Tadej Slabe

Cave Rocky Relief

Tadej Slabe, (born on April 3, 1959) is a research fellow at the Karst Research Institute, of the Scientific Research Centre of the Slovene Academy of Sciences and Arts, being its head since 1995. In 1983 he graduated at Ljubljana University in geography and sociology. His main studies are speleogenesis, especially the speleomorphogenesis of karst caves as parts of karst aquifers. He has presented his knowledge in various karstological periodicals, and at scientific meetings and karstological schools. He reported on the origin of individual rocky forms, on experimental modelling of rocky features in plaster of Paris, on activities that shape the rocky surface in caves, on speleogenetical evidence of rocky relief in particular caves, and on the speleogenetical importance of rocky relief in typical caves of karst aquifers. In his master's thesis (1989) and in his doctoral thesis (1992) he reviewed existing knowledge about rocky relief on the rock surfaces of Slovene caves and extended it with his own work. He cooperates in the planning of motorways over the Slovene Karst and is in charge of karstological control over motorway construction. Newly discovered caves there bring new knowledge about the Classical Karst development.

ZRC 10

Tadej Slabe

Cave Rocky Relief and its Speleogenetical Significance

ZNANSTVENORAZISKOVALNI CENTER SAZU
Ljubljana 1995

Tadej Slabe
Cave Rocky Relief and its Speleogenetical Significance

Zbirka ZRC
10
ZNANSTVENORAZISKOVALNI CENTER SAZU
Zanj: Oto Luthar
Uredila
Dragica Turnšek

Prevedla
Maja Kranjc
Jezikovni pregled
Trevor R. Shaw
Oblikovanje in tehnična ureditev
Milojka Žalik Huzjan
Tisk
Planprint, d.o.o.
Ljubljana 1995

CIP - Kataložni zapis o publikaciji
Narodna in univerzitetna knjižnica, Ljubljana

551.44

SLABE, Tadej
Cave rocky relief and its speleogenetical significance / Tadej Slabe ; [prevedla Maja Kranjc]. - Ljubljana : Znanstvenoraziskovalni center SAZU, 1995. - (Zbirka ZRC ; 10)

ISBN 961-6182-03-X

55617792

CONTENTS

1. INTRODUCTION 7
  - 1.1. Objectives and Scope of Rocky Relief Studies 7
  - 1.2. The Literature About Rocky Features 8
  - 1.3. The Selection of Caves 9
  - 1.4. Gathering and Study of Rocky Relief Material 11

2. THE ORIGIN AND DEVELOPMENT OF THE CAVE ROCKY FEATURES 12
  - 2.1. Factors, Conditions and Processes of Rocky Feature Formation 12
  - 2.2. Properties, Terminology and Classification of Rocky Forms 14
  - 2.3. Rocky Features due to Turbulent Water Flow 17
    - 2.3.1. Hydraulic Bases 18
    - 2.3.2. Scallops and Flutes 19
    - 2.3.3. Celing Pockets 35
    - 2.3.4. Potholrs 46
    - 2.3.5. Columns, Pendants, "čer", and Arches 49
    - 2.3.6. Wall Niches 53
    - 2.3.7. Wall and Ceiling Notches 53
    - 2.3.8. Floor Channels 55
    - 2.3.9. Ceiling Channels 57
    - 2.3.10. The Surface of Rocky Features Downcut by the Water Flow, Extamined by the Scanning Electron Microscope 58
  - 2.4. Along Sediments Cave Rocky Features 61
    - 2.4.1. Above-Sediment Ceiling Channels and Anastomoses 61
    - 2.4.2. Above-Sediment Niches and Pockets 69
    - 2.4.3. Below-Sediment Solution Bevels 71
    - 2.4.4.Below-Sediment Floor Pits 72
    - 2.4.5. Ceiling Pockets due to Water Oozing off the Sediment 73
    - 2.4.6. Below-Sediment Roof Pendants 74
    - 2.4.7. Corrosion Notches and Niches on the Walls 75
    - 2.4.8. The Surface of Rocky Features at the Sediments 76
  - 2.5. Rocky Features due to Trickling and Dropping of Water 78
    - 2.5.1. Laboratory Experiments of Niches Formation due to Water Trickling down from the Roof Fissure 80
    - 2.5.2. Floor Pits due to Water Dropping 84
  - 2.6. Below-Ice Rocky Features 85
  - 2.7. The Formation of Rocky Perimeter due to Condensation Moisture 86
    - 2.7.1. Ceiling Solution Cups, Large Scallops and Ceiling half Tubes 87
    - 2.7.2. The Rocky Surface Etched by Condensed Moisture 87
  - 2.8. Biogene Rock Features 92
  - 2.9. Rocky Features due to Rock Disintegration 95

3. CAVE ROCKY RELIEF - THE EVIDENCE OF FORMATION AND GENESIS OF KARST CAVES 96
  - 3.1. Rocky Relief as a Sign of Characteristic Formation of the Caves 97
    - 3.1.1. The Properties of Rocks Relief in Passages Shaped by Water Flow 97
    - 3.1.2. Rocky Relief Formed by Water Trickling Down 100

3.2. Rocky Relief as Evidence of Karst Caves Development 101
    3.2.1. The Old Rocky Relief in the Development of Uniform Passages 101
    3.2.2. Rocky Relief as Evident of Different Development Phases of a Passage 102
    3.2.3. Rocky Relief of Large Cave Systems 105
    3.2.4. Rocky Relief as an Indicator of Speleogenetical Unit Development - Aquifers 108
    3.2.5. The Development of the Selected Caves According to Rocky Relief Evidence 111
    3.2.6. Rocky Relief as a Speleogenetical Indicator 112

4. CONCLUSION 114

5. REFERENCES 116
6. LIST OF ILLUSTRATIONS 121

7. POVZETEK 124
  Jamski skalni relief in njegov speleogenetski pomen 124
    Uvod 124
    Nastanek in razvoj skalnih oblik 124
    Speleogenetski pomen jamskega skalnega reliefa 126

IZVLEČEK – ABSTRACT 128

1. INTRODUCTION

1.1. *Objectives and Scope of Rocky Relief Studies*

Factors shaping the karst underground leave the traces on the rocky perimeter of the caverns. The associated rocky features are called rocky relief. The relief is frequently an important speleomorphogenetical indicator and, as such an indispensable component of interdisciplinary speleological researches.

The water, either flowing streams or infiltrated water, dissolves and mechanically downcuts the carbonate rocks. Hydrological conditions and factors of cavernosity reflect in the shape of caverns, in cross and longitudinal sections of the channels and cave rocky relief according to the rock lithology. The water deposits fine-grained and coarse-grained sediments and flowstone. Knowledge of their origin, development and age contributes to the explanation of the speleogenesis. All these are the important indicators of both the formation and genesis of a cavern.

In rocky relief one may find traces of water flows; the surface is etched, pitted and transected by various types of scallops, ceiling pockets and potholes. Due to water flow above the sediment top channels occur, percolation water forms half tubes and solution niches, and condensation humidity and biocorrosion etch the rocky perimeter. The knowledge of various factors, effects and conditions of their activity are of great help in karst caves study. This advantage is frequently given by studying rocky relief. The initial stages of cavern formation are reflected in the relief as well as later transformations or, eventually, several factors at the same time. Rocky relief is often the only important indicator of genetic significance. Old passages are dry, fine grained sediments may be transported out of the cavern, the flood water flowing above it is indicated by the rocky features above the sediment level. In short, the records on the cavern's walls are diverse and rich.

To consolidate the bases of rocky relief studies and to evaluate their applicability within speleomorphological and speleogenetical researches proved to be advantageous. The methodological foundations of origin and development of rocky features and their association into rocky relief are determined. At the same time its speleogenetical meaning is evaluated. The development types of channels with characteristical rocky relief may be determined. Two approaches alternated at the study. The first is determination of the factors and processes forming rocky relief and the second approach is regional.

The selection of caves with a large spectrum of rocky relief is adapted to the goal. At the same time the caves were chosen typical of particular regions of the slovene karst.

The gathering of the rocky relief material and its study comprises field work, literature study, modelling of features in plaster of Paris and quantitative analyses of their shape properties.

Acad. prof. dr. I. Gams, prof. dr. P. Habič and colleagues of the Karst Research Institute ZRC SAZU are acknowledged for their help at my work. J. Hajna helped me at plaster modelling, M. Knez at rock thin-section study, S. Morel, F. Drole and B. Otoničar accompanied me into the caves. V. Segala (Department of Geology, Montanistics) has taken photos of rocky forms surface by scanning electron microscope. The annexes were drawn by L. Drame, water and sediment laboratory analyses were done by M. Zadel and M. Luzar. The text was translated by M. Kranjc, and Dr. Trevor R. Shaw, England kindly read it and suggested a few alterations. The study was carried out within the project Origin and development of karst caves, financed by the Ministry of Science and Technology of Republic of Slovenia who also enabled the publishing of this book.

1.2. The Literature About Rocky Features

Frequently in professional literature single rocky features are only described. Rarely is their development explained, but there is no series of studies of rocky relief as a speleogenetical indicator.

The first to treat rocky forms as an indicator of speleogenesis was Bretz (1956). In his work of 1942 he already divided the rocky features due to solution into phreatic and vadose. This classification included only major rocky features; the scallops are just mentioned in the text (1956, 83). In caves in Missouri he studied the transition of the caverns from the phreatic to vadose hydrological zone in respect of their rocky features. He explained the transition primarily by the erosional deepening of the valleys.

Several other researches followed (Renault 1958, 1968; Jennings 1973, 151-164; Gèze 1973; Bögli 1978, 161-168; Maire 1980; Trudgill 1985, 75; Lu Yaoru 1986; White 1988; Ford & Williams 1989) trying to present a wide set of rocky features. The knowledge of single rocky features development was complemented by the studies of Viehman 1959; Rudnicki 1960; Curl 1966; Ewers 1966; Allen 1972; Quinif 1973; Franke 1975; Binni & Cappa 1978; Lauritzen 1981; Cigna & Forti 1986; Lismonde & Lagmani 1987 and their work increased the understanding of karst caves formation. By experiments in plaster Rudnicki (1960), Curl (1966) and Allen (1972) studied scallops, Quinif (1973) the possibilities of ceiling pockets development due to mixing corrosion and Lauritzen (1981) the formation of above-sediment anastomoses. Davis (1951), Renault (1957) and Gilli (1985) studied the weathering of the cave rocky perimeter. These works are evaluated later.

In Slovene speleological and speleogenetical studies, too rocky features are frequently mentioned but there are no integral presentations and explanations of the rocky relief. Surface etched by condensation corrosion in Križna Jama was presented by Hochstetter (1881, 13). The scallops on the walls of the same cave, incised by water flow, are mentioned by Badjura (1909, 31) and Michler (1934, 99). They called the scallops shell-like pits. Brodar (1948-49, 98) mentioned the scallops in Betalov Spodmol and two years later (1952, 479) the wall notches there Brodar described them as a trace of the water level in Postojnska Jama. Gams (1959, 7) published a photo of the pits in a limestone rock in a passage with erosional cross-section. Gams and Habič (1961, 58) described flutes as indicators of flowing water. Gams (1962/63) described the origin of solution cups due to water dripping over the ceiling. In his study about Logarček cave (1963 b) he studied the flutes due to water flow (42), condensation etching (46), pits on the ceiling and the walls (51), scallops (51) and ceiling pockets with smooth walls due to water runing down the ceiling (69). Gams (1964 a, 13) explained that the solution cups on the ceiling of Logaška Jama are due to differential dissolution, while those in Železna Jama developed above the deposit (Gams 1972 a, 29). In 1974 Gams synthesised the overview of rocky forms in his book Kras (101, 102, 160), where he presented the scallops and solution cups. The rocky features are mentioned in the Caving Manual (Gams 1964 b) too. Habe and Hribar (1965, 42) described the ceiling pockets in Gabranca. Habe (1970, 26, 33) illustrated the Predjama speleogenesis by solution pockets and scallops also, and that of Beloglavka (Habe 1976, 197, 200) by rocky notches and solution cups. Habič and Krivic (1972, 105) interpreted the origin of the plunge-pool Trobenta in Pološka Jama. The first systematic overview of rocky features appeared in the Slovene Karst Terminology (Gams 1973). Gospodarič (1974 b, 332, 333, 348) called the small-scale rocky features microforms while studying the speleogenetical importance of sediments in Križna Jama. He described the forms that originated at the contact of limestone and dolomite and presented a scalloped rock by a photo. Gospodarič (1985, 22) described the scalloped wall rocky notches in Trhlovica and solution niches due to water dripping in Divaška Jama (14). Šušteršič (1982, 144) drew the attention to sharp notches in paragenetic channels of Najdena Jama. The features due to rock removal he named speleogens (Šušteršič 1985). Kranjc (1981, 74) described the shape of passages in the caves of Ribniška Mala Gora. By the shape of cave walls he explained the speleogenesis while he studied the recent fluvial sediments (1989). Kranjc (1983) and Habič (1985) described the weathering of the rocky perimeter and flowstone due to microclimatic factors in Predjama and Dimnice. Mihevc (1989, 187, 188) described the rocky features in Mejame and in 1991 (Mihevc 1991 a) the initial and above-sediment ceiling channels in Piskovica and in Brlog na Rimskem. The author tried to interpret the origin of the above-sediment anastomoses in Dimnice (Slabe 1987), the importance of condensation humidity at forming the rim of Komarjev Rov in Dimnice (1988), the along sediment rocky relief (Slabe 1992), formation of scallops (Slabe 1993), the factors influencing on formation of cave rocky surface and to determine the speleogenetical meaning of the rocky relief in Križna Jama (Slabe 1989 b), in Škocjanske Jame (Habič et al. 1989, 30), in Volčja Jama on Nanos and in Ledenica na Dolu (Slabe 1990) as well as speleogenetical importance of rocky relief in selected caves of Istria Karst (1994).

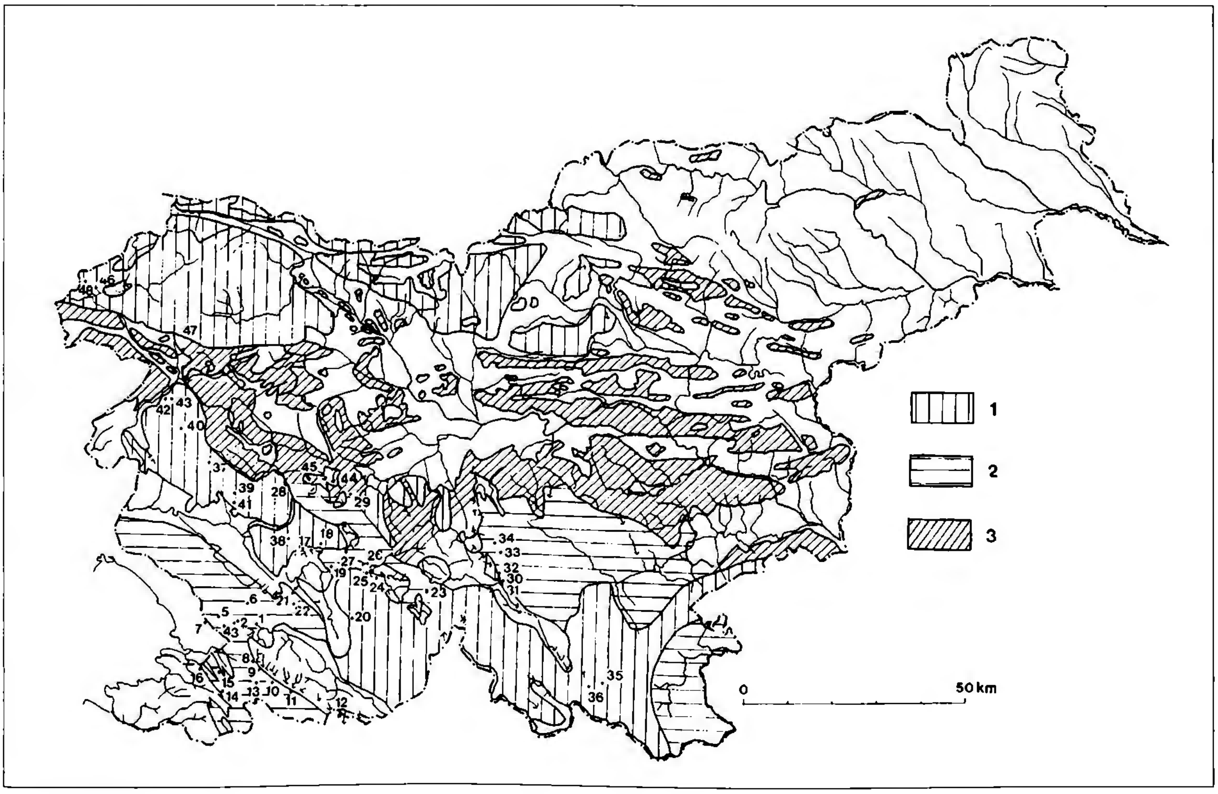
1.3. The Selection of Caves

To evaluate the rocky relief as the indicator of conditions and processes of passages formation, I have chosen various types of caves belonging to typical karst regions. A special problem was set by accessibility, in particular to the passages that are below water level. Therefore such underwater conditions were mostly recorded by the old features, although they are frequently transformed by younger processes.

In selection of caves for evaluation and study of rocky relief as a speleogenetical indicator, their regional connection is extremely important. The possibility and need appeared to distinguish the caves according to their regional development units. This is due to the vertical dissection of the karst relief and to the development from through-flow into simple outflow at high altitudes and throughflow at low altitudes (Habič 1982, 10).

Various karst regions of Slovenia, consisting mostly of limestones (35 % of the area) and dolomites (8%), differ according to altitude above sea level, relative elevation in respect to the karst border, geological setting and tectonic fracturing, the morphology of the surface and its vegetation cover and especially to the mode of drainage through them or even over them sometimes. They may be differentiated according to speleogenetical properties which are visible in active caves, in old and dry caves and in polygenetic caves. Among the rocky units of Dinaric karst (Habič 1991) which lie in a Dinaric trend there are mostly lowlands with karst poljes, depressions and dolines. Large areas of Alpine and small areas of isolated karst mostly trend E-W. The contact with bordering impermeable rocks where continuous streams flow allows the origin of huge caverns in the through-flow areas. With the exception of the Brkini flysch the impermeable rocks are as a rule lower than the bordering carbonate rocks. The surface water percolates into the caves. This mode of water drainage prevails in simple run-off high karst regions.

In through-flow karst regions I have selected the caves in Triest and Istria karst (Fig. 1.1, Table 1.1), in low Notranjska karst with Pivka basin borders, in Ribniška Mala Gora and in fluviokarst of southern Dolenjska. In simple run-off karst regions some caves from the Alpine and high Dinaric karst were chosen. The caves developed mostly in Triassic, Jurassic, Cretaceous, and Palaeogene limestones, in Triassic and Jurassic dolomites (Turkova Jama, Jama V Peklu) and less in carbonate conglomerates (Smoganica) or breccias (Bazinova Jama near Podlaški Topoli). Inside large caves several of these rocks may interchange, including cherts and other less permeable inliers (Predjama, Postojnska Jama).



1.1 Selected caves:

1. outflow karst areas

2. through-flow karst areas

3.outflow-through-flow areas (suggestion P.Habič 1982)

1-48 sequence numbers of the caves

Table 1.1. Selected caves, their types, location, rock and rocky relief and size

Cave's name	1	2	3	4	5			6	7	8
					a	b	c			
			THROUGHFLOW AREAS							
1.Škocjanske Jame	735	perennial swallow hole	Kras	A, K_2^2		*		425	5088	250
2.Divaška Jama	741	old, dry	"	"			*	430	672	89
3.Trhlovca	67	"	"	"			*	432	142	22
4.Vilenica	737	"	"	A, K_2^3			*	418	803	180
5.Lipiška Jama	311	"	"	"			*	397	1194	230
6.Petnjak	952	"	"	"			*	515	285	102
7.Labodnica		through-flow	"	A		*		341	329	817
			Istrian Karst							
8.Kamenšca	2967	temporary swallow hole	Matarsko Podolje	A, K_2^2		*		540	1023	147
9.Ponor v Odolini	1395	per.sw.hole with per.flow	"	" , P		*		470	331	117
10.Dimnice	736	through-flow	"	"		*		567	6020	134
11.Pon. v Jezerini	5484	temporary sawllow hole	"	A, K_2^2	*			491	862	63
12.Novokrajska J.	810	"	Kastav Karst	"	*			500	822	113
13.Grgorečeva Peč.	5307	old, dry	Matarsko Podolje	A,$K_{1,2}$			*	502	76	11
14.Golobja Jama	3754	"	Podgorski Kras	A, Pc			*	410	83	31
15.Beško Ocizeljska	1003	temporary swallow hole	Socerbska planota	"		*		350	2400	150
16.Osapska Jama	1154	seasonal spring	Osapska Dolina	A, Pc, E	*			120	1607	54
			Pivška Kotlina (border)							
17.Predjama	734	swallow hole	Podgora	A, K_2, DT		*		490	7571	143
18.Beloglavka	744	through-flow	Studenški Kras	A, K_2^2		*		560	344	58
19.Postojnske jame	747	swall.h. & through fl.	Postojnski Kras	A, $K_2^{2,3}$		*		511	19555	115
20.Matijeva Jama	270	estavelle	Zg. Pivka	"	*			547	50	36
21.Markov spodmol	878	temporary swall.hole	Slavenski Ravnik	A, K, Pc		*		555	638	20
22.Vodna Jama v Lozi	911	through-flow	"	A, $K_2^{2,3}$		*		560	1235	75
			Notranjsko Podolje							
23.Križna Jama	65	through-flow	border of Cerknica Lake	A, $J_{1,2}$		*		629	8163	32
24.Suhadolica	280	seasonal spring	"	A, $K_{1,2}$	*			553	300	18
25.Mala Karlovica	171	temporary swall.hole	"	"	*			548	14553	20
26.Zelške jame	576	through-flow	Rakov Škocjan	"		*		524	3012	45
27.Planinska Jama	748	spring	Planin.Polje (border)	" , D		*		453	6156	13
28.Ciganska Jama	493	poligenetic	Črnovrška Planota	A, $K_{1,2}$		*		681	277	91
29.Logaška Jama	2490	old, dry	Logaška Planota	"			*	517	280	49
			Dolenjski Kras							
30.Tentera	533	swallow hole	Ribniška Mala Gora	A, $J_{1,2}$	*			503	900	21
31.Griška Jama	2341	"	"	A, K_1	*			512	600	44
32.Finkova Jama (2)	3887	"	"	A, J_1		*		575	1980	65
33.Kompoljska Jama	25	spring	"	"	*			425	113	10
34.Podpeška Jama	17	"	"	A, $K_{1,2}$	*			435	690	20
35.Brlog na Rimskem	4209	swallow hole	Zah. Dol.Podolje	A, $J_3^{1,2}$, D		*		554	401	35
36.Jama v Peklu	2430	"	"	D, T_3^{2+3}		*		485	411	20
			OUTFLOW AREAS **Higher Dinaric Karst**							
37.Velika Ledenica in Paradana	742	(polygenetic) potholes's system	Trnovski Gozd	A, D, $J_{1,2}$		*		1100	1076	385
38.Volčja Jama	743	poligenetic	Nanos	A, D, J_3		*		1060	250	60
39.Led. na Dolu	751	"	Trnovski Gozd	A, $J_{1,2}$		*		995	180	80
40.Bazinova Jama	3486	temporary swall.hole	Banjšice	A, B, K_2^3	*			706	86	21
41.Veliki Hubelj	2880	seasonal spring	Vipavska Dolina	A,D, $J_3^{1,2}$	*			249	440	40
42.Babja Jama	3903	"	Banjšice	A, K_2^3	*			130	370	23
43.Smoganica	823	spring	"	K_2^3		*		505	600	15
			Eastern Dinaric Karst							
44.Turkova Jama	41	through-flow	Logaške Rovte	D, T_3		*		640	900	80
45.Pucov brezen	1777	swallow hole	"	D, $K_{1,2}$		*		640	59	28
			Alpine Karst							
46.Mala Boka	3200	seasonal spring	Soča Valley	A, T_3^{2+3}	*			450	1355	90 (higher)
47.Zadlaška Jama	804	old, dry	Tolminka Valley	B, K, D, T			*	298	1140	41
48.Čo Meander	5706	potholes' system	Kanin	A, K	*			213	193	148

1.4. Gathering and Study of Rocky Relief Material

The characteristics of the chosen caves are determined according to their location, shape and size and shape and location of the passages in respect to the above sea-level altitude. By detailed study of rocky features their typical shapes were gathered (prints: plasticine, Optosil plus), size and location within the rocky perimeter of the passages. The identification is either based on experience or the rocky features were at first documented and later compared with studied material. However, problems frequently occured with the identification of old forms in particular. To identify the old scallops and their connection within a net, a photograph may be of use. Taking the picture the lenses of the objective are parallel to the rock surface and later it is flashed under a steep angle from various sides.

It is necerssary to distinguish the factors which mould the rocky relief at the present time. Thus the rocky features were divided into old and recent ones and the time-table of their origin determined.

The most important factor that shapes the rocky relief is water, either in its the most effective form - stream water or in the form of water film that trickles down the cave walls and is due to condensation from the humid air. In active caves the velocity of water flow, its changing level and chemical properties were recorded. The quantity of condensed moisture was measured and the reasons for condensation attempted to be explained. The rocky relief develops on different rocks. The rocks are distinguished by the rock structure, bedding and fractures. By thin-sections of the rock its composition was determined. The rocky surface was observed under a magnifying-glass or under a scanning electron microscope. The rocky surface frequently reflects the processes which shape the rock. An important factor of rocky relief formation is the sediments. The flood water flows over flutes above thin-grained sediments in the phreatic zones and in semi-phreatic channels the water trickles out of the deposit. The determination of the sediment composition, the size of the particles and the rate of organic C which may accelerate the rock solution proved to be useful. The coarse-grained traction load (Kranjc 1986b, 24) polishes, scratches or bruises the rock and helps to form rock-mills. The dating of the deposits and flowstone helps at time definition of the periods of speleogenetical significance.

The study of rocky formations due to water flow was combined with a literature study of hydraulics. The rocky features were studied by experimental modelling in plaster also. By these experiments, scallops on the channel and on the plaster block, rocky relief of variously sized and shaped tubes (scallops, ceiling pockets), ceiling pockets due to water tricking down from a fissure and the ceiling around them, and the solution niches due to percolation and flutes due to water trickling out the fine-grained sediments were all simulated. The most demanding but successful of the first experiments was study of the origin of the above-sediment ceiling channels. The metric data for a continuous field of scallops enabled statistical processing and comparison of their shape properties which are due to hydraulic conditions in the passage.

Legend:
1 - Cave register number
2 - cave's type
3 - location, through-flow areas
4 - lithology
    A - limestone
    D - dolomite
    K - conglomerate
    B - breccia
5 - rocky relief
    a - rocky relief concordant to the present day cave formation
    b - rocky relief reflecting the present day cave's formation factors and at the same time the indices of the past
    c - rocky relief reflects the past cave's formation
6 - above sea level altitude
7 - cave's length
8 - cave's depth

2. THE ORIGIN AND DEVELOPMENT OF THE CAVE ROCKY FEATURES

2.1. Factors, Conditions and Processes of Rocky Feature Formation

Factors (Table 2.1) cause the processes acting upon the rock and remove their products. They decide on the origin and formation of single rocky features. Lange (1959) names the features due to rock removal, speleogens. The factors act on lines, planes or points. One is turbulent water flow, then a smaller quantity of water flowing on rocky bottom or above fine-grained deposit, percolation water and turbulent air currents. Stable factors acting on the surface are stagnant water or moisture at the contact with the fine-grained sediment. These are characterised by diffusion removal of products of rock solution. The point factors are waterfall, water infiltrated from the fissures in the ceiling, and cave drips.

The shape of caves is mostly due to hydrological conditions. These are typically reflected in the cave rocky relief. In the phreatic zone (Gams 1973, 7; Gams 1974, 34: English: phreatic conditions; Bretz 1956, 15; Trudgill 1985, 72; Ford 1988, 34; White 1988, 150; Ford & Williams 1989, 263 emphasize the bathiphreatic caves; French: zone noyénée, Maire 1980; German: phreatisch, Bögli 1978, 219) the permanently water-filled passages are formed by slow water flow under pressure and on the perimeter large scallops and ceiling cups occur. In the epiphreatic zone (outflow zone - Gams 1974, 34; in English also shallow phreatic zone, Palmer 1982, 178; Ford & Williams 1989, 263; French: zone épinoyée) some parts of the caverns that lie on the local piezometric water level, are seasonally flooded. In such passages the water flow velocity is higher, however during dry periods the water covers the bottom of the stream bed only. On the perimeter there are medium sized or small scallops and on dissected roofs ceiling pockets. The caverns in the vadose zone (aeration zone - Gams 1973, 6; Gams 1974, 33; English: vadose zone, Bretz 1956, 17; Trudgill 1985, 72; White 1988, 150; Ford & Williams 1989, 267; French: zone vadose, Maire 1980, 28; German: vadose, Bögli 1978) are frequently shaped by fast free-surface cave streams (Bretz 1956, 15) or by percolation water. They are exposed to condensed moisture, biogenic corrosion and freeze-thaw effects and all these factors accelerate the rock weathering. The hydrologic zones are mostly due to the situation of the rocky block in respect to nearby impermeable rocks, valleys or lowlands. They control the groundwater table (Habič 1982, 13, 14) which locally varies due to joint frequency of the rock. When water level lowers, the old, horizontal caves, once filled by water, frequently remain dry. In particular in Alpine karst they are transformed by diffuse drips of infiltrated water.

Rocky features develop at hollowing the syngenetic passages while in paragenetic channels (Renault 1968, 580; Maire 1980, 29; French.: galeries paragénétiques) the traces of the rocky perimeter transformation are found above the fine-grained sediments that fill the cave.

The dominant processes influencing the rocky perimeter moulding are solution of the rock, mechanical corrasion and weathering.

The **solvent efficiency** of the rock is dependent on the rate of the surface reactions, on the rate of transport of reactants and products and on the rate of production of H^- and H_2CO_3 by conversion of CO_2 (Dreybrodt 1988, 103). Parallel to the hydrodynamic laminar boundary layer in turbulent flow the boundary layer where the reactants transport and solution products is achieved by molecular diffusion may be determined. The layer gets thinner when the rock is flushed by turbulent flow. There is a transition buffer zone where the efficiency of diffusion increases until the fully turbulent core is reached. The diffusion in turbulent flow is considerably more significant than molecular diffusion. In fully turbulent flow when the effective coefficient of turbulent diffusion is 10^4 larger than the molecular diffusion coefficient the existence of a diffusion boundary layer may be neglected (Dreybrodt 1988, 154). The velocity of water flow increases the rate of dissolution if the reaction rates are faster than the transport rates. However, if water-flow rate is fast relative to the reaction rate, the overall rate becomes independent of flow and becomes reaction rate limited (Trudgill 1985, 19). Hence, in a water flow the rate of rock dissolution is controlled by the flow veloc-

Table 2.1. Rocky features, factors and conditions controlling their origin, and processes shaping them.

ROCKY FEATURES	THE MODE OF WATER FLOW (REMOVAL OF PRODUCTS)	FACTORS	CONDITIONS OF ORIGIN (hydrological zones)	PROCESS ON THE ROCK
large scallops, ceiling pocket,	LINEAR turbulence	water flow	phreatic	corrosion
scallop ceiling pocket, wall notches			epiphreatic	corrosion, mech.act.
scallops, potholes, floor channel, flutes			vadose	corrosion, mech.act.
large scallops, ceiling pocket, channel		air flow	vadose	corrosion
flutes, solution niche, ceiling pocket,		water filtering	vadose	corrosion, mech.act.
below-sediment channel, niche			of deposit	corrosion
ceiling channel, anastomosis	recharge of small water quantity	above deposit	epiphreatic	corrosion
floor channel		on rocky floor	vadose	corrosion
niche, pocket, smooth rock	PLANE	stagnant water	phreatic	corrosion
niche, pocket			epiphreatic	corrosion
niche, wall notch			vadose	corrosion
below-sediment niche, pocket		deposit	epiphreatic	corrosion
below-ice notch, niche		ice cover	vadose	corrosion
biogene furrows		lichens	vadose	corrosion
floor pit	POINT	dripping	vadose	corrosion, mech.act.
ceiling pocket		filtering of a fissure	vadose	corrosion
pothole		falling water flow	vadose	erosion
block breakdown, chip breakdown				mechanical disintegration

ity and chemical properties of the water that, together with rock surface consisting of variously solvent particles, determines the surface reaction rate. The solution rate in an active vadose cave passage of traversible size is usually close to the theoretical maximum of roughly one millimeter per year (Palmer 1982, 190).

Mechanical influence of the water flow on the rock may be divided into the action of the water mass itself and abrasion by the material transported by the water (causing potholes, smooth, bruised rocky surface). The turbulent water flow, that has a rather thin boundary of the laminary layer due to adhesion between water and rock, tears off the surface minute particles isolated by corrosion.

I tried to evaluate the problem of **mixing corrosion** of differently saturated waters or waters with different temperature that become corrosionally aggressive again (Bögli 1971) as the explanation of ceiling pockets origin.

Palmer (1982, 178) mentions the importance of **oxidation of sulphides**. The sulphuric acid is produced when sulphide-bearing water in a phreatic zone reaches the oxygen-rich air.

Cavitation (Scheidegger 1961, 57; Splošni tehniški slovar 1978; Cigna 1983, 481) is not yet proved in the karst underground. Cavitation, i.e. the formation of bubbles, takes place if the hydrodynamic forces in the fluid are so great that the local pressure becomes smaller than the vapour pressure. The cavitation cycles Cigna (1983, 481) divided into the origin of low pressure zone within the flow irregularities, the origin of the vapour pockets when the local pressure becomes smaller than the vapour pressure, and finally the bubbles collapsing. Shock waves are created at the contact with rock. Numerous bubbles that collapse in 10^{-3} to 10^{-4} seconds and reappear immeditaely after the microimplosion cause the pressure that locally reaches tens of megapascales. Rapid and considerable changing of pressure absorbs the air from the rock pores and produces its disintegration. Cigna (1983, 480) presumed the possibility of corrosion due to oxidation in the water enriched by oxygen bubbles. The bubbles are created at the moment when the pressure decreases. In narrow cave passages the highest required water flow velocity is rapidly reached. In larger passages where the differences between the pressures are higher, cavitation is more probable. It would be useful to analyse the siphons as there water flow reaches the highest velocity, to 10 m/s even (Kranjc 1986 b, 209). In phreatic passages the features that occur close to the obstacles are supposed to be controlled by cavitation, in vadose zone such flow velocities can be realized in waterfalls and in rapids. The rocky surface is sponge-like due to cavitation (Cigna 1983, 485). Serban (1987, 24) thinks that cavitation may cause fine capillary holes, varying from 0,5 to 1,5 mm in diameter. The tiny holes appear on flat ceilings in the lowest section of the ox-bow passage. The condition for the cavitation process needs velocities higher than 20 m/s and piezometric values lower than 9 m water column. Cigna suggested (1983, 485) the microscopic observation of the exposed rocky surface because of eventually displaced crystals.

Often various recent factors are interconnected. In the scallops either fine-grained sediments are deposited or sand is whirled at their bottom. The below-sediment channels lead from large ceiling cups having the walls inclined towards the interior. Different conditions of present-day or former cave development are frequently reflected on the rocky relief.

The rock essentially controls the formation of the cave perimeter and the origin of rocky features. The rock constituents have different size and solubility, the rock is either bedded or fractured. The formation of limestone and dolomite is typical. Larger sparitic crystals and the fossils that are as a rule less soluble than the micritic cement often protrude out of the walls. Larger obstacles that cause the chaotic turbulence of the water frequently prevent the origin of rocky features (smaller scallops). The lines of weakness within a rock are actually smaller constituent particles that offer larger surface to the dissolution. Protruding rock particles are more exposed to the water flow and to the water trickling down them they may even fall off due to their own weight. The rock is most soluble at the grains contact and examples of tiny holes in the crystals are rare (Herman & White 1985). Under the microscope we may see that some larger crystals on the corrosionally etched rock surface have not lost their symmetrical form. Ek and Roques (1972, 71) also argued that slow dissolution of large crystals is due to the higher resistance of their surface and to lattice energy. Dolomite is commonly weathered more quickly but if it is cemented by calcite it is more resistant than limestone to water flow (Križna Jama). The more porous the rock is the more efficient is the corrosion. The more homogeneous and solid the constituent parts of the rock are, the more the rocky features are regular.

2.2. Properties, Terminology and Classification of Rocky Forms

The shape of rocky forms is mostly controlled by the mode of carbonate rock solution. For most of rocky forms cut in the rock semi-circular cross-section notches are typical. A deviation is presented by bulges which are commonly the remains of the rock among other rock forms. On very fissured rock where the characteristic forms (scallops, solution cups) from water flow cannot develop due to chaotic turbulence the bulges are the only rocky forms.

The largest rocky feature may be some meters wide and the smallest some millimeters only. The single constituent parts of the rock, either large fossils or sparitic crystals, may be larger than the smallest rocky features. The surface of the rock features is either smooth or rough depending on rock structure and on the nature of the process acting on it.

According to basic shape properties of the rocky features controlled by different factors, they may be divided into four groups:

Channel is an open, tube-like form; the opening in cross-section is larger or smaller than half of its section. The channels may be deep or shallow. Smaller channels are called half tubes. The closed tube is seen on the rocky perimeter in cross-section only. The channels have semi-circular cross-sections if they develop in the phreatic zone. Such are the above-sediment ones and are typical of ceilings or overhanging walls. Emphasized cross-section in shape of letter V reflects their gravitational deepening by the water trickling down. The below-sediment half tubes are found at the lower parts of the walls and at the rocky bottom of the passages.

Pockets and niches are larger or smaller semi-spherical holes. Pockets are from 0,1 m to over 1 m, and niches up to 0,1 m in diameter. Pockets cut down by water flow are commonly found on dissected ceilings. Along a dense network of fissures they may be composite, and along prominent fissure they are deepened in either cylinder or cone shape. Rapid turbulent flow downcuts the elongated scallops. The scallops may be spread all over the rocky perimeter. Potholes are found on rocky bottom like below-sediment solution niches. Long-lasting formation of below-sediment niches make them widen at the bottom. Wide and shallow pockets occur due to condensational corrosion.

Bulge is a part of the rock projecting out of the rocky perimeter. The shape and location of pendants or "čer" are mostly controlled by the rock structure and joint frequency and by the nature of the water flow. Smaller points are shaped by water trickling down the ceiling.

Pieces broken off are larger and **fragments** smaller parts of the rocky perimeter. Both are due to rock weathering. They are angular and limited by straight or slightly curved planes. They occur when the pieces of the rock are broken or the disintegration is continuous and prevailing process of rocky perimeter development.

During my studies I have divided the rocky features into groups according to the factors that influence their origin. Typical location of the rocky feature on the perimeter (for example above-sediment ceiling channel) was very helpful here. I seldom added the adjective to the name to illustrate the process of its development. I used the names that are already common: ceiling pockets, potholes and scallops; some of them I named myself.

1. Rocky forms due to water flow

Scallops are saucer-like depressions, more shallow on the outflow side (Gams 1973, 6; English: scallops (Curl 1966; Allen 1972); German: Fliessfacetten (Bögli 1978, 165); French: vague d'érosion (Maire 1980, 31 after de Joly 1933; Renault 1968). They are from 0,5 to 50 cm long and evolved because of turbulence in flowing water.

Flutes are long grooves in a cave wall with regularly spaced ridges and hollows with semi-circular cross-section at right angles to flow (English: flutes (Curl 1966)) due to water turbulence along rough surface of longitudinal notches on the rocky perimeter of the channels.

Ceiling pocket may reach one meter or more across on the ceiling or on the upper parts of the passage walls (French: coupole à la voûte (Renault 1968, 29; Quinif 1973; Maire 1980, 35), marmite inverse, marmite de pression (Gèze 1973, 9); English: ceiling pocket, solution pocket (Bretz 1942; Bögli 1971; Ford 1988, 43); Italian: cupole (Pasquini 1975, Bini & Cappa 1978); German: Korrosionskolke (Bögli 1978, 163). They are due to water turbulence along the fissures and/ or vortex zones along notches, at lowering or rising or sharp twists of the channel.

Pothole - French: marmite de géant (Renault 1958, 30, 31; Viehman 1959; Corbel 1962; Gèze 1973, 9; Maire 1980, 35; Lismonde 1987); English: pothole (Bretz 1942); German: Erosionskolke (Bögli 1978, 165) develops on rocky floor due to turbulent flow of water containing solid particles.

Floor channel evolves in rocky stream bed due to turbulence of water flow along fissures and/or obstacles or due to a smaller amount of water flowing over rocky floor.

Pendant (Gams 1973, 26) is an oblong wall, ceiling or floor protuberance narrowing outwards.

Jag is a protuberance with oval cross-section.

Pillar - English: pillar (Lange 1959, 81). The form, starting from an initial rectangular joint pattern is preserved while the stream dissolved the surrounding limestone.

"Čer" is the protuberance on rocky floor.

Natural bridge (White 1988, 102), window (Jennings 1979, 21) appears when the water dissolves the projecting parts of the rocky perimeter.

Meander niche (Gams 1973, 22) is a semi-circular or angular niche in the passage wall due to indentation of the water flow along the fissures or meandering along the sediment (English: meander niche, Bretz 1956, 18).

Water level horizon is a linear, oblong notche, 10 cm to 100 cm or more in diameter. It indicates the level of the water flow (English: water level horizon (Lange 1963, 41) or joining of passages.

2. Rocky features at the contact with fine-grained sediments are called "along-sediment".

According to their origin they are classified to above-sediment or below-sediment features.

a. **Above-sediment** channels and pits are typical of passages that were filled up by flood deposits. Due to water flow above the fill in a flooded passage the ceiling uplifts and during the flow decrease the water indents into the walls. The water inflow through the fissures may cause solution cups at the mouths. Tiny pits may develop on the rock if the deposit is even humid (Dimnice).

Ceiling (above sediment) channel (English: ceiling channel, Bretz 1956, 22) is either linear or covolute, 1 to 100 cm in diameter.

Anastomoses are a gradational set of ceiling channels (Slabe 1988, 169, 170; Renault 1968, 569; Gèze 1973, 9; Bögli 1978, 161).

Ceiling pendants are pendants among the channels (Bretz 1956; Renault 1968, 570).

Niches, 1 to 10 cm across are either singular or occur in a network pattern.

b. Below sediment rocky features constitute the rocky relief of cave passages through which slow water flow drains seasonally and deposits on fine-grained sediments on the perimeter (Slabe 1992).

Bevels (below-sediment) 1 to 10 cm in diameter have semicircular bottom. Usually they are close one to another and cover a large area of the lower parts of the passage or its bottom. They are due to water infiltration from the deposit.

Niches are densely distributed on the rocky floor, the walls between them may be corroded and hence of irregular shape. Their size is from 1 to 20 cm. They are due to corrosion below the humid deposit.

Water level horizon notches indicate the level of the sediment in the passage.

Roof pendants are only 1 to 2 cm large with tri-

Tabela 2.2

ROCKY FEATURES DUE TO WATER FLOW IN DIFFERENT HYDROLOGIC CONDITIONS			MODE OF WATER FLOW	DOMINANT PROCESS ON THE ROCK
phreatic zone slow flow	epiphreatic zone faster flow	vadose zone fast flow		
large scallops	scallops, flutes	scallops, flutes	water turbulence at rough rock	corrosion
ceiling pocket	ceiling pocket	wall niches	water turbulence due to passage shape or joint frequency	corrosion
niche, bulge	niche, pendant	niche, pendant, "čer"	turbulence at very fissured rock	corrosion
	pothole	pothole	load included into turbulence	erosion
		ceiling flutes	flushing of overhanging walls	corrosion
		floor channel	low water level or turbulence at transverse obstacles a little water on rocky bottom	mechanical activity, corrosion corrosion
ceiling and wall notch	ceiling and wall notch	wall niche	converged flows, flow water level	corrosion, mech.act.

angular cross- section. They are due to solution of bare rock in flooded channels. On some parts the deposit prevent the contact of water and wall.

3. Rocky features due to water trickling down the perimeter of shafts and passages

Lapies (Bretz 1956, 22) are due to vadose water descending over the vertical or inclined wall.

Niches have circular or angular cross-section, 1 to 5 cm in diameter. They appear in groups. They are due to water trickling down the inhomogeneous overhanging wall.

Roof pendants are 1 to 2 cm long and almost invariably found in groups. They are due to water trickling down the inhomogeneous ceiling.

Ceiling pocket is bell-shaped, from 1 to 50 cm in diameter with inflow tube on the top. It is due to water trickling from the ceiling fissure (Franke 1975).

Floor pit (Lange 1960, 78) is upright, enlarged at the bottom, from 1 to 10 cm deep, due to water drops.

4. The air currents due to moisture condensation give rise to the development of typical rocky features

Scallop is shallow, semi-circular niche at the upper part of the walls or ceiling, from 0,5 to 1 m in diameter.

Solution pocket is rather deeper niche on the ceiling, 100 cm or more in diameter.

Ceiling channel (German: Deckengrübbchen (Bögli 1978, 162) is either linear or convolute, 20 to 100 cm in diameter.

Etchings are either small niches or pendants. Their size and shape are controlled by lithology.

These features, for the moment with adjective "condensation" are distinguished from other similar.

5. Below ice rocky features occur:

Below ice wall notch is a large, longitudinal niche with polished walls. It indicates the border of ice fill in the cave

Below ice runnels (German: Eiswasserrinnen (Bögli 1978, 1963) are due to percolation from the ice.

6. Biogene furrows develop under lichen or bat guano. The lichen ones are smaller (some mm) niches or pendants; the guano ones are larger niches.

7. Due to rock weathering develop

Block breakdown (White 1988, 229) occurs at fissures, or **slab breakdown** at bedding planes (White 1988, 205).

Chip breakdown (White 1988, 230) is due to rock weathering into small pieces or grains.

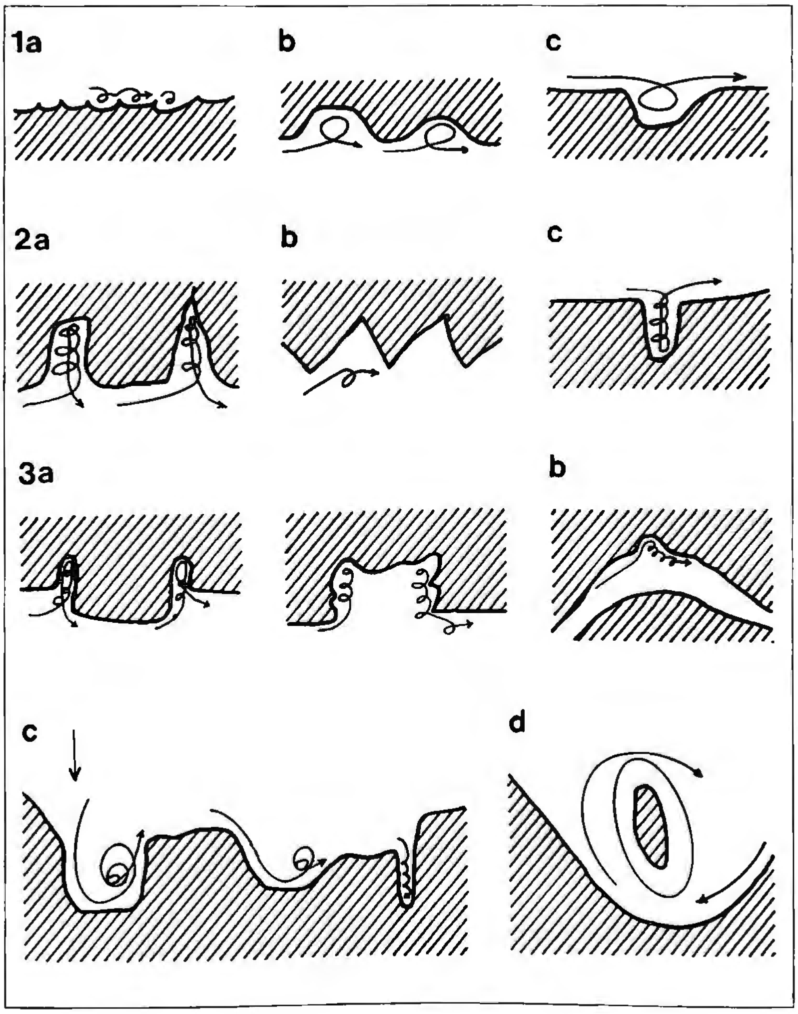
Dome (White 1988, 231; Bini & Cappa 1978, 60; Gilli 1985) and **domed ceiling** are due to ceiling weathering in huge chambers or fractured roof in small passages.

2.3. Rocky Features due to Turbulent Water Flow

Such rocky features (Table 2.2) reflect the hydraulic conditions in passages of various size and shape. The turbulent water flow either dissolves or mechanically erodes the rocks.

On homogeneous, non-fissured rocky surfaces which are parallel to water flow and larger than the eddy diameter, scallops develop in a stream of defined velocity, flutes in longitudinal niches. The surface of the niches is covered by uniform turbulence (Fig. 2.3.1). Larger eddies on dissected ceilings and on the transition between passages which vary in size and inclination, lead to ceiling pockets. The bottom is levelled by the mechanical activity of water and deposits. Along large joints on the walls niches are common. On the bottom of the passages with rapid, usually free-surface flow, potholes occur. They are formed by the material transported by the water. If the perimeter is extraordinarily inhomogeneous, that causes the development of smaller scallops or if it is very fractured that causes large scallops and ceiling pockets, the pendants occurring among the fissures (Fig. 2.3.1, 2b). Chaotic turbulence prevents the initiation of regular, incised rocky features. If the water flow is fast small fissures become more important. Therefore rocky pendants are frequent on the ceiling and walls. On the floor controlled by extremely fast water flow transporting load, are "čer".

In Fig. 2.3.1 are presented some typical eddies in a water flow and illustrating the above statements. There are two sorts of eddies; the first have the flow lines perpendicular to the wall and shape relatively shallow scallops; the second are spiral eddies and create deeper cups. The size and the property of the eddy are controlled by velocity of water flow and its location within the passage. The turbulent areas occur in front of and behind the narrows, in ceiling pockets, below the steps in the riverbed, on rocky blocks, and at the wall bends; the water incises more efficiently along the fissures as well. The change of water flow level or joining of passages is indicated by ceiling and wall water level horizons.



2.3.1 Typical water turbulence
1. *turbulence in homogeneous, solid rock*
   - *a. scallops*
   - *b. ceiling cups*
   - *c. potholes*
2. *turbulence in fissures*
   - *a. ceiling cups*
   - *b. pendants*
   - *c. potholes*
3. *turbulence due to passages shape*
   - *a. ceiling cups*
   - *b. ceiling cups at bends*
   - *c. potholes; below waterfall, downcurrent, in front of an obstacle*
   - *d. pothole at a passage bend*

2.3.1. HYDRAULIC BASES

The velocity and mode of water flow through a defined section of a passage or network of passages with various diameters are controlled by the inclination of the passage in free-surface stream flow and pressure in the phreatic zone. The passages with free water surface may comprise flooded sections and siphons (Habič 1973). In the narrows of flooded passages the water flow velocity is more significant and the pressure on the walls is smaller than in rather larger passages. The higher the pressure on the walls the more efficiently the water widens the passage and seeks new routes. In free-surface stream conduits the pressure on the walls depends on water velocity and on the location of the cusps in the river bed, it depends on the flow level which is also controlled by the atmospheric pressure.

The velocity and type of the water flow are controlled by the friction surmounted when the water flows over more or less inhomogeneous and fissured rocks, by the loss of energy which is induced by junctions of passages with various diameters and gradients, and the result is hydraulic jump and surmounting of obstacles in the riverbed (rocks). Frequently the water transports rock pieces of various sizes. In the caverns one may observe the trend towards level passage diameters either by erosion or deposition of sediments (Kranjc 1989, 20). The sediments are deposited either in front of or behind the narrows.

The result of various diameters and shapes of the passages, of different velocities of viscous water flowing through them and the friction at coarse surfaces or obstacles in the riverbed is either laminar or turbulent flow. The transition between two flows is a function of roughness and pipe diameter (Round & Garg 1986, 22). According to Serban (1987, 26) the critical pipe diameter for turbulent flow origin is 2 cm in diameter, according to Dreybrodt (1988, 80) it is 1 cm, to White (1988, 275) 0,5-5 cm while at 1 cm in diameter the rounded pipe cross-section occurs. The water flow is characterized by Reynolds Number (Re) indicating either laminar or turbulent flow in a pipe with smooth inner surface. If the number, which is increased by the flow velocity and the pipe diameter and decreased by cinematic viscosity of the fluid, is smaller than 2100 (White 1988, 164; Round & Garg 1986, 22) the flow is laminar, if the number is bigger, the flow is turbulent. The velocity of turbulent flow changes by the square of the hydraulic gradient (White 1988, 163). Due to roughness and shape of the passages turbulent flow appears in caves at a lower value of Reynolds Number than in smooth pipes where the flow velocity is the deciding factor. White (1988, 164) Re = 10 quoted as the limit between two flows, while Reynolds (1974, 207) gave Re = 10-200. In free-surface streams the water's turbulence appears at Re = 500 (White 1988, 165). The flow lines in laminar flow are parallel to a pipe's wall, while turbulent flow may be divided into a thin laminar boundary layer at the wall and a turbulent nucleus. The velocity along the walls due to particle adhesion of the viscous water is equal to zero (Boreli 1984, 357) but it increases from the walls towards the centre with the velocity of water particles due to turbulence. The laminar boundary layer in which viscosity and friction play the deciding role in determining the character of the flow (Boreli 1984, 359) gets thinner with increased Re number (White 1988, 163); it is inversely proportional to the square root. The turbulent nucleus thus approaches the wall. There are two reasons for turbulence: if the roughness of the wall is thinner than the laminar boundary layer the turbulence is affected by the viscosity of water within the boundary layer (Duckworth 1977, 163). Inertial forces are also significant for viscosity to smooth the friction (Boreli 1984, 392). If the roughness is more prominent than the thickness of laminar boundary layer, the projections cause additional eddies (Duckworth 1977, 163). Hence, the projections may interrupt the boundary layer at low Reynolds Numbers even. At very turbulent flow the viscous effect expressed in Reynolds Number may even be disregarded (Boreli 1984, 359). In short, at high values of Re the friction coefficient depends on the roughness of rock and is almost entirely indipendent of viscosity, while at low Re it depends mostly on viscosity and less on roughness (Reynolds 1974, 5). In the passages, due to limited homogeneity of the rock and the shape of the walls, the first type of turbulence influences the origin of small-scale features (smaller scallops) incised by fast water flow. For the origin of large-scale features (large scallops, solution cups) which are controlled by slower water flow, the second type of turbulence is deciding. Within the flow eddies of various diameters and unstable lines of water particles occur.

An eddy is a turbulent water mass where the water lines are concentric circles and the velocity at each point inversely proportional to line flow diameter (Duckworth 1977, 91). Towards the centre of the eddy the velocity increases and the pressure decreases. Within the centre itself the velocity is infinite and the viscosity causes the nucleus to act as a solid body. The velocity of its axis is zero (Duckworth 1977, 92, 93). The less viscous the fluid the smaller is the diameter of the eddies (Serban 1987, 16). The velocity of the turbulent mass is tightly connected to the size and shape of the space and the size of the flow. Various eddies influence one another and overlap one another, and kinetic energy is constantly transferred from the large to the small structures (Serban 1987, 17). The number of tiny three-dimensional turbulent structures increases and the structures are smaller with larger Reynolds Number (Serban 1987, 20). Not only friction on the wall but also the geometry of the pipe causes the eddies; it means change in diameter and gradient of the passage and the obstacles within the flow. In front of narrows the flow widens, within the narrows it descends and narrows (Duckworth 1977, 182) and in passages the turbulent zone appears. The losses appear on the bends of the pipes as radial gradient pressure increases outwards. On upper and lower parts of the wall outside the bend radial inner flow occurs (Duckworth 1977, 182). Particular rocky notches on the wall give rise to eddies at Re 10-200. The eddy is controlled by the shape of the notch and complicately changes in respect to Reynolds Number (Reynolds 1974, 207). Larger turbulent zones (Fig. 2.3.1/3a) are active mostly in shaping the ceiling pockets. When supercritical free-surface streams due to velocity increase on steep slopes meet the level floor of the riverbed or breakdown blocks in it, a lot of energy is set free. Hydraulic jump occurs and erosion is more efficient (White 1988, 166). At such places potholes commonly occur. In short, hydraulic conditions depend on numerous circumstances and are reflected on the rock by various features which I will try to present in later sections.

Different types of water flows are distinguished. In steady uniform flow the potential energy decreases due to smaller gradient downstream or pressure in the background. In cross-section the distribution of velocity and pressure is equal along the whole flow (Vuković & Soro 1985, 58). Steady, but not uniform flow occurs when its depth, velocity and pressure change by leaps. Hydraulic jumps are characteristic (Round & Garg 1986, 283). Special type is critical flow in which velocity is equal to the velocity of infinite small particles, and supercritical flow where small obstacles influence downstream (Round & Garg 1986, 284). The water flow changes with time also, besides the base flow there are the pulsated flows too (Boreli 1984, 359). One of important factors shaping the karst underground is seasonal, frequently sharp and considerable changes of the water flow properties. This too is evidenced by the rocky relief.

2.3.2. SCALLOPS AND FLUTES

The scallop is an oval niche some 10 to 100 mm long on the rocky perimeter of the cavern where water flows occur or have occurred. It is deeper and steeper on the inflow side; on the outflow side it is elongated and gradually disappears. Several different types of small scallops are distinguished. Large scallops ressemble shallow solution cups. Flutes are elongated niches of regular shape occurring transversely to the water flow direction. Both features may appear in a network. These features, due to water turbulence at rough rock surfaces, indicate the mode and direction of water flow through the channels.

Several authors have reported studies and determination of the association of scallop length and water flow velocity that forms them. I decided to pay more attention to the comparison of their shape properties and network and to study the factors and processes of their origin and development. The influence of rock on the turbulence is discussed in detail.

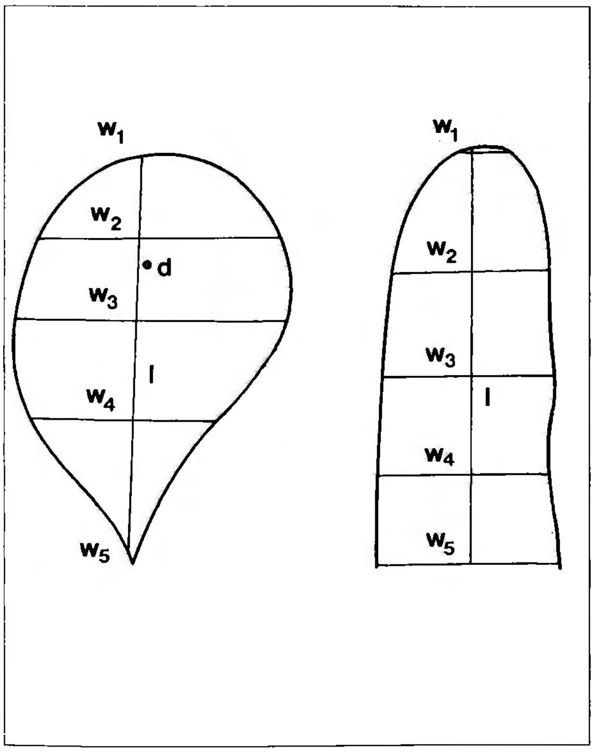
Literature sources about scallops

Shaw (1992, 148, 155, 165) mentions in his History of Cave Science the authors who first drew the attention to scallops. Maire (1980, 31) quotes that the first to record the scallops was R. de Joly in 1933. Bretz (1942, 731) distinguishes phreatic and vadose rocky features due to solution, and emphasised the deciding importance of corrosion in scallops origin. He describes the examples of scallops from which silicate particles protruded. The scallops are described in Bretz's work (1956) where he evaluates rocky features as a speleogenetical indicator.

The scallops' length being associated with water flow velocity was reported by Rudnicki (1960, 17), Curl (1966, 1974), Goodchild & Ford (1971), Allen (1972), Lauritzen et al. (1983) and Lismonde & Lagmani (1987).

Rudnicki (1960) was the first who tried to explain solutional scalloping and its characteristics by experiments in plaster. He states (1960, 29) that faster water flow incises smaller scallops. He says (1960, 30) that the scallops' pattern is mature if the scallops are joined into sets transverse to water flow direction. I assess that such groups are characteristic for the narrows in the cave passages, water level horizons and the outflow sides of breakdown blocks in the riverbed.

Curl (1966, 1974) used in his explanation the analyses of hydraulic properties in the channels, the flow measurements among the electrodes at the model and experiments in plaster. He introduces the theoretical bases of connection between the water flow velocity and the scallop size. He infers that the shape and size are controlled by average velocity of water flow in the channel, by the channel dimension, density and viscosity of water and by diffusion of ions, if the solution is uniform



2.3.2 Closed and open scallop
d = length
š = breadth
g = depth

and the rock homogeneous. He stresses the effect of fissuring and differential solution in particular, as all these factors have an impact on scallop development. The irregularities on the surface of the rock give rise to the occurrence of leeward sides within the water flow and as the scallops appear in groups the influences of previous features are felt downstream. He introduces flutes also.

Renault (1968, 563) explained the origin of small scallops by water flow acceleration due to pebbles. 50 mm long pebbles may cause water circulation with 20 mm/s velocity, which corresponds to origin of scallop, 10-20 mm long. This statement is denied by the fact that the scallops occur in the channels where there are no pebbles, or else, pebbles frequently even polish the channel walls.

Goodchild& Ford (1971) recorded hydraulic reasons for various sizes of scallops by the experiments in plaster. By field observations they predict that the rock structure is very important. According to their opinion corrosion is the predominant process in scallop development.

Allen (1972), as well, was helped by experiments in plaster. The plaster in a 3 m long channel had flowing water, its velocity 28 to 90 cm/s and its depth 1,5 to 15 cm. He argues that we should expect (1972, 7) scallops to arise only at those inhomogeneities that are large enough in diameter, relative to the thickness of the laminar sublayer, to generate turbulent separated flows. Inhomogeneities in the rock influence the scallops distribution; a single irregularity may cause a feature similar to a scallop.

Lauritzen (1983) measured the hydraulic conditions in the cave passage, the size of the scallops and the velocity of their development.

Trudgill (1985, 75) proposes that the initiation and development of the scallops is closely related to lithological inhomogeneities, such as variations in grain solubilities and small fossil fragments, these factors assisting the formation of locally increased turbulences.

Lismonde & Lagmani (1987) tried to complete Curl's studies of hydraulic conditions in uniformly shaped pipes by stressing the diversity of channels.

Ford (1988, 46) stated that the scallops develop by detachment of the saturated boundary layer in the subcritical turbulent flow regime which permits aggressive bulk fluids to erode the solid rock directly without intermediate diffusion through ions. A year later he added with Williams (1989, 305) that the frequency of detachment increases with velocity increase.

The scallops incised by the water flow into the walls of Križna Jama are mentioned by Badiura (1909, 31) and Michler (1934, 99). They named them niches, similar to shells in shape.

Gams mentions the scallops in his study about the Logarček cave (1963 b, 51). In 1974 in his book Kras (101, 102, 160) he presents an overview of the rocky features, scallops included.

The rocky features are mentioned in Caving Manual also.

Habe (1970, 26, 33) explains the Predjama Cave development by solution cups and scallops, and the genesis of Beloglavka Cave by rocky notches and solution cups.

The first systematic overview of rocky forms, scallops included, may be found in Slovene Karst Terminology (Gams 1973).

When Gospodarič studied the speleogenetical importance of the sediments in Križna Jama (1974 b, 332, 333, 348) he named the small-scale rocky features microforms and presented a scalloped rock by a photograph. In 1985 (22) Gospodarič described the scalloped rocky notches in Trhlovca.

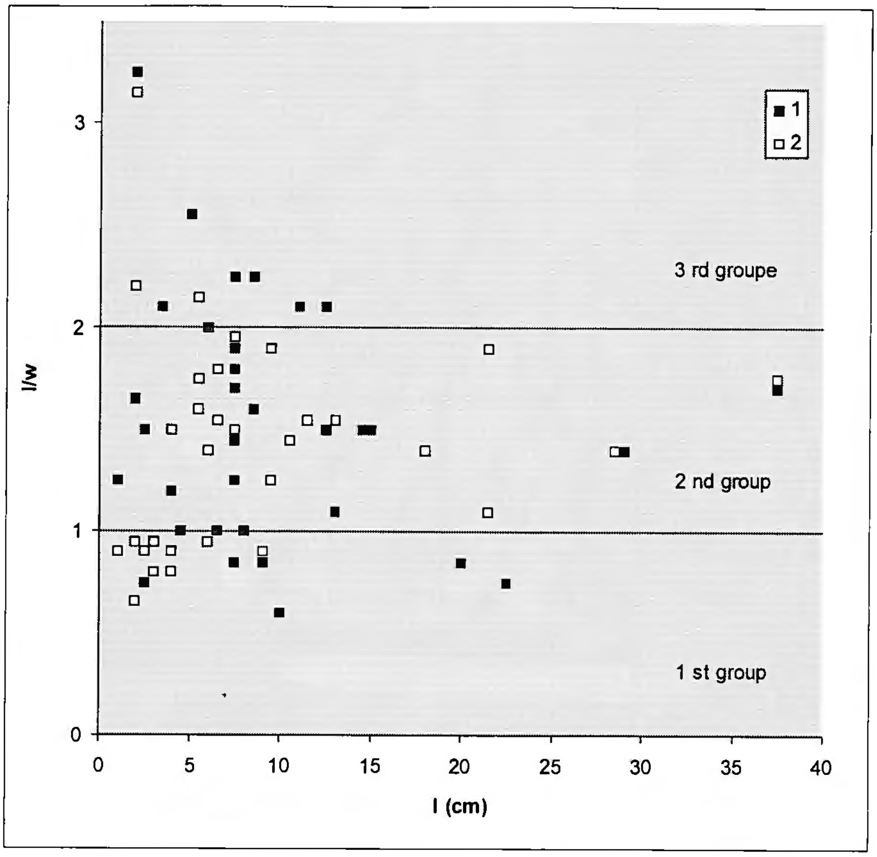
I have described small scallops incised by seasonal fast water flow in Križna Jama (Slabe 1989 b, 203).

The shape and the size of scallops and their network

In selected Slovene caves I documented 75 scallop networks; 53 of them were suitable for further studies. Older scallop networks, transformed below fine-grained sediment or due to condensed moisture, did not maintain sharply enough preserved features; this is why their measurement was impossible.

I divided the shape of a singular scallop into numerical groups which would, together with scallop size, enable statistical computer processing. It was proved that the computer comparison was not necessary because similar numerical values were rather easy to be classified into groups. I determined within each scallop (Fig. 2.3.2) the length, the breadth of the left and right half at the begining, at the first quarter, at half, at the third quarter and at the end and the point and the value of the greatest depth. I measured the radius of inflow, the mostly semicircular ridge of the scallop and the angle of closed scallops. By such means I got the average shape and size of the scallop within a particular net pattern. The average shape more or less deviates from a virtual shape on the rock. This is mostly due to heterogenity and rock structure where the scallops occurred. It was proved that within the pattern nets two types of scallops prevail: the scallops that are at the outflow side closed under wider or narrower angles (Fig. 2.3.2), and the scallops that are opened at the outflow side (Fig. 2.3.2); however there are some that are partly closed in the last third. The shapes occur within the same set pattern or prevail in it. As a rule closed and opened scallops of the same network are ranged into the same group. Due to significant difference in shape I classified opened and closed scallops separately. For scallop comparison according to their shape I eliminated their sizes. Thus I calculated for average scallop shape the ratio between the scallop length and the above mentioned breadths. Similar numerical data I classified into three groups and two intermediary subgroups (Fig. 2.3.3).

Into the first group belong the scallops where ratio between the length and breadth is smaller or equal to 1,1. Closed scallops may be divided into those that have the same breadth at the first quarter and at the third quarter and are the widest at the half, and those that are nar-

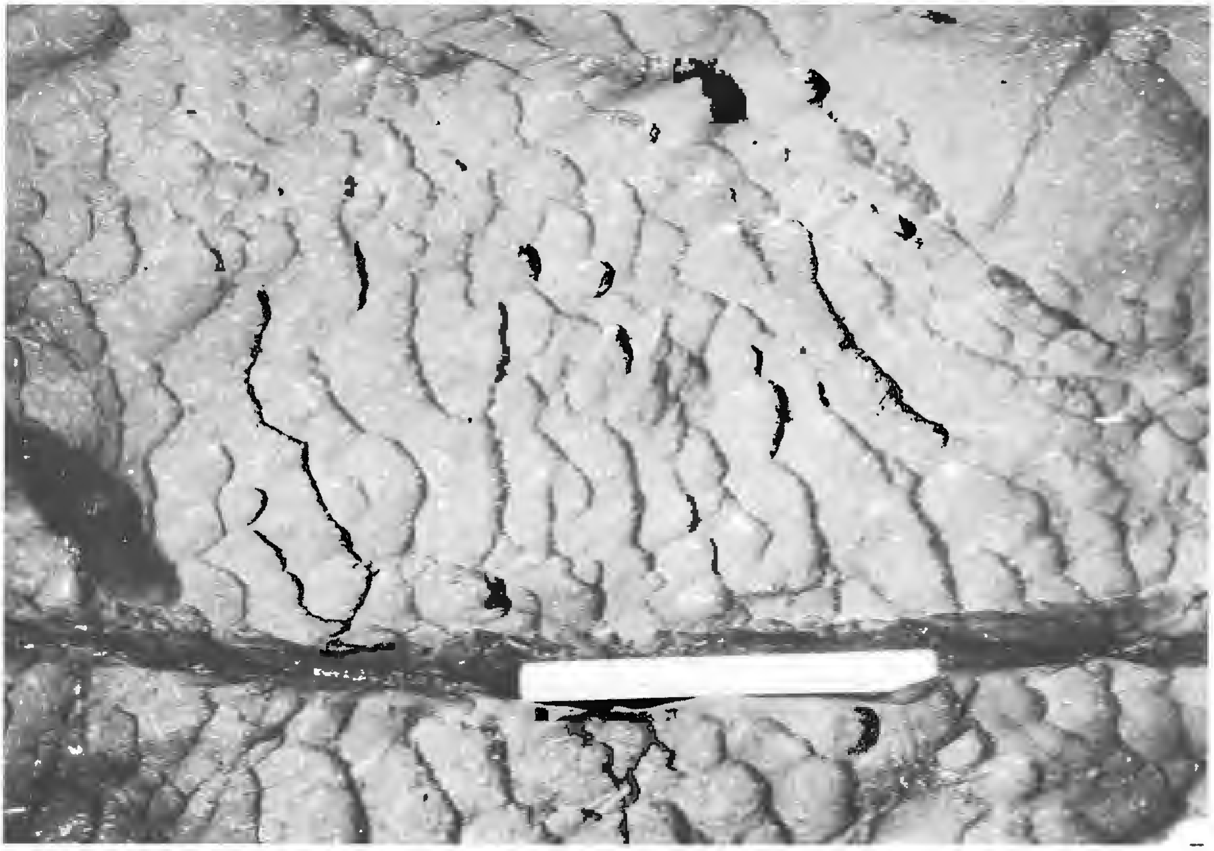


2.3.3 Typical sets of scallops
d/š = the rate between length and breadth of scallop
d = length of scallop
1 open scallops
2 closed scallops

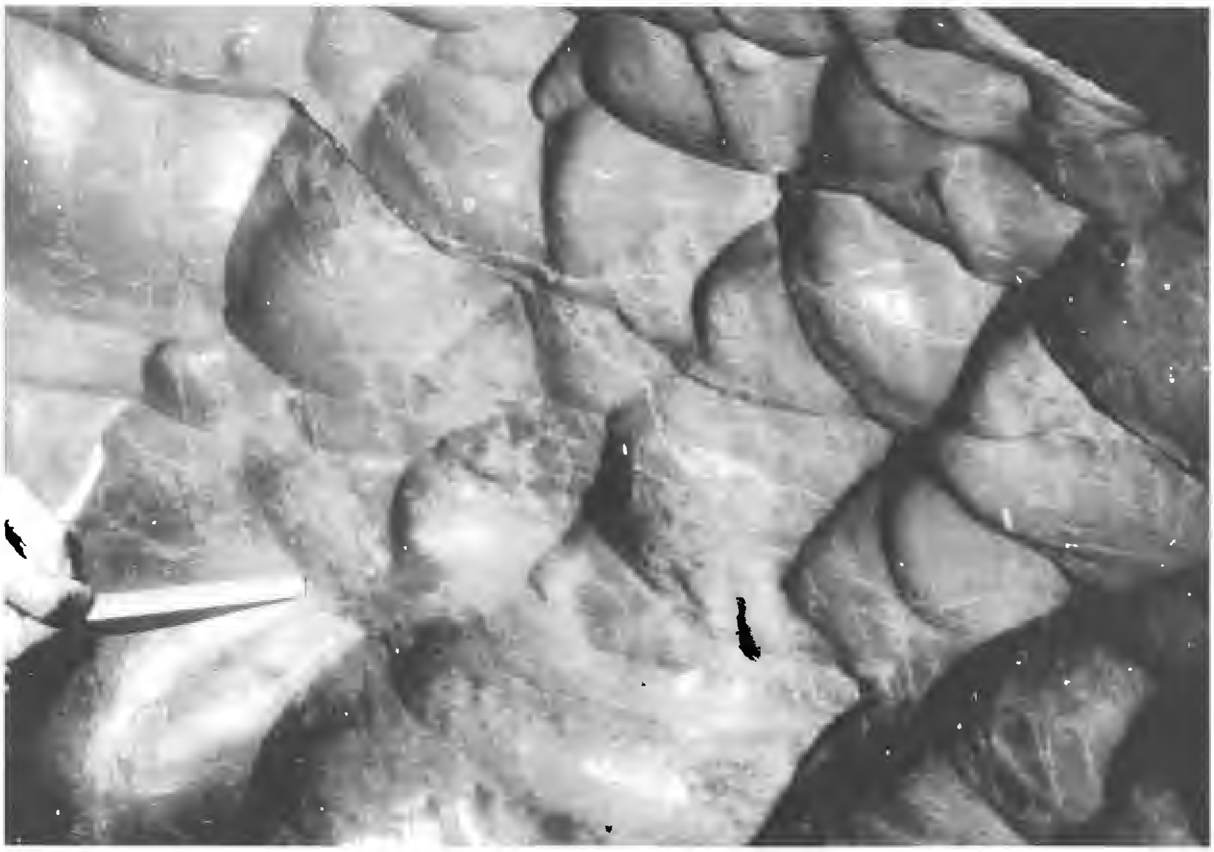
rowed at the half way point. In particular cases (steep wall - 45⁰ Ponor in Odolina, the ceiling in Lokva swalowhole and the ceiling in Kompoljska Jama) the open scallops prevail within a network. As a rule the scallops in the first group are small, from 4,7 to 40 mm in length, and from 2 to 10 mm in depth only. Two cases, 66 and 92 mm in length, are the exception. The scallops occur in packed patterns distributed perpendiculary to the water flow direction (Fig. 2.3.4). As a rule the outflow sides of the closed scallops contact under the angle bigger than 90⁰ (up to 120⁰), the diameter of the inflow semicircular edge is significant in respect to the scallops size. Lateral sides of the scallops are frequently poorly manifested and the pattern resembles flutes. The transverse patterns follow the local trends of the water flow: in Novokrajska Jama they join towards the opening of the siphon, in Pivka Jama they are oriented towards the edge of the breakdown block, where they developed, in Ponor in Odolina the patterns are semicirculary rotated. The smallest scallops, due to drainage of the free-surface stream, from 4,7 to 23 mm in length, occur on steep floors (30⁰ of inclination) and in steep (75⁰) passages. Similar, but larger scallops occur in the narrows within passages that are seasonally flooded. The scallops colonize all the surface of the narrows. The diameters of narrow parts of the passages are from 1 to 2,5 m, their inflow and outflow parts are up to 5 m. In a large ceiling notch in the Lokva swallow-hole the scallops on the outflow side occur on an almost entirely vertical wall. Within a pattern, opened scallops prevail. Slightly larger scallops (33 to 90 mm) occur in less narrow parts of the passages.

Similar wide features have scallops belonging to subgroup 1-2. The scallops have significant radius of inflow, semicircular edges, the outflow ridges contact under the angle 100-130⁰. They are larger than the scallops belonging to the first group, from 40 to 110 mm in length. In two cases (the wall in Logaška Jama, the passage wall in Brlog na Rimskem) closed scallops prevail. The scallops are distributed into a transverse pattern and are not so well expressed as in the first group. The diagonal scallop distribution, characteristic for the networks of the second scallops group is partly indicated in those two caves. Small scallops (floor and lower part of the wall in Markov Spodmol) of this subgroup developed in a free-surface stream on the floor and lower parts of the walls. The others (the wall in Blatni Rov of Zelške Jame, the wall in Logaška Jama, the wall in Brlog na Rimskem, and the wall in central passage of Trhlovca) developed in seasonally flooded channels. The conditions that control their origin are difficult to determine as they are older. In Zelške Jame large scallops occur on the wall, indicating the local water flow to be upstream; in their inflow parts some loam was deposited that solutionally widened them. On the opposite side of the passage the scallops in wall notches are trending downwards. The scallops in the walls in Trhlovca, Logaška Jama and Brlog na Rimskem occur in elongated, semicircular wall notches, 0,5 m in breadth.

To the **second group** belong the scallops with ratio between length and breadth from 1,1 to 2. These too are either opened or closed. Closed scallops are commonly the widest at the half way point, some of them have the same breadth at the third quarter and the others narrow after the first half. The opened ones are almost equally wide from the first quarter onwards; some of



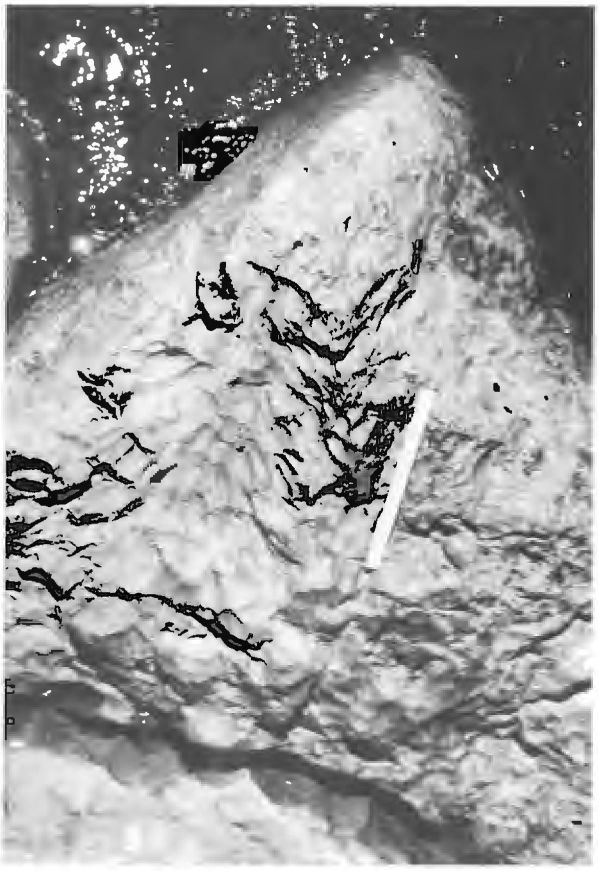
2.3.4 *Scallops on the oxbow passage wall at Blatno Jezero, Beško Ocizeljska Jama (scale = 15 cm)*



2.3.5 *Scallops on the passage wall behind Tobogan, Ponikve v Jezerini* them are slightly more narrow at the last quarter. Such shape is essentially typical of the largest scallops. The radius of semicircular inflow edges of the closed scallops is slightly smaller than in the opened scallops. The closed scallops end by the angle from 80-90⁰. The largest scallops belong to this group, however the difference between the longest and the shortest is considerable: from 24 to 375 mm. In general they are from 60 to 150 mm in length and from 20 to 60 mm in depth. Within the networks consisting of smaller scallops the transverse series are partly stressed. The nets with characteristic connection of lateral edges, limiting the outflow scallop parts, with the diagonal patterns prevail (Fig. 2.3.5). The scallops of the second group mostly occur in flooded channels. The scallops may occur all around, or on the floor or walls only, while on the ceiling solution cups are found. They may occur on breakdown blocks lying in the riverbed (Osapska Jama, Krožni Rov in Črna Jama), however these are slightly wider, within a pattern the opened scallops prevail. To the same group belong the scallops occurring on steep, downwards (45⁰) or upwards (50⁰) inclined sections of floor; these are slightly elongated and on steep ovehanging walls as is the case in the narrows of Logaška Jama. The water flow drained through it upwards. The diameters of the passages with the scallops of this type are larger than the passages containing the scallops of the first group. Smaller cross-sections are 1 m in diameter and reach up to 10 m (Kozinski Rov in Lipiška Jama).

To the **third group** belong the scallops with the ratio between the length and breadth bigger than 2. These too may be divided into closed and opened, the opened prevailing. The radius of inflow edges is more tight than at previous groups, the contact angle of inflow parts being closed scallops is 75-90⁰. The scallops are relatively small, from 10 to 50 mm in length. A special case are very narrow scallops, from 10 to 30 mm in length. The occurrence of rocky blocks controls the shape and size of the pattern (Fig. 2.3.6). The pattern is like that for the scallops of the first or the second group; frequently it starts on the contact with smooth rock surface. The scallops occur on rocks in riverbeds, from 5 to 10 m wide and where the free-surface stream flows. The surface of the rocks is 1 to 2 m above the riverbed bottom. Hence, they develop at high water level. In Hankejev kanal in Škocjanske Jame there is on the upper, horizontal side of the rock a scalloped outflow edge although it is slightly lower. Specially distinctive are the scallops there where the block sharply ends. On the border of the rock the scallops are joined into a transverse pattern. On the inflow part of the rocks there are wider scallops not well marked, distributed in partial transverse patterns and among them there are almost no lateral edges.

To the subgroup 2-3 belong the scallops with the ratio between the length and breadth about 2, but they are larger than the scallops belonging to the third group. They are 50 to 150 mm in length mostly; however among the more narrow scallops, which prevail, wider ones occur as well. This type of scallop is typical of the channels where free-surface streams flow and largely fill them. The water layer is rather deep. The scallops occur either on the floor or on the walls. They are mostly open and characteristic for exposed convex bottoms of the channels (main passage in Križna Jama, a part of uplifted floor in Markov Spodmol), or exposed parts of the walls in front of the passage widenings (the wall 2 to 3 m above the floor in Markov Spodmol, Vzhodni Rov in Predjama: the border of a stream bed).



2.3.6 Scallops on rocky block in the riverbed, Škocjanske Jame (scale = 15 cm)

One type of smaller scallop can be mentioned separately. These are small, some 1 cm long scallops only, up to 0,5 cm in depth. They are mostly circular and the water flow trend is badly expressed. They are either independent or constitute a gradational set of features at the contact with a smooth rocky surface, or there are small surfaces of smooth rock among them. Such scallops occur either below significant falling flows or at inflow,on the upright side of the blocks in the riverbed (Fig. 2.3.7).

In the chosen caves I had the opportunity to see only old large scallops, hence most of them were not well preserved. The largest scallops are 1 to 1,5 m in diameter, 0,3 to 0,5 m in depth (Fig. 2.3.8). Large scallops are shaped as shallow bowls. Their network pattern is hardly distinctive. On the border, projecting rock remained. Slightly smaller scallops are from 0,5 to 0,75 m in diameter, and from 0,1 to 0,2 m in depth. These too are shallow bowls or their cross-section is elliptical. The most distinctive elliptical scallops occurred due to wa-

2.3.7 Scallops on the inflow part of the rocky block, Podpeška Jama (scale = 15 cm)

2.3.8 Large scallops in Pivški Rokav, Planinska Jama (scale = 15 cm)

ter flow draining from below upwards. Their connection in networks is more distinctive and in some cases one may deduce the trend of water flow. Large scallops occurred in flooded channels and they may be found either on walls or ceiling.

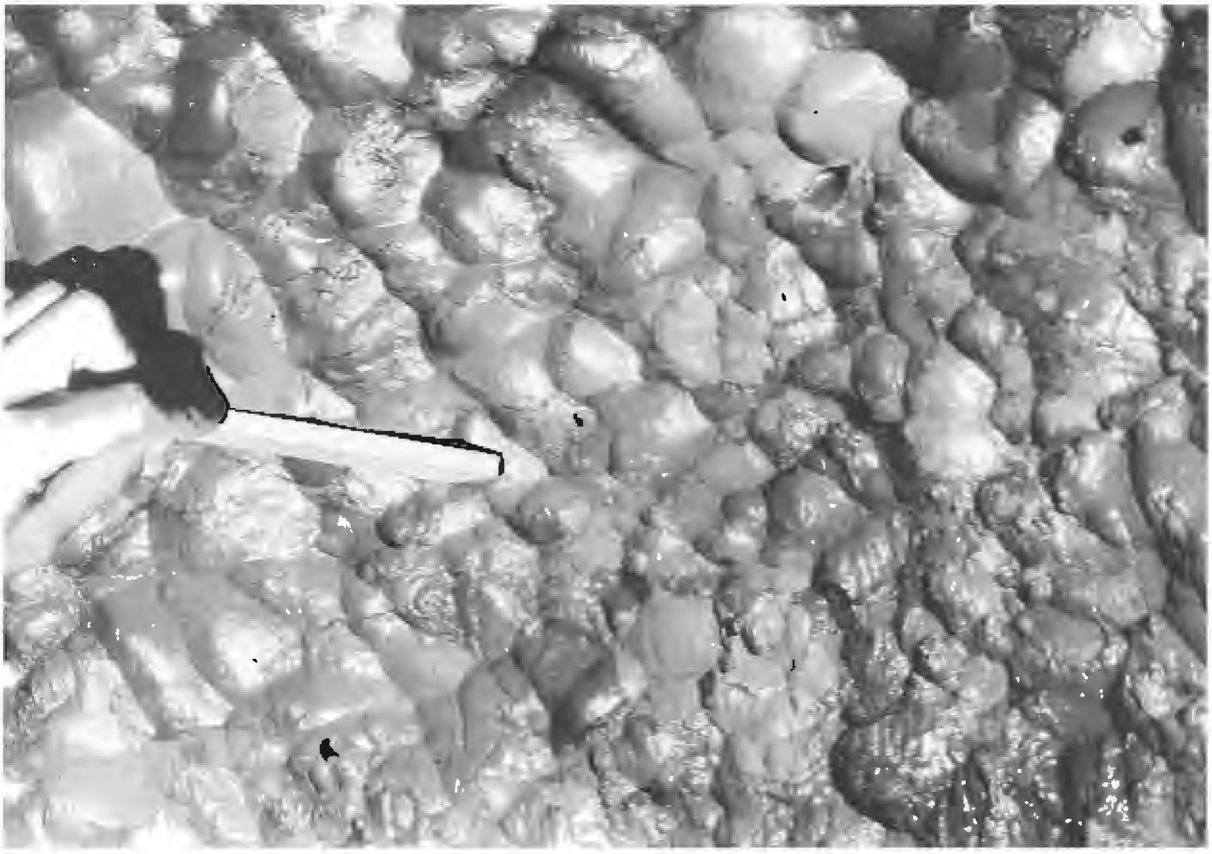
Lithological influence on origin and development of scallops

Scalloping is common on various limestones and is more rare in dolomites, conglomerates, breccias, flowstones and sandstones. The origin and development are controlled also by joint frequency.

On homogeneous limestones comprised of grains uniform in terms of their size and solubility, rather uniform networks of scallops occur. More diverse patterns occur on heterogeneous rock. Such are found in Markov Spodmol on a part of the wall consisting of large intraclasts (Fig. 2.3.9). The crests of the scallops are indented or even missed in some places. On the nearby more homogeneous rock the scallops with sharp and straight crests occur. In Veliki Hubelj, where the limestone is recrystallized in some places and the rock surface is rough, crystals protruding for 1 to 3 cm, there are no scallops. Single small notches are cut in the surface only. On nearby homogeneous limestone there are scallops or else the surface is mechanically polished. A similar example appears in Biološki Rov of Babja Jama. On a seasonally flooded part of the wall in Pivka Jama the scallops are about 3 cm in length and where rudists are protruding from the wall for 1,5 cm, there are no scallops (Fig. 2.3.10). In Predjama too, in the Lokva swallow-hole rudists are protruding from the wall. Over them a net of scallops occur and they are larger, up to 8 cm in length. The pattern is not uniform. On Paleogene limestone the fossils only slightly influence the shape of small scallops (Fig. 2.3.4).

Heterogeneity of the rock influences deviation of trends of particular scallops from the local direction of the water flow and also their different sizes. Such deviation is typical of the nets of large scallops in particular, when at projecting parts of the rock they (Fig. 2.3.5) occur in assemblages. In them the water drains to different sides and the trend of particular scallops may deviate for 60^0 even. The scallops are trending towards the borders of rocky pendants, broken surfaces and breakdown blocks and are appropriately shaped.

On **dolomite** scallops are few, and if they occur they are as a rule of unexpressive shape. On the floor of the riverbed in Stinkotov Rov of Turkova Jama there are in the dolomite 5 to 7 cm long floor-pits, slightly deepened on the inflow side. In Križna Jama and in Veliki Hubelj smaller or larger aggregates of crystals with sparitic cement protrude out of dolomite. There are no scallops but single small niches are cut into the surface of dolomite protruding out of the walls. In Jama v Peklu, Kočevsko, small scallop nets occur only on one section



2.3.9 Scallops on intraclastic limestone, Markov Spodmol

of biosparitic dolomite but they do not occur on broken microsparitic dolomite without calcite veins.

In Smoganica scallops on the pieces of limestone that are larger than 20 cm occur in the riverbed consisting of **carbonate conglomerate**. The scallops, 5 cm in length, are rather irregular. The cement consisting of small pieces of limestone and sandstone is very rough. It projects in dissected cusps out of rocky surface. A similar appearance occurs on **breccia** in Bazinova Jama near Podlaški Topoli. On the near part of the limestone ceiling there are scallops. But there are no scallops on intraformational breccia in Podstrešje of Mala Boka. Breccia consists of small parts of rock (1-3 cm in diameter) interbedded by solid sparitic cement which protrudes out of the walls. In the sparitic cement occur angular pits, elongated at the fissures. In the near channel with limestone brim where similar hydrological conditions appear at high waters, the scallops are 2 to 3 cm in length.

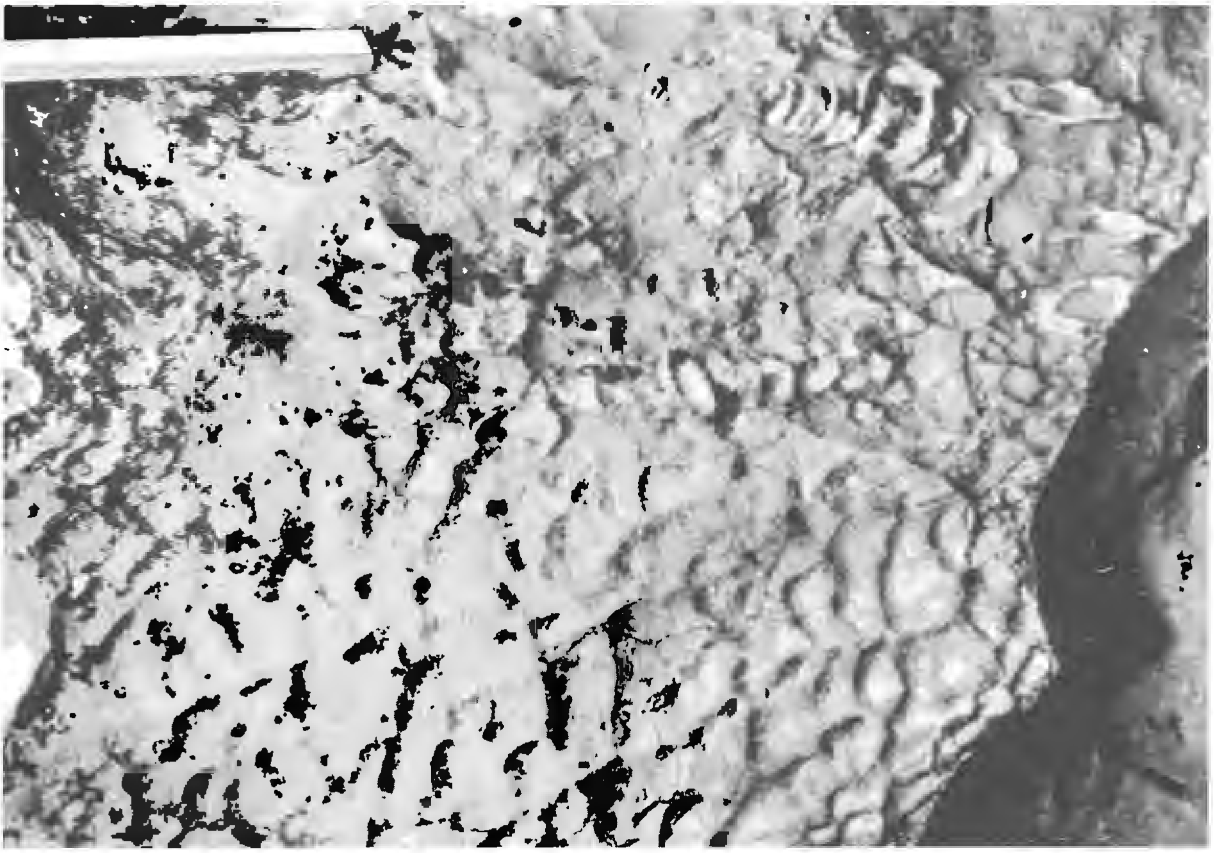
In Lepe Jame of Postojnska Jama the oblong lenses of **chert** protrude out of the walls for at least 2 cm. Their surface is indented by linear and only slightly rounded planes. Around the lenses a well developed pattern of small scallops occurs (Fig. 2.3.11).

The scallops on flowstone resemble those on limestone. On Katakombe of Mala Boka the scallops occur on weathered flowstone. The edges of scallops are rounded and partly resemble ripple marks in the riverbed, covered by sand in Blatni Rov of Križna Jama.

In Smoganica the scallops occur on **quartz sandstone** with calcite cement (Fig. 2.3.12). The scallops are rather long (7 cm) and narrow (3 cm). They may be classified into the third group which corresponds to seasonal shallow flow and homogeneous grained rock.

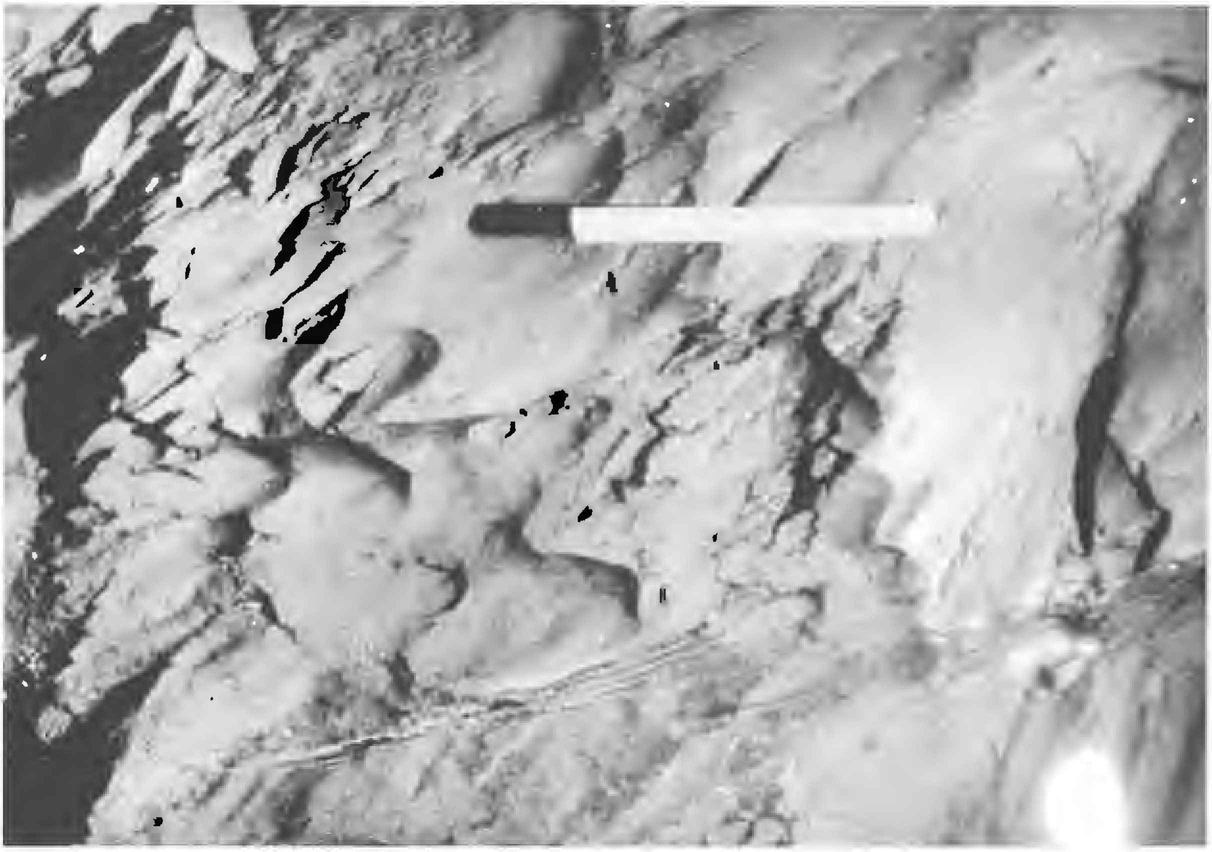
Along thin **fissures** the scallops (Fig. 2.3.13) can elongate (Slabe 1989 b, 203), connected into patterns and dense thin fissures cause sharp differences in the scallop trends and their sizes. Along the fissures the crests of the scallops are usually indented. The ratio between the largest and the smallest scallop within the network occurrring on the fissured rocks may reach 3.

On very fractured and broken rock, scallops do not occur. They may be found only on interjacent, large, non-fractured surfaces. Cusps are cut in the walls of the passages; along distinctive fissures pendants occur. Different influences on scallop development have the fissures filled up by calcite cement. The cement is commonly slightly more persistent than the surrounding rock and protrudes out of the surface for some mm. It controls small scallops (Križna Jama) while it usually does not have an impact on larger ones (Ponikve v Jezerini). Where the calcite veins appear banded when seen in cross-section and there are scallops, their influence is insignificant. When the calcite cement is loose it is not stable in the water flow. Small pieces of rock break off. In Finkova Jama very recrystallized limestone consists of large sparitic crystals. Hence there are no small scallops on the walls cut in by the water flow of 1 m/s of velocity. Small surfaces of sheeting dolomite flushed by fast water flow in Pucovo Brezno are smooth

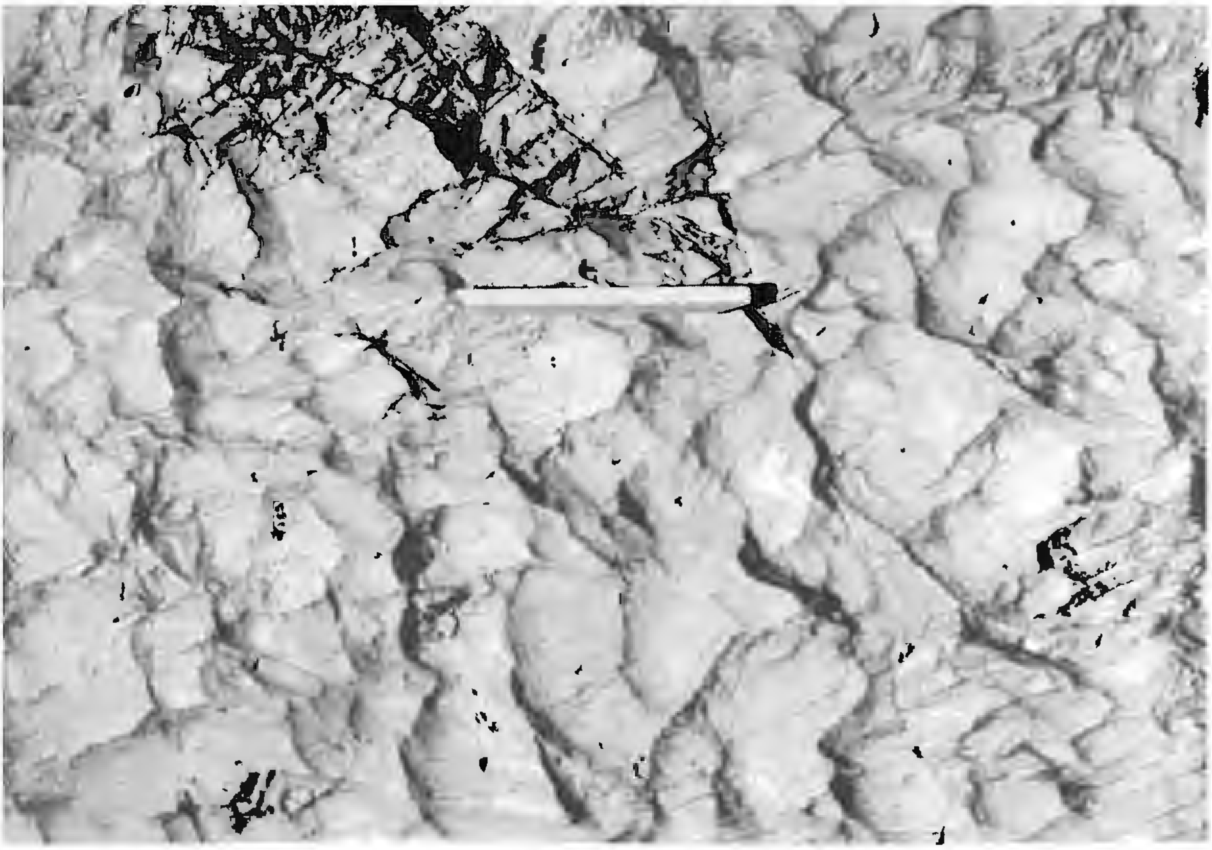


2.3.10 Scallops on Rudist limestone, Pivka Jama (scale = 15 cm)

2.3.11 Scallops and interbedded chert lenses, Lepe Jame (Postojnska Jama) (Scale = 15 cm)



2.3.12 Scallops on sandstone, Smoganica (scale = 15 cm)



2.3.13 Scallops on crushed limestone in Podstrešje, Mala Boka (scale = 15 cm)

The surface of the scallops

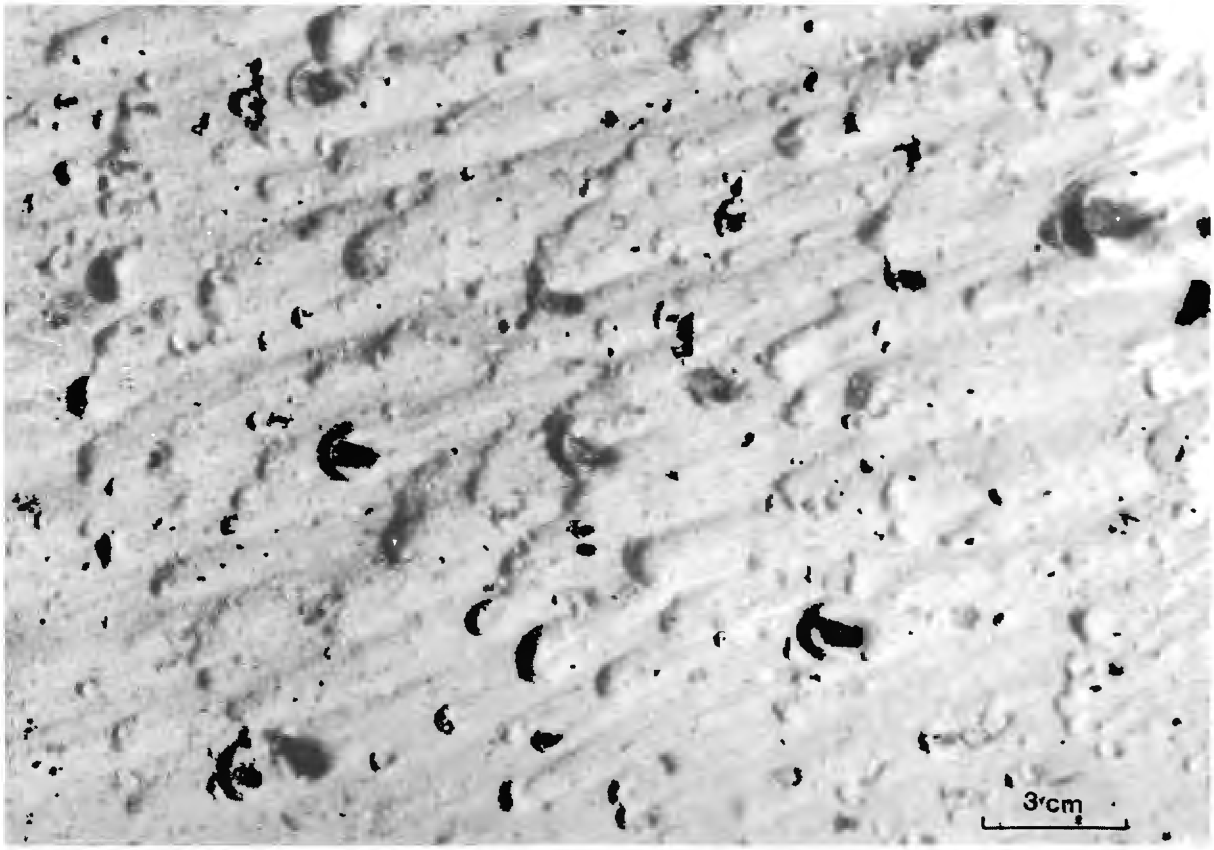
The surface of scallops frequently indicates the process of their development. In comparison to surfaces of other rocky features the surface of scallops, in particular small scallops, is rather smooth. Such is also the surface of small scallops occurring on Paleogene limestone. In Ocizeljska Jama, Alveolines, Nummulites and Orbitolines are not seen on the surface of the scallops. Large scallops in Lokva swallow-hole at Predjama are rough due to Rudists protruding from the surface; small scallops could not develop on such a rock in Pivka Jama (Fig. 2.3.10). It means that the fossils in the rock are differentially resistant against the water flow. The surface of scallops on sandstone is thinly rough which is due to the rock structure.

In short, thin roughness consists of protruding particles or pits, grooves, and concave cut-in features. In the first case these are large sparitic crystals, calcite veins, fossils and intraclasts in a micritic base. In the second case these are pits associated very soluble parts or thin fissures. The protruding particles can indicate the flow direction over a scallop. On the inflow side the surface of calcite veins gradually disappears; on the outflow side it is steep, cut along the calcite layer.

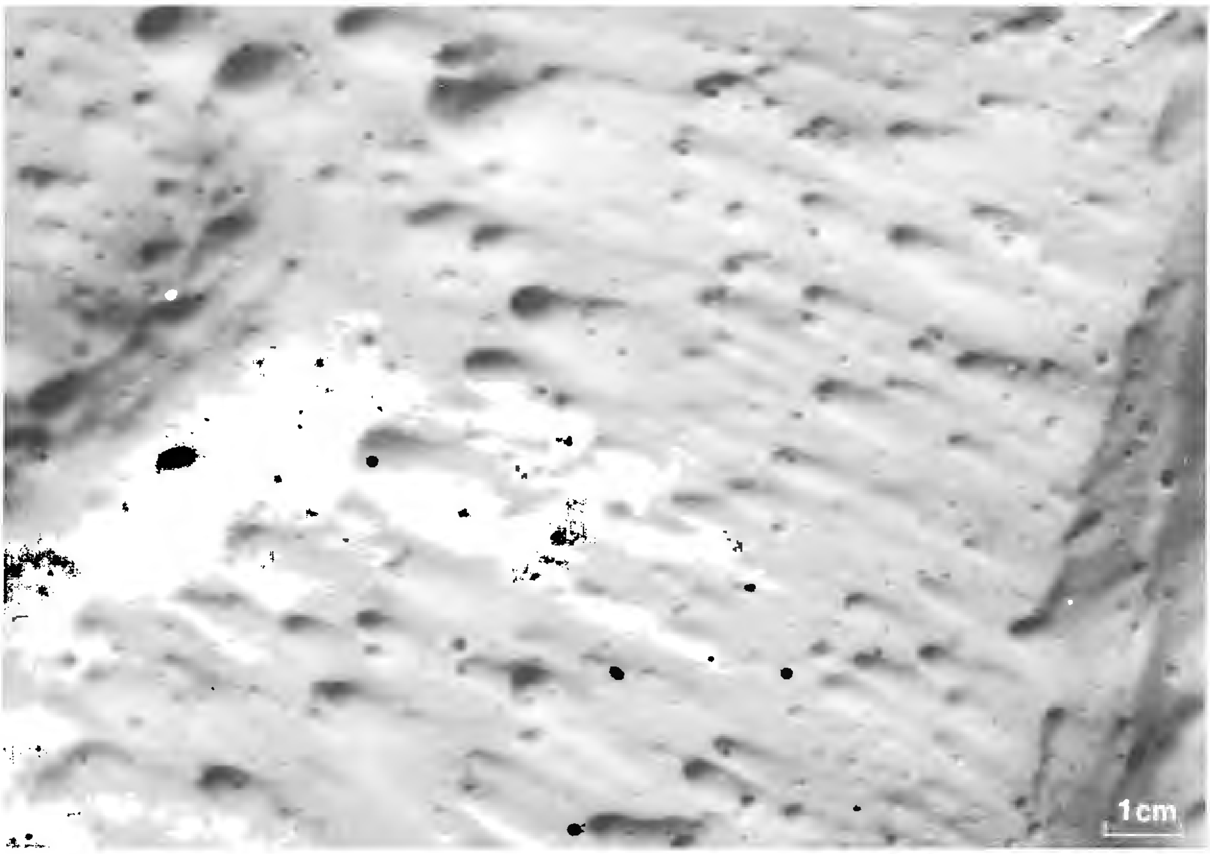
Laboratory scallop modelling in plaster

The water flow with 1 m/s of velocity drained over unfissured, rather homogeneous, semi-circular plaster cast half-tube; 1,4 g/l of plaster was dissolved in water. The water layer depth was 1 cm only. The water distributed into narrow, almost parallel flow line, several centimetres long. Scallops (Fig. 2.3.14), 5 mm in length, 2,5 mm in breadth and 2 mm in depth occurred. They ressemble these of the third group. They are mostly open. Along the obstacles, along larger grains, the water incised the pits first and later transported the grains. In two hours the scallops developed out of the pits. After four hours their form did not essentially change. The experiment was repeated with a water flow velocity of 0,2 m/s. In this case, too, elongated, slightly larger scallops occurred.

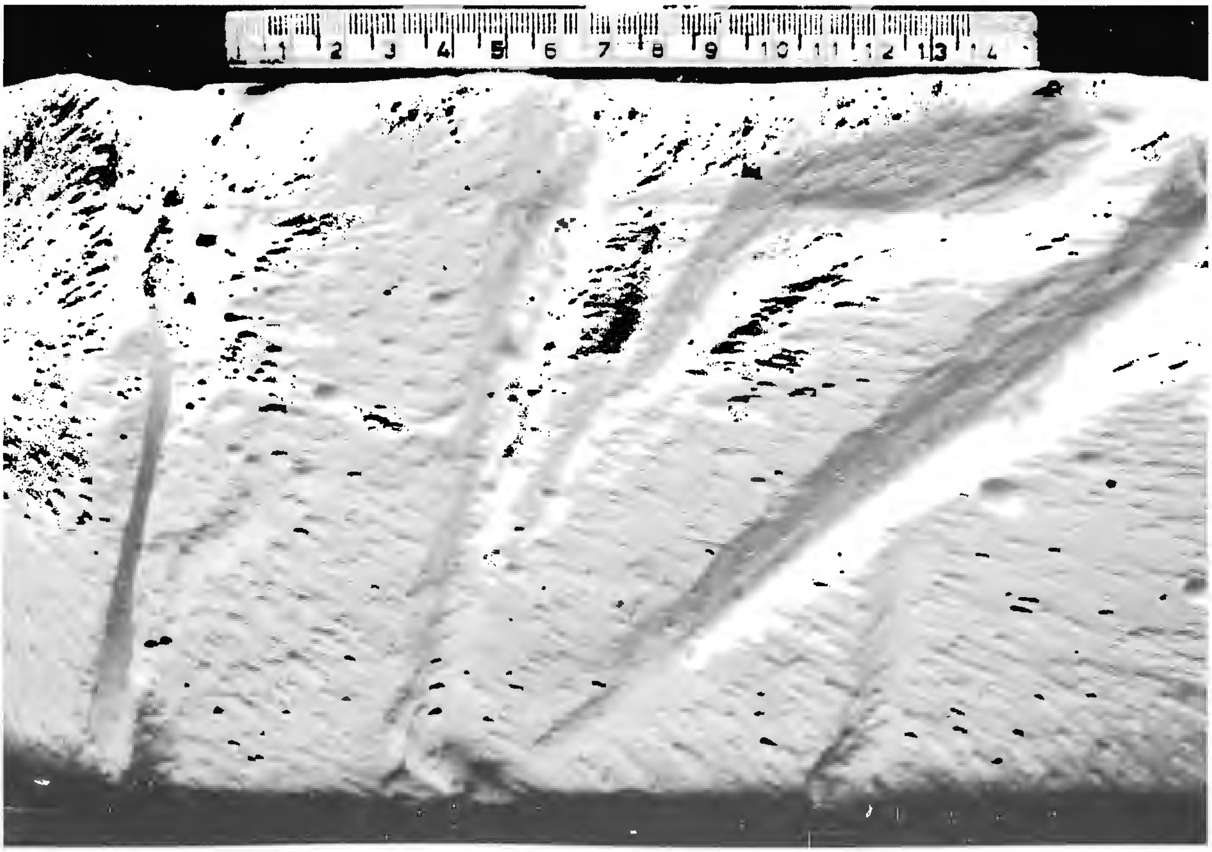
A large, eight-angled plaster block with linear lateral and upper surface, 1,2 m in diameter was dipped into the artificial feed-trough leading to the hydropower station at Planinska Jama. The surface of the block was 1,5 m below the water level, water velocity was 1,4 to 0,9 m/s. In both cases scallops developed on the block (Fig. 2.3.15a). The scallops developed after only two hours and their size and shape did not change later. In the first case they were 1 cm in length, in the second up to 1,5 cm. The scallops were narrow (up to 0,5 cm) and relatively long (3rd group). Single scallops widely open, but if they were connected into a network, they closed. The distribution and trend of the scallops on the surfaces which were exposed to water flow under different angles is typical. In the middle of the inflow lateral plane which was perpendicular to the water flow trend, the pits occurred, while on the border parts of the plane were the scallops which trended towards the edges.



2.3.14 Scallops in tube of plaster



2.3.15a Scallops on block of plaster



2.3.15b Scallops on lateral side of block of plaster

The block in the Podpeška Jama riverbed has similar shape. On the plane (Fig. 2.3.15b) which was exposed to water flow under the angle of 45° the scallops occurred over the whole surface. At the beginning the scallops were parallel to the flow, on the second half they were oriented towards the edges. On the plane that was parallel to the water flow direction the scallops too trending into the flow direction. On the rear side of the block, which was transverse to water flow direction but on the downstream side, small pits occurred only. On the upper side of the plaster the scallops were at first parallel to the water flow, but on the outflow side they trended towards the edges of the block. Such distribution is shown also by the scallops in cave passages over which free-surface streams flow and are lying close below the water level (riverbed in Škocjanske jame).

A plaster block of the same size (Fig. 2.3.16) consisting of beds mixed with variously sized unsoluble or hardly soluble particles of sand was exposed to water flow with velocity 1 m/ s. The lower bed of plaster consisted of particles smaller than 0,1 mm. In the second layer were particles from 0,1 to 0,25 mm, with 20% of particles with 0,5 mm in diameter added. To the third bed of plaster composed by particles from 0,1 to 0,25 mm 10% of insoluble particles, 1,25 to 2,5 mm in size was added. To the fourth layer of plaster 10% of insoluble sand, 5 to 10 mm in size, was added. The scallop distribution on the block was similar to the one described above, different rocks being characteristically shaped. On the most homogeneous plaster good metwork of small scallops occurred. On plaster mixed with large insoluble particles pits occurred around them. On surfaces with few obstacles they were connected in poor but distinctive scallop net. The size of the pits was mostly controlled by the size of the obstacle in the rock and reached a 2 to 3 times bigger diameter than a scallop. Does the rock structure control the scallops size? On the parts of the plaster where obstacles are densely distributed one cannot speak about the scallops net although the plaster surface is porous. At each obstacle a pit occurred that had the shape of an open scallop.

2.3.16 Scallops on bedded block of plaster

The plaster tube, wider at the centre was submerged into water, flow velocity of 1 m/s. The tube was 1,5 m deep in the water. The length of the inflow part of the tube was 35 cm, the outflow part 15 cm, both 13 cm in diameter. The medium part of the tube, 35 cm in length, was 22 cm in diameter. In the inflow and outflow tube scallops of the second group occurred (Fig. 2.3.17). In the first tube the scallops were 12 mm in length, and 9 mm in breadth, in the second 15 mm in length and 11 mm in breadth. Under the same conditions on a plaster block scallops of the third group developed, that is relatively narrow and long. In the medium, larger part of the entire tube the individual solution cups (Fig. 2.3.17), joined at significant inhomogeneities only, occurred. The average diameter of the solution cups was 1 cm. On the contact of the two tubes with different diameter, 3 cm in breadth, notches developed. The notch on the outflow part was remarkably significant, and larger. It consisted of solution cups. The scallops in front of the tube's widening were elongated into shallow floor pits.

The size of the scallops in plaster is slightly smaller than the features occurring under the same condition in limestone. I presume that the scallops on more soluble rock are smaller. The scallops that developed on homogeneous plaster have regular shapes and their surface is smooth. Those developed on the plaster with sand grains are heterogeneous and rough. The scallops are due to plaster solution, coarser, unsoluble particles being swept away by water. The plaster block preserved sharp edges.

Origin and development of scallops

Origin and development of scallops is controlled by rock lithology, velocity and pressure of the water flow with defined viscosity and aggressivity of water and size of channel and shape of the perimeter. The factors vary in different ratio, however the fundamentals for development of characteristic scallop networkss are essentially defined by the hydraulic conditions. The rock determines about the scallops origin, and the shape of a single scallop within a pattern respectively and controls their size.

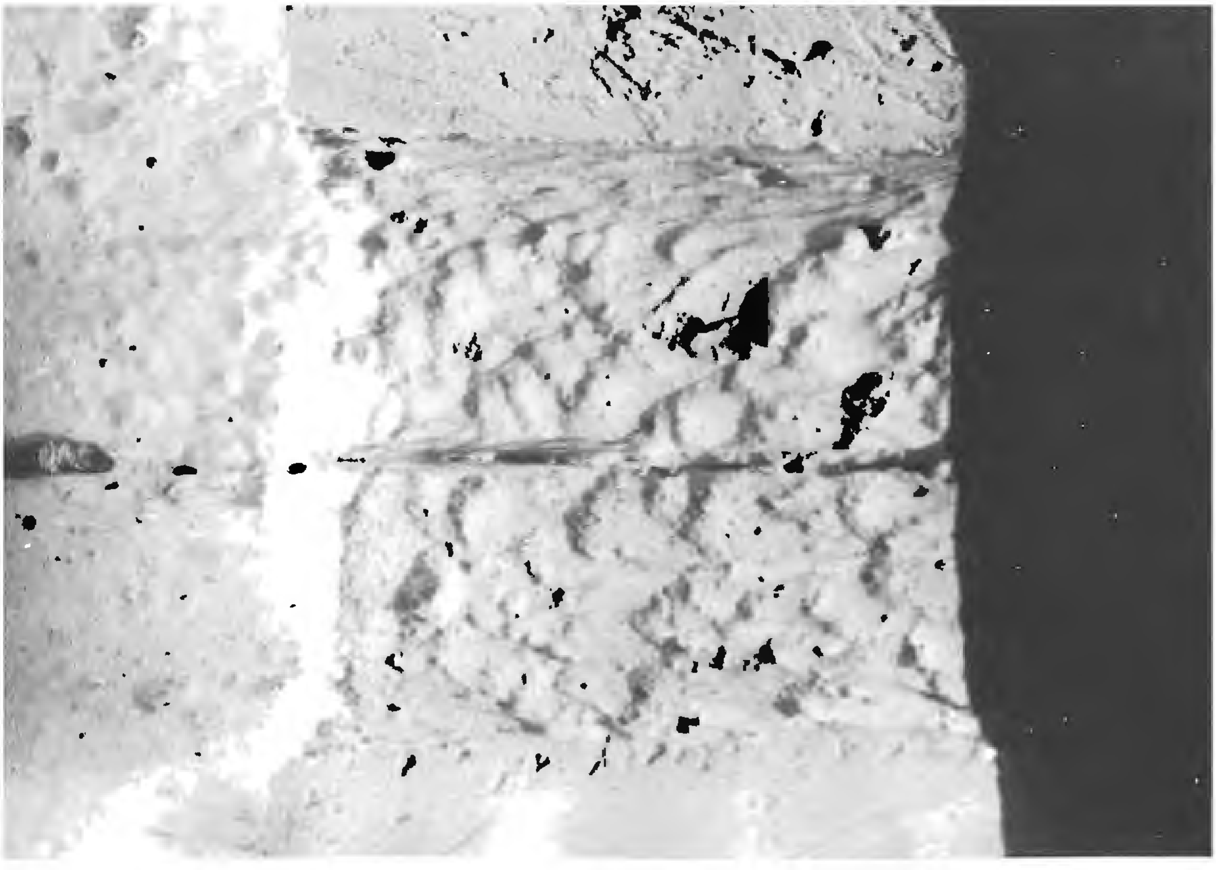
At high Reynolds Numbers the friction depends on roughness of the pipe's perimeter and is almost entirely independent on fluid viscosity, while at small Reynolds Numbers it depends on viscosity and less on roughness (Reynolds 1974, 5). This property of walls reflects, as it seems, the development of small or large scallops respectively. The diameter of vortices in a water flow is mostly controlled by its velocity. The rock structure too influences the size of vortices. At larger obstacles the vortices are greater. If the obstacles of the same size or larger than the scallops occur densely close, the mixing of vortices may cause a chaotic situation in the direction of flow lines and the characteristic scallop net does not appear. To develop a scallop network the size of the vortices must be larger than the size of constituent parts of the rock. The distribution of smaller scallops is controlled not only by hydraulic conditions and space geometry, but primarily by inhomogeneities in the rock. It was nicely shown by plaster modelling. In smaller scallop formation the boundary laminar water layer is interrupted due to non-uniform solution of grains within a rock, inferred also by Ford & Williams (1989, 305). In plaster the water incised a hollow at the obstacle. The obstacles, slightly larger fragments of plaster, were later removed by water. At the same time there occurred the pits and later scallops on more soluble parts of plaster and along small pores. In some cases single scallop is thus open. Allen (1972) stated too that heterogenity within a rock may cause scalloping. If the rock is homogeneous it is evenly covered by vortices and a net of scallops occurs. On homogeneous sand "ripple marks" originate (Hsü 1989, 108) resembling a uniform net of closed scallops.

The uniform heterogenity controls the grain structure of carbonate rocks. Within a net closed scallops of various shape prevail; most of inflow parts are semicircular and outflow parts are triangular.

Is the origin of scallops possible only when the boundary layer of the water flow is substantially thinned or interrupted and its influence may be neglected? In aggressive water the approach of vortices caused by friction on the boundary layer may provoke accelerated rock dissolving due to a locally thinner diffusion layer. This may lead to formation of large scallops which are controlled by slow water flow and the influence of the rock on their formation is modest. However large fragments of rock may prevent the scalloping in fast flow, while during slow flow they influence net formation in particular. Significant heterogeneities frequently give rise to "clusters". In them the water flows to various sides. In Lokva swallow-hole the Rudists protruding off the surface, do not influence on the shape of medium-sized scallops but small scallops did not develop on a similar rock in Pivka Jama.

By good knowledge of the hydraulic properties of turbulent flow and rock structure one may define the rate at which scalloping occurs, or else one may determine the lithology's impact on scallop size. Scallops may develop on particular sections of the perimeter which are big enough for vortices to develop and deviate from the water flow direction under small angles.

The water in the vortices circulates perpendicularly on the surface which is overflowed and this is evidenced also by the elongated and shallow part of the scallop at its outflow side. The largest obstacle to flow lines within an eddy is the scallop's wall which lies the most at right angles to the water flow. This is why the scallops move downstream. But migration is limited by



2.3.17 Scallops in tube of plaster

rock, fissures in particular, with which small scallops are frequently associated. Large scallops, more than 50 cm in diameter, do not suggest the direction of water flow any more.

Increased velocity of water flow decreases the diameter of vortices as well as the scallop's length. The smallest scallops that I found in the chosen caves were 0,4 cm in length and the longest 40 cm in length. The exception are large scallops. Thus they originated by the water flow having velocity from 6 to 0,05 m/s calculated according to the equation of Lismonde & Lagmani (1987, 38):

$$UL/v = 22000$$

in simplified version, or in complete form:

$$UL/v = 20700\ (1-0{,}266(\ln(D/2L)-1{,}5)),$$

which may be adopted only in the passages of regular circular cross-section. U is flow velocity, L is average length of the scallop. These calculations of water flow velocity correspond rather well to those which were obtained on the base of pebble size (Scheidegger 1961, 135), transported by water. The initial size of the scallop mostly depends on the rock. In Markov Spodmol the smallest scallops, only 0,4 cm in length, are found on steep parts of the riverbed indicating the water flow velocity of 6 m/s and the fine-grained, homogeneous rock in which they occur. Typical of limestones is a grained structure and frequently limited homogenity in respect to locally high flow velocity and small vortices within it.

I noticed some characteristic assemblages of scallops within the same network. One may distinguish the scallops with nearly perfect shapes and those modified due to rock heterogeneity. The distribution of vortices that overflow the entire surface of the suitable rock is controlled primarily by the rock, and the turbulence determines the shape of the scallops. In between the initial vortices there are others competing with one another. This is indicated by certain disproportionally small scallops within a network. After a certain time in a regular flow the scallops reach their limiting size and an equilibrium state. In plaster modelling the scallop size did not change after 2 hours.

According to gathered field material and plaster modelling I think that the scallops similar in shape develop under equal hydrological conditions.

When the channel is large enough and the homogeneous rocky surface larger than the critical diameter of vortices, then at a certain velocity independent turbulence occurs at the walls, scallop, belonging to the second group occur. This is the basic, mature scallop type (Fig. 2.3.5). The scallop length decreases proportional to higher flow velocity, and their radius increases also and the scallops become deeper proportional to pressure increase towards the walls. During the experiment in a tube scallops of the second group occur, and under equal conditions in an open flow scallops of the third group. This fact confirms the important influence of the shape and size of the space through which the water flows on the scalloping. In the pipe-like channel of Mala Boka the scallops on the ceiling and the floor are of the same length, however the floor scallops are wider by one third. The flow velocity near the walls would be lower in the wider conduit and, hence, the scallops would be larger in the wider conduits (Serban 1987, 16).

Within the first group, the scallops are classified into transverse series (Fig. 2.3.4), and the size of the space impacts on their development. As a rule such scallops occur in the narrow parts of the cave pasages or they may be found on floor or wall indentations. They are incised by the fast water flow in a flooded passage or open water flow acting by smaller pressure on the walls. I presume that the size of a passage or of its part (longitudinal notches) dictate the regular flow turbulence over the whole cross-section.

The most elongated scallops are found in the third group. It is typical of them to develop when the rock is flushed by shallow, open water flow. Its pressure against the walls is poor. This is why the location of the scallops on the rocky blocks or on exposed convex parts of cave riverbeds and on the walls close below the level of high water is characteristic. When the flow is extremely shallow, thin longitudinal flow lines occur; this was confirmed by the experiments in plaster and is also reflected on the breakdown block of weathered flowstone in Mala Boka. On the inflow edge of the rocky block (Fig. 2.3.6) the net of scallops occurred due to characteristic flushing over the rock. Behind the obstacle the flow became free. The net is more narrow on the inflow side and it widens on the outflow side. The scallops develop at the unform eddy.

The subgroups 1-2 and 2-3 are combinations of the basic groups. In group 2-3 the scallops are characteristically elongated due to exposure on higher parts of the riverbed. The water flow above them is higher, and it means that the pressure against the walls is higher than is the case with scallops of the third group.

With scalloping on carbonate rocks both processes are important, locally accelerated dissolution and direct erosion of the rock by a water bulk. The water transports the less soluble particles of the rock. From a sandstone consisting of quartz particles cemented by calcite, the water removes the quartz pieces when the calcite cement is dissolved. With scalloping in more resistant carbonate rocks the corrosion plays a major role. It was confirmed by microscopic observations of the surface of small scallops which are smooth under high magnification. The scallops occurring during plaster modelling are due to the plaster dissolving. Larger pieces, protruding out of the surface were removed undissolved by the water flow. As a rule scallops do not occur in the passages where mechanical activity of water flow prevails (Babja Jama). The perimeter of such cave passages is smooth.

Comparing the water saturation and the formation of rocky relief in the swallow-hole Finkova Jama and in the active cave Podpeška ama (Ribniška Mala Gora) one may find out that the rock structure is more important in the rocky feature's origin than the saturated or potentially aggressive water. The sinking water is saturated to 21%, the effluent up to 60% (Kranjc 1981, 52). In

Finkova Jama ceiling pockets are found only, while the rocky relief of Podpeška Jama is decorated by all sorts of scallops and ceiling pockets. In the first of these caves the rock is severely recrystallized, in the second one the rocky perimeter consists of rather homogeneous oosparitic limestone.

Various levels and corrosionally aggressive waters have various meanings in the formation of rocky relief. In Škocjanske Jame high waters incise the scallops, the bottom of the riverbed is encrusted by thin layer of flowstone. This is additional confirmation that only a part of the water is active in rocky relief formation.

I presume that the scallops are smaller and characteristically elongated (Group 3) if the rock is easily soluble.

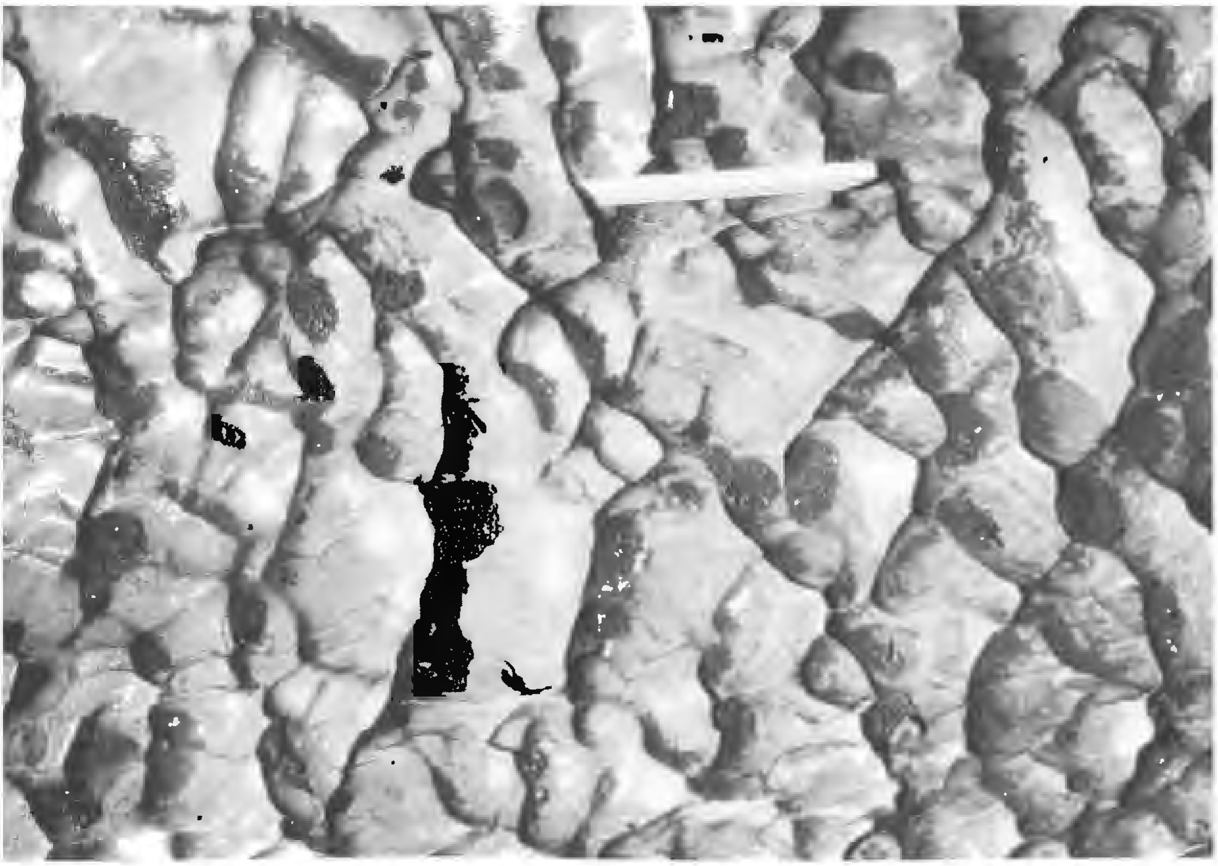
The material transported by water may also cooperate in the scallop's formation. The sand, which is too heavy to be included by the water flow into rectangular turbulence incising the scallops, whirls parallely to the rock surface. The scallops are thus semicircularly deepened at the bottom (Fig. 2.3.18). In seasonally flooded channels (Osapska Jama) where slow water deposits loam, corrosion below the sediments deepens and widens the scallops. This is the combination of scallops and below-sediment floor-pits.

One may assess that the scallops origin is a relatively short-term process. It is understandable that younger, in particular smaller scallops rather quickly cover the older ones. The last water flow over the rock is commonly the deciding one for shaping the cave walls. Only one part of the flow incises the scallops; probably not the long-lasting one but the one which has the greatest effect, as was stated for the entrance channel of Tentera. Lauritzen et al. (1985, 143) calculated that in that flooded channel scallops occur during the highest discharge only, in 5% of the year only. Micrometer measurements enabled the conclusion that the scallops in this channel were forming for approximately 800 years.

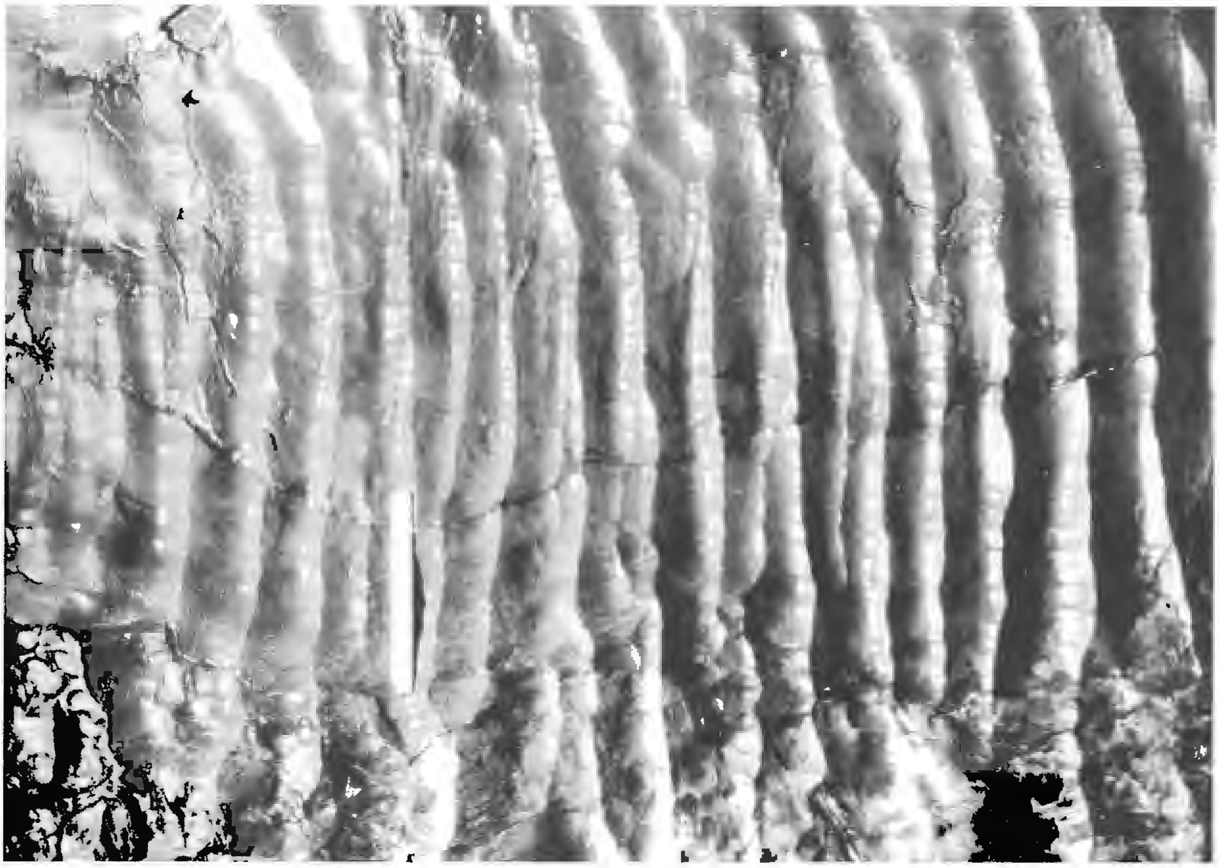
Scallops may occur either in syngenetic or paragenetic passages. In the first case they may be in flooded passages, in passages with free-surface water flow, or in meanders, while in paragenetic passages larger scallops are due to water flow above the fine-grained sediment. Thus the scallops may occur on the entire perimeter or else they occur in connection with other features, below sediment half tubes and pits. Due to water flow efficiency they prevail in the second case.

Flutes and their origin

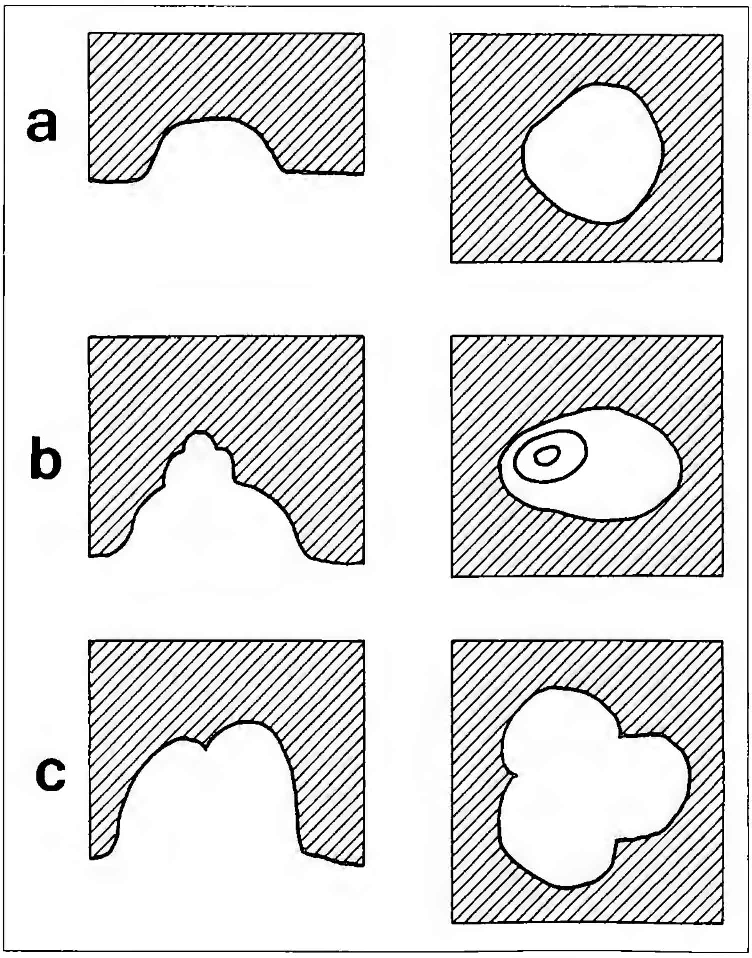
In the chosen caves only one appropriate example of flutes was found. In Markov Spodmol there are upright flutes in the longitudinal rocky notch at the concave side of the curve, 1,5 m above the floor. This means that they are transverse to the water flow direction (Fig. 2.3.19). The flutes are 60 cm in length and this is also the breadth of the wall notch; they are in average 5 cm wide and 1,5 cm in depth. On some ridges among the flutes there are smaller flutes, enlarged downwards. The cross-section of the flute is semicircular, its bottom slightly undulating.



2.3.18 Scallops that were mechanically deepened in Vzhodni Rov, Predjama (scale = 15 cm)



2.3.19 Flutes, Markov Spodmol (scale = 15 cm)



2.3.20 Types of ceiling pockets; longitudinal and cross-section
a. independent, simple ceiling pocket
b. independent ceiling pocket in levels
c. composed ceiling pocket in levels

The origin of flutes was explained by Curl (1966). They should be due to long-lasting washing of the wall by flow of steady velocity. One can infer that flutes are characteristic of longitudinal, semi-circular wall notches. They occur in particular at thinner limestone beds which are variously resistant against the water flow. Undistinctive transverse ridges in the flutes distributed at the distance equal to their breadth evidence that flutes are an extreme example of the first group scallops. I presume that their origin is primarily controlled by a defined rate between the velocity and local dimension of the water flow which is determined by the passage or wall notch diameter. There the water flow has a characteristic turbulence over the cross-section.

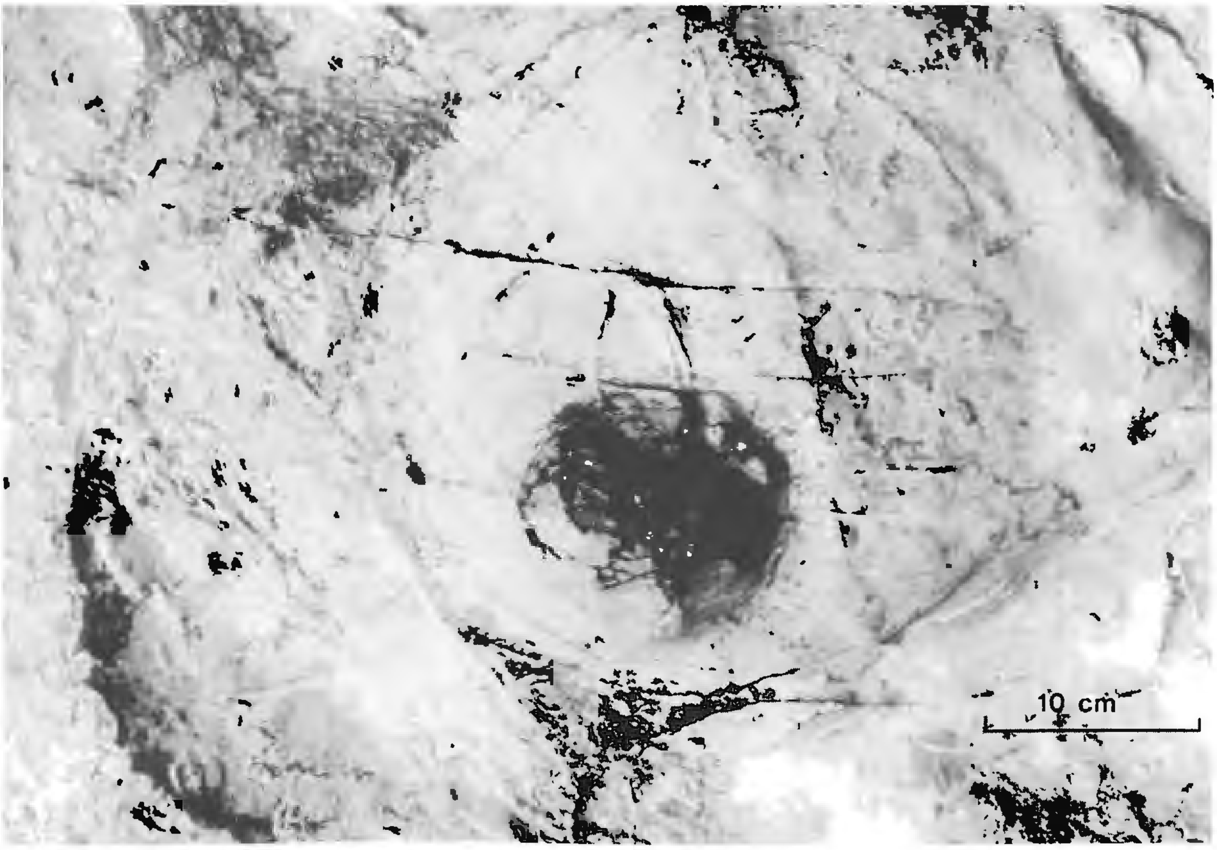
2.3.3. CEILING POCKETS

Ceiling pockets are frequent signs of water flow turbulence in the epiphreatic and phreatic zones. Epiphreatic water channels (Ponikve v Jezerini, Ponor v Odolini, Križna Jama, Lokva swallow-hole at Predjama, Osapska Jama, Dimnice, and old caves as Trhlovca, Brlog na Rimskem, Stara Jama in Postojnska Jama and the upper channels in Predjama) may be either completely flooded or only partly as is siphon Krožni Rov in Črna Jama of the Postojna Cave system. The water flow through such cave passages has a medium velocity; according to scallops its velocity is from 25 to 50 cm/s. The floor is covered by gravel or loam. In the swallow-hole Griška Jama below Ribniška Mala Gora where the water slowly flows over the loam in the initial part of the cave, ceiling pockets occurred on the ceiling and on the upper parts of the walls. The water flow is too slow to incise scallops. The smallest solution cups are found on the ceilings of small, commonly uplifted passages below which deep siphons are located. These are the passages in spring caves at the foot of High karst. The flow velocity in these caves is more than 2 m/s (Matijeva Jama, Babja Jama) suggested also by the pebble size. The lower parts of these caves' perimeters are commonly mechanically smoothed or scalloped as it is the case in Kompoljska Jama.

The rocky features, found in a presently dry cave may suggest that the ceiling pockets developed in deep, flooded phreatic passages due to slow water flow turbulence; the evidence is given by large scallops on the walls of Divaška Jama, Dvorana Palm in Pivka Jama, in Vodna Jama v Lozi and in niches close to the entrance to Križna Jama (Slabe 1989 b, 209), in Brezno na Škrklovici, in Mežnarjeva Jama and in Pečina v Radotah.

According to Renault (1968, 582) and Quinif (1973, 569), citing other authors too, solution pockets are typical of the channels through which the slow-flowing water drains and floor of which is covered by loam. Trudgill (1985, 76) termed them domes due to water turbulence below the piezometric level.

On the base of characteristic features of ceiling pockets Quinif (1973) studied their mode of origin. He placed great emphasis, proved by the experiments, on the importance of mixing corrosion. I did not evaluate yet the importance of the ceiling pocket process. But I



2.3.21 Ceiling pocket in Pekel, Babja Jama asses that the origin, size, shape and location of the ceiling pockets is controlled by the rate between the flow velocity and pressure and by structure of the rock within the characteristically shaped passages.

Shape, size, and location of ceiling solution pockets

Ceiling solution pockets are either independent or composite. The independent ceiling solution pocket (Fig. 2.3.20) incises into a rock. It is simple, or uniform, and mostly of semi-circular cross-section narrowing inwards. To the second group belong independent pockets (Fig. 2.3.20 b), with step change of the cup diameter. To the third group belong composite cups (Fig. 2.3.20 c) on fissured or unfissured rock. Within the composite pockets there are either several smaller ones inside a larger pocket or equal or different sized pockets are laterally connected. Composite pockets may be in lines too. On less fissured rock the pockets are mostly semi-circular; along prominent fissures they are more narrow and deeper. The latter are semi-circular in cross-section or elongated into ellipses. On the same ceiling there may occur the pockets of different shapes as is the case in Zelške Jame, in Stara Jama in Predjama, and in Bar in Dimnice (Slabe 1989 a, 29).

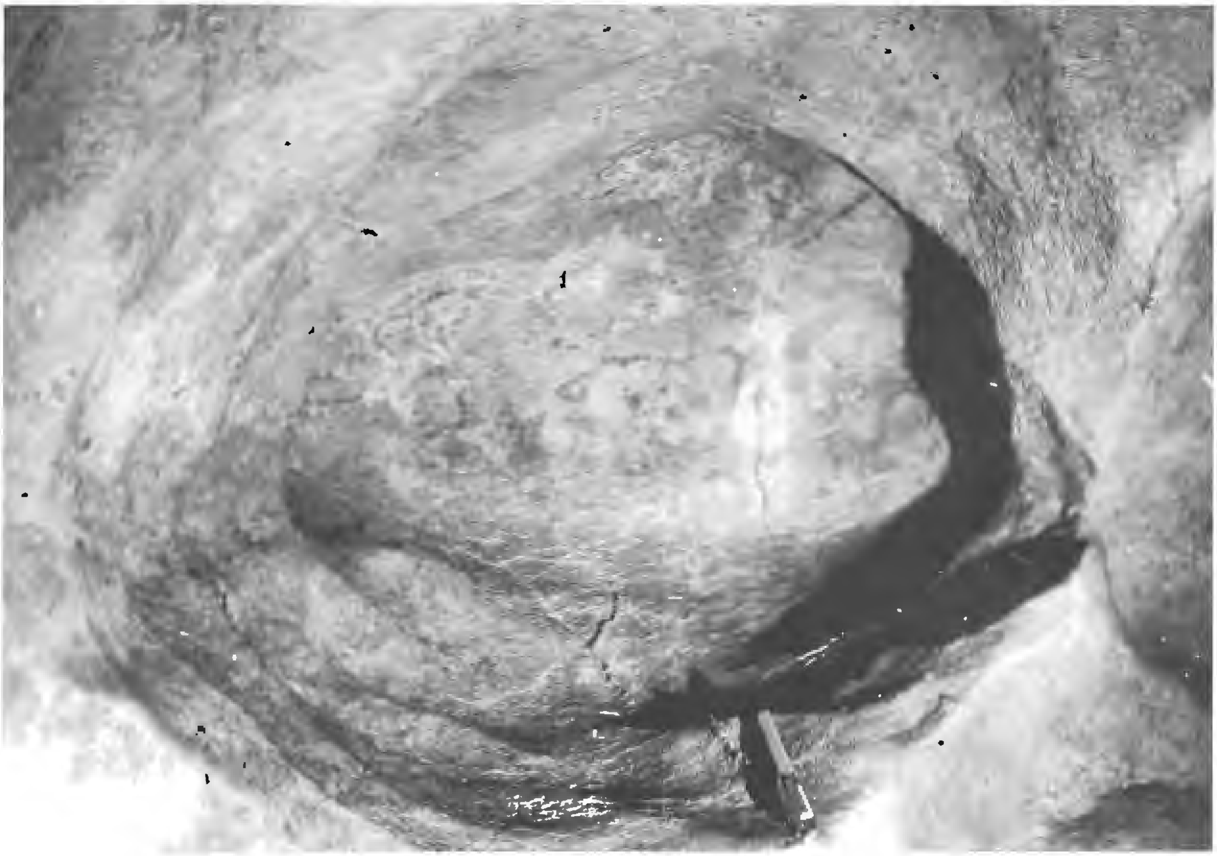
The ceiling solution pockets of the first group may be divided into smaller and larger. Smaller cups, from 8 to 15 cm in diameter and depth, are of rather regular semicircular shape or else, along the fissures are a bit elongated into ellipse shape. Such pockets are typical of ceilings of smaller channels in spring caves at the foot of the High Karst (Fig. 2.3.21, 2.3.22). In Matijeva Jama (Slabe 1989 a, 188) the pockets are close to one another, connected in a network. Larger independent pockets, from 30 to 150 cm in diameter and 15 to 75 cm in depth, are relatively shallow. The bottom is semicircularly rounded, with their axes more or less vertical. Along fissures the depth of such pockets is actually smaller than their diameter. Pockets on the concave side of the meanders in a narrow passage are a bit deeper (Fig. 2.3.23).

Independent pockets in lines are 20 to 150 cm in breadth and 30 to 120 cm in depth. They are deeper than the simple ones. Such pockets are frequently dissected into 3 or 4 levels and the diameter of the most narrow upper part is commonly 3 or 4 times narrower than the diameter of the opening. The pockets that are shallow in respect to their diameter, are semicircular in cross-section (Fig. 2.3.24). The others are enlarged. Along prominent fissures the pockets are frequently narrow, deep, and cylinder-shaped, and their bottoms are circular and flat (Fig. 2.3.25). A special example is a spiral deepened pocket.

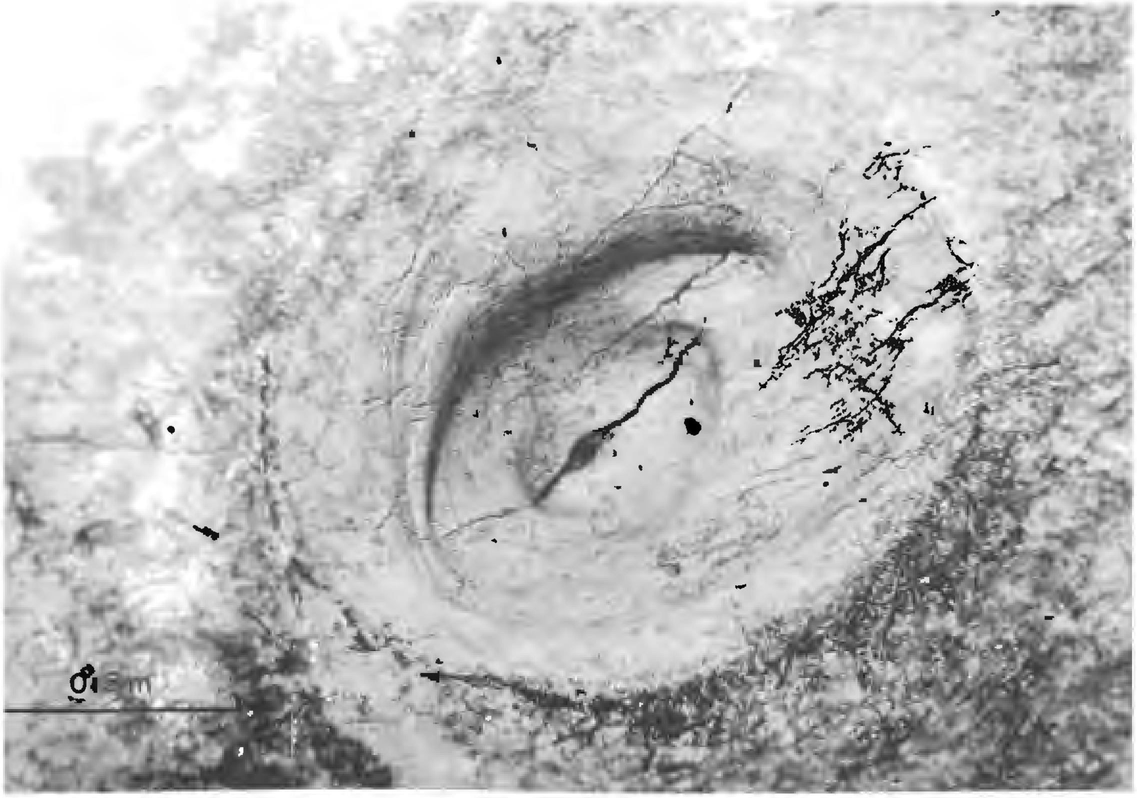
On the bottom of a composite pocket smaller ones are incised (Slabe 1989 a, 31) or they are laterally connected. Two or three pockets are commonly found in a group (Fig. 2.3.26). As a rule one is deeper than the others. Along fissures they are often connected into series. The most dense pattern of pockets appears on fissured rocks where they are joined into common water level horizon (Fig. 2.3.27). The solution pockets within a notch are of various sizes. Sometimes the solution pockets continue into narrow splits and thus their bottom remains invisible (Fig. 2.3.28). In a densely fissured rock they may be connected by anastomoses as the ridges among them are weathered. Such pockets have very irregular forms (Fig. 2.3.29).

Special attention must be paid to the pockets that

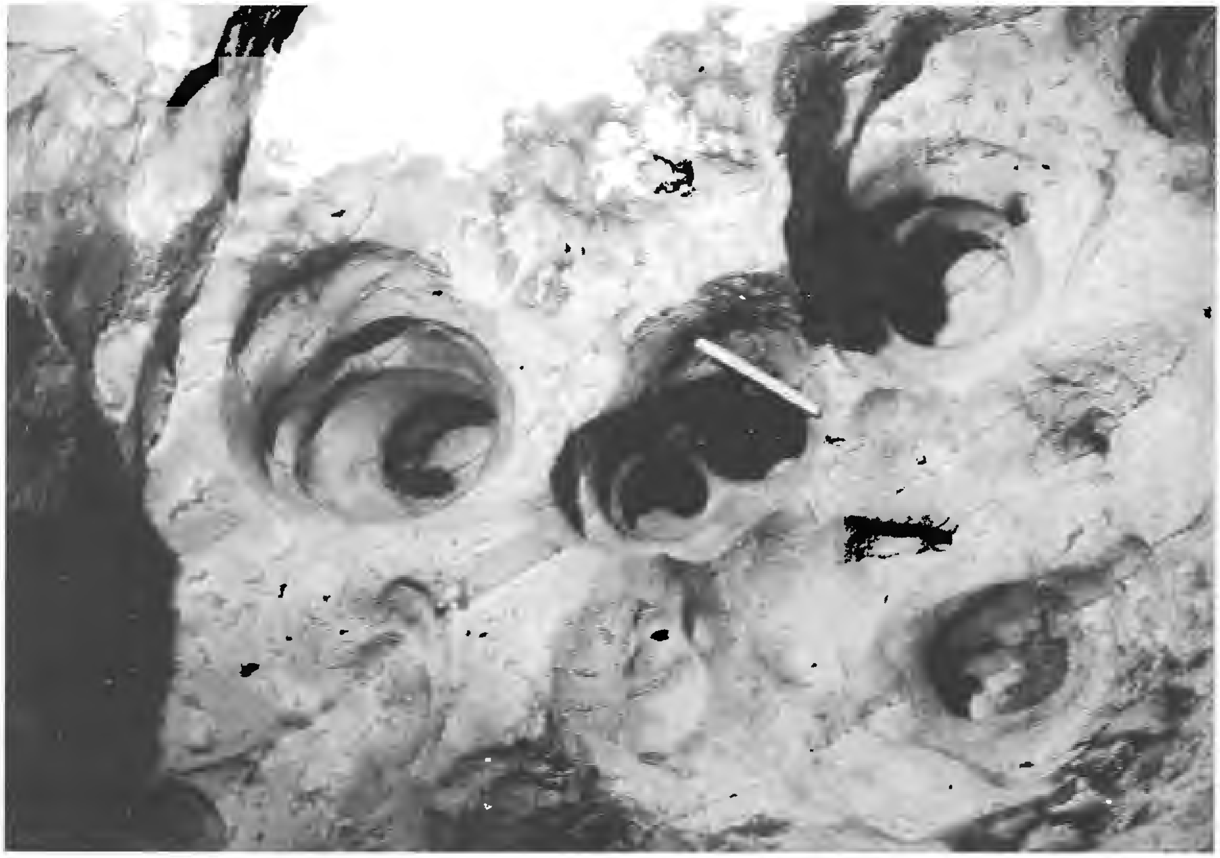
2.3.22 Ceiling pockets, Matijeva Jama



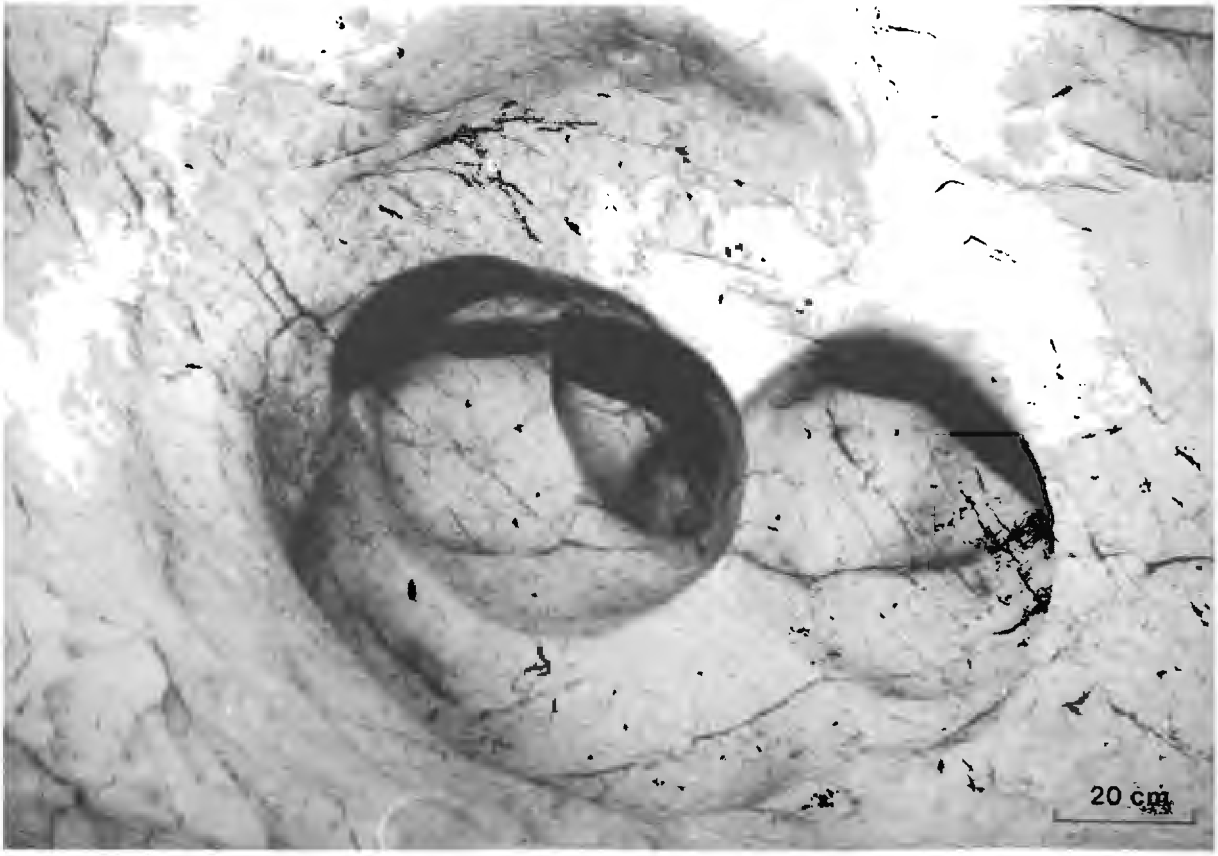
2.3.23 Ceiling pocket on the upper parts of the wall of Ozki Rov, Ciganska Jama



2.3.24 Ceiling pocket, Lokva swallow-hole



2.3.25 Ceiling pockets in Nebesa, Zadlaška Jama (scale = 15 cm)



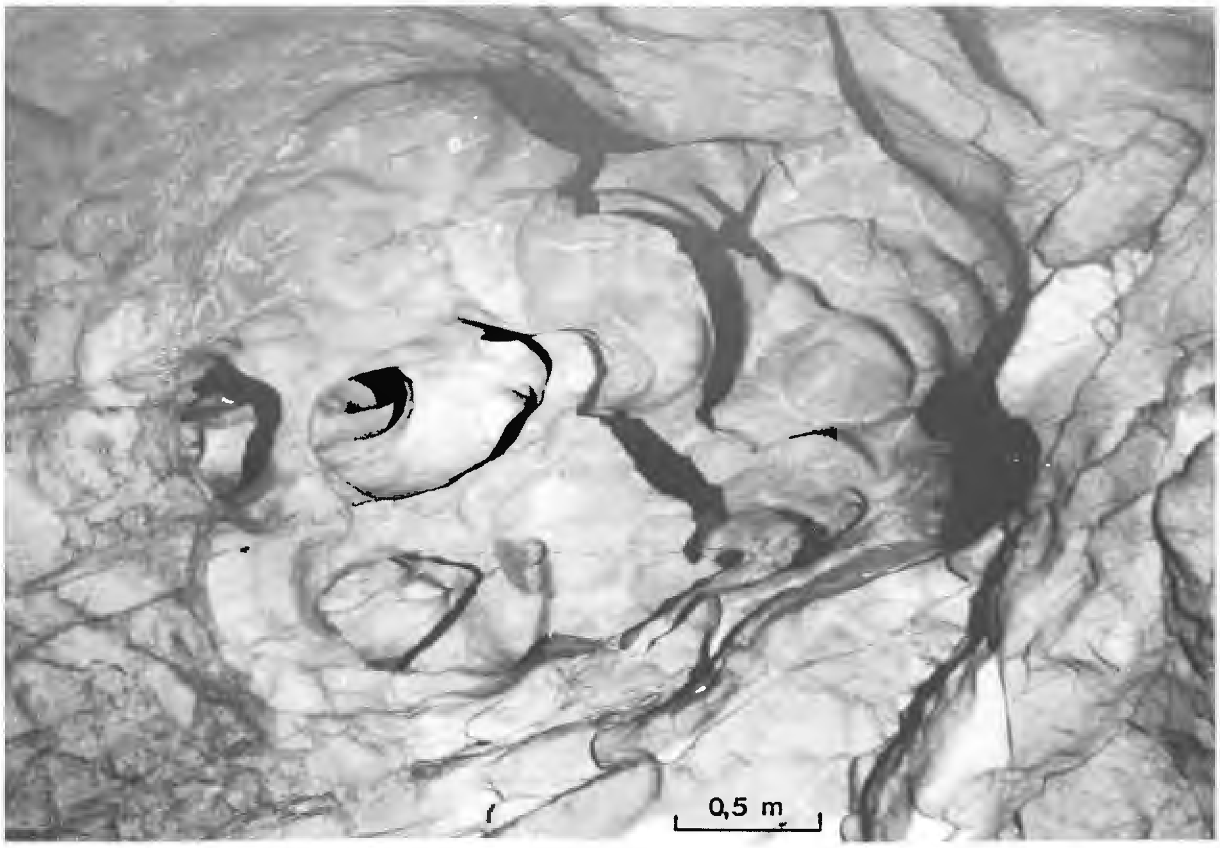
2.3.26 Ceiling pocket in Lokva swallow-hole are 1 to 3 m in breadth and up to 1 m in depth. The bottom is rather flat and the axis vertical. The pockets in Vzhodni Rov in Predjama have a smaller ceiling channel at the ridge. Such pockets are found on the lower parts of the ceiling. The cross-section is semicircular or they are elongated at the fissures. In a water channel in Zelške Jame (Fig. 2.3.30) the bottom of semicircular pockets occurring at the fissures consist of circular planes, and vermaculites show that they are filled by water. In Rakov Rokav of Planinska Jama large and shallow pockets have rough surfaces.

Pockets occur on steeply or gently inclined ceilings which lower in front of a squeeze in the passage or rise behind it. In front of a squeeze the pockets, 1 m in length, are transversely elongated, 20 to 30 cm in breadth and 25 cm in depth. On the outflow side of the squeeze the pockets are slightly elongated in the water flow direction, 1 to 1,5 m in length and 0,75 m in depth. Often they are shallow (Babja Jama) or occur in assemblages (Fig. 2.3.31). In the Lokva swallow hole at Predjama the inflow edge of a pocket behind a squeeze is cut. During the plaster experiment a prominent notch with pockets occurred in front of a constrition in a pipe.

Origin and development of ceiling solution pockets

Ceiling solution pockets are due to vortices at a fissure or heterogeneity in the rock, or else, the vortices are controlled by the shape of the channel. The initial eddies at the origin of the ceiling pockets origin are mostly controlled by the flow velocity and pressure at the obstacle and by the location in the passage, and later only the shape of the ceiling solution pocket determines the vortex. The smallest eddies already are without outflow tails which are characteristic of scallops. The initial vortices that shape the semicircular pockets have flow lines rectangular to the wall. When the pocket widens and deepens regularly such turbulence is characteristic for larger ceiling solution pockets with rounded bottom too (Fig. 2.3.24). In the ceiling solution pockets that occur at prominent fissures and are deeper than the diameter of their opening, or in the ceiling solution pockets which are situated along the fissures, the vortex flow lines are parallel to the wall or spiral. This is evidenced by the flat circular bottom of the ceiling solution pockets (Fig. 2.3.25). The ceiling solution pockets are thus like cylinders or truncated cones. Their bottoms are often composed by several circular flat parts. In the larger ceiling notches, where more ceiling solution pockets are joint, the turbulence is diversified (Fig. 2.3.29). In the composite ceiling solution pockets one of the vortices prevails. In Matijeva Jama the ceiling solution pockets joined into chimneys whose walls are semicirculary dissected.

Ceiling solution pockets in lines are commonly composite (Fig. 2.3.26) and rarely independent (Fig. 2.3.24). At the composite ceiling solution pockets one of the eddies prevails and thus the lines are understandable. Step changes of the vortices diameter are perhaps the consequence of the rock bedding (Slabe 1989 b, 207) and the properties of a fissure, if ceiling solution pockets occurred there. Do the ceiling solution pockets in



2.3.27 Ceiling pocket on fissured rock in Stara Jama, Predjama lines reflect the channel's widening, or the decrease of water level and thus smaller pressure against the walls, and is that the reason that the pockets diameter decreases upwards?

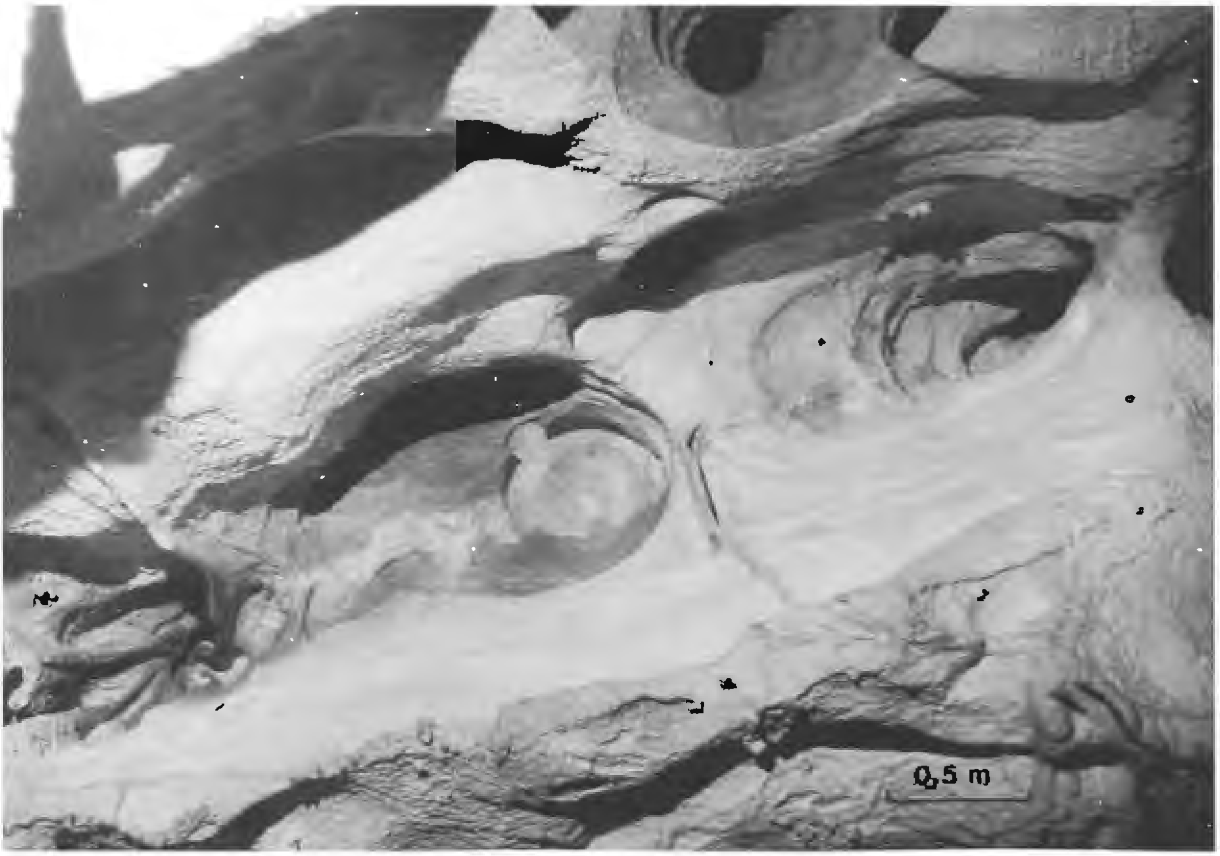
As we stated, according to the ceiling solution pocket's shape their local position, origin and form are mostly controlled by the fissures within a rock and by bedding. Most of the ceiling solution pockets are associated with fissures and bedding-planes. If the fissures are prominent and densely distributed over the rock, there is no possibility for uniform ceiling solution pockets of regular shape to develop. Such an example was found in Zelške Jame (Fig. 2.3.29). The rock structure plays a less important role in the ceiling solution pockets origin. The ceiling solution pockets may develop on the heterogeneous rock, or on densely fissured, thinly fractured rock that prevents the development of scallops. In Turkova Jama we find the ceiling pockets on fine grained dolomite, in Finkova Jama on recrystallized limestone (Fig. 2.3.31). In Predjama the ceiling solution pockets developed over small lenses of quartz (Fig. 2.3.32); their walls are rough.

Ceiling solution pockets may occur at the fissures on the walls where the scallops are (Fig. 2.3.33). The surface of such ceiling solution pockets is scalloped. At the lee-side of ceiling solution pockets the scallops are slightly larger than on the exposed parts of the perimeter.

The smoothness of the ceiling solution pocket's surface depends on the mode of its origin by an eddy or on its connection with trapped air bubbles and on the rock structure. Ceiling solution pockets washed by a water flow of higher velocity have smooth perimeters or less soluble particles of rock (cherts) (Matijeva Jama) protrude out of them. Ceiling solution pockets where the air is seasonally captured have rough surfaces or are rough at their crests only which are above the water level (Rakov Rokav in Planinska Jama).

I wish to point out the characteristic situation of the ceiling solution pockets within a cave passage. The pockets are most commonly found on the ceiling of the wider and higher parts of the passages; they are very conspicous in front of or behind squeezes, at the beginning of flat ceilings behind the uplifted or lowered passages or in larger water level horizons. These are the places of considerable energy loss and characteristic zones of turbulence appear there (Fig. 2.3.1). The water turbulence is not caused by small irregularities on the rock only but by shape of the passage. This was confirmed by the experiment with plaster pipes of various diameters. In spacious parts of the pipe only ceiling solution pockets occurred; in narrow inflow and outflow parts there were scallops. At the contact of pipes with different diameters, larger notches with pockets appeared.

Why do the ceiling solution pockets appear on the ceiling and upper parts of the walls only although we know that the turbulence spreads to all the sides? The gases (Cser & Szenthe 1986, 279) caught under the ceiling and accelerating the corrosion have, in my opinion, rather little effect. The stage of development, the shape of the passage and the turbulent flow in it, are deciding



2.3.28 Ceiling pockets, Logaška Jama

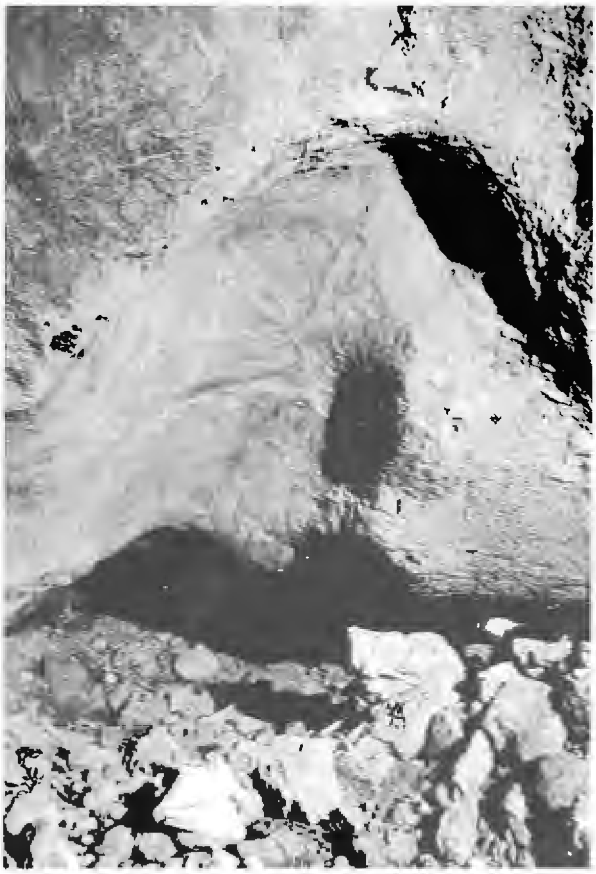
factors. Different rock structures, bedding and fractured passage perimeter cause different diameters and gradients of passage. Breakdowns fall from the roof and notches occur. Actually ceiling solution pockets are the most common. in the larger notches on fissured rock. The water transports and deposits the material in the larger spaces adjusting the discharge to equilibrium. The floor is levelled and the roof dissected. This is why on most of the dissected passages one may observe scallops on the lower parts of the walls and ceiling solution pockets on the roof. I presume that under similar hydraulic conditions large scallops would occur on the perimeter of a pipe-like channel of uniform diameter (Kozinski Rov in Lipiška Jama), or else the passages would be meandering. In the experiment with the plaster tube solution cups appeared on the entire perimeter of wider part of the pipe. The stressed zone of turbulence, due to diameter change within a pipe, widened over the whole length of the enlarged part of the tube. If the medium and wider part of the tube was longer solution cups would appear at the widening or narrowing of the tube only, and scallops would occur in between.

The nucleus of the vortex within a solution cup approaches the wall and accelerates the corrosion. In smaller cups occurring in passages with faster discharge the water mass acts mechanically also. It transports the undissolved particles with smooth suface from the rocky surface.

Frequently the importance of gases including CO_2 rising the turbulent flow and accelerating corrosion is mentioned as the explanation of solution pockets' development. The solution of CO_2 from the air trapped at

2.3.29 The ceiling of Blatni Rov, Zelške Jame

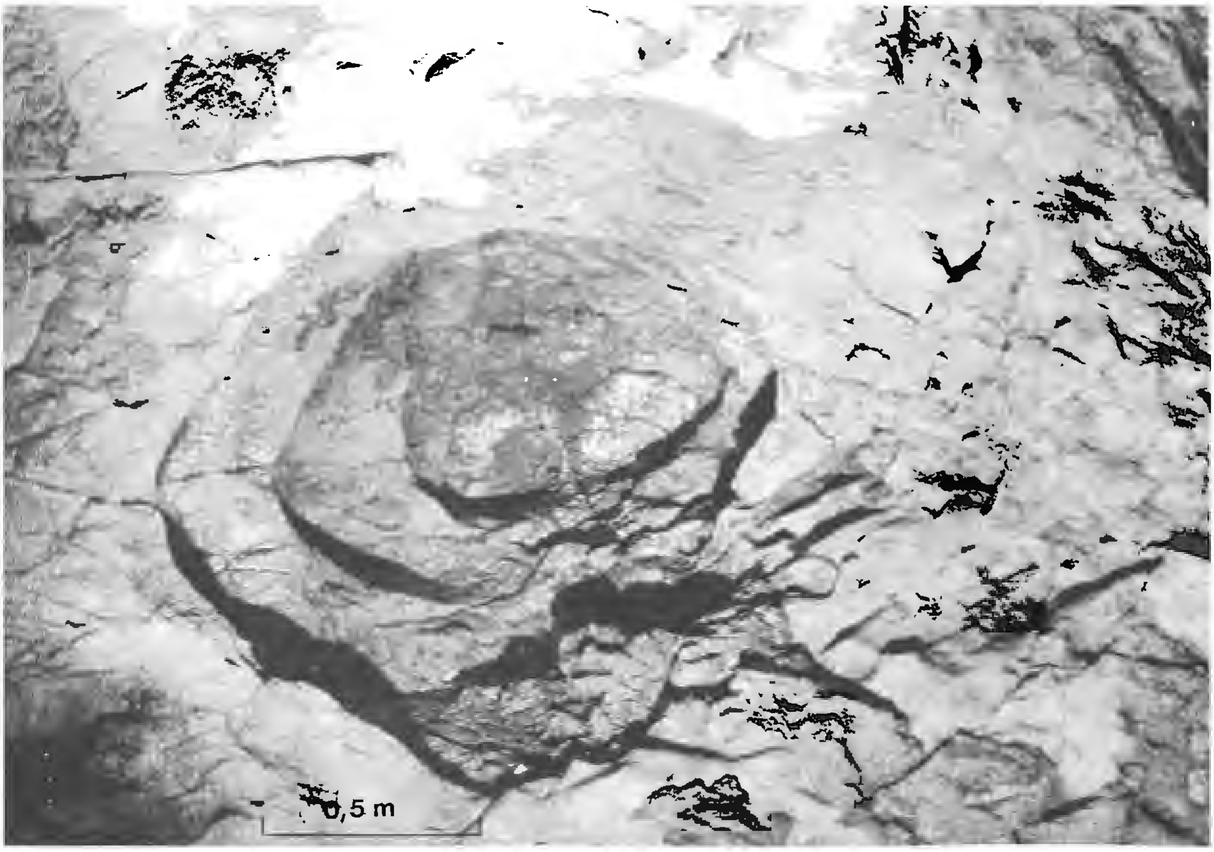
2.3.30 Elongated ceiling pocket at the beginning of Sifonski Rov, Zelške Jame

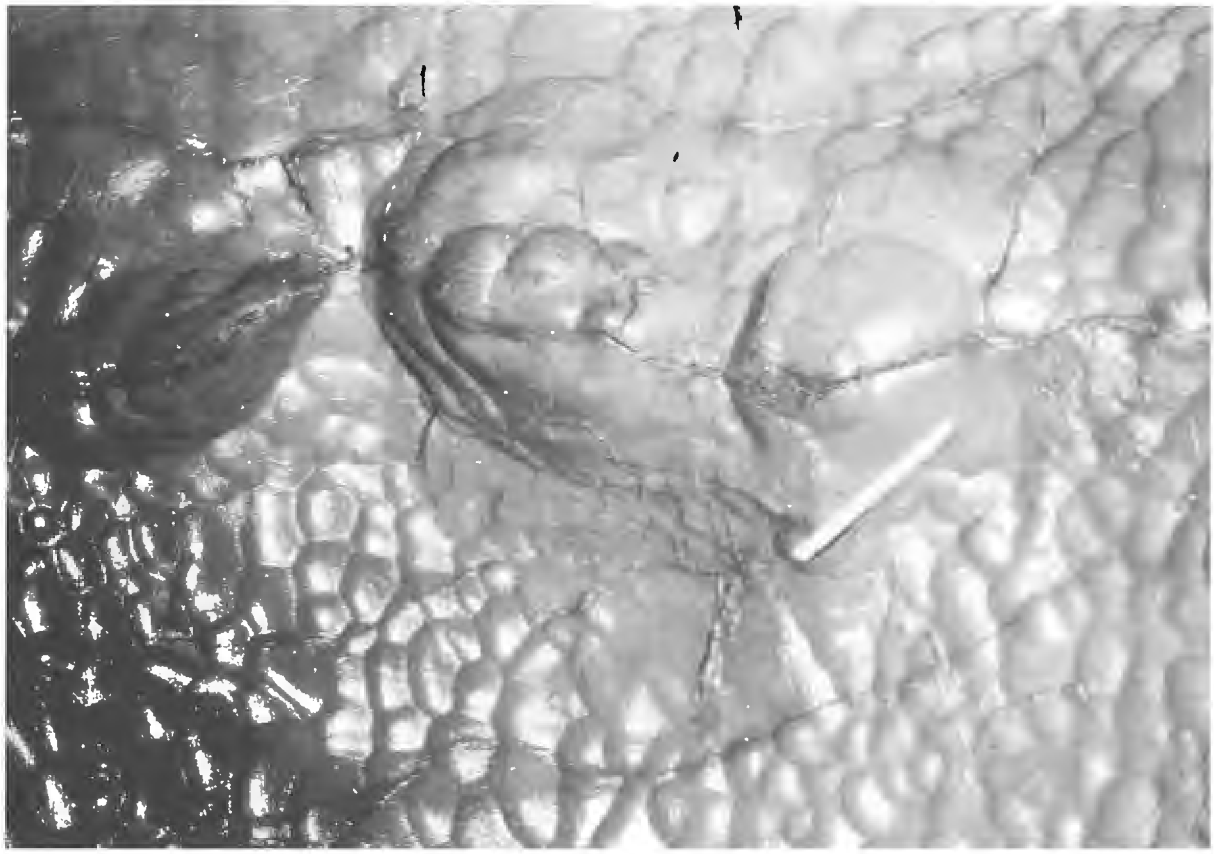


2.3.31 *Ceiling pockets behind the squeeze, Finkova Jama*
2.3.32 *Ceiling pocket on the limestone with cehrts in*

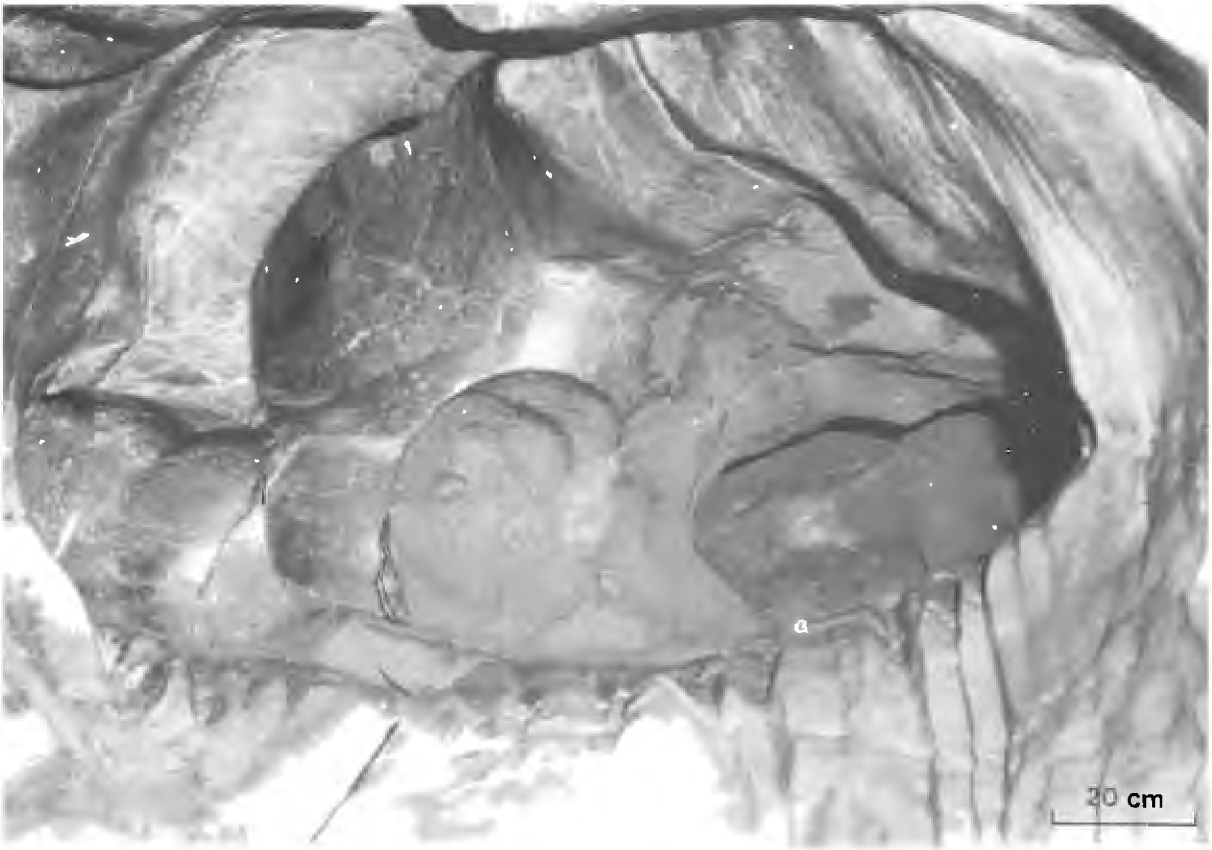
high pressure under the ceiling should accelerate the local corrosion (Bögli 1978, 158; Ford & Williams 1989, 298; Cser 1988, 132). The origin of solution cups with flat bottoms is explained by Cser and Szenthe (1986, 279) by the movement of air bubbles below the ceiling. Old solution cups with flat bottoms without any significant traces of turbulence are found in Vodna Jama in Loza and in Divaška Jama. On the wall below them there are large scallops typical of deep phreatic channels. At the time of our visit the bottom of the solution cups was covered by a dense net of shining drops. Mucke, Völker and Wadewitz (1983) emphasize the importance of condensation corrosion in the ceiling notches where air is caught. The condensation is possible if the water is warmer than the rock. In Rakov Rokav of Planinska Jama the high waters compress and isolate the trapped air into the ceiling notches. The surface of shallow but rather wide solution cups has no distinctive traces of water turbulence and is rough. This may be the effect of condensation corrosion which probably reshaped the solution cups. The solution cups bottoms in Križna Jama are similarly rough. When slower flow shapes the solution cups the unsaturated water convection rising in the centre of the solution cup may play a more important role, and along the borders the outflowing water is saturated. Forti (1989, 72) points out the importance of sulphide oxidation with convection.

The origin of narrow and deep solution cups that continue into fissures at the top is frequently explained by mixing corrosion of variously saturated waters or waters with different temperatures. Due to water mix-

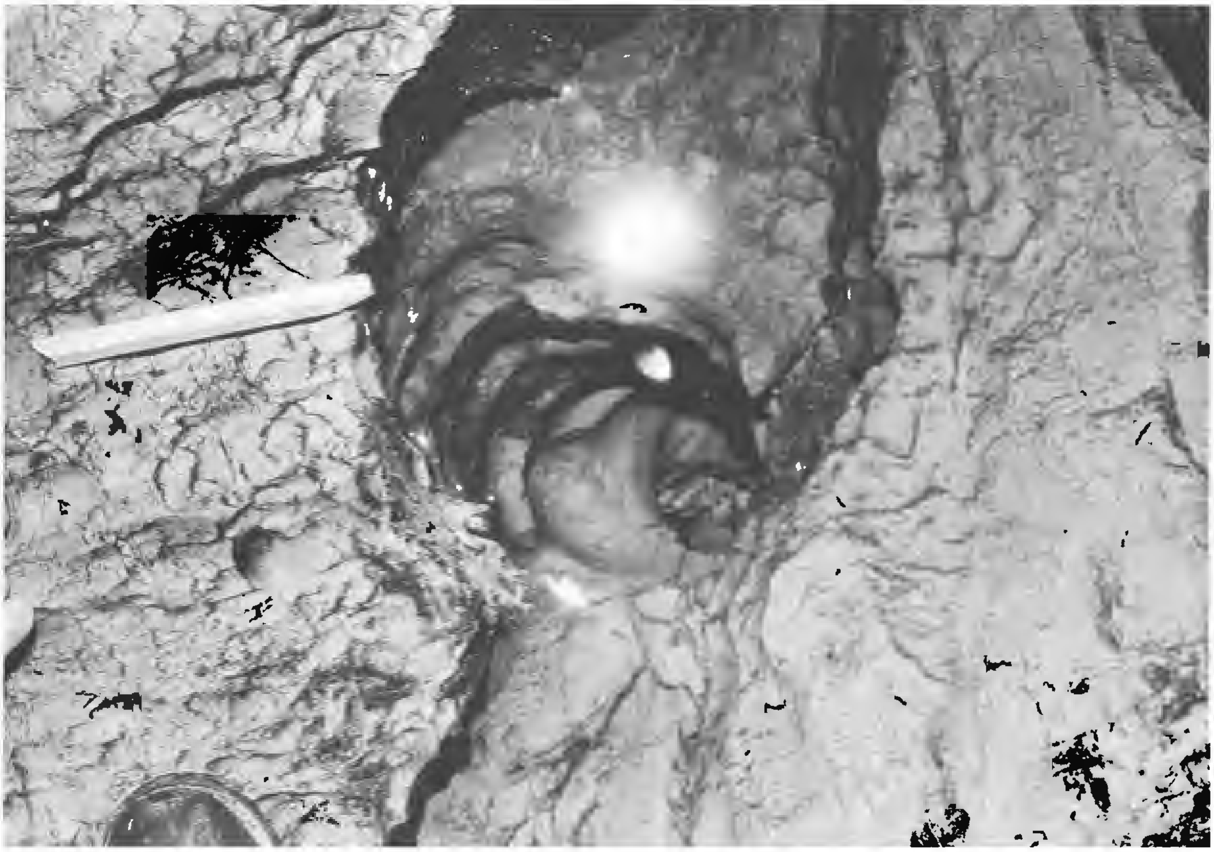




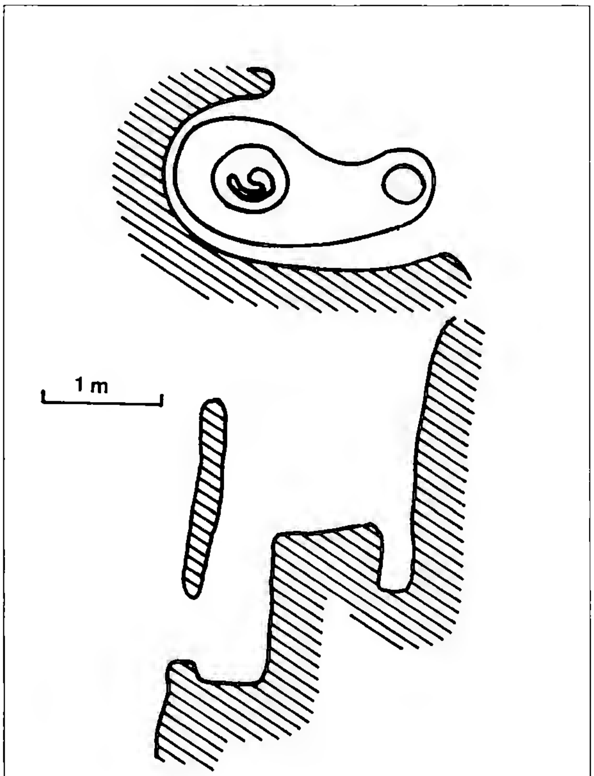
2.3.33 Wall niche with scallops, Markov Spodmol (scale = 15 cm)



2.3.34 Ceiling pocket with below-sediment channels behind the Tobogan squeeze, Ponikve v Jezerini

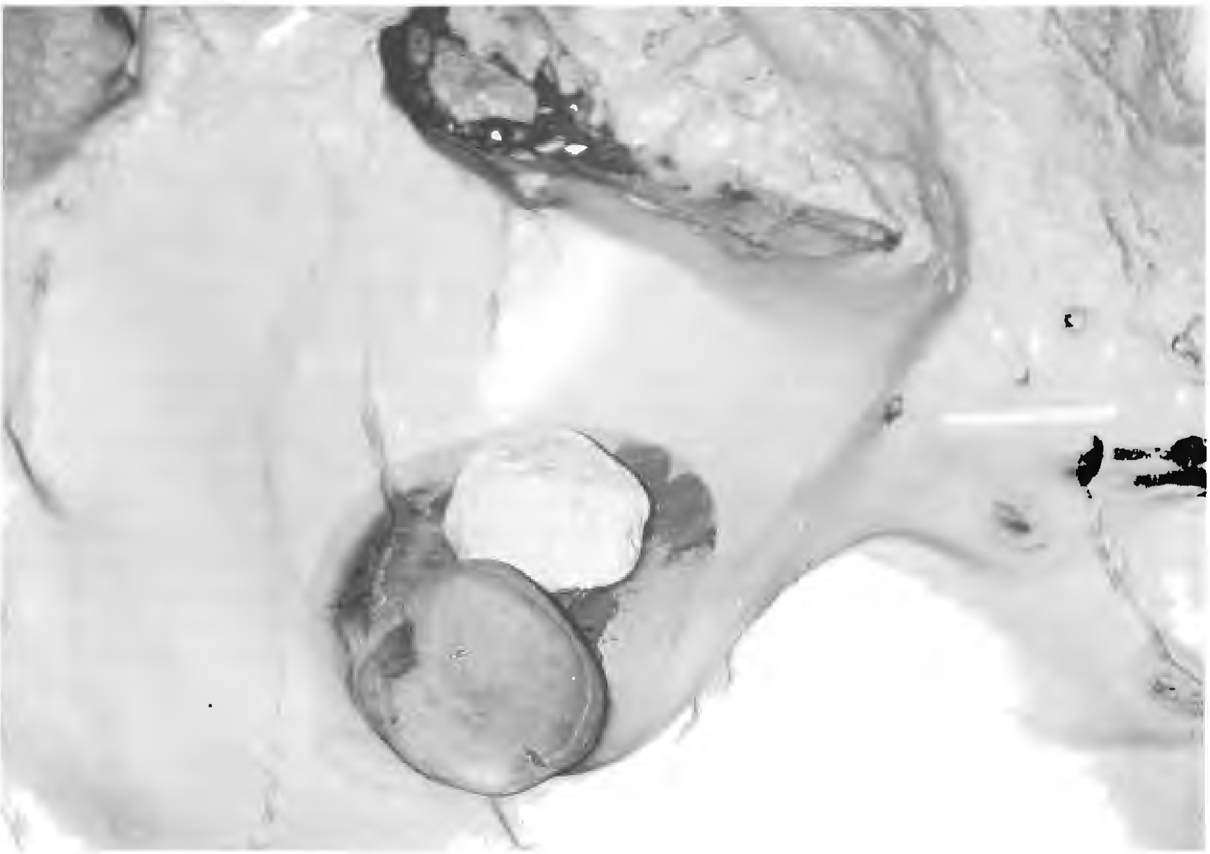


2.3.35 *Pothole in Kopalnica, Mala Boka (scale = 15 cm)*

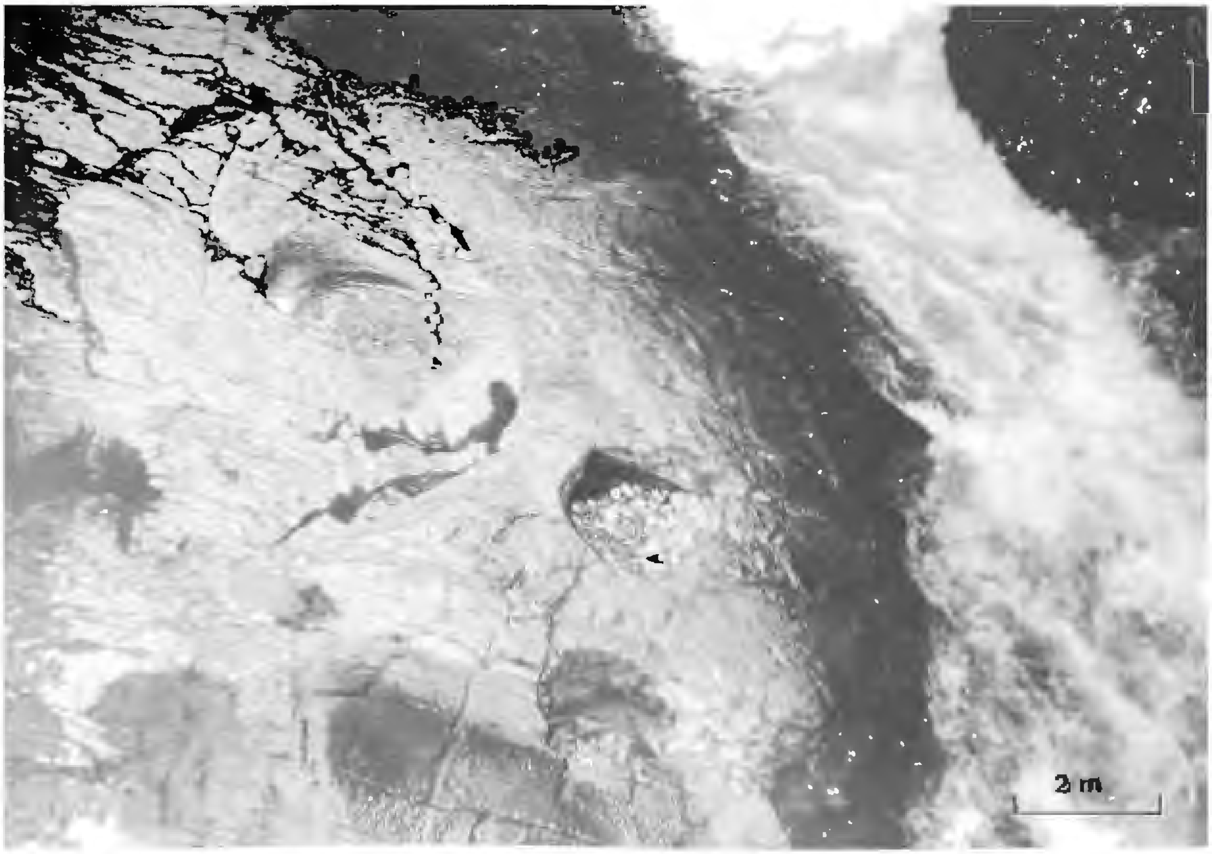


2.3.36 Pothole on rocky block in Hankejev Kanal, Škocjanske Jame

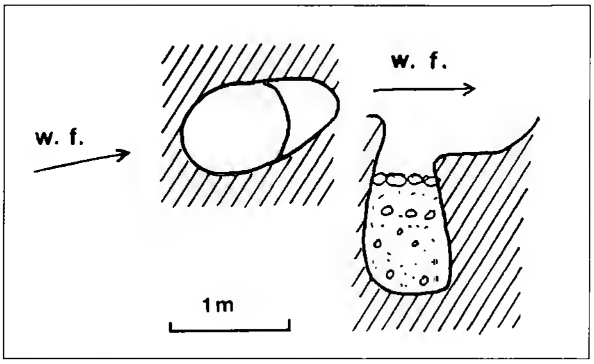
ing it becomes aggressive again (Bögli 1969). Quinif (1973, 570) explained the levels within solution cups by mixing corrosion too, but the examples that I studied do not allow such conclusions. Quinif made narrow and deep solution cups experimentally. He submerged a half broken stone in a vessel filled with water and poured HCl over it, through the fissure HCl. Binni & Cappa (1978, 58) added that for the origin of such solution cup slow flow is required which would suck the water out of the fissures. Such solution cups may originate at water level as the pressure in flooded passage, in particular deeper below the water level, probably does not allow water inflow through narrow fissures. It is clear that the pressure depends on the height of the column and it can be within a fissure which is very high, although narrow. I have yet not succeeded in distinguishing corrosion due to water mixing. In explaining the solution cups in Logaška Jama, Gams (1964 a, 13) suggests mixing corrosion as a probable reason for their origin. Not only are there the solution cups (Fig. 2.3.25) that narrow upwards with their bottom remaining unseen, but also there are the solution cups with flat circular bottoms which are due to vortices (Fig. 2.3.28). Mixing corrosion probably can widen the fissures so that they are more easily used by the vortex. Ford & William (1989, 298) came to the same conclusion. The fissures can also be enlarged by the water which disappears into seasonally dry passage if it is not saturated during recharge. In Logaška Jama the infiltrated water shaped large chimneys.



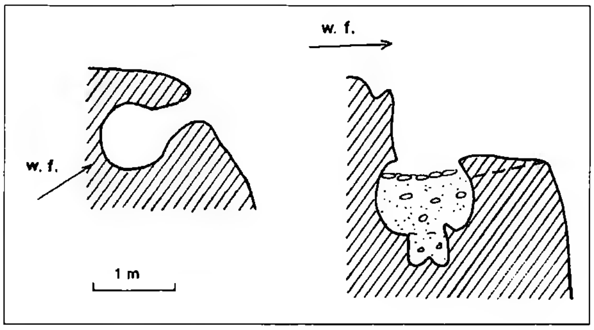
2.3.37 Pothole, Ponor v Odolini (scale = 15 cm)



2.3.38 Potholes in Šumeča Jama, Škocjanske Jame



2.3.39 *Pothole on rocky block in Hankejev Kanal, Škocjanske Jame*



2.3.40 *Pothole on outflow part of rocky block in Hankejev Kanal, Škocjanske Jame*

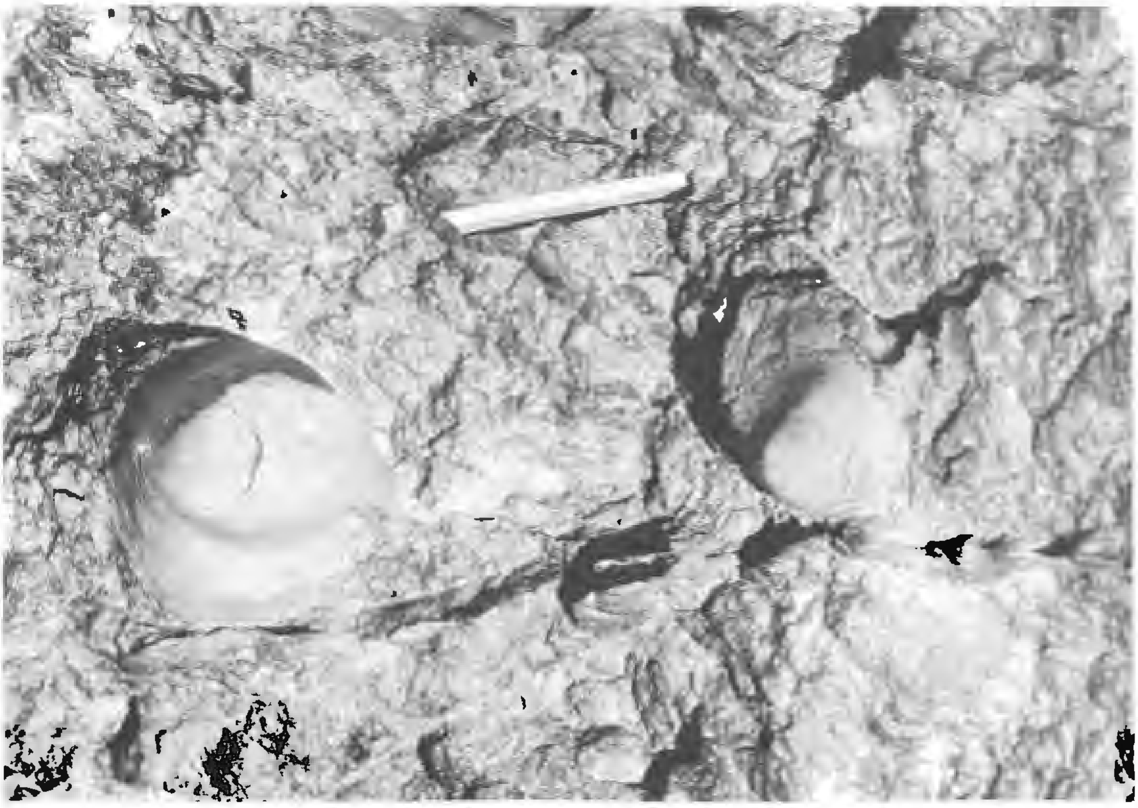
In more spacious parts of the passages the highest waters that flow more slowly deposit loam on the upper part of the perimeter. The loam remains deposited on gently inclined ledges of deep solution cups and when the water filters out of the loam it incises half tubes below the sediment (Fig. 2.3.34).

2.3.4. POTHOLES

Shape, size and location of potholes

Potholes are either independent (Fig. 2.3.35) or composite (Fig. 2.3.36) cups on the rocky floors of cave passages (Fig. 2.3.1). In composite one cups type prevails. They are either simple or in lines.

Potholes can be divided into semi-spherical ones and those that are deeper than the opening diameter (Fig. 2.3.1). Smaller potholes of the first type are from 5 to 10 cm in diameter and of rather regular semi-spherical shape. They are frequently elongated on the outflow side. Very seldom are the small potholes deeper than the diameter of the opening, and if they are, their shape is controlled by their location in front of the obstacle (Fig. 2.3.1). Large potholes of the kind, having a diameter of more than 1 m are shallow in relation to their size. Semicircular pits with flat bottoms are often incised in the bottom (Fig. 2.3.37). To the second type belong potholes that are deeper than the diameter of their opening. Their walls are vertical and the potholes are narrowed inwards and semicircularly enlarged (Fig. 2.3.38, Fig. 2.3.39), in different diameters (Fig. 2.3.39). Their di-

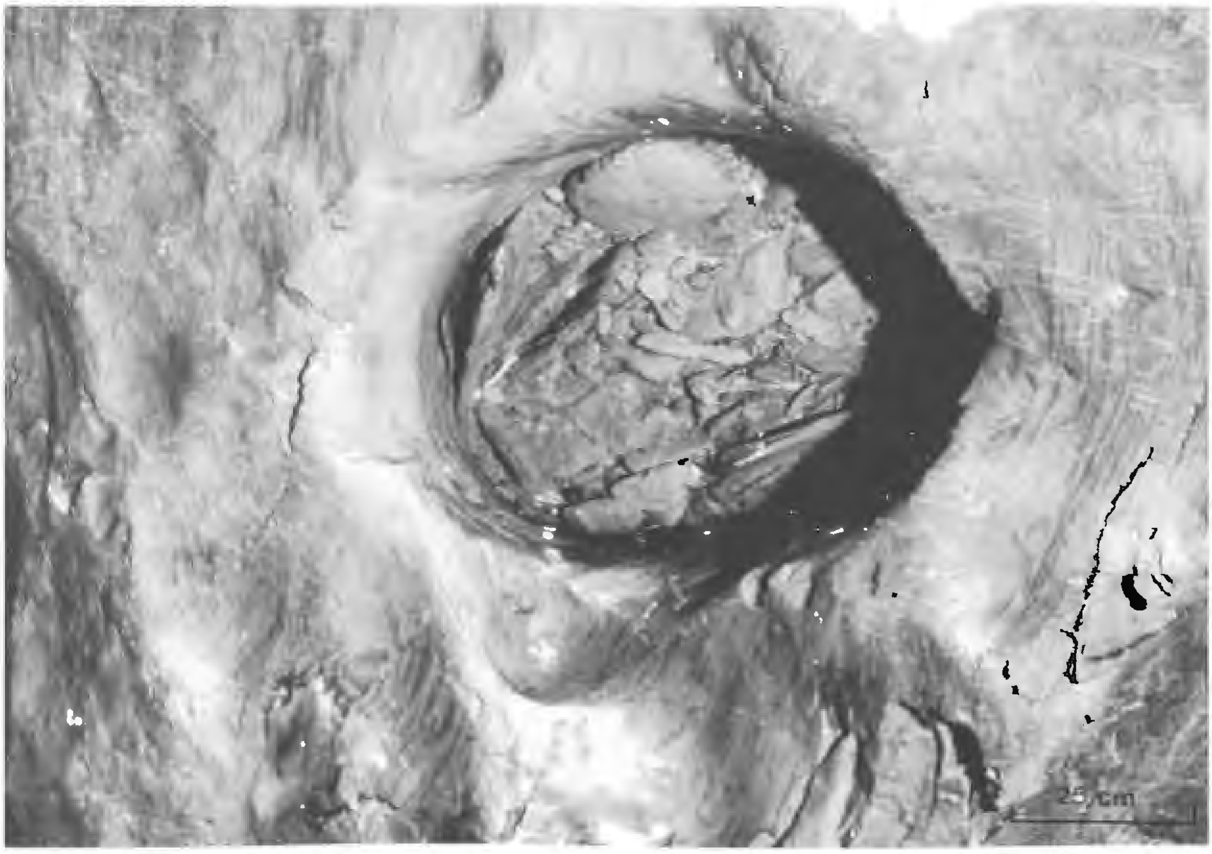


2.3.41 Pothole in Polhov Rov, Mala Boka (scale = 15 cm) ameter is from 20 cm to several metres. The potholes on rocky blocks are frequently lengthened into outflow tails (Fig. 2.3.39) or they continue on the outflow side into flutes (Fig. 2.3.40). The inflow ridges, of hemispherical potholes in particular are slightly steeper than the outflow sides. The bottoms of shallow potholes are hemispherically rounded. The bottoms of deep potholes are flat (Fig. 2.3.41) and they narrow down current (Fig. 2.3.35); they have a spiral at the bottom (Fig. 2.3.36) or a wide protrusion in the centre (Fig. 2.3.40). Often a rocky nucleus remains in a pothole dipping downcurrent. Smaller hemispherical potholes that originated at fissures are elongated in ellipses, while all larger ones have more or less regular semicircular cross-sections. Smaller potholes are distributed along fissures into consecutive or parallel sets. Potholes as a rule have vertical axes and thus in inclined surfaces their upper walls are higher (Fig. 2.3.38).

Potholes develop in limestone, breccia and sandstone.

The surface of potholes is either smooth or there may be seen thin scratches that are horizontal in deeper potholes. A belt of 10 to 20 cm around the potholes is frequently smoothed, and behind it there are scallops on the rock. The scallops may even reach the edge of the potholes (Fig. 2.3.35). The perimeter around the potholes is mechanically smoothed in Babja Jama, while in Polhov Rov in Mala Boka the breccia is coarsely rough (Fig. 2.3.41). The surface of potholes that developed on quartz sandstone in Smoganica is smooth also (Fig. 2.3.42). Microscopic observations (Chapter 2.3.10) demonstrate that friction of solid particles against the rock causes thin roughness of its surface which is by eye determined as smooth.

Large potholes are found in spacious passages behind obstacles. In Babja Jama such a pothole is 4 m in breadth and up 2 m in depth down to the gravel fill. Potholes in small tube-like passages, 1,5 m in diameter are smaller and in particular more narrow. They are entirely flooded by fast water flow. Typical potholes are found on the rocky bottom of steps in steep riverbeds, such as Ponor in Odolina where the potholes are 1 m in diameter. In Beško Ocizeljska Jama below the shafts the potholes (Fig. 2.3.43) are 5 m or more in diameter; their bottom is not seen due to sediments. The potholes are from 1 to 2 m distant from the chimney's wall, which means that they develop on the place where the most of water falls. In Mahorčičeva Jama of Škocjanske jame the potholes are on the bottom of a canyon-like river bed and their diameter is equal to the river bed's breadth and they are separated from each other by thin walls. Higher up, on the edge of the wider part of the river bed there are semicircular rocky wall notches which are remnants of potholes. The potholes on the huge rocky blocks that cover the riverbed have a special location and shape. I observed some examples in Hankejev Kanal of Škocjanske Jame. On the inflow upper plane of the block a semicircular notch occurs (Fig. 2.3.44) which is perpendicular to the water flow direction and 0,5 m in breadth. On the inflow side the notch is more shallow and on the outflow side, where cups are distributed in a set, its wall is steep. On the outflow side of the rocky



2.3.42 Pothole on sandstone, Smoganica

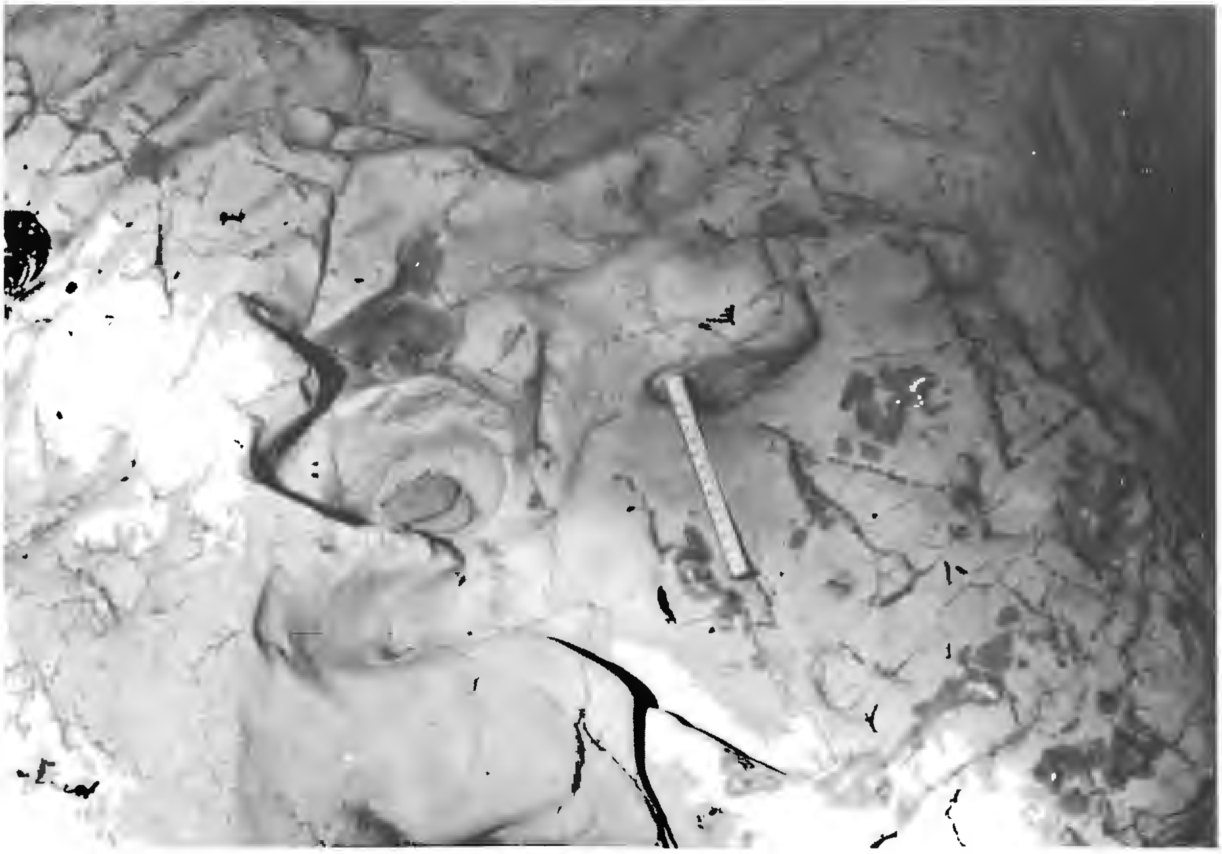
2.3.43 *Pothole below the aven, Ocizeljska Jama*

boulders the cups are often found in lower notches and have outflow channels. The potholes may occur among the boulders which tigthly cover the riverbed. In Markov Spodmol solution cups lie on the rock that have scalloped walls.

Origin and development of potholes

The material included in turbulent flow plays an important role in the origin and development of potholes. This is why potholes commonly occur on the lower part of the cave passage perimeter where the water transports most of the coarse-grained traction load (Kranjc 1986 b, 24). In more narrow passages the mechanical activity of fast water flow can shape the entire perimeter (Babja Jama); however the influence is due to the weight of the material concentrated on the rocky floor.

The pothole originates on the spot where a distinctive vortex appears. In regularly shaped passages this spot is determined mostly by the heterogenity or fissuring in a rock, indicating lines of weakness; in dissected channels it is characterized by the positions where distinctive turbulence occur. The shape of the pothole reflects the properties of the vortex within it. Potholes that are shallow in comparison to their diameter and have semispherical bottoms, and often outflow tails too, are shaped by the vortices having flow lines perpendicular to the wall. But the potholes that are deeper than the opening diameter and the bottoms of which are flat or spiral-like are incised by spiral vortices where the flow lines are almost parallel to the bottom. Larger pebbles



2.3.44 *Potholes on the inflow side of rocky block, Škocjanske Jame (scale = 15 cm)* found in wide solution cups suggest higher power of water incision. Thus the size of the pothole is not a direct consequence of flow velocity only. The diameters of the vortices in a fast water flow are smaller; however the fast and strong flow transports more material. In pothole formation it is thus the water quantity that counts, acting by higher pressure against the walls or falling free over steep steps within a river bed. The largest potholes thus originated in underground river beds (Škocjanske Jame), below the shafts (Ponor in Odolina), in waterfalls (Beško Ocizeljska Jama) or in places of the most distinctive turbulence as behind a narrow channel in Babja Jama. In the formation of the features below the waterfalls cavitation can take part. The levels within a pothole may be explained by the power change within an eddy.

The depth of the pothole is the result of the relationshp between the velocity and the water pressure on the rock and the quantity and size of the material that is transported by the water. Obviously it reflects the time of the development. Deep potholes are often narrowed close to the bottom or the pothole is conically narrowed downwards. This is the result of smaller water power at depth, in particular if the sediment layer is thick. If the pothole is too deep and filled up by sediment or if the water power decreases, its development is interrupted. Deep and filled up potholes in Hankejev Kanal of Škocjanske Jame suggest seasonal or formerly greater water power. Due to the prevailing importance of mechanical incision in pothole origin the rock structure and fissures do not influence the shape of potholes, with the exception the smallest ones. Potholes have commonly uniform, semicircular cross-sections. The axes of potholes are vertical due to the weight of the material that helps in their formation. The character of the vortex influences the shape of the pothole too. On the outflow side of rocky boulders the potholes develop, shallow on the outflow side with outflow channels, due to free recharge of water and thus characteristic turbulence. On the border of the riverbed in Hankejev Kanal there are wide potholes with narrow rocky nuclei inclined in the direction of water flow. Is such shape of a cup associated with its position in the riverbed?

Distinctive turbulence causes better corrosional exploitation of water. Some floor pits (Fig. 2.3.45) bear no traces of wall grinding. Their bottoms consist of twisted flutes distributed in rosettes. Are these the potholes transformed by the corrosion or did the solution cups originate in that way? Half pits in Markov Spodmol and wall flutes in Veliki Hubelj confirm the second hypothesis. I presume that floor pits may develop without material involved by the water transport. Such are also small hemispherical floor pits that have, under the microscope, only a partly and thinly rough surface. It ressembles the surface of small scallops (Chapter 2.3.10) that also occur on leeward places. In Le Trou qui Souffle (Lismonde 1987) there is a huge solution cup on the floor with its scallops on walls. This means that there are no traces there of the mechanical water activity which is characteristic for potholes.

Potholes occur in passages where fast, usually free-surface water flow drains but may be seasonally completely flooded. Thus they occur in vadose and epiphreatic zones. The passages with the most fast water flow containing great amount of load are frequent in swallow holes (Škocjanske Jame, Beško Ocizeljska Jama, Novokrajska Jama, Ponikve v Jezerini) or in spring caves which have in the catchment area seasonally high water pressure (Babja Jama, Matijeva Jama). The gravel in the latter is autochthonous. Partly reshaped bottoms of the riverbeds are found in through-flow caves (Križna Jama, Vzhodni Rov in Predjama). The potholes in these caves are usually smaller, being formed by slower water flow. This is controlled by the permeability and the shape of the passages.

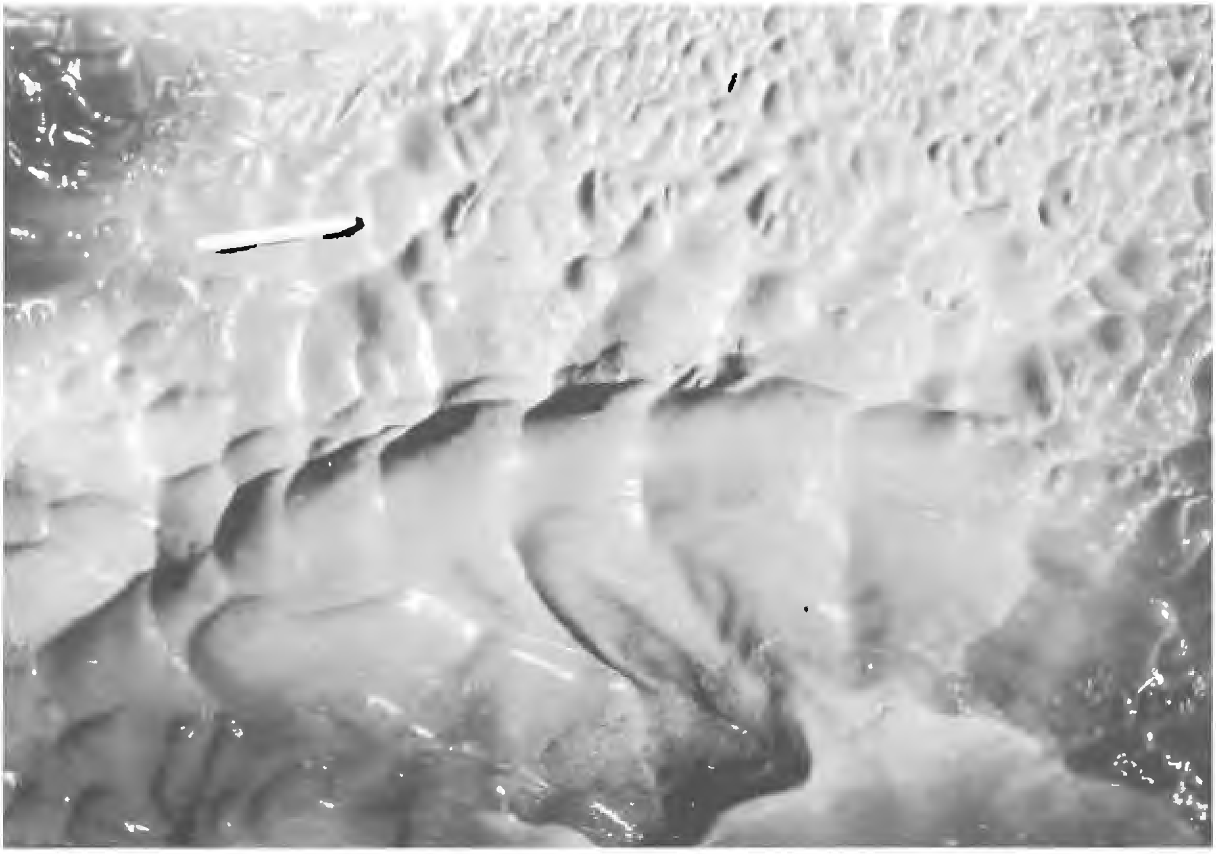
A fast water flow that can transport coarse-grained material tends to remove the sediments out of the caves (Kranjc 1986 b, 278) and uncovers and deepens the rocky riverbed. The potholes are thus characteristic rocky features in the passages through which the water flows with velocity higher than 0,5 m/s, which is evidenced also by the size of the scallops on near walls. Such water flow velocity transports the load consisting of particles larger than 3 mm. Obviously the local hydraulic conditions in the passages are in control of pothole origin. In Smoganica the potholes appeared on the sandstone at the flow velocity of 0,35 m/s; on the nearby conglomerate under the same conditions there are no potholes. This suggests that the rock resistance against the mechanical incision of the water is important. The sandstone is less resistant and lighter. At lower velocity the water carries small pebbles of sandstone in the turbulence.

Mechanical downcutting may act on the rock in connection with other processes. Partly transformed scallops have already been mentioned. In Matijeva Jama there are on the floor narrow (some cm) and relatively deep pits with vertical walls. The pits developed due to a combination of corrosion below the fine-grained sediment deposited by low flood water, and mechanical downcutting by sand included in fast turbulent water flow in the cave effluent.

2.3.5. COLUMNS, PENDANTS, "ČER", AND ARCHES

Columns, pendants, "čer", and arches, these are all parts of the rock that protrude from the rocky perimeter. I have already described smaller protrusions on the walls flushed by water flow. They are constituent parts of the roughness and are controlled by the rock structure. Out from the surface protrude parts of the rock that consist of breccia in Mala Boka, large calcite crystals in Veliki Hubelj, and the cement of conglomerate in Smoganica.

Columns are tall, vertical parts of the passage perimeter. Their cross-section is angular. They occur at the fissures that pass through the rock vertically. The columns occur when the network of fissures is infrequent; if the fissures are dense, the pendants occur.



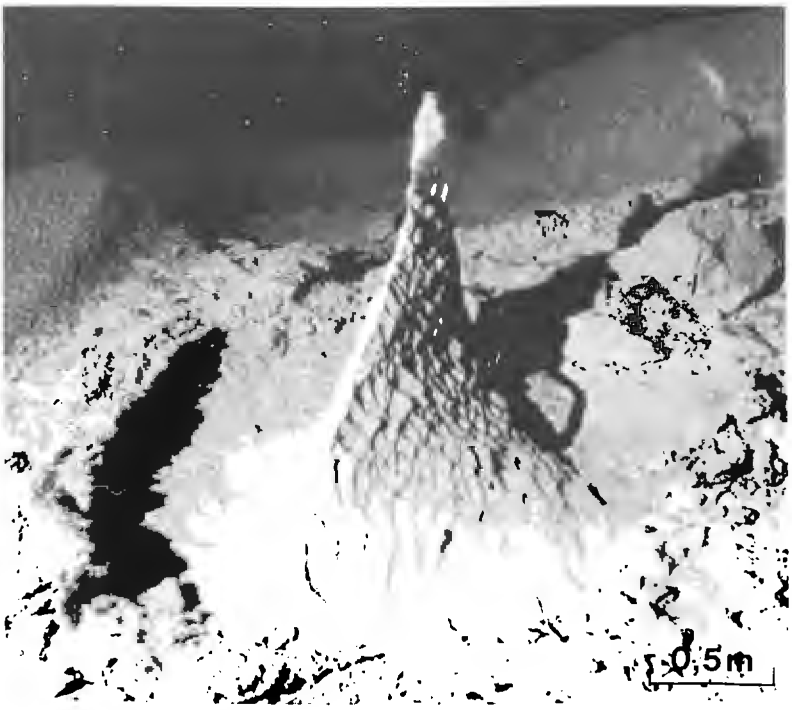
2.3.45 *Pocket, Markov Spodmol (scale = 15 cm)*

2.3.46 *The rocky jag in a niche behind the entrance chamber, Križna Jama, its surface is etched by condensation corrosion*

2.3.47 Rocky pendant in Krožni Rov, Črna Jama (Postojnska Jama)

Jags are singular protrusions with oval cross-section. Their bases are commonly of the same size as their ends. They may be dissected. In a huge niche behind the entrance to Križna Jama a jag (Fig. 2.3.46) developed on the wall among large scallops, indicating passage flooded with slow water flow.

I call pendants oblong protrusions that narrow outwards. In Divaška Jama there are wide pendants on the wall that are semicircularly dissected. They occur as the ridges among large scallops. Larger and wider pendants are found among the ceiling pockets along the fissures in Zelška Jama (Fig. 2.3.29) and in the underground Pivka. They were formed by slow water flow in vadose conditions. Narrower and sharp pendants are found on the ceiling in Male Jame in Postojnska Jama and in Mala Karlovica. On the walls there are medium sized scallops. Also in Križni Rov in Črna Jama (Postojnska Jama) there are sharp pendants on the walls (Fig. 2.3.47) that are dissected somewhere with indented ridges. They developed in the passage where seasonal water flow velocity is 0,25 m/s. In the inflow side of Vzhodni Rov in Predjama which developed in the broken zone and at right angles to it, there are short pendants with relatively strong fixing points but sharp edges. They are found on the ceiling, walls and floor. High waters flow through this passage with velocity exceeding 0,5 m/s. Pendants may be found on the entire passage perimeter perpendicular to the wall, as are those in Krožni Rov, or else they may be rotated under various angles towards or against the water flow direction. The pendants are scalloped if their surface exceeds the scallop length. In the caves where the water deposits sediments there are below-sediment half tubes on or among the pendants (Krožni Rov in Črna Jama in Postojnska Jama, lower part of Logaška Jama). Pendants of the same size, found on the ceiling (Bretz 1956, 22), are formed by the water flow that floods the passage seasonally.



2.3.48 "Čer", Križna Jama (Photo by P. Habič)

2.3.49 *"Čer" in Vzhodni Rov, Predjama*

"Čers" are singular protrusions. They develop in the riverbeds of passages with fast, usually free surface flow. Their fixing points are commonly very strong (Slabe 1989, 88) and they narrow upwards into a point (Fig. 2.3.48). Water flows over such "čer". In Vzhodni Rov of Predjama there is a 1,5 m high "čer" (Fig. 2.3.49) which is narrowest in the lower third, widening upwards. On the narrowest part at the inflow side it is more deeply incised and smooth. On other sides the "čer" is scalloped. At first the water flow deepened the riverbed and later medium high waters prevailed; this is why the "čer" is more narrow up to the water level. In Markov Spodmol there is a larger "čer" with a shallow pothole on the top and a semicircular notch on the inflow side (Fig. 2.3.50). Other sides of the "čer" are scalloped. It is typical of the "čer" that they are rather angular of triangular cross-section. The inflow side is commonly flat or semicircularly incised, on the outflow side they end in sharp or wider crests. This is due to water turbulence at the obstacle. Behind the obstacle on both sides the turbulence zone appears. "Čers" (Fig. 2.3.51) in the wider part of water channel in Križna Jama are dismembered into several legs. Their ridges are indented and below-sediment pits appeared. The "čers" are seasonally flooded and this is why below-sediment corrosion prevails over the short activity of high waters.

In Golobina the water flow incised through a wall a pendant and the an arch developed.

The shape of the pendants that are mostly due to water turbulence along fissures and bedding planes is the result of the relationship between the fissure prop-

2.3.50 *"Čer" with pothole, Markov Spodmol* erties and their distribution and water flow velocity and its pressure. The faster the water flow, the more pointed and short are the pendants. The "čers" occur on the floor where the water flow velocity is the highest and frequently transports the load. Only the most resistant part of the rock, protected against flow remains. In the passages with the highest flow velocity there are no pendants as the water polishes the rocky perimeter by its transported load.

2.3.6. WALL NICHES

These are large semicircular (Fig. 2.3.52) or horseshoe-shaped niches a meter in diameter. The niches in the upper level of Dimnice and in Križna Jama were shaped by large eddies; this is shown also by the solution cups on the upper parts of the walls and on the ceiling. Turbulence caused accelerated incision of water flow into the rock due to fractures less resistant than the wall around the niche. This was flushed by fast water flow. On entrance walls there are smaller scallops. In Križna Jama (Fig. 2.3.52) the scallops on the lee-side of the niche are larger. In the more spacious niche in Dimnice (Bar) there are solution cups only.

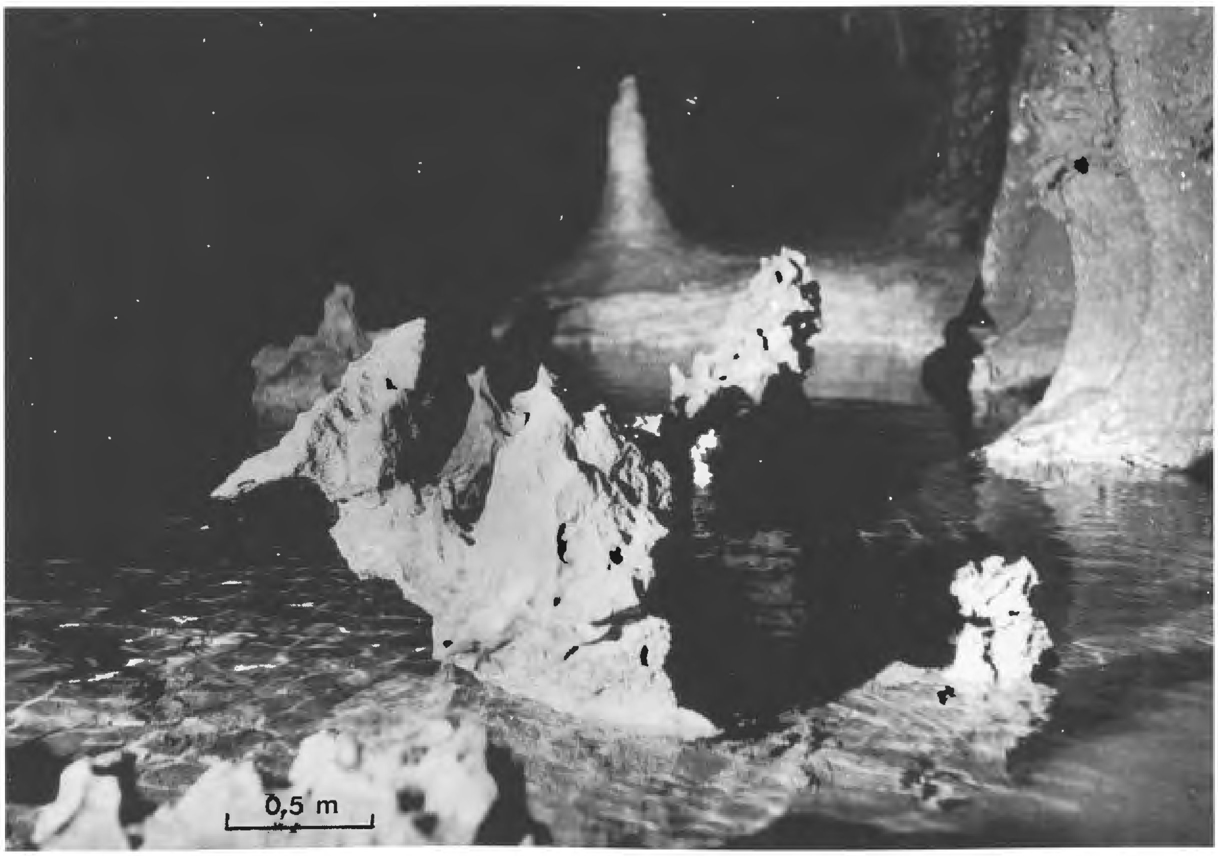
In Blatni Rov of Križna Jama there are smaller wall niches, 1 to 2 m in diameter. They are due to meandering of slow water flow over a fine-grained sediment. The flow deposits the sediment on the inner side of the meander mostly, and on the outer side, if it flows near the wall, it incises into it. Similar dissection is found on the perimeter of the entrance passage in Griška Jama. The niches are semispherically widened as the meander's diameter grows. The origin of such wall-incised meander niches was explained by Bretz (1956, 18) also.

Horseshoe-shaped niches are due to water flow meandering at fissures or bedding-planes pattern. Their shape is controlled by the rock permeability. Often they reflect changed hydrological conditions. In Križna Jama the cave passage changed from a phreatic one to a vadose conduit and the water has taken a shorter way (Slabe 1989 b, 217). When the passages are filled up by sediments or flowstone the water chooses a new way and/or cuts the meanders. When the passage grows, such niches remain on the walls and frequently become lateral passages.

2.3.7. WALL AND CEILING NOTCHES

These are semicircular flute-like notches occurring longitudinally over the walls (water level horizons) and ceilings of chambers. These are larger rocky features that may occupy most of the rocky perimeter. Scallops and flutes are frequent above them.

The notches may suggest the joining of the passages. In Fiženca in Predjama (Fig. 2.3.53) a smaller upper and a larger lower passage joined. In Ponor v Odolini they indicate the parallel converging of smaller passages (Fig. 2.3.54).



2.3.51 "Čers" with below-sediment floor-pits, Križna Jama

2.3.52 *Meander niche, Križna Jama*

2.3.53 *Wall water level horizon in Fiženca, Predjama*

2.3.54 *Ceiling water level horizon, Ponor v Odolini*

2.3.55 *Wall water level horizon, Trhlovca*

2.3.56 *Longitudinal floor channels at the riverbed step, Markov Spodmol (scale = 15 cm)*

Shallow notches are often found on most of the walls of large passages (Križna Jama, Markov Spodmol, Dimnice). They are scalloped. They reflect the long-term level of the water flow. The passage is either deepened (active passage in Škocjanske Jame) or the water flows above the gravel sediments. In Trhlovca (Fig. 2.3.55) the upper part of the oxbow passage is dissected into notches from 1 to 2 m in diameter. On the perimeter of the notches there are scallop, up to 15 cm long. The wall notches are distributed one above the other. Similarly shaped is the rocky perimeter in Rov Koalicije in Postojnska Jama and in Ključavnica in Vodna Jama v Lozi. The notches indicate the passage deepening due to varying recharges of the water flow.

Wall notches are to be found on the upper parts of the passage perimeter that were filled up by loam overflown by the water (Kamenšca, Ciganska Jama). In large chambers the walls of the notches are scalloped indicating slow water flow (Dimnice).

Notches, smaller than 1 m in diameter tapering off very steeply below the water line, develop in standing pools or lakes. Ford (1988, 46) explained their origin by cellular convection causing the sinking of heavy solute ions and ion pairs and a cellular convection carries fresh H^+ ions to the walls at the water surface. Wall notches originated at the water line when modelling the above sediment flutes in plaster. If the passage is filled by water this process, regardless of geological structure, creates flat roofs (Ford & Williams 1989, 307).

The size and the shape of the corrosion notches are thus controlled by the water quantity, by flow velocity and by how long a certain water level persists. Uniform incision of the flow upwards or downwards creates canyon channels (Brlog na Rimskem) without wall notches. Augmented water throughflow may form smaller notches. It is important to distinguish the notches described from ones that are due to accelerated corrosion at the bedding-planes or fissures and from the ones which are controlled by different rock resistance (Smoganica). In such a way normal or inverse ledges occur.

Frequently notches are transformed due to the sediment deposited on their gently inclined lower parts. The sediments protect them against corrosion. This is why water incises into the flank and upper part of the notches.

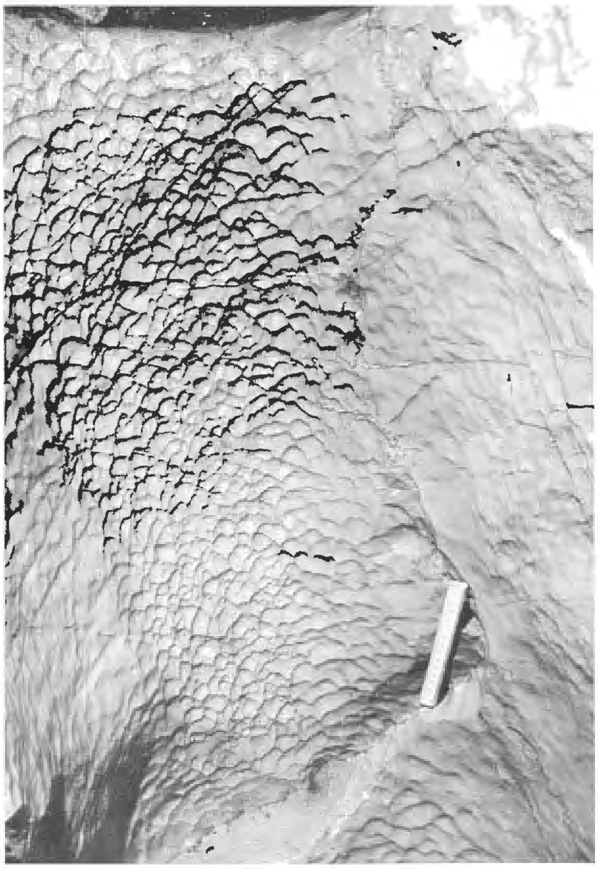
2.3.8.FLOOR CHANNELS

I distinguish the channels incised by the turbulent water flow and those which are due to smaller water quantity drainage over the rocky floor.

In Markov Spodmol there are longitudinal floor channels on a steep rise of the riverbed (75^0) (Fig. 2.3.56). They are 30 cm in breadth and 15 cm in depth, dissected into transverse shallow semicircular notches. They are due to fast and shallow water flow which separates into longitudinal flow lines. Similar channels occurred in the experiment when shallow flow drained over plaster of Paris. The channels are dissected by the turbulence similar to the one which creates the flutes.

In Ponor v Odolini there is a semispherical longitudinal channel on the lowest part of a steep riverbed (Fig. 2.3.57). Its surface is scalloped. The large quantity of water that fills the channel seasonally incises small scallops.

On the inflow and outflow parts of huge rocky blocks transverse channel-like indentations occur as already mentioned in the section on potholes. In the channels that are at the beginning of the block and are more shallow at the inflow side and more steep at the outflow side and at the end of the block there is lower outflow side of the channel the appearance of small potholes is common. Such examples can be seen in Hankejev Kanal in Škocjanske Jame (Fig. 2.3.44). Behind smaller rocks, behind transverse corrugations and at larger transverse fissures, smaller transverse channels occur. These too are frequently deepened by smaller solution cups. All these features appear in the riverbeds shaped by fast free-surface water flow. They are due to water turbulence at the obstacles. Also a transverse channel occurred, 1 cm in breadth and 0,5 cm in depth on plaster covered by waxed paper, due to turbulence of a shallow water flow on the edge. The water in the channels divides into single parallel eddies this is why they are dissected into flutes.



2.3.57 *Floor channel with small scallops, Ponor v Odolini (1 cm = 10 cm)*

On the outflow surface of a huge block in Hankejev Kanal, dipping downwards, there are narrow longitudinal solution bevels of various length. Among them are rounded crests. The bevels are due to dense longitudinal fracturing of the rock. Are they formed by water flowing over the rocky block; and the importance of water level fluctuation remains to be solved.

To the second group belong the channels due to a small quantity of water flowing over the rocky floor.

In Markov Spodmol a small amount of water which flows at low water level from a pond caught above the siphon surface incised a meandering channel, 1 m in depth (Fig. 2.3.58). On the upper side the channel is 1 m wide and at the bottom, where the water flows, some cm only. A small gradient caused the meandering of a small amount of water. On some places the water has already shortened its way and left the meanders. The narrow bottom of the channel is smooth, the walls, semicircularly widened due to seasonal water flow, are thinly scalloped.

On a more inclined river bed in Ponor v Odolini there is a straight channel (Fig. 2.3.59), 5 cm in breadth at the bottom, the cross-section shaped in letter V truncated point. The bottom 10 cm of the channel's wall are smooth; its upper part is scalloped. The channel is incised by low waters flowing from the lateral passages during the dry season of the year.

Slightly larger meandering channels are to be found in Osapska Jama. They are up to 0,5 m in breadth and 0,2 m in depth with smooth walls. On the floor of Brežanski Rov there are rather straight channels which have shallow semicircular cross-section and are up to 5 cm in breadth. They are due to small quantities of water coming from higher pools. At the inflow part of the spring cave the passages rise towards the exit and water captured during low water level runs against the normal flow direction.

A meandering channel, up to 50 cm in breadth and 15-20 cm in depth, and on steep sections deeper and more narrow, is found on the floor of the narrow passage in Ciganska Jama. The bottom of the wider part of the channel consists of two parallel series of shallow solution cups (Fig. 2.3.60). Large sparitic crystals protruding from the bottom of the channel cause the turbulence of a smaller quantity of water and shallow solution cups occur.

In Beško-Ocizeljska Jama there are small meandering floor channels, up to 15 cm in depth. They are connected to solution flutes on the wall of the shaft and to deep potholes which are one to two meters distant from the walls. The water runs over the channels; during the dry season the water trickles over the shafts walls. Periodically a waterfall appears over the walls.

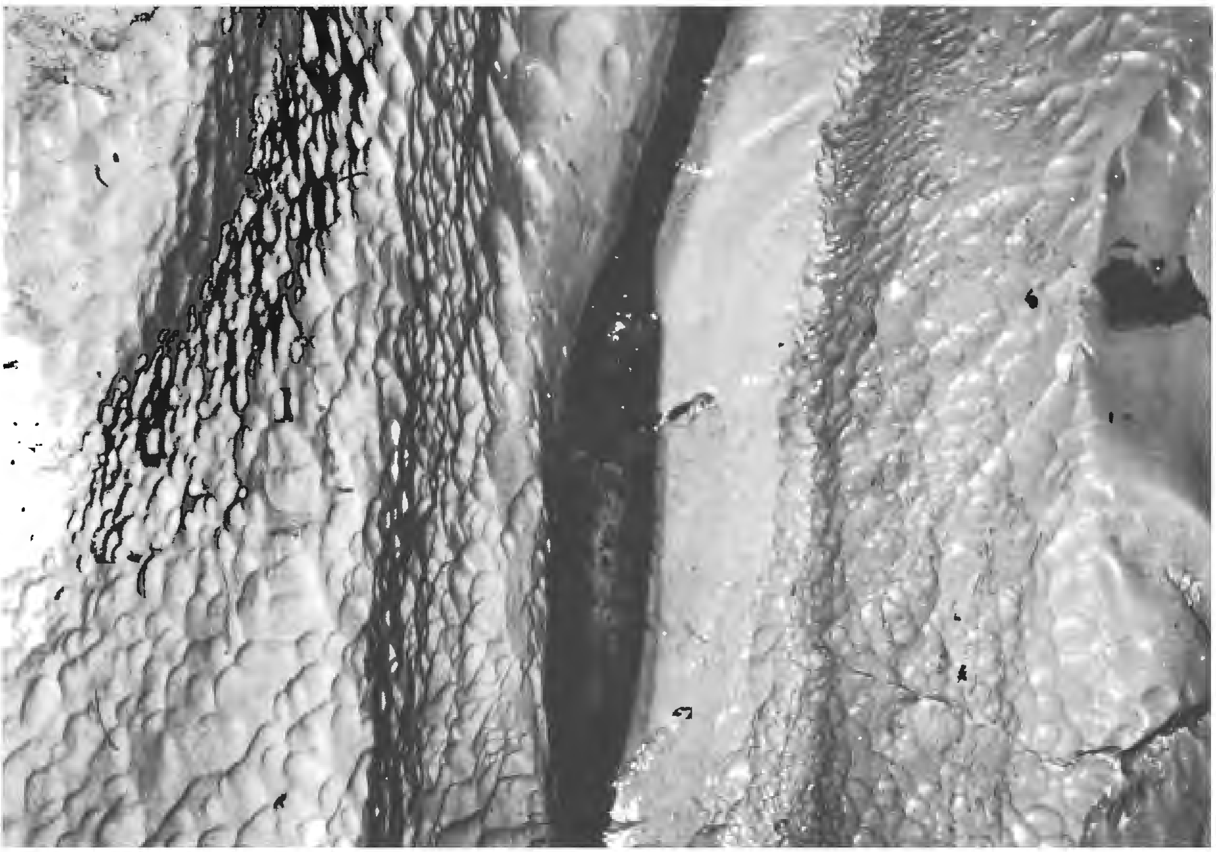
The shape, size and meandering of the channels are controlled by the quantity of water that incises them, by the dipping of the rock where the water runs and by the rock structure. If there is more water and the gradi-

2.3.58 Floor channel, Markov Spodmol

ent of the rock is higher than 10⁰ (Osapska Jama) the channels are rather straight. The development of such channels is impossible if the floor is covered by sediments or boulders. Bare floor is the most common in the passages through which seasonally fast and strong flow runs. On the other hand, in passages where the water is captured in higher pools, small floor channels are common rocky features. Often the channel development is connected to fast water flow also. The upper parts of the meandering channel in Markov Spodmol are semicircularly enlarged and the walls are scalloped; abandoned, higher-lying meanders are transformed into solution cups with large scallops on the edges. Similar is the straight but steeper channel in Ponor v Odolini, which too has only the lower parts of the walls smooth. More water runs through it and its incision dominates the activity of a seasonal fast flow. Thus the channels develop at the same time as the passages develop or else they may occur as younger features in already developed passages, as in Ciganska Jama. Meandering channels develop also in the alpine caves below the shafts or at the bottom of the meanders that connect larger shafts (Velika Ledenica v Paradani).

2.3.9. CEILING CHANNELS

In Ponor v Odolini below the swallow-hole shaft there are shallow, up to 5 cm wide, longitudinal channels on the inclined ceiling (45⁰) (Fig. 2.3.61). The bottoms of the half tubes are flat; the narrow ones have semicircular cross-section. Among the channels there are rounded crests. At the outflow side they end by semi-kettle-shaped notches. They are due to water running over the overhanging wall and swiftly flowing off the rock.



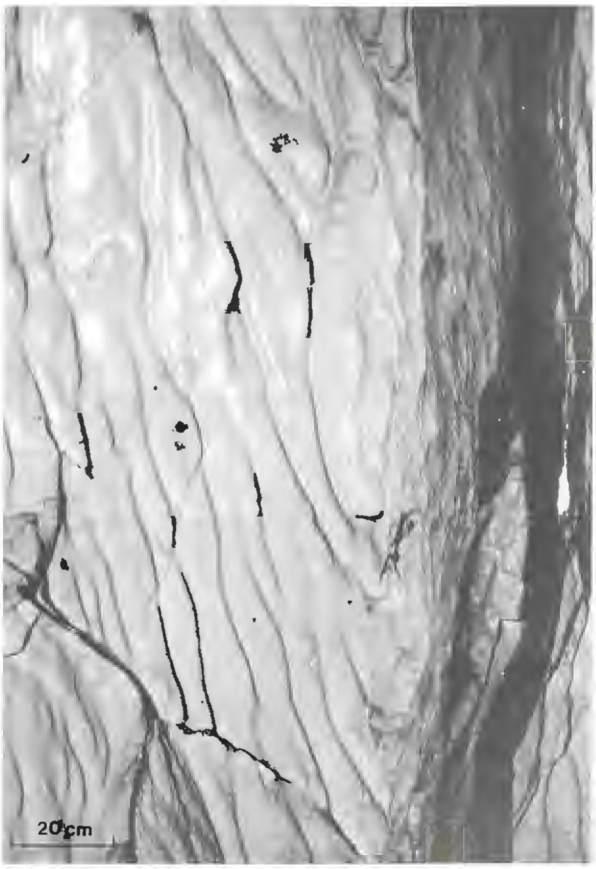
2.3.59 Floor channel, Ponor v Odolini

2.3.10. THE SURFACE OF ROCKY FEATURES DOWNCUT BY THE WATER FLOW, EXAMINED BY THE SCANNING ELECTRON MICROSCOPE

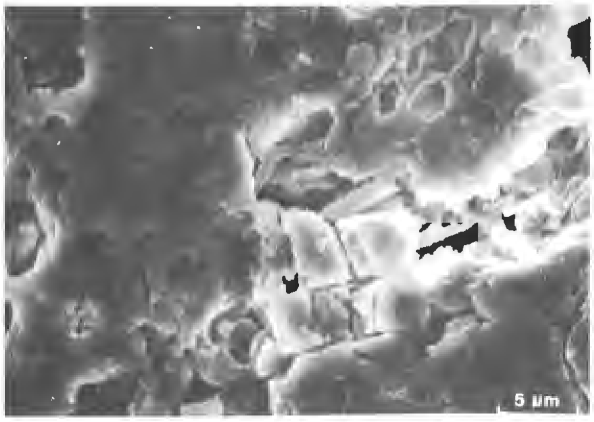
Rocky surfaces polished by fast water flow are exposed to various processes. This is why I decided to use the scanning electron microscope for their recognition. Thin sections of the rock were prepared. Thus the rock structure and its exposed surface, divided into smooth, striated or bruised, may be compared.

The perimeter of the potholes, if observed by an unaided eye, is usually smooth. It is seldom striated. Also the surface of the scallops, the smaller ones in particular, and the walls in passages where mechanical water activity prevails are smooth. The pebbles covering the river bed are polished or they are in potholes. Under the microscope the difference in smoothness or roughness of the rocky surface is clearly seen. Smaller scallops (Fig. 2.3.62) that developed on biomicritic limestone in Križna Jama and on biomicrosparitic limestone in Škocjanske Jame (Fig. 2.3.63) are the most smooth. The heterogeneities on the rock or the calcite veins are only reflected. The surface of larger potholes (Fig. 2.3.64) in biomicrosparitic limestone in Šumeča Jama (Škocjanske

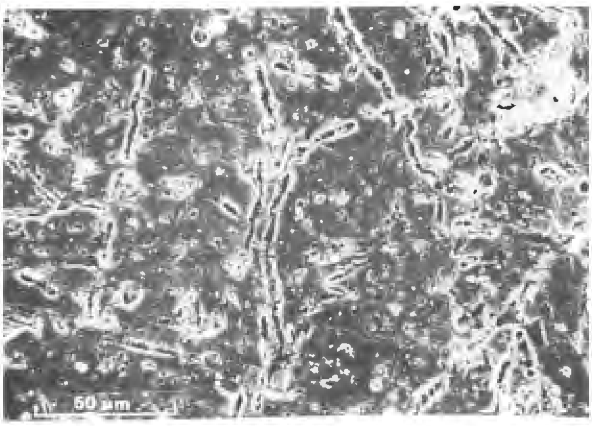
2.3.60 Floor channel, Ciganska Jama



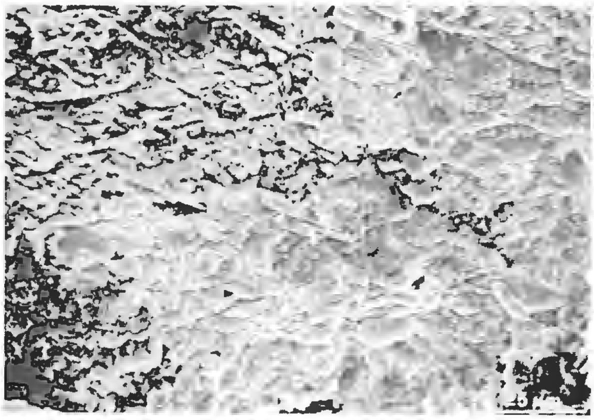
2.3.61 Ceiling channels, Ponor v Odolini



2.3.62 The surface of the scallop, Križna Jama

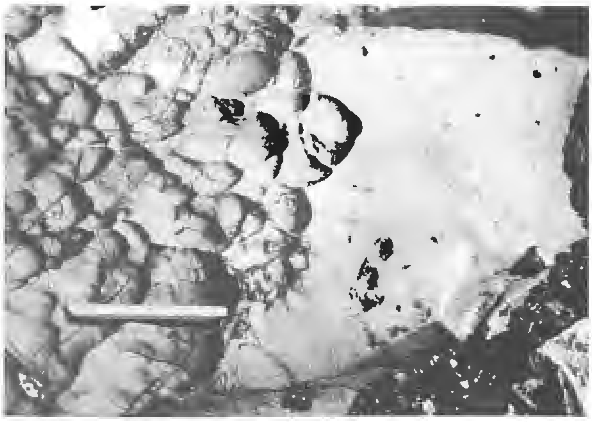


2.3.63 The surface of the scallop in the riverbed, Škocjanske Jame

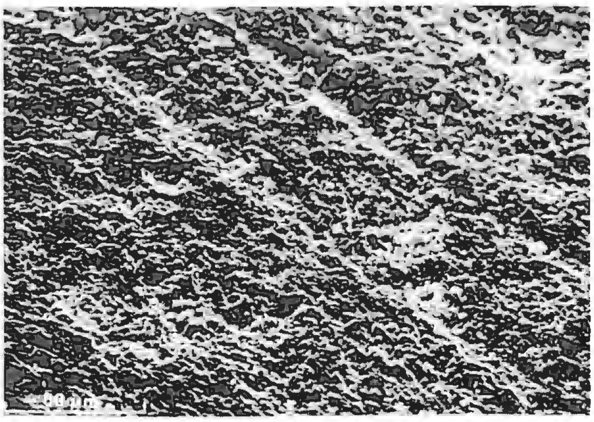


2.3.64 The surface of large pothole in the riverbed, Škocjanske Jame

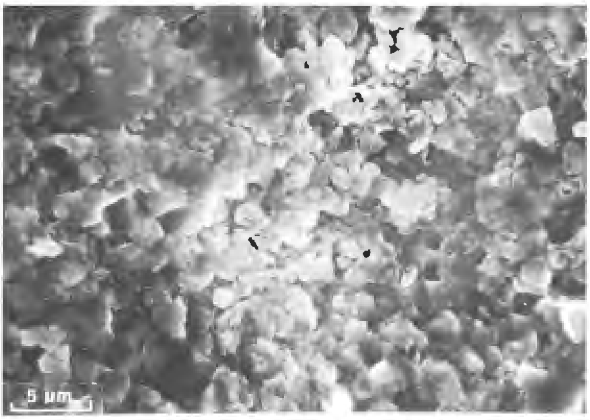
Jame) is uniformly thinly rough all over the perimeter. Slightly more smooth is the surface of smaller, hemispherical floor pits. The surface of the pebbles (Paleogene biomicrite) in Šumeča Jama and mechanically polished walls (Fig. 2.3.65) are also thinly rough. The scratches (Fig. 2.3.66) and small craters (Fig. 2.3.67) where the rock is crushed are well seen on the magnified surfaces, influenced mechanically by the water flow and the material it transports. The bruised surface is the most dissected (Fig. 2.3.68) and this is seen by unaided



2.3.65 Mechanically polished wall, Predjama (scale = 15 cm)



2.3.66 Abraded, (scratched) although mechanically polished wall



2.3.67 *Craters with shattered grains*

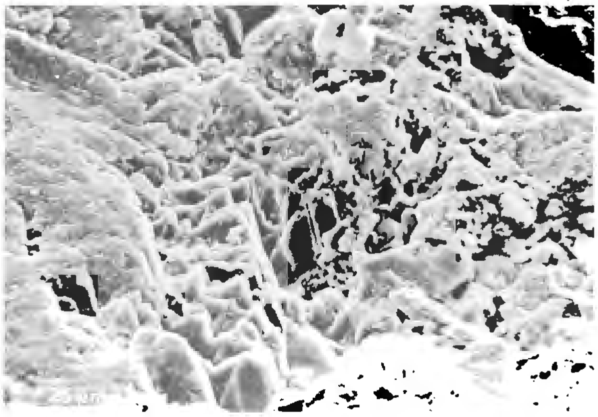
eye already. The craters are deeper (Fig. 2.3.69), the crystals are broken and sharply fractured. The rock structure is not very important on mechanically polished surfaces, the only exception is recrystallized and broken biomicritic dolomite in Pucovo Brezno.

One may assess that the smoothness, and roughness respectively of the rocky surface observed in detail under the scanning electron microscope are due to various processes acting upon it. The polished surface of the smaller scallops and solution cups is controlled by the prevailing corrosion activity of the water flow when turbulent nuclei approaches the wall and remove the less soluble particles of the rock protruding out of it. For both features it is characteristic that they are found on leeward sides far from tracted load, that is on the outflow side of the protuberances, on upper plane of rocky blocks or higher up on the walls. Mechanically polished surfaces that have a rather flat basic plane preserve thin roughness under great magnifications due to pebbles and sand friction against the rocky riverbed. The most exposed parts of rocky blocks and protuberances at the bottom of the riverbed are often bruised.

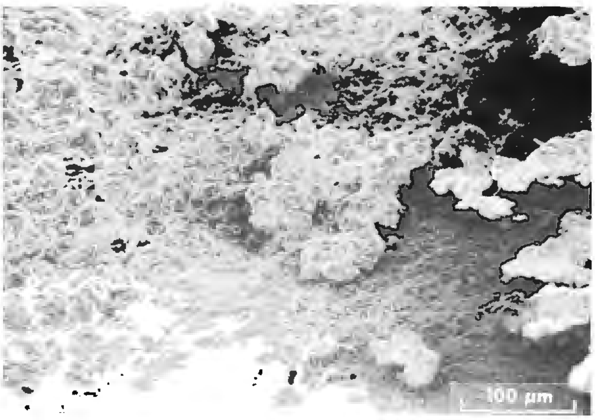
2.3.68 *Bruised surface of the ceiling behind the squeeze, Babja Jama*

As a rule, thus, the water flow polishes the rocky surface; its activity is also mechanical, either due to water mass or the transported material. However, the rock exposed to corrosional activity of a water flow with high velocity may be rough, in particular, if it consists of large fossils, sparitic crystals, breccia or conglomerate. In short, if the surface, regardless if it is inhomogeneous, is polished and its rocky edges rounded, this is the prevailing effect of the mechanical activity of water flow, and when on the surface there are scallops, rocky edges are sharp, corrosion prevails. Most often the rocky features occurring in phreatic conditions are prevailingly corrosive, while the rate of mechanical activity of water flow is more important in fast vadose streams.

The surface of the potholes at the bottom of the riverbed in Škocjanske Jame is coated by thin layer of resinous compound (Fig. 2.3.70). We did not succeed to find out what it is; it was difficult to be removed although we tried with alcohol and acetone. I presume that this is a deposit of polluted Reka. At the edges of the riverbed there is not such coating. Thus it means that it is mostly deposited out of low waters. But one may observe that in recent years this coating has got thinner; years ago the riverbed was slimy and slippery. This is a good result of nature protection efforts for a pure Reka river.



2.3.69 *Bruised surface*



2.3.70 *Resinous layer on the rock in the riverbed, Škocjanske Jame*

2.4. Along Sediments Cave Rocky Features

At the contact with fine-grained sediment water cuts into the perimeter of karst caves the along sediment rocky features which may be divided into above-sediment (Table 2.3) and below-sediment ones. The above-sediment channels and pits are characteristic for the passages that were filled up by flood deposits. Due to water flow above the loam in a flooded passage the channels raise the ceiling and the water incises into the walls when it flows downwards. The water that comes into filled up passages through the fissures may develop solution cups at their mouth. Thin pits occur on the rock near the humid sediment. The above-sediment rocky features are characteristic of the caves in contact karst; they were in Pleistocene frequently entirely filled up by fine-grained sediment.

The below-sediment rocky features make part of cave rocky relief through which seasonally slow water flows and deposits fine-grained sediment on the perimeter. These are bevels and pits, wall notches, roof pendants and solution pockets and wall niches. They are due to water filtration out of the sediment (bevels), to corrosion below the humid sediment (pits) when high waters retreat, or due to dissolution of bare rock in flooded passages (wall notches, roof pendants). The sediment somewhere prevents the contact of water and wall. In seasonally flooded passages the traces of small quantities of fine-grained sediment deposited on the features prevail over the features, left by water flows. The water fluctuation is controlled by changeable short-term climatic conditions on our karst.

Tabela 2.3 Rocky features along the sediments

ROCKYFEATURES		FACTORS OF FORMATION	CONDITIONS OF FORMATON	PROCESS ON THE ROCK
ABOVE-SEDIMENT	ceiling, wall channels	smaller flows above	phreatic zone	
	anastomosis	the sediment	"	
	niches	moisture in the sed. or	"	corrosion
	ceiling pocket	inflow to the sed.	"	
BELOW-SEDIMENT	bevel	filtering of water from the sediment	epiphreatic zone	
	solution niches	moisture in the sediment	epiphreatic zone	corrosion
	ceiling pocket	filtering of water from the sediment	epiphreatic zone	
	roof pendant	water at the contact with the sediment	phreatic zone phreatic zone	corrosion corrosion
	wall notches	water above the sediment	phreatic zone	corrosion

2.4.1. ABOVE-SEDIMENT CEILING CHANNELS AND ANASTOMOSES

Ceiling channels and anastomoses may be found as one of the youngest rocky features in now dry passages in the caves of Primorska (Dimnice, Kamenšca, Škocjanske Jame, Trhlovca, Lipiška Jama), Notranjska (Križna Jama, Planinska Jama, Ciganska Jama near Predgriže, Postojnska Jama, Predjama, Beloglavka, Markov Spodmol) and Dolenjska (Brlog na Rimskem) karst. Certain floods filled several cave levels with fine-grained sediment at the same time (Dimnice) and thus caused the transformation of old passages. In the caves where the water flow exists today, the ceiling channels are preserved only in the higher passages, i. e. the passages that are no more reached by the present water flow. In rare cases when the water flow reached the channels it sharpened the pendants between them. According to rocky relief I presume that the above-sediment channels in those caves originated in the last epochs of Pleistocene or at the transition to Holocene.

I described in detail the anastomosis network in the upper level of Dimnice (Slabe 1987). I presumed that the network originated in a locally obstructed zone when the water flowed over the channels at the contact

2.4.1 Ceiling channel in Blatni Rov, Predjama

with sediment. I described also the above-sediment rocky relief in Križna Jama (Slabe 1989 b, 212). The flat ceilings and above-sediment channels in Brlog na Rimskem were presented by Mihevc (1991 a). The origin of channels due to water flow above fine-grained sediment was confirmed by Lauritzen (1981, 407) by experiment; on plaster a network of small channels developed, only 2-3 mm in diameter. The half tubes are mostly controlled by water flow amidst the sediment particles which were in close contact with the plaster. The half tubes in the caves are commonly larger and they exceed the size of the particles within a deposit. By experiments in plaster I tried to contribute to a more detailed explanation of the origin and development of ceiling channels.

The shape of above-sediment ceiling channels and anastomoses

Large channels (Table 2.3) occupy the whole upper part of the passage; smaller channels (Fig. 2.4.1) may be found on the highest part of the ceiling only. The first are found in the passages (Slabe 1989 a, 23, 36) with vertical walls as is, for example, Turkova Jama. Paragenetic galleries are described by Ford & Williams (1989, 272). Large channels can exceed several metres in diameter, while the diameter of smaller channels is from 1 to 100 cm. Their cross-sections are omega-shaped and they meander. Small channels often lead from the ceiling solution cups that developed along the fissures (Slabe 1989 a, 29). The increasing size of the channels controls their linearity. When the channels developed

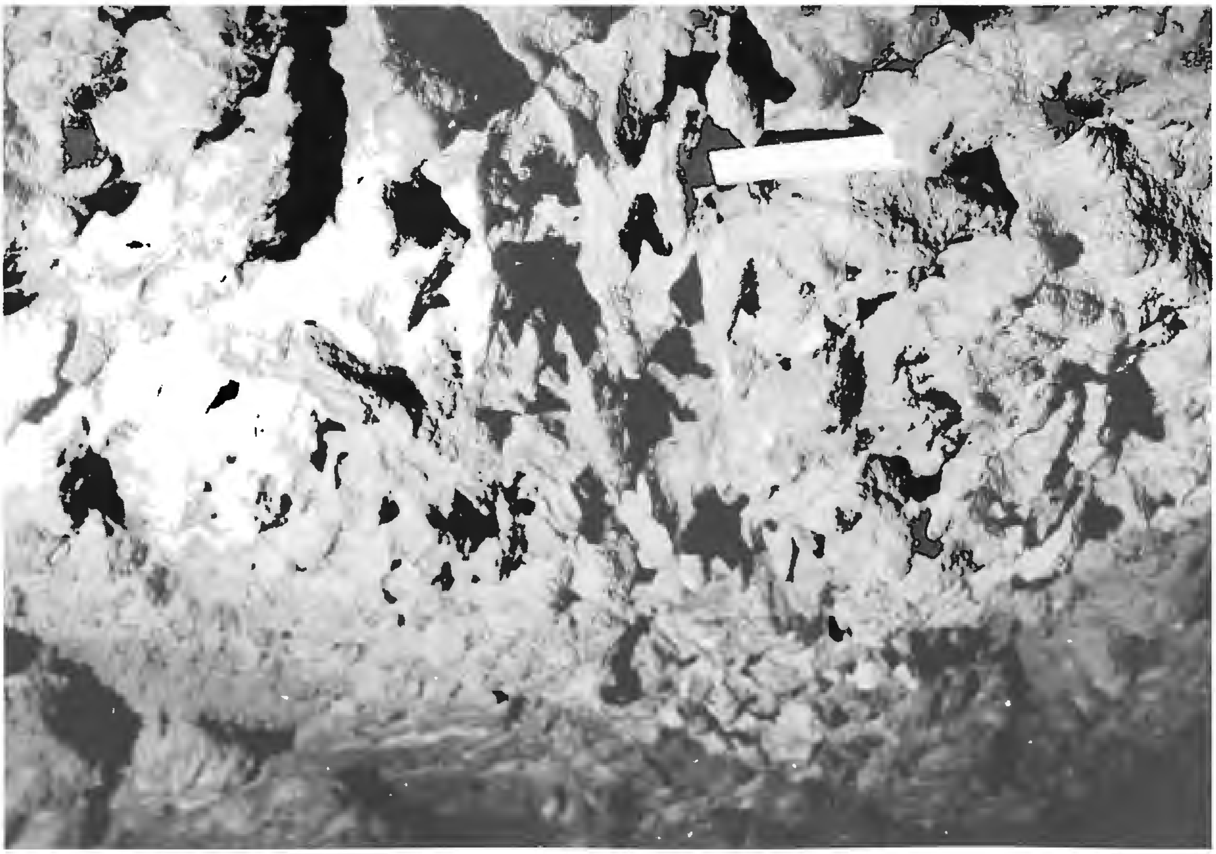
2.4.2 Anastomosis network in Havaji, Brlog na Rimskem

2.4.3 Anastomoses on the ceiling of Kozinski Rov, Lipiška Jama

along fissures they are relatively narrow and tall with semicircular peaks. Along the fissures there are preserved channels with cross-section shaped as an upside down letter V and they meander sharply (Tiha Jama in Škocjanske Jame). This is the result of the fissure network.

Ceiling channels constituting a gradational set of features are called anastomoses (Slabe 1987, 169) and where they developed above the sediment we may add the adjective above-sediment. We know inter-bed and inter-fissure anastomoses. The anastomosis network covering either the whole ceiling in the passage (Havaji in Brlog na Rimskem, Kozinski Rov in Lipiška Jama) (Fig. 2.4.2), a part of a ceiling or only the overhanging walls (Dimnice (Slabe 1987, 171), Trhlovca, Turkova Jama) occupy from some tenth of a metre to several square metres. The network is either independent or associated with channels (Slabe 1987, 172). Two ways of association of channels and anastomoses are distinguished. The first are the channels and anastomoses on the ceiling. The anastomoses on overhanging walls are connected by wall channels. Anastomosis networks originate on surfaces which are inclined up to 30^0 (Fig. 2.4.3). The channels within the anastomoses ressemble independent channels. The networks composed of variously sized channels often appear in levels (Brlog na Rimskem (Fig. 2.4.4), Dimnice (Slabe 1987). The smallest channels, of some cm in diameter only, are commonly strongly curved and remained hanging above the larger, deeper cut channels. Medium sized channels, 10 to 15 cm in diameter and omega-shaped cross-section, are deeper for the size of their diameter. The largest channels, over one meter in size (Havaji in Brlog na Rimskem) have semicircular cross-sections. Larger channels are more linear. Within the anastomoses that did not develop along the fissures, there are among the channels circular or rounded pendants with several legs. The lower plane of the rock into which the channels are incised is rather flat. On the dolomite (Fig. 2.4.5) the channels commonly do not have regular omega-shaped cross-sections and even within the same level they vary in size and shape. The pendants among them are more pointed and thinly dissected. The characteristic sheeting of the dolomite is reflected in the form of anastomosis network with rectangularly linked channels. Within the anastomoses originating in the conglomerate of

2.4.4 Anastomoses in Havaji, Brlog na Rimskem



2.4.5 Anastomoses on dolomite, Turkova Jama (scale = 15 cm)

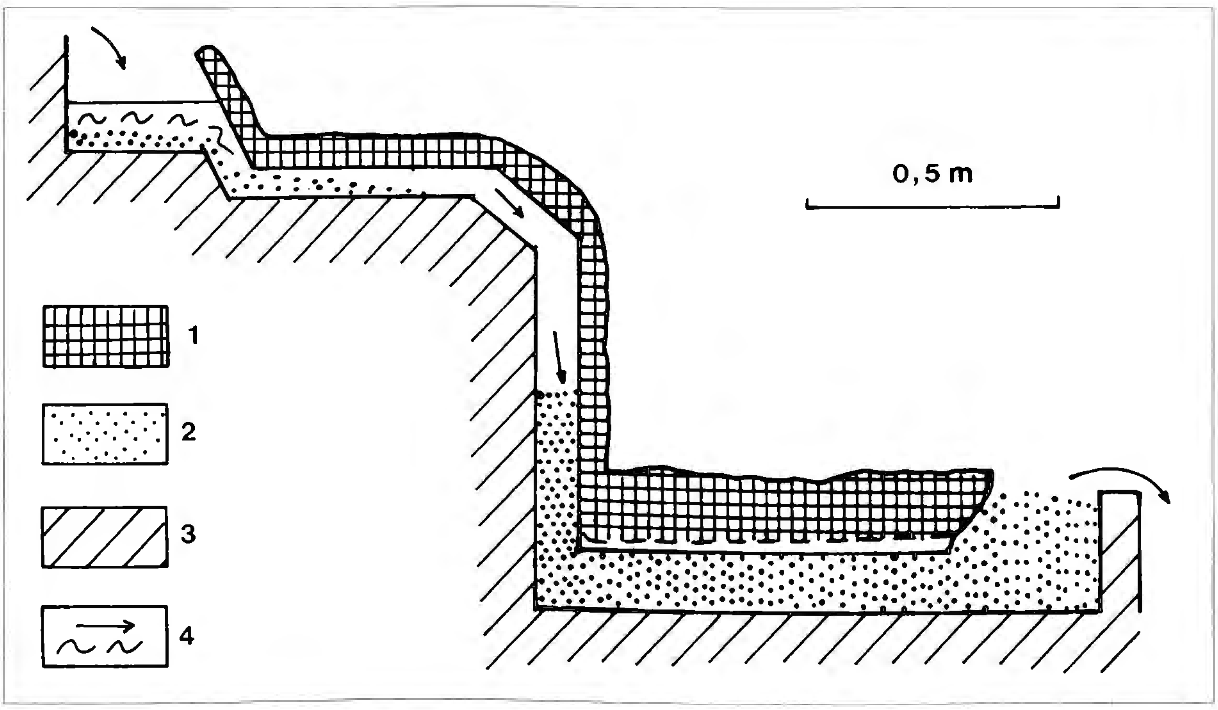
Smoganica Cave there are among the smaller channels pendants which form a constituent part of the rock (Fig. 2.4.6). The shape of larger channels does not reflect the rock structure as they are spread over the various constituent parts.

On surfaces inclined more than 30^0 there are wall channels. When the channels are parallel with the inclined passage or oblique across the wall they are convolute. At the bends smaller pendants remain.

On densely fissured rock there are frequently on the walls and ceiling smaller tubes, 10 cm in diameter, that have entirely developed in the rock (Dimnice, Ledenica na Dolu (Slabe 1989 a, 153)). Such tubes appeared in the experiment in plaster too.

Wall channels appear in the caves that are developed at the contact of carbonate rock above and flysch marl below. The original channels that had the character of interbedded anastomoses (Ewers 1982) developed into passages due to marl erosion. Such a cave is Piskovica (Jekić & Zlokolica 1988, 71; Mihevc 1991 a, 21). The channels are distributed in a rectangular fissure pattern. The longitudinal channels that were the origin of passages are larger. Similar channels are preserved in Poljanska Buža and Kubik caves.

2.4.6 Anastomoses on conglomerate, Smoganica (scale = 15 cm)



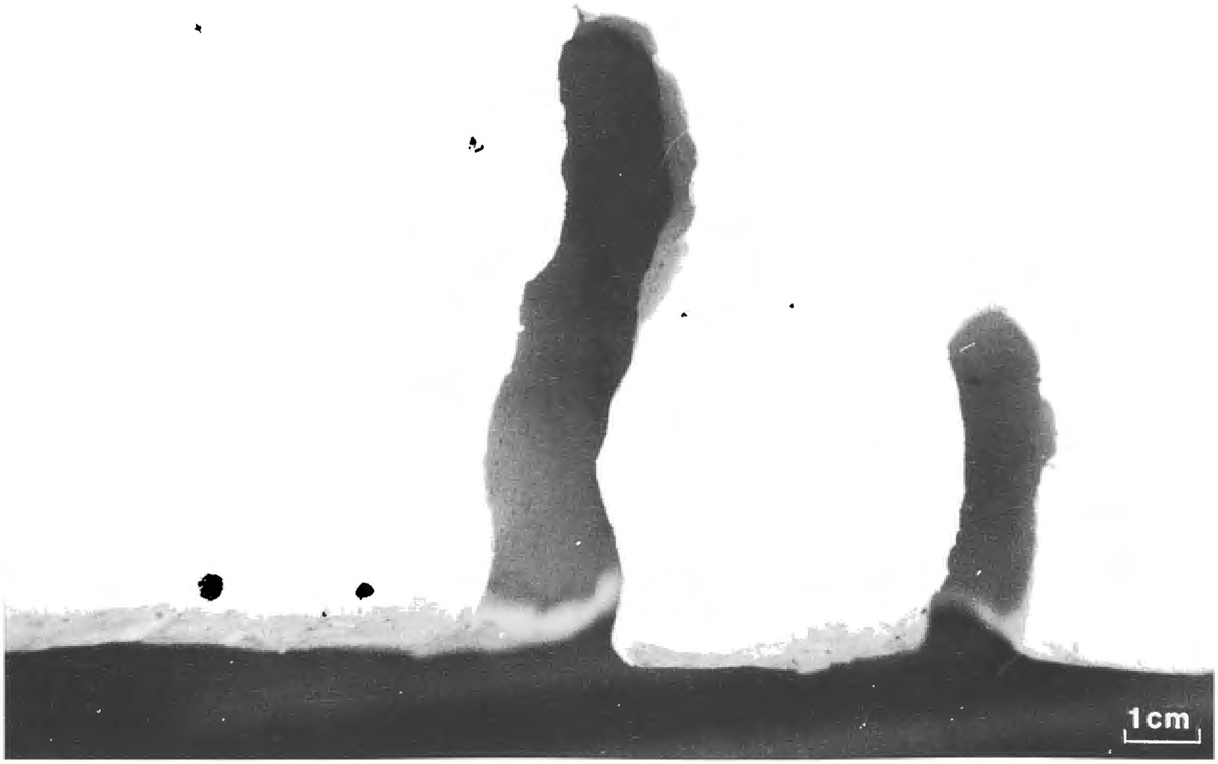
2.4.7 Cross-section of experimental model

Experimental above-sediment channels in plaster of Paris

The results of above-sediment ceiling channels in plaster of Paris are limited due to the small number of experiments. There was no opportunity to monitoring the process of formation. The experiment was observed and regulated at the water inflow into the system and at the outlet. In any case it is sensible to continue with the experiments, as several explanations were gathered regarding the water flow above the fine-grained sediment and several new questions arose.

For the experiments we used tap water, the commercial plaster of Paris ($CaSO_4$ x 1/2 of water) and flysch loam from Blatni Rov in Predjama. At room temperature 1,4 g of plaster was dissolved in water. The loam contained up to 0,5 % of organic carbon. When the loam was soaked in water for a longer time more plaster was dissolved (1,7 g/l).

Below various sized slabs of plaster (0,3 to 0,5 m^2; the largest was 0,7 m in length and 0,7 m in breadth) that were either horizontal, vertical or inclined, a 5 to 8 cm thick bed of loam was deposited. The loam was added to the inflow water, at 1,5 l/s. At the outlet from the system the slabs were below the level of the source and further back above it. Loam quickly filled up the space below the slabs which were below the source level. At first the water flowed regularly over the source obstacle; later single sources occurred with eddies that were rather evenly distributed along the flow. The number of sources later diminished and finally only one prevailed, in some experiments two. The loam was added to the inflow water simultaneously and proportionately, and some of loam drained off. The discharge through the system was slowed down or even interrupted sometimes. The pressure at inlet was 1,5 m of water and after one to five minutes the discharge reappeared with a greater or smaller pulse of water. After the largest pulses several sources reappeared but soon most of them ceased to drain the water. The situation before the blocking of the system reappeared. If too much loam was added, the discharge was restored only by the drying of the system. On such occasions the loam deposited and cracked and the experiment continued. During the first experiments it was already shown that the channels appeared at the contact of plaster due to closing of the system and along the fissures. During the experiment when the slab was some centimeters below the source level two channels appeared only at the contact of plaster. The first was 1 cm in diameter having an omega-shaped cross-section. After some hours the cross-section opened and enlarged (2 cm) and became deeper (2,5 cm). The second channel was 5 cm wide and 3 cm deep. At first the channels acted together later the entire discharge below the plaster slab was overtaken by the larger channel. The smaller channel was blocked due to added loam, but its summit reached the level of the source a bit earlier. Its growth upwards was made possible by the barrier that developed in front of the mouth. Smaller channels appeared on the plaster slabs that were rather high above the source



level. They developed at the sharp bends among the slabs that touched at various angles. Below these contacts the loam accumulated.

The most distinctive network of channels originated on the slab was 0,7 m long and wide, its lower side 0,2 m below the level of the source (Fig. 2.4.7). Loam was added all the time to the system that was active for 120 hours. A half of the submerged plaster surface was thinly fissured; into the second half we cut a rectangular set of incisions, 5 mm deep and 3 mm wide. At first small anastomoses, of some mm in diameter only, developed all over the surface. Larger channels developed on the fissured slab. Deeper channels (Fig. 2.4.8) (up to 2,5 cm) are more narrow (up to 8 mm); more shallow channels (up to 1,5 cm) are wider (1,2 cm) with omega cross-section. Deeper channels have semicircular peaks. The water drained through the plaster too. The fissured slab was linked with some cm thick bed of plaster and at their contact a tube developed, about 5 cm wide with a flat bottom. At the edges the tube is semicircularly enlarged. It is of wide omega cross- section and is rather linear. Smaller channels on the surface of the slab were filled up by loam. Traces of loam at the contact of the plaster slabs show that the water with loam first filled up the less permeable conduits and at the same time enlarged the more permeable. At the outlet from the channel, on the vertical border of the slab, shallow 1 cm wide, channels developed. At the larger source, behind the central channel, the outlet channel had a funnel-shaped mouth. These channels too have developed below the water level of the source at the contact, with ripple marks made by water at the source barrier.

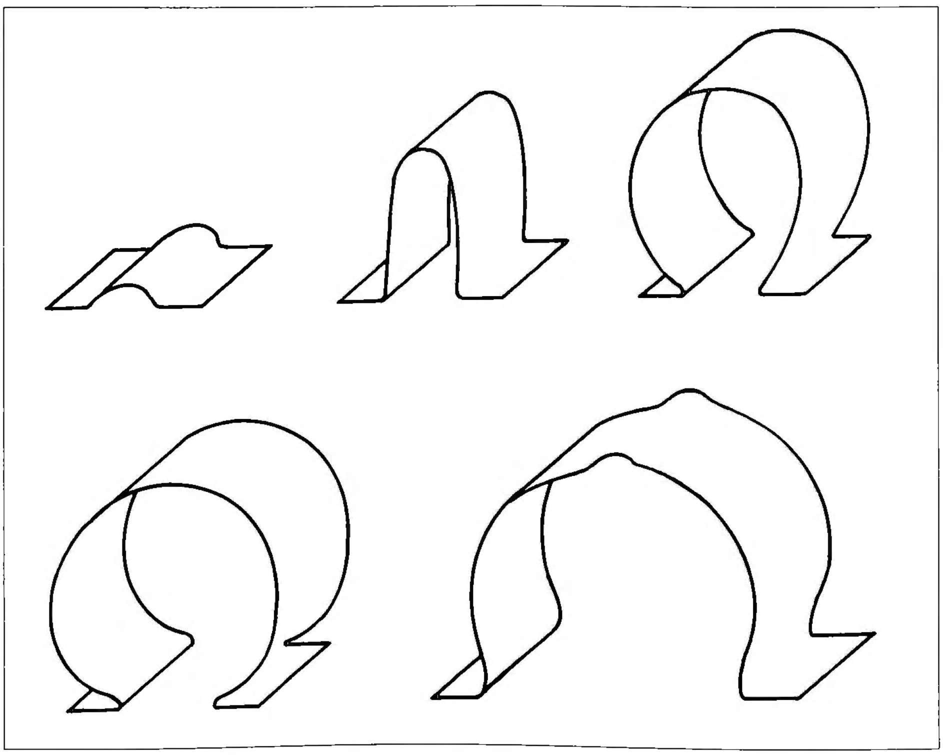
On the lower level of the plaster circular pendants developed among the channels, 10 mm in diameter and up to 3 mm high. On the remaining surface there are small notches, 1 to 3 mm in diameter, or small particles of sand that are constituent parts of the plaster protrude out of the surface. The surface of the channels was smooth there are only single semispherical notches, up to 1 mm wide.

At the end of the experiment we dyed the loam that was transported into the system by the water. On plaster and in loam the channels that were the least permeable, were clearly seen.

Origin and development of above-sediment channels and anastomoses

Referring to observations of rocky features in the caves I presumed that slow flood waters gradually deposit the fine-grained sediments; the filling starts at a leeward position and later trends upwards from the obstacle and from the floor to the ceiling. If the water discharge is low due to smaller permeability of the channels and the flow transports enough of fine-grained material, the sediments fill up the passage almost entirely. Most of the water drains through the upper part of the passage (Dimnice) and a smaller quantity seeks the most permeable conduits below the passage ceiling. The water flows over the sediments under pressure and channels are incised into the ceiling. Size, shape and winding of the channels are due to the shape and permeability of the passages, the water velocity and the properties of the material transported by the water.

These suppositions were confirmed by experiment. I found out that increased inlet pressure water flow may start to erode the sediments. With small water flow velocity too much loam may be deposited as with dense muddy water flow, and the channels get blocked. In experiments with limited inlet pressure drainage was re-



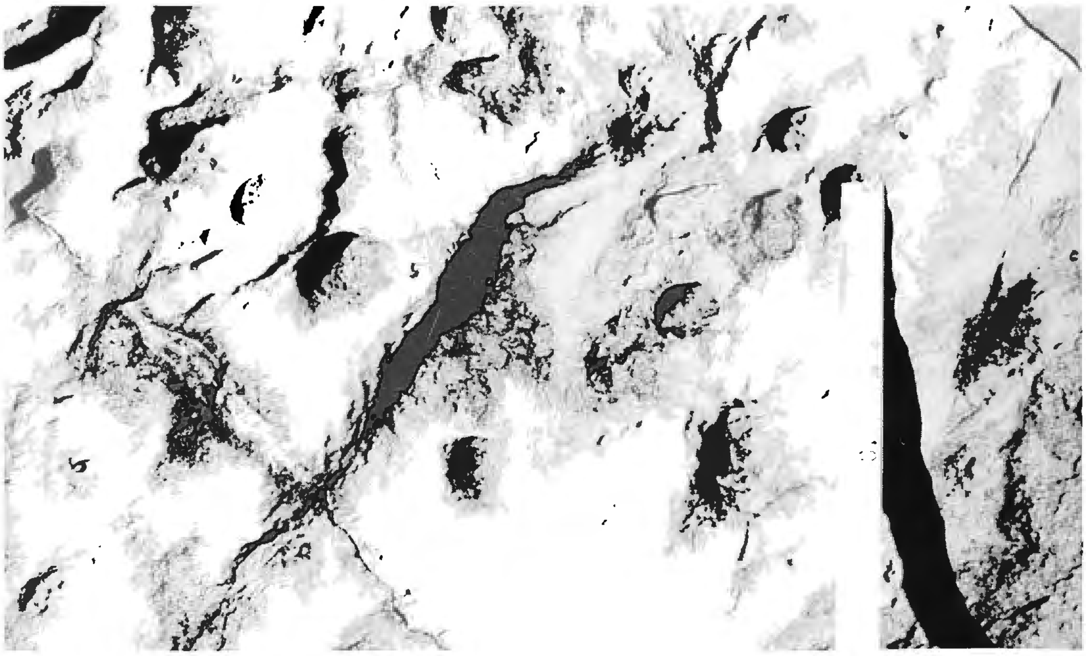
2.4.9 Cross-sections of ceiling channels stored after a long interval and drying of deposited and cracked sediments.

The finest particles of sediment may be transported by very slow flow and when they are deposited a considerably higher, so-called drag force of flow is required than the one existing when the water transported and deposited these particles (Scheidegger 1961, 135). Loam particles of 0,01 mm are deposited at a flow velocity of 1,2 cm/s and eroded at velocity of 40 cm/s only. This is the basic reason for the filling up passages by fine-grained sediments and, of course, for prominent water incision into the ceiling when it flows above the sediments. When the channels are wide enough so that the discharge through them increases, the water incises into the loam below them (Slabe 1989 a, 69). Larger channels are thus semicircular, the lower semicircle of the tube being in the loam. The velocity of water through the anastomose channels is 0,1 to 8 cm/s and the flow is laminar according to Reynolds Number considering the particle size and the diameter of the channel being 10 cm. Turbulent flow appears in channels more than 20 cm in diameter. The distribution of larger channels at the outer borders of the meanders confirms this. The meandering may be caused by water turbulence when the eddies are equal to or greater than the cross-section of the channel or pipe.

Smaller channel permeability increases the sediment deposition. Under pressure the water divides into a net of meandering channels and anastomoses develop. In Brlog na Rimskem there are large channels on the ceiling of larger and higher passages; in lower Havaji a huge anastomose network appears. The anastomoses consisisting of larger channels develop in levels. Smaller networks with equally sized channels have all the channels at the same level. In larger networks, smaller channels remain hanging above the larger ones. When the large channels within a network increase and prevail they may cover other channels and between them single pendants remain only. In Brlog na Rimskem a huge anastomosis net is crossed by a linear channel more than 1 m in diameter. By experiment we proved that the water seeks permeable conduits at the beginning of network formation and sediment deposition. This is confirmed by a series of sources at the beginning of the exeriment and small anastomoses in the plaster. Later, water chooses only the most permeable channels and the smaller ones are filled up by sediment. Smaller channels and incisions made on a plaster slab were filled up by loam and without a trace of the dye which was let into the system at the end of the experiment. Hence the largest channels gradually predominated.

The development of channels from small to large with omega cross-section was presumed when studying the cave anastomoses in Dimnice (Slabe 1987, 176). The supposition was confirmed by the experiment in plaster. Adding the loam, at first a narrow channel developed and later, due to increased permeability as it was the dominant water course, it developed into a channel with omega cross-section. The channel continued to grow into open omega form (Fig. 2.4.9). In the plaster, narrow and deep channels developed at the distinctive fissures; along less distinctive fissures they were more shallow and had omega cross-section. Narrow high channels developed as a result of considerable adding of loam to the water. The loam was deposited and caused sharp incision of water into the plaster. Within the same channel there are some sectors with omega cross-section and elsewhere the channel is narrow and high.

In short, the linearity of the channels is controlled by their permeability. Important factors are how the rock is fractured and the amount of the sediment which is deposited at certain velocities by the water.



2.4.10 Above-sediment niches in Južni Rov, Dimnice

I have already mentioned two systems of connection between anastomoses and channels. The ceiling system (Brlog na Rimskem) develops when the cave is filled up and the water flows above the sediment in the highest parts of the passages only. The wall system is due to water that was captured above the sediment and flows downwards across the passage walls. The channels in the ceiling system are commonly larger; however their size is controlled by the duration of their development. The amount of captured water is commonly insignificant and so are the resulting wall channels. The channels within a ceiling system have omega cross-sections; within the wall system usually not; omega shape is found in anastomosing channels only.

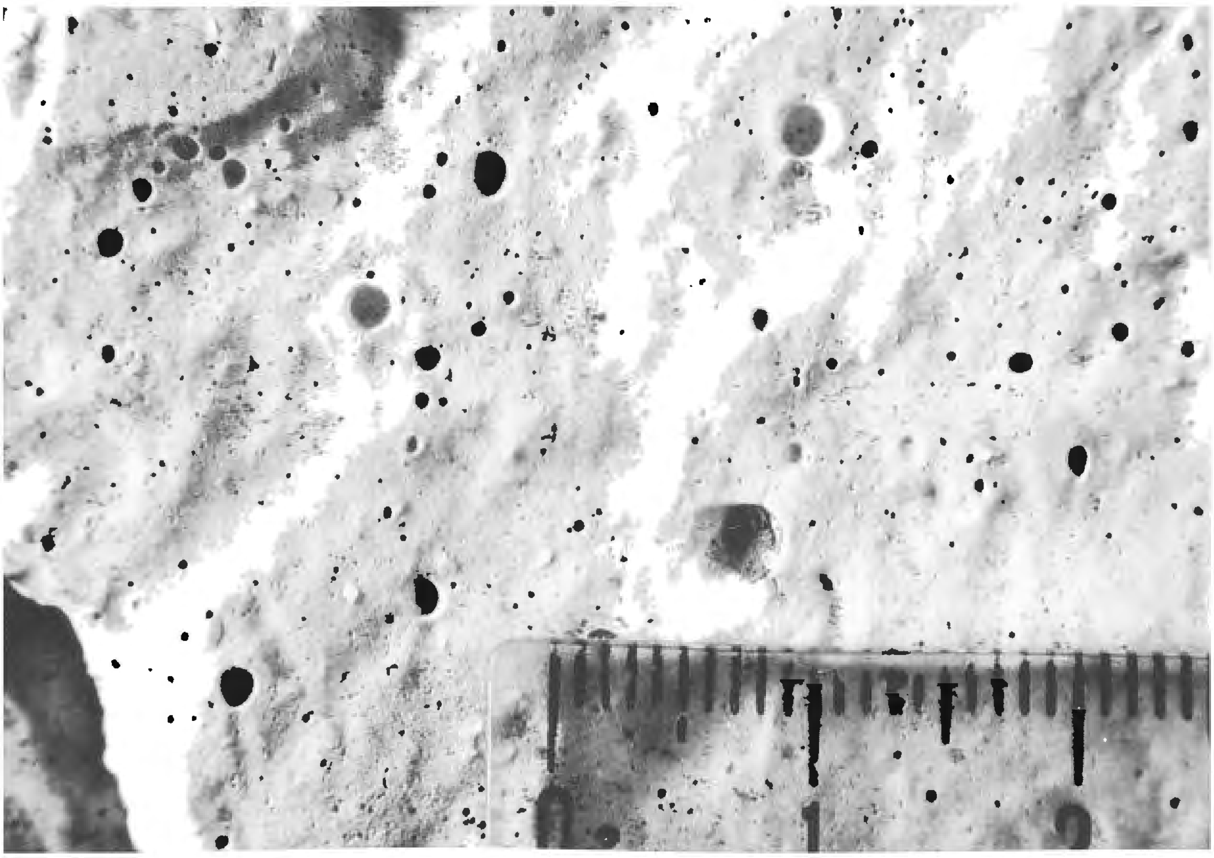
Along dense fissures and bedding planes the water finds its way through the rock and the tubes develop that we observed in Dimnice and in Ledenica na Dolu. The experiment too confirmed their fomation. Water with added loam quickly found its way upwards along the fissures until contact a uniform tube-shaped conduit developed at the plaster.

Smaller ceiling channels (Bar in Dimnice) that are some cm only wide lead from the upper part of the ceiling pockets too. They are due to water filtration from the fissures where the solution cups were formed. In a fissure which is narrow but high the pressure may be high enough to allow water into a passage filled up by sediment.

2.4.2. ABOVE-SEDIMENT NICHES AND POCKETS

The channels that were entirely or predominantly filled up by fine-grained sediment commonly suggest that the whole perimeter or the walls are indented by rather regular hemispherical niches and pockets. The niches (Fig. 2.4.10) up to 5 cm in diameter are typical of solid rocks, and the pockets, from 5 to 20 cm in diameter, of fractured rocks in particular. The largest are found at the most distinctive fissures. In almost all cases the niches have the same depth as the diameter of their opening or they are even deeper. The niches are controlled by the corrosion solution of non-fissured or less fissured rocks. Corrosion by the moisture within a sediment acts equally on the entire rock surface and rounds the niches (Lang 1959). Densely distributed niches are connected and the walls among them are dissected into thin pendants (Volčja Jama on Nanos). Solution is more distinctive at the contact with porous deposits which restore the aggressive water. Small, hemispherical niches (Fig. 2.4.11), some mm in diameter, appeared in plaster too. The mode of wall solution is thus the effect of structure, porosity and fracture of the rock, the humidity of the sediment and the duration of the process.

In particular, larger pockets are due to water inflow through fissures in the rock to the contact with the sediment, where the water spreads and dissolves the rock. Rarely the water pressure is high enough that for it to



2.4.11 Above-sediment niches in plaster

2.4.12a Below-sediment bevels, Križna Jama (Photo by Habič)

flow off the fissure and incise a small channel (Bar in Dimnice).

The niches on the walls of the caves that were for a short time filled up by flood sediment from the flysch border (Južni Rov in Dimnice, Matevžev Rov in Postojnska Jama) are rather regularly hemispherical with

2.4.12b Below-sediment becels, Markov Spodmol (scale = 15 cm)

2.4.13 Below-sediment channels on overhanging wall, Griška Jama smooth walls. The niches and pockets on the walls of the caves (Volčja Jama on Nanos (Slabe 1990, 173), Velika Ledenica in Paradana) where the sediment remained for longer time, are frequently filled up by the agglomerated deposits. A sudden lowering of water level caused the sediments to be slowly washed off the caves by diffuse recharge of the infiltrated water. The cave changed in character and passed from a phreatic conduit to a vadose conduit of a simple outflow aquifer. The sediments were often partly carbonates. They developed by long-term weathering of the surface above the cave (Zupan 1990, 18) and hence frequently recrystallized into spherical concretions. The dark coating of the niche surface are Mn minerals, the remains of carbonate weathering.

2.4.3. BELOW-SEDIMENT SOLUTION BEVELS

In parts of epiphreatic passages that are not exposed to fast water flow below-sediment solution bevels occur. Usually they occur on the lower parts of cave walls. The bevels develop on inclined, vertical and overhanging walls. The largest are 15 cm deep, but smaller ones are more frequent (Fig. 2.4.12a, 12b). Their cross-section is V-shaped, and the bottom is rounded. Among them are rather sharp shillows. On gentle sloping surfaces among the bevels where the loam may be deposited, smaller channels develop and they lead into larger ones. On overhanging walls there are, below sharp mouth on the border, funnel-shaped bevels (Fig. 2.4.13) that widen downwards the wall. Frequently one may observe the formation of bevels in connection with other rocky features. They distroy the wall pendants (Črna Jama in Postojnska Jama, lower part of Logaška Jama) or they lead from ceiling pockets with gentle sloping walls. The shillows among the channels that are exposed to corrosion activity of water flow are sharpened (Fig. 2.4.14a); mechanical activity makes them smooth and rounded (Fig. 2.4.14b). I presumed that the bevels are formed by the water that filtrates out of freshly deposited or saturated old sediments. They are deposited on gentle sloping sectors of the rocky perimeter.

I tried to gain an understanding of the bevel's development by an experiment in plaster. The plaster block with a flat upper side and variously inclined lateral sides (vertical, gentle, gradient of 60^0 and overhanging with the same inclination) was exposed to flood water to which loam from Blatni Rov, Predjama was added. In the cave, the bevels occur below this loam. When the loam was deposited from that water the water level was lowered. The water filtered out of moistened sediment that covered the upper, horizontal plane of the block and the upper parts of gentle and vertical lateral sides. Runnels of washed plaster occurred and shallow notches appeared in the loam. After repeated flooding the water has chosen its way by the bevels into washed runnels again. The bevels started to develop. On the upper part of the gentle plane the bevels were the most densely distributed but they were small and widened downwards. The water thus concentrated into smaller courses. On the vertical plane the bevels were of rather uniform width along the entire length (Fig. 2.4.15). The mouth between the upper horizontal plane and the walls have strong curves and define the direction of the trickling water. When more water flowed over the overhanging walls funnel-shaped bevels occurred. On the upper part the bevels are deeper; downwards the same quantity of water spreads over a larger surface and the bevels are more shallow. A small quantity of water spreads on the ceiling and causes pendants; more water incises wider, short and semicircularly ended bevels. Two limitations in the experiment were perceived. The surface of very soluble plaster became rough and as it was not flushed by water most of it was covered by loam. At the same time the quantity of deposited loam was relatively small and not a lot of water was filtered out of it. The bevels are therefore infrequent. Water trickled out of the sediment in drops at intervals and on some sectors the bevels are winding (Fig. 2.4.16).

The distribution of the bevels and their size are controlled by the water quantity oozing out of the sediment; their form is controlled by the inclination of the surface where the water trickles. A large amount of water regularly oozing out of the sediment incises densely distributed, linear and (in respect to breadth) shallow bevels; when there is less water the bevels are less fre-

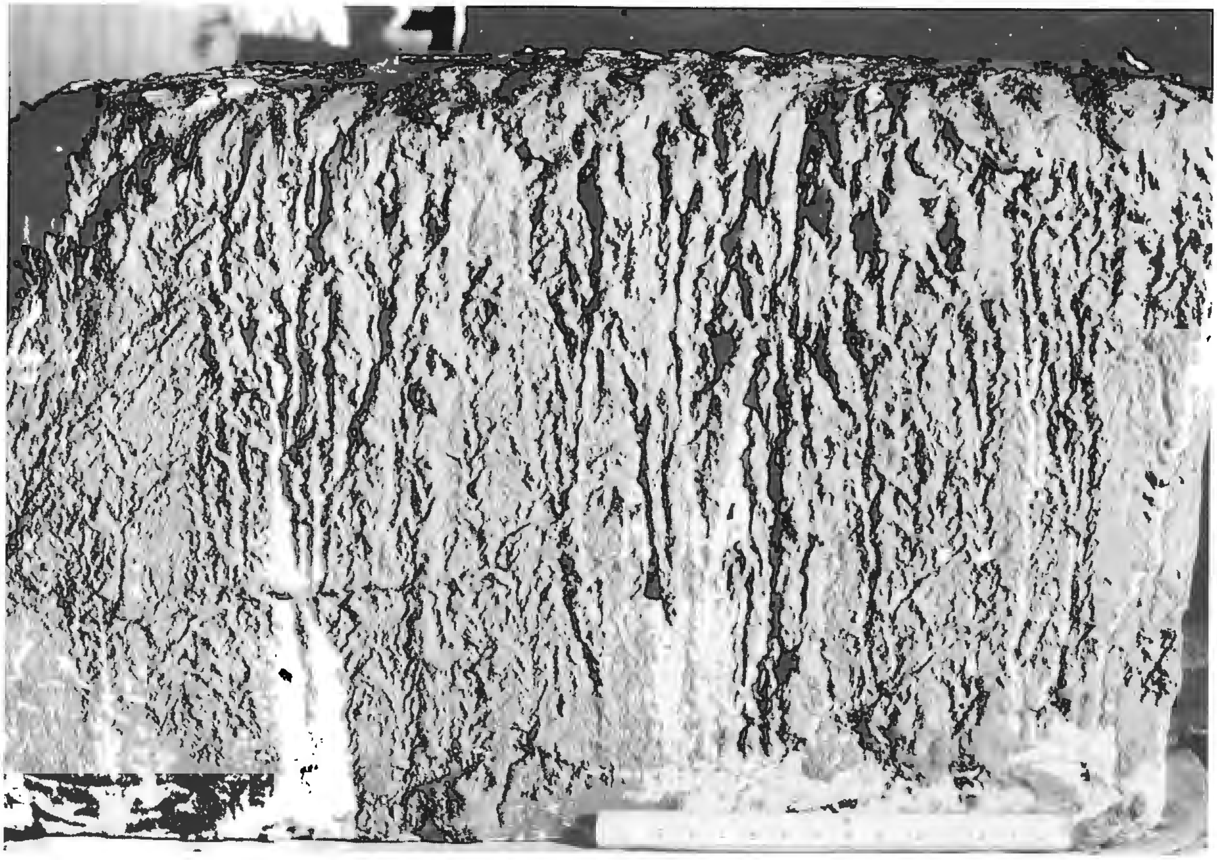
2.4.14a Corrosionally transformed below-sediment bevels, Križna Jama

2.4.14b Below-sediment bevels rounded by mechanical acting of water stream, Ponikva v Jezerini (scale = 15 cm)

quent but deeper, and sometimes winding. The decrease of trickling water may be evidenced by small bevel inside a larger one. The water quantity is controlled by the amount of sediment. The origin of bevels on the cave walls is thus controlled by relatively large amount of sediments and in particular by frequent flooding.

2.4.4. BELOW-SEDIMENT FLOOR PITS

These are mostly small hemispherical pits (Fig. 2.4.17a), about 5 cm in diameter on average. Larger pits are less frequent. In Kompoljska Jama (Fig. 2.4.17b) the pits in the wall corrosion notches are up to 20 cm long. All deeper pits are characterized by vertical walls in the upper part and small widenings just above the bottom; the bottom is rather flat. The pits commonly developed above the river bottom, either on gently inclined walls or on rocky blocks and boulders. The pits are due to corrosion below the sediment that is deposited on concave parts of the rock. At first they deepen cylindrically and when they are deeper more sediment is deposited which is not restored and which prevents the contact of water with the rock. Above the sediment water remains after retreat of flood waters. This is why corrosion prevails on the lateral sides of the pits. Densely distributed pits tend to unite and among them single pendants remain only. The pits occur only in passages where seasonal flood waters appear. The water transports the sediment from the walls, or the sediment remains on some concave points only. Slow water flows frequently deposit the sediment in thick layers and they prevent the contact with wall (Griška Jama). Due to high waters that seasonally wash the passage perimeter, the formation of below-sediment pits is often connected with formation of other features. They develop on the bottom of scallops and fast flows may add outflow tails (Fig. 2.4.18). Mechanical erosion frequently cooperates in their formation, polishing the perimeter and seasonally incising them.



2.4.15 Channels on vertical wall of plaster block (scale = 15 cm)

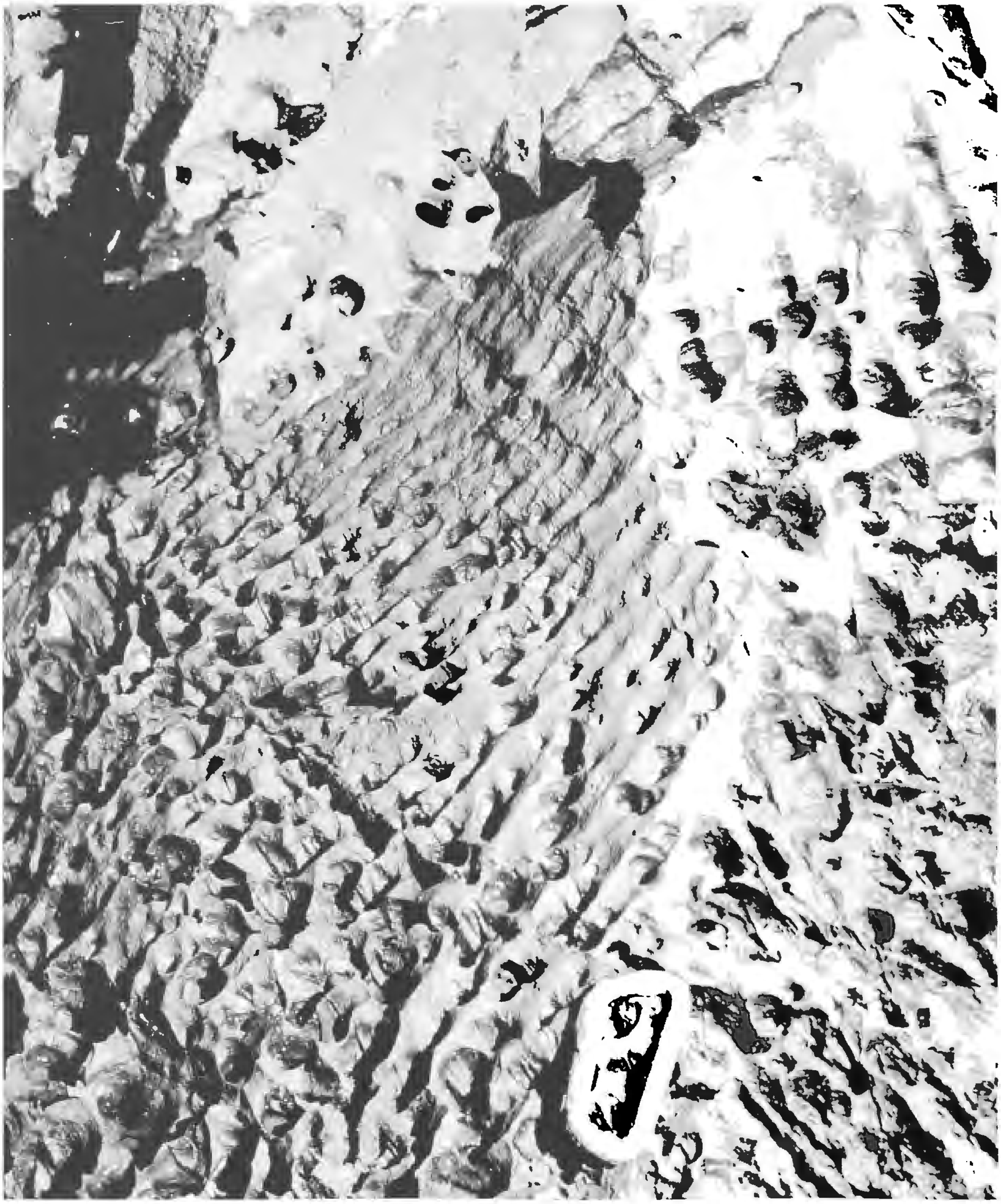
2.4.5. CEILING POCKETS DUE TO WATER OOZING OFF THE SEDIMENT

I presume, according to the location of ceiling pockets on a block of rock protruding out of upper part of the wall in Južni Rov of Zelške Jame and to their shape - they are namely bell-shaped, narrowed upwards into a small tube (Fig. 2.4.19) - that they were formed by percolation water that oozes out of fine-grained sediment. This sediment is deposited by seasonal high waters at the ledge at the bedding plane. Water percolates through the fissure and the ocket is formed at its mouth. Such oozing is possible only when the water restores the sediment; it means that water flow transports the old sediment and when the flow reduces it deposits anew. When sediment is continuously deposited the ledge would come encrusted by thicker layers and the contact of water and fissure would be obstructed. In the experiments in plaster (Chapter 2.5.1) ceiling pockets developed when the water was oozing out of a sponge covering the plaster slab (Slabe 1990, 181). I presume that the process described only transformed the pockets. The nearby ceiling is covered by pockets but they are shallow, and hemispherical. The ceiling was at first formed by the water flow. With time the water seldom reached the passage; it reduced and deposited the sediment. The water oozing off the sediment after the retreat of high

2.4.16 A section of channel on vertical wall of plaster block waters transformed the pockets along the fissures, primarily by deepening them.

2.4.6. BELOW-SEDIMENT ROOF PENDANTS

Below-sediment pendants appear in passages seasonally flooded by a slow water flow which deposits thin layer of fine-grained sediment at the ceiling and on the overhanging walls. In Črna Jama within the Postojnska Jama system the perimeter of the siphon in Krožni Rov is shaped in such a way. Roof pendants are also found in periodically flooded passages of Vodna Jama in Loza and in Zelške Jame. A film of deposit covers rough rock. The pendants (Fig. 2.4.20), up to 1 cm long, are due to gravity accumulation of the sediment on the protruding particles of the rock. Thus they are protected against corrosion. Downwards on the rocky perimeter the pendants gradually pass into below-sediment pits. Pendants appear when the passage is flooded



2.4.17a Below-sediment floor pits, Najdena Jama

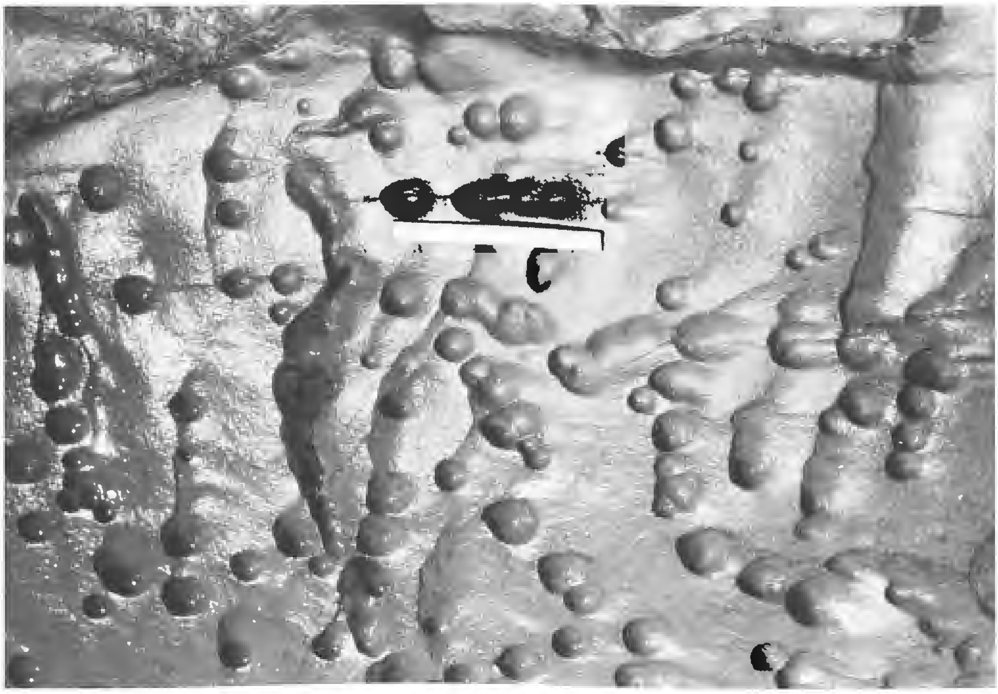
2.4.17b Below-sediment solution cup, Kompoljska Jama (scale = 15 cm)

and pits when it is dry again as the corrosion acts only at the contact with humid deposits.

Ceiling below-sediment pendants occur as a result of water trickling from the ceiling fissures. The water transports fine-grained deposit and spreads it in a thin film all over the ceiling. On the points of pendants a thin layer of loam deposits and impedes solution. Such are the pendants on the dolomitic ceiling in Dvorana Jeze in Turkova Jama.

2.4.7. CORROSION NOTCHES AND NICHES ON THE WALLS

Wall notches appear at the water level horizon when the water slowly flows above the fine-grained sediment. The incision of water into the walls at the sediment deposited in thick layers on gently sloping surface of the rocky perimeter is characteristic. The deposit protects the rock against corrosion. Thus the lower parts of the passages with a circular cross-section may be widened. The water enlarges their lateral sides. Smaller wall notches are frequent along the bedding planes in the passages that were formed parallel to the rock bedding.



2.4.18 Below-sediment pits due to water flow, underground Pivka (scale = 15 cm)

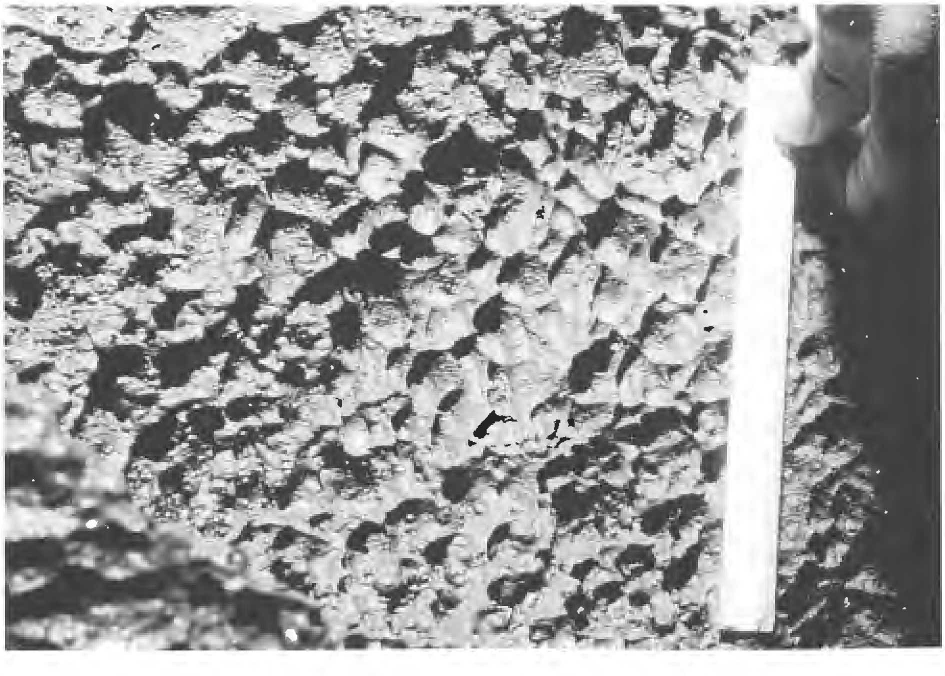
2.4.19 Below-sediment ceiling pockets in Blatni Rov, Zelške Jame

The water dissolves the rock most at the bedding planes and deposits sediments on upper parts of the beds. The sediments protect the rock against corrosion. The semicircular notches are truncated at the bottom. In Kompoljska Jama (Fig. 2.4.17b), through which seasonally fast water flows, such notches are up to 0,2 m deep. On them below-sediment pockets occur. In Vodna Jama in Loza there are notches along the bedding planes and longitudinal fissures; seasonally slow water flows in the cave and deposits more sediments, up to 1 m in thickness. On their borders the below-sediment bevels, up to 0,15 m deep, are incised.

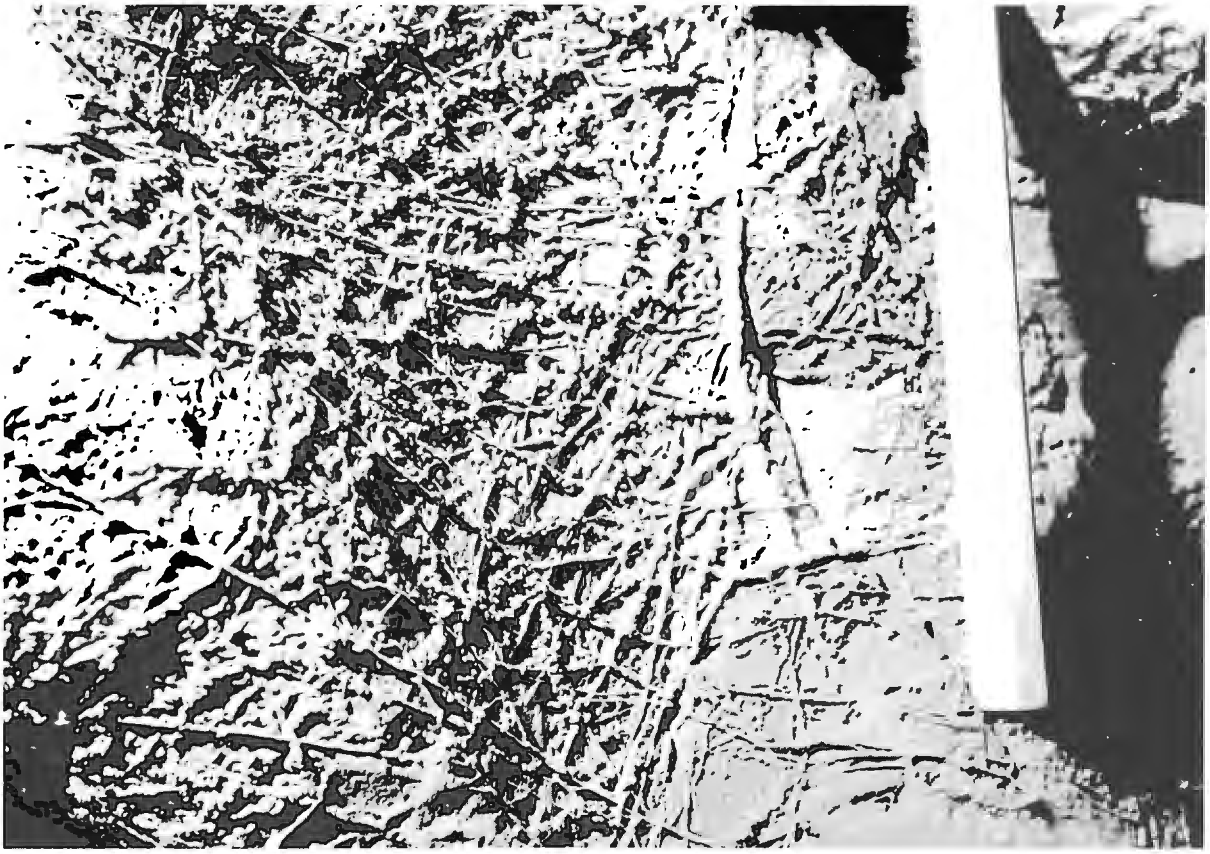
Wall niches occur due to meandering of slow free-surface streams along the fine-grained sediment (Chapter 2.3.6), as for example in Blatni Rov of Križna Jama.

2.4.8. THE SURFACE OF ROCKY FEATURES AT THE SEDIMENTS

The relationship between the efficiency of corrosion and the structure of the rock is the most important factor deciding whether the surface of rocky features is smooth or rough. The corrosion acts proportionately to the entire surface of relatively homogeneous rock and makes it smooth as the jutting particles expose larger surface but it does not flatten larger irregularities. Thin calcite veins thus form a box-work (Fig. 2.4.21). Large fossils and silicate particles protrude out of the rock and as a rule the most rough is that surface of dolomite composed of variously sized crystals and calcite veins.



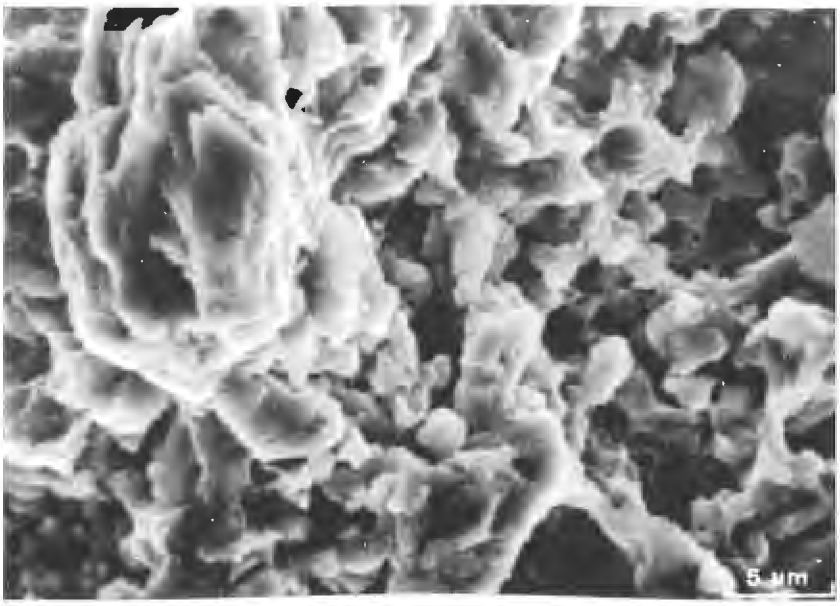
2.4.20 Below-sediment roof pendants in Krožni Rov, Črna Jama (Postojnska Jama)



2.4.21 *Box-work*

Under magnification by electron scanning microscope all the surfaces of rocky features, although smooth to the naked eye, are unsmooth in detail (Fig. 2.4.22). Some larger crystals or cluster of small ones protrude out of the rock. Thin roughness is due to grained rock structure. The flow in the bevels is too weak to tear the protruding crystals off the rock. The characteristic thinly rough surface of the rocky features at the sediments suggests their corrosional origin. The rock solution is accelerated by fresh flood waters that come mostly from non-carbonate rocks. The water may become aggressive via sediments as they often contain organic matters (Slabe 1989 b, 212) and carbon dioxide is built up from the carbon.

The rocky surface that is (was) covered by the sediments is frequently weathered. On it non-degradable and slowly degradable substances remain. The weathering is due to slow flushing of solution products. The dolomite becomes soft at the contact with clay according to Renault (1968, 561, 562) the acid, unsaturated fine-grained sediment absorbs Ca_2^+.



2.4.22 Below-sediment rocky surface

2.5. Rocky Features due to Trickling and Dropping of Water

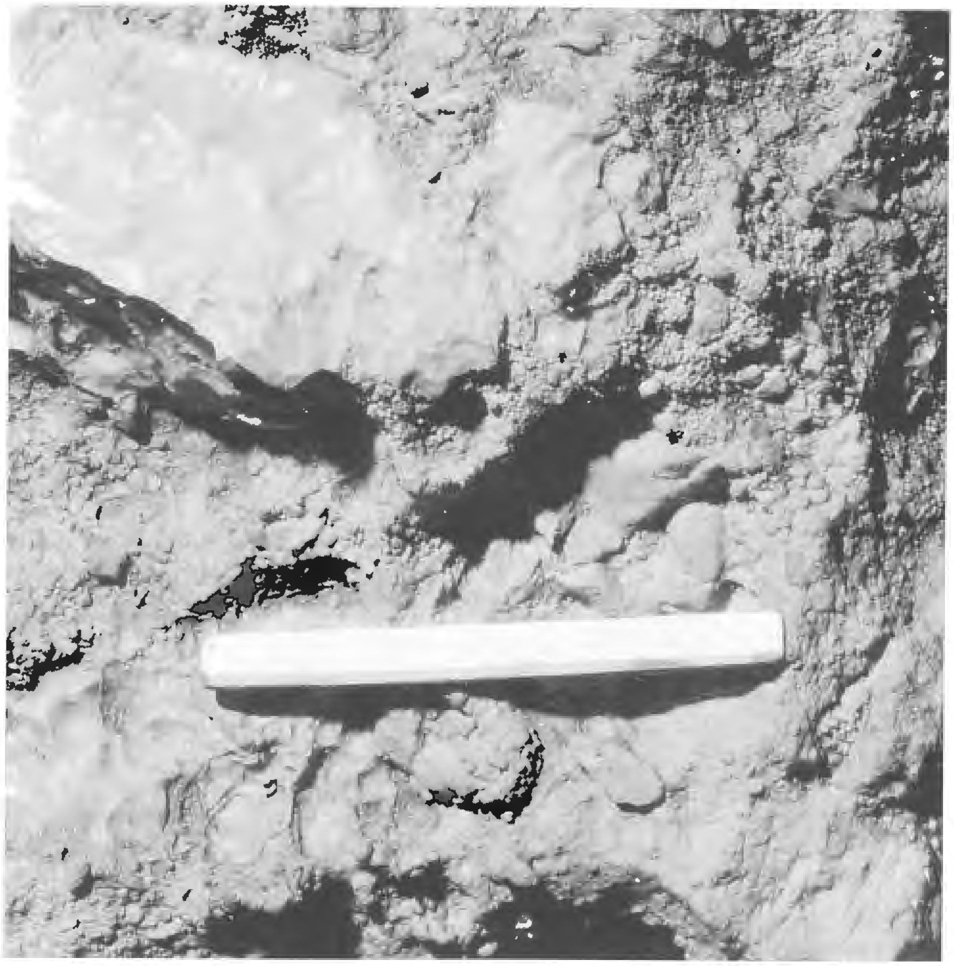
Infiltrating water trickles down the cave walls or drops fall off them. Trickling means a small amount of water or a water film. When more water flushes the walls there is vertical water flow.

Such rocky relief is characteristic of mountain caves, either shafts or cave systems, or for polygenetic caves (Ciganska Jama, Volčja Jama) and for entrance potholes into lower lying caves (Logaška Jama, Dimnice). Such relief is found in lowland caves below a flysch cover (Kamenšca). Gams (1975, 114) determined the temperature between 6 to 7°C as a threshold when the non-active and aggressive percolation waters pass into flowstone-depositing water in the caves that are above 1000 m a.s.l. In high mountain caves the rainwater has lower hardness; this is why it usually does not deposit flowstone (Gams 1963a, 10). The carbonate level and solvent capacity were determined for the sample of the percolation water captured from the wall in lower part of Ledenica na Dolu in the time of low waters (October). The water contained 95 mg $CaCO_3$/l. Almost the same level of $CaCO_3$/l (96 mg) was recorded when the added calcium carbonate (pro analysi) was measured. The water was on the limit of corrosion activity. One may conclude that larger amount of trickling water coming directly from the surface is more efficient in its formation capacity. In caves where the walls are covered by ice, the water from melting ice may be efficient too. However it is true that the quantities of such water are moderate. In shafts the water spreads out in a thin film or spray, enlarging the shaft to a diameter much greater than the breadth of a canyon that would be produced by the same amount of flow (Palmer 1982, 190).

2.5.1 Wall channels, Kamenšca (scale = 15 cm)

The trickling water flows over various rocks which are frequently fractured and differently inclined. A changing amount of water either flushes over large surfaces of the rock or the water reaches the rock at certain points only. When there are no substantial obstacles in the rock the water film rather uniformly spreads over the rocky surface (ceiling pockets) or the water converges into streams (bevels).

a) On a vertical surface which may be smooth, frequently occur elongated pits from 10 to 30 mm long and from 5 to 10 mm wide if the rock is homogeneous. They are connected into vertical sets. On a slightly inclined surface (up to 20°), where the water starts to converge into small streams, there occur shallow, semicircular half-tubes, 1 cm in diameter at the most. These half-tubes are frequent as well, on inhomogeneous rock in particular, and they are dissected into niches (Fig. 2.5.1). The niches are due to water trickling down the inhomogeneous rock. Less soluble particles of fossils or larger crystals in the rock remain as ridges. Small half-tubes often make a part of the perimeter of larger semi-circular channels, up to 15 cm in diameter. They developed below the fissures through which a considerable amount of water flows. The trickles of percolation water at particular points have shaped larger vertical semi-circular channels in Smoganica. Among larger channels there are distinctive ridges widening outwards and suggesting fast linear solution of the walls. The origin and development of half-tubes is mostly controlled by the structure of the rock where the water trickles down and by joint frequency. The more homogeneous the rock is the more the half-tubes have regular shapes. In Smoganica the contact between coarse-grained and fine-grained limestone breccia does not play a visible role in the features; however the surface of the first mentioned is more rough. Calcite veins protrude out of half-tubes surface in Bazinova Jama near Podlaški Topoli. In Jama R3 on Podgorska Planota nummulites protrude out of small half-tubes in Palaeogene limestone. Some of them have kept weak attachment points only. In similar conditions alveolines dissect the rocky surface in Brezno near Škrklovica. On the walls of the shafts in Velika Ledenica in Paradana, consisting partly of dolomite and partly of limestone, there are no typical features due to percolation water. Angular rocks protrude out of the dolomite (Fig. 2.5.2). The surface of limestone is more smooth,and there are pits in it. The clusters of recrystallized dolomite crystals predominate over the



2.5.2 Aven wall at the contact of limestone and dolomite, Velika Ledenica v Paradani (scale = 15 cm)

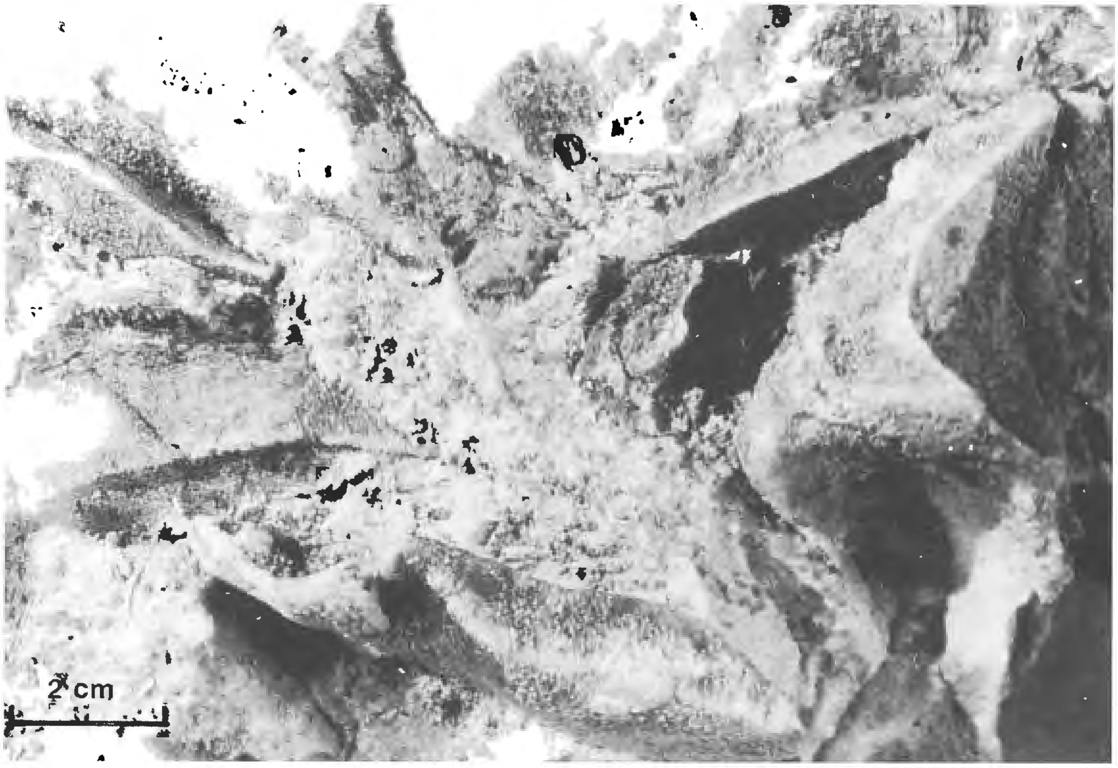
relatively weak influence of trickling water. In Čo Meander at Kanin where huge fossils protrude out of the wall (Fig. 2.5.3) there are no characteristic traces of percolation water. On extremely fissured rock the shapes of half-tubes are scarcely visible. Within fault zones narrow and thinly indented cusps developed and protrude out of the walls (Ledenica na Dolu). Not only trickling water but also weathering of fractured rock transform their surface. The vertical surface of rock that is homogeneous and not fractured is smooth. A thin film of water trickles down the cave walls in supercritical laminar flow at 0,3 to 2 m/s velocity, and causes the development of vertical walls. When the water amount increases, the water leaves the wall and gathers into small waterfalls, the velocity increases and reaches the supercritical turbulent regime. In such a way the vertical walls develop still more as the hydraulic jumps occur along the obstacles causing erosion (White 1988, 168, 297). The water tears off the larger crystals of rock protruding out of the walls. Below the shafts, fine-grained sand is accumulated (Zupan & Mihevc 1988). On horizontal sectors of the shaft walls shallow solution cups develop due to rock bedding (Fig. 2.5.4). The erosion is the most prominent here due to vertical walls above.

b. On gently inclined wall larger, and in particular deeper runnels shaped in letter V prevail. The more gentle is the wallslope, deeper they are. They reach up to 10 cm in depth. The runnels are due to the larger amounts of water gathered in some places. On surfaces that are slightly inclined and with a small amount of water, small, meandering runnels, 1 cm in diameter, occur (Ciganska Jama near Predgriže). When the surface is densely fissured and more steeply inclined (80^0) the niches, wider on the lower part, occur (Fig. 2.5.5). The fissures accumulate the trickling water.

c. Shallow niches (Fig. 2.5.6), connected into networks, occur due to water trickling down overhanging inhomogeneous walls (from 90^0 to - 30^0). They are from 1 to 3 cm in diameter. On more inclined walls they are slightly smaller and their ridges accentuated. They are due to the smaller amount of water that trickles down the overhanging inhomogeneous rocks; larger amounts of water would, if the rock is appropriate, polish the wall. Small niches are transition features to ceiling pendants.

d. Solution cups, pendants and runnels develop due to water trickling over the roof.

As one may observe in Volčja Jama and in Ledenica na Dolu, in Kamenšca and in Ciganska Jama near Predgriže, the roof pendants (Fig. 2.5.7) have triangular cross-section and rounded tops. They are up to 1 cm long and wide. Under the microscope (Fig. 2.5.8a, 8b) notches may be seen in the niches among the pendants. The rock is less fractured on the pendants. The pendants develop under thin films of water that accumulate on the rock particles jutting out of the roof. However, this water is less aggressive; it even deposits from



2.5.3 Wall in Čo Meander, Kanin Mts.

the solution and thus the difference between the pendants and interlying niches increases.

In Ciganska Jama there are small runnels on the inclined ceiling (Fig. 2.5.9), with sharp ridges that are dissected into pendants. On the near horizontal sector of the ceiling there are pendants (Fig. 2.5.7). The runnels follow the fracturing of the rock surface and in the direction of higher permeability they are distributed in sets, from 10 to 15 cm in breadth. In the experiment in plaster too, when the ceiling surface was inclined the water flowed by shallow runnels from the solution cup in the direction of the surface dipping.

The conclusions about the origin of the described features were reached mostly on the basis of numerous cases in Slovene caves. We attempted, also, to confirm the explanation of the ceiling formation, and of solution cups in particular, by experiments in plaster.

2.5.1. LABORATORY EXPERIMENTS OF NICHES FORMATION DUE TO WATER TRICKLING DOWN FROM THE ROOF FISSURE

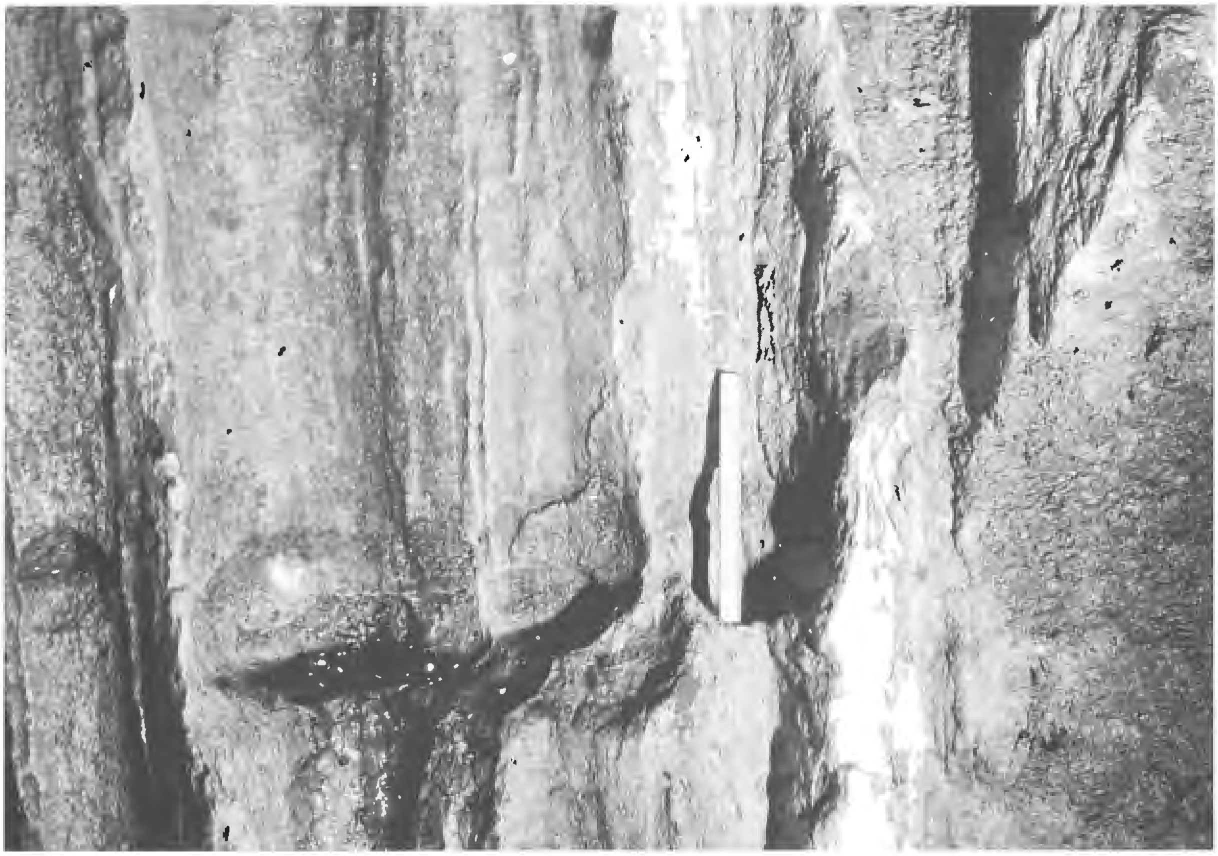
The water flowed through vertical channels, 1,5 mm in diameter, from the hollow on the top of a plaster cylinder with a flat bottom. After two hours niche already occured, 5 mm in diameter and 2 mm deep. After an hour it was 1 mm deeper but the diameter remained the same. The inlet canal started to widen and by increased recharge the niche deepened only near the mouth where a 2 mm wide and 3 mm deep concave bottom developed. The plaster is very soluble and this is why the canal enlarged. The transition from laminar to turbulent flow in water gives rise to niche initiation.

During other experiments we decreased the water inflow to reduce fast widening of the canals. The plaster was covered by sponge from which the water regularly percolated into the canal. At the mouth single drops were falling. The niche was proportionately widened and deepened. After two days, when the experiment stopped as the canal was enlarged, the niche was 25 mm in breadth and 7 mm in depth (Fig. 2.5.10). The surface of the niche was smooth.

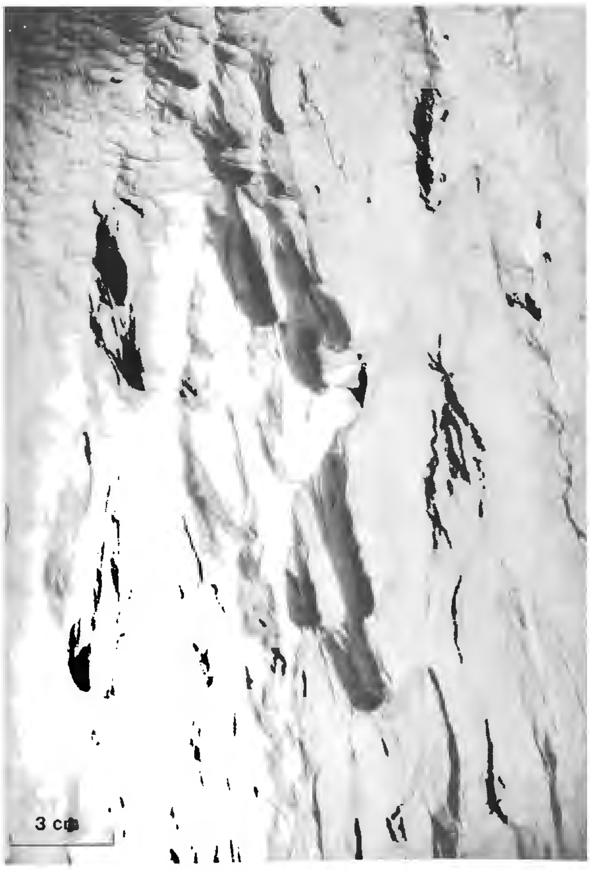
On ceiling surfaces that were inclined less than 30°, more narrow niches occurred (Fig. 2.5.11). The niches were up to 1 cm deep and continued in the direction of gradient into wider channels. Most of water percolating through the canal was drained by them. The upper border of the cups was steep.

The greatest trouble with the experiments in plaster is plaster's extreme solubility which enables the development of larger niches or runnels as the inflow canals are widened too fast. But the experiments confirmed the possibility of ceiling cups formation by percolation water.

Due to water percolation the ceiling cups developed in Volčja Jama (Fig. 2.5.12) on Nanos and in the entrance part of Trhlovca. In Zelške Jame the percolation water oozed from fine-grained sediment deposited on the lateral ledges. When the water comes from the fissure it spreads over the ceiling. The cups, commonly from 10 to 15 cm in diameter, are 15 cm deep, while in Trhlovca they are 1 meter deep, upright and bell-shaped.

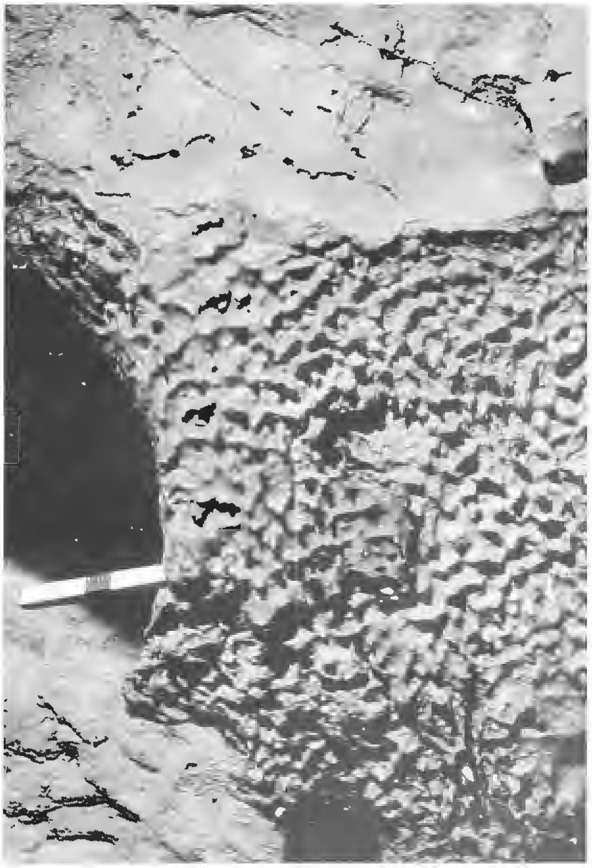


2.5.4 Wall pockets of the entrance shaft, Logaška Jama (scale = 15 cm)

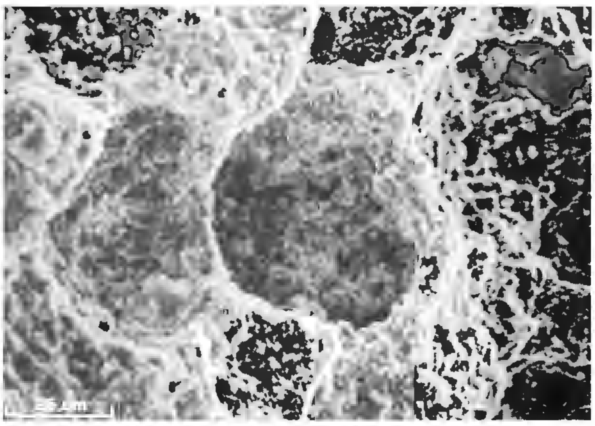


2.5.5 Pits along the fissures on the wall, Ledenica na Dolu

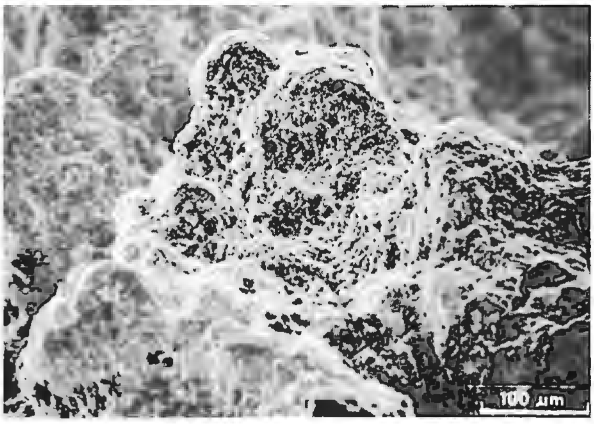
2.5.6 Pits on overhanging wall, Ledenica na Dolu



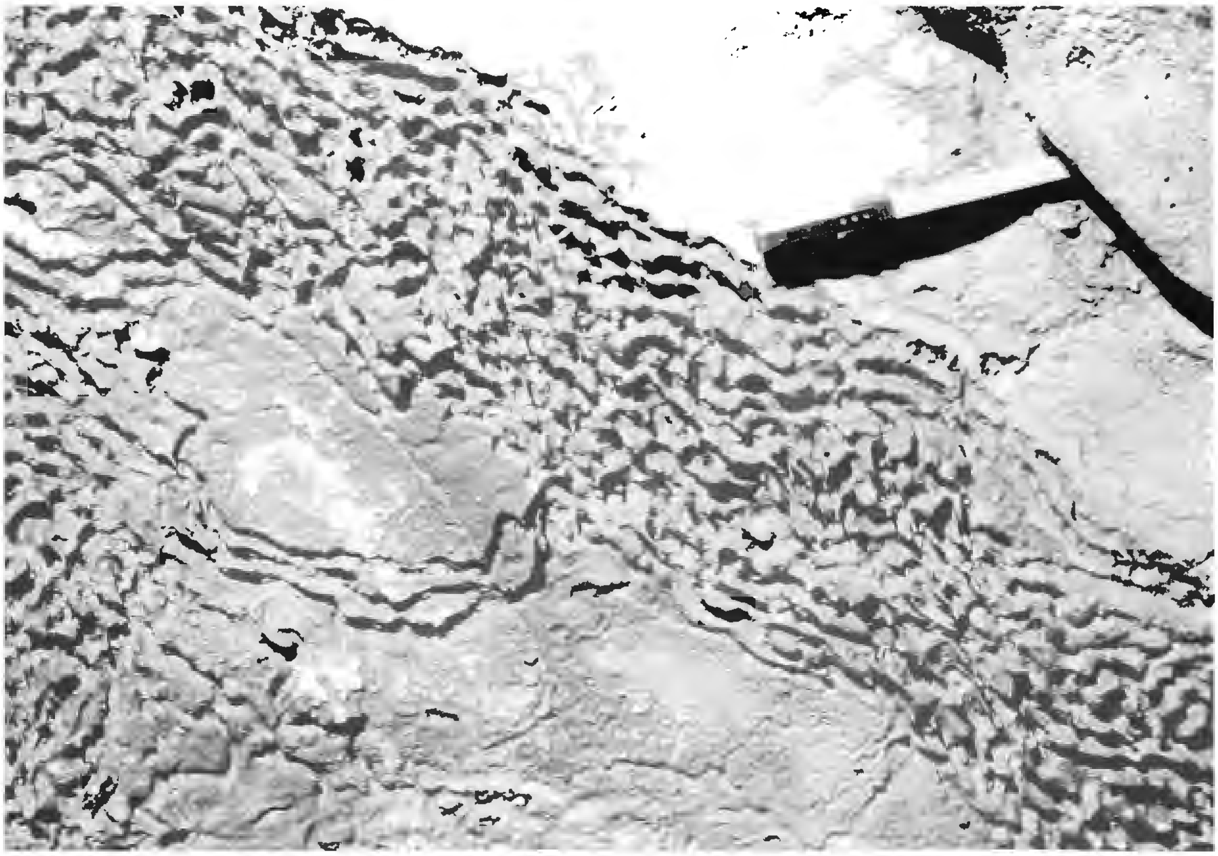
2.5.7 Roof pendants, Ciganska Jama



2.5.8a Etched surface among roof pendants

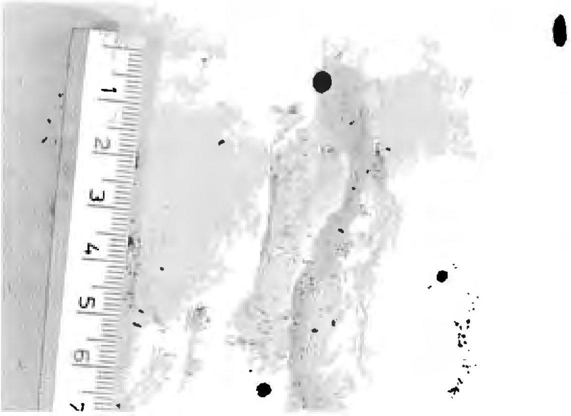


2.5.8b The surface of roof pendants



2.5.9 Ceiling channels, Ciganska Jama

2.5.10 Ceiling pit in plaster



2.5.11 Ceiling pits in plaster

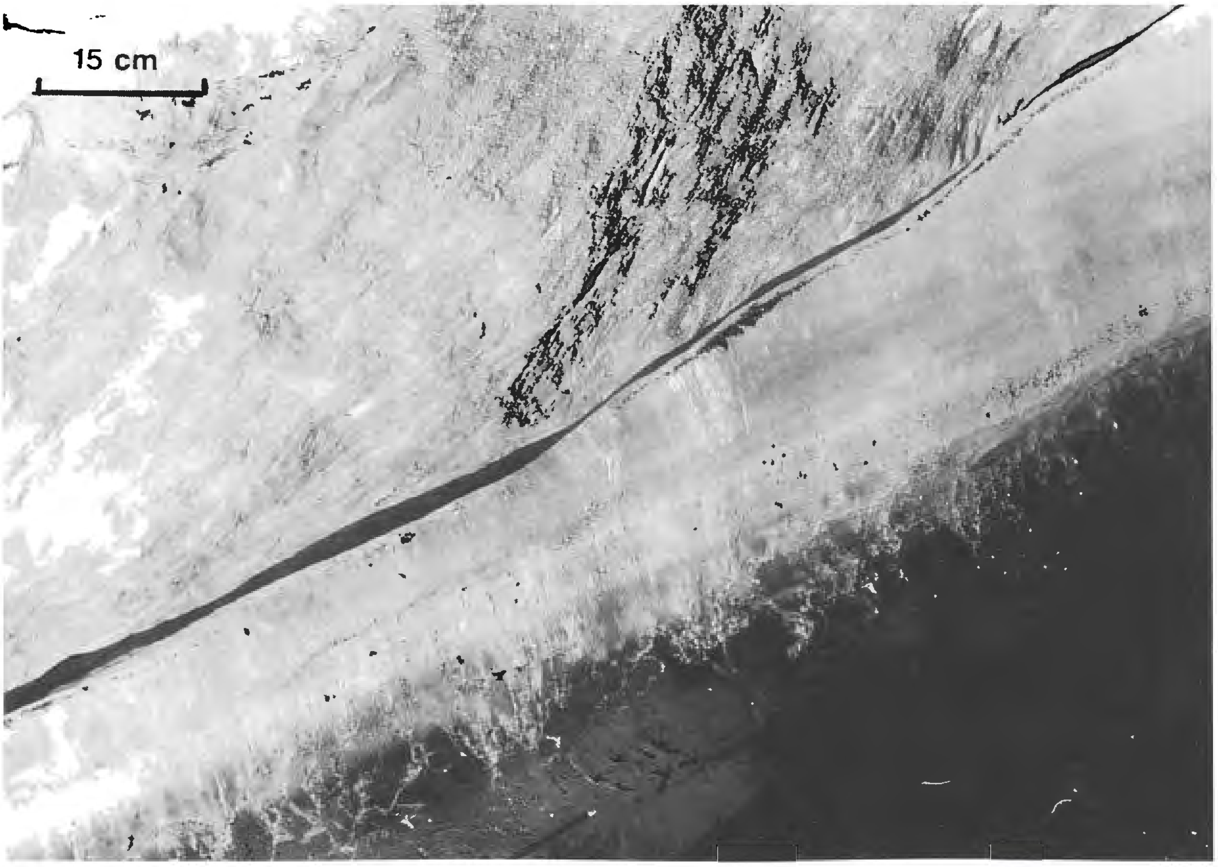
On the borders of the last ones a smaller amount of water trickles over a channel. The axis of the cups is due to gravitational washing of the surface vertical; that was confirmed by the experiment in plaster. The solution cups are composite if there are several inlets of water within a diameter of their formation. Franke (1975) stated that the diameter of the solution cups is directly related to the quantity and aggressivity of the percolation water. By increased inflow the diameter augments; by increased corrosion water capacity it is smaller but the solution cup deepens faster. On very soluble plaster the solution cups deepened faster at increased inflow. Percolation water may transform the solution cups downcut along the fissures by the eddies of the water flow. Is this the mode of origin of some deep solution cups in Logaška Jama? On the ceiling of this cave shaped by slower water flow there are chimneys due to water infiltration from the surface.

In the experiment in plaster three characteristic surfaces developed that are concentrically distributed around the inflow canal. The inner surface of the solution cup is smooth as it was rather evenly flushed by water. The smooth surface of the cup is due to gravitational accumulation of water on the protruding particles of the rock and they are faster corrosion. The medium circle is rough and pointed. The water film that covered it was thinner. The same amount of water as in the first case spread over a larger surface. The outer surface is

2.5.12 Ceiling pockets, Volčja Jama on Nanos dissected into narrow or wide but shallow bevels where the water flowed without interruption. One may conclude that the surface formation and its smoothness is due to various amounts of water flowing over the rocks of various structure.

2.5.2. FLOOR PITS DUE TO WATER DROPPING

Floor-pits develop on rocky floors to which smaller amounts of water percolating from the roof drop or trickle down. Gospodarič (1985, 14) named the features occurring at the end of Obhod in front of Modrijanova Dvorana corrosion holes. The bottom of the floor pits is hemispherically rounded, from 5 to 15 cm in diameter and they are up to 10 cm in depth. Larger floor hollows into which a vertical water stream falls and eddies the material accumulated below the walls, I count among the potholes. Such features occur below the chimney in Ledenica na Dolu (Slabe 1990, 193); larger ones are found below all the rocks in the river beds of streams (Beško Ocizeljska Jama, Ponikve v Odolini). I tried to simulate the way of forming floor pits by experiment in plaster to which the water was dripping from 1,2 m. At first a hemispherical pit occurred, 1 cm in diameter. The drops, falling to its bottom, are diffused. The perimeter of the pit is therefore smooth and the surface around it is thinly washed due to water spray sprinkling of the pit. During the pit's increasing it widened at its lower part. This is the result of the pit's walls indentation due to spraying drops from the bottom. During the experiment when the drops falling on the plaster increased, or the drops were more frequent or even collected into a trickle, the water accumulated in the pits, eroded the walls and finally got through into outflow half tubes. The water mostly erodes the rock mechanically by its mass, but when there is too much water accumulated in the pits it also dissolves the rock. Upright pits that have the upper parts of their walls steep and the lower parts more gentle developed on inclined surfaces of plaster too. Hence, the decisive factors in the pit's formation is the mode of inflow and the amount of water, the height of the water fall and the inclination of the surface where they develop. Old floor pits, partly filled up by fine-grained sediment may be found on the rocky floor of Ciganska Jama near Predgriže. They may be ranged among the below-sediment pits, but the shape of hemispherical bottom indicates the origin due to water dropping and, consequently shows the polygenetic character of the cave. In caves with thin roofs the water may come to the pits from drips out of the soil and it covers the bottom (the shaft Morska Lilija). This is why they are a bit enlarged above the bottom.



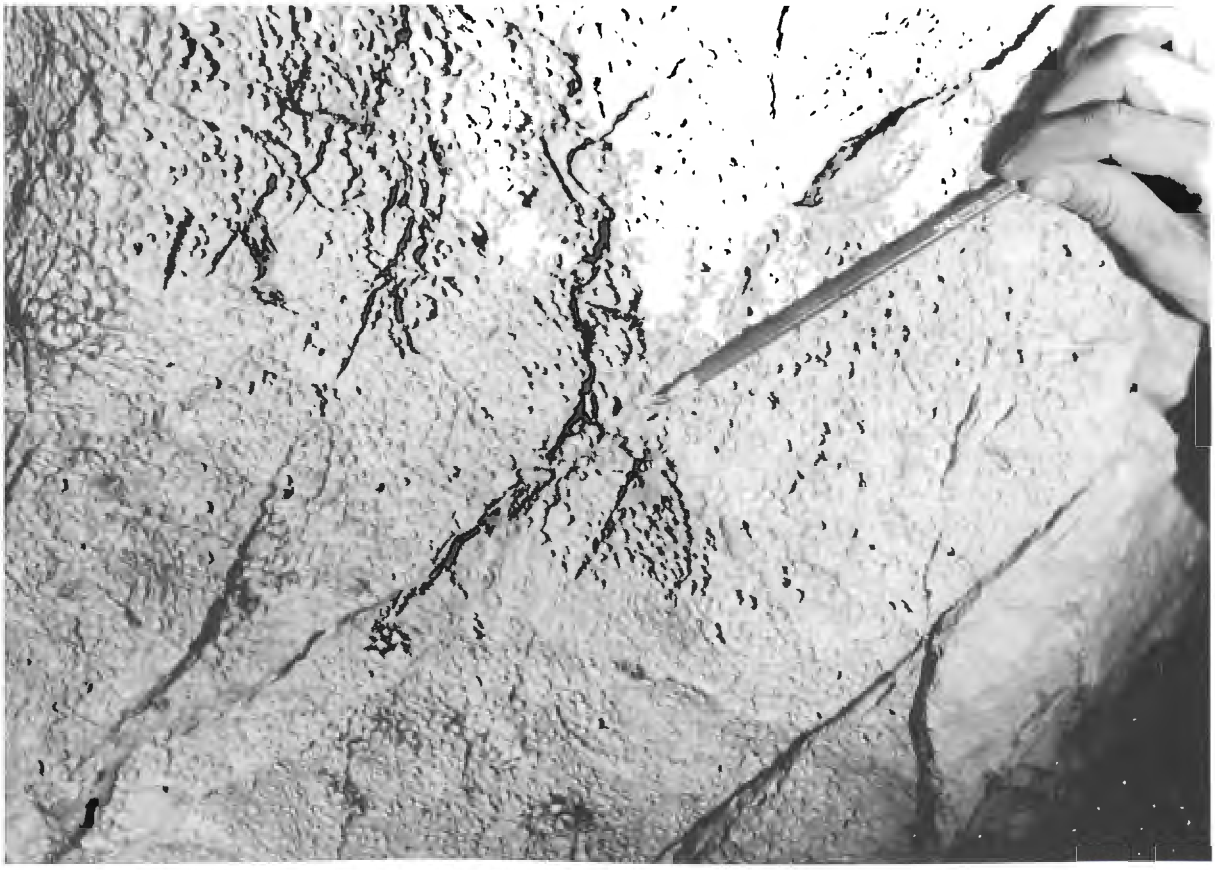
2.6.1 Polished wall of below-ice notch

2.6. Below-Ice Rocky Features

The perimeter of caves moistened by the percolation water and cooled by cold winter air is often covered by ice. Smaller amount of frozen humidity on the walls causes weathering and breaking of the rock mostly. Thicker ice cover transforms the rock by corrosion when the ice melts. The water in the ice cave Ledenica na Dolu had rather low carbonate hardness (18 mg $CaCO_3$/l) and when we added calcium carbonate the hardness augmented by 4 mg. The low hardness of glacier waters was stated by Gams (1967, 55).

In the entrance part of Velika Ledenica in Paradana, which is covered by ice almost the whole year, the walls are rounded and rather smooth. The lower part of the passage where the ice remains the longest is slightly enlarged and the walls are overhanging (Fig. 2.6.1). The notches below the ice are due to corrosion at the contact with the ice that melts near the wall. Smaller pendants have a larger surface exposed to corrosion and they disappear. The rock is hence smooth and along the fissures only slightly concave. The nearby, rather fractured rock that is not covered by ice weathers and the perimeter is composed of smaller or larger, rather even planes. Frequently below the ice which is the most thick just at the bottom of the passage, the rocky boulders are transformed from angular into rounded form (Volčja Jama). On the ceiling of the already mentioned entrance part into Velika Ledenica in Paradana there are small niches on solid rock (Fig. 2.6.2). I suppose that they are due to the melting of thin ice cover which covers the ceiling of the passage. Short-term moistening of the rock by a small amount of humidity caused the solution of the most soluble parts.

When the ice melts traces of water trickling down appear - these are below-ice half tubes (Ledenica na Dolu) and wall niches. The below-ice half tubes are relatively large. By concentrated water inflow the half tube would only deepen but as it is frequently covered by ice it widens also.



2.6.2 Below-ice pits

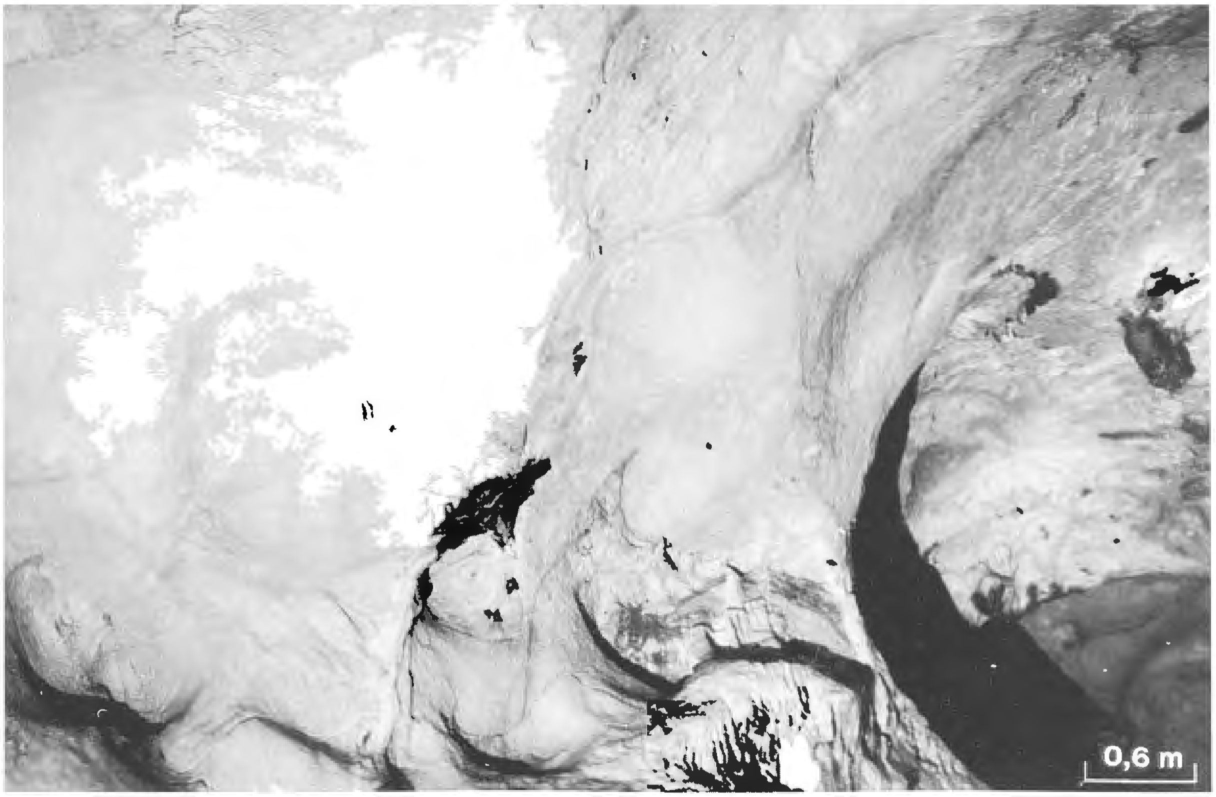
2.7. The Formation of Rocky Perimeter due to Condensation Moisture

In almost all caves where the air circulates the humidity is condensationed on the rocky perimeter. This condensation is due to cooling of the warmer air at the contact with colder air or circulation of warmer air over the colder walls. When warmer, relatively moist air cools, the surplus of moisture is deposited on the rocky perimeter. The condensation is more in caves where more air penetrates (Trhlovca) or where a considerable water stream flows from the surface (Škocjanske Jame, Postojnska Jama, Križna Jama). I have measured the quantity of condensation and proved it by air temperatures and air circulation in a closed passage of Komarjev Rov in Dimnice (Slabe 1988, 84).

The Italian authors Cigna and Forti (1986) studied this problem in detail and they caution that the importance of condensation corrosion is discriminated. Their studies are not limited to karst caves only but they present the processes and features in thermal caves, in caves where the corrosion is accelerated by strong acids and in lava tubes and ice caves. They divide the features due to condensation corrosion into scallops, solution cups and features similar to ceiling channels. In karst caves the air exchange with the external air is decisive for the corrosion, in particular the penetration of warm summer air. By way of example they have taken a thermal cave and calculated the amount of dissolved limestone in the condensed water.

Andrieux (1970) studied the climatic conditions controlling moisture condensation on rock and the mode of this condensation. If the base is dry the drops separate at first; if it is humid, a water film occurs. Martini (Renault 1968) presents corrosion by condensing out of warmer air flow on a cooler ceiling and forming ceiling channels and solution cups. Renault (1968, 571), citing Martini's statements, stresses that the condensation corrosion is possible in the entrance parts of the caves only. Pasquini (1975) mentions the role of percolation water which augments the humidity in the passage and controls the condensation on the walls. To the study presenting Pasquini's (1975) hypothesis, Bögli added an example of condensation corrosion at the contact of air masses with different temperature and 100% of humidity.

As air moves into a cave it is either cooled or warmed by contact with the cave walls. At the same time moisture may either evaporate from or condensation on the walls. Thus both direct heat transfer between wall and air and latent heat absorption or release are important in determining cave air temperature distributions (Ford & Cullingford 1976, 337). Gèze (1965, 135) too stresses the importance of corrosion due to condensed moisture. The percolation water is saturated and in the passage it deposits flowstone and releases CO_2 which is absorbed by the moisture in the air, and by



2.7.1 Large scallops in entrance part, Trhlovca

2.7.2 Scallops on the roof between Šumeča Jama and Tiha Jama, Škocjanske Jame

increased temperature it becomes aggressive. Rocky laces and solution cups appear, and old flowstone is dissolved. He demonstrates that the condensation may be abundant, by an example from the Trou de Glou where a virtual stream resulted from a large amount of warm air from which the moisture separated. Ford and Williams (1989, 303) stated that condensation corrosion could be biogeneous where there is a large number of cave bats on a leeside.

The results of microclimatic factors in Dimnice were studied by Habič (1985). Due to exchange of the internal and external air controlled by the condensed moisture the traces of weathering are seen on the speleothems. The condensed moisture can freeze in a cold period. The condensation zone may be identified by characteristic changes on the speleothems far into the cave interior, even in the areas where no freeze-thaw effect is felt.

2.7.1. CEILING SOLUTION CUPS, LARGE SCALLOPS AND CEILING HALF TUBES

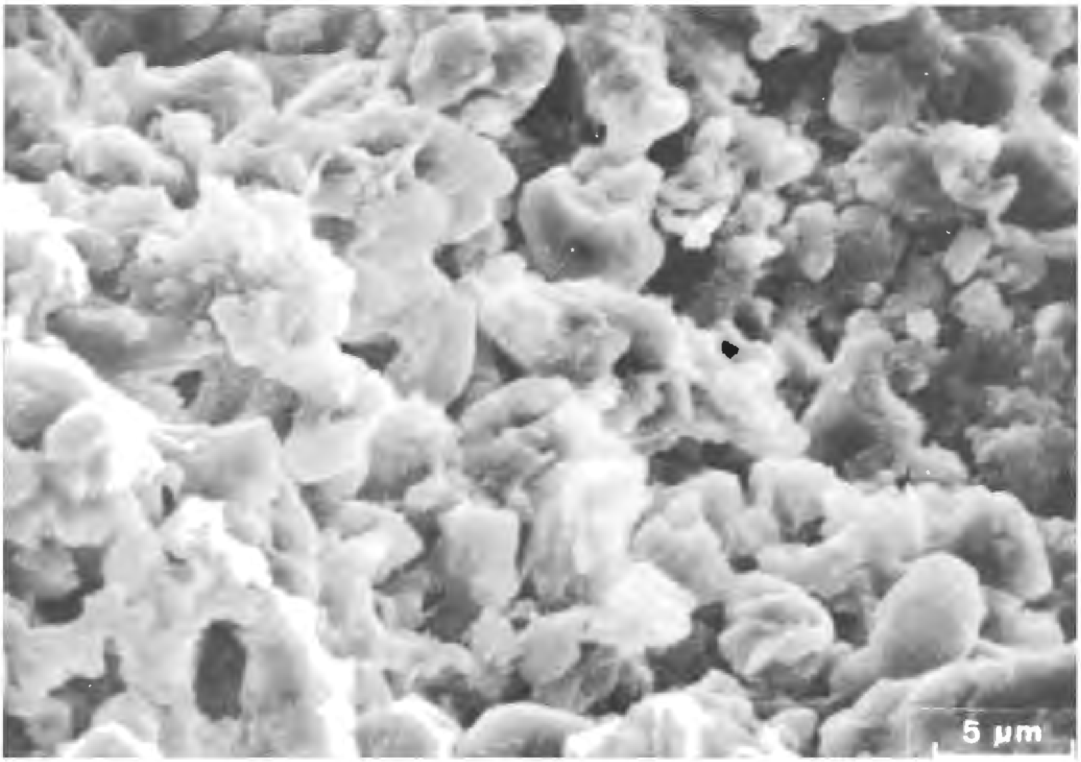
The efficiency and properties of rocky relief formation due to corrosion caused by condensed moisture depend mostly on the quantity of moisture and on the air circulation direction. I suppose, that solution cups, scallops and ceiling half tubes developed due to air circulation though I do yet have proofs, for except less prominent rocky features and the humid rocky perimeter.

Solution cups (Fig. 2.7.1) on the ceiling of the entrance part of Trhlovca cave are 1 m in breadth and 0,3 m in depth. On the concave parts of the ceiling they look similar to a scallop network. Their surface is rather smooth and moistened, and it shows signs of fresh corrosion. In the final part of Tiha Jama, above Šumeča Jama in Škocjanske Jame, there is an abundant amount of condensation on the ceiling and it is dissolving the flowstone. Shallow and wide scallops (Fig. 2.7.2) occurred there. The air from Šumeča Jama, warmed by the underground river Reka, warm in summer, rises and circulates into Tiha Jama; at the bottom, cooler air flows out of the passage. Such air mass circulation yields high condensation. One may take into account the importance of evaporating organic substances which were transported by the polluted river. The size and the shape of shallow and large scallops are due to typical air circulation. The faster the air circulates, the smaller are its eddies.

Half tubes occur due to slow discharge of warmer air below the ceiling of the passages in the entrance part of Trhlovica there is a shallow, semi-circular half tube, 1 m in breadth in the passage, remote from the direct external influences. Its surface is more rough than the nearby rock.

2.7.2. THE ROCKY SURFACE ETCHED BY CONDENSED MOISTURE

Condensed moisture often transforms old rocky features and this may be seen on their surface. The rocky surface exposed to the condensation corrosion may be divided by the naked eye into smooth, rough, and weathered. Under the magnification of the microscope it is in all cases rather rough (Fig. 2.7.3). The smoothness or roughness of the surface is controlled by the relationship between the corrosion efficiency, which is mostly due to the amount of moisture separated from the air, and the inhomogeneity of fractured rock on which moisture is deposited. On the rock where there are larger insoluble inliers there are no characteristic traces of air circulation, although it is evident that the amount of moisture is considerable. In the entrance part of Zadlaška Jama there are pendants on the roof, up to 10 cm long and indented. These are the remains of a recrystallized, partly soluble deposit that combined with the carbonate rock and protected it against solution. Single coarse-grained calcitic veins protrude out of the walls also. They too are less soluble than the nearby rock. Smaller shallow niches on thinly weathered breccia are due to soluble parts of the rock (Fig. 2.7.4). In Medvedji Rov in



2.7.3 Rocky surface, etched by condensation corrosion

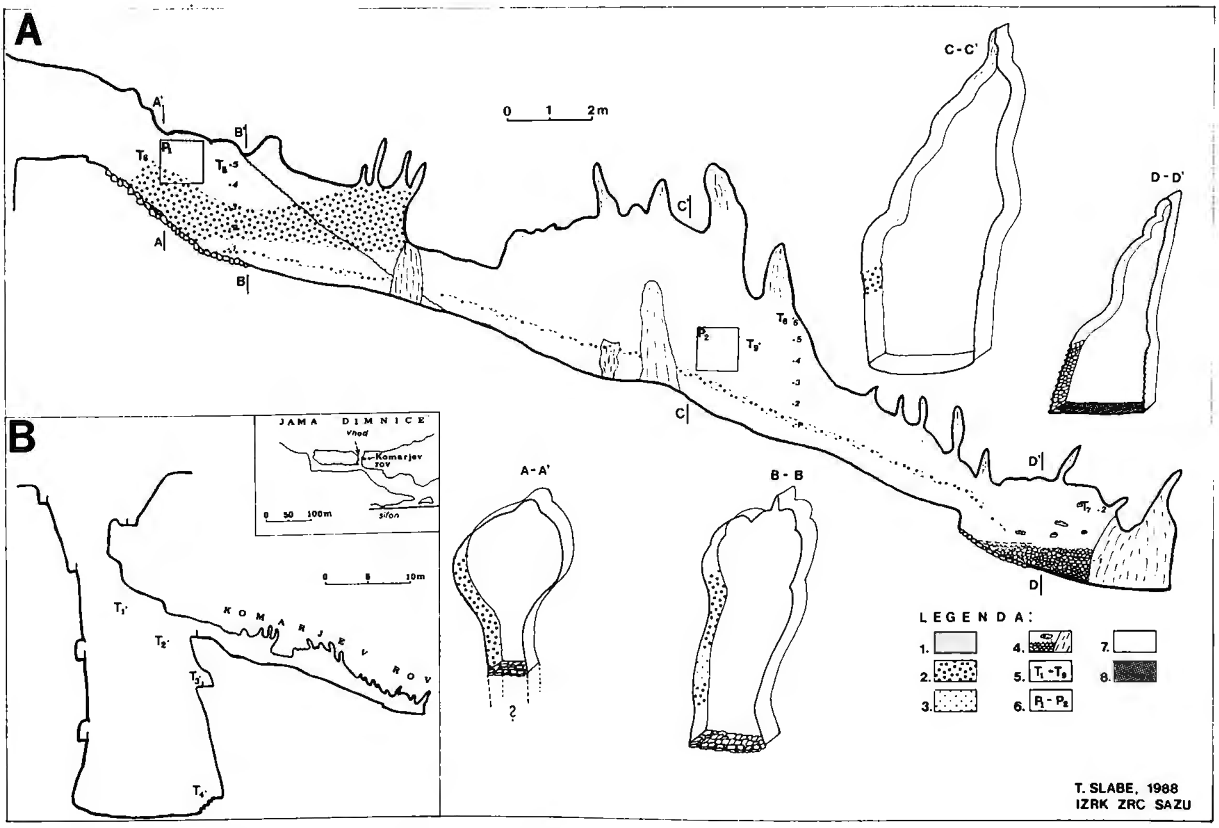
Križna Jama there are calcite veins - boxwork - protruding out of the wall due to moderate condensation corrosion (Fig. 2.7.5 they are less soluble than the surrounding micritic rocks. In Križna Jama and in Golobja Jama there are elongated notches up to 10 mm deep, connected into a network on the walls and ceiling. There is a lot of condensed moisture and the solution is washed away. In Golobja Jama the flushing is increased by the water that seasonally percolates through the thin roof.

The surfaces exposed to condensation moisture

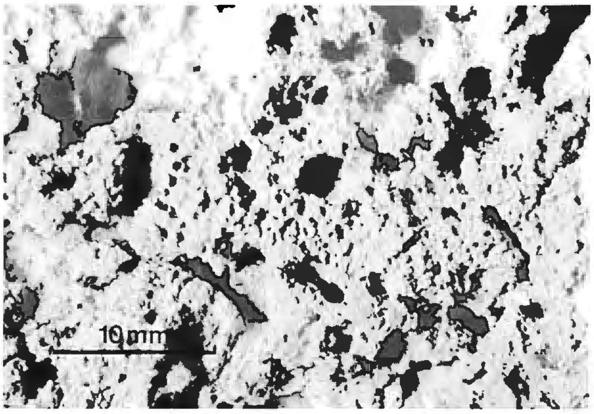
2.7.4 Breccia, etched by condensation corrosion, Zadlaška Jama (scale = 15 cm)

2.7.5 Etched rocky surface due to condensation moisture, Križna Jama

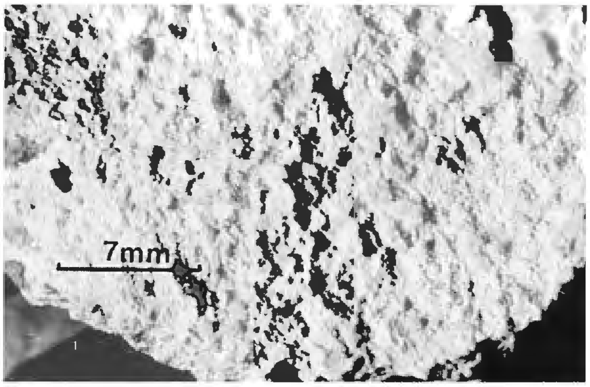
are often weathered. The rock is encrusted by a soft layer of undissolved rock that may be spread over it. Such cases are found in the entrance part of Volčja Jama on Nanos, in Križna Jama and in Ciganska Jama. In the last cave the weathered layer of rock is 3 mm thick. The signatures and dates on the walls cut with sharp object into the soft surface date from 1890 and I infer that in 100 years 1 mm of rock was weathered. The weathered rocky surface impedes contact by the moisture and actually prevents rapid wall corrosion. In Velika Kozinska Jama too, the ceiling on the transition to the lower part of the cave is weathered from 3 to 5 mm. The condensation is moderate and there is not enough moisture to wash the weathered rock away. We measured the quantity of $CaCO_3$ in the rock and in the weathered layer that encrusts it. In the rock there was 95,7% and in the weathered layer 2% more. It seems that most of the moisture dissolves the most soluble parts. During dry periods the water evaporates from the solution. On the surface the calcite crystals dissociate. The weathered layer in the cave was humid. In dry laboratory air it dried and became more solid; the calcite was recrystallized.



2-7-6 A. Small-scale condensation etching of western wall, Komarjev Rov
1. - smooth rocky surface
2. - spongework
3. - rocky surface with bulges
4. - flowstone
5. - points of temperature measurements
6. - PVC foil
7. - rocky surface without condensation
8. - loam
B. Location of Komarjev Rov within the entrance shaft and cave



2.7.7 spongework on the wall



2.7.8 the surface of the wall with bulges

Condense corrosion on the rocky perimeter of Komarjev Rov in Dimnice

The cave Dimnice with double entrance is located at Matarsko Podolje near Markovščina. The stream from the flysch Brkini flows in it and sinks in a blind valley near Velike Loče. The cave system is composed of a huge upper level, transformed by breakdowns and decorated by flowstone, 2000 m in length; the second level is 40 m lower, and 4000 m long.

The entrance to Komarjev Rov opens 18 m below the surface of the 40 m deep entrance shaft (Fig. 2.7.6B) The passage (Fig. 2.7.6A) is 29 m long and lowers gradually. The lowest point is a closed pocket 10 m below the level of the entrance. It is from 1,5 m to 3,5 m high and up to 1,5 m wide. The walls and rocky floor are somewhere encrusted by flowstone, and on the bottom is loam. Some debris has fallen from the passage walls.

Dimnice (Smoking Cave) is a special type of climatic cave consisting of two connected, unequally deep shafts and a horizontal cave. When the outer air is cooler than the cave air it penetrates through the deeper entrance shaft, warms underground and rises through a nearby shaft together with warm air from the cave interior. The warmer cave air becomes misty on the cooler surface, according to Gams (1972 b, 35).

I measured the air temperature once per week, during the most remarkable summer condensation, at the points of the passage that are marked on the longitudinal cross-section (Fig. 2.7.6A and B). During the winter, when the cave walls are mostly dry, I made some additional measurements. The temperature conditions refer to July 29, 1987. Regular measurements indicate that the temperature remains the same during the whole summer. At the end of summer the temperature increases only slightly. Smaller variations were observed after long-lasting bad weather when the temperature in the passage decreases and the air circulation is interrupted.

The temperature in the shaft (Fig. 2.7.6B) gradually decreases with depth: T1 = 11°C, T2 = 7,6, T3 = 6,1, T4 = 5,4°C. At the bottom of the shaft the temperature is more than 20°C lower than the noon temperature outside. I have measured the temperatures in Komarjev Rov (Fig. 2.7.6A) at each half meter. The most remarkable differences occur in the initial part of the passage where the temperature of the air falls by half a degree for each half metre (T5 (1-5), Fig. 2.7.6A). The temperature of the air on the floor is thus for 2°C lower than at the ceiling. I measured slight differences, 1,3°C only, at T6 (1-6).

In the air layer above the passage floor I measured the same temperature at T7 (6,3°C) as in the lowest layer at T6 and T5; the air below the ceiling reached 7°C. Thus in the whole passage there is a layer of cooler air above the floor with temperature of 6,4°C. In this layer there is either no condensation corrosion or it is moderate.

At T5-1, where a thermograph, hydrograph and barograph were placed, the temperature and air moisture measured on ten days in July were unchanged, while the air pressure increased for 10 mb in good weather. The daily changes of the outside temperatures are not reflected in the lower layers of air in the passage. Condensation in lower part of the passage was moderate and I could not measure the amount of condensationd moisture. Only a few drops of water accumulated on the PVC foil. The temperature differences between the air and the rock at the height of the foil were insignificant. At point 8, 2 l of water accumulated on the PVC foil in two weeks. In this part of the passage the condensation is the most significant. The temperature difference between the air and the superficial layer of the rock at the first foil was about 1°C.

The temperature of the superficial layer of rock, as well as the temperature of the air, increases towards the roof. The rock is thus warmed by warmer air and by the warmth released at condensation. Above the floor, in the coolest air layer where there are no signs of condensation corrosion, there are no temperature differences between the wall and the air.

The water samples were saturated, which may be the consequence of the dust we caused by moving through the passage. In the laboratory we recorded in two samples 30 mg Ca/l and in the third sample 60 mg Ca/l which is probably due to the period of evaporation. I tried to determine the moderate air circulation by a smoke experiment. In the middle of the entrance part of the passage we placed a smoke source. Warmer air rose and covered the upper parts of the walls and ceiling along the passage and made its exit from the passage above the floor.

Three typical climatic situations may be distinguished in a passage: summer, transitional spring and autumn, and winter conditions. In summer the air in the upper part of the shaft, where the sun reaches, warms. The layer of air below the level of the entrance into Komarjev Rov is warmer than the lower air layer in the passage. The cold air from the passage circulates above the floor to the shaft, and below the ceiling, warmer air comes into the passage. It covers the cooler rock on the ceiling and upper parts of the walls. The cooled air descends, and some of it continues its way to the interior where the process of circulation continues. Warm humid air cools at the walls and deposits the moisture. Most of the moisture is deposited in the entrance part of the passage; towards the interior condensation decreases rapidly. The first squeeze in the passage, 10 m in, is the limit between abundant and moderate condensation. When the air in the shaft cools it penetrates the passage where it dries up due to the warmer environment, and the condensation ceases. The summer climatic conditions last from late spring to autumn. On the ceiling and upper parts of the walls about 14 l per square meter of condensed water is separated in this time. Condensation is relatively moderate due to small temperature differences between the air and the rock, due to not very humid warmer air and insignificant air circulation. It is slightly more noticeable when the entrance shaft is humid and the warmed air may be moistened in the shaft.

Transitional climatic conditions occur in spring and autumn when the temperatures in the shaft and the passage are equal. There is no air circulation in the passage and the walls are dry. In winter, cold air from the surface penetrates into the entrance shaft. Some of the cold air appears in Komarjev Rov as well and pushes the warmer air upwards towards the exit. At the contact of these two air layers most of the moisture is deposited. The process lasts only a short time; it is limited to the time of cold air deposition and the condensation is moderate.

The surface of the rocky passage perimeter may be divided in terms of corrosion etching into three morphological types:

1. Smooth surface with traces of smaller fragments. From a part of the rocky surface where the solution is the highest undissolved fragments of sparit fall off (Type 1).

2. Sponge surface with hemispherical smaller notches of irregular shape, from 1 to 2 mm in diameter (Fig. 2.7.6A, 2.7.7.) Where there is still less condensation, corrosion smaller indentations pass into larger ones, up to 8 mm long, of the same breadth, that are composed of semispherical solution niches. The surface among them is corroded by smaller niches, 1 mm across. There is not enough moisture to dissolve tightly conglomerated aggregates of sparitic grains.

3. Surface with pendants, 1-3 mm long and often with slightly narrow sparitic grains (Fig. 2.7.6A, 2.7.8). The surface in between is encrusted by thin layer of recrystallizd calcite. This occurs on the parts of the wall where there is the least condensed moisture. The corrosion is more effective at the fissures and hence the wall breaks up. The breaking is slow and the fragments are small.

The transition between the particular types of the rocky surface is progressive. On the ceiling and the upper parts of the walls of passage entrance, where the condensation corrosion is the most effective, the rocky surface is smooth (Fig. 2.7.6A). The Type 1 progressively passes into interior and downwards, in correlation with condensed moisture diminishing, into a spongework surface of Type 2. In the region of smallest condensation, behind the first squeeze in the passage, the rocky surface of Type 3 prevails. Above the lower layer where there is no condensation or it is too weak to dissolve, a narrow layer of Type 2 reappears. At the contact of lower cold winter air penetrating into the passage and the warmer interior air, the condensation is the most effective. The boundary of vertical temperature air layering and the associated condensation corrosion is best seen on the bottom of the passage. The lower part of the walls where there is no condensation corrosion is encrusted by flowstones, above, where the flowstone is removed by condensation corrosion the walls are thinly etched.

In short, the distribution of various amounts of condensed moisture on inhomogeneous rock is due to air circulation in closed passages, dipping downwards. Corrosionally aggressive condensation water dissolves the lighter bed of dismicrite above and slightly more soluble biomicrosparite below. It seems that the aggressivity of the condensation water in the passage does not change and the different etching of the rocky perimeter is mostly due to different amounts of condensed moisture and related flushing of the dissolution.

In the period when moisture evaporates from the rocky surface, a thin layer of calcite crystals deposted from the solution encrusts the walls. There is not enough moisture to wash away the dissolved rock. Such layers are most frequent on those parts of the rocky surface where there is the least condensed moisture (Type 3) and evaporation is the most effective. The recrystalization slows down further rock dissolving. It seems that the flowstone is less soluble than the rock, as one may find the remains of flowstone on projecting parts of the rock.

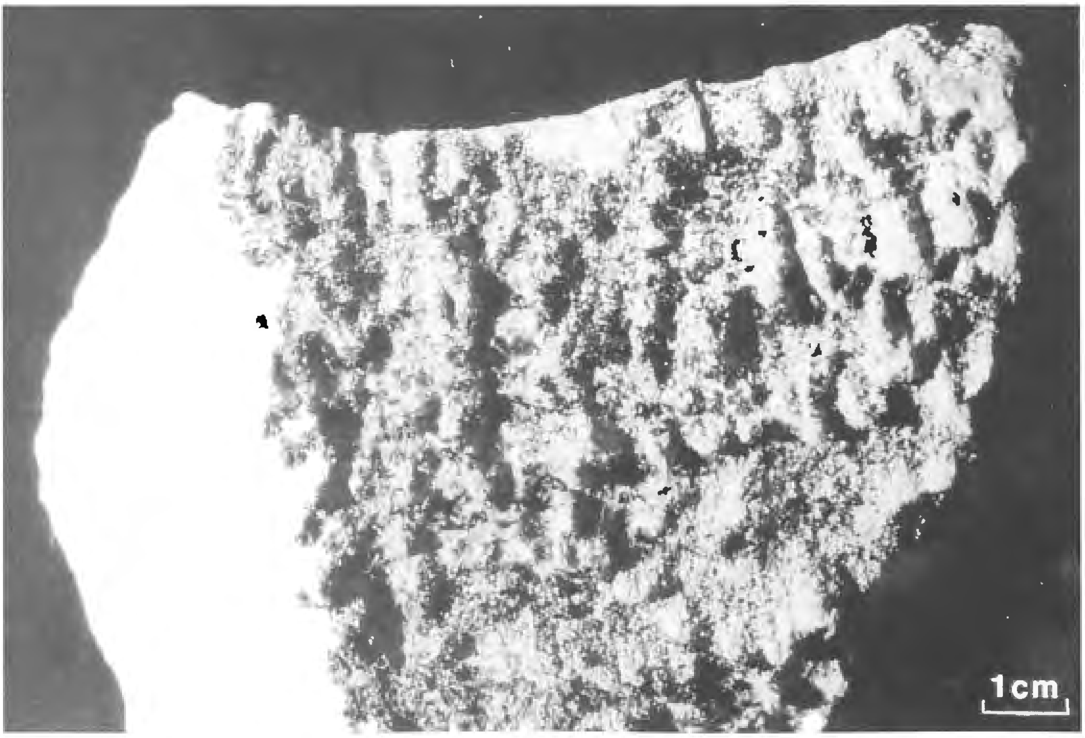
2.8. Biogene Rock Features

I observed the etched rocks below the lichens that cover the passage walls, and the etched rocky floor beneath the guano and bear indications in Križna Jama.

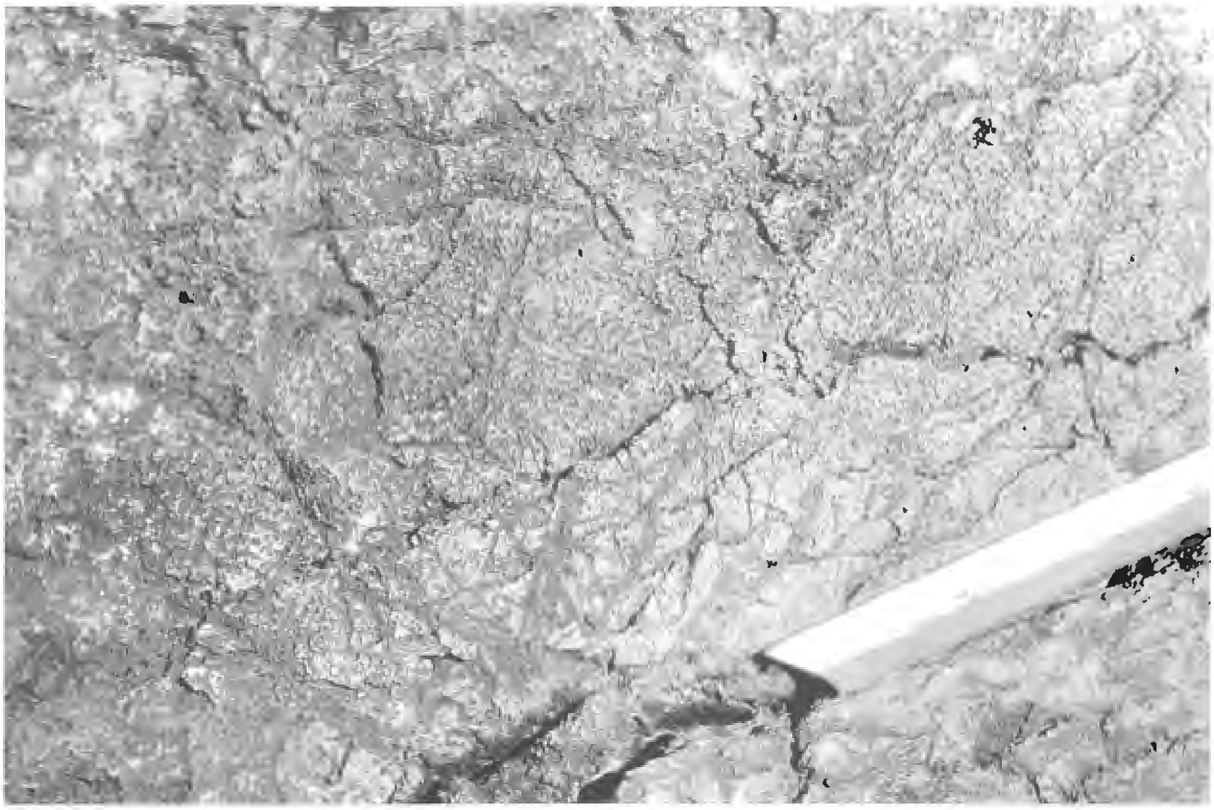
Biogene factors are chemical or physical (Ollier 1984, 10). Biogene materials are mostly transported underground by water, either by streams or percolation water that transport soil into the caves. Their allochthonous character is stressed by Delay and Aminot (1975) also. Caumartin (1959) states that microorganisms in fine-grained deposit, form moon-milk out of dolomite by ammonia and nitrite acids and accelerate the occurrence of CO_2 by degrading organic substances. Trudgill (1979) studied the influences of organic acids on carbonate rock by experiments and Dreybrodt (1988, 33) inferred them theoretically. Trudgill stated that under the influence of organic acids the rocky surface becomes smooth.

The water streams deposit the fine-grained sediment and by wet procedure of oxidation by potassium dicromate (Pochon 1954) we determined the rates of organic carbon. In Križna Jama the rates of organic carbon reach 1%, in Predjama 0,5%. Samples 1 (0,69% of organic carbon), 2 (0,18%) and 3 (0,77%) were taken from the bank in Križna Jama. In the second sample, the fine-grained sediment from the surface of the dam, there is the least organic carbon; only 50 to 100 m below the surface its level increases to 0,69%. Slightly below the average (0,56%) level of organic carbon was found in the deposit from a lateral ledge that is reached by infrequent very high waters. Below the sediment there are half tubes. There is the most organic carbon (1%) in the sample of the deposit above which ceiling and wall channels occur. The level of organic carbon in an organic substance is about 58% (Scheffer & Schachtschabel 1975). The analyses of fine-grained sediments done by the Institute workers (Kranjc) for archaeological purposes show the following amounts of organic carbon: the least in old, dry sediments, on average less than 0,5% and the most in fresh sediment transported by underground streams where the highest rate was found in Labodnica (2,5%). Scheffer and Schachtschabel (1976, 51) quote that in soils with little humus there is less than 1% of organic carbon; in soils with the highest amount of humus there is from 8 to 15%; the average in arable soil should be 1,5 to 4%. By comparing we may assess that the rate of organic substances in the sediments is not negligible and one may suppose that the process of mineralisation, CO_2 formation occurs. It seems that the deposit including organic carbon increases the solvent capacity of the water. In the water from a water supply 132 mg $CaCO_3$ and 1,4 g of plaster per liter were dissolved while in a liter of water with added sediment, 1,76 g of plaster and 184 mg of $CaCO_3$. Is this the effect of increased water efficiency or just dissolving of carbonates in the sediment?

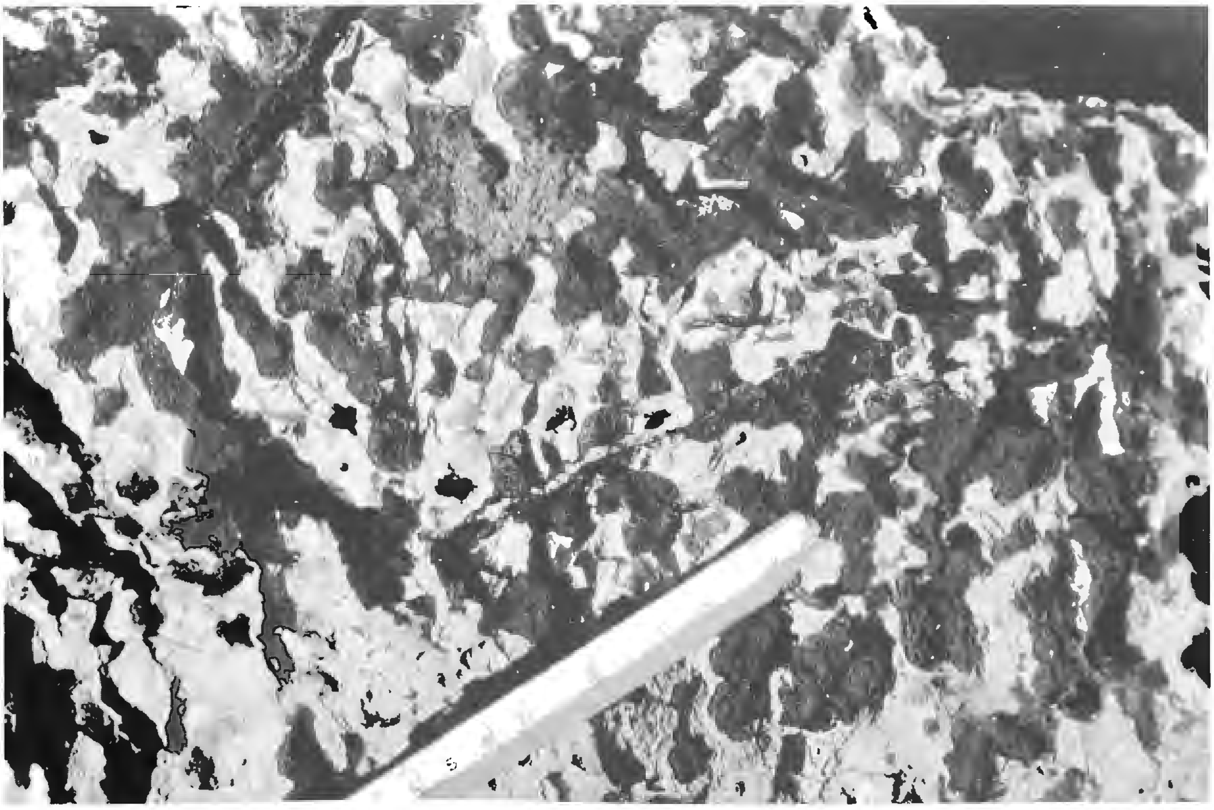
Epilithic lichens give rise to smooth surfaces; endolithic lichens excavate cavities in the rock and cause rough, careous weathering, so that the limestone be-



2.8.1 Rock surface under the lichens, Volčja Jama on Nanos



2.8.2 Notches under the liches in entrance part, Veliki Hubelj

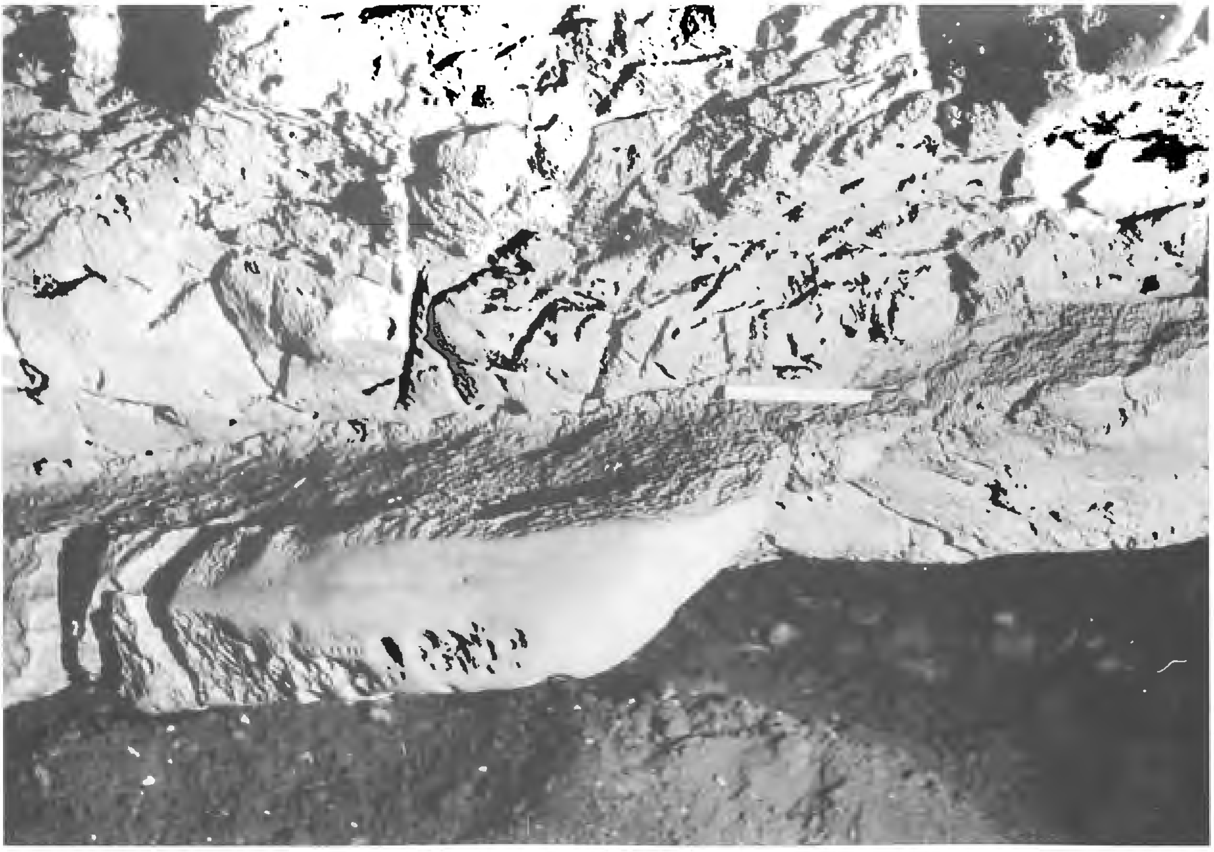


2.8.3 Notches below guano, Veliki Hubelj comes pitted with minute holes (Sweeting 1967, 194). The lichens may break the mineral into minute parts (Ollier 1984, 55). Trudgill (1985), using a scanning electron microscope, found that algae indented into rhomboid crystals. The most detailed study of lichen influence upon carbonate rocks was done by Viles (1987). Oxalic acid dissolves calcite. Fungi cause the origin of niches and the hyphae of algae the half-tubes. He termed such microtopography biokarst (467, 468). The notches start among the crystals while the furrows within them even. The bacteria acids attack the carbonates too (Gams 1974, 65; Chorley 1984). There are frequent studies reporting the influence of sea bioerosion on carbonate rock. This is not the subject of this study but the method used by Palmer and Plewes (1993, 139) could be useful. They actually filled the biogene indentations by epoxy pitch and later dissolved the calcite. In this way the effects on the limestone are well seen and the cause may be recognized.

Some parts of the walls in the entrance of Volčja Jama are colonized by lichens (Fig. 2.8.1). Daylight penetrates into the cave parallel to the wall. The rocky surface under the lichens is weathered into flake pendants that overlap each other and are oriented towards the exit. In the notches among the pendants there are lichens that have weathered tubes through some of the pendants. I suppose that the rock solution is accelerated as the rock remains rather damper under the lichens that extract nutrients from rock minerals (Slabe 1990, 182). The surface beneath a thin layer of lichens (Fig. 2.8.2) in the entrance passage of Veliki Hubelj is weathered similarly but in the form of small holes. The daylight hits the wall directly. Probably the lichens covered all the rocky surface and weathered the more soluble parts of the rock faster. Now they are preserved in the furrows and notches along tiny fissures. It shows also the influence of a seasonal water flow that washes away the rock particles. More detailed analyses of direct lichen influence upon the rock weathering are required.

Another example of biotic weathering of the rock occurs in the passage beyond the entrance into Veliki Hubelj where the rocky bottom and breakdown boulders above are thinly dissected. These are singular or compound furrows (Fig. 2.8.3) covering the surface of 1 to 10 cm^2 and up to 3 cm deep, filled by guano. The surface among the furrows is thinly rough. Beneath the guano the more soluble parts of the rock dissolve and deepen hemispherically. The guano is accumulated in the notches. Water floods the cave seasonally, washes the exposed parts of the rock away and moistens the guano. This causes faster solution of the rock. The notches widen and deepen. I not yet found out whether the weathering of the rock is due to guano only or to the increased amount of water that remains within it when the high water recedes. Their origin is similar to that of below-sediment floor-pits.

In Križna Jama the rock is polished by bears (Slabe 1989 b, 214). This a projecting part of a polished rock (Fig. 2.8.4) that was not weathered by condensation corrosion as was the case with the nearby rock.



2.8.4 Bear signs, Križna Jama

2.9. Rocky Features due to Rock Disintegration

Due to rock disintegration block breakdown or slab breakdown occur (Gams 1973, 8). The surface of slabs ranges from 1 dm^2 to more than 1 m^2. If it is smaller it is called a fragment. The blocks are limited by straight or inclined planes. Due to concentrated disintegraion of the roof domes occur or domed ceilings which is typical of spacious caves (entrance part of Dimnice, chambers in Postojnska Jama). The examples from epiphreatic passages are mentioned by Bini and Cappa (1978, 60). In smaller caves too the ceiling may be domed if the rock is very fractured. Such is the lower part of the entrance passage in Volčja Jama (Slabe 1990, 175) and in Paradiž in Škocjanske Jame.

Rock disintegration is affected by the rock structure, and by the mechanical, hydraulical and climatical factors (Renault 1957). The combination of these factors is reflected in the mode of weathering or disintegration and, consequently, in the features of the rocky relief.

Different rock structures impact on the mode of disintegration of fractured limestone and dolomite. The limestone in Volčja Jama (Slabe 1990, 176) disintegrates more slowly; the fragments are cube-shaped or square-shaped with straight or slightly distorted planes. Dolomite often disintegrates into thin flakes according to longitudinaly or transversely fractured beds. Thin-bedded limestone layers frequently come off in plates - such is a part of ceiling in Paradiž. Along the bedding planes slab breakdown occurs. Such was the formation of the flat ceiling in the entrance part of Volčja Jama (Slabe 1990, 175). Prominent disintegration is controlled by thin diagenetic fissures within a rock and by clay impurities among the carbonates.

The prevailing reasons for disintegration are mechanical tectonic in particular. The rock is most fractured in fault zones; this is why the disintegration is most efficaceous between two fault planes when the rock is not conglomerated into breccia. On the walls and ceiling notches occur, such as in Ledenica na Dolu (Slabe 1990, 186) and in Paradiž where there are tiny tubes only on densely fractured rock. Larger speleothems that are found nearby on less fractured rock, could not remain, due to their weight. The formation of the perimeter along lense-shaped broken zones (Čar 1982, 87), where rocks occur as blocks that may be displaced is also characteristic (Slabe 1990, 174). We may conclude that tectonically controlled block breakdowns are confined by straight planes of various size. Thus the rocky relief features are angular as well. Such a type of broken piece is called block breakdown.

Decompression of a rocky perimeter is most frequently seen in the formation of larger cave spaces (Gilli 1985) but eventually, when the rock is more fractured, in smaller caverns too. Domed ceilings are inversely graded due to block or slab breakdown.

The weight of the rock influences the wall's disintegration too. Gently inclined layers in the lower parts of the entrance in Volčja Jama are dissected by upright fissures.

Rock disintegration is more rapid if it is exposed to water or a stream. Solution is the highest along the fissures and it augments the rock's instability. A water stream may tear off the pieces of rock that are less tightly fixed to the perimeter. Thus the perimeter is dissected along crushed zones in particular but also along the fissures and bedding planes where more solid parts of the rock remain as pendants. An appropriate example of such a passage is Vzhodni Rov in Predjama which is parallel but also transverse to the fault zone. A very fractured and unstable perimeter prevents the formation of the features that are characteristic of the water turbulence. The fluctuation of water level may accelerate the rock disintegration by changing the pressure against the walls (Gams 1961, 50) and by compressing the air into ceiling holes. In mountain caves disintegration is accelerated due to corrosionally active water that infiltrates through the fissures and bedding planes and widens them.

Climatic factors controlling the formation of rocky relief due to weathering and breaking down may be divided into freezing of the moisture and its condensation on the rock, and to thermal changes within rocks. The breakdown of the rock, studied in Predjama by Kranjc (1983), is accelerated due to freeze-thaw effect at the perimeter. Higher ice pressure in the fissures loosen the rock. Such a type of disintegration is typical of caverns where the cold winter air penetrates and remains (Ledenica na Dolu, entrance parts of Velika Ledenica in Paradana, Grgorečeva pečina in Matarsko Podolje). The effect of freezing is prominent on fractured rock only. The influence of condensation corrosion upon the rock disintegration is moderate. The moisture effectively dissolves the rock along the fissures. On unfissured rock it causes the dissolution of more soluble particles and freeing of the larger grains that protruded out of the surface (Komarjev Rov in Dimnice). The thermal changes within rocks are less important for the disintegration as the temperature fluctuations in Slovene caves are rather moderate. Major temperature differences (up to 10°C) occur in the entrance parts of lowland caves and in open mountain shafts.

3. CAVE ROCKY RELIEF - THE EVIDENCE OF FORMATION AND GENESIS OF KARST CAVES

Rocky relief in the karst caves primarily reflects the efficiency of water acting on the rock under characteristic hydrological conditions. Active passages are formed by water streams, the shafts by water trickling down. The rock structure is different, often fractured; this is why it disintegrates. Other processes are usually less important. At the perimeter of the passage several factors may interact or they alternate during the entire cavern genesis.

The shape of the passages and a considerable proportion of rocky relief with straight planes of block breakdown or domed ceilings indicate that the tectonics of bedded rocks impacts importantly on the formation of the rocky perimeter of the cave. The dissection of the passages through which the water streams flow provokes the areas with marked water turbulence. The passages frequently have sharp curves and sudden changes of the cross-section. For speleogenesis the fault zones or distinctive fissures are extremely important, while for the formation of the perimeter thinly fissured rock may be effective alone. The perimeter of water passages with rounded cross-section is commonly dissected in the more easily understood rocky relief. Densely fractured passage walls, where the surfaces between the fissures are smaller than the size of the eddies in various fast water flows, frequently shape into pendants. Scallops occur on smaller unfissured surfaces where the turbulence is less chaotic than along the fissures. The rocky relief is efficiently shaped by larger amounts of percolation water. A considerable proportion of rocky relief in the selected caves contains above-sediment rocky features (Chapter 2.4). They indicate frequent infilling of cave passages by fine-grained flood sediments and water flow above the deposit. The thin dissection of the rock surface controlled by its structure is due to relief etching by less efficient condensed moisture and by biotic factors. Higher amounts of condensation moisture and the water from thick ice cover may round the rock and smooth it. However these last factors seldom shape the rocky relief to a great extent. Usually they transform it only partly.

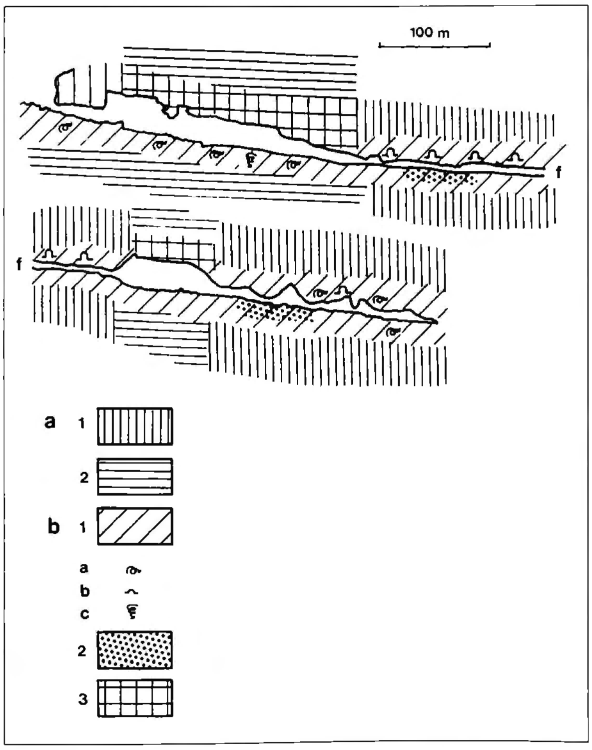
The properties of the passages may also be defined with respect to the rocky relief which is the result of various factors and their efficiency. Their development is either uniform or diverse. In uniform development one of the factors prevails, either water flows in phreatic passages, or water trickling down shafts. As the first type of diverse passages one may consider the type where several recent factors interact at the same time: water stream, rock weathering, deposition of fine-grained sediments and the water percolation out of them. Such passages occur in the phreatic zone where the two first factors are active or in the epiphreatic zone where a very large amount of sediments is deposited seasonally. High waters may entirely fill up the passages, while low waters shape the bottom of the river bed only. In the second, more frequent, type of diverse passages there are more traces of ancient conditions in the rocky relief (Kozinski Rov in Lipiška Jama: large scallops and above-sediment anastomoses), or recent and ancient conditions (Novi Rov in Beško Ocizeljska Jama: small scallops incised over the large ones) and processes of their formation. The old rocky features may be partly transformed by recent processes (condensed corrosion). In large cave systems the alternation of various types of passages is frequent; still more diverse but at the same time typically distributed are the passages within individual aquifers.

3.1. Rocky Relief as a Sign of Characteristic Formation of the Caves

3.1.1. THE PROPERTIES OF ROCKS RELIEF IN PASSAGES SHAPED BY WATER FLOW

The mode of passage formation may be explained by their cross-section and rocky relief. According to the distribution of rocky features and their interaction on the passage perimeter the eventual changeable speleogenetical conditions may be taken into account. The same conditions and processes are, however, differently expressed in variously sized and shaped passages. This may be noticed by their longitudinal section in particular.

The cave cross-section is one of the bases for studying speleogenesis, stated Gams (1961, 47) when he summarized various passage cross-sections and their dependence on the bed position by studying Slovene caves and the literature. I use the expression passage cross-section (profile of the cave passage, Gams 1973, 23) as the cave may be composed of several passages with different cross-sections. Gams (1961, 48) infers that the passage cross-section is controlled by the former passage shape, by the structure and lithology, by hydraulics and the influence of the nearby cross-sections, by the previous development features and by cave sediments. He presented the cross-sections by photos (Gams 1974, 103). Šušteršič (1985, 81), referring to Lang, terms the products of the rock removal speleogens. He distinguishes between passive variables that are due to the rock properties and active variables that are direct factors of the mass transport. He stresses (Šušteršič 1985, 85) that different shapes of cross-section indicate the successive conditions within their development. Maire (1980, 29) divides the development bases of the passages and related cross-sections to syngenetic and paragenetic passages and the passages controlled by free surface water flow. Ford and Williams (1989, 294, 299, 272) divide the passages and their cross-sections into phreatic, vadose and paragenetic.



3.1.1 Hydrological zone and rocky relief, Novokrajska Jama

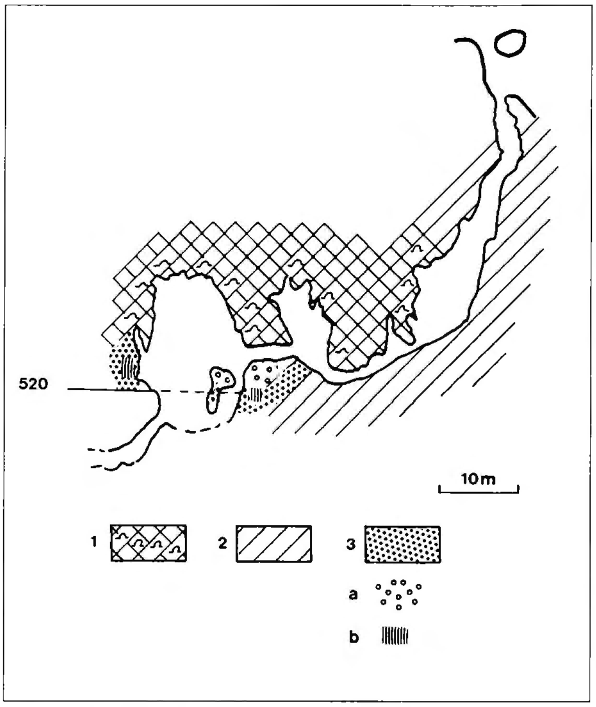
- *A. 1. epiphreatic zone*
  - *2. vadose zone*
- *B. 1. Rocky relief formed by water flow*
    - *a. scallops*
    - *b. ceiling pockets*
    - *c. potholes*
  - *2. Below-sediment rocky relief*
  - *3. Rocky relief due to perimeter disintegration*

The properties of the passages, in particular the varieties in larger cave systems, are the bases for explaining the karst underground speleogenesis. I shall present the passages rocky relief that are controlled by characteristic hydrological conditions at the formation of selected caves.

a. Passage rocky relief in phreatic zone

I have divided the passages within the selected caves by their rocky relief (Table 2.2) shaped by different water flows. Large scallops or even ceiling pockets are found on the perimeter of the passages through which a slow flow circulates. The flow velocity mostly reached 5 cm/s. In the selected caves these are commonly large passages; however the water direction flow is hard to explain by the rocky features. The water that in many cases flowed above the fine-grained sediment had incised the mentioned features in the gentle or inclined passages where its direction was either upwards or downwards. In the passages that were once filled by water flow faster than 5 cm/s there are larger scallops of Type 2. They are from 15 to 40 cm in length. On the ceiling, solution cups are frequent. The flow velocity is from 5 to 20 cm/s.

I have observed only old (accumulation phase, Gams 1961, 51) such passages. Their perimeter is frequently transformed due to rock weathering, free-surface flow (Fig. 3.2.3) and corrosion at the contact with fine-grained sediment (Volčja Jama, Kozinski Rov in Lipiška Jama). On old rocky features more recent ones occurred, or recent features are found on the lower parts of the walls only (Logaška Jama, Fiženca in Predjama). They were partly transformed by condensation corrosion also (Križna Jama). Similar sections may be found



3.1.2 Rocky relief, Matijeva Jama
1. ceiling pockets due to water flow
2. erosionally polished passage perimeter
3. below-sediment rocky relief
a. below-sediment pits
b. below-sediment channels

in low altitude, through flow but also in high altitude outflow aquifers of our karst. In solid, thick-bedded rock the cross-sections of the phreatic passages (Kozinski Rov in Lipiška Jama) are rather semi-circular (efforation profile, Gams 1974, 103), ellipse-shaped (the niche in Križna Jama) or else they adapt to fractured (dolomite in Turkova Jama) and bedded rock.

I did not find networks of passages (Jennings 1980, 6) (spongework) due to slow water flow of some meters per day or by corrosionally active mixtures of fresh and sea water in the selected caves.

b. Passage rocky relief in epiphreatic zone

Passages in the epiphreatic zone are seasonally filled by water that is usually more rapid than in the phreatic zone or they are flooded and partly filled up by fine-grained sediment.

In the passages where there is water flow of medium velocity there are medium sized scallops of the Type 2, from 5 to 15 cm long on the perimeter and solution cups on the ceiling. In the wider parts of the passages, where slightly larger scallops are on the walls, below sediment bevels and pits are frequent (Fig. 3.1.1). In the passages where the perimeter is fractured, pendants are found (Vzhodni Rov in Predjama). In such passages the flow velocity reaches from 20 to 50 cm/s. Faster water flow transforms the eventual traces of older formation of the passages and examples where younger traces are seen over the older ones (Novi Rov in Beško Ocizeljska Jama: smaller scallops over larger) are scarcely. Epiphreatic passages, seasonally attacked by high velocity flow, have scallops of Type 1 on the perimeter and in bottlenecks small scallops of Type 2. The scallops are some cm long only, indicating that the flow velocity through such passages usually exceeds 50 cm/s. Fast waters transport sand and gravel, and pothole the floor. In the longitudinal section of the passage that varies in size, one may observe traces of the first and of the second types of flow as the flow velocity increases with narrowness. The passages are either gentle or steep and, as we have seen in Mala Boka, even vertical.

In the Tentera swallow-cave below Ribniška Mala Gora I have measured the length of the scallops in the entrance part and in the passage with anastomoses. The scallops on the ceiling, 8 m above the floor, are 7 cm long, diminishing towards the floor. At the edge of the river, 1 to 2 m above the floor, the scallops are 5 cm long. Within a riverbed there are smooth slightly elevated inlet parts, the most exposed to the water activity, while on their outflow side a net of small scallops is formed, up to 1 cm in length. In the anastomosis network of passages, the floor of the upper parts in particular is covered by a thin film of loam; the scallops are from 5 to 10 cm long. Referring to the Lismonde and Lagmani (1987, 38) equation for the size of the scallops, we get the following distribution of flow velocity within a cave:

the ceiling of Tržiščica passage	0,35 m/s
Tržiščica river bed 1 to 2 m above the floor	0,50 m/s
Tržiščica river bed floor	2,5 m/s
the narrow parts in the anastomosis passage	0,25 to 0,50 m/s

Measuring the gravel in the cave Kranjc, (1981, 52) concludes that it was transported by a water flow exceeding 2 m/ s; thus it is equal to the velocity that incises the smallest scallops. The inflow exposed parts of the rock are mechanically smoothed by water flow. The passage is most penetrable during low or medium high waters as the narrowness behind the passage blocks high waters. In the anastomosis network of the passages, with the exception of the bottlenecks, the flow velocity is smaller.

Similar distribution of various scallop sizes may be observed in the main passage of Križna Jama (Fig. 2.3.52). On the dissected perimeter of the river bed there are on the exposed, lower parts of the walls and on the floor scallops up to 3 cm long, 1 to 2 m above the floor; their length is 5 cm. At the same height but on the leeward sides of the wall niches, the scallops are up to 8 cm long. In the bottleneck, where only high waters flow and flood it entirely, the scallops are all over the perimeter, up to 3 cm in length. The various size of scallops are due to various flow velocities. They are governed by the efficiency with which the passage transmits water and by its shape.

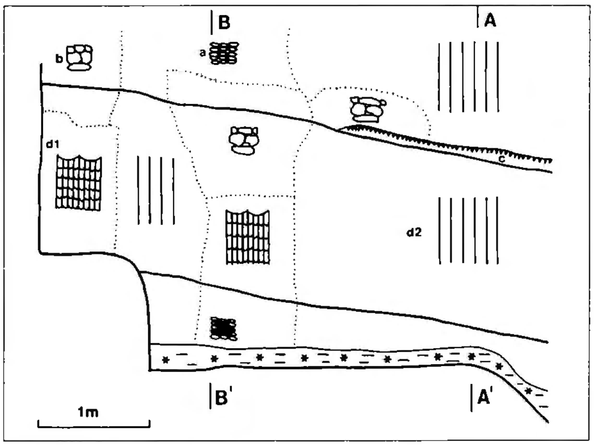
Smaller passages may be excluded where seasonally fast water flow occurs. On the ceiling small solution cups may be found, the floor and the walls being mechanically polished. Where turbulence occurs there are potholes. The water velocity in these passages often exceeds 2 m/s. The prevalent mechanical polishing of the water flow prevents the formation of scallops. Such passages appear in spring caves at the border of High Karst (Babja Jama, Matijeva Jama and Suhadolica) where autochthonous gravel is carried in the eddies.

A characteristic section of seasonally flooded passage where slow and medium fast water flow alternate, is Krožni Rov in Črna Jama. Periodically faster water flow incised medium-sized scallops and ceiling cups during high waters. Fine grained sediment is deposited from slower water flow or captured water. Scallops occur below the deposit and also below-sediment bevels and pendants. The formation of Blatni Rov in Zelške Jame, which is flooded in its lower parts only is similar.

The passages have similar cross-sections to the phreatic passages and the river beds are seldom deepened due to fast water flow with free surface (Tentera, entrance part of Podorna Jama of Lokva and Jama v Peklu). The longitudinal connection of the passages with circular or elliptical cross-sections with fissure network may be observed in Mala Boka. Circular or elliptic passages developed in thick-bedded limestone, the fissure network in very fractured breccia. The first are covered by small scallops, the second ones are dissected into small pendants and pits. Hence in equal hydrological conditions the impact of rock structure prevails. The fissure network passages are characteristic of dolomite too (Jama v Peklu). Šušteršič (1994, 20) accentuates the importance of the fissure properties at the formation of passage cross-sections. Less suitable is the frequently met distinction that the passages may be divided into those due to mechanical activity of water and the transported material against the rock, and others due primarily to rock solution. Their properties were summarized by Gams (1961, 49). The first should have a circular profile and polished walls while the shape of the second should be adapted to rock structure and joint frequency. However, we have ascertained that the fissure network passages (Slepič in Križna Jama, a part of the passage in Podpeška Jama) and most of the passages with circular cross-section (Mala Boka, Beško Ocizeljska Jama, Zelške Jame, Ponikve v Jezerini, Ponor v Odolini) may have scallops all over their perimeter. The prevailing process of scallop formation is corrosion. The perimeter of the passages that developed mostly mechanically is polished (Babja Jama).

The rocky relief of estavelles

Estavelles have special type of rocky relief. Matijeva Jama is an estavelle (Fig. 3.1.2) at the border of Palško Jezero. This is one of the contact springs at the border of karst lakes distributed along the southern foot of Javorniki; their low waters flow underground past Postojna towards Malni (Habič 1968, 49). At the bottom of the entrance pothole, 30 m deep, is a major chamber with pond. During drought the pond is 3 m deep and continues in a submerged passage. The highest lake's level is 556 m above sea-level; the lowest water level in the cave is at 518 m (Habič 1968, 49). After heavy rain more than 6 m^3 per second of water comes out of the estavelle; when the water level decreases a stream flows into the cave.

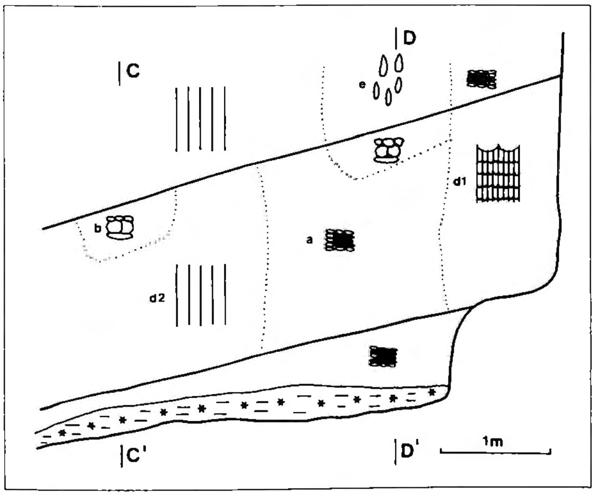


3.1.3 SW wall of the chimney, Ledenica na Dolu

On the ceiling of the lower part of the cave there are hemispherical solution cups (Fig. 2.3.22). Their surface is due to inhomogeneous rock thinly rough. The floor and inclined walls of the lower part of the cave are covered by below-sediment pits. The perimeter of the entrance passage is mechanically polished. The lower part of the cave is seasonally flooded. High water flows upwards in the cave and whirls gravel and sand. The rocky relief thus reflects the alternation of frequent fluctuation of the water level in the lower part of the cave and periodical eruptions of water out of the cave.

c. Passage rocky relief in vadose zone

Fast free-surface water flows are characteristical of larger swallow-hole and spring caves where true river beds are formed (Škocjanske Jame, Postojnska Jama: a part of the underground Pivka, Pivka Jama, outflow part of Planinska Jama). On the perimeter and in particular on the rocky floor of the passages, small scallops of Type 3, flutes, potholes, "čer" and floor channels prevail (Table 2.2). The inflow, exposed rocky surfaces are often polished or bruised.



3.1.4 NE wall of the chimney, Ledenica na Dolu

Free surface water flow runs over the shafts and vertical passages (Ponor v Odolini, Beško Ocizeljska Jama, the step in Markov Spodmol). Ceiling channels (Fig. 2.3.61) occur. On gentle sloping sections the floor channels are covered by small scallops (Fig. 2.3.57); below the shafts or steep parts of the river bed there are potholes.

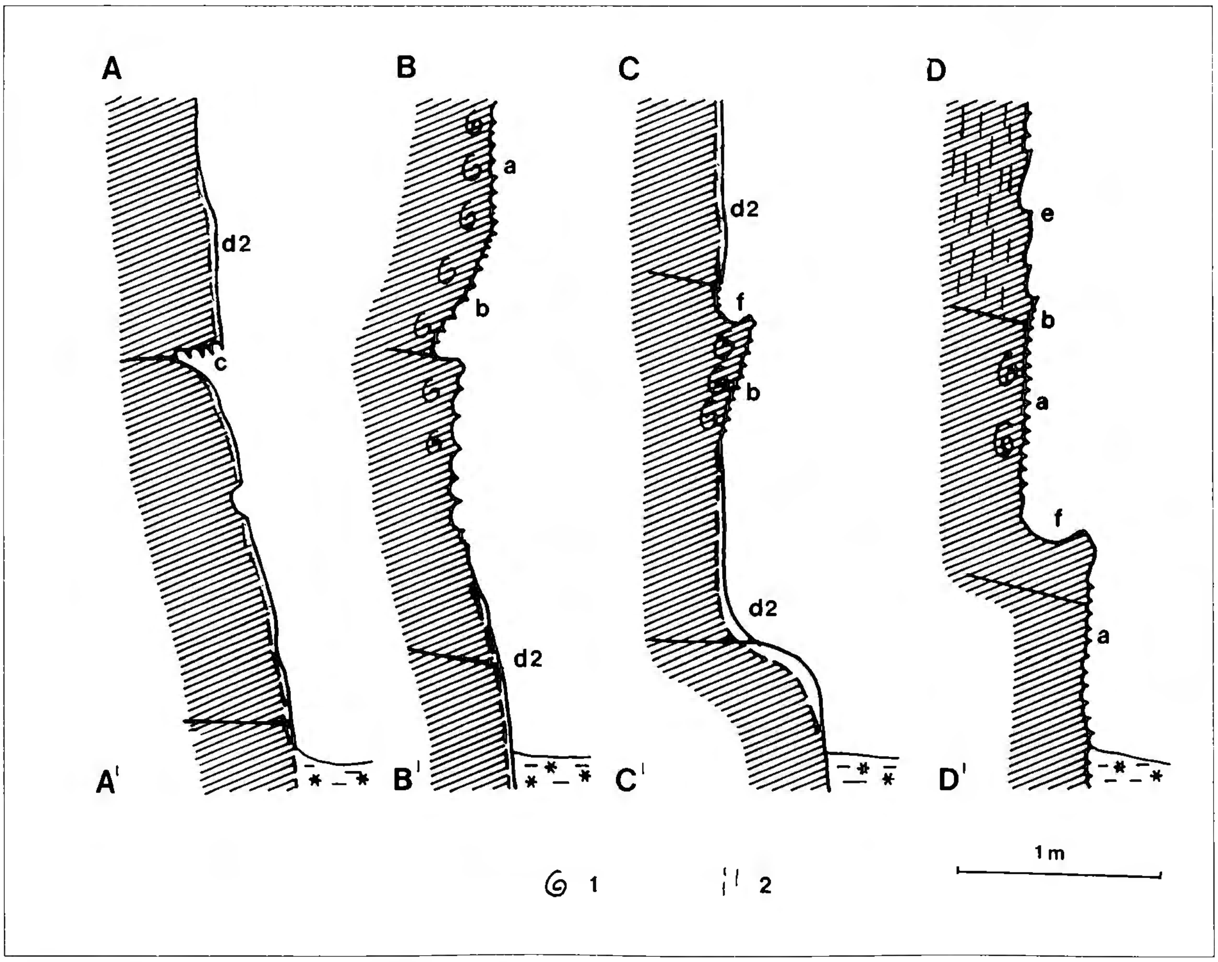
Lower free-surface water flows drain over the bottom of meandering passages (Kamenšca, Velika Ledenica in Paradana). In Kamenšca there are smaller scallops on the floor, below the falls there are shallow cups.

The cross-sections of vadose passages frequently indicate the deepening of passages that were formed in the phreatic or epiphreatic zone by free-surface water flow (Križna Jama). Circular or elliptic passages are thus deepened by meanders (inflow passage in Brlog na Rimskem, upper passage in Trhlovca, Fig. 2.3.55 and by canyons; lower part in Beško-Ocizeljska Jama (Mihevc 1991 b, 46)). An appropriate example of keyhole shaped cross-section indicating the deepening of the passage by various amounts of water is in Vodna Jama v Lozi. In Smoganica there is a similar passage cross-section due to different resistence of various gently inclined rock layers.

3.1.2. ROCKY RELIEF FORMED BY WATER TRICKLING DOWN

In a detailed observation of a chimney in Ledenica na Dolu I was assessing the connection between the rock structure, bedding and joint frequency, inclination of the wall and the features occurring on it.

In the middle of the cave a narrow through route opens towards SE, to the passage that ends in a chimney. The lower part of the chimney is incised meander-like into the passage wall, 5 m deep and crossing the bedding. It is 20 m high and closed on the top by wedged breakdown blocks. The chimney makes part of the cave system that developed by vertical percolation of aggressive water. The water reached the impermeable basement in a fissure and by meandering found by-pass. By gradual incision into the rock the chimney widens and deepens, in particular at its internal part. A large surface of the chimney is encrusted by flowstone. But below the thin flowstone one may recognize the shape of the rocky surface. During the cool half of the year the lower part of the chimney is covered by ice that melts in summer but on the bottom it remains until early autumn. At that time the bare walls reveal the characteristic fea-



3.1.5 Chimney's cross-section, Ledenica na Dolu
1. thinly fissured rock
2. fossils in the rock

tures due to trickling down of aggressive water. I have studied the lower, 3 m wide belt of the chimney where most of the characteristic features are. Singular rocky features of this kind are presented in Chapter 2.5.

a) On a vertical wall there are 10 to 30 mm long, 5 mm wide and 5 mm deep elongated niches. The water accumulates into streams on vertical walls and the niches are distributed in vertical rows (Fig. 3.1.3, Fig. 3.1.4, Fig. 3.1.5).

On the northern vertical wall the rock is more homogeneous and the rocky surface is evenly smooth.

b) On an overhanging wall, gradient 90^0 to 30^0, there are shallow niches of irregular shape (Fig. 2.5.6, Fig. 3.1.3, Fig. 3.1.4, Fig. 3.1.5). The largest is up to 30 mm in diameter, and they are 10 mm in depth.

c) Roof pendants occur on the ceiling of the indentation along a bedding plane (Fig. 3.1.3, Fig. 3.1.5).

d) On inclined walls there are runnels. On slightly inclined vertical walls the runnels are up to 10 mm wide and 10 mm deep (Fig. 3.1.3, Fig. 3.1.4, Fig. 3.1.5 d1).

Half tubes are incised into the steeply dipping wall (Fig. 3.1.3, Fig. 3.1.4, Fig. 3.1.5 d2), the deepest among them reaching 10 cm in depth and 7 cm in breadth at the top of the opening.

e) In the inclined wall, gradient about 80^0, densely dissected by thin upright fissures, there are niches of hemispherical shape (Fig. 2.5.5, Fig. 3.1.4, Fig. 3.1.5). Circular cross-sections are from 10 to 30 mm in diameter.

f) In almost horizontal or only slightly inclined sections of the lower rock layer that protrudes out of the wall, larger but shallow cups occur (Fig. 3.1.5), up to 10 cm across and up to 2 cm in depth. On the outflow side they are widely open.

3.2. Rocky Relief as Evidence of Karst Caves Development

3.2.1 Small scallops on larger ones, Beško Ocizeljska Jama

Due to aquifer karstification one may frequently trace the changes of hydrological conditions within a cave development. Once-flooded passages are presently dry; free surface flow drains through them or they are transformed by infiltrated water. The changes reflect in their rocky relief as well; it is composed of one type of rocky feature or by several different types. It is difficult to date the periods that left these traces in the cave. Rocky relief offers just an insight into their time-scale distribution. Younger rocky forms cover older ones.

3.2.1. THE OLD ROCKY RELIEF IN THE DEVELOPMENT OF UNIFORM PASSAGES

Rocky relief in the passages that had uniform development is described in Chapter 3.1. The traces of passages formation in phreatic, epiphreatic or vadose zone indicate the previous water flow drainage. Quickly changed hydrological conditions allowed the preservation of the rocky relief that was formed in phreatic conditions. The caves of such morphology prevail in the Slovene Istrian karst where the piezometric water level decreased due to opening of the flysch barrier surrounding this karst area. The traces of older phreatic water flows in the present-day dry passages may be found in other parts of the Slovene karst, in through-flow lowland as well as in outflow Alpine karst.

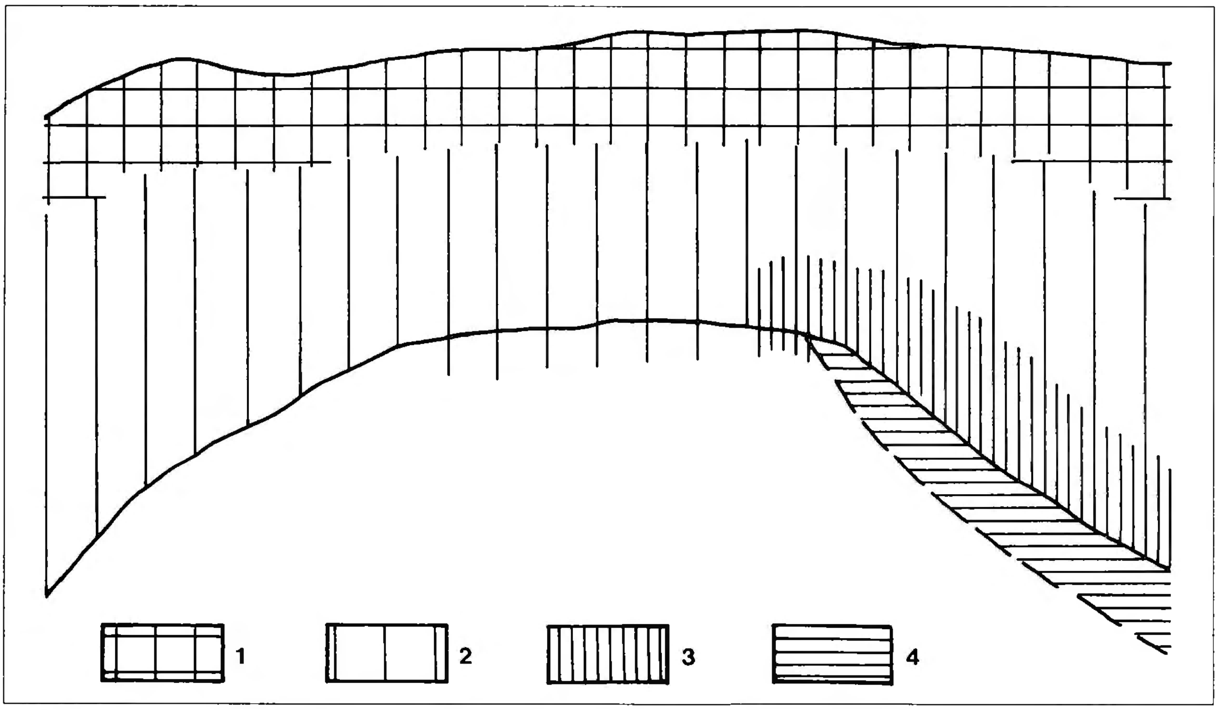
3.2.2. ROCKY RELIEF AS EVIDENT OF DIFFERENT DEVELOPMENT PHASES OF A PASSAGE

The rocky relief of passages that were formed under different conditions consists of rocky features which are due to changeable factors of the same type (different velocity of water flow); or the rocky perimeter of the passages was formed by various factors, percolation water, drainage of water above the fine-grained sediment or by corrosion due to condensed moisture and other causes which frequently caused partial transformation of older rocky relief.

a. Traces of changed hydrological conditions

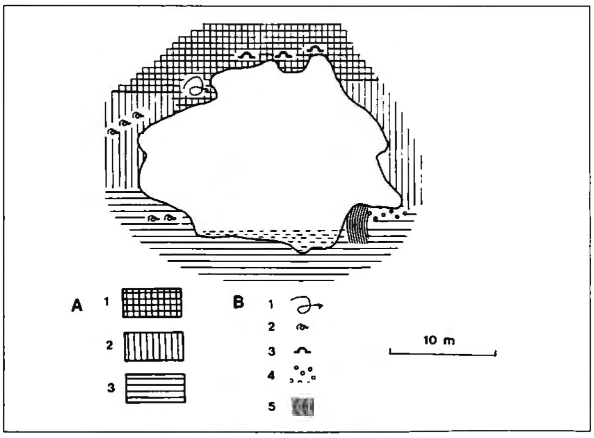
In the seasonal swallow-hole system named Beško Ocizeljska Jama there are on the walls of Novi Rov large scallops, of 1 m or more in diameter. On them there are some centimeters long scallops (Fig. 3.2.1). At first the passage was formed in the phreatic zone. Later it was partly transformed by more rapid water flow that did not last for a long time, or appeared at high waters only.

A network of variously shaped and sized scallops may be observed on a small section of projecting, horseshoe shaped passage in Markov Spodmol (Fig. 3.2.2). The floor of the inflow side of the passage that rises at an angle of 25^0 is smooth up to the first turning, i.e. in its steepest part. On the outer border of the semicircu-



3.2.2. Distribution of scallops in one section of the passage, Markov Spodmol

1. larger scallops, Type 2, old
2. larger scallops, Type 2/3
3. small scallops, Type 2/3
4. small scallops in channel, Type 1



3.2.3 Cross-section of Pivški Rokav, Planinska Jama (near Golgota) and hydrological zones of rocky relief formation

A
1. phreatic zone
2. epiphreatic zone
3. vadose zone
B
1. large scallops
2. medium sized and small scallops
3. ceiling pockets
4. below-sediment pits
5. below-sediment channels

lar-ended smooth surface there are scallops of Type 2-3 on the gently rising surface. This shape is characteristic for the scallops on the convex parts of the floor or on rocky blocks behind which the flow runs over a step. Such scallops are on the lower parts of the walls also. On the floors that descend by a gentler gradient (10^0) smaller scallops of Type 2-3 exist that are typical of fast but shallow water streams. They are from 2 to 5 cm long and 1,5 cm deep. The smallest scallops are on the floor that descends steeply at the outflow part. At first they are 2 cm long; on the steepest part, where the river-bed narrows into a semicircular passage, gradient of 45^0 and more, there are scallops of Type 1, only 0,42 cm long. The transitions between different scallops are gradual. On the upper parts of the walls and on the ceiling there are larger scallops of Type 2, characteristic of the passages with slow water flow. These scallops are older and it seems that they covered the entire passage perimeter. Later they were covered by smaller scallops on the lower parts of the walls incised by faster free surface water flow. The shape and distribution of the scallops are thus controlled by changed hydraulic conditions in characteristically shaped passages.

The rocky relief of Planinska Jama

Gospodarič (1974a) studied the gravel in this resurgence cave (Fig. 3.2.5). He stated that this indicated that the speleogenesis of the caves between the Pivka Basin and Planina Polje is similar (1974a, 180). He published the results of the study two years later (Gospodarič 1976). He determined several erosional and accumulation phases of the passages development but they could not be seen by the rocky relief. The first erosion period he associates with coloured chert gravel transported by the water velocity of 2 m/s; during the second period the water velocity of 3 m/s transported gravel of white chert. In early Würm the passages were filled up by laminated loam. The flood loam had been deposited in late Würm also. In the Holocene the sheet erosion, the floor subsidence, the speleothems collapse and the flowstone deposition appeared (Gospodarič 1976, 112). Kogovšek (1982) studied the hydrodynamics of vertical water percolation into the cave and its corrosional efficiency.

The rocky relief of Rakov Rokav reveals two distinctive development phases. The first one is the period of slow water drainage through meandering and waterfilled passages. In the higher-lying parts of the passage that are not reached by the present-day high waters there are large scallops and ceiling cups. A period of deepening and levelling of the passage came next. Even today the river incises there where it had not yet reached the rocky bottom. The water that washed the sediments out of the cave frequently drained slowly and stagnated at the breakdowns. The walls were encrusted by a manganese coating. The present-day highest discharges reach velocity of 2 to 3 m/s. in the initial passages, that have the smaller cross-sections. The water flow thus incises small scallops.

Several development phases may be deduced from the rocky relief in Pivški Rokav also (Fig. 3.2.3). Slow water flow left ceiling cups and large scallops in the higher parts of the passage (Fig. 2.3.8). In some places gravel is cemented above them. The levelling and deepening of the passage was actually the consequence of higher flow velocity. The passage deepened rapidly and old rocky features are preserved. Recent, gradual deepening of the passage and seasonally slower discharge of high waters in wider parts of the passage are indicated by medium large scallops found on the walls above the mean level of Pivka river. Fast flow that incises small scallops shapes the present river-bed. Younger above-sediment features preserved in the higher dry passages, indicate the cave filling up by fine-grained sediments. Gospodarič (1976, 112) dated the flood loam to Upper Würm.

Gospodarič (1976, 65) supposed that Pivka initially flowed through Rakov Rokav in Planinska Jama and the former route towards Malni was later used by Javorniški Tok. The rocky features confirm similar development phases in the upper parts of Postojnska Jama (Chapter 3.2.3) and in the upper part of Pivški Rokav in Planinska Jama. In both caves the oldest traces of cave development were left by slow water flow. May we associate the origin of the traces of faster epiphreatic discharge through both caves? There are wall notches indicating the deepening of the Planinska Jama passages and small to medium scallops and ceiling cups in the higher-lying (at 520 to 530 m above sea-level) passages of Postojnska Jama.

b. The rocky relief of polygenetic caves

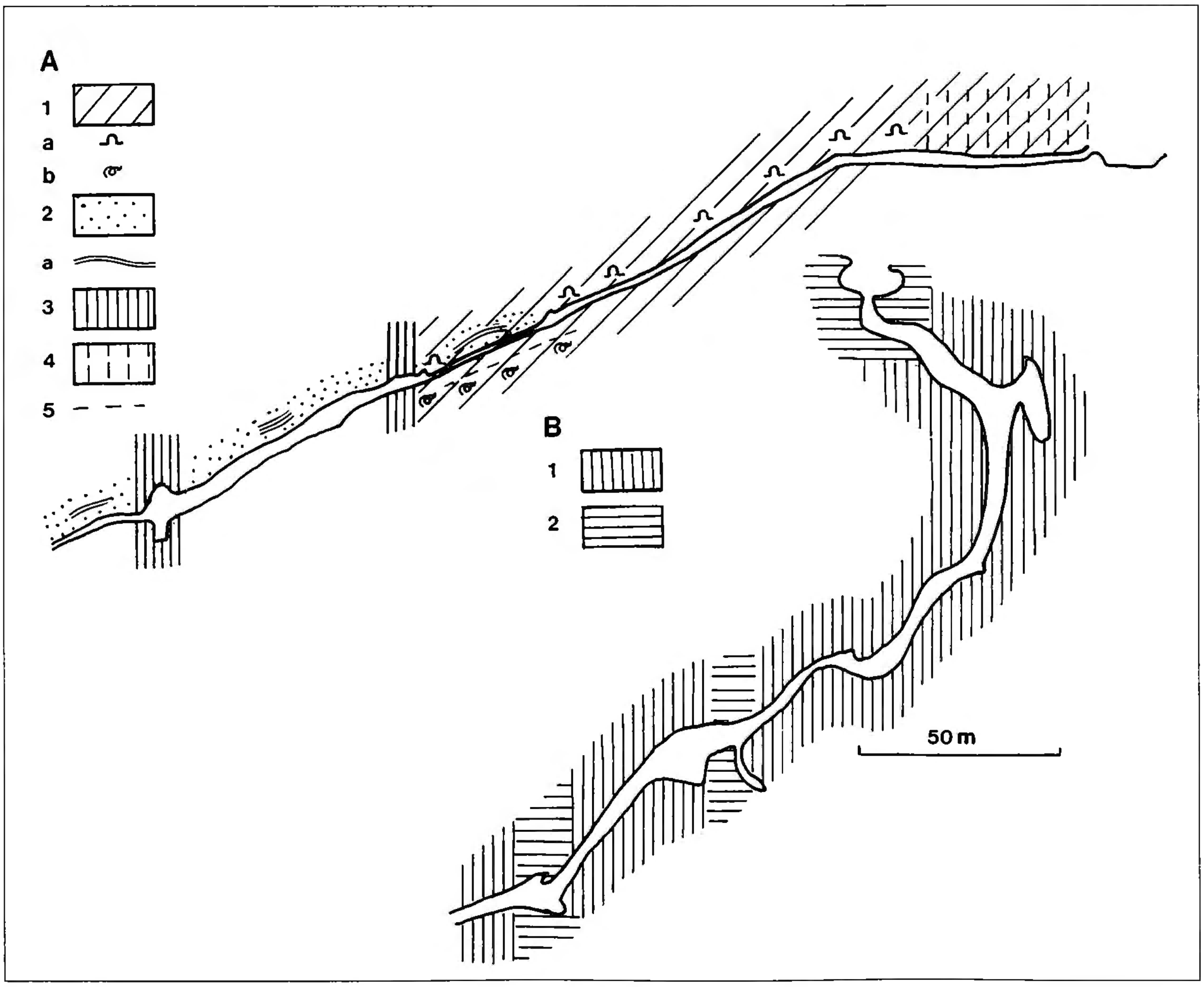
Although the rocky relief of polygenetic caves is characterized by formation due to various factors that are the consequence of changed hydrological conditions, they are distinguished from those described above because of their peculiarity. Most such caves were at first formed by water flows. Changed hydrological conditions - aquifers or their parts changed from through-flow to simple outflow - caused due to rapid vertical dissection of the karst that these caves are nowadays formed by the infiltrated water. Frequently it reaches the caves at some points only and thus the old rocky relief is preserved. I gathered the characteristics of the rocky relief in the caves of outflow aquifer on Trnovsko Banjška Planota.

The region of the high Dinaric plateaus of Notranjska, elevated up to 1800 m a.s.l. (Habič 1975, 81), is mostly a simple outflow karst area. Seldom it is of a composite type - outflow and through-flow - and this mostly in its eastern part in the area of Logaške Rovte. The diffuse recharge percolating vertically through the vegetation covered, drains to different sides. The water gathers at springs at the border of the lower valleys or karst poljes at the altitude of the gravity springs, where there are less permeable areas. Geological structure, rock fractured in Alpine and Dinaric directions, strike and dip of strata as well as a strongly dissected surface, are the most decisive factors controlling the underground waters. The water regime is directly controlled by the rainfall and the recharge in the springs quickly reacts (Habič 1982, 14).

The results of the underground water drainage in an outflow karst are typical karst caves. A theoretical type cave is a system with entrance shafts, avens in levels and interlying hanging water streams in meandering passages in the central part, with gently inclined passages in front of the resurgences and deep springs that is commonly siphon-like. Up to now the following types of the caves are accessible: 1. simple shafts of various size; 2. larger systems of deep shafts developed at the contact with thinner layers of flysch or dolomite, and also along former glaciers or snow fields (Habič 1982, 15); 3. swallow-holes controlled by the contact with impermeable rocks; 4. valley springs, commonly siphon-like, the exception being Veliki Hubelj that is a free-surface gravity spring above Ajdovščina and Smoganica on impermeable rocks below Banjšice; 5. polygenetic caves which are old, horizontal or gently inclined caves at various above sea levels and interrupted by avens. A special microclimatic type are ice caves.

Habič (1974) presented the properties of the caves on Trnovski Gozd. Rocky relief in Volčja Jama and in Ledenica na Dolu is explained in Acta Carsologica (Slabe 1990, 165). Velika Ledenica in Paradana was described by Mihevc & Gams (1979), Mihevc wrote about the avens types in it (1990). Zupan & Mihevc (1988) studied the origin of the cave sediments in it. The sediments in Babja Jama were studied by Kranjc (1982, 1989). The same author inferred that the pebbles at the lee side of the cave are corrosionally etched (Kranjc 1985).

Similar as is the case for most caves at more than 1000 m of altitute it is true for the selected caves: Velika Ledenica in Paradana, Ledenica na Dolu on Trnovski Gozd and Volčja Jama on Nanos the present-day prevailing percolation of mostly corrosionally aggressive



3.2.4 Rocky relief and hydrological zones of its formation in Ciganska Jama

A
1. rocky relief shaped by water stream
a. ceiling pockets
b. scallops
2. along-sediment rocky relief
a. above-sediment channel
3. rocky relief shaped by trickling water
4. rocky relief transformed by condensation corrosion
5. floor channel
B
1. epiphreatic zone
2. vadose zone

waters. However, their shape with gently inclined passages suggests an origin in an entirely different environment to the one that rules today.

Older traces of speleogenesis may be perceived at the rocky perimeter of high-level, gently inclined passages. At first a slow stream flowed through Volčja Jama and the passages were waterfilled. Later they were filled up by fine-grained sediments (Slabe 1990, 173). The sediments remained in the cave for a long time, the water infiltrating through the roof washing them away slowly. Similar development may be deduced from rocky features in Velika Ledenica in Paradana. In Ledenica na Dolu there are only traces of water drainage along the fine-grained sediments (Slabe 1990, 185). In Volčja Jama and in Velika Ledenica in Paradana the perimeter was etched and thinly dissected at the contact with the sediments. The waterfilled zone and the flood deposition in the cave are typical properties of lowland karst development. The sediments that filled Volčja Jama and Velika Ledenica in Paradana are due to weathering in warm climatic periods. The sandstone in Velika Ledenica in Paradana is incorporated into sediment that contains not only the minerals of the rocks around the cave but also quartz grains. These grains are rounded and indicate allochthonous, eolian or fluvial origin. Coarse grains of quartz probably had their origin in a parent rock (Zupan 1990, 35). Into Volčja Jama too the clastic sediments were transported by water and were later subdued to diagenesis (Zupan 1990, 18). Were the passages in different caves but at the same altitude filled up in the same period or is the sedimentation local? The first hypothesis may indicate that the sedimentation was controlled by impermeable Pliocene cover where superficial streams flowed (Habič 1970, 129). The impermeable rocks are locally preserved for a longer time. Strong karstification followed as the sediments are preserved in the caves and were diagenetically transformed.

In time most of the sediments were removed by the percolation water. Water is an important factor of the second typical phase of cave formation in the upper part of mainly outflow karst. Where there are no traces of percolation water the old sediments are preserved. Hence in the upper parts of cave systems, certain trickles of percolation water predominated even in the time of melting of the abundant snow and ice that covered the surface during cold Pleistocene epoch. Mihevc & Gams (1979, 13) assumed that cave formation was most prominent in Würm when there was snow on Trnovski Gozd at altitudes from 1250 to 1300 m and avalanches accumulated the snow in Paradana and from the cave the streams trickled out. The formation of smaller passages among the avens probably belongs to the time of the most water trickling out. The rocky perimeter of the upper parts of the cave is at present formed not only by percolation water but also by corrosion beneath the ice cover and by weathering due to moisture freezing. There, where these factors are moderate, so also are the traces of corrosion traces due to condensed moisture and biocorrosion. Roof collapse connects old caves to the surface.

In short, tectonic uplifting of the aquifer and lowering of border valleys caused remarkable karstification and allowed preservation of the oldest rocky relief, if, obviously it is not obscured by the present-day cave formation processes. Higher caves where old rocky features are frequently preserved are actually transformed by aggressive water, by weathering of the perimeter due to freeze-thaw effect, and by corrosion below the ice. Slower, however enough conspicous for the preservation of older rocky features, is the karstification in the areas that consist not only of carbonates but impermeable rock layers too; the latter enabled the preservation of active water caves at higher altitudes. Thus polygenetic caves may be divided into the ones where are the traces of older formation and the others through which water drained. Spring caves commonly contain recent features directly related to present-day seasonal high-velocity flow through them. The karstification was faster than the valleys entrenchment, this is why larger cave system do not appear at higher altitudes (Habič 1970, 130).

Rocky relief in Ciganske Jame near Predgriže

Ciganske Jame is located at north-western, higher part of Notranjska at the border of Črni Vrh polje. In the cave there are older traces of water drainage in the phreatic zone and also diffuse water percolation that still persists today (Fig. 3.2.4). The later process is less efficient as the water infiltrates at some places only and so traces of the former cave development are well preserved. There are scallops on the floor of a narrow part of the passage with a circular cross-section, through which water used to drain fast. In larger parts of the cave and along the fissures in the narrow passage there are ceiling cups. Flood water filled the cave with fine-grained sediments, and above them smaller amounts of water drained by above-sediment channels. The water stream that transported the sediments out of the cave partially transformed the ceiling channel also. Percolation water in the narrow passage incises half tubes and pits on the walls and a floor channel also. The entrance parts of the cave are formed by condensation moisture corrosion.

Another type of polygenetic cave may be added. These are swallow-caves at the contact with flysch. The caves that are active only during high waters are transformed by the percolation water infiltrating from a thin flysch cover above them. An appropriate example is Kamenšca below the flysch of Brkini.

3.2.3. ROCKY RELIEF OF LARGE CAVE SYSTEMS

Even more informative than the rocky relief in particular passages is the speleogenetical importance of that in genetically associated cave systems. Their rocky relief reflects the changes of hydrological conditions during the formation of certain parts of the cave, seasonal infilling by fine-grained sediments with water drainage above them, and, of course, more recent factors that have partly transformed older passages. Let me mention two examples of frequently visited caves on the Pivka basin border.

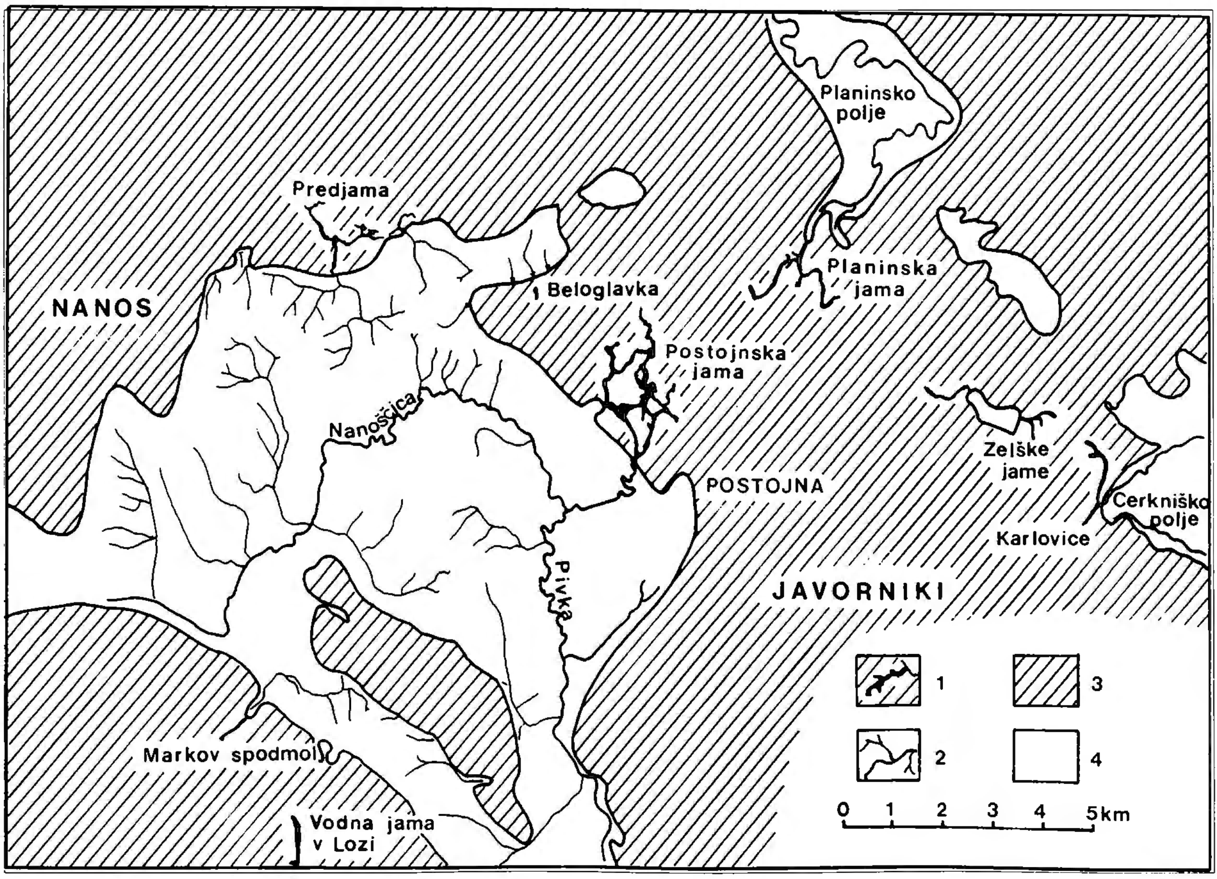
Gams (1974, 214) called the Pivka basin the Postojna Karst Polje. The karst outflow prevails there. The waters run off the flysch (Fig. 3.2.5) in numerous directions. In the east side, Pivka disappears into the karst of Postojna. The waters from the SW, from the valley near Studeno, flow in the same direction. From the northern part of the basin the waters drain into Podgora at the foot of the Nanos, and the Lokev is a tributary flowing to Vipava. Higher on the border of the basin there are either dry caves or caverns filled by sediments. In the south, the waters disappear in blind valleys at the border of the Slavinje karst and drain towards the Reka. There are karst springs at the foot of Javorniki.

Brodar (1952, 71, 72) distinguishes four phases of the basin's surface and related cave development. The main erosion phase is supposed to start in the younger Pliocene and to last to the end of the Pliocene or even to the beginning of the Pleistocene. The first considerable accumulation phase belongs to the old Pleistocene. He attributes a younger erosion phase to the end of the old and partly in the younger Pleistocene. In the last accumulation phase the water transported red loam into the caves red loams and deposited it in the higher passages. Gams (1965) associates the swallow-holes and caves between Postojna and Belsko with the remains of blind valleys at the contact of flysch and limestone. Gospodarič & Habič (1966, 28) infer that the main accumulation terrace is of Riss age, although Brodar (1952) attributed it to the interglacial before Riss. Gospodarič (1989) summarizes the knowledge about the hydrographical phenomena and hydrogeological properties of the rocks in the western part of the Pivka basin. Mihevc (1991 b, 162) describes the types of contact karst in the Pivka basin, its gelogical structure and hydrological properties.

Rocky relief of Postojnska Jama

The longest Slovene cave system, Postojnska Jama (Fig. 3.2.5), consists of several caves with independent entrances: the underground Pivka, Lekinka and Pivka Jama with active passages; Črna Jama with seasonal water flow; and Magdalena, Otoška and Postojnska Jama with dry galleries.

Brodar (1952, 44) places the paleo Pivka flow in the cave at 538 m above sea-level. Rakovec (1951) describes the climate before the Würm culmination. Brodar (1966) analyses cave development phases already described (1952). Gospodarič & Habič (1966) describe the



3.2.5 The Pivka basin and a part of Notranjsko Podolje with selected caves

1. caves

2. superficial water flows

3. limestone

4. impermeable soil: flysch and alluvium runoff from the Pivka basin in the Quaternary, based on morphology around Postojna. The main passages of Postojnska Jama should date to the end of Lower Pleistocene. They place the development in a presently dry galleries of Postojnska and Otoška Jama before the Mindel Riss interglacial (1966, 28). Gams (1965) analyses two main development periods of Postojnska Jama referring to the size and inclination of the passages. The passages at 537 m belong to the first period and the passages at 520 m to the second. Gospodarič (1969, 43) divides the cave development into eight phases: cavitation of horizontal rocky passage, gravel infilling before the Riss Würm interglacial, flowstone deposition, gravel erosion, repeated flowstone deposition, the flood up to 536 m above sea-level and erosion of the sediments, and again flowstone deposition as the latest epoch of the cave history. Gospodarič (1976) analyses the sediments and the flowstone in the cave and their speleogenetical importance. He classifies the gravel of coloured chert as medium Quaternary, the gravel of white chert as Riss, red loam as Riss Würm interglacial and flood loam as early and late Würm.

I tried to complete the cited knowledge by studying the cave rocky relief (Fig. 3.2.6), although it offers only partial insight into the cave development. The former perimeter of a presently dry passage is significantly transformed due to weathering, and is encrusted by flowstone and deposits. Frequent changes within the development of a dense network of passages caused younger rocky features to cover older ones. Short-term development phases are not reflected in rocky relief.

The rocky relief in the caves may be divided into four development units. On the ceiling and upper part of the walls of the passage Rov Brez Imena large scallops and ceiling pockets occurred at 540 to 545 m above sea-level. Probably the ceiling pockets between Velika Gora and Koncertna Dvorana (530 m a.s.l.) belong to the same time, as well as large scallops and ceiling pockets in Dvorana s Palmo in Pivka Jama at 500 m above sea-level. Similar traces left by slow water flow in the phreatic zone are found in a small passage which joins Male Jame at 520 m a.s.l. and in small passages below the ceiling (530 m a.s.l.) in Spodnji Tartar. These traces indicate the early period of cavitation. The passages were formed before the medium Quaternary infilling by sand and coloured chert gravel according to which Gospodarič (1976, 85) inferred the older development of Otoška Jama and Zgornji Tartar. The phreatic conditions of passage formation differ from the conditions when the gravel was deposited. The eroded flowstone in Pisani Rov (Zupan 1991, 193) at 530 m a.s.l. has been dated to the beginning of Mindel.

The relief typical of epiphreatic channels draining the water flow of medium velocity is found at the lower part of the perimeter of Rov Brez Imena, in Pisani Rov and in Stare Jame. Medium sized scallops and ceiling pockets indicate a water velocity of 0,25 to 0,35 m/s. These features lie at 520 to 530 m a.s.l.

Even younger are the traces of more rapid epiphreatic water flow at 510 to 520 m above sea-level. The water flowed from the underground Pivka direction through both Tartars and through the initial loop in Male Jame towards Lepe Jame. Small scallops remain on the walls. Gospodarič (1976, Table 2) attributes the passages development at this altitude to early and middle Würm.

According to the rocky relief one may trace another, even younger period of the cave development. Infrequent above-sediment rocky features suggest that younger sinking streams periodically flooded the upper passages up to 530 m above sea-level. Anastomoses are found at the border of Koncertna Dvorana, in Rov Koalicije and in Matjažev Rov covering older traces of water streams. Hence the cave was filled up by fine-grained sediments. Gospodarič (1976, Table 2) classifies the flood loam as of Würm period.

The relief of the underground Pivka river bed is formed by present-day waters of medium velocity in water-filled sections and free surface high velocity flows in the larger parts of the cave.

To summarize: the oldest water flows drained in the phreatic zone from the SE towards N and NW and through the cave of Pivka Jama. At that time or a little later, the water drained from Otoška Jama towards E and NE. Probably there were more swallow-holes. Younger, epiphreatic water streams that drained from the south to the north, have formed Stara Jama. Zgornji Tartar was reactivated when the water from the SW, from the ancient passages of the underground Pivka, drained towards the N.

The cave rocky relief may provide evidence of the most distinctive consecutive development phases, the mode of drainage through the passages, and the direction of water flows.

Rocky relief of Predjama

A lot of papers were written about the ponor cave Predjama and the castle above it. The most detailed description of its development was made by Habe (1970). Gams (1974, 219) studied it also. Šebela (1991) analyses the superficial geological structures and their influence on the cave development. Habe (1970, 73) implies that at the end of Pliocene and at the beginning of Pleistocene the water drained into Fiženca and Erazmov Rov from the present-day valleys of Belščica and Osojščica, from Šmihelske and Stranske Ponikve and from a part of Nanoščica. The strong Belški Potok stream flowed through Vzhodni Rov when Stara Jama and Zahodni Rov were dry. This tributary joined the cave due to rapid deepening of the passages. When the water flow was displaced into lower-lying passages the two independent streams of Ribnik and Mrzlek started to appear and joined Belščica (Habe 1970, 76).

According to the rocky relief (Fig. 3.2.7) in the passages we may infer several development phases of the cave. Slow water flow shaped Fiženca and Erazmov Rov in the phreatic zone. The upper part of Fiženca is composed of several smaller, meandering passages. The same indicates the cross-section of the final part of the passage (Fig. 2.3.53). A slightly faster water flow drained from Konjski Hlev to Stara Jama in the entrance part of the cave. Larger scallops and ceiling pockets indicate the flow of medium velocity through water-filled passage towards the cave interior. The water gradually formed the passages at lower altitudes. The oldest traces of the water drainage in Vzhodni Rov are medium-sized scallops on the upper sides of the walls and solution cups on the ceiling. The breakdown in Polževa and Črna Dvorana and seasonal high waters caused to be the entrance part of the cave frequently flooded. The water flow upwards in Blatni Rov left larger scallops on the ceiling of the passage up to Črna Dvorana. More frequent high floods, after the present-day bottom of the cave had been already formed, are suggested by above-sediment features. The cave was filled by the sediments up to Imenski Rov, i.e. the whole Blatni Rov, the passage connecting Severjeva Dvorana and Vzhodni Rov, and the old passages of the central part of the cave. The present-day waters drain through the lower passage and, during floods, partly submerge Blatni Rov where fine-grained sediments are deposited. Below-sediment solution bevels occur.

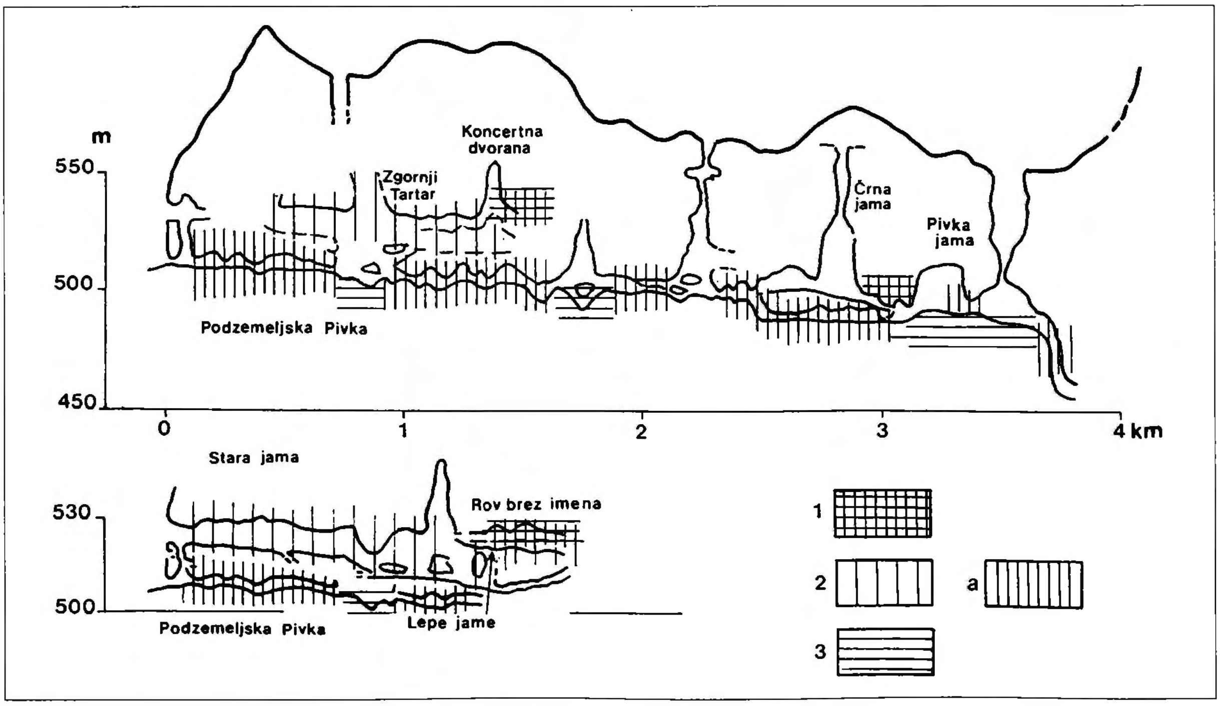
The rocky relief of Vzhodni Rov indicates that during the recent cave development the most efficient water flow is of high and medium velocity which floods one part of the passage. It incises scallops and smaller potholes and deepens the riverbed. In the swallow-hole of Lokva the rocky relief (scallops, ceiling cups) is formed by faster water that seasonally floods the whole passage. In the entrance part of the passage only the bottom of the river bed (small scallops) is formed by high velocity flow.

3.2.4. ROCKY RELIEF AS AN INDICATOR OF SPELEOGENETICAL UNIT DEVELOPMENT - AQUIFERS

I tried to evaluate the importance of cave rocky relief in karst aquifer studies. Again a need for interdisciplinary speleological studies emerged. At the same time it may be confirmed that an understanding of the rocky relief is one of the bases for explaining the conditions under which various factors controlled the karst underground development. I shall present the results about the speleogenetical meaning of the rocky relief in selected caves of Kras. For a complete presentation of karst area speleogenesis not enough caves have yet been studied and the accessible caves offer only a limited insight into the aquifer development. However the hypothesis is offered as a basis for further studies. It has been proved that karst areas often have individual speleogenetical properties with several local varieties.

Speleogenetical importance of rocky relief in selected caves on the Classical Karst

The Classical Karst is the area between Vipava valley on the N and NE, Brkini on the SE, Trieste Bay on the SW and the Soča valley on the NW (Melik 1960, 188). The waters that drain through the area are gathered on the flysch of the Brkini, Senožeče and Vipava valleys, and of the Karst Pivka basin, and the Soča Valley gravel. From the surface the water disappears dif-



3.2.6 Hydrological zones shaping Postojnska Jama
1. phreatic zone
2. epiphreatic zone with slow water flow
a. epiphreatic zone with more rapid water flow (present-day formation)
3. vadose zone

fusely underground and reappears at the coast. Larger swallow-holes developed at the contact with the flysch as Škocjanske Jame. The Reka river is reached again in Kačna Jama and in Labodnica. I included in my studies (Fig. 3.2.8) the swallow-hole Škocjanske Jame, the through cave Labodnica and the dry caves of Divaška Jama, Trhlovca, Vilenica, Petnjak and Lipiška Jama. Close to the surface there are dry caves with traces of water flow preserved in the rocky relief or in the sediments. These caves were unearthed at the construction works for the motorway. At first they were formed as phreatic conduits, and later transformed by faster water streams, as evidenced by smaller scallops and gravel, and finally filled up by fine-grained sediments.

Gams (1974, 197) infers that the Classical Karst got its main relief in Tertiary when it was lower than the flysch in the Vipava valley and Brkini. Radinja (1972, 214) provides evidence of the period when water drained on the Karst surface, by the remains of paleofluvial material. After the anticline displacement that started in the Miocene, the flysch remained on the elevations only. The streams transported it into the caves (Gams 1974, 197). According to Maucci (1960) the karstification started at the end of the Pliocene.

Rocky relief of Škocjanske Jame, Labodnica, Trhlovca, Divaška Jama, Vilenica, Lipiška Jama and Petnjak

Summaries of the previous studies on Škocjanske Jame are provided in the publication of the Karst Research Institute workers (Habič et al. 1989). Knez (1994) studies the phreatic channels developed along the bedding planes.

In the lower passages of Škocjanske Jame (Fig. 3.2.9) and in Labodnica the rocky relief is formed by the Reka river. Its discharge in Škocjanske Jame can increase to 387 m^3/s; during drought about 500 l/s disappear in the river bed some 5 km before reaching the swallow-hole at Škocjan. The contact karst along the ponors of Notranjska Reka was presented by Gams (1983) and Mihevc (1991 b, 125). Reka is the largest Slovene sinking river and the huge underground spaces confirm this. The cave consists of upper dry passages and lower active ones that are obstructed and at the same time linked by two huge collapse dolines. The water passages are canyon-like with steep walls close to the river bed. Hankejev Kanal is particularly canyon-like. 77 m high ceiling the passage enlarges to a width of 15 m. In front of the final Mrtvo Jezero the passage is 40 m wide and 120 m high. The gradient of the Reka between the ponor in Mahorčičeva Jama and Martelovo Jezero in front of the siphon is 35 $^0/_{00}$ (Kranjc 1986 a, 112). The water drains through this passage relatively fast; only after heavy rain it starts to choke and the flood water level in the cave may reach 80 m. The transport of fluvial sediments through the cave was studied by Kranjc (1986 a). The sand in the cave is poorly sorted and this indicates the torrential character of the flow. The amount of limestone gravel increases towards the interior of the cave. The gravel on the slope in Czoernigova Jama was deposited by flow more rapid than at the present-day (Kranjc 1989, 92). In the entrance part, in front of the swallow-hole to Šumeča Jama, the river bed is cut in rock, and sections with cascades and waterfalls alternate with lakes. Large potholes are incised into the rock. In Šumeča Jama and in Hankejev Kanal the river flows through the breakdown blocks. On them and on the rocky perimeter of the river bed there are, typical small scallops (Fig. 2.3.6) and potholes of various size (Fig. 2.3.38), due to a high flow velocity of almost 2 m/s. The wall niches in Mariničeva Jama and in Hankejev Kanal indicate the levels of the water flow. The Reka is the most efficient during high waters. A thin film of flowstone encrusts the bottom of the river bed.

The rocky relief of the water passage in Labodnica consists of small scallops, of rather irregular shape due to fractured rock, and also ceiling cups. The scallops indicate the higher flow velocity. On the lee-side walls in the active passage and on breakdown blocks in the lower part of the chamber there are below-sediment solution bevels and pits. This part of the cave is seasonally flooded.

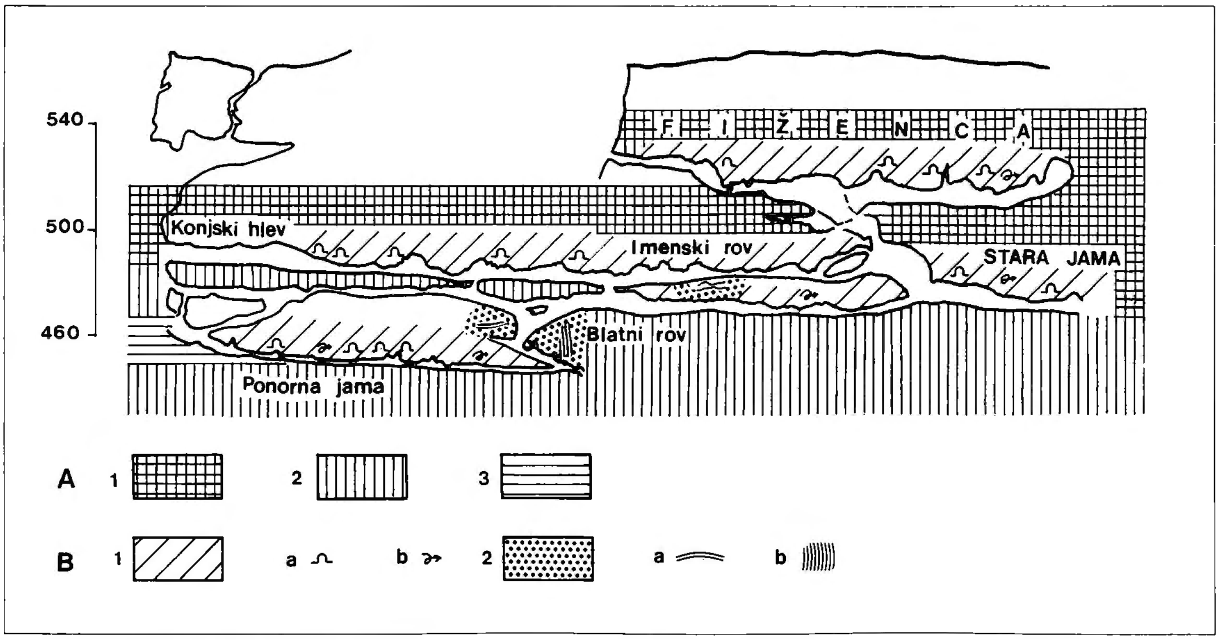
Rock weathering is an important process in the formation of the rocky perimeter in the selected caves, in particular the huge passages in Škocjanske Jame. In Petnjak it is accelerated by moisture freezing due to cool winter air penetration into the large rock-shelter. In Škocjanske Jame and in the entrance part of Trhlovca the rock is etched by the condensed moisture. Traces of percolation water in Divaška Jama are floor pits due to water dropping through shallow cave roof. Percolation water has shaped the avens in Labodnica.

The speleogenetical importance of the sediments in Škocjanske Jame, Divaška Jama and Trhlovca was analysed by Gospodarič (1984, 1985). The passages and sediments at altitude of 370 to 390 m in Škocjanske Jame (Gospodarič 1984, 45) date to Early Pleistocene. The passages associated with the formation of the nearby caves are characterized by meanders and low cross-sections in present-day active passages. In the Middle Pleistocene the active passages are thought to be at 310 to 330 m a.s.l. The river was less torrential than it is nowadays and it sank underground at several places at the same time (Gospodarič 1983, 23). Gams (1983, 23) suggests that the Reka drained through several passages at the same time and that one of them was Tiha Jama. During the Würm the caves were exposed to the sharpest changes. Hankejev Kanal was deepened, and older sediments were removed from the upper passages (Gospodarič 1984, 45). In the cold Würm culmination (W3) the cave became connected to the surface by the collapse dolines Mala and Velika Dolina (Gospodarič 1983, 166).

The old rocky relief in Škocjanske Jame (Fig. 3.2.9) is preserved on some sections of the perimeter only, and consists of ceiling cups, scallops and above-sediment anastomoses. Hence it reflects minute phases within the cave development. The ceiling cups due to slow water flow in waterfilled passages are found in Mariničeva Jama, in Dvorana Ponvic and in Müllerjeva Dvorana of Tiha Jama, at 310 to 330 m a.s.l. According to Gospodarič (1984, 45) the Middle Pleistocene sediments are preserved at this altitude. I infer that the Globočak collapse doline blocked the water route through Tiha Jama. Gradually the main water passage developed into the upper part of Hankejev Kanal. When the water route was restored and was again passable for all the waters, the passages previously filled up by sediments in the central part of the cave became active for a short time. Small scallops in Czoernigova and Brihta Jama are the evidence for this. The water had high velocity over the sediments in the seasonally flooded passage. This period was short term as the passage preserved its angular perimeter. In short, the cave relief described and the sediments indicate the diverse periods within the cave development under changeable climatical conditions as the cave was being deepened. A sharp cut down of the water streams into the rocky bottom followed and the role of the main passage in the initial part of Škocjanske Jame was overtaken by Mahorčičeva Jama and Mariničeva Jama. The central part of the cave and Hankejev Kanal deepened substantially too. Wall notches reflect the progressive passage deepening. The water flow was free-surface, and the rocky relief developed proportionally. Active passages became more linear and canyon-like. Gospodarič (1988, 93) attributes the initial period of rapid downcutting of the water flow to changed glacioeustatic conditions in the Adriatic Sea due to climatical and hydrological changes in the Upper or Middle Würm.

Gospodarič (1985, 32) was of the opinion that Trhlovca was filled up by brown laminated loam in the Günz glacial before Divaška Jama was excavated. That cave too is thought to be filled up by laminated loam in Mindel. Both caves were filled up by red and brown loam transported from the surface by water during the Riss. Šušteršič (1972/73, 239) considers that Trhlovca is a swallow-hole with typical cross-section. Vilenica too would have been formed by a sinking stream (Šušteršič 1972/73, 322). Gams (1984, 7) connects the development of Vilenica with the period of lowering of the piezometric level and hence the streams from the flysch disappearing underground. At the same time he estimates (Gams 1984, 8) that there are no traces of weathering due to freezing in the cave and that its entrance belongs to the Holocene. And what is the evidence of the old rocky relief in these caves?

Traces of slow water flow in the phreatic zone are seen in Trhlovca (large scallops and ceiling cups) and in Petnjak (ceiling cups) at 400 m above sea-level. If the Gospodarič analyses of the sediments are accurate these traces must have been formed in pre-Günz periods. Trhlovca was later transformed by a slightly faster water flow, that at first flowed in the epiphreatic zone towards the cave interior and deepened the cave into a narrow, meandering passage. The rocky relief that developed in the phreatic zone marks the central passage by medium sized scallops on the perimeter. I infer that after lowering of the piezometric level the caves were



3.2.7 Rocky relief and hydrological zones shaping Predjama

A

1. phreatic zone

2. epiphreatic zone

3. vadose zone

B

1. rocky relief shaped by water flow

a. ceiling pockets

b. scallops

2. along-sediment rocky relief

a. above-sediment channel

b. below-sediment channel

reshaped by sinking waters that used older passages. The sinking waters gathered from the flysch patches and flooded the cave seasonally. A smaller network of above-sediment anastomoses is the evidence for this.

The traces of slow water drainage in the phreatic zone (large scallops and ceiling cups) are to be found in Divaška Jama (360 to 390 m a.s.l.), in the upper part of Vilenica and in the upper passages of Lipiška Jama (340 m a.s.l.). Due to piezometric level lowering the water gained velocity through the cave. It left medium-sized scallops (Kozinski Rov in Lipiška Jama). The passages were still water-filled. Seasonal water level increase is suggested by the traces of water flow that drained upwards through the old passages in Vilenica and in Lipiška Jama. After the Riss Würm interglacial the floods did not reach the upper part of Vilenica (Zupan 1991, 203). There is no evidence from the rocky relief that Vilenica was formed by a sinking river. Its upper parts lie at the same elevation as the epiphreatically transformed central part of Trhlovca.

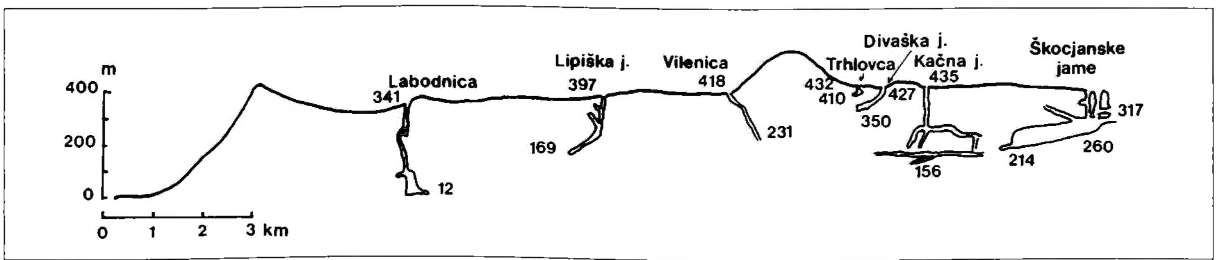
In the lower parts of Lipiška Jama (Kozinski Rov), in Vilenica and in Škocjanske Jame, namely in Tominčeva and Tiha Jama and in the upper part of Hankejev Kanal there are above-sediment anastomoses. Probably they developed above the young Würm fine-grained sediment that may be traced in other passages of Škocjanske Jame up to 350 m above sea-level (Gospodarič 1984, 42). In that time the cave was almost completely filled up by the sediments. The floods may be recognized in the flowstone in Tiha Jama also that has been out of reach of erosion for at least 13000 years (Gospodarič 1983, 166). The flowstone dating from Kozinski Rov (Zupan 1991, 196) is evidence for the older, pre-Riss floods. Older paragenetic rocky relief is preserved only in Trhlovca. In nearby Divaška Jama there are no such traces.

3.2.5. THE DEVELOPMENT OF THE SELECTED CAVES ACCORDING TO ROCKY RELIEF EVIDENCE

The oldest rocky relief in most of the selected caves is, as a rule, the trace of slow water flow in the phreatic zone. In through-flow karst it is preserved in the upper parts of large cave systems (Predjama, Postojnska Jama) in old, dry caves (Logaška Jama, Trhlovca, Divaška Jama, Golobja Jama and others) or in huge passages through which the water flows still nowadays (Pvški Rokav in Planinska Jama). Smaller surfaces of such relief may be found in some polygenetic caves on present-day, higher mostly outflow karst (Volčja Jama). The dating of the rocky relief formation could not possibly be directly evaluated. Rather spacious passages reflect the long duration of formation and a considerable runoff of water. In formerly water-filled passages there are almost no spongework traces (Bretz 1956, 15, 16) such as ceiling pockets, pendants and arches. This indicates rather distinctive water flows through the caves and the opening of impermeable barriers that surrounded the carbonate rocks. The caves started to form as a network of anastomosis channels along the bedding planes and fissures (Šušteršič 1994, 19, 20). The subsequent cave development is due to rock bedding and very fractured carbonate rocks. The passages are therefore often meandering, and cave network appears at the vertical and horizontal axis.

In the epiphreatic zone typical passages are formed also. Seasonally flooded passages with frequent traces of higher water velocity or below-sediment rocky features are commonly at lower elevations and younger than those described above. This is due to distinctive vertical tectonics of the karst areas and removal of the related impermeable rocks. During constant karstification the traces of underlying phreatic conditions are disguised. Free surface streams form larger passages. Šušteršič (1994), too, accepts the properties of the Slovene karst aquifers in tiers as it was proposed by Worthington (1991) in particular. Ewers (1982, 377) emphasizes the importance of fractured rock for the mode of karst underground formation.

The variety of climatic conditions in Pleistocene controlled another distinctive phase within the cave development. In glacial periods the waters filled up the caves by sediments (Gams 1956, 3). This is confirmed by rocky relief. Fast water flows transported gravel into the caves. Probably the superficial water streams reappeared in many places (White 1988, 307). The caves were frequently flooded and filled up by fine-grained sediments. Older sedimentation is preserved in polygenetic caves that are today higher above the water level. Younger deposits are found in most caves of the through-flow low karst. One such flood period that probably included most of our low karst appeared, according to Gospodarič (1976, 100, 112; 1982, 191) sediment studies, during the Upper Würm glacial or in the



3.2.8 Cross-section over Kras

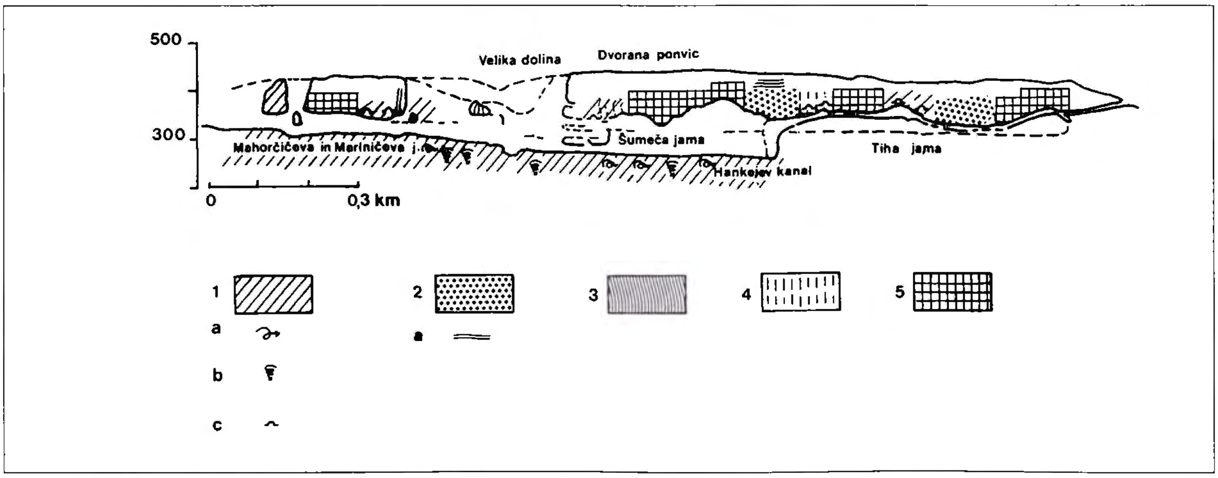
postglacial. The floods were due to substantial climatic changes including a lot of rainfall and snow and ice melting. Relatively young above-sediment rocky features are found in the caves at the border of the Pivka basin and on the Classical and Istrian karst. Gospodarič (1988, 94) attributes the rise in the sea level to this period. The preservation of thiss kinds of rocky features suggests the degree of the floods that filled high, previously dry passages. The period of karstification followed, downcutting and deepening the caves and removing the deposits.

3.2.6. ROCKY RELIEF AS A SPELEOGENETICAL INDICATOR

The study of rocky relief may contribute to the explanation of karst underground development. There are few examples illustrating several periods of the particular parts of the cave development. Commonly the speleogenetical comparison of the rocky relief in the caves that consists of several passages and in polygenetic caves is more successful. Almost always, however, it is possible to compare the prevailing rocky relief in typical caves of the karst areas belonging to a speleogenetic single activity. The present-day outflow karst was karstified the most rapidly. Vertical cave systems and polygenetic caves are characteristic. The vertical water drainage through the caves is usually diffused and thus the old rocky relief could be preserved at least in some places. The kartification in most of the present-day through-flow karst regions was slower although it was distinctive enough to preserve the old rocky relief which is the indicator of the typical development phases. Younger processes in dry caves, as condensation moisture corrosion and biocorrosion but not the perimeter disintegration, are not efficaceous enough to reshape older traces of water flows. The older rocky relief is partly preserved in above-sediment rocky features.

Karstification by lowering of the undeground water level in the aquifer is mostly controlled by vertical dissection of the karst areas with respect to the surrounding impermeable rocks that present a hydrogeological barrier. The vertical karst dissection is due to tectonics and erosional lowering of the surrounding valleys and lowlands. The regional water table is indirectly controlled by the sea level. Climatic changes influence the latter and also the infilling of the caves by sediments. Erosion of impermeable rocks was prominent in glacial periods. During warmer (interglacial) periods karstification and emptying of the caves by water flows was more typical. The streams cut down into the rocky bottom of the passages and provide water to lower lying, flooded parts of the aquifers. The more rapid the karstification, the better the typical rocky relief is preserved in the vertical section of the cave. The development of caves (Cerknica cave system) at much the same above sea-level, disregarding the surrounding impermeable water barrier, actually prevents the preservation of old rocky relief. Different transformation processes may appear and more prominent younger ones can disguise the older traces of the cave development. This is typical of the karst areas that are subsiding and where the waters deposit sediments.

Frequently the speleogenesis was not uniform but occurred in steps. This is mostly due to relatively quick changes of climatic conditions and piezometric water level, and the transport and deposition of sediments. At a defined altitude above sea-level one prevailing factor may leave traces or there may be several different factors in sequence followed by quick lowering of the piezometric water level leaving the cave dry. Therefore



3.2.9 Rocky relief in Škocjanske Jame

1. Rocky relief that is (was) shaped by water stream
  - *a. scallops*
  - *b. potholes*
  - *c. ceiling pockets*

2. Along-sediment rocky relief
  - *a. above-sediment channels*
  - *b. above-sediment anastomoses*

3. Rocky relief shaped by trickling water

4. Rock transformed by condensation corrosion

5. Rocky relief shaped by perimeter disintegration the traces left by slow water flows in phreatic caves are preserved. Slow karstification would transform them, the sediments would hide them, quick karstification in stages, preserves them. However it is true that the lower parts of the perimeter in some spacious old passages may be transformed by faster water flows (Fiženca in Predjama, Logaška Jama). The cross-section of Pivški Rokav in Planinska Jama indicates relief that reflects slow water recharge in the deep phreatic zone, medium water flow that left the scallops on the walls and fast water flow that forms the present-day cave river bed. In the western part of the Istrian karst as well (Slabe 1994 b) the traces of slow water flow prevail in the phreatic zone of all the higher lying caves. Younger factors, such as percolation water, condensed moisture or biotical etching, eventually partly covered them. The prevailing relief is due to fast opening of the flysch border. In Zadlaška Jama the development by stages is due to the glacier that filled the valley and later melted. In the through-flow karst regions the most remarkable epiphreatic streams are in accessible active caves. Because of fast karstification in stages vast passages with free surface flow are few.

In short, the karstification in stages controlled the diverse cave formation and at the same time enabled the preservation of old development traces. But it is difficult to distinguish among the extremely diverse development periods that occurred in all or most of the passages at the same elevation. Younger processes covered the traces of older ones.

4. CONCLUSION

The rocky features composing the morphology of the karst caves are controlled by different speleogenetical factors acting upon the rock. Water flows, infiltrating water and other factors influence the rock and remove their products. The rock that composes a rocky cave perimeter controls the origin of various rocky features and influences their development and formation by its structure, and how it is bedded and fractured. Actually the same factors can form different features on different rocks. carbonate rocks are usually fine-grained and rather homogeneous. On such rock the rocky features develop the best. On inhomogeneous and very fractured rock the basic rocky features do not occur. The shape of passages reflects how the rock is fractured. The typical hydraulic conditions occur when water drains through a passage composed of different sectors of various diameters and gradients. These too are reflected in rocky features. In uniform tube-like passages the scallops may occur all over the perimeter. In zones of prominent turbulence ceiling pockets occur. The rock controls the origin of rocky features that are due to other factors (trickling water, air circulation) of cave wall development. In changeable conditions the rocky features can be formed by several factors at the same time. Eventually, the most effective prevails. Faster water flow incises ceiling pockets and scallops. Seasonally slower water flow or stagnating water deposit sediment on the gently inclined walls of the solution cups and channels occur below it, and the bottoms of the scallops enlarge. When the conditions are unchanged for a long time the mature features of typical shape and size occur. During rocky feature formation its size and shape are just the stages in its development.

In active karst caves the rocky relief commonly reflects their similar or diverse recent formation. Several different development phases may occur in the same cave. In vast caves the rocky relief is actually a mixture of the past development phases and their present-day formation. The evidences of different development phases are preserved in old caves also. The rocky relief is the result of efficiency of younger development factors that have occurred in the same part of the cave. They may entirely transform the old relief or just slightly cover it. The most efficient factors of the rocky relief transformation are water flows, percolation water and rock weathering. Smaller streams in above-sediment channels frequently just pass over the old rocky relief; condensation corrosion and biogene factors dissect the surface of old rocky features.

Often the rocky relief illustrates the various sequences of the most expressive development phases of the cave. It offers relatively complete insight into mode of cave formation in these periods. The way the water flow drained through the passages can be perceived, as well as the deposits and the water flow above them. A prominent polygenetic character of the cave is best seen when the water flow traces are covered in some places by rocky features due to percolation water.

Rocky relief often does not offer a complex insight into the cave development. It reflects just the most efficient development periods or the moment of present-day cave formation or the obstruction of former prevailing factors. The development phases of the cave cannot be directly measured in time by the rocky relief only.

The best view of diverse speleogenetical importance of rocky relief is given by caves, typical of the aquifer, that were exposed to uniform development. Fewer different development phases are reflected in the rocky relief of a particular cave or of it part. The rocky relief is an indicator of different development phases in karst areas, especially where the piezometric water level sharply decreased or the caves were filled up by flood sediments. Although caves are not commonly formed at uniform levels, some swallow-holes are exceptions; the old traces of their formation, old rocky relief or sediments, are comonly preserved in levels. This is due to fluctuations, or lowering of water level in the whole aquifer. The significance of the rocky relief studies as a speleogenetical indicator increases in association with other speleological phenomena such as: the location of the cave within the aquifer, its shape or the shape of its parts, present-day factors of its formation, and the sediments and flowstone in it.

In short, rocky relief is an important, although limited, indicator of the recent and former formation of karst caves. According to previous results we may ascertain that its investigation is an indispensable part of speleomorphogenetical studies. Diverse systems of described relationships may be understood from the rich material offered by our karst. Experimental modelling in plaster proved to be useful. I maintain that it is a step forward from more or less successful investigation of the factors influencing the rock. The simulation needs to know most of them. New possibilities for studying the rocky features are offered by quantitative analyses and comparisons of their shape properties. Process that acts upon the rock may be rather reliably explained by microscopic observations of the rocky surface.

However new ways of further study are opening in respect of the formation of single rocky features, types of rocky relief and its evaluation as a speleogenetical indicator.

5. REFERENCES

Allen, J.R.L., 1972: The origin of cave flutes and scallops by enlargement of inhomogeneities.- Rassegna speleologica Italiana, 14/1, 3-20.

Andrieux, C., 1970: Contribution à l'étude du climat des cavités naturelles des massifs karstiques.- Annales de spéléologie 25, 441-559.

Badjura, R., 1909: Križna jama.- Dom in svet, 30-33, Ljubljana.

Bini, A., Cappa, G., 1978: Considerazioni sulla morfologia delle cupole.- Quaderni del museo di speleologia 4(7/8), 47-62, L'Aquila.

Boreli, M., 1984: Hidraulika.- Građevinski fakultet univerziteta u Beogradu, p.515, Beograd.

Bögli, A., 1969: La corrosione per miscela d'acque.- Atti e memorie 8, 19-34, Trieste.

Bögli, A., 1971: Corrosion by mixing of karst waters.- The Transactions of Cave Research Group of GB, Vol.13, No 2, 109-114.

Bögli, A., 1978: Karsthydrographie und physische Speläologie.- Springer-Verlag, p.292, Berlin, Heidelberg, New York.

Bretz, J.H., 1942: Vadose and phreatic features of limestone caverns.- The journal of geology, V.1, N. 6/1, 675-811, Chicago.

Bretz, J.H., 1956: Caves of Missouri.- p. 490, Rolla, Missouri.

Brodar, S., 1948/49: Betalov spodmol-ponovno zatočišče ledenodobnega človeka.- Proteus 4/5, 1948, 97-106, Ljubljana.

Brodar, S., 1952: Prispevek k stratigrafiji kraških jam Pivške kotline, posebej Parske golobine.- Geografski vestnik 24, 43-77, Ljubljana.

Brodar, S., 1966: Pleistocenski sedimenti in paleolitska najdišča v Postojnski jami.- Acta carsologica 4, 54-138, Ljubljana.

Caumartin, W., 1959: Quelques aspects nouveaux de la microflore des cavernes.- Annales de spéléologie 14/1-2, 147-157.

Chorley, J.R. &A.S. Schumm & E.D. Sugden, 1984: Geomorphology.- Methuen, p. 605, London & New York.

Cigna, A. A., 1983: Alcune considerazioni preliminari sull'erosione per cavitazione.- Le grotte d'Italia, 479-486.

Cigna, A.A.; P. Forti, 1986: The speleogenetic role of air flow caused by convection.- International Journal of Speleology, 41-52, Trieste.

Corbel, J., 1962: Marmites-de-géant, tinajitas, vagues d' érosion, niches.- Spelunca 2/3, 34-37.

Cser, F., I. Szenthe, 1986: The way of cave formation by mixing corrosion.- 9° Congreso International de Espeleologia, 276-280, Barcelona.

Cser, F., 1988: Role and morphological traces of mixing corrosion in caves.- International Symposium on Physical, Chemical and Hydrological Research of Karst, 132-145.

Curl, R.L., 1964: On the Definition of a Cave.- Bulletin of the National Speleological Society 26/1, 1-6.

Curl, R.L., 1966: Scallops and flutes.- The Transactions of Cave Research group of GB, 7/2, 121-160, Nottingham.

Curl, R.L., 1974: Deducing Flow Velocity in Cave Conduits from Scallops.- The NSS Bulletin 36/2, 1-5.

Čar, J., 1982: Geološka zgradba požiralnega obrobja Planinskega polja.- Acta carsologica 10/4, 1981, 78-105, Ljubljana.

Davis, W.E., 1951: Mechanics of Cavern Breakdown, Bull. of the Nat. Spel. Society V 3, 36-43.

Delay, B. et A. Aminot, 1975: Données sur la nature chimique de la matière organique présente dans les sédiments souterrains.- Annales de Spéléologie 30/3, 495-512.

Dreybrodt, W., 1988: Processes in karst Systems.- Springer-Verlag, p. 288, Berlin, Heidelberg.

Duckworth, R.A., 1977: Mechanics of Fluids.- Longmans, p. 275, London and New York.

Ek, C. & H. Roques, 1972: Dissolution experimental de calcaires dans une solution de gaz carbonique - note préliminaire.- Trans. Cave Research Group of Great Britain, Vol 14, N 2, 67-72.

Ewers, R.O., 1966: Bedding plane anstomoses and their relation to cavern passages.- Bull. of the National Spel. Society, V. 28/3, 133-141, Missouri.

Ewers, R.O., 1982: Cavern Development in the Dimensions of Lenght and Breadth, A. Thesis, p. 398, Mc Master University Hamilton, Ontario.

Ford, T.D. & C.H.D. Cullingford, 1976: The Science of Speleology.- Academic Press, p. 593, London etc.

Ford, D., 1988: Characteristics of Dissolutional Cave

System in Carbonate Rocks.- Paleokarst, 25-57, Springer-Verlag New York.

Ford, D., P. Williams, 1989: Karst geomorphology and Hidrology.- U. Hyman, p. 601, London.

Forti, P., 1989: The role of sulfide-sulfate reaction in speleogenesis.- Proceedings of 10th Int. Congres of Speleology, Budapest-Hungary, 71-73.

Franke, W.H, 1975: Correspondence between sintering and corrosion.- Annales de spéléologie, 30/4, 665-672.

Gams, I., 1956: Pitanja recentnosti i fosilnosti na slovenskom krasu.- Izveštaj o radu 4. kongresa geografa FNRJ (Beograd), 73-77.

Gams, I., 1959: O legi in nastanku najdaljših jam na Slovenskem.- Naše jame 1, 4-10, Ljubljana.

Gams, I., P. Habič, 1961: Brezno pod Grudnom.- Proteus 24/2, 58-60, Ljubljana.

Gams, I., 1961: Prečni jamski profil in njegova odvisnost od lege skladov.- Naše jame 2 (1960), 47-54, Ljubljana.

Gams, I., 1962: Slepe doline v Sloveniji.- Geografski zbornik 7, 263-306, Ljubljana.

Gams, I., 1962/63: Kako nastanejo korozijske kotlice?.- Proteus 25/1, 26-28, Ljubljana.

Gams, I., 1963 a: Meritve korozijske intenzitete v Sloveniji in njihov pomen za geomorfologijo.- Geografski vestnik 34 (1962), 3-18, Ljubljana.

Gams, I., 1963 b: Logarček, Acta carsologica 3, 5-74, Ljubljana.

Gams, I., 1964 a: Logaška jama.- Naše jame 5 (1963), 11-19, Ljubljana.

Gams, I./ed/, 1964 b: Jamarski priročnik.- Mladinska knjiga, p. 151; Ljubljana.

Gams, I., 1965: H kvartarni geomorfogenezi ozemlja med Postojnskim, Planinskim in Cerkniškim poljem.- Geografski vestnik 37, 60-101, Ljubljana.

Gams, I., 1967: Faktorji in dinamika korozije na karbonatnih kamninah slovenskega dinarskega in alpskega krasa.- Geografski vestnik 38 (1966), 11-68, Ljubljana.

Gams, I., 1971: Podtalne kraške oblike.- Geografski vestnik 43, 27-45, Ljubljana.

Gams, I., 1972 a: Železna jama (kat. št. 2678).- Naše jame 13 (1971), 28-33, Ljubljana.

Gams, I., 1972 b: Ekskurzije.- 6. kongres speleologov Jugoslavije, Sežana - Lipica 10- 15 okt.- 34-36, Postojna.

Gams, I. /ed./, 1973: Slovenska kraška terminologija.- Zveza geografskih institucij Jugoslavije, p. 76, Ljubljana.

Gams, I., 1974: Kras.- Slovenska matica, p. 360, Ljubljana.

Gams, I., 1975: Jama pod Babjim zobom in vprašanje razčlenitve würma.- Naše jame 17, 111-116, Ljubljana.

Gams, I., 1983: Škocjanski kras kot vzorec kontaktnega krasa.- Mednarodni simpozij "Zaščita Krasa ob 160 letnici turističnega razvoja Škocjanskih jam", Lipica okt. 1982, SOZD Timav, 22-26, Sežana.

Gams, I., 1984: Nastanek Vilenice v luči geomorfološkega razvoja Sežanskega krasa.- Sežanski kras, 7-11, Sežana-Lipica.

Gèze, B., 1965: La spéléologie scientifique.- Le rayon de la science 22, p. 190, Paris.

Gèze, B., 1973: Lexique des termes français de spéléologie physique et de karstologie.- Annales de spéléologie, 13, 23-49.

Gilli, E., 1985: Le mode de creusement des cavités de grandes volume.- Actes du seminaire sur les grands volumes souterrains, 15-28, -4. mars 1984, Paris.

Goodchild, M.F. &Ford, D.C., 1971: Analysis of scallop patterns by simulation under controlled conditions.- Journal od geology, 79, 1, 52-62, Chicago.

Gospodarič, R., & P. Habič, 1966: Črni potok in Lekinka v sistemu podzemeljskega odtoka iz Pivške kotline.- Naše jame 8, 12-32, Ljubljana.

Gospodarič, R., 1969: Speleološki procesi v Postojnski jami iz mlajšega pleistocena.- Naše jame, 10(1968), 37-46, Ljubljana.

Gospodarič, R., 1970: Speleološke raziskave Cerkniškega jamskega sistema.- Acta carsologica 5, 109-169, Ljubljana.

Gospodarič, R., 1974 a: Izvor apnenčevega proda v Planinski jami.- Acta carsologica 6, 169-182, Ljubljana.

Gospodarič, R., 1974 b: Fluvialni sedimenti v Križni jami.- Acta carsologica 6, 327-366, Ljubljana.

Gospodarič, R., 1976: Razvoj jam med Pivško kotlino in Planinskim poljem v kvartarju.- Acta carsologica 7, 5-139, Ljubljana.

Gospodarič, R., 1981: Generacije sig v klasičnem krasu Slovenije.- Acta carsologica 9/1980, 87-110, Ljubljana.

Gospodarič, R., 1982: Stratigrafija jamskih sedimentov v Najdeni jami ob Planinskem polju.- Acta carsologica 10/8, 1981, 173-195, Ljubljana.

Gospodarič, R., 1983: Hydrogeologic Features of Some Karst Parts of Slovenia.- Hydrogeology of Dinaric Karst, Field trip to the Dinaric Karst, [s.p.].

Gospodarič, R., 1984: Jamski sedimenti in speleogeneza Škocjanskih jam.- Acta carsologica 12, 1983, 27-48, Ljubljana.

Gospodarič, R., 1985: O speleogenezi Divaške jame in Trhlovce.- Acta carsologica 13/1984, 5-36, Ljubljana.

Gospodarič, R., 1988: Paleoclimatic record of cave sediments from Postojna karst.- Annales de la Société Géologique de Belgique, T. 111, 91-95.

Gospodarič, R., 1989: Prispevek k vodnogospodarskim osnovam Pivke, Acta carsologica 18, 21-38, Ljubljana.

Habe, F., F. Hribar, 1965: Sajevško polje.- Geografski vestnik 36, 1964, 13-44, Ljubljana.

Habe, F., 1970: Predjamski podzemeljski svet.- Acta carsologica 5, 5-94, Ljubljana.

Habe, F., 1976: Morfološki, hidrografski in speleološki razvoj v studenškem flišnem zatoku.- Acta carsologica 7, 144-215, Ljubljana.

Habič, P., 1964: O podzemeljskih ledenikih na Nanosu.- Naše jame 5/1963, 19-29, Ljubljana.

Habič, P., 1968: Javorniški podzemeljski tok in oskrba Postojne z vodo.- Naše jame 10, 47-54, Ljubljana.

Habič, P., 1970: Hidrogeološke značilnosti visokega krasa v odvisnosti od geomorfološkega razvoja.- Prvi kolokvij o geologiji Dinaridov 2. del, 125-133, Ljubljana.

Habič, P., & P. Krivic, 1972: Nova odkritja v Pološki jami.- Naše jame 13 (1971), 98-108, Ljubljana.

Habič, P., 1973: O vodnih sifonih v kraških jamah.- Naše jame 14/1972, 15-24, Ljubljana.

Habič, P., 1974: Nekatere speleološke značilnosti Trnovskega gozda.- Naše jame 16, 61-78, Ljubljana.

Habič, P., 1975: Razlike med alpskim in dinarskim krasom.- Naše jame 17, 77-84, Ljubljana.

Habič, P., 1982: Pregledna speleološka karta Slovenije.- Acta carsologica 10 (1981), 5-22, Ljubljana.

Habič, P, 1985: Razpadanje in uničevanje kapnikov pod vplivom naravnih dogajanj in človekovega poseganja v kras.- Naš krš 11/18-19, 21-31, Sarajevo.

Habič, P., & M. Knez, & J. Kogovšek, & A. Kranjc, & A. Mihevc, & T. Slabe, & S. Šebela, & N. Zupan, 1989: Škocjanske jame spleological revue.- Int. J. Speleol. 18/ 1-2, 1-42.

Habič, P., 1991: Geomorphological classification of NW Dinaric karst.- Acta carsologica 20, 131-164, Ljubljana.

Herman, J.S., & W.B. White, 1985: Dissolutin kinetics of dolomite: Effects of lithology and fluid flow velocity.- Geochimica et Cosmochimica Acta, Vol. 49, 2017-2026.

Hochstetter, v.F., 1881: Die Kreuzberghöhle bei Laas in Krain und der Höhlenbär.- Denkschriften der mat. -naturwiss. Classe der Kaiserlichen Akademie der Wissenschaften, 43, 1-18, Wien.

Hsü, K.J., 1989: Physical Principles of Sedimentology.- Springer-Verlag, p. 233, Berlin, Heidelberg.

Jekić, M., M. Zlokolica, 1988: Pećina Piskovica.- Speleobih 1-2/88, 69-78, Sarajevo.

Jennigs, J. N., 1973: Karst.- The M.I.T. Press, sec.ed., p. 252, Cambridge, Massachusetts and London.

Jennings, J.N., 1979: Cave and Karst Terminology.- ASF Newsletter 83, 4-21, Brodway N.S.W.

Jennings, J.N., 1980: The problem of cavern formation.- ASF Newsletter 89, 2-19, Brodway, N.S.W.

Knez, M., 1994: Phreatic Channels in Velika Dolina, Škocjanske jame.- Acta carsologica 23, 63-71, Ljubljana.

Kogovšek., J., 1982: Vertikalno prenikanje v Planinski jami v obdobju 1980/81.- Acta carsologica 10(1981), 107-125, Ljubljana.

Kranjc, A., 1981: Prispevek k poznavanju razvoja krasa v Ribniški Mali gori.- Acta carsologica 9/1980, 27-81, Ljubljana.

Kranjc, A., 1982: Sedimenti iz Babje jame pri Mostu na Soči.- Acta carsologica 10 (1981), 197-212, Ljubljana.

Kranjc, A., 1983: Dinamika odpadanja sige v Golobji luknji, Predjama.- Acta carsologica 11 (1982), 99-116, Ljubljana.

Kranjc, A., 1985: Un exemple de corrosion sur les galets carbonatés.- Spelunca Mémoires 14, 80, Nancy-Metz

Kranjc, A., 1986 a: Transport rečnih sedimentov skozi kraško podzemlje na primeru Škocjanskih jam.- Acta carsologica 14/15, 109-116, Ljubljana.

Kranjc, A., 1986 b: Recentni fluvialni jamski sedimenti.- Doktorska dizertacija, p. 336 + annex., Univerza v Ljubljani.

Kranjc, A., 1989: Recent fluvial cave sediments, their origin and role in speleogenesis.- Dela SAZU, Razred za naravoslovne vede, Dela 27, p. 167, Ljubljana.

Lange, A., 1959: Introductory notes on the changing geometry of caves structures.- Cave studies 1-11, 69-90, San Francisco.

Lange, A.L., 1960: Geometrical Basis for Cave Interpretation.- Bulletin of the National Speleological Society 22, 77-84.

Lange, A.L., 1963: Planes of repos in caves.- Cave notes V5 No 6, 41-48.

Lauritzen, S.E., 1981: Simulation of rock pendants - small scale experiment.- 8th international congres of speleology, 407-409, Georgia.

Lauritzen, S.E., I. Andrew, B. Wilkinson, 1983: Meam annual runoff and the scallop flow regime in a subarctic ennvironment.- Trans. British Cave Research Association 10/3, 97-102.

Lauritzen, S.E., J.A. Abbot, R. Arnesen, G. Crossley, D. Grepperud, A. Ive, S. Johnson, 1985: Morphology and Hydraulics of an Active Phreatic Conduit.- Cave Science 12/4, p. 139-146.

Lismonde, B., A. Lagmani, 1987: Les vagues d'érosion.- Karstologia 10-2, 33-38.

Lismonde, B., 1987: Une marmite remarquable du Trou qui souffle.- Karstologia 10-2, 39-42.

Lu Yaoru, 1986: Process of karst caverns' development and three phrases' flow.- Comunicacions, 9^0 Congreso International de Espeleologia, 273-276, Barcelona.

Maire, R., 1980: La spéléologie physique.- Spelunca 4eme serie, 20, Spécial no.3, 1-56, Paris.

Maucci, W., 1960: Evoluzione geomorfologica successiva all' emersione definitiva.- Bolletino della Società Adriatica di scienze naturali 51, 165-189, Trieste.

Maucci, W., 1975: L'ipotesi dell' "erosione inversa", come contributo allo studio della speleogenesi.- Le grotte d'Italia Vol.4-1973, Bologna.

Melik, A., 1960: Slovensko Primorje.- Slovenska matica, p. 547, Ljubljana.

Michler, I., 1934: Križna jama.- Proteus 5, 97-102, Ljubljana.

Mihevc, A., I. Gams, 1979: Nova odkritja v Ledenici v Paradani, (kat.št. 742).- Naše jame 20 (1978), 7-20, Ljubljana.

Mihevc, A., 1989: Kontaktni kras pri Kačičah in ponor Mejame.- Acta carsologica 18, 171-194, Ljubljana.

Mihevc, A., 1990: Morfologija brezen od odvisnosti strukture na primeru Velike ledenice v Paradani.- Četvrti skup geomorfologa Jugoslavije, Pirot 20-23. juna, 71-76.

Mihevc, A., 1991, a: Ravni stropi, inicialni in stropni kanali ter stropne anastomoze na primerih jam Piskovice in Brloga na Rimskem.- Naše jame 33, 19-27, Ljubljana.

Mihevc, A., 1991 b: Morfološke značilnosti ponornega kontaktnega krasa.- Magistrska naloga , p. 206, Univerza v Ljubljani.

Mucke, B., R. Völker, S. Wadewitz, 1983: Cupola formation in occasionally inundated cave roofs.- European regional conference on speleology, Sofia - Bulgaria 22.-28. 9. 1980, 133-137, Sofia.

Ollier, C., 1984: Weathering.- Longman, sec. ed, VII, p. 270, London.

Palmer, A.N., 1982: Geomorphic interpretation of karst features.- Ground water as a Geomorphic Agent - R.G. La Fleur, 173-209.

Palmer, T. & C. Plewes, 1993: Boring and bioerosin in fossils.- Geology Today Vol 9, No 4, 138-142.

Pasquini, G., 1975: Considerazioni sulla percolazione e sulla condensazione.- Le grotte d'Italia V4/4, (1973), 323-327.

Pochon, J., 1954: Manual technique d'analyse microbiologique du sol, Masson et C^{ie}, 89-91.

Quinif, Y., 1973: Contribution à l'étude morpholoqique des coupoles.- Annales de spéléologie 28/4, 565-573.

Radinja, D., 1972: Zakrasevanje v Sloveniji v luči celotnega morfogenetskega razvoja.- Geografski zbornik 13, 197-243, Ljubljana.

Rakovec, I., 1951: Jamski lev iz Postojnske jame, Razprave 1 SAZU, 127-172, Ljubljana.

Renault, P h., 1957: Sur deux processus d'éffondrement karstique.- Annales de spéléologie 12, 19-46, Paris.

Renault, Ph., 1958: Éléments de spéléologie karstique.- Annales de Spéléologie 13, 21 - 48.

Renault, Ph., 1968: Contribution à l'étude des action mécanique et sédimentologiques dans la spéléogenèse.- Annales de spéléologie 23/3, 529-596.

Reynolds, A.J., 1974: Turbulent Flows in Engineering.- John Wiley & Sons, p 462, London, New York, Sydney, Toronto.

Round, G.F., V.K. Garg, 1986: Applications of Fluid Dynamics.- Edvard Arnold, p.403, Avon.

Rudnicki, J., 1960: [Experimental work on flutes development].- Speleologia Tom 2, Nr. 1, 17-30, Warszava.

Shaw, T.R., 1992: History of cave scinece.- Second edition, p. 338, Sydney Speleological Society.

Scheffer, F., P. Schachtschabel, 1976: Lehrbuch der Bodenkunde.- Ferdinand Enke Verlag, p. 394, Stuttgart.

Scheidegger, A.E., 1961: Theoretical geomorphology.- Springer-Verlag, p. 333, Berlin, Göttingen, Heidelberg.

Serban, M., 1987: Wall microrelief in caves - effect of turbulence.- Theoretical and Applied Karstology 3, 1-30, Bucuresti.

Slabe, T., 1987: Jamske anastomoze v Dimnicah.- Acta carsologica 16, 167-179, Ljubljana.

Slabe, T., 1988: Kondenzna korozija na skalnem obodu Komarjevega rova v Dimnicah.- Acta carsologica 17, 79-92, Ljubljana.

Slabe, T., 1989 a: Skalne oblike v kraških jamah in njihov pomen pri proučevanju Dimnic, Križne in Volčje jame ter Ledenice na Dolu.- Magistrska naloga, p. 228, Univerza Edvarda Kardelja v Ljubljani.

Slabe, T., 1989 b: Skalne oblike v Križni jami in njihov speleogenetski pomen.- Acta carsologogica 18, 197-220, Ljubljana.

Slabe, T., 1990: Skalne oblike v dveh poligenetskih jamah visokega krasa.- Acta carsologica 19, 165-196, Ljubljana.

Slabe, T., 1992: Naravni in poskusni obnaplavinski jamski skalni relief.- Acta carsologica 21, 7-34.

Slabe, T., 1993: Fasete, pomembna sled oblikovanja in razvoja kraških votlin.- Acta carsologica 22, 139-177, Ljubljana.

Slabe, T., 1994 a: Dejavniki oblikovanja jamske skalne površine.- Acta carsologica 23, 369-398, Ljubljana.

Slabe, T., 1994 b: Jamski skalni relief in njegov pomen pri proučevanju oblikovanja in razvoja izbranih jam slovenskega istrskega krasa.- Annales, series historia naturalis 1, 155-162, Koper.

Splošni tehniški slovar, 1978, 1st part, Ljubljana.

Sweeting, M.M., 1967 The Weathering of Limestones with particular references to the Carboniferous Limestones of Northern England.- V: Essays in Geomorphology /Ed. G.H.Dury, Heinemann, 177-210, London.

Šebela, S., 1991: Površinske geološke strukture in njihov vpliv na oblikovanje Predjame.- Magistrska naloga, p. 115+16 anex., Fakulteta za naravoslovje in tehnologijo, VTOZD Montanistika, Ljubljana.

Šušteršič, F., 1972/73: Med Škocjanom in Labodnico.- Proteus 35, 320-322, Ljubljana.

Šušteršič, F., 1982: Morfologija in hidrografija Najdene jame.- Acta carsologica 10 (1981), 127-155, Ljubljana.

Šušteršič, F., 1985: Speleometrična izhodišča za proučevanje jamskih prečnih prerezov-. Naš krš v.11, No.18-19, 81-87, Sarajevo.

Šušteršič, F., 1991: S čim naj se ukvarja speleologija.- Naše jame 33, 73-85, Ljubljana.

Šušteršič, F., 1994: Jama Kloka in začetje.- Naše jame 36, 9-30, Ljubljana.

Trudgill, S.T., 1979: Chemical polish of limestone and interaction between calcium and organic matter in peat drainage waters.- Trans. British Cave Research Assoc. 6/1, 30-35.

Trudgill, S., 1985: Limestone geomorfology.- Longman, p. 196, London and New York.

Viles, H., 1987: A quantitative scanning electron microscope study of evidence for lichen weathering of limestone, Mendip Hills, Somerset.- Earth surface processes and landforms 12, 467-473.

Viehmann, J., 1959: Contributions à la connaissance de la genèse des marmites.- Speleologia 1/3, 145-175, Warszawa.

Vukovič, M., A. Soro, 1985: Osnovi hidraulike.- Beograd.

White, W.B., 1988: Geomorphology and Hydrology of Karst Terrains.- Oxford University Press, p. 464, New York etc.

Wilford, C.E., 1966: "Bell Holes" in Sawarak Caves.- Bulletin of the National Speleological Society 28/4, 179-182.

Worthington, S.R.H., 1991: Karst hydrology of the Canadian Rocky Mountains.- Mc Masters University, p. 370, Hamilton, Ontario.

Zupan, N., A. Mihevc, 1988: Izvor in mineraloška analiza sedimentov v Veliki ledenici v Paradani.- Speleobih, 10. kongres speleologa Jugoslavije, Sarajevo 27.-30.10. 1988, 17-24.

Zupan, N., 1990: Izvor in mineralna sestava jamskih peskov in ilovic.- Magistrska naloga, p. 102, FNT, VTOZD Montanistika, Geologija, Ljubljana.

Zupan, N., 1991: Flowstone datations in Slovenia.- Acta carsologica 20, 187-204, Ljubljana.

6. LIST OF ILLUSTRATIONS

SELECTED CAVES
1.1 Selected caves:
  1. outflow karst areas
  2. through-flow karst areas
  3. outflow-through-flow areas (suggestion P.Habič 1982)
1-48 sequence numbers of the caves
2.3.1 Typical water turbulence
  1. turbulence in homogeneous, solid rock
    a. scallops
    b. ceiling cups
    c. potholes
  2. turbulence in fissures
    a. ceiling cups
    b. pendants
    c. potholes
  3. turbulence due to passages shape
    a. ceiling cups
    b. ceiling cups at bends
    c. potholes; below waterfall, downcurrent, in front of an obstacle
    d. pothole at a passage bend
2.3.2 Closed and open scallop
  d = length
  š = breadth
  g = depth
2.3.3 Typical sets of scallops
  d/š = the rate between length and breadth of scallop
  d = length of scallop
  1 open scallops
  2 closed scallops
2.3.4 Scallops on the oxbow passage wall at Blatno Jezero, Beško Ocizeljska Jama (scale = 15 cm)
2.3.5 Scallops on the passage wall behind Tobogan, Ponikve v Jezerini
2.3.6 Scallops on rocky block in the riverbed, Škocjanske Jame (scale = 15 cm)
2.3.7 Scallops on the inflow part of the rocky block, Podpeška Jama (scale = 15 cm)
2.3.8 Large scallops in Pivški Rokav, Planinska Jama (scale = 15 cm)
2.3.9 Scallops on intraclastic limestone, Markov Spodmol
2.3.10 Scallops on Rudist limestone, Pivka Jama (scale = 15 cm)
2.3.11 Scallops and interbedded chert lenses, Lepe Jame (Postojnska Jama) (Scale = 15 cm)
2.3.12 Scallops on sandstone, Smoganica (scale = 15 cm)
2.3.13 Scallops on crushed limestone in Podstrešje, Mala Boka (scale = 15 cm)
2.3.14 Scallops in tube of plaster
2.3.15a Scallops on block of plaster
2.3.15b Scallops on lateral side of block of plaster
2.3.16 Scallops on bedded block of plaster
2.3.17 Scallops in tube of plaster
2.3.18 Scallops that were mechanically deepened in Vzhodni Rov, Predjama (scale = 15 cm)
2.3.19 Flutes, Markov Spodmol (scale = 15 cm)
2.3.20 Types of ceiling pockets; longitudinal and cross-section
  a. independent, simple ceiling pocket
  b. independent ceiling pocket in levels
  c. composed ceiling pocket in levels
2.3.21 Ceiling pocket in Pekel, Babja Jama
2.3.22 Ceiling pockets, Matijeva Jama
2.3.23 Ceiling pocket on the upper parts of the wall of Ozki Rov, Ciganska Jama
2.3.24 Ceiling pocket, Lokva swallow-hole
2.3.25 Ceiling pockets in Nebesa, Zadlaška Jama (scale = 15 cm)
2.3.26 Ceiling pocket in Lokva swallow-hole
2.3.27 Ceiling pocket on fissured rock in Stara Jama, Predjama
2.3.28 Ceiling pockets, Logaška Jama
2.3.29 The ceiling of Blatni Rov, Zelške Jame
2.3.30 Elongated ceiling pocket at the beginning of Sifonski Rov, Zelške Jame
2.3.31 Ceiling pockets behind the squeeze, Finkova Jama
2.3.32 Ceiling pocket on the limestone with cehrts in Stara Jama, Predjama
2.3.33 Wall niche with scallops, Markov Spodmol (scale = 15 cm)
2.3.34 Ceiling pocket with below-sediment channels behind the Tobogan squeeze, Ponikve v Jezerini
2.3.35 Pothole in Kopalnica, Mala Boka (scale = 15 cm)
2.3.36 Pothole on rocky block in Hankejev Kanal, Škocjanske Jame
2.3.37 Pothole, Ponor v Odolini (scale = 15 cm)
2.3.38 Potholes in Šumeča Jama, Škocjanske Jame

2.3.39 Pothole on rocky block in Hankejev Kanal, Škocjanske Jame
2.3.40 Pothole on outflow part of rocky block in Hankejev Kanal, Škocjanske Jame
2.3.41 Pothole in Polhov Rov, Mala Boka (scale = 15 cm)
2.3.42 Pothole on sandstone, Smoganica
2.3.43 Pothole below the aven, Ocizeljska Jama
2.3.44 Potholes on the inflow side of rocky block, Škocjanske Jame (scale = 15 cm)
2.3.45 Pocket, Markov Spodmol (scale = 15 cm)
2.3.46 The rocky jag in a niche behind the entrance chamber, Križna Jama, its surface is etched by condensation corrosion
2.3.47 Rocky pendant in Krožni Rov, Črna Jama (Postojnska Jama)
2.3.48 "Čer", Križna Jama (Photo by P. Habič)
2.3.49 "Čer" in Vzhodni Rov, Predjama
2.3.50 "Čer" with pothole, Markov Spodmol
2.3.51 "Čers" with below-sediment floor-pits, Križna Jama
2.3.52 Meander niche, Križna Jama
2.3.53 Wall water level horizon in Fiženca, Predjama
2.3.54 Ceiling water level horizon, Ponor v Odolini
2.3.55 Wall water level horizon, Trhlovca
2.3.56 Longitudinal floor channels at the riverbed step, Markov Spodmol (scale = 15 cm)
2.3.57 Floor channel with small scallops, Ponor v Odolini (1 cm = 10 cm)
2.3.58 Floor channel, Markov Spodmol
2.3.59 Floor channel, Ponor v Odolini
2.3.60 Floor channel, Ciganska Jama
2.3.61 Ceiling channels, Ponor v Odolini
2.3.62 The surface of the scallop, Križna Jama
2.3.63 The surface of the scallop in the riverbed, Škocjanske Jame
2.3.64 The surface of large pothole in the riverbed, Škocjanske Jame
2.3.65 Mechanically polished wall, Predjama (scale = 15 cm)
2.3.66 Abraded, (scratched) although mechanically polished wall
2.3.67 Craters with shattered grains
2.3.68 Bruised surface of the ceiling behind the squeeze, Babja Jama
2.3.69 Bruised surface
2.3.70 Resinous layer on the rock in the riverbed, Škocjanske Jame
2.4.1 Ceiling channel in Blatni Rov, Predjama
2.4.2 Anastomosis network in Havaji, Brlog na Rimskem
2.4.3 Anastomoses on the ceiling of Kozinski Rov, Lipiška Jama
2.4.4 Anastomoses in Havaji, Brlog na Rimskem
2.4.5 Anastomoses on dolomite, Turkova Jama (scale = 15 cm)
2.4.6 Anastomoses on conglomerate, Smoganica (scale = 15 cm)
2.4.7 Cross-section of experimental model
2.4.8 Ceiling channels in plaster
2.4.9 Cross-sections of ceiling channels
2.4.10 Above-sediment niches in Južni Rov, Dimnice
2.4.11 Above-sediment niches in plaster
2.4.12a Below-sediment bevels, Križna Jama (Photo by Habič)
2.4.12b Below-sediment bevels, Markov Spodmol (scale = 15 cm)
2.4.13 Below-sediment channels on overhanging wall, Griška Jama
2.4.14a Corrosionally transformed below-sediment channels, Križna Jama
2.4.14b Below-sediment channels rounded by mechanical acting of water stream, Ponikva v Jezerini (scale = 15 cm)
2.4.15 Channels on vertical wall of plaster block (scale = 15 cm)
2.4.16 A section of channel on vertical wall of plaster block
2.4.17a Below-sediment floor pits, Najdena Jama
2.4.17b Below-sediment solution cup, Kompoljska Jama (scale = 15 cm)
2.4.18 Below-sediment pits due to water flow, underground Pivka (scale = 15 cm)
2.4.19 Below-sediment ceiling pockets in Blatni Rov, Zelške Jame
2.4.20 Below-sediment roof pendants in Krožni Rov, Črna Jama (Postojnska Jama)
2.4.21 Anastomoses rocky surface
2.4.22 Below-sediment rocky surface
2.5.1 Wall channels, Kamenšca (scale = 15 cm)
2.5.2 Aven wall at the contact of limestone and dolomite, Velika Ledenica v Paradani (scale = 15 cm)
2.5.3 Wall in Čo Meander, Kanin Mts.
2.5.4 Wall pockets of the entrance shaft, Logaška Jama (scale = 15 cm)
2.5.5 Pits along the fissures on the wall, Ledenica na Dolu
2.5.6 Pits on overhanging wall, Ledenica na Dolu
2.5.7 Roof pendants, Ciganska Jama
2.5.8a Etched surface among roof pendants
2.5.8b The surface of roof pendants
2.5.9 Ceiling channels, Ciganska Jama
2.5.10 Ceiling pit in plaster
2.5.11 Ceiling pits in plaster
2.5.12 Ceiling pockets, Volčja Jama on Nanos
2.6.1 Polished wall of below-ice notch
2.6.2 Below-ice pits
2.7.1 Large scallops in entrance part, Trhlovca
2.7.2 Scallops on the roof between Šumeča Jama and Tiha Jama, Škocjanske Jame
2.7.3 Rocky surface, etched by condensation corrosion
2.7.4 Breccia, etched by condensation corrosion, Zadlaška Jama (scale = 15 cm)
2.7.5 Etched rocky surface due to condensation moisture, Križna Jama
2.7.6
A. Small-scale condensation etching of western wall, Komarjev Rov
1. - smooth rocky surface

2. - spongework
3. - rocky surface with bulges
4. - flowstone
5. - points of temperature measurements
6. - PVC foil
7. - rocky surface without condensation
8. - loam
B. Location of Komarjev Rov within the entrance shaft and cave
2.7.7 spongework on the wall
2.7.8 the surface of the wall with bulges
2.8.1 Rock surface under the lichens, Volčja Jama on Nanos
2.8.2 Notches under the liches in entrance part, Veliki Hubelj
2.8.3 Notches below guano, Veliki Hubelj
2.8.4 Bear signs, Križna Jama
3.1.1 Hydrological zone and rocky relief, Novokrajska Jama
A. 1. epiphreatic zone
2. vadose zone
B. 1. Rocky relief formed by water flow
a. scallops
b. ceiling pockets
c. potholes
2. Below-sediment rocky relief
3. Rocky relief due to perimeter disintegration
3.1.2 Rocky relief, Matijeva Jama
1. ceiling pockets due to water flow
2. erosionally polished passage perimeter
3. below-sediment rocky relief
a. below-sediment pits
b. below-sediment channels
3.1.3 SW wall of the chimney, Ledenica na Dolu
3.1.4 NE wall of the chimney, Ledenica na Dolu
3.1.5 Chimney's cross-section, Ledenica na Dolu
1. thinly fissured rock
2. fossils in the rock
3.2.1 Small scallops on larger ones, Beško Ocizeljska Jama
3.2.2. Distribution of scallops in one section of the passage, Markov Spodmol
1. larger scallops, Type 2, old
2. larger scallops, Type 2/3
3. small scallops, Type 2/3
4. small scallops in channel, Type 1
3.2.3 Cross-section of Pivški Rokav, Planinska Jama (near Golgota) and hydrological zones of rocky relief formation
A
1. phreatic zone
2. epiphreatic zone
3. vadose zone
B
1. large scallops
2. medium sized and small scallops
3. ceiling pockets
4. below-sediment pits
5. below-sediment channels
3.2.4 Rocky relief and hydrological zones of its formation in Ciganska Jama
A
1. rocky relief shaped by water stream
a. ceiling pockets
b. scallops
2. along-sediment rocky relief
a. above-sediment channel
3. rocky relief shaped by trickling water
4. rocky relief transformed by condensation corrosion
5. floor channel
B
1. epiphreatic zone
2. vadose zone
3.2.5 The Pivka basin and a part of Notranjsko Podolje with selected caves
1. caves
2. superficial water flows
3. limestone
4. impermeable soil: flysch and alluvium
3.2.6 Hydrological zones shaping Postojnska Jama
1. phreatic zone
2. epiphreatic zone with slow water flow
a. epiphreatic zone with more rapid water flow (present-day formation)
3. vadose zone
3.2.7 Rocky relief and hydrological zones shaping Predjama
A
1. phreatic zone
2. epiphreatic zone
3. vadose zone
B
1. rocky relief shaped by water flow
a. ceiling pockets
b. scallops
2. along-sediment rocky relief
a. above-sediment channel
b. below-sediment channel
3.2.8 Cross-section over Kras
3.2.9 Rocky relief in Škocjanske Jame
1. Rocky relief that is (was) shaped by water stream
a. scallops
b. potholes
c. ceiling pockets
2. Along-sediment rocky relief
a. above-sediment channels
b. above-sediment anastomoses
3. Rocky relief shaped by trickling water
4. Rock transformed by condensation corrosion
5. Rocky relief shaped by perimeter disintegration

7. POVZETEK

JAMSKI SKALNI RELIEF IN NJEGOV SPELEOGENETSKI POMEN

Uvod

Dejavniki, ki oblikujejo kraško podzemlje, zapuščajo sledi tudi na skalnem obodu votlin. Nastajajo skalne oblike, ki jih povezujemo v skalni relief.

Iz speleoloških proučevanj, ki sem jih opravil kot sodelavec Inštituta za raziskovanje krasa, sem sklepal, da je skalni relief lahko pomembna sled oblikovanja in razvoja votline. Odločil sem se postaviti temelje proučevanja skalnega reliefa in celoviteje ovrednotiti njegovo uporabnost v speleomorfoloških in speleogenetskih proučevanjih. Opredelil sem metodološke osnove proučevanja nastanka in razvoja skalnih oblik ter njihove povezanosti v skalni relief. Hkrati pa sem skušal opredeliti speleogenetski pomen skalnega reliefa v posameznih predelih našega krasa. V študiji se torej prepletata dva pristopa. Prvi je opredeljevanje dejavnikov in procesov, ki oblikujejo skalni relief rovov in drugi je regionalni.

Cilju sem prilagodil tudi izbor jam, saj sem skušal zajeti čimširši spekter skalnega reliefa. Hkrati sem želel izbrati večino tipov jam, ki so značilni za posamezne predele slovenskega krasa.

Zbiranje gradiva o skalnem reliefu in njegovo proučevanje je sestavljeno iz terenskega dela, študija literature, poskusnega ustvarjanja skalnih oblik na mavcu in kvantitativnih analiz njihovih oblikovnih značilnosti.

V uvodnih delih študije sem opredelil namen proučevanja skalnega reliefa, strnil sem dognanja iz literature in predstavil jame, v katerih sem proučeval skalni relief. V nadaljevanju sem opredelil skalne oblike, jih poimenoval glede na njihove oblikovne značilnosti in klasifikacijo. Nato pa sem podal ugotovitve iz proučevanja nastanka in razvoja skalnih oblik. V drugem delu sem predstavil skalni relief kot sled oblikovanja in razvoja votlin. Predstavljeni so tipi rovov glede na skalni relief in prečni prerez. V izbranih jamah v različnih predelov našega krasa pa sem skušal opredeliti speleogenetski pomen skalnega reliefa. V sklepnem delu je ovrednoten pomen proučevanja skalnega reliefa v speleologiji.

Akademiku prof. dr. I. Gamsu in prof. dr. P. Habiču ter sodelavcem na Inštitutu za raziskovanje krasa ZRC SAZU se zahvaljujem za pomoč pri delu. Pri laboratorijskih poskusih z mavcem mi je pomagal J. Hajna, pri proučevanju zbruskov kamnine pa M. Knez. V jamah so me spremljali S. Morel, F. Drole in B. Otoničar. V. Segala (Oddelek za geologijo, Montanistika) je z elektronskim vrstičnim mikroskopom fotografiral površino skalnih oblik. Priloge je narisal L. Drame, laboratorijske analize voda in naplavin sta prispevala M. Zadel in M. Luzar. Besedilo je prevedla M. Kranjc, dr. T. Shaw pa ga je prijazno prebral in predlagal nekaj sprememb. O dognanjih proučevanja jamskega skalnega reliefa sem poročal sproti, predvem v Krasoslovnem zborniku (Slabe 1987, 1988, 1989, 1990, 1992, 1993; Habič et al. 1989).

Proučevanje je potekalo tudi v okviru projekta Nastanek in oblikovanje kraških votlin, ki ga je omogočilo Ministrstvo za znanost in tehnologijo Republike Slovenije. To je podprlo tudi tiskanje knjige.

Nastanek in razvoj skalnih oblik

Skalne oblike, ki sestavljajo relief kraških votlin, so posledica delovanja različnih speleogenetskih dejavnikov na kamnino. Vodni tokovi, polzeča voda in drugi dejavniki povzročajo procese na kamnini in odnašajo njihove proizvode. Kamnina skalnega oboda rovov s svojo sestavo, skladovitostjo in pretrtostjo pogojuje nastanek različnih skalnih oblik in vpliva na njihov razvoj ter oblikovanje. Isti dejavniki namreč lahko na različni kamnini oblikujejo raznovrstne skalne oblike. Pogosta značilnost karbonatnih kamnin je njihova drobnozrnata in dokaj homogena sestava. Na takšni kamnini pa se skalne oblike najlepše razvijejo. Na nehomogeni in močno pretrti kamnini osnovne skalne oblike ne nastanejo. Pretrost kamnine se odraža tudi na obliki rovov. Če se skozi rov, ki ga sestavljajo odseki različnih premerov in strmcev, pretaka vodni tok, nastanejo značilne hidravlične razmere. Tudi te odsevajo v skalnih oblikah. V enoličnih cevastih rovih so lahko po vsem obodu fasete. V conah izrazitega vrtinčenja nastanejo stropne kotlice. Kamnina različno vpliva tudi na nastanek skalnih oblik, ki jih oblikujejo drugi dejavniki (polzeča voda, zračni tok) oblikovanja jamskih sten. V spremenljivih pogojih lahko skalno obliko oblikuje več dejavnikov hkrati. Prevlada seveda bolj učinkoviti. Hitrejši vodni tok vreže stropne kotlice in fasete. Iz občasnega počasnejšega vodnega toka ali stoječe vode pa se na položne stene kotlice odloži naplavina in pod njo nastanejo žlebiči, širijo se dna faset. V nespremenljivih pogojih skalne oblike dosežejo stopnjo zrelosti, značilno obliko in velikost. V obdobju nastajanja skalne oblike pa sta velikost in oblika le stopnji v njenem razvoju.

Skalne oblike sem pri proučevanju njihovega nastanka in razvoja razdelil v skupine po dejavnikih, ki povzročajo njihov nastanek. Dejavniki so, poleg osnovne podobe skalnih oblik, temelj za njihovo poimenovanje (npr. nadnaplavinski žleb). V pomoč je tudi značilna lega skalne oblike na obodu (npr. nadnaplavinski stropni žleb). Redko sem imenom dodal še pridevnik, ki ponazarja proces njihovega oblikovanja. Uporabil sem imena, ki so že uveljavljena: stropne kotlice, draslje, fasete, več oblik sem poimenoval sam.

1. **Skalne oblike, ki nastanejo zaradi dolbljenja kamnine z vodnim tokom:**

Fasete so mreža korozijskih vdolbinic, ki so plitkejše na odtočni strani (Gams 1973, 6; an: scallops (Curl 1966, Allen 1972); nem: Fliessfacetten (Bögli 1978, 165); fr: vague d'érosion (de Joly (1933) navaja Maire 1980, 31, Renault 1968)). Dolge so 0,5 do 30 cm. Nastanejo zaradi vrtinčenja vodnega toka ob hrapavi površini skale.

Rebra so žlebiči s polkrožnim prečnim prerezom, ki so zaporedno povezani v mrežo (an.: flutes (Curl 1966)). Nastanejo zaradi vrtinčenja vode ob hrapavi površini vzdolžnih zajed na skalnem obodu rovov.

Stropna kotlica, ki doseže meter in več premera, je vdolbina na stropu ali na zgornjih delih sten rova, (fr.: coupole à la voûte (Renault 1968, 29; Quinif 1973; Maire 1980, 35), marmite inverse, marmite de pression (Gèze 1973, 9); an.: ceiling pocket, solution pocket (Bretz 1942; Bögli 1971; Ford 1988, 43); it.: cupole (Pasquini 1975; Binni & Cappa 1978); nem.: Korrosinskolke (Bögli 1978, 163)). So posledica vrtinčenja vodnega toka ob razpokah in vrtinčastih con ob zajedah, znižanju, povišanju ali ostrih zavojih rova.

Draslja (fr. marmite de géant (Renault 1958, 30, 31; Viehman 1959; Corbel 1962; Geze 1973, 9; Maire 1980, 35; Lismonde 1987), an. pothole (Bretz 1942); nem.: Erosionskolke (Bögli 19789, 165)) nastane na skalnih tleh. Izdolbe jo vodni tok, ki v svoje vrtinčenje vključi trdne delce.

Talni žleb je žleb v skalni strugi. Je posledica vrtinčenja vodnega toka ob razpokah in ovirah ali pretakanja manjših količin vode po skalnih tleh.

Nož (skalni nož, Gams 1973, 26) je podolgovata stenska, stropna ali talna štrlina, ki se navzven oži.

Rogelj je šrtlina z ovalnim prečnim prerezom.

Steber (an.: pillar (Lange 1959, 81)) je večji navpični del oboda, štrlečega iz sten, ki je nastal ob navpičnih razpokah, ob katerih se zajeda voda.

Čer je štrlina na skalnih tleh.

Mostič (natural bridge (White 1988, 102), window (Jenings 1979, 21)) nastane, ko voda razje štrleče dele skalnega oboda.

Stenska niša (Gams 1973, 22) je polkrožna ali oglata vdolbina v steni rova. Nastane zaradi zajedanja vodnega toka ob razpokah, ali vijuganja ob naplavini (an.: meander niche (Bretz 1956, 18)).

Stenska ali stropna zajeda je ravna, vzdolžna vdolbina s premerom od 10 cm do metra in več. Kaže na nivo vodnega toka (an.: water level horizon (Lange 1963, 41)) ali združevanje rovov.

2. **Skalne oblike, ki so nastale ob stiku z drobnozrnato naplavino, imenujem obnaplavinske.** Po načinu njihovega nastanka jih delim na nadnaplavinske in podnaplavinske.

a. **Nadnaplavinski žlebovi** in vdolbinice so značilnost rovov, ki so bili zapolnjeni s poplavno naplavino. Zaradi pretoka vode nad ilovico v poplavljenem rovu žlebovi povišujejo strop in se zajedajo v stene, ko voda odteka navzdol. Voda, ki priteka v zapolnjene rove skozi razpoke, lahko ob njihovem ustju naredi kotlice. Drobne vdolbinice pa nastanejo na kamnini že ob sami vlažni naplavini (Dimnice).

Stropni (nadnaplavinski) žleb (an.: ceiling channel (Bretz 1956, 22)) je raven ali vijugast in ima premer velik od 1 do 100 cm.

Anastomoze so mreža stropnih žlebov (Slabe 1988, 169, 170; Renault 1968, 569; Geze 1973, 9; Bögli 1978, 161),

Stropne štrline so štrline med žlebovi (an.: pendants (Bretz 1956; Renault 1968, 570)).

Vdolbice imajo premer velik od 1 do 10 cm in so posamične ali pa gosto prepredajo kamnino.

b. **Podnaplavinske** skalne oblike sestavljajo skalni relief rovov, skozi katere se občasno pretakajo počasnejši vodni tokovi in na obod odlagajo drobnozrnato naplavino (Slabe 1992).

Žlebiči (podnaplavinski) s premerom 1-10 cm imajo polkrožno dno. Žlebiči so ponavadi tik drug ob drugem in prekrijejo večje površine spodnjih delov sten rova ali njegovo dno. Nastanejo zaradi izcejanja vode iz naplavine.

Vdolbinice so gosto razporejene na skalnih tleh, stene med njimi so lahko prežrte in so zato nepravilnih oblik. Merijo od 1 do 20 cm. So posledica korozije pod vlažno naplavino.

Stenska zajeda kaže na nivo naplavine v votlini.

Stropne konice so velike le cm ali dva in imajo trikotne prečne prereze. Nastanejo zaradi raztapljanja gole skale v zalitih rovih. Naplavina namreč mestoma prepreči vodi stik s steno.

3. **Skalne oblike, ki nastajajo zaradi polzenja vode po obodu brezen in rovov** (Slabe 1990, 187).

Žlebiči (an.: lapies (Bretz 1956, 22)) nastanejo zaradi polzenja vode po navpični ali položni steni.

Vdolbinice so okroglega ali oglatega prečnega prereza in imajo premer velik od 1 do 5 cm. Povezane so v mrežo. Nastanejo zaradi polzenja vode po nehomogeni previsni steni.

Stropne konice so dolge 1 do 2 cm in so povezane v mrežo. Nastanejo zaradi polzenja vode po nehomogenem stropu.

Kotlica je zvonasta vdolbina na stropu. Njen premer meri od 1 do 50 cm in na vrhu ima dotočno cevko. Nastane zaradi polzenja vode iz stropne razpoke (Franke 1975; Slabe 1990).

Talna vdolbinica (floor pit (Lange 1960, 78)), ki je pokončna, nad dnom razširjena in globoka od 1 do 10 cm, nastane zaradi kapljanja vode.

4. **Tudi zračni tokovi zaradi kondenzacije vlage iz njih povzročijo nastanek značilnih skalnih oblik**:

Faseta je plitka polkrožna vdolbina na zgornjem delu sten ali na stropu rova. Njen premer meri 0,5 do 1 m.

Kotlica je nekoliko globlja vdolbina v stropu. Ima 1 m in več premera.

Žleb na stropu (nem.: Deckengrübbchen (Bögli 1978, 162)) je raven ali vijugast. Njegov premer meri 20 do 100 cm.

Razjede (Slabe 1988) so manjše vdolbinice ali štrline. Njihovo obliko in velikost določa sestava kamnine.

Te oblike, zaenkrat še opisno s pridevnikom kondenzen, ločim od drugih podobnih.

5. Pod ledom nastajajo **podledne skalne oblike**:

Podledna stenska zajeda je večja, vzdolžna vdolbina z gladkimi stenami. Izpričuje rob zapolnitve votline z ledom.

Podledni žlebiči (nem.: Eiswasserrinen (Bögli 1978, 1963). Nastanejo zaradi izcejanja vode iz ledu.

6. **Biogene razjede** nastanejo pod lišaji, iztrebki netopirjev. Prve so manjše (nekaj mm) vdolbinice ali štrline, druge pa nekoliko večje vdolbinice.

7. **Zaradi razpadanja kamnine nastanejo**:

Odlom - blokovni (block breakdown (White 1988, 229)) nastane ob razpokah, skladovni pa ob lezikah (slab breakdown (White 1988, 205)).

Odkrušek (chip breakdown (White 1988, 230) nastane zaradi razpadanja kamnine v manjše dele ali posamezna zrna.

Kupola (dome (White 1988, 231; Bini & Cappa 1978, 60; Gilli 1985)) in obokan strop sta posledici razpadanja stropa večjih votlin ali pretrtega stropa manjših rovov.

Speleogenetski pomen jamskega skalnega reliefa

V aktivnih kraških votlinah je skalni relief največkrat odsev njihovega enotnega ali raznovrstnega današnjega oblikovanja. V isti votlini pa se lahko zvrsti več različnih razvojnih obdobij. V večjih votlinah je skalni relief zato splet sledi preteklih razvojnih obdobij in njihovega današnjega oblikovanja. Sledi različnih razvojnih obdobij so ohranjene tudi v starih jamah. Skalni relief je posledica učinkovitosti mlajših razvojnih dejavnikov, ki se vrstijo v istem delu votline. Ti stari skalni relief lahko povsem preoblikujejo ali le delno prekrijejo. Najbolj učinkoviti dejavniki preoblikovanja skalnega reliefa so vodni tokovi, prenikajoča voda in razpadanje kamnine, manjši tokovi v nadnaplavinskih žlebovih pogosto le prepredejo stari skalni relief, kondenzna vlaga in biogeni dejavniki pa le razčlenijo površino starih skalnih oblik.

Iz skalnega reliefa pogosto nazorno razberemo raznolika zaporedja najbolj izrazitih razvojnih obdobij votline. Nudi nam tudi dokaj popoln vpogled v način oblikovanja votline v teh obdobjih. Razberemo lahko način pretakanja vodnih tokov skozi rove, zapolnitev rovov z naplavino in pretok vode nad njo. Najlepše je razviden izrazit poligenetski značaj votline, v kateri so sledi vodnega toka le na posameznih mestih prekrite s skalnimi oblikami, ki nastanejo zaradi prenikajoče vode.

Skalni relief nam pogosto ne nudi celovitega vpogleda v razvoj votline. V njem se namreč odražajo le najbolj učinkovita razvojna obdobja oziroma trenutek sedanjega oblikovanja votline ali prekinitve nekdanjih prevladujočih dejavnikov. Razvojnih obdobij votline iz skalnega reliefa tudi ni moč neposredno časovno opredeliti.

Najbolj nazorno je raznovrstni speleogenetski pomen skalnega reliefa razviden predvsem v jamah, značilnih za kraški predel, ki je bil izpostavljen enotnemu razvoju. Manj različnih razvojnih obdobij se odraža v skalnem reliefu posamezne votline ali njenega dela. Skalni relief je sled različnih razvojnih obdobij predvsem v kraških predelih, v katerih se je izrazito hitro, skokovito znižal piezometrični vodni nivo in so bila zapolnjena z naplavinami. Čeprav se votline večinoma ne oblikujejo po enoličnih etažah, izjema so nekatere ponorne jame, pa so stare sledi njihovega oblikovanja, stari skalni relief ali naplavine, ohranjene v nadstropjih. To je posledica nihanja, predvsem nižanja vodne gladine v celotnem kraškem predelu, ki pa je bilo pogosto lokalno različno hitro. Smiselnost proučevanja skalnega reliefa kot speleogenetske sledi se zato povečuje v povezavi z drugimi speleološkimi znaki kot so: položaj votline v vodonosniku in njena oblika oziroma oblika njenih delov, sedanji dejavniki njenega oblikovanja, ter naplavina in siga v njej.

Skratka, skalni relief je pomemben, čeprav omejen razpoznavni znak sedanjega in nekdanjega oblikovanja kraških votlin. Po dosedanjih izsledkih pa lahko trdimo, da je njegovo poznavanje neobhoden del speleomorfogenetskih študij. Pestre splete omenjenih razmerij lahko razberemo že iz bogatega in raznovrstnega gradiva, ki ga nudi naš kras. Za koristna so se izkazala tudi poskusna oblikovanja skalnih oblik na mavcu. Trdim lahko, da so korak naprej od sklepanja po bolj ali manj uspešnem razpoznavanju dejavnikov, ki oblikujejo skalo. Poustvarjanje namreč terja poznavanje večino le teh. Nove možnosti za proučevanje skalnih oblik so nakazala kvantitativna razčlenjevanja in primerjave njihovih oblikovnih značilnosti. Proces, ki deluje na kamnino, lahko dokaj zanesljivo razberemo tudi z mikroskopskim opazovanjem skalne površine.

Širina zajete problematike omogoča le počasno in neenakomerno grajenje temeljev, kar se odraža tudi v mojem dosedanjem delu. Vse hitreje se odpirajo poti nadaljnjega proučevanja: tako glede oblikovanja posameznih skalnih oblik, tipov skalnega relifa ter njegovega vrednotenja kot speleogenetske sledi.

IZVLEČEK – ABSTRACT

CAVE ROCKY RELIEF AND ITS SPELEOGENETICAL SIGNIFICANCE

Processes that shape the karst underground leave traces on the rocky perimeter of the caves. Rocky features representing rocky relief occur. Frequently it provides important evidence on the formation and development of the cave.

The origin and development of rocky features is studied. Rocky relief as an indicator of the mode of cave passage formation under different hydrological conditions and its speleogenetical significance in various caves is presented. The speleogenetical significance of rocky relief in selected areas of the Slovene karst is evaluated.

JAMSKI SKALNI RELIEF IN NJEGOV SPELEOGENETSKI POMEN

Dejavniki, ki oblikujejo kraško podzemlje, zapuščajo sledi tudi na skalnem obodu kraških votlin. Nastajajo skalne oblike, ki jih povezujemo v skalni relief. Ta je pogosto pomembna sled oblikovanja in razvoja kraških votlin. Proučen je nastanek in razvoj najbolj značilnih jamskih skalnih oblik. Predstavljen je skalni relief kot sled načina oblikovanja rovov v različnih hidroloških pogojih ter njegov speleogenetski pomen v razvojno raznovrstih jamah. Ovrednoten je speleogenetski pomen skalnega reliefa v izbranih predelih slovenskega krasa.

Tadej Slabe, dr.
Inštitut za raziskovanje krasa
Znanstvenoraziskovalni center
Slovenske akademije znanosti in umetnosti
Titiov trg 2
66230 Postojna

Tadej Slabe, Ph. dr.
Karst Research Institute
Centre for Scientific Research of the
Slovene Academy of Sciences and Arts
Titiov trg 2
SI-66230 Postojna, Slovenia

Zbirka **ZRC**

1
Dušan Kos
Med gradom in mestom
Odnos kranjskega, slovenještajerskega in koroškega plemstva do gradov in meščanskih naselij do začetka 15. stoletja. Ljubljana 1994.

2
Eva Holz
Razvoj cestnega omrežja na Slovenskem ob koncu 18. in v 19. stoletju. Ljubljana 1994.

3
Dušan Kos
Imago Iustitiae. Historični sprehod skozi preiskovanje, sojenje in pravo pri plemstvu v poznem srednjem veku. Ljubljana 1994.

4
Historični seminar • Historisches Seminar • Historical Seminar = Pot na grmado • Der Weg auf den Scheiterhaufen • The Road to Pile. Ljubljana 1994.

5
Monika Kropej
Pravljica in stvarnost. Odsev stvarnosti v slovenskih ljudskih pravljicah in povedkah ob primerih iz Štrekljeve zapuščine. Ljubljana 1995.

6
Janja Žitnik
Orel in korenine med »brušenjem« in cenzuro. Ljubljana 1995.

7
Darinka Trpin in Branko Vreš
Register flore Slovenije. Praprotnice in cvetnice. Ljubljana 1995.

8
Blaž Resman
Barok v kamnu. Ljubljansko kamnoseštvo in kiparstvo od Mihaela Kuše do Francesca Robbe Ljubljana 1995.

9
Fran Ramovš
Kratka zgodovina slovenskega jezika I, Ljubljana 1995.

ISBN 961-6182-03-X

9 789616 182034