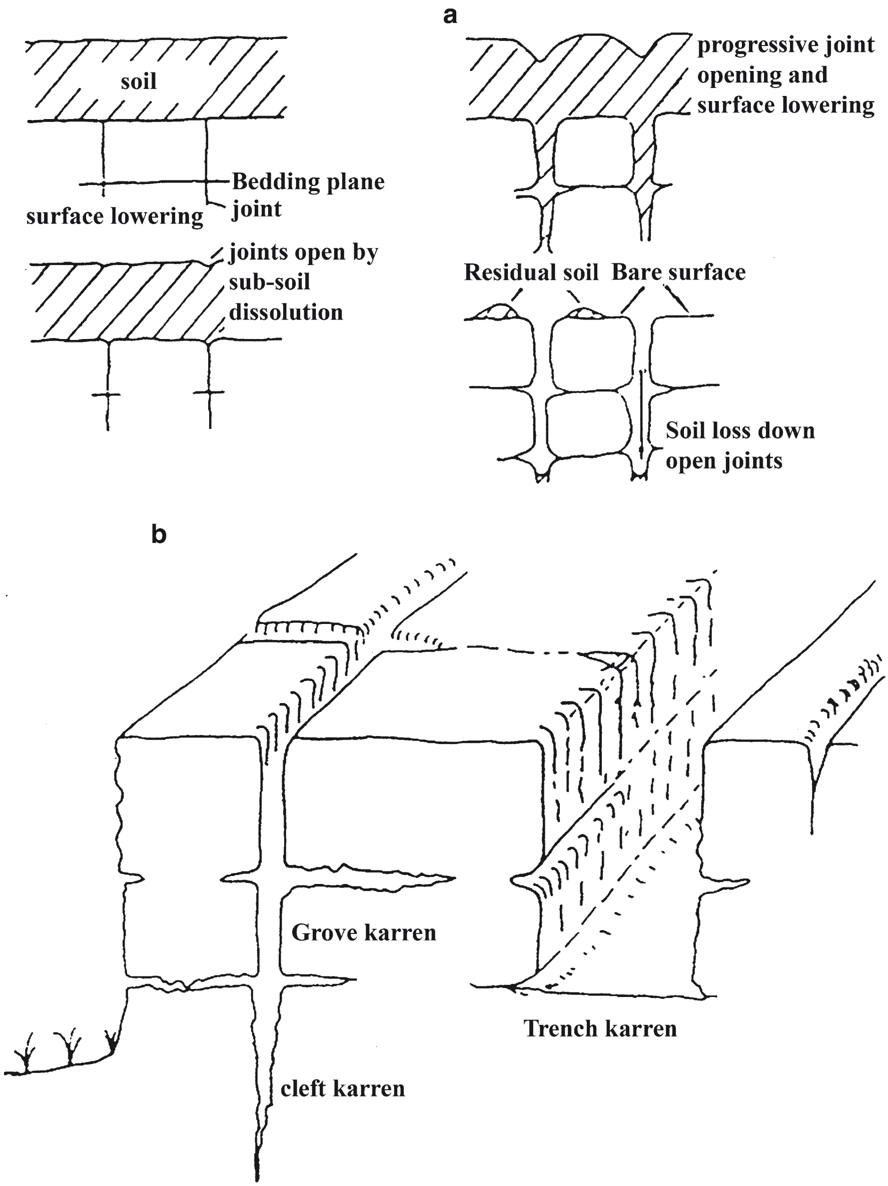


Fig. 4.52 The development of the grike (**a**) which was created by under soil solution (Trudgill, 1985) and types of grike and (**b**) according White, 1988

trench karren (Fig. 4.52b; White, 1988). Pluhar and Ford (1970) used the term 'splitkarren' for the grikes, which are few centimetres long. Grikes which are filled with soil are called 'clutter' (Howard 1963). 'The solution grooves' are features between grikekarren and rillenkaren. These forms are embryonal, small grikes, which develop of such cracks or bedding planes, which are perpendicular. They develop like rillenkarren. The cause of their development is sheet water (White 1988).

A runnel-like grike is also a transitional form. These forms have similar morphological characteristics to those of rinnenkarren. These forms remind us to grikes in the following morphological characteristics: their depth is the same in the total length of the form, their walls are vertical. They are similar to rinnenkarren in the following characteristics: pits can dissect their bottoms, their direction is the same as the dip direction of the slope and their bottoms can be made up of parts with various inclinations. They are frequent and occur in groups for example on the Assiago Plateau. They occur individually on the slopes of the roche moutannée for example in Totes Gebirge. Probably former grikes were changed into partial runnels due to the influence of flowing water in them.

Microgrikes are type of grikekarren. They are a few centimetres long. Their width and depth are of a few millimetres. They often occur in two various directions. Their occurrence is continuous basically due to their great density. They develop on such slopes, which lost their ice cover less than 50 years ago. Such areas were described by Gams (2002) from northern foreground of Triglav Peak. Namely these forms are repeated on the slopes of these areas. They develop on bare slopes, with shallow water sheet. Therefore the water does not move compared to the rock. This water development is termed as water cover by Veress and Zentai (2004). Its water creates microgrikes as it percolates into the rock (Veress and Zentai 2004).

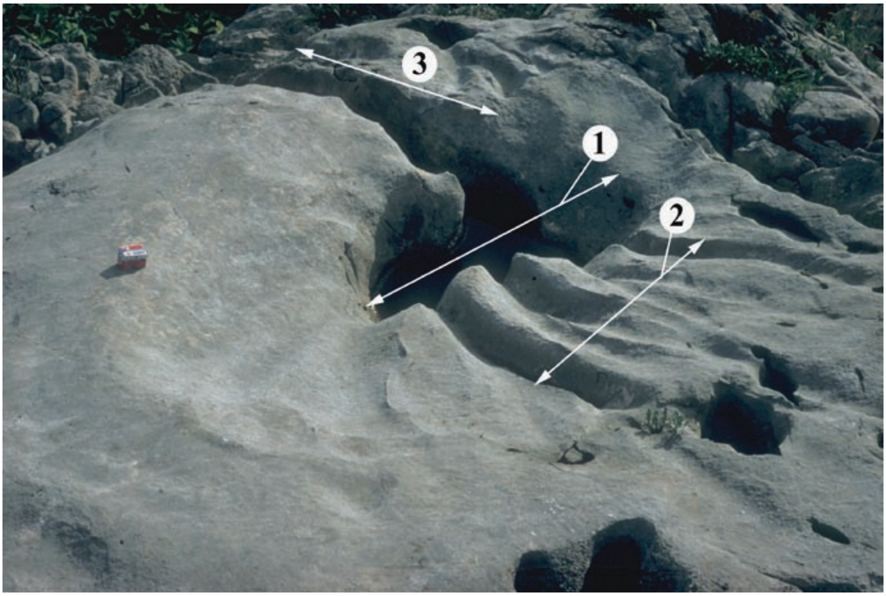
We can also distinguish another, special type of grikekarren too. This is the lattice-like complex karren form. The grikes of this form have two various directions (Picture 4.45).

4.2.2 Kamenitzas

The shape of the kamenitzas (solution pans) resembles a dish or a plate, but their form is very varied (Picture 4.46; Rose and Vincent, 1986a; Horváth and Zentai, 1995; Zwolinski, 1996). Bögli (1976) distinguished two varieties. The smaller are termed karren dish while the greater forms are called kamenitzas by Bögli (1975). Probably those forms are kamenitzas too, which are termed 'leafkarren' by Szunyogh et al. (1998). The 'leafkarren' occur at the head or at the margins of the channels (runnels). They have non-planar bottoms, their shape is stretched out (oval), their extension is great compared to depth. Their length is 0.5–1 m while their width is 5–10 cm. They are open from the direction of the boundary channel. One type of the kamenitzas varieties is the microkamenitzas. It can only be investigated with electron microscope as it is sometimes less than a millimetre across. These forms develop due to algas mostly (Smith et al. 1996).

Kamenitzas are grouped according to their morphological situation, their cross section, their morphology and their top view. According to their situation they may occur on planar surfaces (the dip of surface is mostly small), in the surroundings of

Picture 4.45 Lattice-like karren (Totes Gebirge)



Picture 4.46 Kamenitza with feeding channel and decantation channel (area marked 1/4). Legend: 1 – kamenitza, 2 – feeding channels, and 3 – decantation channel with karren canyon

rinnekarren (at the heads of the runnel and at the margins of the channel) and in rinnenkarren (at bottom of the runnel). Their shape may be a circle, or stretched out, or like the letter T and irregular. The kamenitzas can be classified according to their cross section as symmetrical (Fig. 4.53.I) and asymmetrical (Fig. 4.53.II). According to Horváth and Zentai (1995) uvala kamenitzas (Picture 4.47; Fig. 4.53.III), complex kamenitzas (Fig. 4.54.I) and kamenitzas system (Fig. 4.54.II; Picture 4.48) may develop from kamenitza. Uvalas kamenitzas are built of several part forms, which can be circular or stretched out forms or they can resemble the shape of letter T. Uvala kamenitzas can have symmetrical and, asymmetrical cross section (Fig. 4.53.III). Uvala kamenitzas develop if two or more kamenitzas coalesce (Picture 4.47). A smaller kamenitza can be found on the inside of a complex kamenitza while kamenitza system is built of neighbouring kamenitza parts (horizontally) and of internal kamenitzas (vertically).

Kamenitzas and rinnenkarren may be connected to each other as follows:

- One or several channels lead to a kamenitza.
- One or several runnels branch out (decantation runnel) of a kamenitza (Picture 4.21).
- A channel leads to a kamenitza, but it has a decantation runnel, too (Picture 4.46).

Inside kamenitzas there are scour grooves (of concentric pattern), bottom remnants kamenitza terraces (at various elevations), gap-like canyon forms (narrow

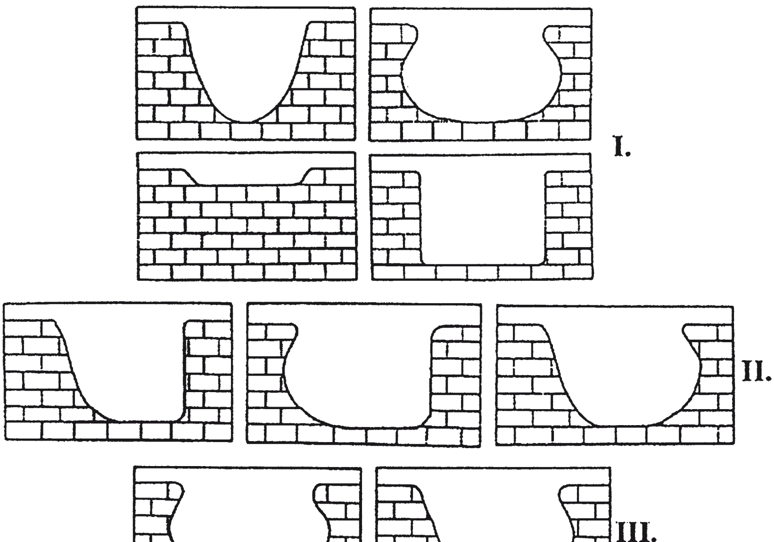
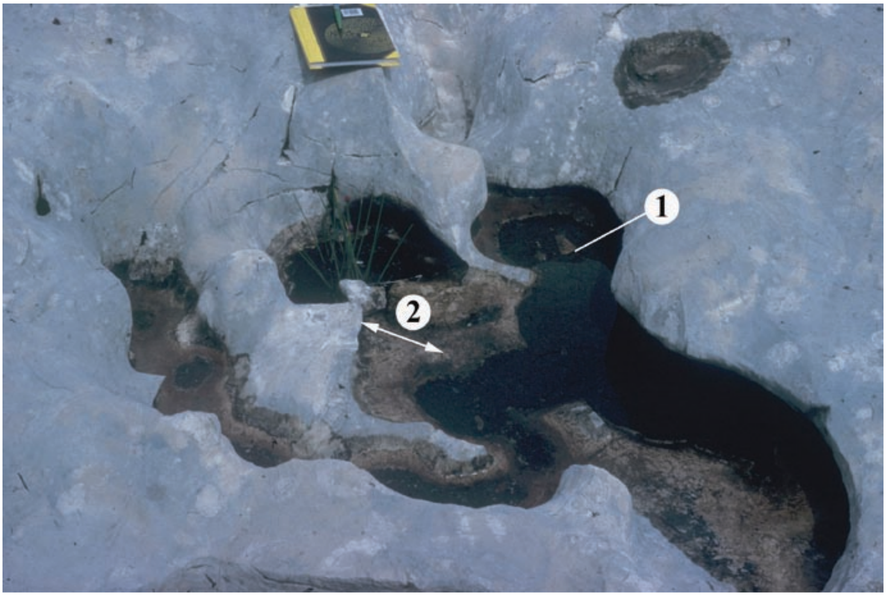


Fig. 4.53 Symmetrical (**I**), asymmetrical (**II**) kamenitzas, uvalas kamenitzas (**III**) according to Horváth and Zentai, 1995 (research area marked 1/4)



Picture 4.47 Uvala kamenitza (area marked 1/5). Legend: 1 – part kamenitza, and 2 – terrace

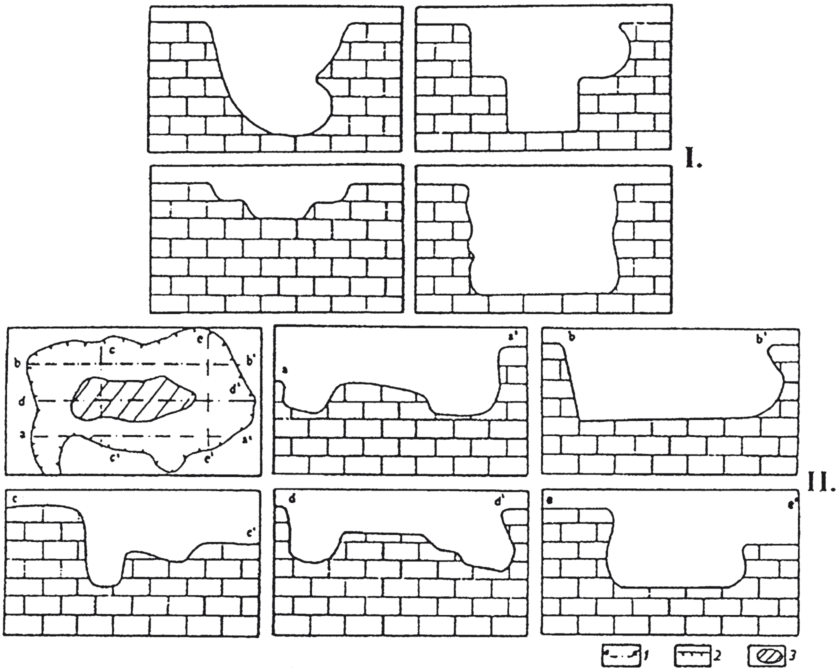
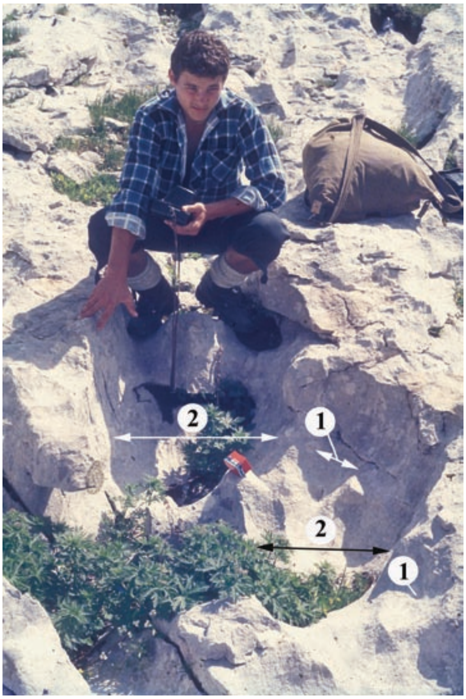


Fig. 4.54 Complex kamenitza (**I**) and kamenitza-system (**II**) according to Horváth and Zentai (1995) (research area marked 1/4). Legend: 1 – place of profile, 2 – margin of the kamenitza and its decantation channel, and 3 – higher part of kamanitza bottom



Picture 4.48 Kamenitza system with Spitzkarren (Dachstein). Legend: 1 – part kamenitza, and 2 – internal kamenitza

runnel sections with vertical side walls connected to the margin of the kamenitza), rinnenkarren and trittkarren. System of karren forms may develop at the bottom of great kamenitzas (Fig. 4.55). Such forms are spring karren channel caves, which lead the water to the inside of kamenitzas, the karren channel cave which leads the water from the kamenitza, in addition to channels, pits and internal kamenitzas.

Their development is explained not only with solution, but also with other impacts (e.g. frost weathering, Rose and Vincent, 1986a). The shape of the kamenitza may develop during lateral solution particularly if its wall is overhanging and if there is a scour groove on its wall. Jennings (1985) explained this process with the fact that the soil and the litter at the bottom of the kamenitza lead the water of the kamenitza into lateral direction. The overhanging kamenitzas are covered with soil and plants according to Horváth and Zentai (1995) in Totes Gebirge. According to them the development of the overhanging walls happens as follows: soil and plants develop, in the initially shallow and gently-sided forms. The soil and the plants can store water, thus it turns the water to the walls; therefore lateral solution can increase. The value of the pH in the water, which is greater at the bottom of the kamenitza under soil than in the water above the soil also contributes to this process. According to Williams (1968) and Rose and Vincent (1986a) the cause of the lateral solution is the precipitation of the dissolved calcareous matter due to evaporation at the bottom of the kamenitza. This 'crust' pre-

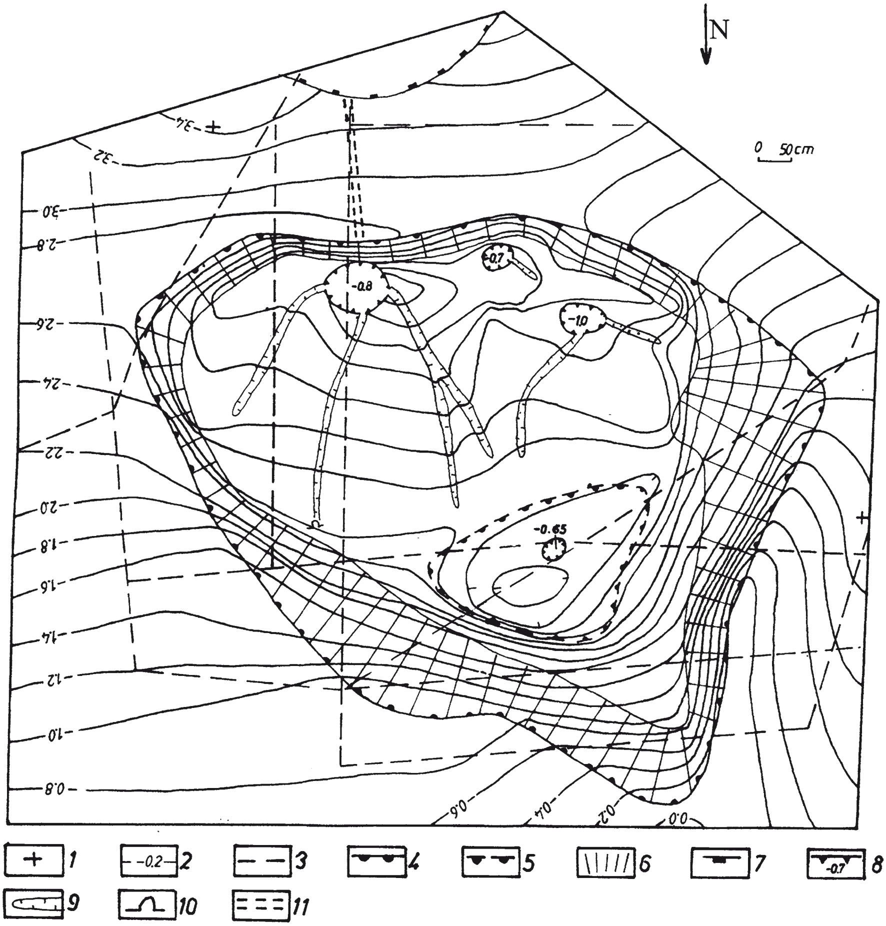


Fig. 4.55 Giant kamenitza (research area marked 1/4, Veress et al. 1995). Legend: 1 – point of theodolite, 2 – contour line in local system, 3 – joint, 4 – external margin of giant kamenitza, 5 – margin of internal kamenitza (partial kamenitza), 6 – slope of the kamenitza, 7 – schaft, 8 – pit margin (its depth in m), 9 – channel, 10 – spring karren cave, and 11 – through karren cave

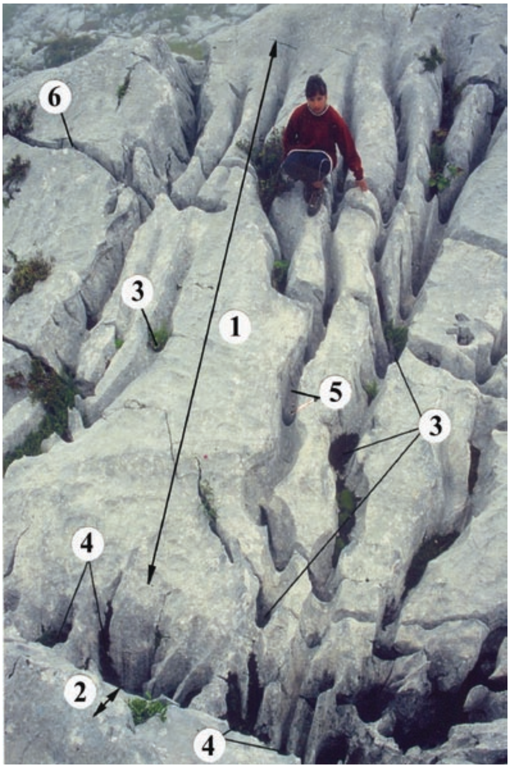
vents the seepage of water into the rock. According to the above-mentioned authors the kamenitzas of Grait-Borrow (Lancashire) developed at calcareous spar infills. If the infills parish out (due to organic acid or non-karstic effects) the development of kamenitzas are prevented or stopped because the water may seep into the rock at these places.

Scoure grooves develop during local solution, which happens at the soil level. Because these forms may develop in kamenitzas without soil, they may be created at lasting water levels too. According to Fridtjof (1954) kamenitza terraces develop from former kamenitza bottoms. Such a bottom develops at a former lasting water level. Later smaller kamenitzas develop, which denudate partly the original kamenitza bottom. This process may happen when lower water levels develop inside the form. The evolution of decantation runnels causes the development of the lower water level(s). According to Horváth and Zentai (1995) these forms develop during lateral solution on the soil patches of the former kamenitza bottoms. Widening internal kamenitza develops due to the lateral solution of the soil patch at the original kamenitza bottom. Therefore a part of the bearing bottom also denudates.

4.2.3 Pitkarren

They are tubular and perpendicular forms, several decimetres across and often more than 1 m deep, in the rock. The diameter of these forms is several decimetres, while their depth can be often greater than 1 m (Picture 4.49). Pits mostly occur together with other karren forms. They sometimes create independent population, too. Pits may develop outside rinnenkarren (shaft pits) or inside runnels (channel-bottom pits). One type of the channel-bottom pits (blind pit) develops where the rinnenkarren are crossed by cracks, which developed to grikes by widening (Picture 4.50). Those pits, which belong to this type are probably

Picture 4.49 Pitkarren (area marked 1/4)



Picture 4.50 Pits of a channel (area marked 1/1). Legend: 1 – bedding plane, 2 – head of cuesta, 3 – channel bottom pit, 4 – channel end pit, 5 – channel, and 6 – grike

blind forms. Soil and plants are found in them. Another type of the channel-bottom pits has a greater diameter and is not always blind. There is no soil or plant inside these forms. The forms develop during the subsurface capture of the runnels (subsurface capture pits). The channel end pits occur at the lower end of the rinnenkarren (Pictures 4.4 and 4.50), but their margins are at the same level with those of the rinnenkarren. Their morphology resembles that of the shaft pits. The characteristics of shaft pits are the following: their side slopes are arched and concave, dissected with half-pits and wall karren (Picture 4.51). Shaft pits represent transitions into shafts. Pits develop along cracks. Seepage water and plants at their bottoms contribute to their deepening (Ford and Williams, 1989, Ford and Williams, 2007).

Pits smaller than 1 cm, are termed micropits (Ford and Williams, 1989). The micropits are created by blue and green algaes (Folk et al. 1973). Micropits, however, also develop on surfaces, which lost their ice cover some decades ago (Veress and Zentai, 2004). Micropits occur in patches and show great density. The colour of such a surface is black and is termed 'phytokarst'. (The naming refers to the role of the plants.)

Picture 4.51 Shaft pits (area marked 1/4). Legend: 1 – wandkarren

4.2.4 Schichtfugenkarren (Bedding Grikes)

Schichtfugenkarren have several centimetres (at most) vertical extension, but their extension is some tens of metres horizontally. Schichfugenkarren are grikes, which have horizontal situation, and small dip in the rock. Probably they extend to several metres into the rock. They develop along bedding planes (Picture 4.27). They are forms of steep slopes. They are lonely forms, but they may occur above each other, too. In general wandkarren and schichtfugenkarren occur together. The development and the situation of these two forms may vary (see Fig. 4.32 and the wandkarren Chapter). The schichtfugenkarren of a wall are older than the wandkarren, which are at the same place.

Schichtfugenkarren develop where gently dipping beds outcrop along steep slopes usually. These slopes are usually the head slopes of the cuestas, which are built of heads of beds. Solution, which happens along bedding planes, plays a role in the development of schichtfugenkarren (Weber 1967). The development of schichtfugenkarren may happen in two ways. If water percolates into the rock from the bedding plane surface, it creates schichtfugenkarren during solution, as it flows along bedding planes (Fig. 4.56a). They may be produced if the water, which flows down on the wall percolates into the rock and dissolves

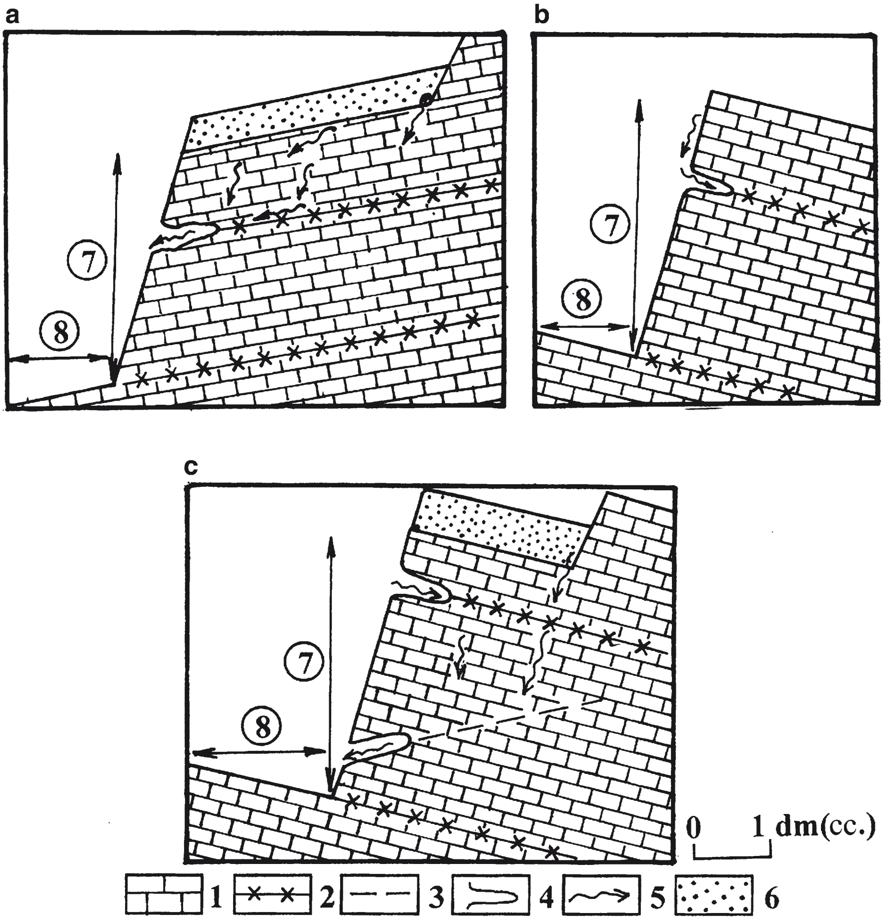


Fig. 4.56 Genetic types of schichtfugenkarren developed on heads of beds (Veress, 2003). Legend: (**a**) inclinations of the bedding plane and the head of bed are similar, (**b**) inclinations of the bedding plane and the head of beds are opposite, (**c**) inclinations of joint and head of bed can be opposite (see top and bottom parts of figure) or similar (see middle of figure). 1 – limestone, 2 – bedding plane in the rock, 3 – joint, 4 – schichtfugenkarren, 5 – infiltration of unsaturated water (see the bottom part of the figure), 6 – snow, 7 – head of bed, and 8 – bedding plane in the surface

it along the bedding planes (Fig. 4.56b). The chance of this later process is smaller because only a small amount of water can reach deep into the rock from the wall. If the dip of the schichtfugenkarren and dip of the bearing slope are the opposite of each other, the water which causes the development of the schichtfugenkarren, may percolate both from bedding planes and head slopes, too (Fig. 4.56c).

4.2.5 *Napfkarren*

These pit-like form which is wider at their lower ends develop at the lower end of soil-mantled slope. Later the soil denudates and the form is exposed.

4.3 Karren Developed Due to Rain Drops

4.3.1 *Rainpits*

They are several centimetres in depth and diameter. Their shape is circular (from above) and spherical calotte (in lateral view). They are not common, but if they develop, their density is really great (Picture 4.52). According to Jennings (1985) they are created by rain drops (e.g. falling from leaves). Probably their development is due to organic acids and hydrocarbonate solution. The organic acid and the CO_2 are produced by algaes. In the former case they develop on bare limestone while in the later case they are created where the surface is covered partly with soil patches. According to Jennings (1985) their density is very great. In this case they may coalesce with each other. They make the rock look like a sponge.

Picture 4.52 Rainpits (Assiago Plateau)

4.4 Karren Forms of Complex Development

4.4.1 Karren Cavities

These forms are seldom described in literature. Different terms are used to designate these forms, for example, cavernous subsoil weathering (Jennings 1985) kavernosen karren (Bögli, 1960, 1980), tunnel karren (White, 1988), karren shafts or wells (Ford and Williams, 2007). The karren shafts or wells develop along bedding planes or along cracks in the epikarst. Their sizes are varied (their length and depth are from several centimetres to 2–3 m), and their situation may also be varied. Their cross section tends to be circular or elliptical (Ford and Williams 2007). Probably one kind of this karren type represents 'Löcherkarren' described by Weber (1967).

Gams (1973) termed those cavities subsoil cavernous karren which have greater sizes and circular cross section and developed under soil. Slabe (1999) called the features subcutaneous tube that are filled with sediment and soil and their diameter is smaller than 1 m.

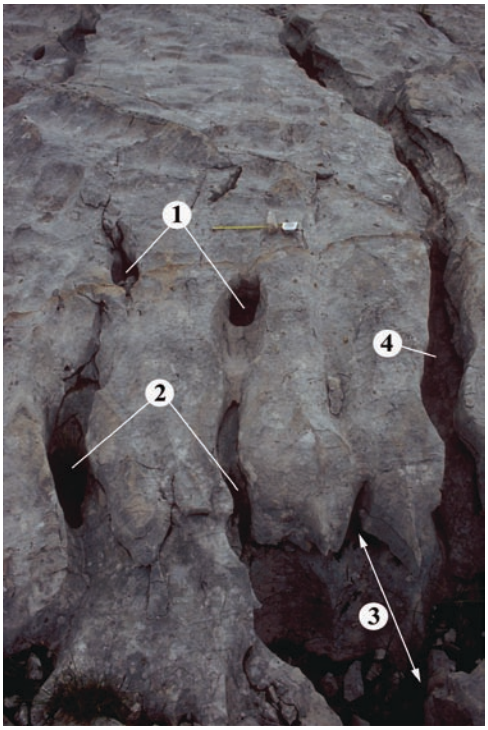
Karren cavities are mostly irregular and they have variable sizes and shapes, sometimes they are like erosional karsts caves. We use the term karren caves for these forms. They are sometimes smaller, their width and vertical sizes are of several decimetres, while their lengths are several metres.

Karren caves develop due to water seepage. First the water seepage creates a fissure-system later the flowing water increases these fissures and a karren cave is created. The development of the cave happens along fractures and bedding planes. The process may happen independently from or depends on surface solution. Karren caves may develop among surface karren forms (Figs. 4.5 and 4.55) or under channels (Fig. 4.9; Picture 4.53).

Karren caves may be swallet type karren, spring karren channel and through karren caves (Pictures 4.53 and 4.54; Figs. 4.5, 4.9d and 4.57). Swallet karren caves can lead from kamenitzas or rinnenkarren. Spring karren caves may open into a pit, a rinnenkarren, a kamenitza or a grike (Picture 4.54). Term karren channel cave is used for those karren caves which are under rinnenkarren. Swallet karren caves and spring karren caves occasionally present delta-like forms (Fig. 4.57). Delta-like swallet karren caves develop at the channel bottoms in case of regression, subsurface captures. Spring mouths which are at various altitudes on the sides of grikes belong to spring karren caves (Fig. 4.57; Picture 4.54), new spring mouth develops when subsurface capture happens in the karren cave (karren cave swallet). Probably this process may happen under other karren forms, too. It is possible that a karren cave system develops under rinnenkarren (along bedding planes where cavities developed, Fig. 4.57). The karren cave system has several forms located under one another. This type of karren cave develops mainly on gentle and great slopes. A karren cave may develop compared to any channel as follows:

- The channel situated above the karren cave does not continue towards the surface (blind channel). A pit may be found on the roof of the cave between

Picture 4.53 Sinkhole karren cave and through karren cave (area marked 1/2). Legend: 1 – type II channel, 2 – karren channel swallet (pit), 3 – through karren cave, and 4 – karren cave part which lost its roof



Picture 4.54 Spring karren cave (area marked 1/2). Legend: 1 – upper spring karren caves, 2 – lower spring karren caves, 3 – grike, and 4 – Channel. Note: the two levels of the spring karren caves indicate that subsurface capture happened in the karren cave

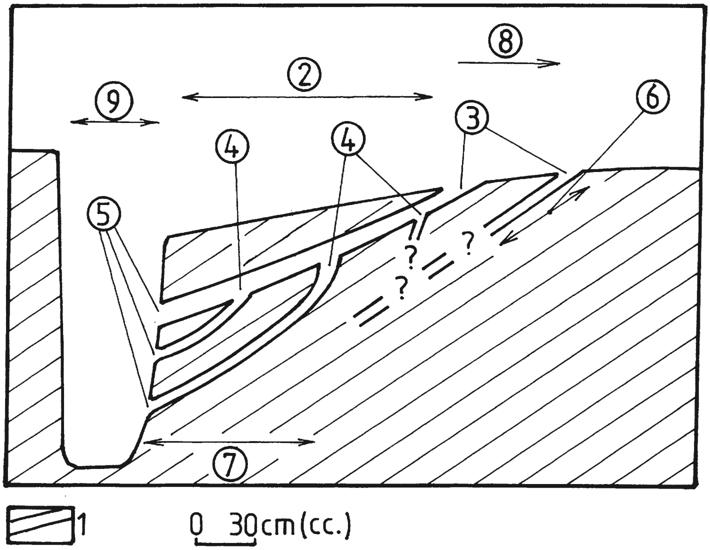


Fig. 4.57 Karren channel cave system (observation on research area marked 1/2, Veress 2000a). Legend: 1 – bedding plane, 2 – through karren cave, 3 – karren channel swallet, 4 – karren cave swallet, 5 – debouchure, 6 – swallet karren cave, 7 – spring karren cave, 8 – retreat of subsurface capture, and 9 – grike

the karren cave and the surface. The development of this form happens partly and totally due to later solution or cave in (which expands from downwards towards the surface). This form is an open-in pit. The channel of this pit was created after the development of the pit by regression of the channel (Fig. 4.58a). We use the term blind channel with pit for such a channel.

- If subsurface capture occurs on the channel, the runnel may continue beyond the point of the subsurface capture (Fig. 4.58b) and pit channel swallets develop. According to their morphology these forms are channel-bottom pits. Swallet karren cave may develop if solution happens along bedding planes, too. Then swallet karren (karren sinkhole) without pits may develop, further developing into swallet karren caves or trough karren channel caves (Fig. 4.58c).
- The places in a big channel of subsurface capture regress towards the channel head. Just like the subsurface capture sites of the epigenetic valleys on karst (Jakucs, 1977). These processes are proved by those type II and III channels which develop at the channel-bottom pits of the great type I channel. Namely the lower situated pits of the rinnenkarren bottom are not active nowadays. The pits get water from only those rinnenkarren bottom parts, which are above them. These rinnenkarren bottom parts extend the area between two neighbouring karren bottom pits. The internal channel, which leads to a lower situated pit, often continues beyond the higher situated pit too. This proves that the higher situated pit developed later than the internal channel. On the other hand, the internal channel is younger than the lower situated pit as it regressed from its lower margin.

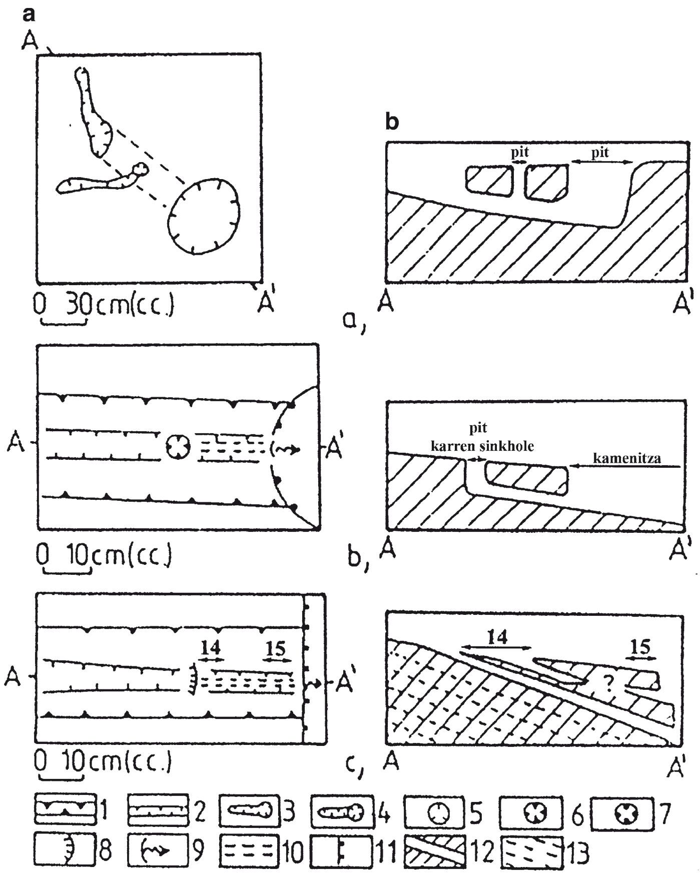


Fig. 4.58 Types of subsurface capture (Veress, 2000a). Legend: (**a**) on top view, (**b**) profile: 1 – type I channel, 2 – type III channel, 3 – blind karren channel with karren cavity, 4 – blind karren channel with pit, 5 – pit, 6 – Channel-bottom pit (karren channel swallet), 7 – kamenitza, 8 – karren channel debouchure cavity, 9 – mouth/entrance of the spring karren cave, 10 – karren cave, profile: 11 – grike, 12 – karren cave, 13 – bedding planes, 14 – swallet karren cave, and 15 – spring karren cave

Often only terraces remained from the inner channel bottoms, which regressed from the lower positioned pit from the above situated channel-bottom pits. We can explain this phenomenon with the fact that a newer internal channel developed from the higher situated pit (Fig. 4.8; Picture 4.19), which is widening to destroy a large part of the previous bottom. It could also be observed that channel-bottom pits resulting from a succession of subsurface captures, are getting gradually smaller towards the channel head (Fig. 4.8; Picture 4.19), with the explanation lies in the fact that the higher situated subsurface captures sites (pits) are always younger than the lower situated (pits) ones.

4.4.2 Spitzkarren (Pinnacle Karren, Solution Spikes)

This karren type is built mostly of such elevations tops, which are pointed and are several decimetres high (Pictures 4.55 and 4.48). A round variety of spitzkarren develops if solution takes place under the soil. Then the clints become narrow because the grikes, which are under the soil, are widening and their tops are rounded due to solution. Solution flutes may develop on the side slopes of such pinnacles (Ford and Lundberg, 1987). We observed that the elevations develop on those rock parts which are bordered by Megalodus skeletons in the Totes Gebirge. According to Bögli (1976) spitzkarren are remnant forms and present margins and top forms preserved from the original surface against grikes and rinnenkarren. Trudgill (1985) refuses this idea and claims their development is the result of a usual type of solution: a rock clint which is bordered by cracks from all directions can become smaller due to solution, along clint margins. The tetrahedral karren develop on steep slopes (Choppy, 1996). Their karren forms are built by a group of elevations of slanting axis (Picture 4.9). The tetrahedral may be considered as a particular spitzkarren, too.

Micropinnacles develop between scallops and their height is less than 1 cm (Veress and Zentai, 2004). They occur on slopes, which lost their glacier cover recently (see Chapter 4.2.1).

Picture 4.55 Spitzkarren (area marked 1/2)

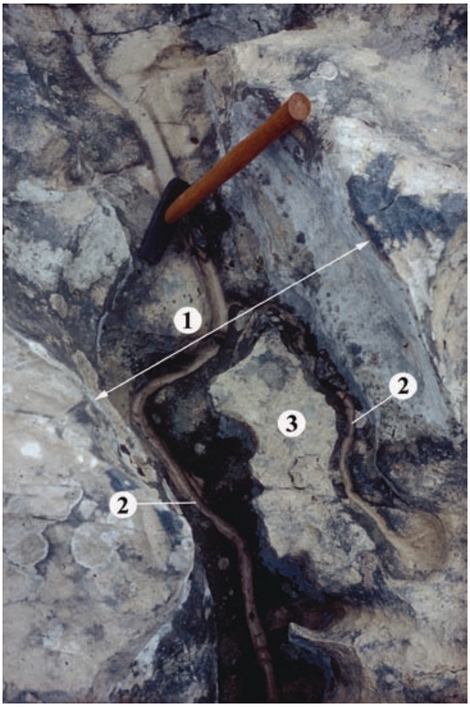
4.4.3 Karren Mounds

Karren surface parts of the karsts may denudate in various degrees as intensity and the time period of solution vary, too. We use the term karren mounds for those forms which do not denudate or only denudated in a smaller degree compared to their surroundings. Karren tables, karren inselbergs and karren monadnocks belong to this type. A karren table develops if a boulder is transported on the limestone surface (Picture 4.56). The limestone is not dissolved under the boulder, while the surroundings of the boulder are affected by solution. According to Bögli (1961) karren tables denudate due to karren formation and frost weathering. The flat part of the karren table may be absent due to its denudation, or sliding of the boulder. The legs create hummocks of various height (remnant mounds).

Karren inselbergs and monadnocks are surface remnant and formed when runnels are connected to each other, as their surroundings deepen due to linear solution. Thus karren inselberg and monadnocks are remnant surfaces. Such remnant surfaces are also classified according to the ways in which they are separated from their surroundings.

The altitude of the monadnocks is concordant with the surfaces they were separated from karren formation may occur on their surfaces. Karren formation may have happened before the forms become separated (earlier karren formation on monadnocks) or after separation (later karren formation on monadnocks). Bottom monadnocks develop at the bottoms of older karren forms. Channel-bottom monadnocks are more frequent (Picture 4.57). In this case the remnant surfaces develop at the bottoms of the channels.

Picture 4.56 Karren table (area marked 1/5)



Picture 4.57 Bottom karren inselberg (area marked 1/2). Legend: 1 – type I. channel, 2 – type III. channel, and 3 – bottom inselberg

The altitude of the surfaces of the karren inselberg decreased during separation. Surfaces, which were lower than their surroundings before their separation are also considered karren inselberg. Bottom inselbergs may develop at the bottoms of the channels, and of meanderkarren (Figs. 4.35 and 4.46).

When neighbouring channels are widening the remnant surfaces between them may denudate to narrow karren ridges (ridge inselbergs). Peninsular inselberg may develop when the remnant ridges between the channels are not separated from their surroundings at their upper ends.

Remnant surfaces may develop, if the water drifted by the wind cannot dissolve the surface in the same way. We do not know about the existence of such forms in high mountains. They may occur in areas, which are in high mountain environment and where velocity of the wind is great (Diego de Almagro Island). The forms were described by French researchers (Jaillet et al. 2000) as karren mounds developed in wind shadows (aeolian karren ridges). We distinguished two types of such forms: tied dune karren inselberg and whale-back dune karren inselberg (Veress et al. 2006d). The tied dune karren inselberg develops behind a boulder on marble surface. The water drifted by the wind does not reach the area sheltered from wind by the boulder. Therefore, solution does not affect this area, whereas it dissolves the area outside the wind shadow. The whale-back dune karren develops if the wind blows the water along the depressions of the glacier (glacial strial) and solution occurs there. The surface part, which is surrounded by the rivulets, may be dissolved by rainwater only. Therefore mounds bordered by rivulets, emerge in a spindle-like shape.

4.4.4 Heads of Bed Karren

Such features are solution remnants of escarpment series. Grikes and pit rows develop along the bedding planes of (sub) vertical beds during solution and leave behind bed remnants. In the English literature they are termed bedding grikes (Ford and Williams, 1989, Ford and Williams, 2007). This karren type develops both on bare slopes and under soil and may turn into pinnacle karst as the escarpment denudate into narrow ridges because of the widening of the bordering grikes.

4.4.5 Clints, Clasts, Karrennasen

The rock body, particularly if it is thinly-bedded is fragmented during karren formation. If the rock mass is dissected along bedding planes, it is termed clints. If the size and the shape of the debris are irregular, it is termed clast (Trümmerkarren, shillow). If the debris, which develop during karren formation, becomes rounded, it was termed karrennasen by Bögli (1960) and Jennings (1985). These forms are remnants of karren formation.

4.5 Karren Features Development Due to Organic Acids

4.5.1 Root Karren

Root karren are tubes, cavities, channels in the rock, created by organic acids produced by plant roots. They mostly occur along the roots of trees in broad-leaved forests. With altered vegetation due to climate changes, root karren may be transformed considerably. Other plants (pine, *Pinus mugo*) may develop in the root karren of deciduous forest. If root karren lost their soil they are destroyed (because of frost weathering), or they turn into other karren forms (e.g. pitkarren).

Chapter 5
Karren Assemblages

Abstract In this chapter we discuss the karren assemblages of the karst of the high mountains that we discovered: grikekarren-rinnenkarren, rinnenkarren-grikekarren(s), rinnenkarren-pit, rinnenkarren-grike, wall karren-schichtfugenkarren and pit-grikekarren assemblages. We also analyze the type of denudation on the areas of the karren assemblages. Furthermore, we present the karren denudation of glacier valley slopes.

Keywords Karren assemblages • Local solution • Denudation • Bedding plane

Karren assemblages and systems of forms were distinguished by Bögli (1976, 1980). He ranked spitzkarren, flachkarren, karren table to karren assemblages, while karrenfields, and schichttreppenkarst belong to the systems of forms. The following karren assemblages and giant karren are distinguished in the present literature (these forms are later termed karst).

Flachkarren are gently sloping surfaces, on which various karren forms (e.g. rinnenkarren and grikes) are created (Bögli 1980). Limestone pavements develop on with gently dipping strata. Its surface is separated into clints by grikes (Williams 1966; Vincent 2004). They are surfaces truncated by glaciers. Kamenitzas, decantation runnels and pits occur on the clints of the limestone pavement. The karrenfield is a karren surface created on greater and steeper slopes of a few 100 m of extension.

The naming of karren has to change for karst, if karren predominate the whole landscape. Schichtrippenkarst is a feature, characteristic of high mountains (see below) with rock strata of steep dip. Such a feature is created when the glacier destroys a surface creating steps and karren (Bögli 1960) Schichttreppenkarst are termed by Bögli (1980 where beds are thinner and clints are dissected by frost wedging and root growth.

Further, karst types can be mentioned, which are created from various karren. Thus, cryptokarst described by Salomon et al. (1995) is composed of large karrenfields under complete soil and vegetation cover. The stone forest consists of an emerging rounded stone 'teeth' (Chen et al. 1986), developed under

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tropical climate over a longer period. This karren assemblage is composed of towers and joined pits in tropical areas. The tsingy, characteristic of Madagascar, is a karst feature also developed under tropical climate. The tsingy is composed of giant grikes and clints, various pinnacles and ridges (Rossi 1986; Middleton 2004; Veress et al. 2006a, 2008a). Perna and Sauro (1978) described ruiniform karst, which developed under soil and has wide grikes which are separated by clints which are not sharped into pinnacles. Landscapes with variously developed (and large size) grikes are termed corridor karst (Jennings and Sweeting 1963), labyrinth karst (Brook and Ford 1978; Brook and Feney 1996). These karst types do not necessarily occur in high mountains. The grikes of the labyrinth karst form squared valleys and closed depressions in the later stages of their development. This karst type occurs mostly in tropical, temperate, desert and semi-desert areas and develops on limestone, dolomite and sandstone surfaces. The arrête and pinnacle karst developed under tropical climate show pinnacles a few metres high (Willford and Wall 1965; Williams 1971; Osmaston and Sweeting 1982).

A glacier valley is dissected by step boulders if it is aligned in the same direction as the strike of the beds and the bearing rock is well bedded with slanting beds. It can also occur that dip direction of the beds is similar to that of the valley slope. In that case, a front slope is created, where the bed planes end, a series of bedding planes evolve. The beds of the bedding plane surface tilt towards the direction of the beds of the front slopes. Classical cuestas develop at the bottom of the valleys and on valley slope parts whose direction is opposite of the dip direction of beds. Any bed (or bed group) tilts towards the front slope, which in turn covers the beds. This system of forms, which developed during karren formation of the surfaces is termed 'Schichtrippenkarst' by Bögli (1976. Karren formation on surfaces, which tilt concordant or discordant related to the dip, may differ considerably. Runnels end at bedding planes if they are found on beds whose dip direction is the same as that of the valley slope. They lead to grikes or pits which are on the bedding planes. The front slopes do not undergo karren formation or its intensity is small because they may overhang. Where the dip direction of the beds is discordant with the valley slope on schichtrippenkarst, the channels of the slope with bedding planes lead to pits and grikes which developed along the lower margins of the front slopes. Runnels contribute to the development of pits and grikes because water flow leads to them. But the grikes also affect the karren formation on bedding planes. Due to their deepening, the altitude difference increases between the surface of bedding planes and the bottom of the grikes. Therefore, the velocity of the water flow increases on the bedding planes (Veress 2000d). Such cuesta surfaces may develop on surfaces where the dip directions of the beds and those of the valley slopes are concordant, even if karst forms, for example dolina, developed there (Fig. 5.1).

Simple and considerably long and (mostly straight) bearing slopes favour the development of karren assemblages. Table 5.1 presents the types and main characteristics of karren assemblages (Veress 2000d, 2003).

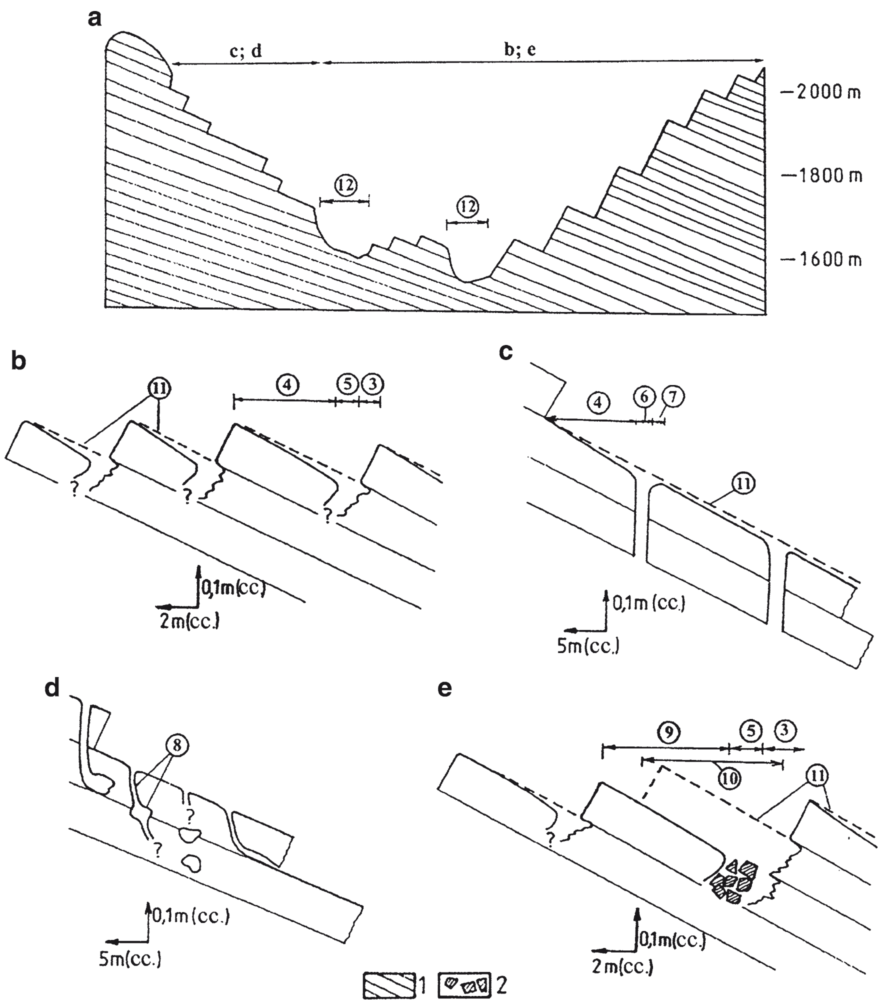

Fig. 5.1 Some types of karren surface development (Veress 2000d, transformed). Legend: 1 – bedding plane, 2 – blocks of stone formed by cut up of karren a beds, 3 – basset slope of bedding escarpment, 4 – bedding plane slope of bedding escarpment, 5 – karren assemblage of pit and grike, 6 – fissure, 7 – ridge of karren origin, 8 – caverns and passages of karren origin (karren cavities), 9 – bedding plane surface of complex origin (both glacial and karren), 10 – bed ruined/destroyed by karren formation, 11 – original surface, 12 – paleodoline or rock basin (**a**) cross-section of a glacial valley, (**b**) surface denudation on neighbouring bedding planes, (**c**) localized surface denudation on the bedding plane, (**d**) forming of caverns, and (**e**) intermittent surface and bed denudation

Table 5.1 Types and characteristics of karren assemblages (Veress 2003)

Karren assemblages	The bearing surface: Its altitude (m)	The bearing surface: Angle of slope	Development environment	Denudation of rock
Grikekarren–rinnenkarren	1,600–1,800	Small, medium	Under soil, or bedding plane surface, where is bordered by soil	Total bed
Rinnenkarren–grikekarren	1,600–2,100	Medium	Under soil, or bedding plane bordered by soil or at the boundary of beds	Surface of bedding planes, or total bed
Rinnenkarren–pit	1,800–2,100	Small, medium	Surface of bedding planes	Cavity development
Rinnen karren–grike	1,800–2,100	Medium	Surface of bedding planes	Cavity development, surface of bedding planes
Wall karren–schichtfugen-karren	1,600–2,100	Great	Bed head	Regression of the surface of the bed heads
Pit–grikekarren	1,600–2,100	Small, medium	At the lower margin of bedding planes surfaces	Shortening of bedding planes surfaces

5.1 Types of Karren Assemblages

- Grikekarren–rinnenkarren karren assemblages

Primarily, it consists of grikes whose direction is identical with the strike of the slope. Grikes developed along cracks. They develop from pits, which are stretching towards to the strike direction of the slope. We can distinguish many transitions between the pit forms and grike forms. The latter are several decimetres wide and of variable depth ranging from a few decimetres to 1–2 m. Solutional notches and niches occur on their side walls along the bedding planes.

Remnant surfaces occur between grikes aligned down slope. The remnant surfaces are dissected by small, straight runnels whose length is of several decimetres. They are relatively wide up to 1 dm compared to their depth, which is less than 1 dm. Their density is high. Ridges between the runnels may be gently rounded (rounded karren). The runnels are not complex. Other karren forms (e.g. pits) or kamenitzas are absent from their internal parts and their surroundings. Some runnels developed from grike to grike and many cross the grikes and continue beyond them. These runnels must have developed earlier than the grikes.

These assemblages developed on the lower parts of glacier valleys on surfaces with bedding planes between the altitudes of 1,600 and 1,800 m. Soil and plant patches occur in their surroundings. Such assemblages probably began to develop on bare surfaces from where glaciers retreated. Later, karren formation went on under the soil in these places. Hence their development continued even after soil and plants were destroyed. Since grikes are filled with soil and plants, runnels which are dissected by grikes might have been created before the development of the soil. While the development of the grikes began under soil cover, ridges may also have been reformed under soil covering. The runnels, which are between the grikes might develop after the denudation of the soil. The solution forms on the walls of the grikes along bedding planes were also created at the levels of soil accumulation after the soil was removed.

- Rinnenkarren–grikekarren assemblage(s)

The lengths of the runnels are several metres and their depths and widths are several decimetres; these features' direction extend in down slope runnels are simple, but their form may be complex, too. Type III channel occurs at the bottom of the bearing channel. The channel sometimes coalesce (see below).

It is important to note that runnels of this assemblage occur between two beds on the surface of the bed floor. The runnels of the bed floor are fed by water, which flows on the outcrop parts of the bearing bed but they are also fed by rain water fallen on the topmost bed via grikes and pits.

Grikes may also develop along the dip strike direction of the slope, but the former are more common. Strike direction grikes cross the runnels. Channel bottom pits often develop at the cutting points of the runnels and grikes. The number of the pits may be also considerable. The width of the grikes is not considerable. It is usually between 1 and 10 cm.

The morphology of the surface between the runnels is varied. If runnels are smaller, the surface between them is planar. If they are larger, rounded ridges are formed from the original surface. We observed that the planar remnant surfaces change gradually into rounded ridges downwards along dip direction of slope. Therefore, development of the rounded parts may also happen by the widening of the neighbouring runnels and not only by under soil solution.

The water of the bearing surface of this karren assemblage reaches the rock through pits and grikes, along the lower margins of the steps. According to our observations, this assemblage may occur anywhere in the bearing surface between the altitude of 1,600 and 2,100 m (asl.). Soil and plant patches can often be seen in the surroundings of these assemblages.

Such assemblages often occur together with grikekarren–rinnenkarren assemblages. We observed these two kinds of assemblages near each other, found in patches and mixed in each other's neighbours.

- Rinnenkarren–pit assemblages

Here runnels are long and several decimetres deep. Their depths are usually greater than their widths. The runnels are often connected to each other and they create runnel systems. They may be often false meandering or true meandering. The morphology of the runnels is varied: if complex, kamenitzas, basins, occur at their bottoms or channel-bottom pits and channel end pits are found.

The ridges between the runnels are not rounded. 'Leafkarren' (Szunyogh et al. 1998), trittkarren, rillenkarren and spitzkarren occur on the surface parts between the runnels. These forms are spread almost continuously. The density of the forms proves that solution is (almost) superficial on the surfaces between runnels. Because these remnant surfaces are parts of a planar surface, probably created by superficial solution during the denudation of the original surface. Karren tables (few decimetres in size) attest to superficial denudation.

These assemblages occur between the altitudes of 1,800 and 2,100 m (asl.). But they can also occur at the same altitude of grikekarren–rinnenkarren assemblages.

Two varieties of this type can be distinguished. The runnels are less deep and their sides are less steep if the angle slope is greater. Kamenitzas and trittkarren are less characteristic on steeper slopes. Runnels are deeper and have steeper sides if the dip of the slopes is smaller. Kamenitzas, trittkarren and smaller channels (they are some centimetres wide and deep) often occur on ridges between greater channels.

- Rinnenkarren–grike assemblages

These assemblages occur on large bedding plane. Here runnels are long. The total length of such a runnel system is considerable. The morphology of the runnels of the runnel systems is identical with that of runnels of rinnenkarren – pit assemblages. The runnels are connected to grikes with considerable width. (These grikes are not karren forms.) The surface of the bedding planes is dissected by grikes resulting in surface parts which show independent karren formation (Veress et al. 1996a). On their area smaller units (karren cells) may develop, which are described later. Such assemblages occur between the altitude of 1,800 and 2,100 m (asl.).

- Wall karren–schichtfugenkarren assemblages

These assemblages occur on steep slopes, which are built of bed heads. Wall karren , which are spread between schichtfugenkarren or crossed the schichtfugenkarren are characteristic of these assemblages. They have various length, width and depth.

Such assemblages are very varied in altitude and may occur anywhere from 1,600 to 2,200 m. They occur at lower altitude (e.g. near 1,600 m) where soil and plants (e.g. *Pinus mugo*) can be found at the upper margin of the bearing slopes. With increasing elevation the assemblages can occur continuously and repeatedly even where the soil is absent.

- Pit–grikekarren assemblages

These assemblages develop at the lower margin of slopes with escarpment. The assemblages are widespread between 1,600 and 2,100 m. Pits connected by grikes of various width dominate the less developed variety of such assemblages. The direction of the grikes coincides with the strike direction of the slope. The runnels on the bedding planes of the slope are connected to pits. If the assemblages are more developed, the pits partly or totally may coalesce and numerous windows and natural bridges emerge. The walls of the grikes are overhanging. The grikes may be often widening downwards. The runnels shatter the pits and the margin of the grikes because they cut deep into the surface of the slope with bedding planes. ('Comb karren' develop during the process.) This form is termed 'comb karren' by Szunyogh et al. (1998). The limestone is separated into debris and boulders because of the coalescing of the karren forms. A zone of debris develops during the process, which is a few metres wide. Some boulders derive from the escarpment, but mostly from bedding plane. The boulders develop with the breakdown of the rock of the grike walls, concerning breakdown of the projecting parts of the 'comb karren'.

The rinnekarren–grikekarren, the pit–grikekarren and the wall karren–schichtfugenkarren assemblages develop only on schichtrippenkarst. While the grikekarren–rinnenkarren, the rinnenkarren–grike and the rinnenkarren–pit assemblages may develop on non-schichtrippenkarst, too.

5.2 Surface Development on the Area of the Assemblages

The rock may denudate during karren formation along the slope with escarpments (these are the front slopes), or along bedding planes. The slope with head of beds backsteps as wall karren develops on it (This is a direct cause.). This process may happen when the height of schichtfugenkarren increases. This phenomenon contributes to the collapse of the rock. (This is an indirect cause.) The development of the pit–grikekarren assemblages causes the regression of slope with escarpment and the shortening of the surface bedding plane, too.

The rock may denudate during the karren formation of the surface with bedding plane along its surface, when karren cavity develop along a single bed.

The superficial denudation may happen uniformly or locally on various areas. The uniformly superficial solution happens on bedding planes with small width of the 'Schichtrippenkarst', as rinnenkarren–grikekarren assemblages develop on such surfaces. Denudation may show various degrees in case local solution. Namely, the angle of the slope increases downwards on such bedding planes, where rinnenkarren–grikekarren assemblages develop (Fig. 5.1b). Therefore, the characteristics of the original planar slope change. The slope is transformed giving way to the development of various karren zones on the slope (see Chapter 6). The karren formation and karren forms may have different ages. The age of the karren forms decreases towards the lower part of the slope. Namely due to the greater surface denudation on the lower part of the slope, the already existing karren forms can be destroyed and newer features can develop on their sites.

Local solution may happen on surfaces with bedding plane on non-schichtrippenkarst where rinnenkarren–grike assemblages develop. The local solution proves that steps develop at great-sized grikes. The height of these steps is of several decimetres. The dip direction of their surface is opposite the dip direction of their face with bedding planes (Fig. 5.1c;Veress et al. 1996a). This surface development type is characteristic primarily of the non-'Schichtrippenkarst'.

The matter of the rock decreases during the development of cavities. This process does not result in the denudation of the surface (Fig. 5.1d). The phenomenon occurs where pits and karren caves develop as their development is continuous at the bottom of the channel.

The lower boundary of the cavity development is not known. Probably the process goes on to several metres into the rock if it has great thickness and it is well dissected with cracks. In this case the surface which is glacier formed can remain unchanged. Denudation of the surface shows small degree that can be dissected with channels in a small degree too.

If the rock has thin lamination, cavity development can only reach a smaller depth. The karren caves and channel which are above them may coalesce into each other, and rock, which suffered cavity development collapses. In the first case the dissection of the bearing surface increases, while in the latter case it is separated into boulders. If the rock is separated into a boulder then karren formation of the surface stops completely. This surface development with karren formation occurs on 'Schichtrippenkarren' and on non-'Schichtrippenkarst' too. But it is also true that it does not occur often, and its occurrence is not considerable.

The denudation of the beds happen if karren formation occurs on the surface with bedding plane, which is between the top set bed and the floor bed. Rinnenkarren–grikekarren may, develop in this place. The grikes, the pits and the runnels, which cross the top set beds, dissect them into various parts. The cutting of the top set beds continues due to frost weathering and insolation weathering. Smaller-greater debris may stay at the same place, if the dip of the surface is smaller, or if front slopes bounder the surface with bedding planes. Pit–grikekarren assemblages develop at lower margins of the front slope and even the presence of front slopes cannot slow the process. The forms of the assemblages receive the boulders, which develop during the dissection of the beds. Due to the denudation of the bed parts newer and newer beds outcrop. Karren formation is renewed as a result (Fig. 5.1e).

The remnants of top set beds were separated by notches and niches like forms, which develop along bedding planes. This process occurs where grikekarren–rinnenkarren assemblages develop. As the beds are pelt, grikes can deepen continuously for a long time. Namely due to denudation of the top set beds the grikes can be shallow. Therefore, their plants get sufficient light during the deepening of the forms due to subsoil solution.

5.3 Surface Development of Glacier Valleys Due to Karren Formation

A lot of cuestas outcrop at the lower and smaller bottoms of glacier valleys. Therefore, 'Schichtrippenkarst' develops. Karren formation is controlled by escarpments with front slopes. Namely the development of the surfaces with bedding planes, which are at the lower margins of front slopes, depends on the presence of the pit–grikekarren assemblages and its development intensity. The expansion of bedding planes, which occur at the margin of head of beds, decreases because of the development of the pit–rinnenkarren assemblages. At these places rock corridors (bogaz; Cvijič 1924) develop, which are winding and there are debris and collapsed materials at their bottoms. Certain front slopes of escarpments are destroyed entirely because the surface consumption happens partly or totally at bedding planes. The altitude may be preserved or increases to a smaller degree at certain head of beds. Solution increases to the direction of the lower part of the bedding plane, namely as mentioned before. The above described phenomenon occurs if the neighbouring bedding planes denudate similarly (Fig. 5.1b). The altitudes of the neighbouring front slopes with head of beds may change considerably when they are compared to each other. When the karren formation of the neighbouring bedding planes is different, the denudation of these surfaces has different degrees. Therefore, the neighbouring front slopes with head of beds may increase in their altitude, while the altitude of other slopes may decrease (Fig. 5.1e). Therefore, 'Schichtrippenkarst surfaces are dissected in a growing degree. Naturally the development of the surface is also similar if the denudation of the neighbouring bedding planes has similar characteristics, but the process can have various intensities due to some reason.

Surfaces with non-bedding planes where the denudation of the rock happens due to cavity development, the surface, which was formed by glacial can be preserved considerably (Fig. 5.1d). The bedding plane parts are separated into smaller surface parts, which undergo karren formation among some great-sized grikes (Fig. 5.1e). Superficial denudation (in the case of rinnenkarren–grikekarren assemblages) and cavity development (in the case of rinnenkarren–pit assemblages) can occur on the 'Schichtrippenkarst' of the higher valley bottoms (Fig. 5.1c, d). These surfaces shorten as pit–grikekarren assemblages increase, which develop at the ends of the bedding planes.

Chapter 6
Local Karren Belts

Abstract In this chapter we describe the karren belts of the slopes and the karren forms. Using the karren formation characteristics of the slopes, we present the karren formation development typical for the embryonic, young, and mature stages of karren formation.

Keywords Karren belts • Slope units • Belt pattern • Sheet water • Rivulet • Seepage • Development of the slope6.1 Karren Belts on a Slope

6.1 Karren Belts on a Slope

Some karren forms develop in belts on the slope. Various slope units such as convex, concave and straight slope units contribute to the development of the belt pattern (complex slope). The belt pattern indicates that the current characteristics of the flowing water differ on the various parts of the slope. Thus, the manner and the degree of surface denudation are also different. According to the occurrences of various karren forms on the slope, the following current characteristics can be seen on the slope:

- The development of water cover is sheet water in the belt of the rillenkarren, where the slope part is convex. The water flow is turbulent intermittently. (Where as the water flow is laminar at other times.) It can be caused by the fact that current velocity of the sheet water increases on the convex slope part. Therefore, its thickness decreases. As the sheet water is thin, due to the impact of rain drops and snow flakes falling onto the sheet water, it has a turbulent flow.
- The development of the water cover is also sheet water, on the areas of the straight slope parts (solution bevels). The flow of the water is laminar. The fact that rillenkarren end at the upper margins of these surfaces and that solution decreases can be due to the fact that turbulent flow does not develop at these places. According to several authors (e.g. Ford and Williams 1989), solution has such characteristics on those surfaces, which cause planar surfaces to develop and such planar slope parts can be preserved. Turbulent flow, which occurs for a short period of time, causes solution in a smaller degree

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(Emmett 1970) rainfall and further more melt water falling on the surface also cause solution. Turbulent flow is absent as the surface is primarily flat and the thickness of the sheet water is great. Namely, the velocity of the flowing water decreases on a straight slope. The flow is turbulent only at a few places on the planar surfaces. Turbulent flow does not always develop at the same places. Its condition is that the water, which causes the solution at these places, originates from the same places and does not flow from other places. Hence, the water comes from the snow, which covers these surfaces. Melt water can dissolve, but its degree is small, because it is laminar. This small solution increases the equalization and smoothness of the surface. Trittkarren develop if turbulent flow is created in the same places on the planar surfaces.
- The water flows in rivulets (and it is turbulent) on the concave slope unit at the lower parts of the slope. The thickness of the water of the rivulet increases on the convex slope part which can cause the development of turbulent flow. This phenomenon contributes to the development of turbulent flow. The turbulent flow of the water rivulets may also be caused by straight slopes (or slope units) if the angle of the slope is great enough. As the angle of the slope increases, the velocity of the flow increases too. The turbulent flow will be continuous. The belt of rinnenkarren develops here.

The belts of karren forms may develop on such a slope, which has been already created before karren formation, or on such slopes which developed during karren formation. In the later case, for example, they can be created on such slopes which lost their soil cover or on such a slope which is the side slope of an already developed karren form (see bellow).

Belts of karren forms may be regular or missing or local on the slope. Regular pattern consists of three belts: rillenkarren, solution bevels and rinnenkarren. Such pattern occurs if the angle of slope is between 10° and 50°, furthermore the upper part of the slope is convex and the middle part of the slope is straight, while the lower part of the slope is concave. If karren forms with infiltration origin or soil patches develop on the slopes, they can moderate or defer the belts or the current system on the slope. Regular zonality belts will not always develop in three zones. There may be four (Fig. 6.1a), or five zones (Fig. 6.1k). The fourth and the fifth zones are water leading zones (pits). If the development pattern is missing, rinnenkarren (Fig. 6.1b) or rillenkarren (Fig. 6.1e), or solution bevels may be absent (Fig. 6.1d). The zones may consist of the same kind of karren forms (Fig. 6.1d) or various karren forms (Fig. 6.1l). It can also happen that only a single karren zone develops on the slope.

(**f**) absence of rinnenkarren, rillenkarren occur locally, (**g**) rillenkarren occur on peaks inside solution bevel (rillenkarren occur on remnant surfaces), (**h**) absence of rinnenkarren; rillenkarren that are linked to trittkarren develop locally, (**i**) solution bevel occurs locally with trittkarren, (**j**–**k**) trittkarren zones also develop, (**l**–**m**) trittkarren create a belt with other karren forms, (composite belt), (**n**) two solution bevels, and (**o**) the lower solution bevel is transformed into rinnenkarren and trittkarren while the upper solution bevels remains a solution bevel, 1 – the line of the dip of the bearing slope, 2 – large karren form (gryke, edge of channel), and 3 – karren mound (cone)

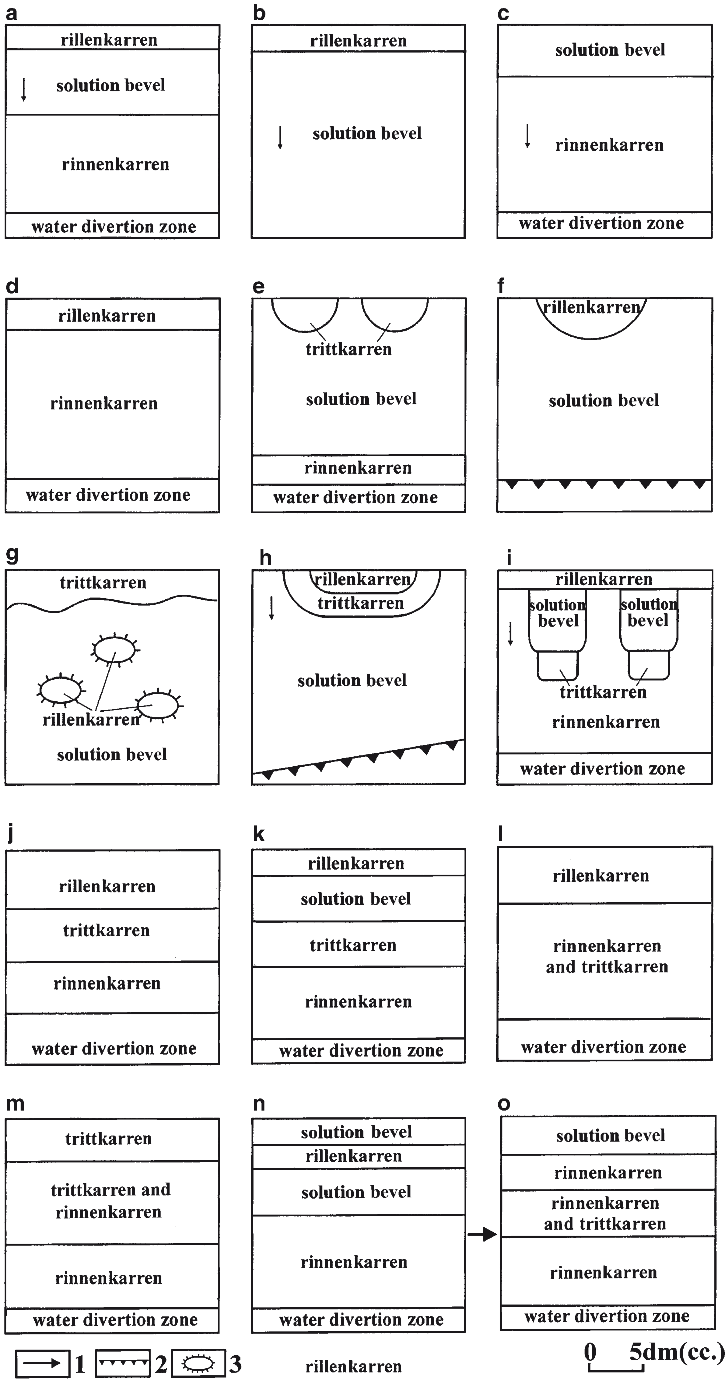


Fig. 6.1 Belts of karren forms that develop due to water flowing on slopes (Veress 2003). Legend: (**a**) regular development, (**b**) absence of rinnenkarren, (**c**) absence of rillenkarren, (**d**) absence of solution bevel, (**e**) absence of rillenkarren; trittkarren develop adjacent to solution bevel,

According to the above facts during regular development, the water cover of the slope may be sheet water but intermittent turbulent flow on the upper part of the slope. It may be laminar flow (the water is melt water) in the middle of the slope. And it may be of rivulet origin, but the flow is turbulent on the lower part of the slope. If the development type of the belts is missing, then some or one of these above-mentioned water flows can be absent from the water flow system.

Trittkarren zone may develop, which may be formed on different parts of the slope. This zone may be bordered with different types of karren belts (Fig. 6.1j, k). It is frequent that the belt is complex. Then several kinds of karren forms occur in the same zone. Thus, trittkarren may create a common zone (belt) with other karren forms (e.g. rinnenkarren; Fig. 6.1m).

The belts can occur partially local. In this case, many versions can be distinguished. Thus, local rillenkarren occur with solution bevels (Fig 6.1h). Remnant surfaces (Fig. 6.1g) with rillenkarren on their tops can outcrop from uniform solution bevels. It may also occur that the local zone is built from two parts. Fox example, there are rillenkarren and trittkarren (Fig 6.1h), or there are solution bevels and trittkarren (Fig. 6.1i) in a belt. In these cases the development of the sheet water is local (e.g. at the local mounds) because snow patches remain at these places under which trittkarren and solution bevels may develop too. The absence of rinnenkarren may be explained with the short expansion of the slope as rivulets do not develop

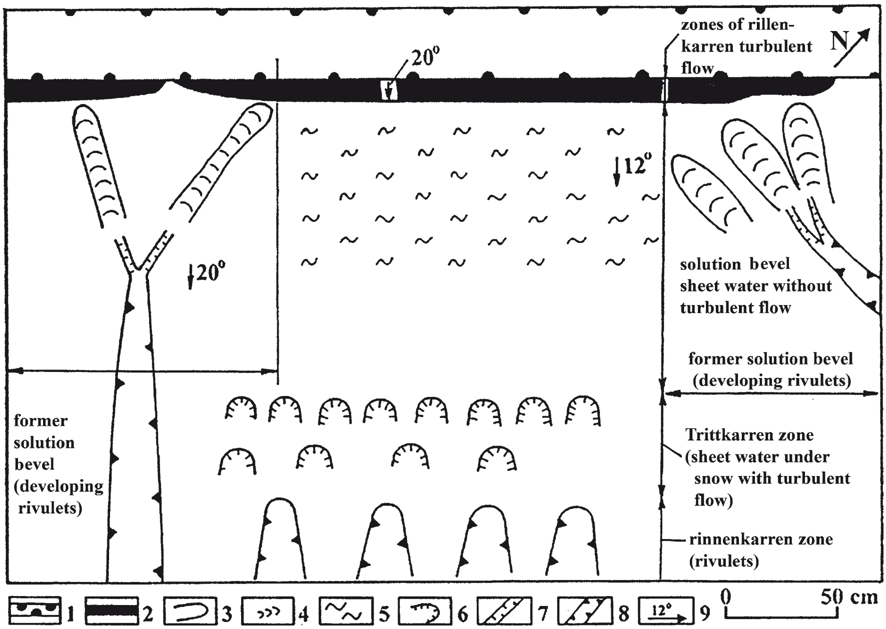


Fig. 6.2 Changing of the karren belts of a solution bevel (research area marked 1/2, Veress 2003). Legend: 1 – grike, 2 – rillenkarren belt, 3 – channel-like forms with great width and small depth, 4 – trittkarren of channel-like forms, 5 – embryonal trittkarren of solution bevel, 6 – trittkarren under the solution bevel, 7 – upper leading part of the channel, 8 – channel, and 9 – slope direction and slope angle (note: a part of the area can be seen in Picture 4.5)

on short slopes. We present an example of local zone belts in Fig 6.2. The local appearance may be original (primary). Then several solution bevels develop, which are independent from each other. It may be subsequent, too. In that case, the runnels extend up towards the upper part of the slope. Therefore, the solution bevels are dissected into parts by channels. This is not surprising. Namely solution bevels are not stable karren forms if they develop due to snow. The aggressively developing runnels can extend to the areas of the solution bevels even if conditions of the existence of the solution bevels remain for a long time. Secondary zonality is thought to be local, which was created by regression of the runnels, and can be seen in Fig. 6.2.

Single zones may develop into double if slope conditions make it possible. Two solution bevels can develop too, which surround the rillenkarren zone (Fig. 6.1n). In this case, different zones may also change. We present a bedding plane surface from Dachstein in Fig. 6.3 and in Picture 4.4 as an example. Here lower solution bevels and the rillenkarren zone were transformed. During the transformation of the area trittkarren developed on the lower solution bevels (marked C, which can be seen in Fig. 6.4) and this surface part was dissected by runnels, too (Fig. 6.1n, o). Further more rinnenkarren, which develop due to antiregressional processes and extend from the upper parts of the slope to downwards, can also dissect this area as well as the narrow channels that developed as the continuation of the rinnenkarren like forms (Fig. 6.4).

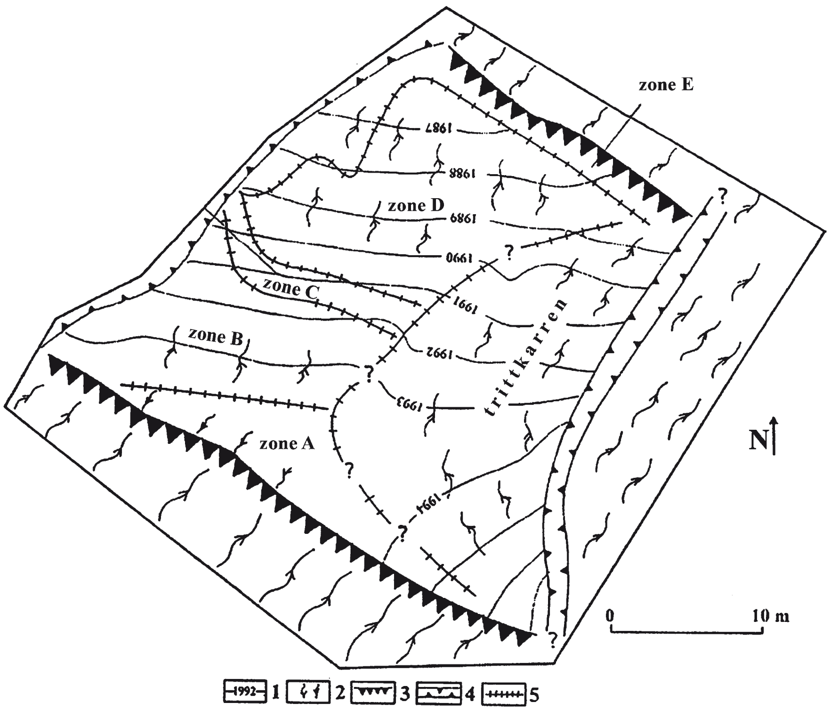


Fig. 6.3 The relief draught-morphological map of a bedding plane surface (research area marked 2/1, Veress and Tóth 2002). Legend: 1 – contour line, 2 – bedding plane (with line of dip), 3 – bedding head, 4 – solution grike, 5 – zone boundary (the area is shown in Picture 4.4)

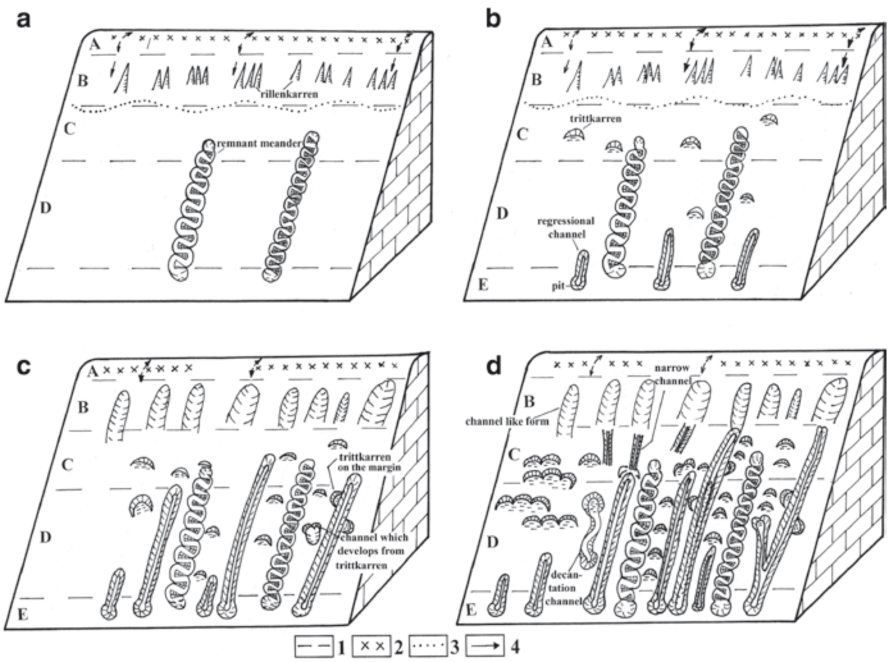


Fig. 6.4 Karren belts of developing of the bed-plane surface shown in Fig. 6.3 (Veress and Tóth 2002). Legend: 1 – the boundary of the zone, 2 – the boundary of the directions of the different surface water currents, 3 – the lower boundary of the different surface water current, 4 – the direction of the water current. (**a**) rillenkarren zone develops in the B belt, meanderkarren are created in the D belt, (**b**) the development of the regression channels in belt D (rinnenkarren belt) the first trittkarren are created in belts C and D, (**c**) the forms of rillenkarren belt change to channels (rinnenkarren belt) in the B belt, and (**d**) trittkarren belt and rinnenkarren belts develop on the lower solution bevel (C zone); the channels are created by regression, and antiregression partly (note: there are two solution bevels on the slope: marked A zone and the marked C zone (this latter one changes during the karren formation of the slope))

6.2 Zonality (Belts) Developed on Karren Forms

Secondary zonality develops on the already existing karren forms. The expansion of this zonality is local and imperfect as the bearing slope of the karren form is small. Secondary zonality develops mostly on karren forms of bare surfaces: on trittkarren, on slide slopes of channels and grikekarren (Fig. 6.5). Mostly two zones develop: a rillenkarren zone and solution bevels. Rillenkarren develop on the risers of the trittkarren, if they are not perpendicular (Fig. 6.5a). Rillenkarren do not develop on a perpendicular riser, because only few raindrops hit the sheet water. Rillenkarren may develop on the upper part of the treads of the trittkarren (Fig. 6.5b), and on the total area of the tread (Fig. 6.5c). In the earlier case, the lower part of the tread can be considered as a solution bevel, while in the latter one the solution bevel is the foreground. The development of rillenkarren on the trittkarren has two reasons:

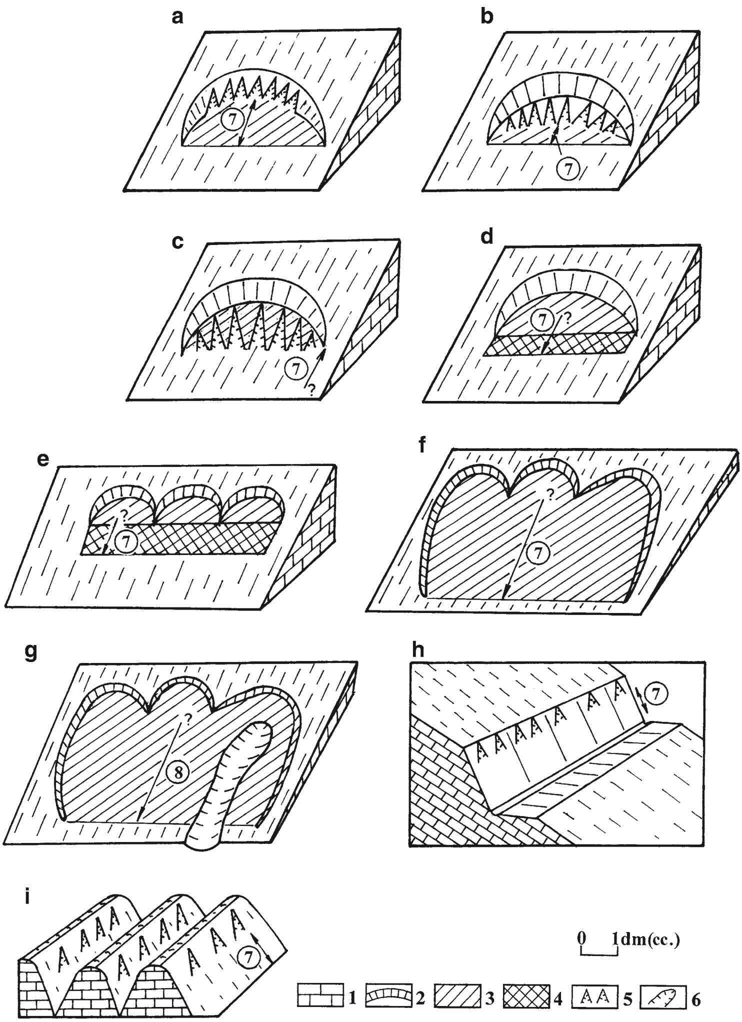
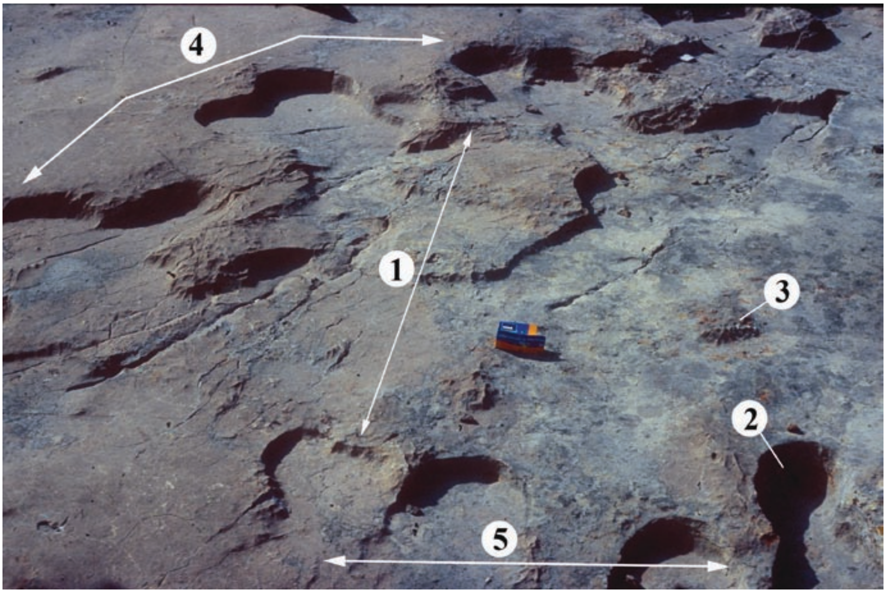


Fig. 6.5 The secondary belt on karren forms (Veress 2003). Legend: 1 – limestone, 2 – the tread of the trittkarren, 3 – the riser of the trittkarren, 4 – fore ground, 5 – rillenkarren, 6 – channel, 7 – solution bevel, and 8 – transforming solution bevel; rillenkarren belt on the riser (**a**), rillenkarren belt on part of the tread (**b**), or the rillenkarren belt develops on the total area of the tread (**c**), therefore the solution bevel can develop on the total area of the tread (**a**), on a part of it (**b**), or on the bearing slope (**c**) on the foregrounds (**d**, **e**), further it may develop on the tread of the nishen-karren (**f**, **g**), but solution bevel may develop on the wall of the channel (**h**), or on the walls of grikes (**i**) too, if rillenkarren develop on the upper parts of the slopes

- The trittkarren do not develop further. For example, because snow does not remain on the areas of the trittkarren for a long time and raindrops hit the sheet water in trittkarren.
- The trittkarren is developing and active. The rillenkarren develop on their areas when there is no snow cover. Hence the rillenkarren are not destroyed by melt



Picture 6.1 The belt of the tread of the Nischenkarren (area marked 2/1). Legend: 1 – solution bevel, 2 – channel which develops on the solution bevel, 3 – mound with rillenkarren, which developed on the solution bevel, 4 – riser of nischenkarren, and 5 – trittkarren which denudate the solution bevel (the map of the area is shown in Fig. 4.3)

water. Because the area of trittkarren is dissolved to a smaller degree or the rillenkarren develop again.

Probably the foreground and the treads of the nischenkarren are also solution bevels (Fig. 6.5e, f). Such zonality may occur on slopes with low slope angle (flachkarren). In this case solution bevels develop where the water flow changes from turbulent to laminar flow.

Runnels and trittkarren may develop on the areas of the nischenkarren (Figs. 4.3 and 6.5g, Picture 6.1). Runnel occurrence is probably due to the discontinuity of the water sheet. Rivulets are created on the threads of the nischenkarren. With local turbulent flow trittkarren develop.

Two zones develop on the side slopes of runnels and grikekarren (Fig. 6.5h, i; Picture 4.44). Rillenkarren develop on the upper part at the side slopes, while solution bevels develop on their lower parts.

6.3 Development of the Slope

A karren surface develops during karren formation if the process is long-lasting. The result of the process is either lower solution bevels, or certain forms become dominant. We present various karren surface development models in Fig. 6.6.

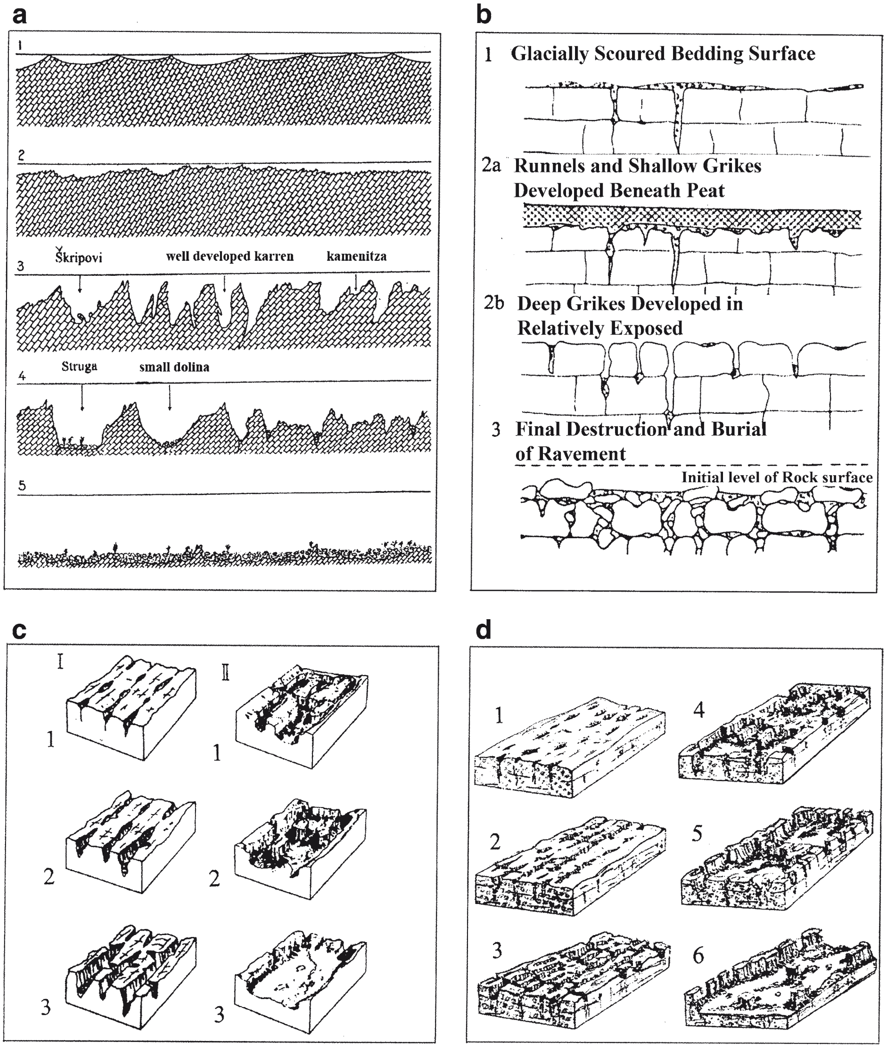


Fig. 6.6 The development of surface karren formation (**a**) on glacial-free surface (after Cvijič 1924), (**b**) the surface was covered with glacial originally (after Williams 1966), (**c**) original surface with grikes (after Brook and Ford 1978), and (**d**) original surface with pits (after Brook-Feeney 1996). Legend: (**a**) There are channels and sharp ridges of few meters (1–2 part-figures), there are channels, which can be about 3–4 m deep, for example 'skipovi', karst wells, kamenitzas (3 part-figure), there are 'struga' and dolinas forms (4 part-figure), the remnant will parish the surface will be covered with debris (5 part-figure), (**b**) glacier will form the surface (1 part-figure) grikes and runnels develop under the soil (2a part-figure), 'truncated' grikes remain with the denudation of the surface between the grikes (2b part-figure), debris will cover the surface (3 part-figure), (**c**) 'labyrinth karst' develop because grikes will widen and they will create 'streets' (I.1–I.3 part-figures), 'clints' and towers will develop because of the dissolution and freeze and thaw disintegration (II.1–II.2. part-figures), depressions develop (II.3. part-figure), and (**d**) strings of solution pits (1–3 part-figures) coalesce to form intersecting networks of grikes or karst streets (2 and 3 part-figures), as grikes and streets enlarge and coalesce, grike depressions and karst platea are formed often with residual clints or towers projecting from their floors (4 and 5 part-figures), the coalescence of grike depressions and 'karst platea' ultimately leads to the formation of marginal erosion surfaces surmounted by residual clints or karst towers (6 part-figure)

(These models may be applied to other karst areas, too.) We can classify the process of karren formation development with karren formation on slopes. This process may have different types in a high mountain environment. The characteristics of the slope affect the development types. The various types are the following: the development of slope may be embryonic, young or mature (Veress and Zentai 2004). Mature slope development can occur on bare slopes or on those with *Pinus mugo*. The bare slope can be straight and planar, straight with small dip, planar with greater dip and complex slope. The slopes of the embryonic and young karren formation stages happen on slopes which lost their ice cover several decades ago.

Young channels, microkarren, solution bevels and non-karren surface parts can be found on such slopes, which show embryonic karren formation. The depth of the young channels is less than 5 cm and their density is also small. Scallops and microtrittkarren occur on the upper margin of such slopes (Fig. 6.7). The rinnenkarren of the more developed (young) slopes are bigger, and longer than 10 cm. The density of these channels is also greater than that of embryonal karren slopes. They do not wedge out. Rillenkarren also occur on the ridges between these channels. Meanderkarren also occur on such slopes. Microgrikes create an independent belt on the upper part of the slopes (Fig. 6.8).

The characteristics of embryonic and young stages of slope development are the following (Veress and Zentai 2004):

- Melt water can cover these slopes. This water can be sheet water, water cover or both of them.
- Microgrikes are created by sheet water, under snow or on snow-free surfaces by the percolating laminar water flow (Fig. 6.9).
- Microgrikes promote help the development of turbulent current of sheet water. Microtrittkarren and scallops develop due to the turbulent flow. We estimated the thickness of the sheet water flowing on the slope less or at maximum 1 cm. Scallops are less than 1 cm deep and it proves that thickness of the water is small. The development of turbulent water flow causes the surface denudation of the slope. Therefore, microgrikes are destroyed partly or totally where this flow develops. Such flow is created if a lot of melt water develops. The quantity of snow is considerable on the slope and the melting of the snow is rapid.
- The quantity of melt water decreases in the same summer. The cause of this decrease may be the decrease in snow amounts. If the quantity of the water decreases fast and considerably on the same part of the slope, mixed form assemblages develop. First scallops develop if there is more water (at water flow) and later when the quantity of the water is less microtrittkarren are created (at percolating water). We observed young channels in the middle and at lower parts of these slopes. This can happen because the sheet water is divided into rivulets at the lower part of the slope as the water quantity decreases. Then young channels begin to develop under the rivulets. Sheet water may remain

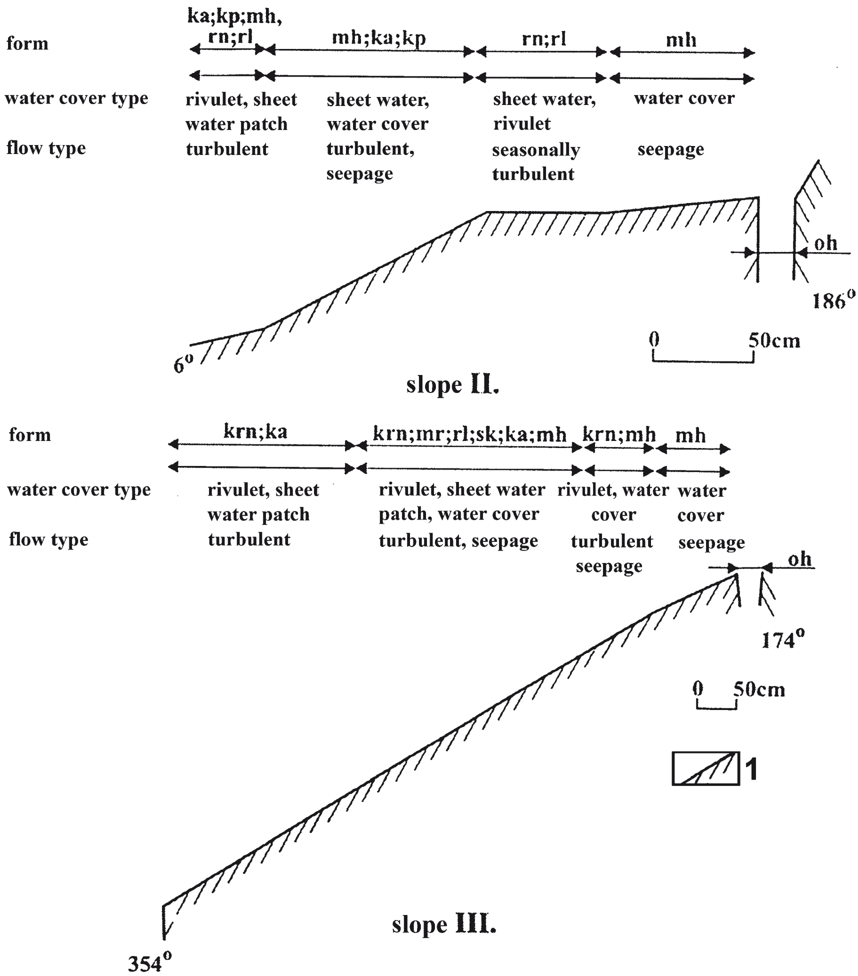


Fig. 6.7 Karren forms of embryonal karren formation slopes (research area marked 3/5, Veress and Zentai 2004). Legend: 1 – rock, mh – microgrike, ka – scallops, kp – microspitz, sk – microtrittkarren, rl – rillenkarren, Au – soluation bevel, Auf – solution bevel 'patch', krn – young rinnen, mr – meanderkarren, and oh – grike

mostly on the upper slope. But the thickness of the sheet water decreases as more and more sheet water flows into the growing channels as time goes by. The solution will be small because the sheet water is thin, and therefore it is lamiliarly flowing. The sheet water remains for over a shorter period of time. Therefore, newer karren features do not develop any more. But micropinnacles are destroyed therefore the slope becomes planar. As channels grow further during this process, the sheet water becomes even thinner. Water cover develops from the sheet water. Then newer microgrikes develop under the water cover.

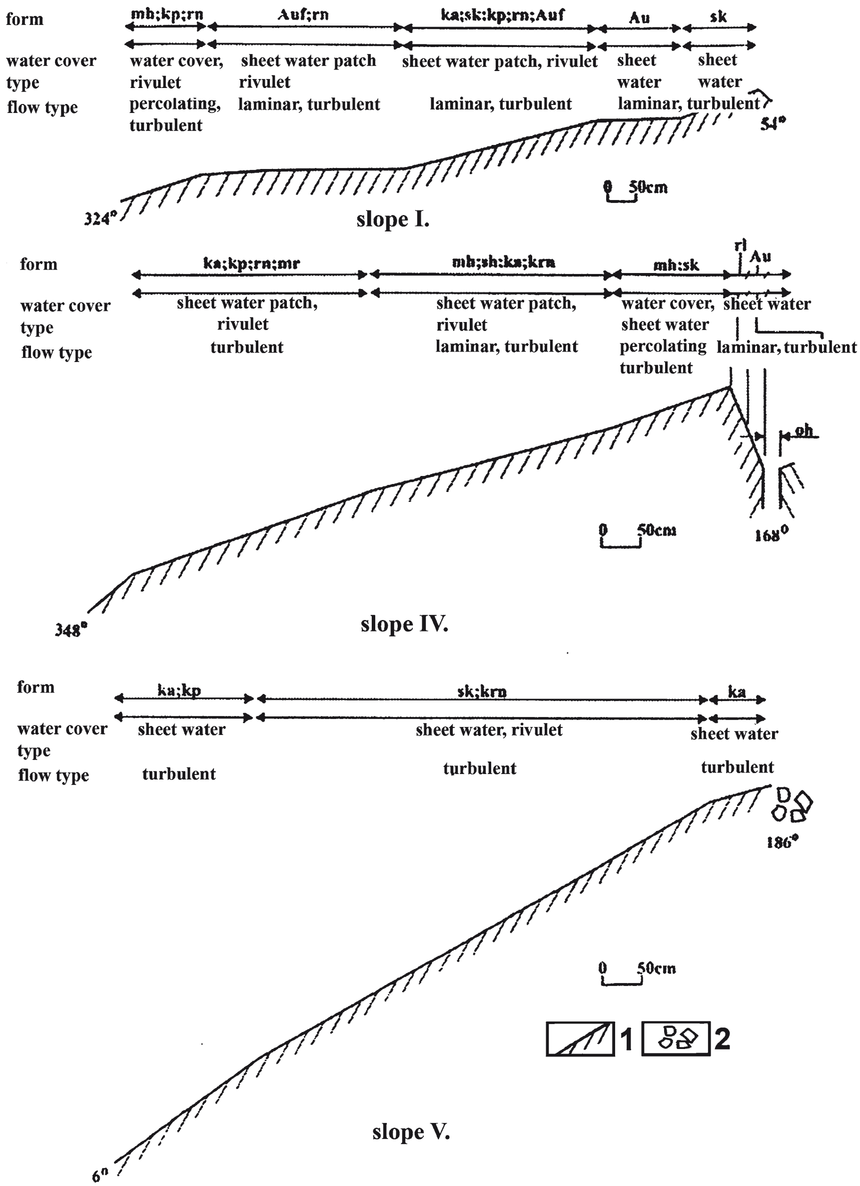


Fig. 6.8 Karren forms of young karren formation slopes (research area marked 3/5, Veress-Zentai 2004). Legend: 1 – rock, and 2 – debris, mh – microgrike, ka – scallops, kp – microspitz, sk – microtrittkarren, rl – rillenkarren, Au – solution bevel, Auf – solution bevel 'patch', rn – rinnenkarren, krn – young rinnen, mr: meandering runnel (meanderkarren), and oh – grike

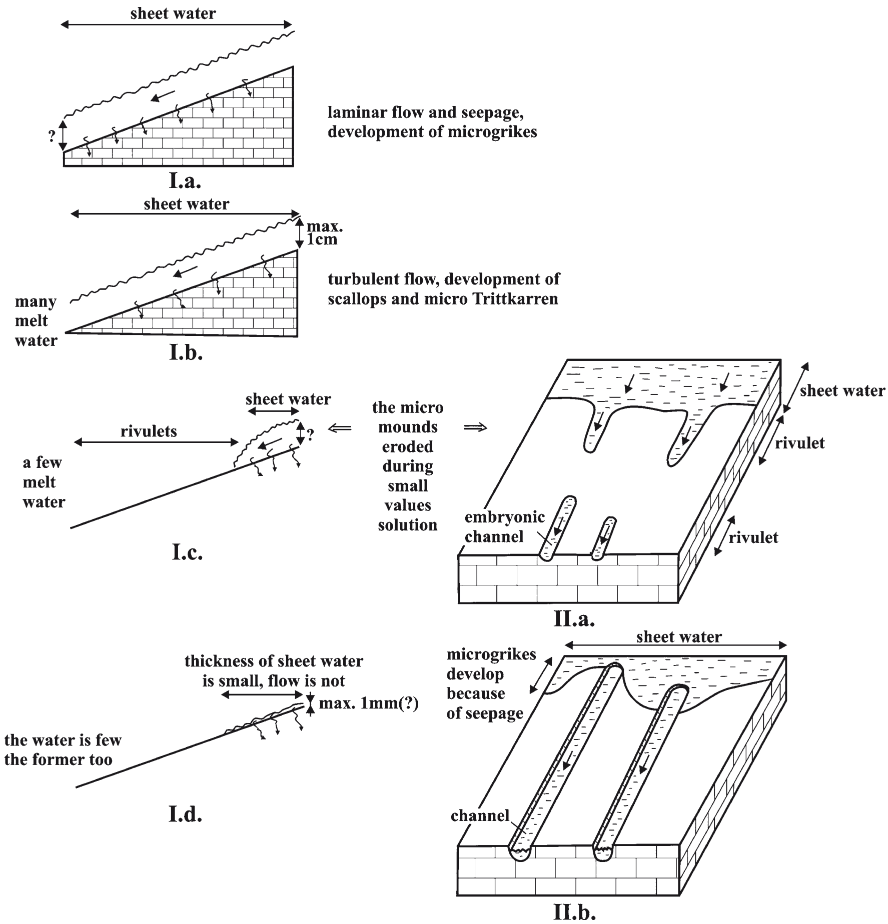


Fig. 6.9 Model of development of initial surface karren formation of the slope (Veress-Zentai 2004). Ia–Ib – embryonic karren formation phase, Ic–Id and IIa–IIb – young karren formation phase

- As channels grow year after year, more and more water flows into them. Therefore, sheet water is divided into patches. Despite this fact microkarren found on ridges between channels due to the following facts.
  - Smaller-greater snow patches remain on the slopes. Therefore sheet water or water cover can develop there.
  - The snow, which fills the channel, can decrease the amount of the water, which flows into the channel.

Type A and type B channels with kamenitzas and pits may develop on straight, bare and planar slopes with small slope angle. Channels dissect the upper part of the slope to a smaller degree. The channels are smaller and have smaller density there (Table 4.2). The quantity of the dissection does not increase in the middle or on the lower parts of the slopes where channels (type B channels) lead to pits or grikes. Therefore, planar surface parts remain from the original slope surface. Where kamenitzas, pits and grikes are absent the channels continue to the middle and lower parts of the slopes. They mostly reach the wide grikes and shafts which are found at the bottom of the slope. Narrow ridges develop between the channels. With increasing width and density ridge development is favoured. This characteristic occurs mostly on the middle parts of the slopes (Table 4.2). Type A channels also contribute to the dissection of surfaces between the channels. The slopes are shortening from their lower ends because the grikes, which border them below are widening. As the narrow ridges are destroyed in the middle and lower parts of the slopes they become lower and are ruined. Newer channel generations develop. These newer channel generations are created from type II channels at the bottom of the older type I channels. The lower part of the slope will be steeper and greater compared to the upper part. The slope may be separated into independently developed parts due to the grikes which have direction identical with that of the strike direction. As angle increases, the development of the channels may increase. At the same time kamenitzas and pits are not created as slopes are steeper and steeper. Karren formation of the slope changes as such forms are absent. Fewer meanderkarren develop because kamenitzas are absent. The channels will be longer if pits are not formed.

The density of channels is great on straight and steep slopes. V-shaped channels only increase to a small extend. Ridges remain for a long time between the channels. The slopes become stable.

Great channels develop on straight slopes with *Pinus mugo*. They may have great density. The ridges between the channels are destroyed because of the great density and great sizes of the channels. The slope is destroyed in its total length to the same extend. Therefore, the slope angle does not change. Grikes in strike direction may develop in the internal of the slope. Therefore, the lower slope parts may be separated from that with *Pinus mugo* patches. Further more, such channels may develop in considerable number on the lower part of the slope which receives their water from the bare slope section.

Nischenkarren, uvala trittkarren, and solution bevels develop below and upon each other on flachkarren (Fig. 4.3). The denudation of several karren surfaces at various levels at the same time is characteristic of nishchenkarren (Picture 6.1). The expansion of the solution bevels increases during the regression of the risers of higher-lying trittkarren and the regression of the risers of the nihschenkarren. While their areas decrease because of the regression of the risers of the lower-lying trittkarren. But because of the regression of the risers of the latter forms, newer solution bevels develop on lower areas. Therefore the surface with small dip angle denudates along several levels. The denudation of the surfaces with solution bevels happens due to karren formation in the following manner: partly the expansion of the solution bevels slows down and their evolution, too (because solution occurs on them) and partly their surface is dissected (runnels develop on their areas).

The upper convex section of a complex slope becomes gentler where the karren form the belt. The height of the ridges between them decreases as rillenkarren are widening. Therefore, solution bevels extend up the slope and become smaller as runnels regress. The altitude of the solution bevels decreases because of the development of trittkarren on their areas. The lower concave slopes parts are dissected by rinnenkarren. This process extends up-slope. The side slopes of the local and small mounds become gentle, their height decreases and rinnenkarren are absent. Finally, they smooth in into their surroundings.

Chapter 7
Coalescing of Karren Forms

Abstract In this chapter we present karren forms which are prone to coalescing, the resulting forms of coalescing, the phases coalescing (connected to each other, union) and the reasons behind the processes. We introduce the karren cells, discuss their characteristics and describe their development. Furthermore, we analyze the complex relationship between the levels of karren formation in high mountains.

Keywords Coalescing • Connect to each other • Union • Karren cell

Karren forms may coalesce due to solution (joining) as they increase (Veress 1995, 2000e). We can separate this process into two phases. In the first phase the karren forms connect to each other while we use the term union of the karren forms for the second phase. The original shapes exist in their total dimensions during connection. But the original shapes do not exist during the union. Such forms develop during the union of the forms whose shapes are similar to the shapes of the original forms or these forms are like uvalas. But it can also occur, that new karren forms develop, or that this new form is not a karren form at all. Usually the karren forms, which belong to the same type can reach the phase of union.

The following karren forms belong to the same type and are connected to each other (Veress 2000e, 2003):

- Channel and channel
- Pit and pit (Pictures 7.1 and 7.2)
- Grike and grike
- Trittkarren and trittkarren
- Kamenitza and kamenitza
- Two parts of meandering karren
- Rain pits

Those forms which belong to various karren types and are connected to each other can be as follows:

- Pit and grike (Picture 7.3)
- Kamenitza and grike (Picture 7.4)

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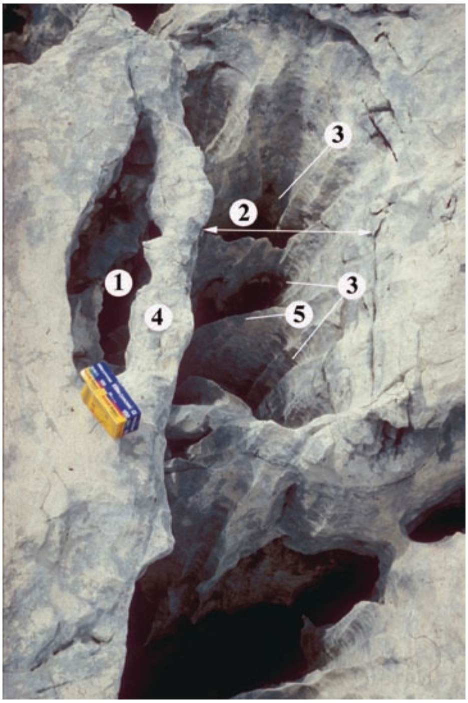
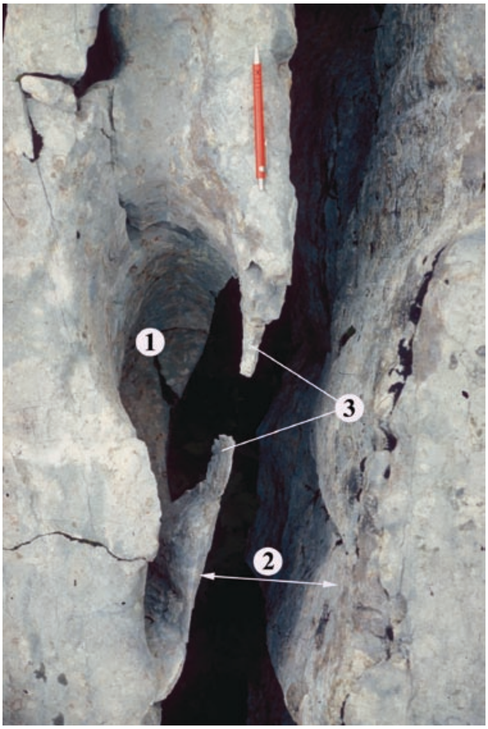
Picture 7.1 Initial phase of pit connected to each other (area marked 3/2). Legend: 1 – boundary wall, and 2 – window

Picture 7.2 Developing phase of pit connected to each other (area marked 3/2). Legend: 1 – pit, 2 – karren bridge, and 3 – window

Picture 7.3 Pit and grike connect to each other (area marked 3/3). Legend: 1 – pit, 2 – grike, 3 – pit in the grike, 4 – bridge, and 5 – remnant of boundary wall



Picture 7.4 Part union between a kamenitza and a grike (area marked 3/3). Legend: 1 – kamenitza, 2 – grike, and 3 – of karren bridge



- Channel and grike
- Channel and pit
- Channel and kamenitza
- Channel and karren cave

7.1 The Forms of Coalescing

Characteristic forms of coalescing due to solution primarily develop when the forms are connected to each other.

During the union of the forms, those forms which were created when they were connected to each other, are destroyed further and will perish partly or totally.

7.1.1 Forms Developing When They Are Connected to Each Other

Drainage divides develop at the bottoms of the channels where the channels are connected to each other (Veress 1995, 2002). Drainage divides of the bottoms of the channels are ridges, which cross the bottoms of the channels, and their height and width are of several centimetres. Steps may develop at the bottom of the channel during the capture of the channel.

Boundary walls develop between neighbouring pits and grikes. The direction of the boundary walls may be longitudinal or crossing. In the previous case, the direction of the boundary walls is concordant with the direction of the forms, but in the latter case they are not the same. We can determine the phases of coalescing due to solution when we take the morphology of the boundary walls into account. Connection of the forms develop when the boundary walls are truncated. Union of the karren forms occurs when the boundary walls are destroyed totally.

Destruction of the boundary walls may happen at various places. If the process spreads downwards, boundary wall remains develop, which have various shapes and heights (Fig. 7.1a). The boundary walls may be cut through in the middle. Then windows develop (Fig. 7.1b); karren bridges develop if the lower parts of the boundary walls are destroyed. Windows may develop on the bridges, too (Picture 7.5). The boundary wall bridges can be situated on the upper parts of the walls (Fig. 7.1c). Then the boundary walls are destroyed with the exception of the upper parts of the walls. The situation of the bridges may be medium (in the middle of the wall). These bridges develop if two windows are created on the boundary walls, which are under each other (Fig. 7.1d). Two bridges may also be formed on the same boundary wall when two windows develop.

Windows may develop on other places, too. They may occur on the roofs of karren caves, on the skirts of the loops of meanderkarren (Picture 4.37), on ridges between channels (Fig. 4.13) at the bottom of the pits and at the bottom of the channels, if a karren cave developed under the channel (Fig. 4.9d; Picture 4.53). Roof

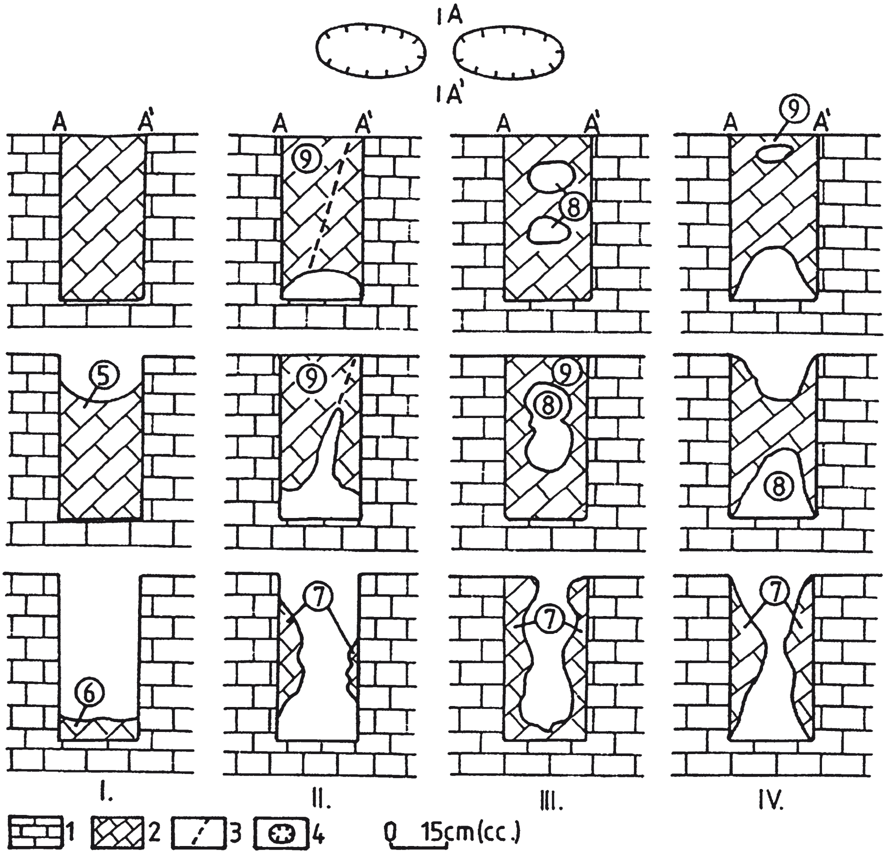


Fig. 7.1 Forms developed by growing together (conceptual sketch, Veress 2000e). Legend: cross section: 1 – limestone, 2 – partition wall, 3 – fault, in plan: 4 – pit, 5 – partition wall remnant, 6 – ruined partition wall, 7 – partition wall stub, 8 – window, and 9 – partition wall natural bridge; destruction of the partition wall takes place downwards (I), upwards (II), from the middle (III), downwards and upwards opposite each other (IV). A–A′: place of profile

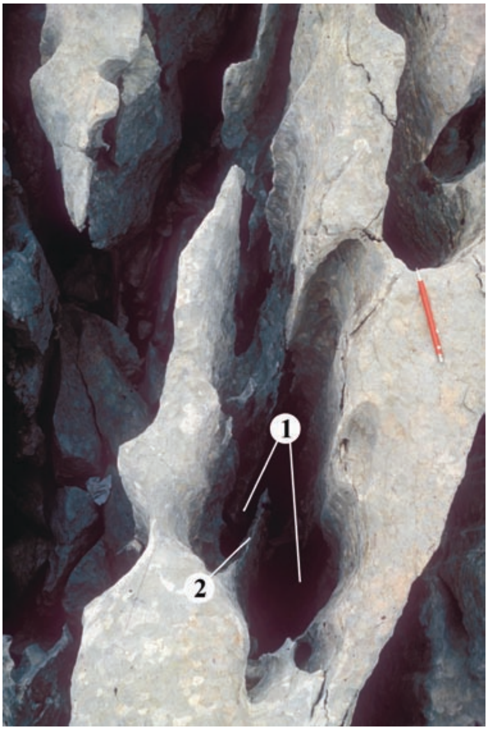
windows of karren caves or windows of the bottom of the channel may create rows. The windows are separated by karren bridges. The neighbouring windows of the rows may coalesce if karren ridges are destroyed.

Rock ears were described by Szunyogh (1999), on the sides of channels, which are partly filled with soil. One of their types developed when pockets are connected to each other due to subsoil solution.

7.1.2 The Forms of Union

The forms of the unit are bridge remains (Picture 7.4), the boundary wall remains, the boundary wall wrecks (Fig. 7.1; Picture 7.6), the boundary wall stumps (Fig. 7.1) and

Picture 7.5 Window due to solution development which occurs on a bridge (area marked 3/4). Legend: 1 – grike, 2 – karren bridge, and 3 – window



Picture 7.6 Wreck of boundary wall (area marked 3/3). Legend: 1 – pit, and 2 – boundary wall wreck

the rock ribs. Bridge remnants develop if the central part of the bridges collapse. Therefore, only the stump or stumps of the bridges remain. These forms occur repeatedly between channels and karren caves, which coalesce. But those are current also between coalescing pits. Bridge remnants of karren caves are the remnants of former roofs. The majority of the original boundary walls still remain at boundary walls. The boundary wall wrecks are remnants of the original boundary walls whose majority was destroyed. They occur at the bottom of the new form. During the development of boundary wrecks such remnant forms remain, which are several centimetres high ridges and are dissected by mounds. The wrecks are the highest where several karren forms are connected to each other. The boundary stumps develop if the central part of the boundary wall is destroyed totally. The margin remnants of the forms create a collar-like border. The boundary wrecks and boundary stumps develop during the destruction of the vertical boundary walls. Rock ribs are remnants of the boundary wall or remnants of karren form bottoms. Their situation is horizontal and they widen towards their ends. The widening ends are rounded.

7.2 Types and Causes of the Form Connection

The connection of the forms develops during primary and secondary processes. The primary processes are connected with the increasing karren forms, while the secondary processes are independent from them. The connections due to primary processes are directed by the structure of the rock (cracks, bedding planes). The connection may happen between karren forms with various sizes or types. If various karren forms are connected, the smaller forms remain as wrecks at the margins of the greater karren forms. For example, there are pit wrecks (Picture 7.3) or kamenitza wrecks (Picture 7.4) at the margins of the grikes.

7.2.1 Connections Due to Primary Causes

7.2.1.1 Connections Which Are Independent of Rock Structure

The cases of these connections are the following:

1. It may happen between widening kamenitzas, where boundary wall stumps remain when the kamenitzas coalesce into each other.
2. It may occur when channel and cave karren are connected to each other. Windows develop during the process. Later (see under) an evolved channel develops because of the union (Figs. 4.9d and 7.2; Pictures 7.7 and 7.8). The development of the windows may begin when a channel and a karren cave increase due to solution (primary cause). It can continue when bridges break down (secondary cause).

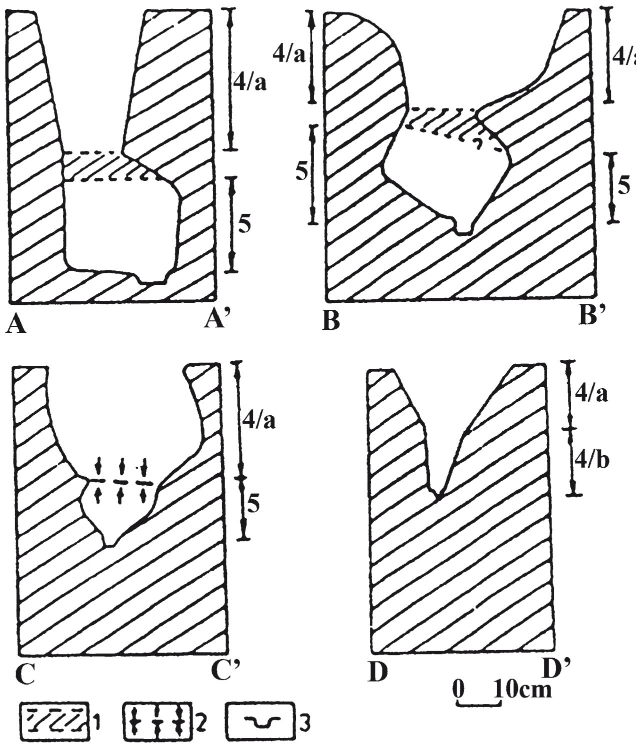
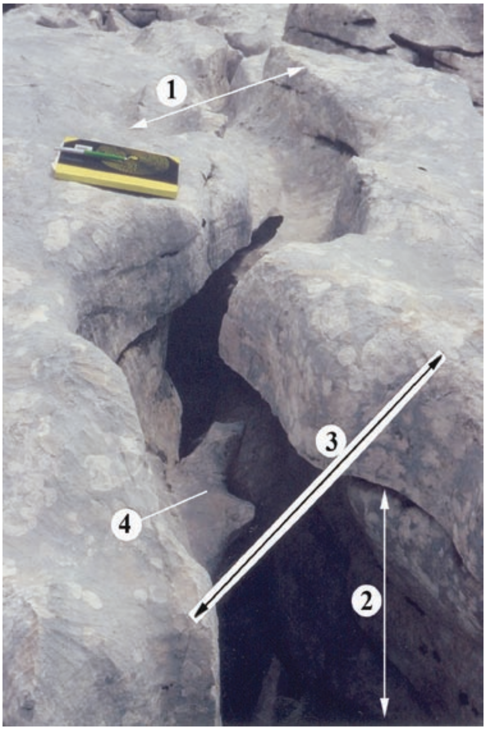


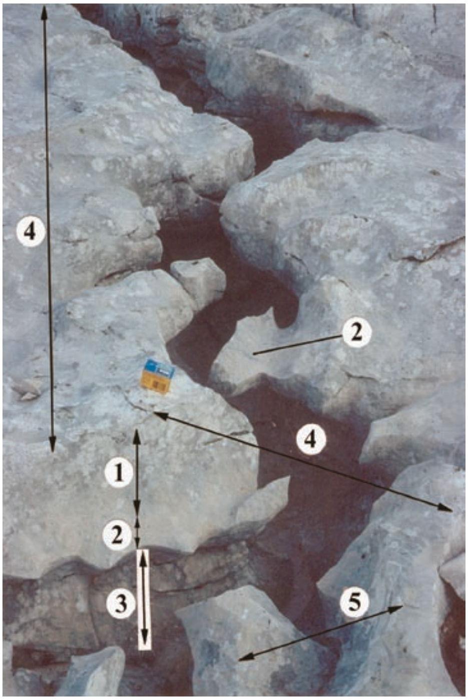
Fig. 7.2 Characteristic cross-sections of an evolved channel in various stages of development (research area marked 1/2, Veress 2000a). Legend: 1 – roof destroyed by collapse, 2 – roof destroyed by merging of a channel and a karren cave, 3 – type III channel; 4a – upper channel section developed by surface solution independently from subsurface capture, 4b – lower channel section intensively developing due to beheading, 5 – channel section (former karren cave) developed by subsurface solution. Comment: in the A–A′ and B–B′ cross sections, the evolution occurred with the collapse of the roof of the karren cave; in the case of the C–C′ cross section, it occurred through coalescing; subsurface capture occurred between the C–C′ and D–D′ sections

3. The connection of the channel may also occur during the regression of the channels (Veress and Nacsa 2000; Veress and Tóth 2001). The end of the regressional channel may reach the end of another regressional channel (Fig. 7.3a). But the end of a regression channel may reach the side part of another channel. In the first case, the heads of the channels meet and are connected to each other during the process, while in the latter case 'false beheading' or 'real' beheading occurs. The original direction of flow of the water along the bottom of the 'beheaded' channel does not change during 'false beheading'. The original direction of flow of the water along the bottom of the 'beheaded' channel changes during 'real' beheading. The cases of 'false beheading' are the following (Veress and Nacsa 2000):

   - Regressional tributary channel which causes 'false beheading' deepens in a smaller degree (Fig. 7.3b). Channel bottom watershed divide develops at the



Picture 7.7 Channel and karren cave which are partly coalescing (area marked 1/2). Legend: 1 – channel, 2 – former karren cave, 3 – evolved channel, and 4 – roof remnant



Picture 7.8 Evolved channel (area marked 1/2). Legend: 1 – channel part, 2 – roof remnant, 3 – former karren cave part, 4 – channel with double profile, and 5 – channel with simple profile

upper end of the tributary channel, where the 'false beheading' takes place. A step develops where it is connected into the main channel. The step is the remnant of the side of the main channel. The bottom of the tributary channel hangs above the bottom of the main channel, where its regression happened.

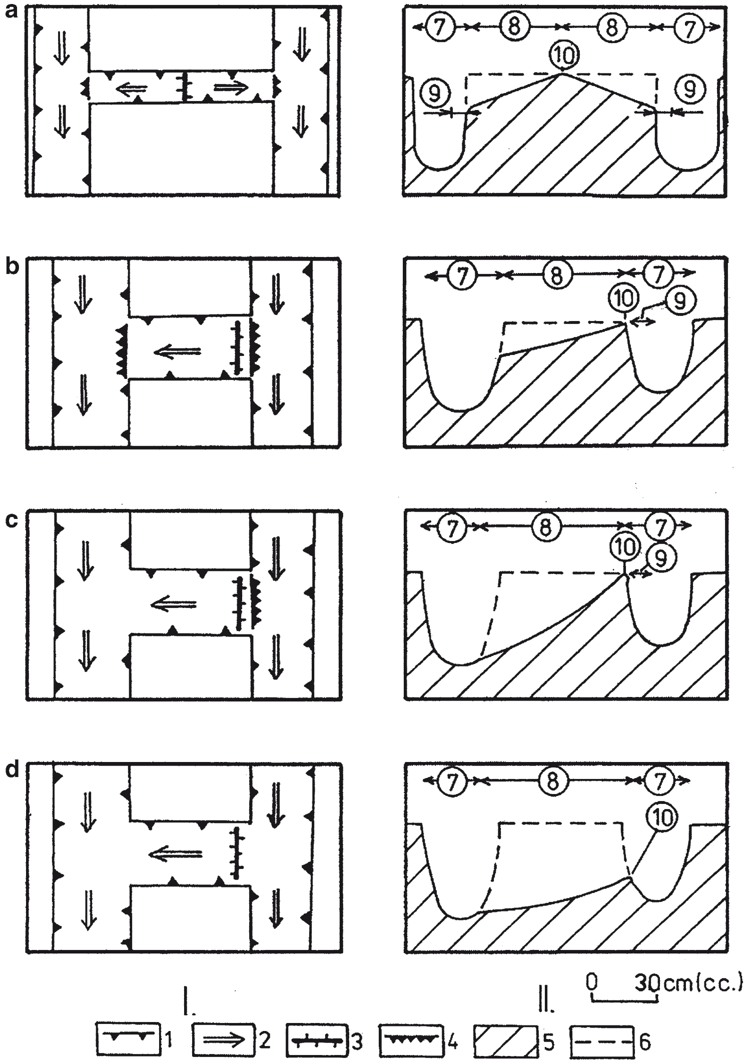


Fig. 7.3 Coalescing of channel ends (**a**) and false beheading (**b**–**d**) (Veress and Nacsa 2000). Legend: 1 – type I channel, 2 – slope direction of type I channel bottom, 3 – channel bottom watershed divide, 4 – step, 5 – limestone, 6 – ground surface before channel entrenchment , 7 – master channel, 8 – regressing tributary channel, 9 – step, and 10 – channel bottom watershed divide; I – view from above, II – cross section (**a**) the regressing tributary channel heads join, (**b**) the beheading channel deepens constantly, (**c**) the beheading channel deepens mainly at its lower part, and (**d**) the beheading channel deepens in its whole length in a greater value (note: profiles were takes among the beheading and coalescing channels)

- The lower end of the regressional tributary channel deepens considerably. Channel bottom watershed divide with step develops at the place of the 'false beheading'. The bottom of the tributary channel is connected gradually into the bottom of the main channel from where the tributary channel retreated (Fig. 7.3c).
- The regressional tributary channel deepens totally in its whole length. The side of the main channel which undergoes 'false beheading' is destroyed totally. Only bottom watershed divide develops there (Fig. 7.3d).

'Real' beheading is frequent at type II and type III channels if the channel is perpendicular to the other channel. The regressional channel end may capture the other channel (Fig. 7.4a). Channel beheading can happen in a way when the beheading channel cuts through the beheaded channel (channel crossing Fig. 7.4b). In both cases the water from the beheaded channel flows into the beheading channel. The beheaded channel part which is under the capture place does not get water from the channel part which is above the capture place. If the capturing channel does not cut through the captured channel, then bottom watershed divide may develop at the lower margin of the capture place. If the capturing channel cuts through the captured channel then, two steps may develop at the lower and upper margins of the capture place.

The bottom watershed divide develops if a channel retreats to another channel (Fig. 7.4c). If either channel deepens more intensely, then it destroys the bottom of the channel which deepens to a less degree. The dip of the latter one will be the opposite of the original. (Obsequent channel part develops.) Wreck channel develops if the upper and lower channel ends are captured, too.

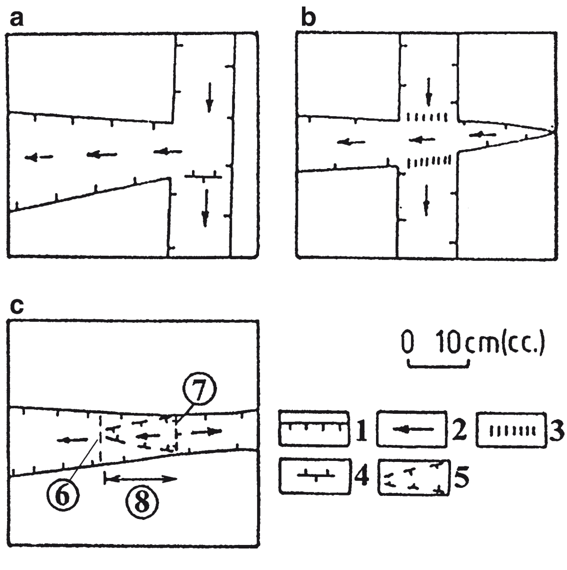


Fig. 7.4 Channel beheadings due to regression (Veress 2000a). Legend: (**a**) channel beheading channel merging of a channel head and a channel rim, (**b**) channel beheading by a crossing channel, and (**c**) channel beheading at the junction of channel heads, 1 – channel edge, 2 – slope direction of channel bottom, 3 – step, 4 – channel bottom water divide, 5 – former channel edge, 6 – former watershed divide, 7 – present watershed divide, and 8 – obsequent channel section

4. Karen inselbergs and karren monandnock may develop when the channels are connected into each other. Karren inselbergs and karren monandnock may develop on surfaces which are separated by main channels and tributary channels. Furthermore, if karren caves breakdown, and at such channels, the development is anti-regressional. But they may develop on the area of loops too. These forms may be created in the following ways:

   - The karren monandnock may develop during the connection of channel ends if two tributary channels of the same main channel retreat into each other. The karren monandnock develops at the side of the main channel (Fig. 7.5a). But it also may develop at their end (Fig. 7.5b, c). In the later case, the main channel is separated into two tributary channels with folk-like pattern.
   - The karren monandnock may develop during ‘false beheading’ if the regressional end of the tributary channel reaches the margin of the main channel. It may happen if an arched tributary channel develops from the straight main channel (Fig. 7.6a). But it can also happen if an arched tributary channel develops from the arched part of the main channel (Fig. 7.6b). Furthermore, karren monandnock may develop if one or two straight tributary channels develop at the arched part of the main channel (Fig. 7.6c). Karren monandnock may develop between main channels, too. One and one tributary channels of the two main channels contribute to the development of the karren monandnock (Fig 7.6d).
   - A karren monandnock may develop during real beheading. Then this form is surrounded by a main channel and two of its tributary channels. The separation of the karren monandnock finishes when the tributary channel, which is created faster, reaches the laterial part of other tributary channel which developed earlier (Fig. 7.7).
   - Caves may have a role in the development of the karren monandnock rarely. Then the end of the tributary channel reaches the main channel above the place of its karren cave (or one of its other tributary channels). The development of the karren monandnock ends when the roof of the karren cave collapses (Fig. 7.8a).
   - If the main-channel has a small depth and forms a loop, the water, which flows at its bottom knocks the channel margin. The water flows over the channel margin. The overflowing water creates an anti-regressional channel. The lower end of such a tributary channel may reach the main channel as its length increases. Therefore, a karren monandrock develops. This form is independent from the recess part (Fig. 7.8b). The anti-regressional tributary channel becomes hanging quickly (steps develop at both ends of the joining channels), as the main channel deepens quickly due to the water flow, which contains more solvent and consequently its entrenchment is quicker. Such tributary channels do not receive water from the main channel any more. The bottom watershed divide does not develop in the anti-regressional tributary channel.
   - The karren inselberg and karren monandrock may develop during real or false meandering at recesses. The cut-off of recess may happen at the karren neck

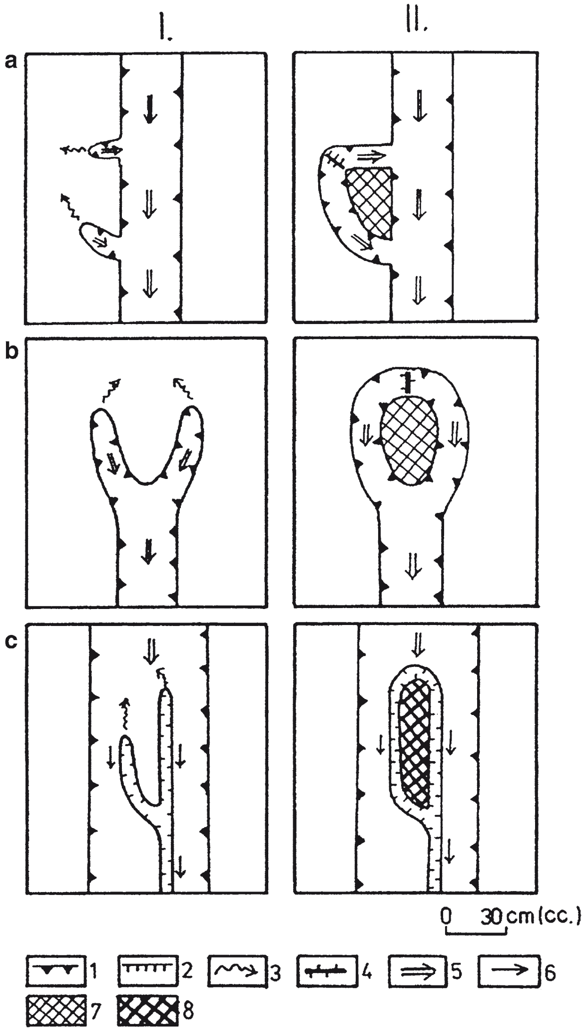


Fig. 7.5 Development of karren inselberg and monadnock by the merging of channel ends (Veress and Nacsa 2000). Legend: 1 – type I channel, 2 – type III channel, 3 – direction of the regression of the channel end, 4 – channel bottom watershed, 5 – slope direction of type I channel bottom, 6 – slope direction of type III channel bottom, and 7 – monadnock, 8. bottom monadnock, I – initial phase, II – fully developed phase, (**a–b**) connection of channel ends of type I tribunary channels, and (**c**) connection of channel ends of type III tribunary channels

with 'false budding' or 'real' budding. At false budding the karren recess is not cut off by the flowing water of the channel. In this case, rainfall falling on the recess and its neck create channels. These are the tributaries of the channels building the bend and they have a hanging position. False budding can happen at the neck or at any other parts of the recess. It may happen when

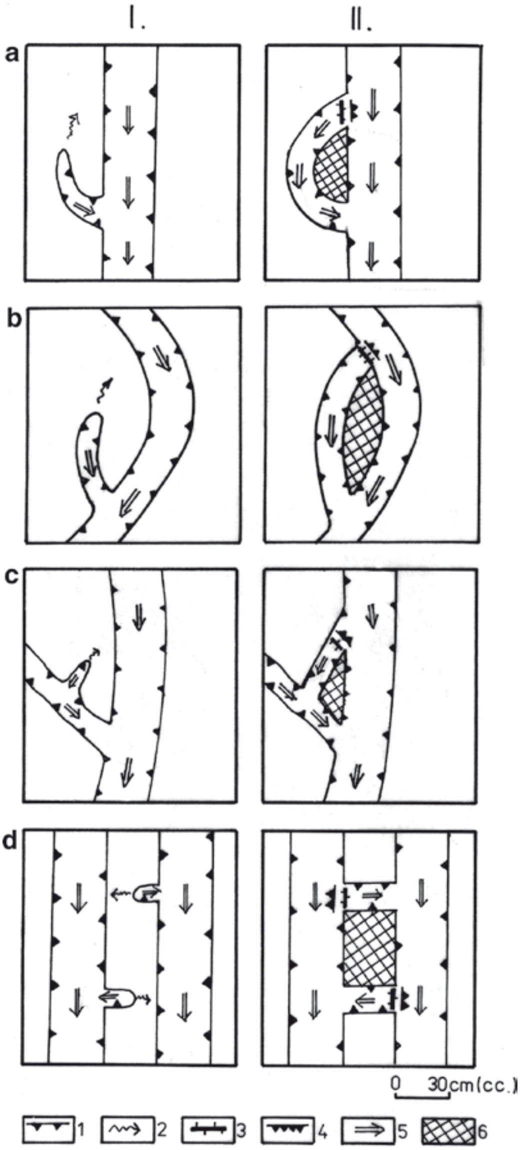


Fig. 7.6 Developing of karren monadnocks with false beheading (Veress and Nacsa 2000). Legend: 1 – type I channel, 2 – direction of regression of channel end, 3 – channel bottom watershed, 4 – step, 5 – slope direction of type I channel bottom, and 6 – monadnock, I – initial phase, II – fully developed phase, monandrock develops: (**a**). between a straight main channel and an archy retreating tribunary channel, (**b**) between of an arched main channel and an archy retreating tribunary channel, (**c**) among a straight type I main channel and straight retreating tribunary channels from the main channel and a tribunary channel which develops from the former one, and (**d**) between tribunary channels which are retreating in the oppose direction, originating from two main channels

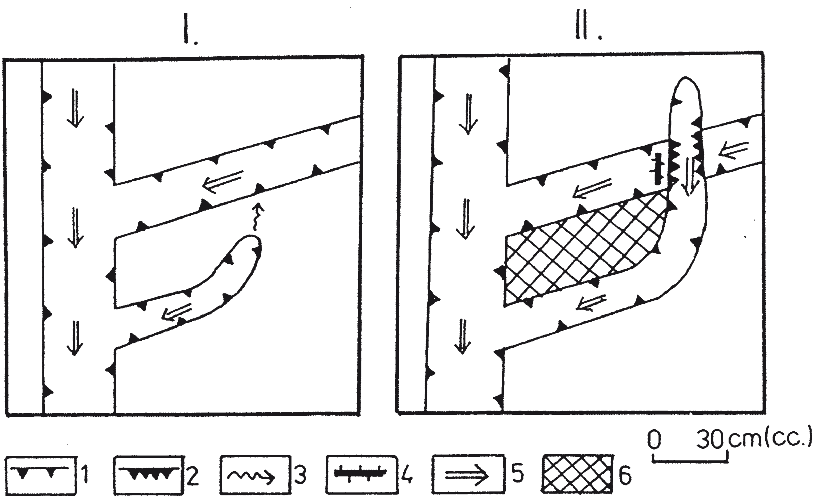


Fig. 7.7 Development of karren monadnocks with true beheading (Veress and Nacsa 2000). Legend: 1 – type I channel, 2 – step, 3 – direction of regression of channel end, 4 – channel bottom watershed, 5 – slope direction of type I channel bottom, and 6 – monadnock, I – initial phase, and II – fully developed phase

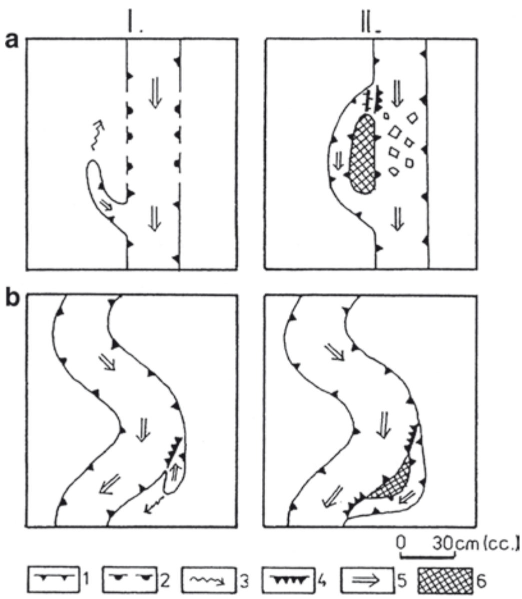


Fig. 7.8 Development of karren monadnocks after the opening up of a karren cave (**a**) and with the development of anti-regressional channel and (**b**) (Veress and Nacsa 2000). Legend: 1 – type I channel, 2 – karren cave, 3 – direction of regression of channel end, 4 – step, 5 – slope direction of type I channel bottom, and 6 – monadnock, I – initial phase, II – fully developed phase

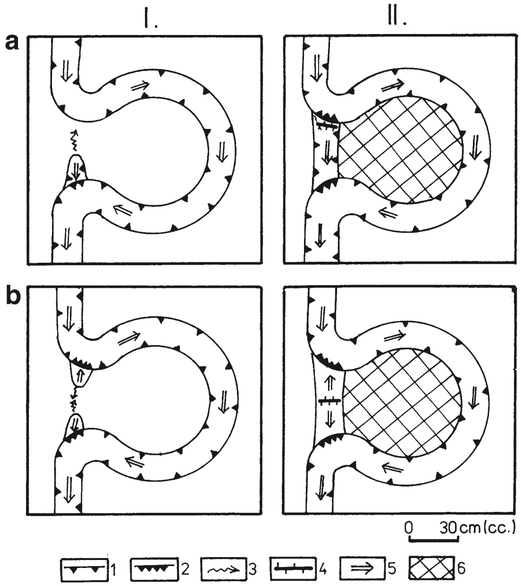


Fig. 7.9 Development of karren monadnocks with false budding of bends in the case of regression of 1 (**a**) or 2 (**b**) tributary channels (Veress and Nacsa 2000). Legend: 1 – type I channel, 2 – step, 3 – direction of regression of channel end, 4 – channel bottom watershed, 5 – slope direction of type I channel bottom, and 6 – monadnock, I – initial phase, and II – fully developed phase

a single channel retreats (Fig. 7.9a), or by the connection of two retreating channels (Fig. 7.9b). In the primary case a bottom watershed divide develops at the end of tributary. (Steps develop at its both ends.) In the latter case, the bottom watershed divide develops at the connection of the two channel heads. One and two steps develop at the mouths of the two tributaries.

- At real budding (the loop is attached) the recess is separated by the flowing water in the channel. This process can occur most simply at type III channels, because they are only a few centimetres deep. When the dip of the main channel (type I channel) is small and the meander zone of the type III channel is wide, and the length of the curve is long, the flowing of the water does not follow the curve of the loop, but it flows over the neck. Thus an intensively developing anti-regressional channel is created at the neck. The budding ends if the depth of the anti-regressional channel exceeds the depth of the channel in the bend. The separated channel section becomes hanging, its both ends are connected to the channel section which is on the area of the neck with steps. As bend slippage may happen on the surface of the recess, pointed inselberg may develop with small lateral extension (Figs. 4.35 and 7.10a). The phenomenon can be observed at type II channel, too. In these cases the cut-off of the recess occurs during the development of type III channel.

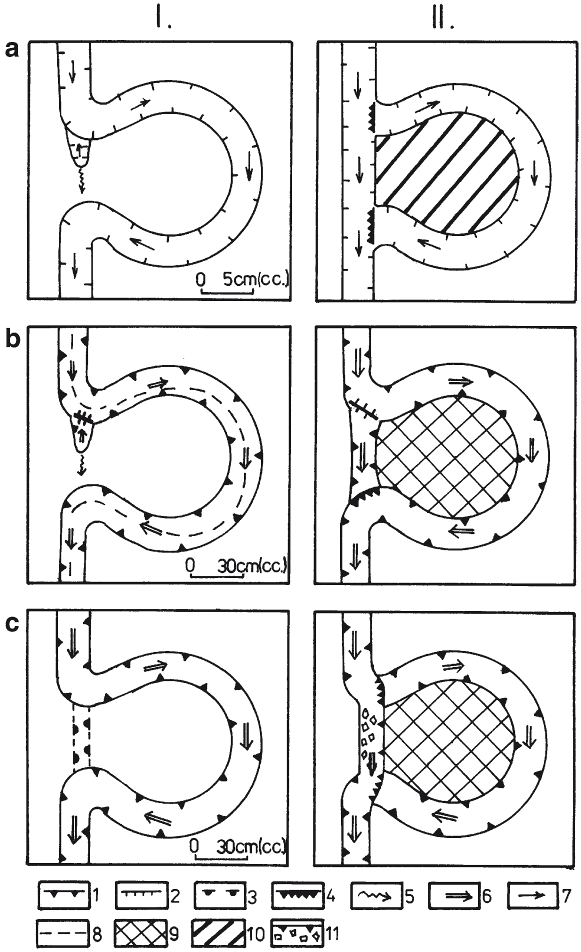


Fig. 7.10 Development of karren monadnocks with true budding of bends (Veress and Nacsa 2000). Legend: 1 – type I channel, 2 – type III channel, 3 – karren cave, 4 – step, 5 – direction of regression of channel end, 6 – slope direction of type I channel bottom, 7 – slope direction of type III channel bottom, 8 – channel-line, 9 – monadnock, 10 – karren inselberg at the bottom, and 11 – opened-up channel, I – initial phase, and II – fully developed phase (**a**) an anti-regressional channel is created by water which flows on the neck part, (**b**) the neck part is dissolved through because of the swinging of the channel-line, and (**c**) the neck part is destroyed because of cave-in of karren cave

- True budding may also develop in type I channels mostly when the channel consists of a single meander (loop meander in an over developed channel; Veress 1995, 2002). The channel line of the water (flowing in the channel) swings because the channel is meandering. The channel line hits the channel rims at the neck. The water of the channel flows over the neck, which results in partial budding of the loop (Fig. 7.10b; Picture 4.38).

The developing anti-regressional channel at the neck and the bottom of the meandering channel can deepen together. Both channel sections remain active because water can flow in the anti-regressional channel and in the cut-off part of the main channel. The lower end of the anti-regressional channel hangs above the bottom of the main channel and bottom watershed divide develops at its upper end. The monandnock created by the anti-regressional channel may be cut up to residual remnants by further channels during false beheading.

- Karren cave may develop at the neck (Picture 4.37). The development of the monandnock is finished when the roof of the karren cave breaks down (Fig. 7.10c). The budded bend is hanging, it joins the existing channel sections with steps at the neck.

Morphological maps may be constructed from any karren surfaces, which have various forms. Channel connections and those karren monandnock and karren inselberg, which developed during the process may be presented on such a morphological map. We can sketch the solution history of the mapped surface if we know the development sequence of channel connections and the monandnock (Veress and Nacsa 2000; Veress and Tóth 2001). This is the following in the case of the karren surface represented in Fig. 7.11:

- Channels marked I and II develop due to regression, which have an arched pattern. The channel marked II is the tributary channel of the channel marked I (Fig. 7.12a). Hence a series of monandnock develop.
- The monandnock marked VII developed when the channel marked II is beheaded by the channel marked III/a, which develops quickly. The bottom water divide of channel marked II proves the real beheading. (As the direction of the channel marked III/a is parallel with the direction of that water divide.)
- The channel marked III/b reaches the channel marked VI as it retreats from the channel marked III. False beheading took place. (As the direction of the bottom water divide is perpendicular to the directions of the channel. Therefore, a monandnock marked VIII develops, Fig. 7.12d.)

7.2.1.2 Forms Connected to Each Other Controlled by Rock Structure

In this case if karren forms with different sizes or different types are connected to each other, the undeveloped form always grows into or on the developed form (Fig. 7.13a). Or the vertically positioned form grows into the horizontally positioned form (Figs. 7.13b and 7.14). Bottom windows develop during such a connection.

The similarly developed karren forms may be distinguished into the following types. Windows develop near the pits and grikes that developed between joints, which go downwards and reaching each other at the end. Karren bridges occur above these windows (Fig. 7.15a). Boundary wall remnants develop if the fractures convergent upwards. But windows and karren bridges may develop too if the cracks cut each other under the surface of the time of the connection (Fig. 7.15b).

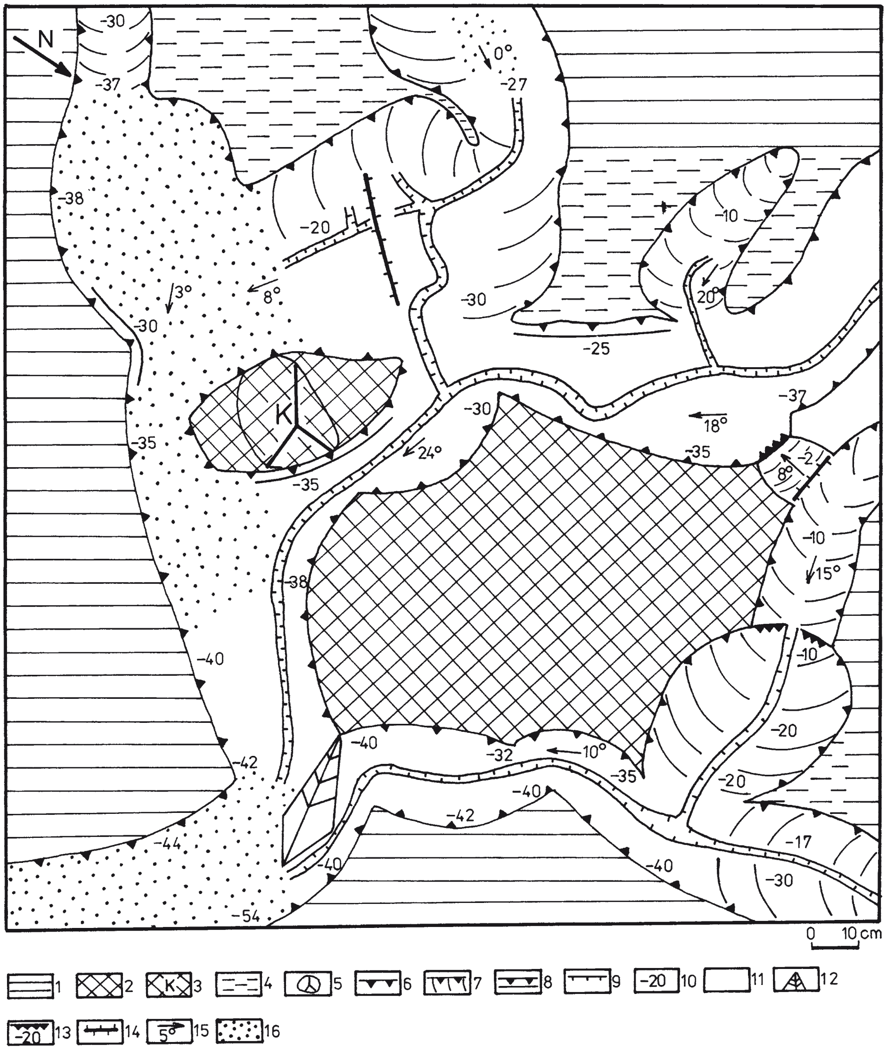


Fig. 7.11 Morphological map of a karren surface part (research area marked 1/2, Veress and Nacsa 2000). Legend: 1 – little or no karren development along the boundaries of the mapped area, 2 – monadnock, 3 – monadnock, of which surface suffered karren formation, 4 – half-inselberg, 5 – karren mounds, 6 – type I karren channel (vertical-sided), 7 – type I channel (gently sloping-sided), 8 – type I channel (overhanging-sided), 9 – type III channel, 10 – channel with depth (in centimetres) indicated at point where it was measured between the bottom and the rim, 11 – channel bottom without sediment, 12 – skirt (slippage of channel line), 13 – step with depth (in cm), 14 – channel bottom watershed divide where the coalescing of two channel ends occurred, 15 – slope direction and angle of channel bottom, and 16 – soil and weathered debris

Further more, one or some cracks are arched (Fig. 7.15c). Grike system develops if grikes occur between or among more than two or several fractures. Boundary wall remains develop between the grikes (Fig. 7.15d).

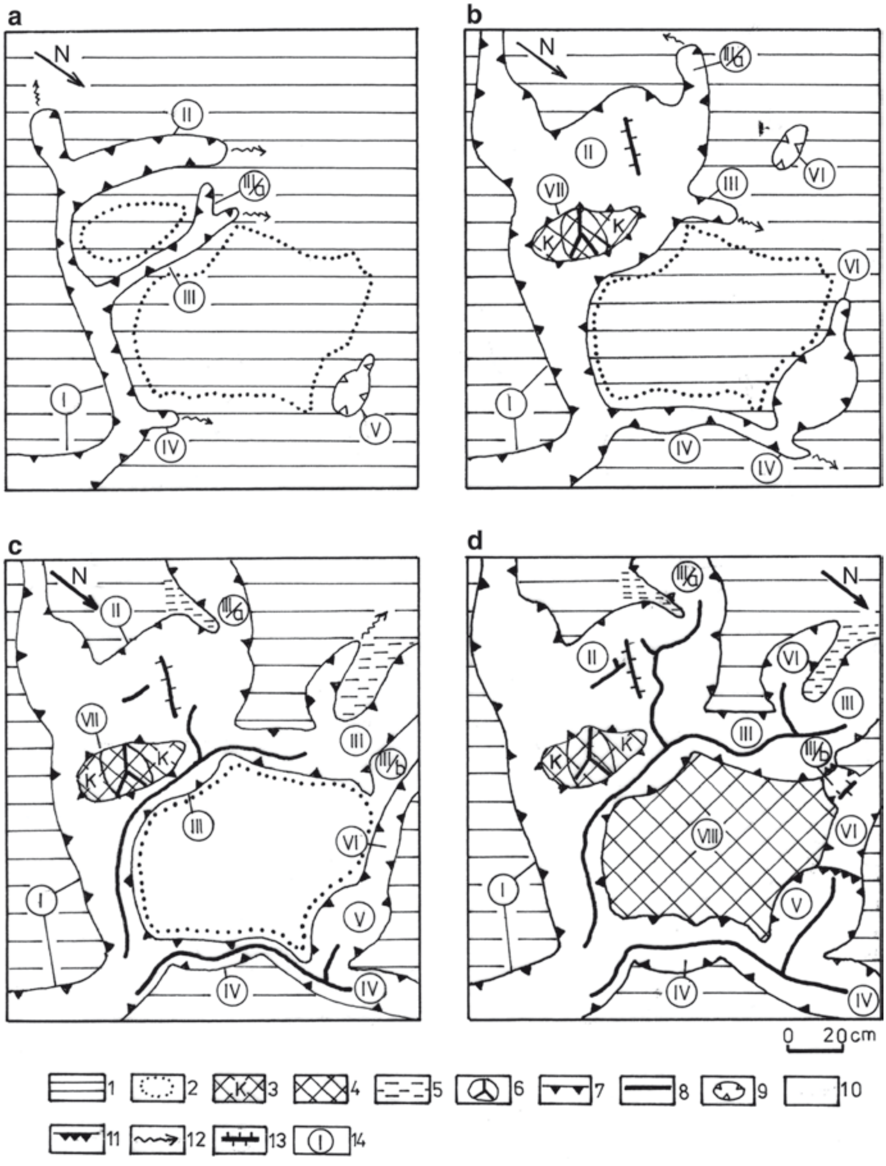


Fig. 7.12 Karen formation history of the ground surface shown in Fig. 7.11 (Veress and Nacsa 2000). Legend: 1 – surface without karren forms, or surface showing no reconstructable karren forms, 2 – monadnock or inselberg which developed latter, 3 – monadnock, of which surface suffered karren formation, 4 – monadnock, 5 – half-inselberg, 6 – karren mound, 7 – type I channel, 8 – type III channel, 9 – initial kamenitza, 10 – channel bottom and solution pan bottom without covering sediment, 11 – step with depth (in cm), 12 – direction of regression of channel end, 13 – channel bottom watershed, and 14 – identifying labels of channel, kamenitza and monadnock (**a**, **b**, **c**) (the letters indicate different arbitrarily chosen relative ages of the karren formation history) former condition, (**d**) present condition

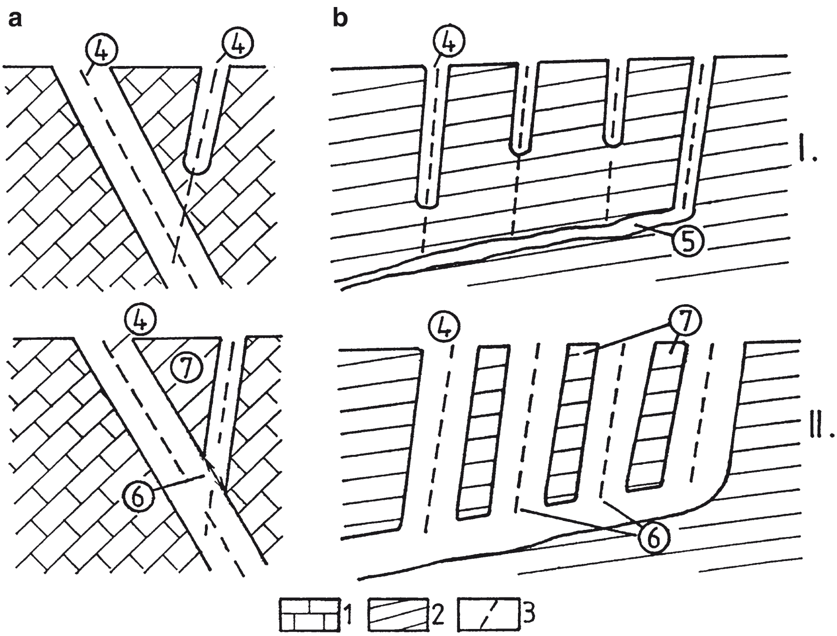


Fig. 7.13 Connection of karren forms of different sizes and types (conceptual sketch, Veress 2000e). Legend: (**a**) connection of pits of different sizes (on growing), and (**b**) connection of different karren forms, I – stage before connection, and II – connection, 1 – limestone, 2 – bedding plane, 3 – fault, 4 – pit, 5 – cave, 6 – window, and 7 – natural bridge

Lateral solution happens in those pits and grikes which are filled with soil (Jennings 1985). These forms can be dissolved into each other along the pockets and notches (scour groove) during subsoil solution. In this case the connection is controlled by the rock structure considerably, too.

7.2.2 *Forms Connecting into Each Other Due to Secondary Causes*

These processes may be of solution or other origin. Such processes may be termed as follows:

- Boundary walls between pits may be cut through due to solution, if the rock is well bedded and the water seeps from the pit bottom into the direction of the neighbouring pit along the bedding plane (Fig. 7.16a). This phenomenon may also occur, if the seeping water of the rock is led by a slanting positioned crack to a part of the boundary wall (Fig. 7.16b). In the previous case windows develop, where the boundary walls are cut by the bedding plane, which leads the water.

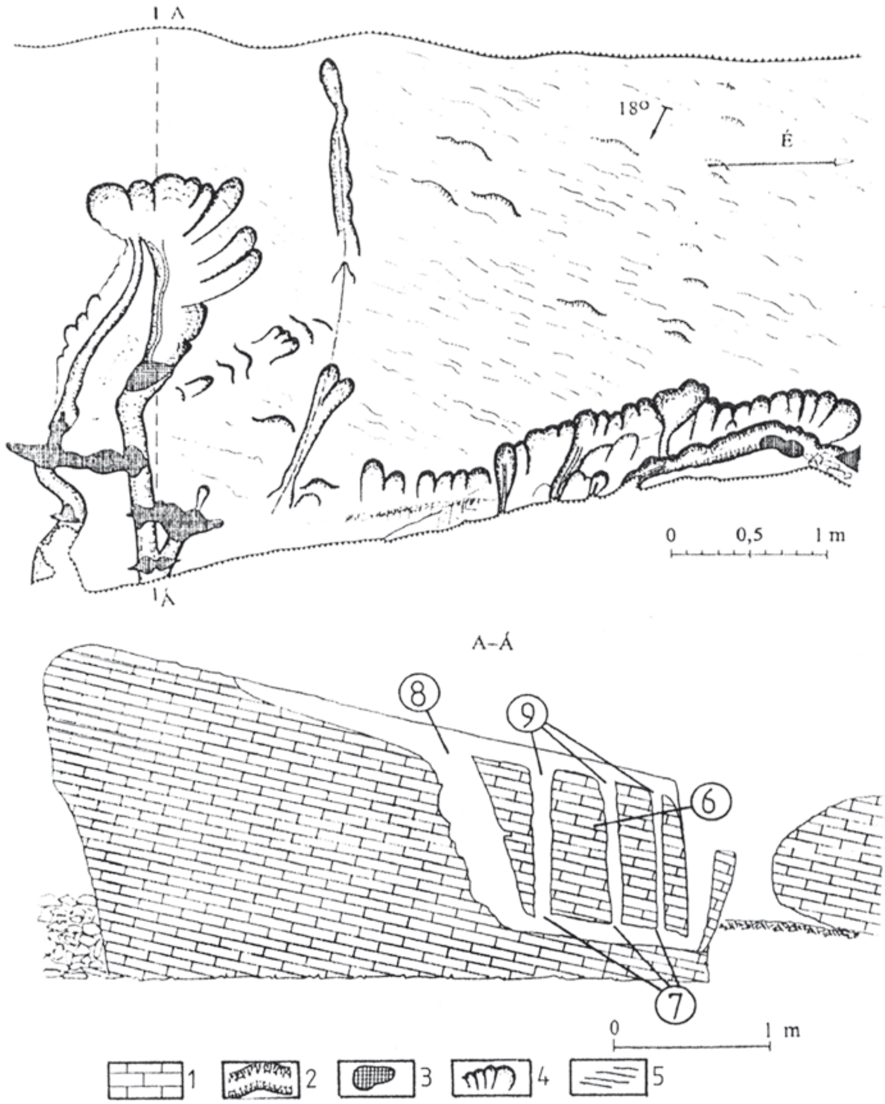


Fig. 7.14 Partition wall natural bridges between channel bottom pits (research area marked 1/4, Szunyogh 1995). Legend: 1 – limestone, 2 – channel, 3 – pit, 4 – leaf karren, 5 – staged rock surface, 6 – natural bridge, 7 – window, 8 – channel bottom pit formed by channel beheading, and 9 – channel bottom pit formed after beheading

In the later case it happens, where the boundary walls are cut by a crack which leads the water.

- The water flowing on the boundary walls may cause the dissolution of the boundary wall. In such a case windows may develop anywhere on the boundary walls.

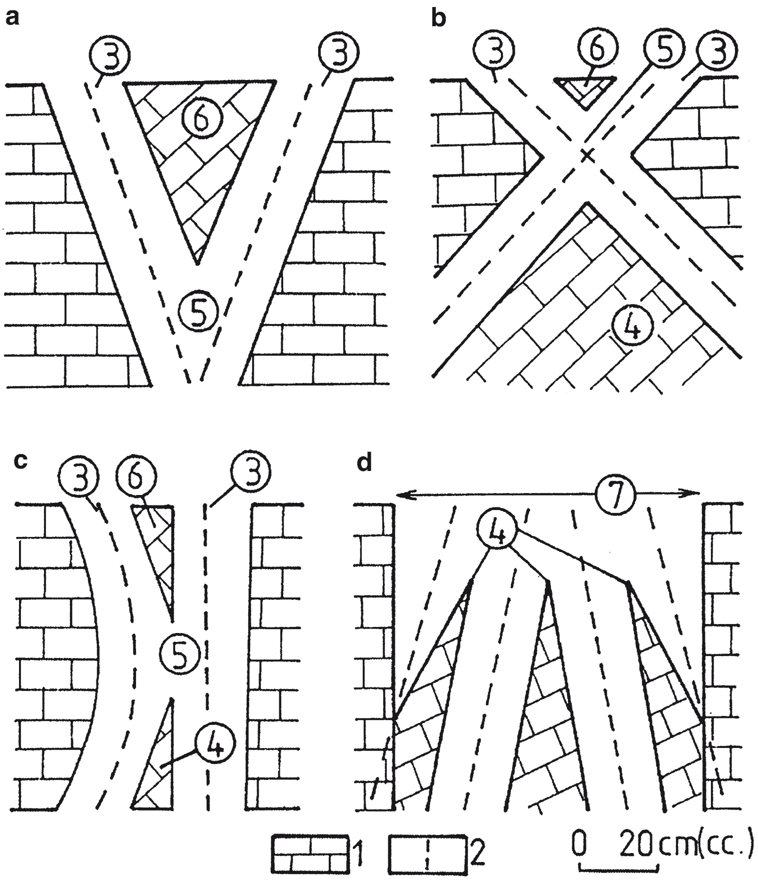


Fig. 7.15 Connections formed by growing of similar sized karren forms (conceptual sketch, Veress 2000e). Legend: fault lines, on which the forms develop and converge downwards (**a**), upwards (**b**), cambered (**c**), with different directions and (**d**), 1 – limestone, 2 – fault, 3 – pit, 4 – partition wall remnant, 5 – window, 6 – natural bridge, and 7 – composite fissure

- The boundary wall between the channels is cut through (meanderkarren), where the channel line reaches one or both walls of the channel. Namely under solution happens at these places, because solution can be more intense at such places as water flows faster. The channel line reaches the wall of the channel at false meanderkarren and at true meanderkarren. If false meandering happens, the channel line reaches the walls of the channel at one place. This is the point where the channel changes its direction. If this place is near another channel, a window develops during the solution on the boundary walls (Fig. 7.17a). At the concave merging of the loops of the meanderkarren the channel line touches the boundary walls of the loop for longer period of time the channel line and for a longer distance due to the seepage. The value of the downward solution will be

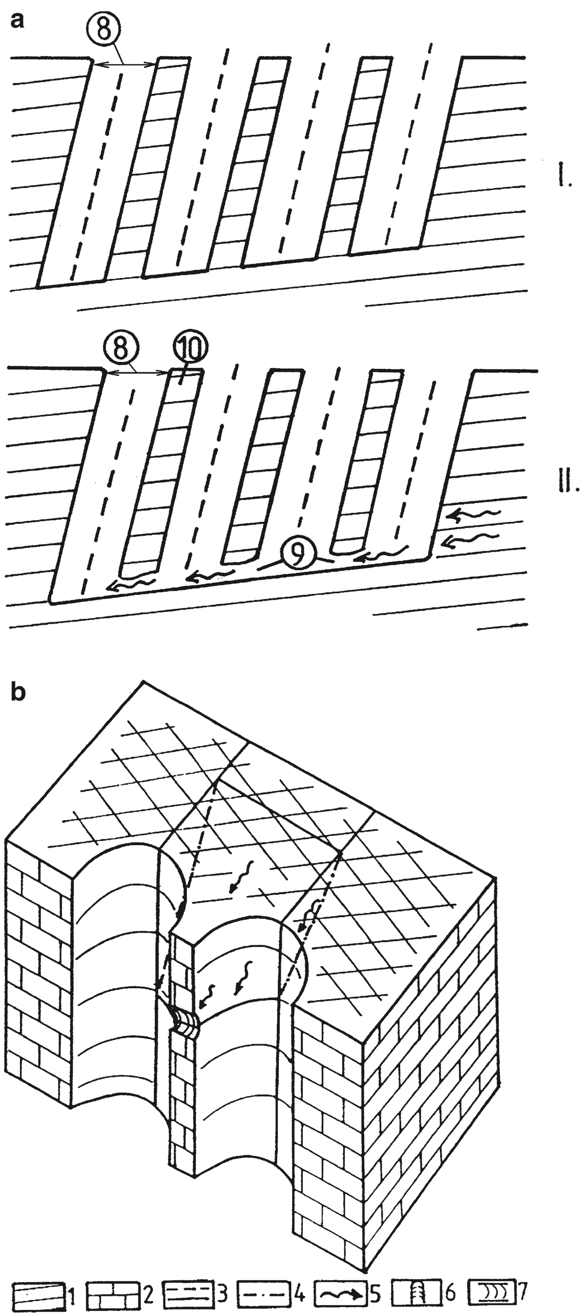


Fig. 7.16 Window development caused by solvent filtration on bedding plane (**a**) and fault plane (**b**) (conceptual sketch, Veress 2000e). Legend: I – stage before connection, and II – stage after connection, 1 – bedding plane, 2 – limestone, 3 – fault, 4 – fault plane, 5 – infiltration on fault plane, as well as on bedding plane 6 – pit, 7 – window, on cross-section: 8 – pit, 9 – window, and 10 – natural bridge

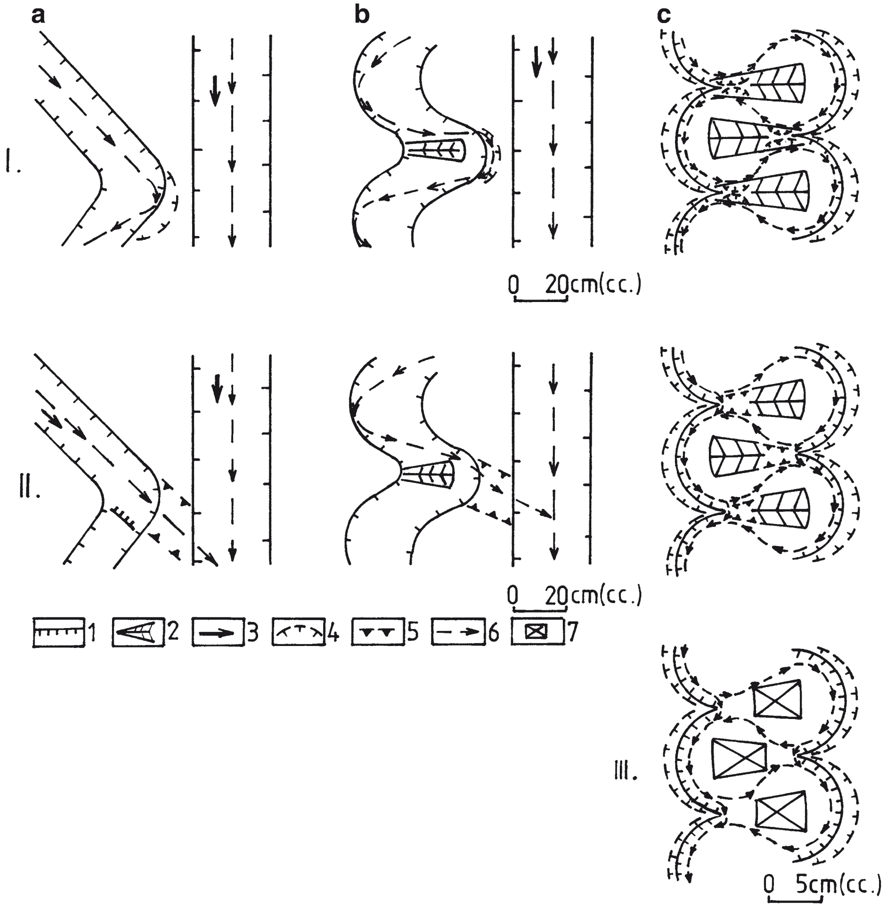


Fig. 7.17 Window development on channel's side walls (conceptual sketch, Veress 2000e). Legend: (**a**) window development between falsely meandering and straight channel, **a**.I development of overhanging wall, **a.**II window development, (**b**) window development between meandering and straight channel, **b**.I development of overhanging wall, **b**.II window development, (**c**) window development on meandering channel's skirt, **c**.I overhanging walls develop on the skirt's neck, **c**.II window development between the opposite overhanging walls, **c.**III channel bottom inselberg develops by destruction of natural bridge, 1 – channel's rim, 2 – skirt, 3 – direction of slope the channel bottom, 4 – overhanging channel wall and skirt wall, 5 – window, 6 – channel line, and 7 – channel bottom monandrock

greater and greater. The ridge between the two neighbouring meanderkarren is cut. Windows and karren ridges develop, which have long shapes and their margins are arched (Picture 7.9; Figs. 7.17b and 7.18). The necks of the skirts will be thinner and thinner, because the channel line reaches side walls, too (Fig. 7.17c.I). The water flowing at the bottom cannot flow over the skirt, if the height of the neck is sufficiently great. It will dissolve the neck. A window and

Picture 7.9 Oscillation flow, which caused meanderkarren; the window developed by the oscillation of the flowing water, on wall (Valley of Triglav Lakes). Legend: 1 – type I channel, 2 – meanderkarren, 3 – skirt, 4 – window which is on wall between meanderkarren and channel, and 5 – ridge

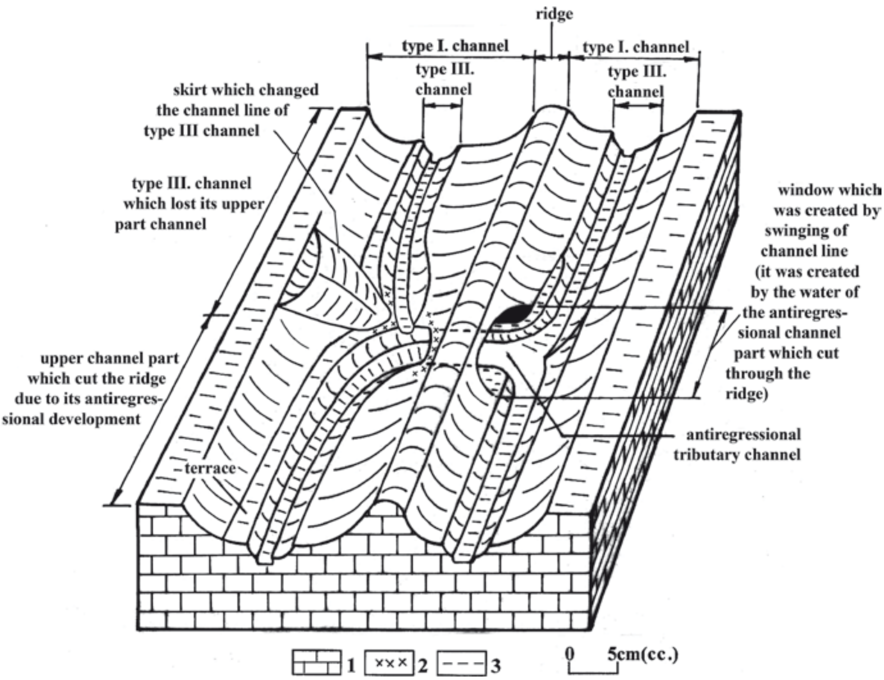


Fig. 7.18 Because of the swinging channel line anti-regressional channel develops which results in window formation in the ridge (research area marked 1/2, Veress 2003). Legend: 1 – limestone, 2 – former bend of the type III which is created by capture, and 3 – karren cave (note: the skirt meander caused the oscillation on the channel line)

a karren bridge develop in this case (Fig. 7.17c.II; Picture 4.37). Bottom karren inselbergs develop if the karren bridges are destroyed (Fig. 7.17c.III; Picture 4.36).

- Tunnels, rock ears may be created by the acids produced by the roots of the plants in the karren forms. These forms can connect karren forms which are relatively far from each other.

Processes of non-solution origin which cause the connection of the forms are the following:

- Frost weathering
- Collapse
- The pressure caused by the roots

Forms, which are connected to each other during these processes may grow, or may be transformed or destroyed. Already formed windows grow, karren bridges decrease during frost weathering. Karren bridges and boundary walls are cut through because of breakdown. The remnants of the boundary walls can tilt from their original positions. The same process happens due to the pressure caused by the roots when the boundary walls tilt or change their original positions. If pits and rain pits develop on these later remained forms, the above-mentioned processes are favoured.

7.3 United Karren Forms Types

7.3.1 The Union of Similar Karren Forms

- Most frequently the union may proceed between pits. The process may happen among the pits in a group (Fig. 7.19) or between such pits, which create lines (Figs. 7.20 and 7.21). This later process is considerable if the crack which connects the pits, developed into a grike already due to solution widening. Mostly the union takes place at the lower parts of the pits. Therefore, a series of karren bridges develop which have a high position. First, pit uvalas develop from two or three uvalas if pits found among a line are united (Fig. 7.21I–II). Grikes and grikekarren develop if these pit uvalas are united (Picture 7.10; Fig. 7.21III). Frequently pits constructing a line are united not only in longitudinal but in cross-sectional directions too. In this case, corridors develop. Greater pits, further more irregularly shaped depressions, develop if pits of a pit group are united (Fig. 7.19).
- Frequently grikes of the grikekarren unite too. This may happen in two ways. Complex grikes develop, and later corridors are created from these forms if the upper parts of the boundary walls are destroyed by solution. If the lower part of the rock walls are cut through, the boundary walls fall out. During the process a

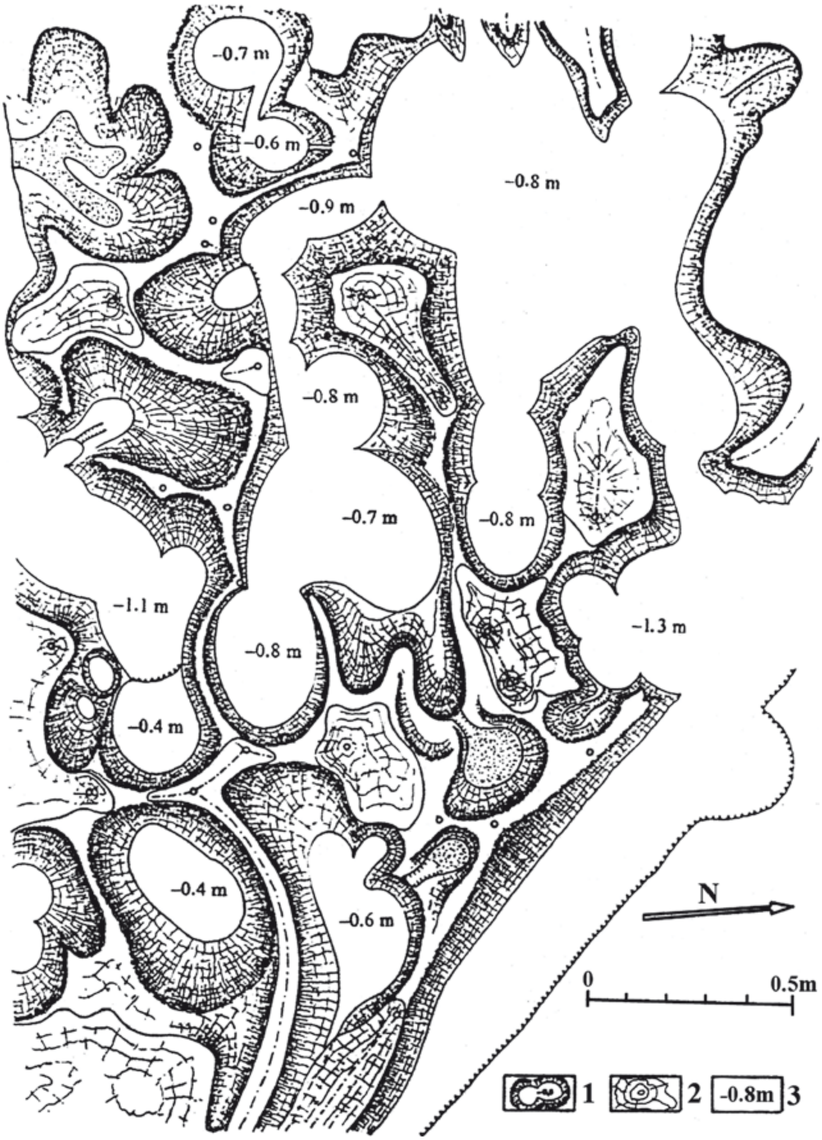


Fig. 7.19 Connected pits of a group of pits (research area marked 1/2, Szunyogh 1995). Legend: 1 – pit, 2 – cone-formed pitch, and 3 – pit with depth value (in m)

wide grike may develop. If the rock is well bedded, the lowest positioned bed may be separated completely from the floor bed. This bed is peeled off.

- Most rarely channels also may be connected. Then the karren bridges which are between channels breakdown and uvala channels develop.
- Kamenitza uvalas develop when kamenitzas are united.

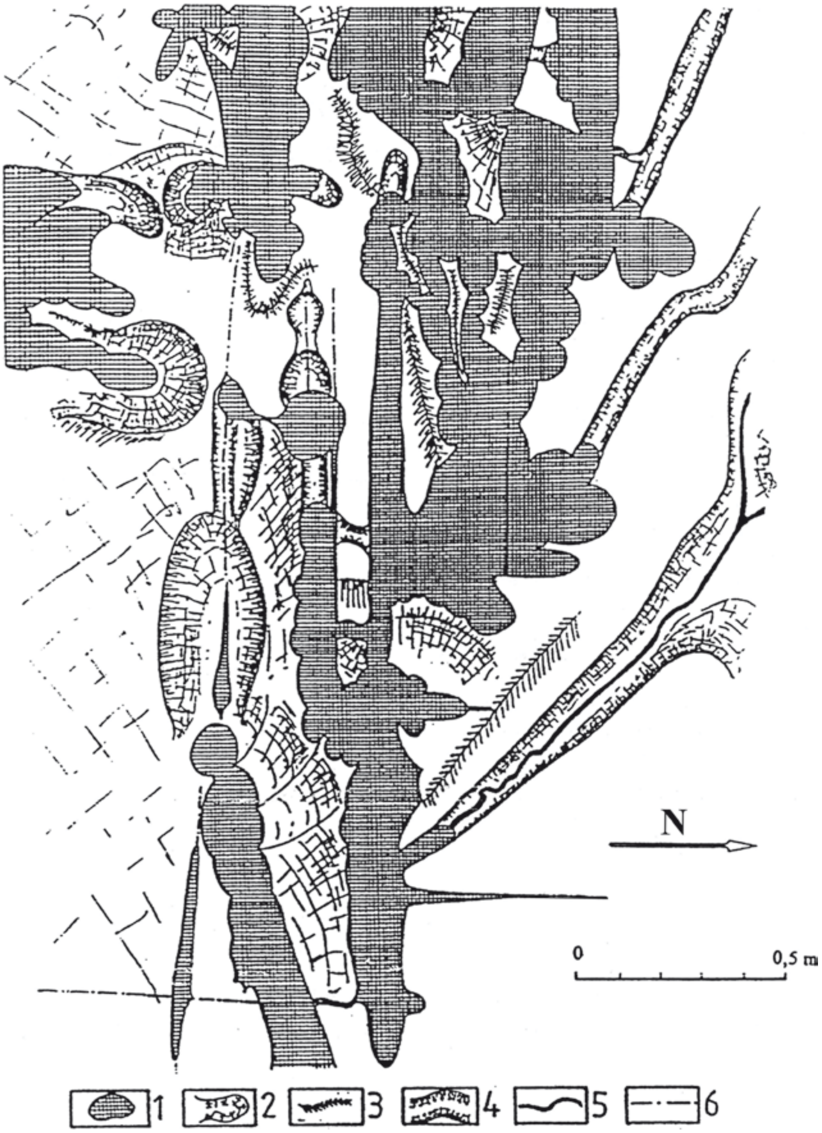


Fig. 7.20 Grikekarren formed of pits (Totes Gebirge, Szunyogh 1995). Legend: 1 – pit, 2 – basin-like bottom, 3 – sharp ridge breaking up the surface, 4 – type I channel, 5 – type III channel, and 6 and fault line

- Trittkarren uvalas develop if trittkarren of a group (but in a line) of trittkarren are united. Channels develop if the direction of the trittkarren is concordant with the dip direction of the slope (Picture 4.26).

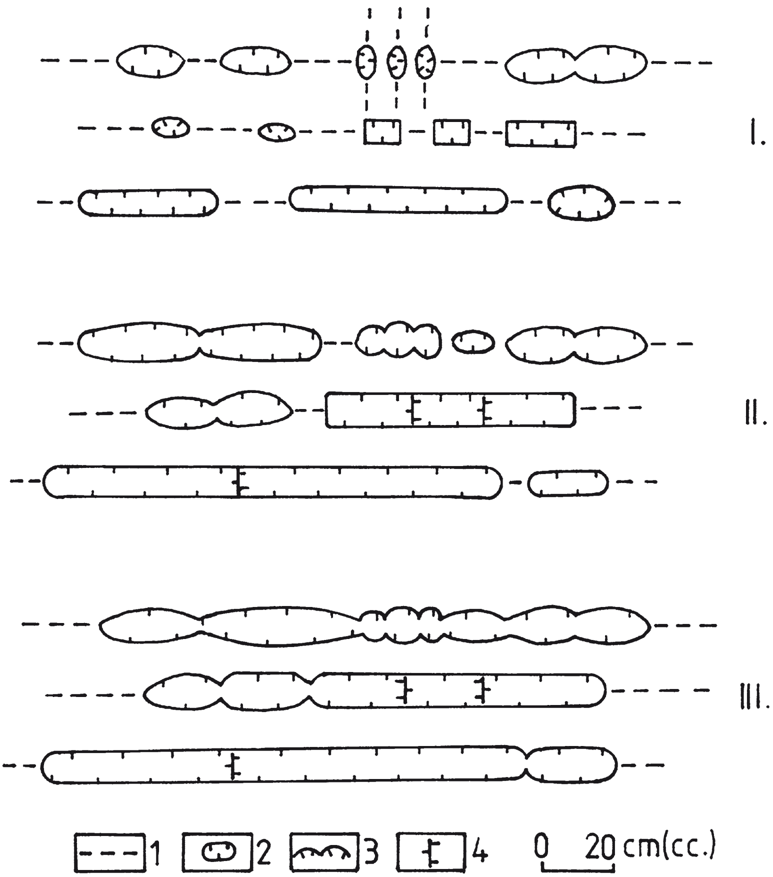


Fig. 7.21 Grikekarren which was created by the union of different pits (by using examples from Valley of Triglav Lakes, Veress 2003). Legend: I – karren pit is formed, II – pits and grikes develop partly, and III – grikekarren develops, 1 – joint, 2 – pit, 3 – arcue margin grike, which has wall stumps, and 4 – straight margin of the grike, which has wall remains

7.3.2 The Union of Different Karren Forms

Joining of different karren forms with solution mostly takes place at the phase of the connection into each other. Various karren forms may unite rarely. For example, we mention the coalescing of channel and karren cave (an opened-up channel develops). The karren caves, which are under channels, lost their ceiling. It happens partly due to solution. The solution happens from down to upwards from the karren cave and from upwards to downwards from the channel. It may happen due to breakdown. Karren bridges and karren windows develop at the beginning of the process with local breakdown of the ceilings. The windows are circular shaped if

Picture 7.10 Grike which developed from coalescing pits (area marked 3/2). Legend: 1 – pit remnant, and 2 – grike

the channel crosses the karren cave. They are elongated if the channel is above the karren cave in its total length. Channels develop to the karren sinkhole of the former karren cave, which have a characteristic profile. The cross-section of this type is becoming narrower from upwards and the shape under this part is almost circular (Figs. 4.9d and 7.2; Picture 7.8). Ceiling remnants occur on the side of the channels (Figs. 4.9d and 7.2; Pictures 7.7 and 7.8).

7.4 Karren Cells

Karren cells are karren 'islands' on any slope. They develop independently from each other. According to Veress (2003) the characteristics of karren cells are the following (Figs. 7.22 and 7.23):

- A karren cell is a part of a slope. The karren cell is distinguished from its surroundings or other karren cells regarding its morphology and hydrology (Fig. 7.23).
- Karren cells can develop with greater chance if the dip of the bearing slope is smaller than 10°.

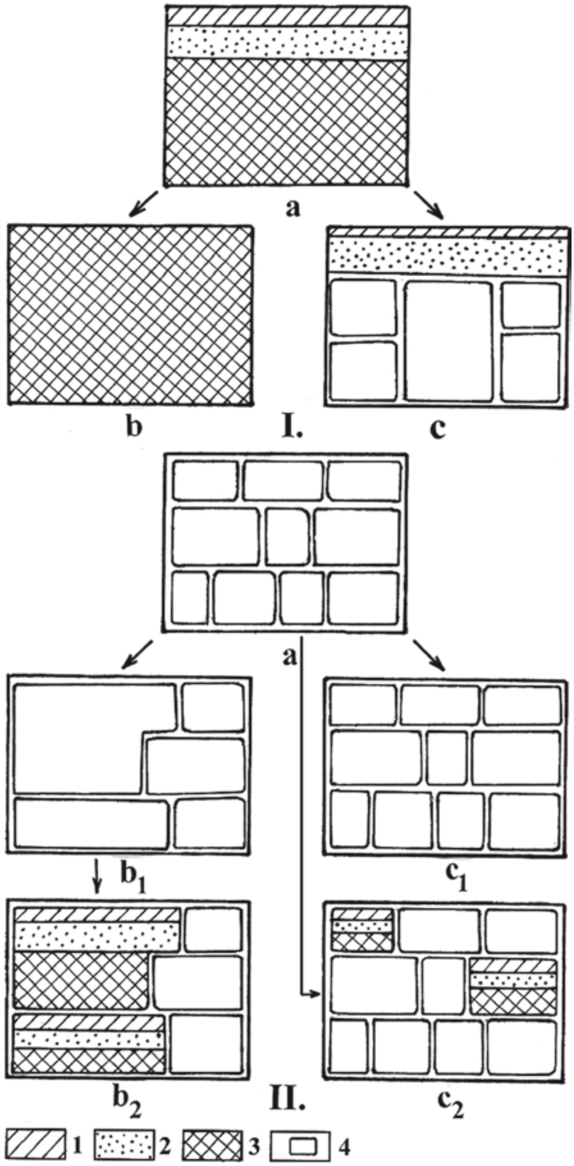


Fig. 7.22 Some developing types of karren cells (Veress 2003). Legend: 1 – rillenkarren belt, 2 – solution bevel, 3 – rinnenkarren belt, 4 – karren cell, I.a initially karen belts can be found on the slope, I.b rinnenkarren belt occurs on the slope, I.c karren cells develop in the rinnenkarren belt, II.a several karren cells develop on the slope at the beginning, b_1 the karren cells spread in the direction areas of the neighbouring karren cells, b_2 belts of karren form develop on some karren cells c_1 condition of the karren cells becomes stable, c_2 belts of karren forms develop on a part of the original karren cells

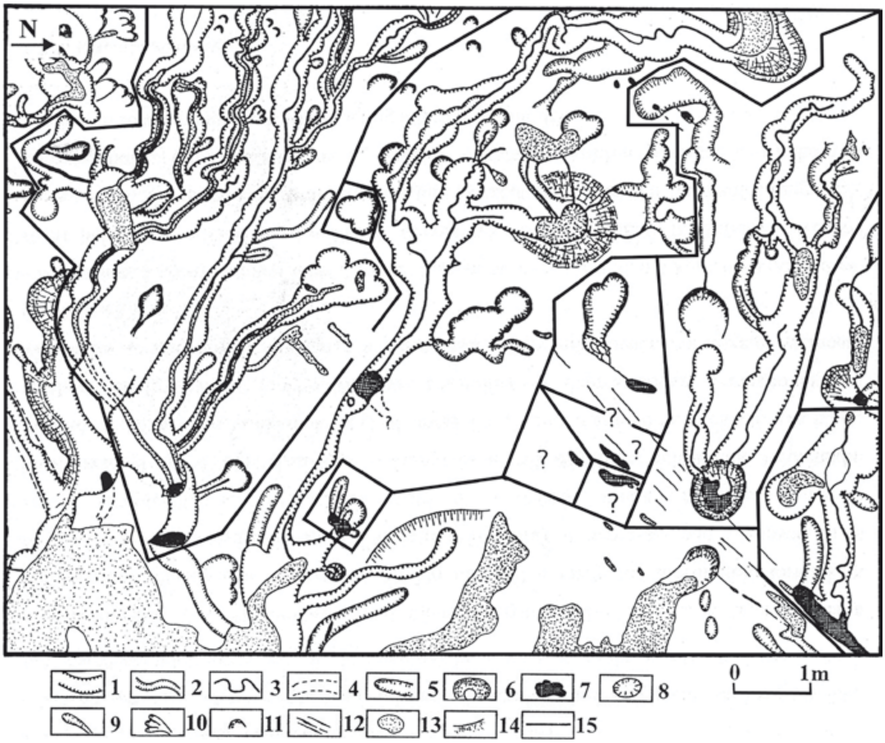


Fig. 7.23 Karen cells (resrached area marked I/2 using Szunyogh et al. 1998 map). Legend: 1 – type I channel with depth value of 20–25 cm, 2 – type II channel with depth value of 5–10 cm, 3– type III channel, with depth value of 1–2 cm, 4 – karren cave, 5 – trough-like depression (kamenitza), 6 – pot-like depression (kamenitza), 7 – pit, 8 – kamenitza, 9 – long depression, which leads into to a channel, 10 – leafkarren, 11 – trittkarren, 12 – joint which developed by solution, 13 – plant, 14 – step, and 15 – boundary of karren cell

- The water which gets to the area of the karren cell does not flow out of its area. A pit or a karren cave can be created in the internal of the karren cell. These karren forms lead its water under the surface. The area of the karren cell may be ‘bordered’ by a karren watershed divide. The watershed divide is the ridge between two karren cells. It is usually not continuous, but it is a wide zone. Its morphology is hard to recognize. The karren watershed divide does not always close the water circulation between the neighbouring karren cells. The melt snow of a karren cell flows into the area of other neighbouring karren cells in certain cases for various time periods.
- Its area is various. Its expansion may be from several decimetres to several tens of square metres.
- The shape of karren cell is determined by the pattern of its karren forms, the dip direction of the bearing slope and the neighbouring karren cells. Its shape is

often elongated but mostly has an uneven form. Its expansion (size) and its shape depend on the cell density of the bearing area and the sequence of the cell development and their development velocity.

- The forms of the karren cells do not show various belts on average.
- One or several karren cells can occur on a karren surface, too.
- The neighbouring karren cells may occur in a way that wide non-karren surface can be found between them. But they may develop directly next to each other, too. In that case non-karren zones are absent between them. Channels can retreat to the area of the neighbouring cell during the development of a karren cell. The area of the pervious form is connected to the karren cell partly or totally.
- The most important forms of karren cells are rillenkarren, rinnenkarren, pits and karren caves.
- The karren cells may expand, deepen, be transformed, be connected into each other and destroyed during their development (Fig. 7.22). Therefore, karren cell becomes more and more dissected and deeper and have cavities. Its karren forms may be destroyed or soil and plants develop on their forms during its development. In the previous case the karren cell may be destroyed. Its area will be covered with debris. In the latter case the solution intensity increases on its area. New karren forms may exist on the area of the karren cells, too (e.g. kamenitzas). Secondary zonality of a karren form may occur on their area. The bearing surface is dissected by karren forms (mainly by channels) during the development of the karren cells. The area of the karren cells forms a depression. This process happens mainly if the ridges which are between the channels are destroyed. Debris develops. If the debris does not cover the surface, then a new generation of channels develop.

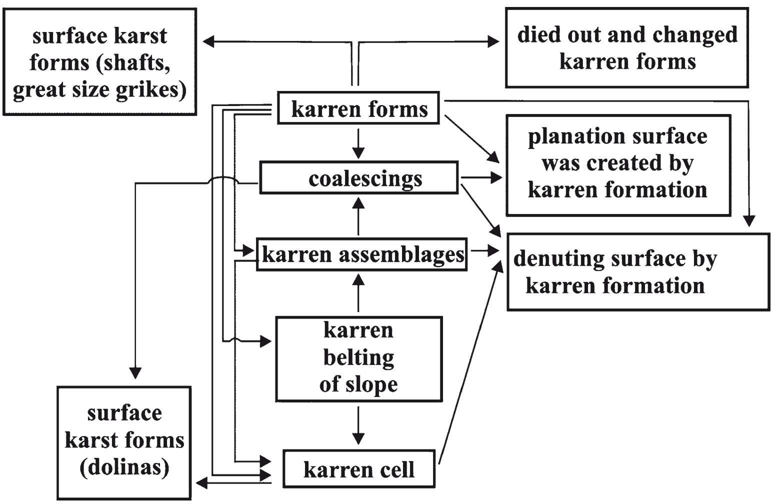


Fig. 7.24 Relationship of karren formation levels to each other and to karstification

7.5 Relationship System Between the Levels of Karren Formation in High Mountain

The various karren formation levels may be transformed into each other during karren formation. In general the ‘lower’ karren formation level may develop into a ‘higher’ karren formation level. The opposite process can be true as well. The groups of the karren forms may develop to different karren formation levels. The level of the karren formation is determined by karren formation conditions. An even surface as well as other karst forms such as dolines can be formed (Fig. 7.24) during karren formation of a given karren formation level. Debris which were created during karren formation can cover the even karren surfaces. These even karren surfaces can suffer karren formation again.

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