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## EXPERIMENTAL MODELLING OF CAVE ROCKY FORMS IN PARIS PLASTER

### RIASSUNTO

*I vari morfotipi presenti su pareti e soffitti delle cavità (scallops, cupole di corrosione e canali di volta, nella fattispecie) sono il risultato di particolari fattori morfogenetici e quindi il loro riconoscimento è utile nella ricostruzione degli avvenimenti idrogeologici e delle vicissitudini evolutive delle cavità stesse e delle aree in cui 'esse si aprono.*

*Si è ormai giunti a formulare modelli genetici ed evolutivi precisi e circostanziati per quasi tutti i morfotipi, tuttavia è parso opportuno eseguire, con l'aiuto di J. Hajna, una serie di esperimenti di modellizzazione dello sviluppo di alcune forme, ricreando in laboratorio le particolari condizioni idrogeologico - genetiche ed utilizzando del gesso al posto della roccia calcarea.*

*Buoni risultati hanno ottenuto gli esperimenti volti a originare gli scallops e le cupole di corrosione. Più complesso si è dimostrato invece ottenere i canali di volta: gli esperimenti si sono comunque dimostrati utili a meglio definire i modelli genetici, nonostante i limiti di questo tipo di modellistica.*

*Appena iniziati sono gli studi sulla forma dei morfotipi in funzione delle dimensioni e delle irregolarità dei condotti idrici.*

*Si dovranno quanto prima verificare con maggior precisione anche i rapporti fra dimensione delle morfologie e tipologia delle modellizzazioni: spesso infatti i morfotipi ottenuti avevano dimensioni inferiori alle aspettative teoriche ed agli esempi reali. Non si è inoltre ancora potuto eseguire, per problemi squisitamente finanziari, un numero statisticamente significativo di modellizzazioni. Così come non è ancora stato possibile effettuare modellizzazioni secondo ipotesi genetiche diverse da quelle oggi più accreditate o modificare alcuni dei fattori genetici.*

### SUMMARY

*Cave rocky relief is frequently an important speleomorphogenetical indicator. Genesis and development of the caverns may be understood if the conditions, factors and processes of the karst underground cavitation are known. One of tools is experimental modelling of rocky forms in Paris plaster. However, it requires an image of the karst caverns formation. I tried to explain the origin and development of the above-deposit ceiling channels and anastomoses, below-deposit half-tubes, facets, solution pockets, due to water percolation and solution niches due to water dropping to the rock.*

### POVZETEK

*Speleomorfogenetski dejavniki zapuščajo sledi tudi na skalnem obodu votlin. Oblikuje se jamski skalni relief, ki je pogosto pomebna speleogenetska sled, še zlasti, če ga sestavljajo skalne oblike,*

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katerih nastanek in oblikovanje znamo razložiti. Sklepanja o nastanku nekaterih jamskih skalnih oblik sem zato skušal preveriti z njihovim poskusnim poustvarjanjem na mavcu, čeprav nam mnogo raznovrstnega študijskega gradiva nudi naš kras.

Dokaj uspešni so bili poskusi s fasetami v žlebu in na mavčnem bloku, stropnimi kotlicami, ki nastajajo zaradi polzenja vode iz razpoke in oblikovanje stropa okoli njih, pa z vdolbinicami, ki nastanejo zaradi kapljanja in žlebičev, ki nastajajo zaradi izcejanja vode iz drobnozmate naplavine, ki jo odlože poplavne vode. Najzahtevnejše, a za prve poskuse uspešno, je bilo proučevanje nastanka nadnaplavinjskih stropnih kanalov. Pri delu mi je pomagal J. Hajna. Poročilo je del projekta Nastanek in oblikovanje kraških votlin, ki ga financira Ministrstvo za znanost in tehnologijo Republike Slovenije.

Zaključimo pa lahko, da so takšni poskusi dober študijski pripomoček in bi z njimi vsekakor kazalo nadaljevati, saj njihove prednosti odtehtajo poznane pomanjkljivosti. Natančneje pa bo potrebno določiti velikostna razmerja poskusov, le ti so pogosto manjši od primerov v naravi, in število njihovih raznovrstnih ponovitev, ki povečuje gotovost dosežkov.

Širina zajete problematike omogoča le počasno in neenakomerno grajenje temeljev, kar se odraža tudi na poteku mojega dosedanjega dela. Se pa vse hitreje odpirajo poti tovrstnega nadaljnje proučevanja. Izkazalo se je namreč kot koristno in trdimo lahko, da je korak naprej od sklepanja po bolj ali manj uspešnem razpoznavanju dejavnikov, ki vplivajo na oblikovanje skalnega oboda kraških votlin, saj poustvarjanje terja poznavanje večino le teh. V poteku so poskusi z oblikovanjem skalnega reliefa v različno velikih in vijugastih rovih, skozi katere se pretaka vodni tok.

## Introduction

Speleomorphogenetical factors leave the traces on the rocky rim of the caves. Thus formed cave rocky relief is frequently an important speleogenetical indicator, in particular if it is composed by the rocky forms which origin and development could be precisely explained. Therefore I tried to check the conclusions about the development of some rocky cave forms by their experimental modelling in Paris plaster, although a lot of heterogeneous study material is offered by our karst.

Rather successful proved to be the experiments with scallops in a channel and on the plaster block, with ceiling pockets originated by the water trickling down out of the fissure and the formation of the ceiling around them and with solution niches which result due to dropping and half tubes which originate due to water filtration of fine grained sediments deposited by the flood waters. Of the greatest pretension but successful for the first experiments, was the study of the origin of the above sediment ceiling channels. J. Hajna helped me at this work. The report makes a part of the project Origin and genesis of the karst caves, financed by the Ministry of Science and Technology of the Republic of Slovenia.

At my experiments I used the industrial plaster ( $\text{CaSO}_4 \times 1/2$  water), tap water and river water (Planinska jama) and for the forms connected by the fine grained sediments in the cave the flysch loam deposited by the flood waters in Blatni rov of the Predjama cave. The advantage of plaster replacing the rock lies in its high solubility enabling quick formation of various features. At room temperature in water 1,4 g of plaster dissolved. The loam contained up to 0,5% of organic carbon. When the loam soaked in the water for longer time more plaster was dissolved (1,7 g/l). The time advantage enables the observation of the shapes formation.

## Some Sources of relative experiments

Most of the cave rocky forms and the interpretation of their origin by various processes in various conditions were described on the base of the observations within

the caves and conclusions connected with other speleological signs. More rare are the studies reported about the experiments of the laboratory modelling of the particular shapes.

Paragenetic transformation of the ceiling because of water infiltration above the fine grained sediments was confirmed by LAURITZEN (1981, 407) already by his experiment when on the plaster he got a small net of runnels, having diameter from 2 to 3 mm only. Similar size have the particles constituting the deposit. The runnels thus originated due to water current among the particles of the deposit which were in close contact with plaster. The tubes in the caves are as a rule much bigger as they considerably surpass the size of the particles composing the deposit.

By the experiments in plaster RUDNICKI (1960), CURL (1966), GOODCHILD & FORD (1971) and ALLEN (1972) studied the scallops.

RUDNICKI (1960) was the first who tried to explain the origin and the properties of the scallops. He stated (1960, 29) that bigger the flow velocity is, smaller the scallops are. He says (1960, 30) that the scallops net is mature when scallops are united into series which are transverse to the water current direction. I have stated that such series are characteristic for narrow passages in the channels, wall notches and outflow parts of rocky blocks in the riverbed.

CURL (1966, 1974) set up the basis of the relation between the flow velocity and the size of the scallops. He infers that the shape and the size are the result of the average velocity of the water flow in the channel, of channel dimension, of density and viscosity of the water and of ions diffusion if the solution is steady and the rock homogeneous. He stressed the importance of various properties, the fissures in the rock in particular, causing the irregularities at the scallops origin.

GOODCHILD and FORD (1971) tried to define by modelling in plaster the hydraulic causes for various sizes of the scallops.

ALLEN (1972) poured over the plaster in 3 m long channel the water with the velocity of 28 to 90 cm per second from 1,5 to 15 cm deep. He accentuates that the scallops originate only if the unhomogeneties in the rock are big enough to form the independent eddies at the wall. Unhomogeneties in the rock influence upon the scallops distribution, but a singular unhomogeneity may initiate the form similar to scallop.

QUINF (1973) stated by the dissolving the limestone in HCl the probability of the origin of the ceiling pockets due to corrosionally active water mixture. In a bowl of water he dipped a broken rock and through the fissure he poured HCl. On the bottom of the fissure deep and narrow pocket occurred.

EWERS (1966, 1972, 1982) modelled in salt the anastomoses, but they are the initial channels and not the rocky features.

MOWAT (1962) ascertained by dissolving the stony plates of irregular forms the statement of LANG (1959) that the concave parts of the rock are getting round while the convex parts remain sharp.

Several experiments of minute formation of the rocky surface due to rainwater trickling down the rock were made (GLEW & FORD 1980; DZULYNSKI & GIL & RUDNICKI 1988). But these experiments are not the case of the actual study.

## **Rocky relief at the contact with the sediment**

At the contact with fine grained sediment the water frequently dissects the rim of the karst caverns into rocky relief at the contact with the sediment (SLABE 1992). It consists of above-sediment and below-sediment rocky features. The above-sediment ceiling chan-

nels and solution niches are characteristic for the channels which were filled up by the flood sediments. Due to water drain above the loam in a flooded channel the ceiling channels raise the ceiling and water does not incise into the walls when it flows downwards. The water that comes into filled up channels through the fissures may downcut at the mouth the solution cups. Thin solution niches originate on the rock at the humid sediment. The above-sediment rocky features are characteristic for the caverns of the contact karst which were in Pleistocene frequently entirely filled up by fine-grained sediment.

The below-sediment rocky features make a part of the rocky relief of the channels where seasonally slow water current appears and deposits fine-grained sediment on the rim. These are flutes and floor-pits, wall notches, roof pendants and solution cups and wall niches. Their origin is due to water filtering off the sediment (flutes), corrosion below the humid sediment (floor-pits) when high waters retreat or due to dissolution of a bare rock in phreatic channels (wall notches, roof pendants). The sediment namely prevents on some places the contact of water and wall. In seasonally flooded channels frequently prevail the traces of inundation of smaller quantity of fine grained sediment above the features which were left by the water current. The water level oscillation is the result of short lasting changeable climatic conditions on our karst.

The origin of most of the described rocky features I tried to explain mostly in respect to their shape properties, their position on the rocky rim and conditions at which they are formed. The assessment about the origin of the above-sediment ceiling channels and the below-sediment flutes I completed by the experiments in plaster.

#### *Experimental above-sediment ceiling channels in plaster*

Below differently large plates of plaster (0,3 - 0,5 m<sup>2</sup>; the biggest was long and wide 70 cm) either horizontal, vertical or in various inclinations 5 to 8 cm thick layer of loam was flooded. The loam was added to the inflow water. Ahead of outflow of the system the plates were below the level of the spring and in the background above it. The loam quickly filled up the spaces below the slabs which were below the level of the spring. At first the water flew over the spring's bar evenly later particular springs with eddies occurred being rather uniformly distributed along the overflow. The number of springs gradually diminished and finally one predominated, although at some experiments two springs remained. The loam was added to the inflow water simultaneously and proportionally some of it flew off. The drainage through the system occasionally slowed down or stopped even. Yet in the hinterland 1,5 m high column of pressure was possible the discharge opened by smaller or bigger push of water after 1 to 5 minutes. After the biggest pushes several springs were restored. Most of them dried up soon, but the situation that existed before the system was filled up was restored. If we added too much loam the discharge was rejuvenated only by drying up the system. The loam sedimented and cracked and we carried the experiment on. At the first attempts already it was shown that the runnels appeared at the plaster contacts due to composition and closing of the system and at the fissures. During the experiment when the plate was some cm only below the spring level two runnels occurred at the contact of plaster. The diameter of the first one was 1 cm and cross section was omega shaped. After some hours the cross section opened, widened (2 cm) and raised (2,5 cm). The second runnel was 5 cm wide and 3 cm deep. At the beginning the runnels operated simultaneously, later all the discharge below the plaster surface was undertaken by the bigger runnel. Smaller runnel was filled up due to loam addition and its summit overpassed the level of the spring a bit earlier. Its raise upwards enabled the dune which occurred at the mouth. Smaller

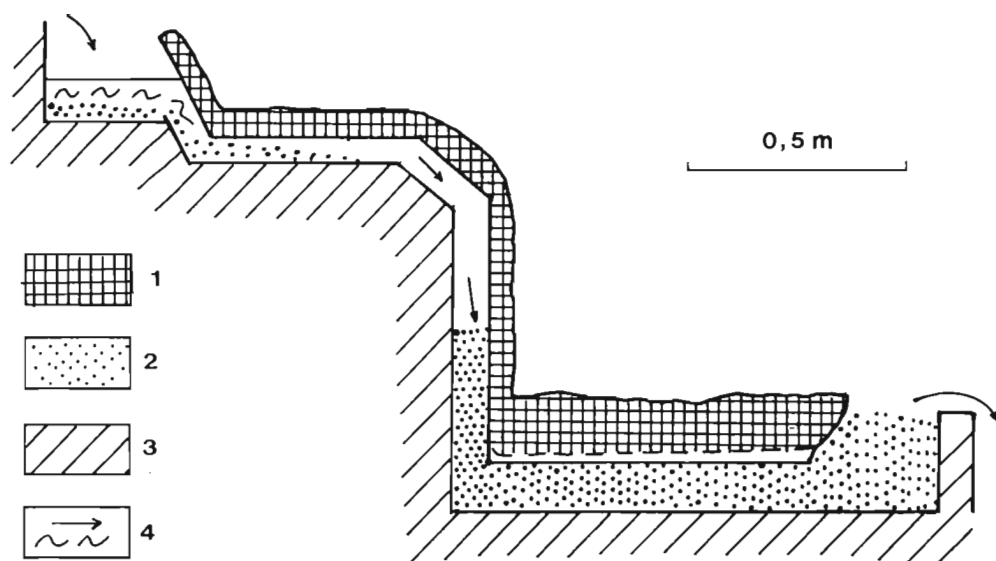


Fig. 1: Cross section of the experimental model - 1. plaster, 2. loam, 3. wooden casing, 4. water current.



Fig. 2: Ceiling channels.

runnels occurred on the plaster plates which were pretty high above the spring level. They were formed at sharp bends between the plates which contacted under various angles. Below the bends the loam was deposited.

The most marked system of runnels occurred on the plate which was 0,7 m long and wide and which bottom was placed 0,2 m below the spring's level. Into the system (fig. 1) that works 120 hours the loam was added all the time. A half of the waterfilled surface of the plaster was thinnly fissured, into the second half we cut rectangular net of incisions, 5 mm deep and 3 mm wide. At first on the entire surface, among the incisions and fissures included, appeared small joint anastomoses, diameter of some mm only. Bigger runnels occurred on the fissured plate. Deeper runnels (fig. 2) (up to 2,5 cm) were narrower (up to 8 mm), more shallow runnels (up to 1,5 cm) were wider (1,2 cm) with omega-shaped cross section. Deeper runnels had half-circular tops. Regarding the size outstands a runnel which rather directly connects the dissected net of fissures. To establish the permeability of the runnels was rather complicated due to fact that the water drained through the plaster too. The fissured plate was namely connected by some cm thick layer of plaster and on the contact of both a tube, 5 cm wide with flat bottom occurred. Along the edge the tube is semi-circularly widened. Its wide omega cross-section shape is rather direct. Smaller runnels on the surface of the plate were filled up by loam. The traces of loam at the contact of plaster slabs indicate that the water filled by loam at first less permeable conduits and at the same time forced itself more permeable ones. At the outlet of the runnels, on the vertical edge of the plate, shallow, 1 cm wide, straight runnels occurred. At bigger spring only, behind the central runnel the outflow runnel has bigger funnel-shaped mouth. These runnels too developed below the water level of the spring, namely at the contact with the dunes that water had deposited before it blocked the spring.

Before we ended the experiments we dyed the loam that was transported by the water into the system. On plaster and in the loam the runnels which were permeable the last, were clearly manifested.

### *The origin and the development of ceiling channels and anastomoses*

After observing the rocky features in the caves I presumed that slow flood waters gradually deposit the fine grained sediments, filling the channel in lee-ward places at first and then from the obstacles upstream and from the bottom towards the ceiling. If the water discharge is slow, being the result of smaller channels permeability and the flow transports enough of fine-grained material, the sediments fill up the channels almost entirely. Major part of the water drains through the whole upper part of the channel, and smaller quantity of water searches more permeable routes below the channels ceiling. The water flows over the sediments under the pressure and runnels do incise into the ceiling. Size, shape and winding of the runnels are controlled by the shape and permeability of the channels, velocity of water discharge, lithology and how much the rocks are fissured and properties of the material, transported by the water.

The presumptions were proved by the experiment. I stated also that at increased pressure in the background more swift water current may start to erode the deposits. Due to smaller discharge velocity too much loam is deposited, which is the case at dense muddy current and the runnels get blocked. At the experiments which had limited column of pressure the discharge was renewed after long lasting interruption until the deposits which settled down and cracked, were dried up.

The smallest particles of the sediments may be transported by extremely slow water flow and when they are deposited much bigger lifting force to move them again is

required than had been the initial water velocity when it transported these particles and deposited them (SCHEIDEGGER 1961, 135). The loam with the particles of 0,01 mm size the water deposits at the velocity of 1,2 cm/s and erodes not earlier than at the velocity of 40 cm/s. Smaller the particles of the sediment are bigger the difference of the velocity is when the water includes them in its current again. This is the basic reason that the channels are filled up by the fine-grained sediments and, of course, for marked incise of water flowing above the sediment and incising into the ceiling. When the runnels are big enough that the discharge augments too the water starts to cut into the loam below them (SLABE 1989, 69). This is why bigger runnels are semi-circular, the lower half-circle being namely in the loam already.

Smaller conduit permeability accelerates the sediment deposition. The water under pressure divides into branchwork net of winding runnels and anastomoses start to be formed (SLABE 1987; MIHEVC 1991). The current markings (fig. 3) consisting of bigger runnels are characterized by being multi-storeyed. Smaller nets with equally sized runnels have all the runnels at the same level. In bigger nets smaller runnels remain hanging above larger ones. If the large runnels existing within the net widen and predominate that may cover other runnels and among them singular pendants remain only. By the experiment we found out that at the beginning of the net formation during fast deposition of the sediments the water searches several permeable conduits. It was proved also by numerous springs at the beginning of the experiment and by small anastomoses on the plaster. Later water chooses the most permeable runnels and fill up the smaller by the sediment. Smaller runnels and incisions which were done on the plate were filled up by the loam and without any trace of dye which was introduced into the system at the end of the experiment. Consequently the biggest runnels predominated completely.

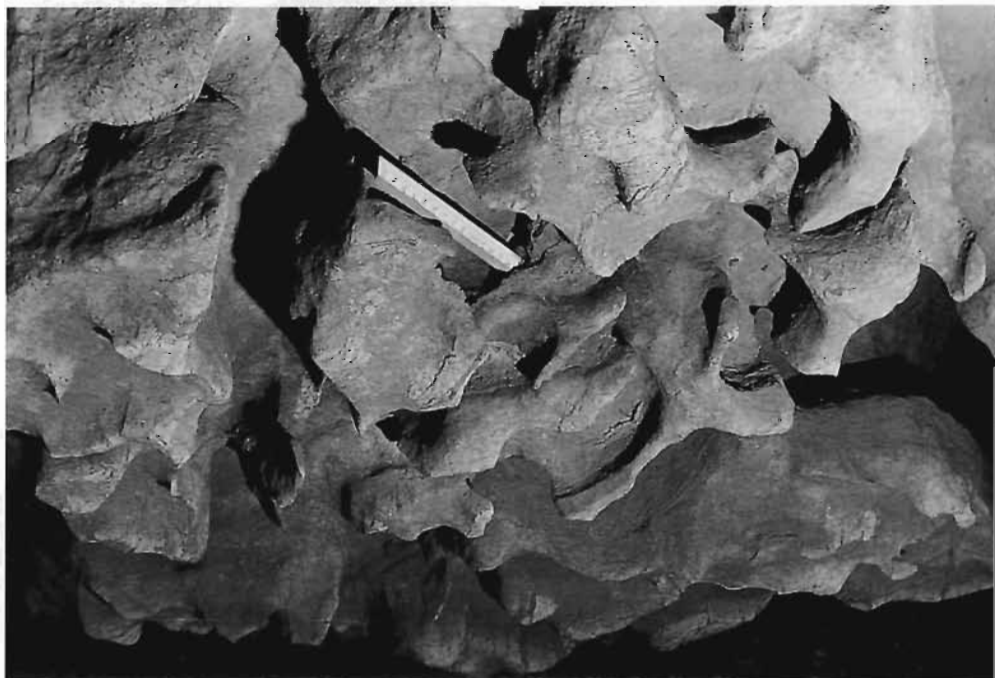


Fig. 3: Anastomoses (scale is 15 cm).

I assumed the development of runnels from small to large with omega cross section on the example of cave anastomoses in Dimnice (SLABE 1987, 176). The hypothesis was confirmed by the experiment in plaster. When adding the loam a narrow runnel occurred at first and later, due to bigger permeability as it was the predominating water course has developed into runnel with omega cross section. The runnel then grew into height and widened into open omega shape. In plaster along more expressive fissures narrow and deep runnels developed, along less expressive fissures they were more shallow and had omega cross section. Narrow and high runnels occurrence is due to abundant adding of water with loam. The loam was deposited and water quickly incised into the plaster. Within the same runnel there may be either the sections with omega shaped cross section or narrow and high runnels.

The experiments with the ceiling channels in plaster confirmed the hypothesis (SLABE 1987, 178) of their formation by water current in phreatic zone above the fine grained sediments. They also contributed the starting point for the explanation of their various shapes. The results of above ceiling channels formation are due to small amount of the experiments of limited value. The biggest deficiency of the experiments is that one may not monitor the formation of ceiling channels. Yet the experiment may be observed and controlled by water inflow within the system and outflow out of the system. In any case the continuation of the experiments is recommended as they contributed many explanations in respect to water drainage above the fine grained sediments and opened the way for new.

#### *The above sediment solution niches and floor pits*

The rim of channels that were filled up by the fine grained sediment is frequently weathered by semi-circular notches. The notches of some mm of diameter occurred in plaster too. The manner of notching the walls depends on the composition, porosity and fissures within the rock, humidity of the sediment and duration of the process.

#### *Experimental below-sediment half tubes*

In the parts of epiphreatic channels which are not exposed to swift water current the below sediment half tubes occur (fig. 4). As a rule they are found on lower parts of the cave walls. The half tubes originate on gentle or vertical walls but even on the over-hanging ones. The largest half tubes are 15 cm deep, but generally they are smaller. Their cross section is V-shaped with rounded bottom. Among them there are quite sharp edges. On gentle surfaces among the half tubes where the loam may be deposited, small half tubes occur leading over bigger edges towards the larger ones. On the overhanging walls there



Fig. 4: Below sediment runnels.





Fig. 5: Below sediment runnels on the vertical plane of the plaster model (scale is 15 cm).

are below the sharp mouth on the edge funnel-shaped tubes which widen down the wall. There are narrow edges among them only. I inferred that the tubes are formed by water filtrating out of freshly deposited sediment or out of moistened old one. It is deposited by the water current on the gentle sections of the rocky rim.

I tried to illustrate the origin of half tubes by the experiment in plaster. The plaster block with flat upper surface and variously inclined lateral planes, it means vertical (fig. 5), gentle sloping with  $80^\circ$  of gradient, overhanging with the same inclination and overhang was exposed to flooding with water where the loam from Blatni rov in Predjama cave was added. Below such water in the cave the half tubes originate. When the loam deposited we lowered its level. Out of moistened sediment that covered even the upper, horizontal plane of the block and the upper parts of the gentle sloping and vertical lateral plane the water percolated. The belts of washed off plaster occurred and shallow notches in the loam. After repeated flooding the water chose again its way over the notches into the washed off belts. Half tubes started to be formed (Fig. 6). The half tubes were the most densely distributed but small on the upper part of the gentle sloping plane widened downwards. The water namely joins into smaller flows. On the vertical plane the half tubes are rather equally large over the whole length. The mouths between the upper horizontal surface and the walls have sharp bends and control the direction of the trickling water. If over the overhanging walls more water flows funnel-shaped half tubes occur. On the upper part the half tubes are deeper, downwards the same amount of water spreads over bigger surface and hence the half tubes are more shallow. Smaller amount of the water disperses on the ceiling and causes the formation of clints while bigger amount incises wide, short and semi-circular ended half tubes.

The half-tubes are incised by the water that trickles out of fine grained sediment.

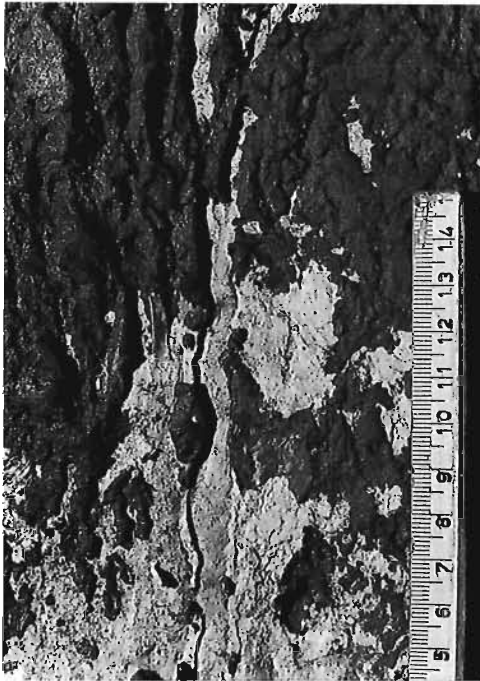


Fig. 6: Bevel on the vertical plane of the plaster model.

At the same time the quantity of deposited loam, due to size restriction of the experiment, was relatively small and smaller quantities of water were trickled out of it. The water was flowing from the upper, well moistured layer of the sediment. This is why the half-tubes are distributed scarcely. Within short temporal intervals the water filtered out of the sediment in drops and on some places the half-tubes are therefore winding.

## Scallops

The scallops (fig. 7; Slabe 1993) are longitudinal pits associated into a net on the rocky rim of the passage. They are formed by water currents due to eddies appearing at the rough rock surface.

### *Formation of scallops in plaster by the laboratory experiment*

Over the solid and rather homogeneous plaster, cast into the semicircular shape, the current, 1 m/s velocity flew. The deepness of the current was 1 cm only. In shallow current the water was distributed into narrow, some centimeters long, almost parallel flow lines. The scallops, 5 mm long, 2,5 mm wide and 2 mm deep, mostly opened, developed. Along the obstacles, at the coarser grains, at first the water cut small pits and later transported the grains (fig. 8). In two hours the scallops have been developed out of pits. After four hours their shape was no more substantially changing. I repeated similar experiment with water current having the velocity of 0,2 m/s. In this case too

Hence, they originate, when the water level in the cave lowers. The distribution of the half-tubes and their size are controlled by the water quantity filtered out of the sediment. Bigger water quantity trickling steady out of the sediment incises dense, straight and according to wideness shallow half-tubes, smaller quantity, however, the half-tubes distributed scarcely, but they are deeper and may be winding. The decrease of the trickling water quantity reflects in a small half-tube within the bigger one. Their shape is mostly controlled by the surface gradient, where the water trickles. On vertical surface the half-tubes are equal along the whole length, on overhanging walls they are widened downwards. The water quantity is controlled by the amount of the sediments. Big quantities of sediment or frequent floods are necessary for the origin of the below sediment half-tubes.

Two restrictions appeared during the experiment. The surface of very soluble plaster became rough and as it was not washed by the water current much more loam stuck on it than on the limestone.

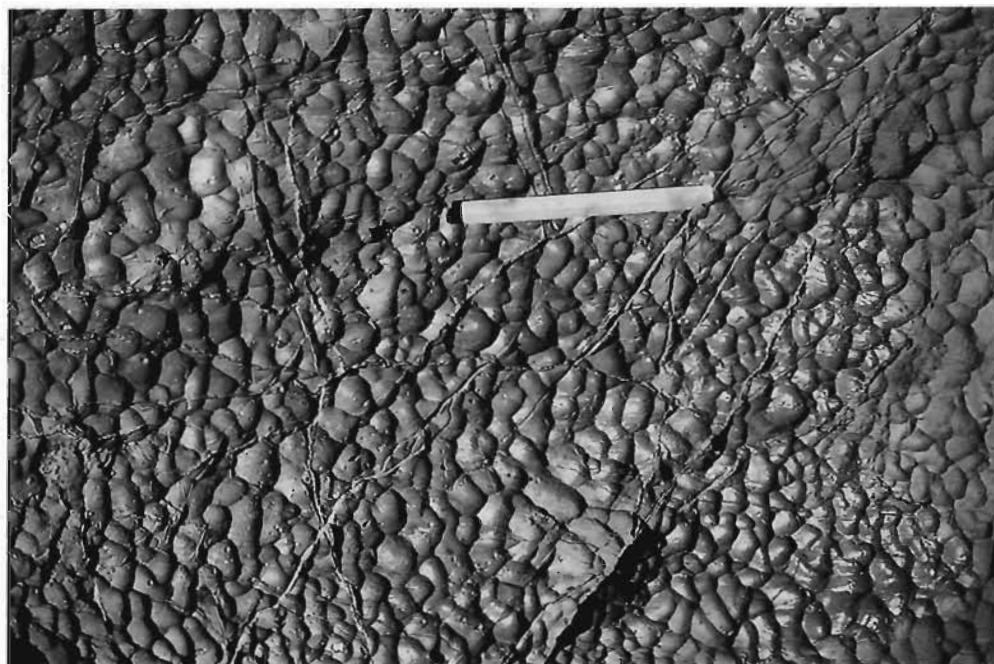


Fig. 7: Scallops.

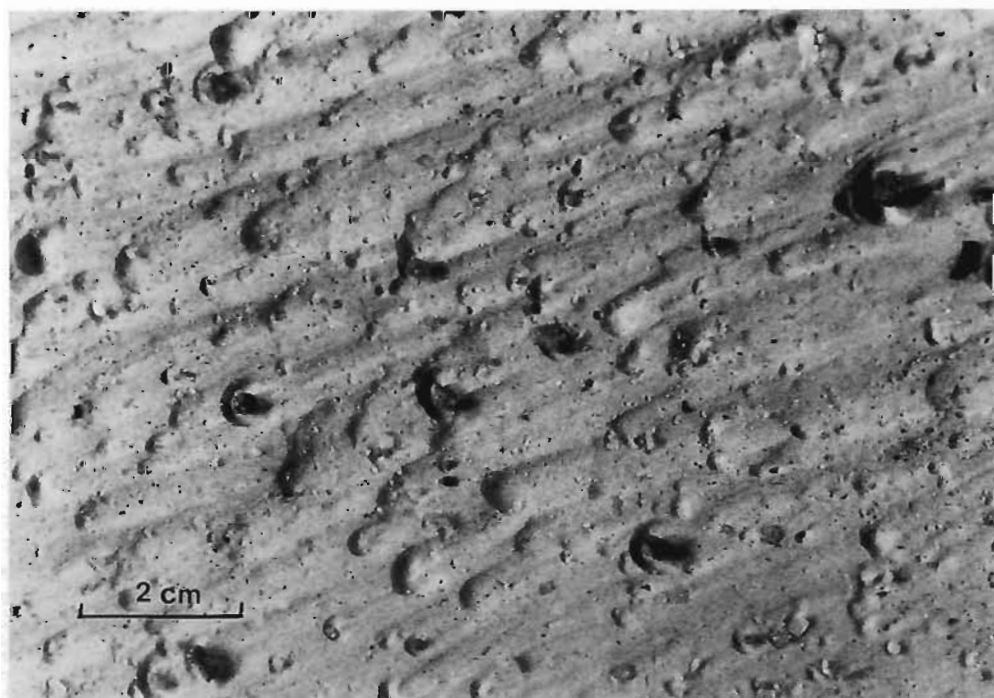


Fig. 8: Scallops on unhomogeneous plaster.

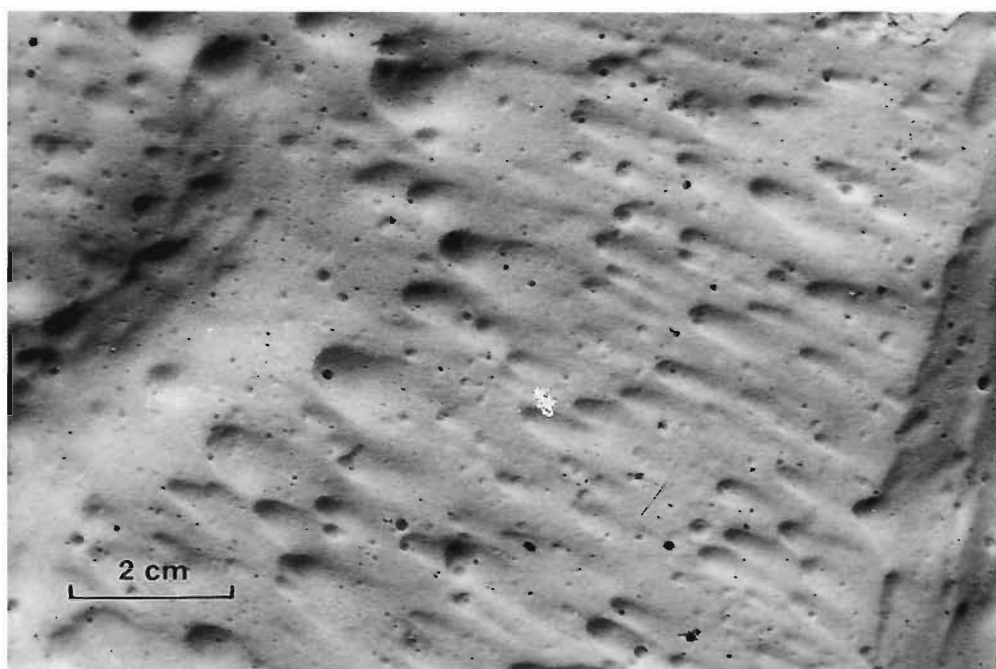


Fig. 9: Scallops on homogeneous plaster.



Fig. 10: Scallops net on the plaster block.

the elongated, but a bit larger scallops developed.

Bigger plaster block with eight angles and straight lateral and upper planes, 1,2 m of diameter, was dipped into the artificial waterbed which leads towards the hydropower station at the entrance to Planinska jama. The surface of the block was 1,5 m below the water level, the flow velocity was 1,4 and 0,9 m/s. In both cases the scallops developed on the block (fig. 9) after two hours already and later their size and shape did not change any more. In the first case they were up to 1 cm long and in the second up to 1,5 cm. The scallops were narrow (up to 0,5 cm) and relatively long, hence similar to the scallops which develop below shallow open currents in the caves. Rather marked is their deepening on the inflow side, disappearing slightly on the outflow side. Particular scallops are widely opened, when they lie one close to the other and are united into a net, they are closed. The distribution and orientation of scallops on the surfaces, exposed to water current below different angles is characteristic too. In the middle of the inflow lateral plane which was perpendicular to the water current direction the pits developed while on the marginal parts of the surfaces scallops which were oriented towards the borders. Similar is the shape of rocky blocks in the riverbeds within the caves. On the plane (fig. 10) which was exposed to water flow below the angle of 45° the scallops appeared on the entire surface. At the beginning the scallops are parallel to the current, in the second half they are oriented towards the borders. On the plane, parallel to the water flow the scallops too are oriented in the same direction. On the back side of the block lying transversely to the flow direction but in lee-ward position, only small pits developed. On the upper plane of the plaster the scallops are at the beginning parallel to water current while on the outflow side they are oriented towards the borders of the block. The same distribution of the scallops is found on the rocky blocks in the riverbeds

in the caves where open currents flow and are situated close to the water level (the riverbed in ěkocjanske jame).

The plaster block of the same size (fig. 11) composed by layers to which were added variously large particles of non-soluble or poorly soluble grains of sand, was exposed to water current having the flow velocity of 1 m/s. The lower layer of plaster was composed by the particles smaller than 0,1 mm. In the second layer the particles of 0,1 to 0,25 mm were mixed with 20% of particles having the diameter of 0,5 mm. To the third layer of plaster, composed by the particles of 0,1 to 0,25 mm 10% of non-soluble particles, 1,25 to 2,5 mm of diameter, were added. To the fourth layer of plaster 10% of non-soluble sand, particles having 5 to 10 mm of diameter, were added. The distribution of the scallops on the block was similar to above described example, various rocks were characteristically shaped. On the homogeneous plaster nice nets of scallops occurred. On the plaster mixed with larger non-soluble particles bigger pits develo-

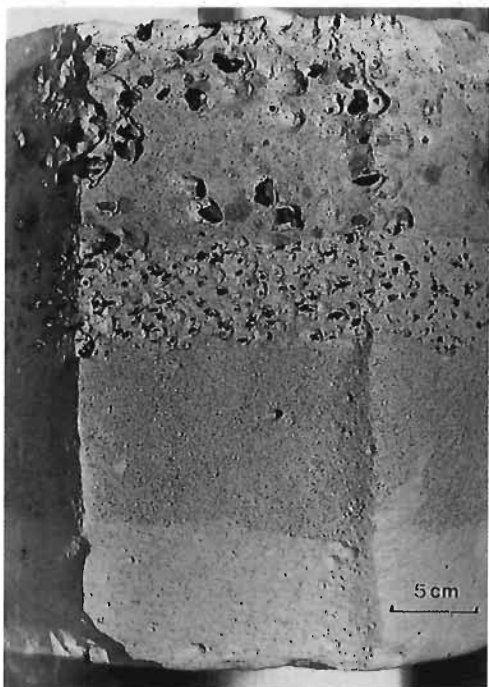


Fig. 11: Scallops on the layered plaster block.

ped around the grains. On the surfaces with scarce obstacles they were united into hardly discernible net of the scallops. The size of the pits was controlled by the size of the obstacles and reached 2 to 3 times bigger diameter than was the size of the scallops under the same conditions. Consequently the size of the scallops is influenced by the rock structure. On these parts of the plaster where the larger obstacles are more densely distributed no signs of the scallops net was perceived, although the plaster surface is porous at the obstacles. At some obstacles the pits occurred shaped like widely opened scallops.

A plaster tube, wider in the middle, was dipped into the water flow with 1 m/s of velocity. The tube was 1,5 m deep in the water. The length of the inflow tube's part was 35 cm long, the outflow part 15 cm and both of them had 13 cm of diameter. The middle part, 35 cm long, had the diameter of 22 cm. In the inflow and outflow tube the scallops occurred (fig. 12), 15 mm long and 11 m large. Under the same conditions on the plaster



Fig. 12: Scallops in a plaster tube.



block narrow and long scallops occurred. In the middle, wider part of the tube the pockets occurred all over the rim.

The size of the scallops on plaster is a bit smaller than the size which developed on limestone under the same conditions. I anticipate that the scallops on better soluble rock are smaller. The scallops that appeared on homogeneous plaster have regular shape and their surface is smooth. The ones on the plaster with sand grains are more heterogeneous and rough. The scallops developed by the plaster solution and only bigger, non-soluble particles were transported by the water. The sharp edges of plaster which do preserve in swift water current evidence, that the scallops are shaped by the corrosion.

### *Origin and development of the scallops*

The decisive factors to originate and develop the scallops are rocks, flow velocity and water flow pressure with a certain viscosity and aggressivity, the size of the passage and the shape of the rim. The mentioned factors are interlaced at various relationships but the basis of formation of the characteristic nets of the scallops are mostly defined by hydraulic conditions (SLABE 1993, 163). The rocks decide about the origin of a scallop, about the shape of a singular scallop within a net respectively and influences to its size (SLABE 1993, 153).

At big Reynolds Numbers the abrasion coefficient depends on the roughness of the tube-brim and is almost independent on viscosity of the liquid, while at small Re Numbers it depends on viscosity and only slightly on roughness (REYNOLDS 1974, 5). It seems that this property is reflected at the formation of small and large scallops too. The characteristic diameter of eddies within the water current is mostly controlled by its velocity. Also the rock structure influences to the size of eddies. At bigger obstacles the eddies increase. If the obstacles are of the same size or even bigger than the scallops, densely one by one, the mixing of eddies may cause chaos in the flow lines and the characteristic net of the scallops does not occur. For the origin of the scallops network the size of the eddies must be bigger than the size of the constituent particles of the rock. However, the distribution of smaller current marks is controlled beside the hydraulic conditions and space geometry, mostly by the unhomogeneities in the rock. It was nicely indicated at the plaster experiments. Does it mean that at the formation of smaller scallops the boundary laminar water layer is interrupted as was stated by FORD and WILLIAMS (1989, 305). In plaster the water notched the pits along the obstacles at first and later transported the obstacles, the bigger particles of plaster respectively. At the same time the pits and later facets occurred on more soluble parts of plaster and along smaller fissures. The facets that occurred at rare obstacles and were not united into a net and these occurring on the border of cut off rocky surfaces, are opened. The singular facet is thus opened. ALLEN (1972) stated as well that a singular unhomogeneity within a rock may cause the origin of the facet. If the rock is homogeneous it is evenly coated by eddies and a net of scallops develop. A regular distribution of unhomogeneities is enabled by granular composition of carbonate rocks. Closed facets prevail within a net. The inflow parts of most of them are semicircular and the outflow parts triangular. By a profound knowledge of the hydraulic properties of the turbulent flow and rock composition one may define the relationship when the facets do occur, or one may determine the influence of the rock composition to their size. The facets appear on the sections of the rim which are large enough that a net of eddies may develop and which deviation from the main current direction is below smaller angles. When the facets reach the size dictated by the flow velocity and hence the size of eddies including the rock composition, they do not change any more.

Is the origin of the facets possible only at considerable tapering off or interruption of the boundary layer when its influence upon corrosion and erosion is negligible. In the aggressive water already the approaching of eddies caused by attrition on the boundary layer may cause accelerated dissolution of the rock and thus locally thinner diffusion layer. In such a way bigger facets may develop which are the result of slow water current and their formation is not influenced by the rock composition. While bigger rock particles may prevent the formation of facets by the swift current, in slow flow they influence to net formation mostly. In the ponor cave of Lokva brook rudists jutting out the surface do not influence to the shape of medium sized facets, although on the similar rock at Pivka jama and at Postojnska jama (Šebela 1992) the facets do not develop.

The experiments in plaster help us to explain the characteristic shapes of facets within the singular nets. More long and narrow are the facets cut by open water flow, wider are the facets in phreatic zone. In respect to their shape similar facets develop in similar hydrologic conditions but they are influenced as well by the size and shape of the space, where the water current flows.

### **The traces of the percolating water**

#### *Ceiling pockets*

The water percolating through small conduits along the fissures in the ceiling disperses over the rock surface when it reaches the passage. Larger water surface enables the same quantity of water to be more corrosive, and it may, however, take over CO<sub>2</sub> from



Fig. 13: Ceiling pocket in plaster.



the air if the concentration is higher than the one in the water. The ceiling pocket starts its growth along the fissure upwards (FRANKE 1975). On the inclined ceiling the pocket is elongated in the direction of the gradient and disappears as the upward half.

#### *Laboratory experiments to shape the ceiling pockets in plaster*

The water flow through the vertical conduits, 1,5 mm of diameter, from the pit on the summit of the plaster cylinder (fig. 13) with flat bottom. After two hours already developed the pit, 5 mm of diameter and 2 mm deep. After one hour it was 1 mm deeper while the diameter remained unchanged. But the inflow channel started to widen and by increasing discharge the pit widened at the mouth only, where 2 mm wide and 3 mm deep concave bottom appeared. The plaster is very soluble this is why the channel widened. The flow changed from laminary to turbulent and the pits started to develop.

At other experiments we decreased the water inflow to prevent the excessive widening of the channels. The plaster was covered by sponge and the water regularly percolated through it into the channel. At the mouth singular drops appeared. A pit developed which constantly widened and deepened. After two days when the experiment was interrupted due to channel's widening the pit was 25 mm large and 7 mm deep. A slow spreading of the pit to a 50 mm belt around it was perceived.

On the ceiling surfaces inclined for 300 more narrow pits occurred. They were 1 cm deep and ended in the direction of the gradient by wider bevels. Most of water percolating through the small conduit ran over them. The upper edge of the pocket was steeper.

The axis of the pockets is vertical due to gravitational washing, the same was confirmed by the plaster experiment too. The solution pockets are composed if there are several water inflows within the diameter of their formation. FRANKE (1975) stated that the pockets diameter is proportionate by the quantity and aggressivity of the percolating water. By increased inflow the diameter augments, by the increased corrosion of the water power it is reduced and the pocket deepens faster. In the well soluble plaster the pockets deepened fast at the increased water inflow.

At the experiments with plaster three characteristic surfaces appeared which are concentrically distributed along the inflow channel. The inner surface of the pocket is smooth and relatively regularly bathed by the water. Its smooth surface is the result of gravitational water accumulation on the jutting out particles of rock and they are subdued to accelerated corrosion. The medium ring is rough and pointed. The water film overflowing it was thinner. The same quantity of water as in the first case overflowed all over the larger surface. This is the property of roof pendants development (SLABE 1990, 177). The outer surface is dismembered into narrow or wide but shallow bevels where the water current was concentrated. The formation of the surface is controlled by various quantity of water overflowing different kind of rocks.

The biggest problem at the experiments in plaster is its excessive solubility unabling the development of bigger pits or solution cups as the inflow channels widen too fast. However the possibility and the manner of ceiling pockets development, shaped by the percolated water, was confirmed.

#### *Floor pits due to water trickling*

The floor pits develop on the rocky ground where small amount of corrosionally active water, percolating through the roof, trickles or drips. The diameter of floor pits having the hemispherical bottom is from 5 to 15 cm, they are up to 10 cm deep. I tried

to illustrate the process of the floor pits formation by the experiment in plaster to which the water trickled from 1,2 m high. At first hemispherical pit occurred having the diameter of 1 cm. The drops falling to its bottom were scattered. Hence the rim of the pit is smooth and the surface around it, due to water spray, is spongework. By the increase the pit widened in its lower part. This is the result of the pits walls wash away due to spray of the drop from the bottom. At the experiments when the dropping over plaster was more intensive and more frequent or even joint into jet the water accumulated in the pits, washed away the walls and sometimes even developed into outflow runnels. The pits which have the upper walls steep, and the lower more gentle developed on the inclined plaster surfaces. Hence, at the floor pits formations are decisive the manner and the quantity of inflow water, the height from where the water falls and the inclination of the surface into which they incise.

## Conclusion

The Paris plaster may be well moulded, the cracks may be easily made. During bigger experiments it is sometimes problematic to add the plaster several times as the contacts between the masses are usually the weak points in the rock and water quickly finds its way (ceiling channels). At the experiments with water flow smaller sand particles being in the plaster come into question. Along them eddies occur and the water after tearing them off add them to the mechanical activity. It is true that they may be eliminated, however the natural rock where there are the traces of water flows is unhomogeneous. Smaller obstacle presents rather high porosity of plaster and at higher hydrostatic pressures (ceiling channels) the water filtrates through it. Solubility of plaster is often too fast. The channels leading into ceiling pockets widened too fast and the interruption of the process enabled the development of bigger bevels. Also the surface around the pits due to water drops and water spray eroded quickly. Soon the pits started to loose their shape. The flooded plaster in a stagnant water becomes rough this is why more loam stuck on it at the experiment with the below sediment solution bevels as it would be the case with limestone. Referring to the experiment with facets on very soluble plaster block one may infer that under the same conditions a bit larger forms would develop in the limestone.

We may conclude that such experiments serve as a useful study instrument and the continuation is recommended as their advantages requite its inconveniences. In future the size ratio of the experiments must be more precised, they are usually much smaller than is the case in the nature and the number of diverse repetitions augmenting the reliability of the experiment must be determined.

The breadth of the treated problematics enables slow and unequal building of the foundations of the rocky relief studies and is reflected in my previous work. But the ways of the future studies do open more and more. It was namely shown as useful and I may maintain that it is a step forward from more or less successful recognition of the factors influencing the development of the cave rocky rim as the simulation requires the knowledge of most of them. The experiments with rocky relief in variously sized and meandering channels with water current are undertaken.

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