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ORIGIN OF FINE-GRAINED CARBONATE CLASTS IN CAVE SEDIMENTS

IZVOR DROBNOZRNATIH KARBONATNIH KLASTOV V JAMSKIH SEDIMENTIH

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Nadja Zupan Hajna: Izvor drobnozrnatih karbonatnih klastov v jamskih sedimentih

V vzorcih jamskih klastičnih sedimentov se velikokrat nahajajo velike količine drobnih karbonatnih zrn. Ugotovila sem, da je njihov izvor v mehkih belih conah preperele karbonatne kamnine s sten jamskih rovov. Preperele cone apnenca in dolomita nastajajo na jamskih stenah, kadar nanje deluje selektivna korozija. Nepopolno raztapljanje pripravi karbonatno kamnino na mehansko erozijo in transport njenih trdnih delcev. Kjer je preperela karbonatna kamnina v stiku z vodo, tekočo ali kapljajočo, ta lahko trga njene, s selektivnim raztapljanjem izpostavljene delce. Voda jih odnaša naprej po rovih, ko transportna moč vode pade, se delci usedajo v obliki drobnozrnatega karbonatnega sedimenta velikostnega reda gline, melja in drobnega peska.
Ključne besede: preperevanje, nepopolno raztapljanje, selektivna korozija, mehanska erozija, avtohtona karbonatna zrna.

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Nadja Zupan Hajna: Origin of fine-grained carbonate clasts in cave sediments

In many samples of cave clastic sediments the high amount of carbonate clasts is significant. It was found out that their origin is usually in soft white zones of weathered carbonate rock on cave walls. Weathered zones of limestone or dolomite form on the cave walls when the selective corrosive is going on. Incomplete dissolution prepares the carbonate rock for the mechanical erosion and transport of its particles. Where the weathered carbonate rock is in contact with water, both flowing and dripping, it may tear off the particles resulting from selective corrosion. Water carries them along cave passages and when its transporting power decreases, particles accumulate in the form of a fine-grained autochthonous carbonate deposit, in size of clay, silt or fine sand.
Key words: weathering, incomplete dissolution, selective corrosion, mechanical erosion, autochthonous carbonate grains.

INTRODUCTION

During my past research I had been surprised by high occurrence of carbonate clasts in cave sediments (Zupan Hajna 1997, 1998). In my work I was mostly interested in the origin of fine carbonate clasts that are present in sediments and also in the ways in which the rock has to be prepared, so that water is able to carry it away from the cave walls in the form of small particles. I tried to found out their origin and the process of their formation. By some research was clear that their origin is in soft zones of a white, silt- or clay-like substance on the cave walls (Fig. 1). These zones are soluble residues of limestone and dolomite incomplete dissolution (Zupan Hajna 2001). I have discovered that all of the carbonate rock does not dissolve immediately; and this signifies that it is not carried away from its primary place in its ionic form, but that the disintegrated particles may remain on the cave passages walls. An incomplete dissolution may just prepare the carbonate rock for the mechanical transport of its particles by the flow of water. To what extent the carbonate rock dissolves at its secondary site or may get carried away in some other way, still remains unknown to us. The transported carbonate particles of about the size of those of silt or clay may get accumulated in the cave passages as the clastic cave sediments.

To the question, whether the incomplete dissolution of the carbonate rocks represents an important factor or is it only one of the peculiarities that occur in the formation of the cave passages, I cannot provide a precise answer because water may be incessantly washing away the already coroded rock at the same time as it decomposes. We are able to detect strongly weathered

Fig. 1: Weathered limestone on the cave wall.
Sl. 1: Preperel apnenec na steni jamskega rova.

limestone or dolomite on the cave passages walls only where they are protected from further dissolution and mechanical erosion.

Mineralogical analyses have already proved that all the carbonate rocks do not dissolve immediately, but are washed away by water in the form of particles (Zupan Hajna 2000, 2001). Some of the cave sediments contain a large share of carbonate clasts, as has been already described by Newson (1971a), which originate from the passage walls (Zupan & Mihevc 1988). Carbonates in the clastic cave sediments do not present themselves only as individual layers of flowstone alluvium or as a cohesive, binding element; they are in fact fragments of the original primary rock, lithoclasts of the size order of silt or clay.

The method frequently used extracting all the carbonate from the cave sediments already before undertaking more serious analysis is in its essence flawed. It bypasses the important fact that all carbonate rock does not dissolve completely on the cave passage walls.

The way in which the carbonate rock is carried away from its primary site depends mostly on its chemical and mineral composition and on the chemical and hydro-mechanical characteristics of the water, which in a karst environment represents the predominant natural solvent as well as the erosive and alluvial agent. The rock may be carried away from its primary site in the form of ions or mechanical particles, that is, by means of chemical or mechanical erosion, or in some cases by the combined action of both. The ratio between them is influenced by the water flow with all its characteristics, as well as by the structure and mechanical properties of the rock. In the dissolution processes, however, the biogenic corrosion may have an effect as well. Formation of carbonate clasts is depend on chemical and mechanical erosion of water flow and on lithological characteristics of the carbonate rocks.

I have assumed that the mechanical alluvium of the solid particles from the crystallised and dolomitised limestones, which are composed of the sparitic grains, is greater than that of the micritic uncrystallised and non-dolomitised limestones. Similarly when the carbonate rock is already tectonically significantly decomposed, the fine gravel will get mechanically washed away by water much more easily and would dissolve faster as well. If it is not already decomposed, its disintegration is much more affected by the process of dissolution. In this way its mineral composition and structure gains in significance. Dissolution first corrodes the edges and irregularities on the surface of grains. Whether the dissolution is carried out to completion depends on many factors. The chemical process may just superficially attack the rock so that all the rest is being performed by water which may afterwards just wash the already corroded particles away. There exist therefore two forms of sediment transport: dissolution and washing away.

According to Dreybrodt (1988) the overall dissolution rate is determined by the dissolution on the crystal's surface, by the transportation of ions through the border layer, by the speed of the conversion $CO_2 + H_2O = H^+ + HCO_3^-$. Mechanical activity of water flow on the rock is divided into the action of water mass itself and abrasion by transported material (Trudgill 1985).

CARBONATE CLASTS AS PART OF CAVE SEDIMENTS

Autochthonous carbonate gravel and sand are created when larger or smaller pieces of rock are broken from the cave walls and then carried away and rounded by the flow of water. These rock fragments are torn off especially from broken zones, from breakdowns and, due to the temperature fluctuations, also from the cave entrance areas (Gospodarič 1976, Kranjc 1989). Carbonate silt may be formed by the disintegration of already extant carbonate gravel and sand, which are created in the above-mentioned manner or, as we shall see, they are formed by the weathered cave channels walls being washed away.

I had already noticed the enlarged ratio of carbonate clasts of the size order of silt or clay in cave clastic sediments during my previous research. Beside non-carbonate minerals in autochthonous sediments, which are brought into the cave by water stream, I have detected the presence of carbonate clasts in recent sand and silt in Velika ledenica in Paradana (Zupan & Mihevc 1988), in silt sediments in the springs in Malni (Zupan Hajna 1997, 1998), in some sand and clay samples from cave Brlog at Rimsko (Zupan Hajna 1998) as well as in sedimentl flood clay in Martel's Chamber in Škocjanske jame and in Labodnica (Zupan Hajna 1995). Whether the minerals of calcite or of dolomite will appear in the form of carbonate clasts depends principally on whether the cave passages are being formed out from limestone or dolomite.

As autochthonous carbonate clastic sediments in the cave fluvial sediments I thus consider these particles to be those that originate from cave passages walls themselves. Autochthonous carbonate clastic sediments in the cases I am describing, do not have anything in common with the cements or flowstone crusts, which are precipitated as autochthonous chemical sediments in the clastic cave sediments. The presence of smaller carbonate particles in cave sediments of the size of silt or clay, as well as the presence of carbonate colloids in subterranean water streams are mentioned in by several authors. I state some of them below.

Zogović (1966) noticed that dolomite may dissolve incongruent and that there are mineral grains left behind, which are extracted from the base in the form of silt. He found out that the fine dolomite sand may get accumulated in the narrow passages and obstruct or slow down the flow of water.

During his tracing test in the Mendip Hills of England, Newson (1971a) detected the rise of the carbonate clasts ratio and the fall of the quartz part in cave sediments between the entrance and exit of the cave system. He studied the rise of the carbonate content in clastic sediments and their transport along the system. Simultaneously, he investigated the diminishing of the grain size in the sequence sand - silt - clay and the roundness of the quartz sand, that became more and more pronounced along the system. He tried to discover the reasons for the large quantities of carbonate materials in the nets, placed during high waters, in the abrasion processes on the cave walls. He emphasises the importance of abrasion for the cave development. Abrasion with quartz sand, which is carried by water in the form of the suspended charge, seemed to him to be of special significance. He also detected the renewal of the erosion force with the introduction of fresh limestone material, added to the already present suspended charge, along the subterranean stream. Abrasion is more effective at high water, but only in the river-bed area. In his ensuing treatises Newson (1971b, 1972) consecrated his efforts mostly on the hydrological factors of the mechanical erosion in the subterranean environment. He did not concern himself in any detail however with the origin of carbonate particles, the same applies to Smith & Newson (1974).

Silt and clay size carbonate clasts in cave sediments are not mentioned by many authors and for that reason they appear all the more interesting. Ford & Williams (1989) state the large presence of autochthonous carbonate clasts in the suspended charge of the size order of silt and clay, which originates from the weathered cave walls. Worthington (1991) ascertained that only few authors ever mentioned the presence of carbonate particles in the suspension and the cave sediments.

In his opinion, it is not so surprising that during limestone dissolution its less soluble particles get released; they are afterwards swept away by the water stream and are accumulated in the lower energy cave environment. Šušteršič & Mišič (1996) state, in their research in the Pipar's Channel of the Najdena jama, that they detected the formation of carbonate silt on the permanently wet dolomite wall and the movement of these particles with the simultaneous trickling down of water, as well as their being carried away and deposited by means of slightly stronger flow into the smaller water pools. After analysing colloids and particles of the karst water channel in the Swiss Jura, Atteia (1997) mentioned calcite and dolomite as constituent parts, and their presence seemed to him quite intriguing.

In addition to carbonate clasts, which form a part of the suspended charge of underground water streams, we may find in the research literature also mention of carbonate particles in the suspension of water percolation trickles. Carbonate particles in the suspension of water trickles in Planinska jama cave are mentioned by Kogovšek & Habič (1981), who tried to determine the ratio between corrosion and erosion in dependence upon the quantity of water, regarding the quantity of the chemically dissolved material and the quantity of the suspension in the sinking water. In their treatise they ascertained that erosion and corrosion prove to be equally effective during the precipitation, for in the same time period almost equal quantities of carbonates had been dissolved as were transported into the cave in the form of the suspension. The carbonate suspension in water trickles is mentioned also by Kogovšek & Zupan (1992) in cases from Planinska jama and Pivka jama. They relate its origin to carbonate rock weathering on the surface and the transport of the weathered rock particles through the open fissures into the cave. Kogovšek (1994) explains the presence of carbonate particles in the suspension of the water trickles in Vilenica with their formation through their contact with the soil, where the dissolution is faster, and through the transport along the open fissures into the cave. Treatises on carbonate suspension in sinking water have in common their mentioning of carbonate particles as a part of the charge that the water is carrying away from the surface and through the open fissures into the cave.

The presence of carbonate clasts in clastic cave sediments is predominantly related to the freezing and thawing of ice. The glacier and the water coming from under the glacier, as well as the thawing ice mechanically erode carbonate rocks on the surface. Water then carries the eroded, finely grained carbonate particles into the cave and deposits them there. Audra (1995) associates the deposition of carbonate »varves« in the high-mountainous caves to large quantities of water that flows from under the surface glaciers, laden with silt, which afterwards gets deposited in the cave passages.

We should, however, not overlook the fact that in high-mountain caves there may also be found such clay sediments, which are composed of carbonate clasts of different origin. What kind of origin this may be I will endeavour to describe later.

Let me emphasise the fact that in my work I have not concerned myself with: the mechanics of the carbonate clasts transport, with the mechanical and chemical properties of water which carries clastic sediments along caves, with the sedimentation of clastic sediments in cave passages nor with the quantifying or granular analysis of clastic sediments.

Mineral composition of the samples were investigated by X-ray powder diffraction method at the Geological Institute of NTF, Ljubljana by Phillips diffractometer. The approximate ratio of minerals is given in respect to the height of the main reflection of a particular mineral in the X-ray record.

EXAMPLE - CARBONATE CLASTIC SEDIMENTS FROM SOME CAVES OF KANIN MOUNTIN

Geological and speleological characteristics

In the region of Kaninsko pogorje the gratest number of deep caves are to be found at Rombonski podi (Gabrovšek 1997). In the cave investigated there is a picturesque succession of gradational shafts with meanders and older, but now inactive horizontal passages (Morel 1989, Audra 2000). Within caves we may come across breakdown (collapse) blocks and gravel, whereas in their horizontal parts there are also older stratified loam and sands, which are occasionally covered by recent sands and clay, that are now being washed away by trickles of water (Morel 1989). Recent fine-grained sediments are accumulating mostly under the active shafts in the deeper areas of the caves (Manca 1998). As a part of the carbonate autochthonous clastic sediments research, we undertook also an x -ray analysis of selected loams from Črnelsko brezno and Čehi 2 cave, the entrances of which are located in the areas of Goričica under Hudi vršič north of Rombon and Renejevo brezno at Kaninski podi (Fig. 2). The basic data of the caves are from Cave Register of Speleological Association of Slovenia and Karst Research Institute ZRC SAZU.

According to the Basic Geological Map, 1 : 100 000, sheet Beljak and Ponteba (Jurkovšek 1986) the region of Kaninsko pogorje is composed of Upper Triassic Dachstein limestone T_3^{2+3}.

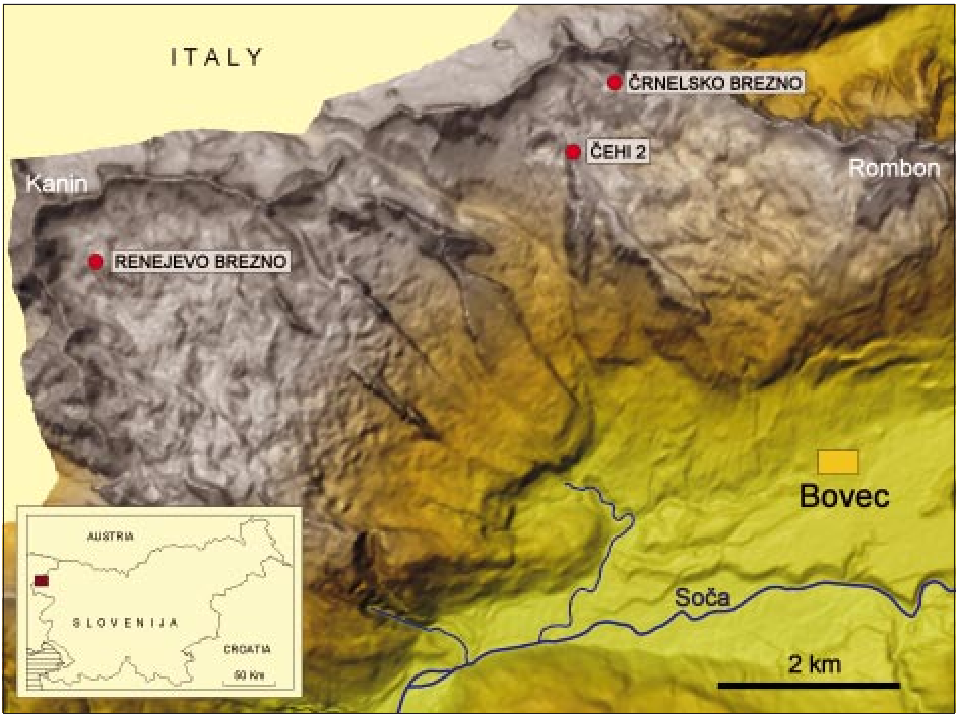

Fig. 2: Location of the cave entraces Čehi 2, Črnelsko brezno and Renejevo brezno.
Sl. 2: Lege vhodov v jame Čehi 2, Črnelsko brezno in Renejevo brezno.

Limestone layers in general dip in SW direction under the angle of 15° to 40°. At the base of the Dachstein limestone there is the Norian-Rhaetian "Main dolomite", which is clearly visible in the Možnica and Krnica valleys, as well as in deeper parts of certain caves. Dolomite dips in SW direction at angles of 25° to 50°. In the Led Zeppelin Cave on the Italian side of Kanin mountain, cavers came across the dolomitised limestone at a depth of 800 m (1330 m above the sea), while the dolomite layers occur at a depth of approx. 850 m and continue down to the cave's bottom at the depth of 960 m (Manca 1998, Audra 2000) In Vandima cave the dolomitised limestone was not detected until the very bottom of the cave (-1042 m), yet it was found in two neighbouring caves Čehi 2 and Črnelsko brezno (Gabrovšek & Pintar 1993). The same authors state that it is precisely the contact zone between the limestone and strongly dolomitised limestone - almost dolomite -, that provides the basis for predominantly horizontal and easily passable cave galleries with numerous chambers and gorges with lakes. Dachstein limestone is placed upon the main dolomite in normal position, whereas between both lithological levels there is a horizon (zone) of heavily altered comb-like rocks (Čar & Janež 1992). The karst features on the earth's surface are, in the case of dolomite, manifested in a different way to that on limestone because the dolomite is subject to more pronounced mechanical weathering (Kunaver 1983).

Gabrovšek (2000) records that during his research of Renejevo brezno at a depth exceeding 700 m they came across heavily weathered meander walls where the weathered part of the rock reached several cm into its interior. Water washed the weathered fragments away from the wall and grains carried thus are accumulated in the form of white mud in the cave's bottom. A part of this mud was carried further along passages by water and it is quite interesting that the same mud was cementing the breakdown (collapse) also in its continuation. I noticed the piling up of the carbonate sand at the bottom of shafts in Skalarjevo brezno on Kanin mountain, yet unfortunately, I did not take any samples thereof.

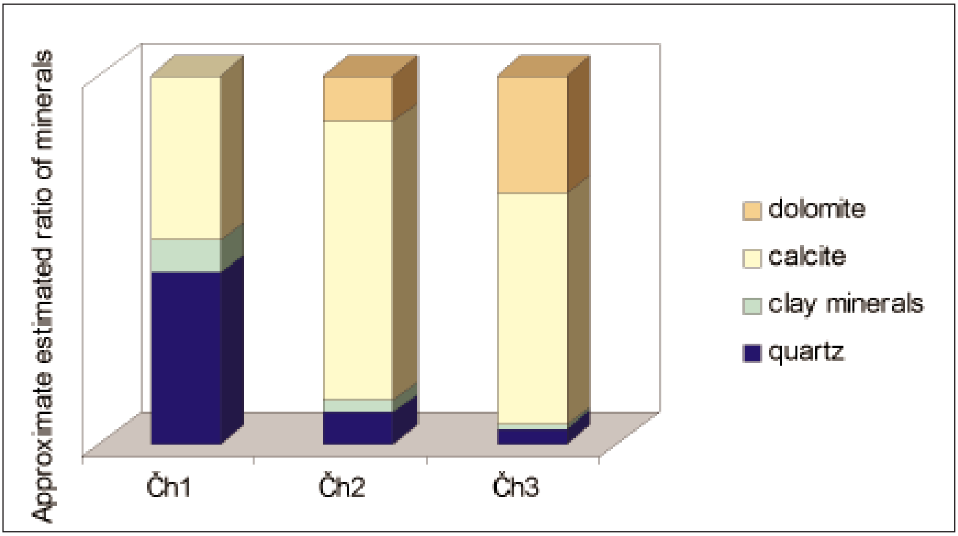

Fig. 4: Mineral composition of samples from Čehi 2 cave.
Sl. 4: Mineralna sestava vzorcev iz jame Čehi 2.

Čehi 2 cave, no. 6200

The entrance into Čehi II cave lies on the mountain-ridge south of Hudi vršič at an altitude of 2034 m (y = 53855 735, x = 5136 950). Down to a depth of 900 m, deep shafts succeed one another, interrupted by shorter horizontal galleries, after which the cave continues in the form of sloping passages intersected by some smaller shafts. The cave is concave in its shape (Audra 1995). Currently this cave with its total depth of 1485 m is the deepest cave in Slovenia (SiOL 2002).

S. Glažar provided me with clastic sediments samples from the cave. The first sample Čh1 from the bottom of the smallest shaft located at the depth of 400 m in front of the other shaft called "Grosso e stanco" is a milky brown clay (7.5 YR 5/4) containing weathered fragments of limestone. The second sample Čh2, was taken from the gallery "Veccio Tribola" at the depth of

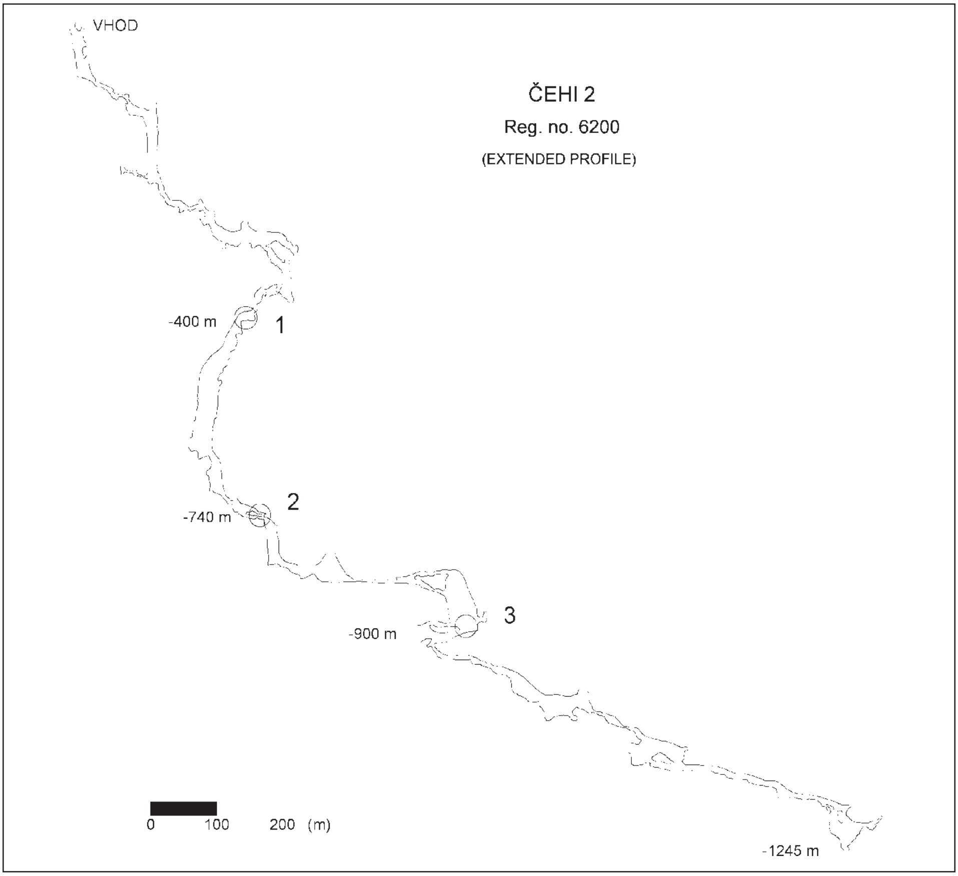

Fig. 3: Čehi 2 to the depth 1245 m with position of the samples: 1 - sample Čh1, 2 - sample Čh2 and 3 - sample Čh3 (Načrt jame: Abisso Ceki2, Antonini 1992).
Sl. 3: Jama Čehi 2 do globine 1245 m z lego vzorcev: 1 - vzorec Čh1, 2 - vzorec Čh2 in 3 - vzorec Čh3 (Cave map: Abisso Ceki2, Antonini 1992).

740 m, is a white clay (10 YR 8/2(8/3)) with a touch of yellowish brown shade. The third sample Čh3, brought from a depth of 900 m beside Bivak, is white clay (10 YR 8/2). The position of samples is indicated in the extended profile (Fig. 3). The mineral composition of samples taken from Čehi 2 cave was determined by the method of X-ray diffraction (Fig. 4).

The clay from the depth of 400 m (the Čh1 sample), contains predominantly quartz and calcite, as well as some clay minerals. Some minerals of the illite/muscovite group are also present, whereas one finds hematite only in traces. The sample does not contain dolomite.

The white clay from the depth of 740 m (the Čh2) sample contains mostly calcite. The amount of dolomite is greater than that of quartz, and the amount of both is relatively insignificant. The sample contains very small amounts of clay minerals (illite/muscovite and chlorite).

The white clay from the depth of 900 m (the Čh3) sample consists mostly of calcite; while the amount of dolomite has significantly risen; there is little quartz, while clay minerals exist only in traces.

Proportional to the rising depth one clearly discerns the increase of carbonate grains in clastic sediments as well as a simultaneous fall of quartz and clay minerals ratio.

Črnelsko brezno cave, no. 6040

The entrance into Črnelsko brezno cave is situated south of Črnelski Vršič under the Velika Črnelska špica. The cave's entrance lies at 2080 m above sea level (y = 5386 170, x = 5137 707). The maximum depth of the cave is 1198 m. In its entrance area and down to a depth of 520 there is a succession of larger and smaller shafts, whereas from that point on the cave extends in the form of narrow, horizontal galleries, which were formed along the tectonic fracture (Nagode 1993) and are intersected by other smaller shafts.

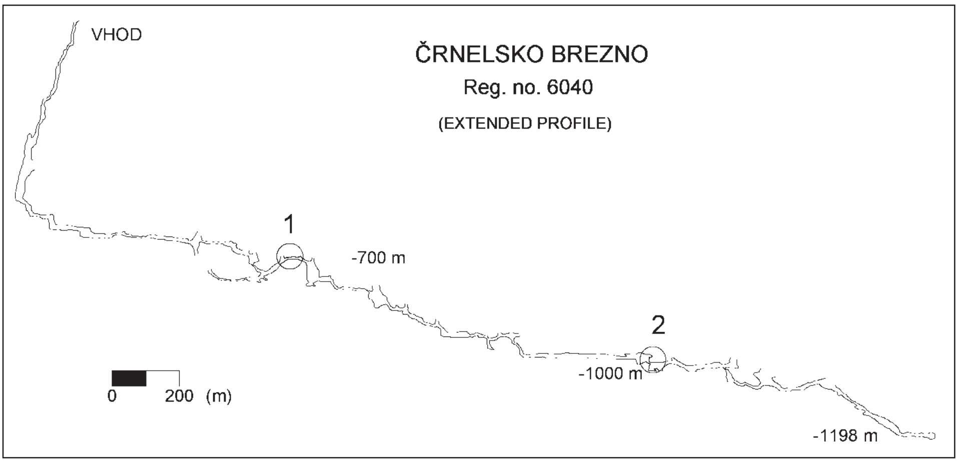

Fig. 5: Črnelsko brezno with position of the samples: 1 - sample Čr1, 2 - sample Čr2. (Načrt jame: Veliko Sbrego, Antonini 1989)
Sl. 5: Črnelsko brezno z označeno lego vzorcev: 1 - vzorec Čr1, 2 - vzorec Čr2. (Cave map: Veliko Sbrego, Antonini 1989)

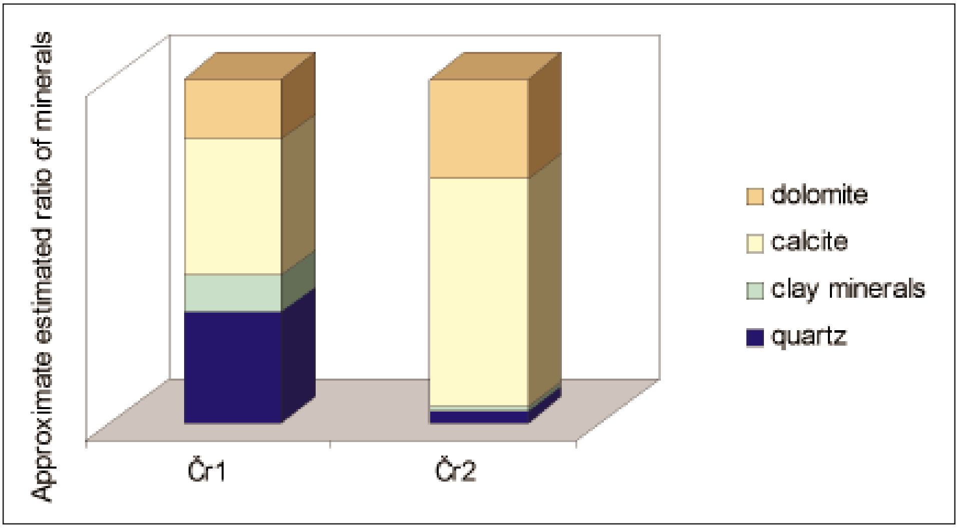

Fig. 6: Mineral composition of samples from Črnelsko brezno.
Sl. 6: Mineralna sestava vzorcev iz Črnelskega brezna.

P. Audra collected the samples primarily for purposes of paleomagnetic dating (Audra 2000) and he brought me for analysis two samples of clastic sediments from the cave. The position of the samples in the cave is indicated in the extended profile (Fig. 5). The mineral composition of samples taken from Črnelsko brezno cave was determined by the method of X-ray diffraction (Fig. 6).

The clay gathered from the Ho-Chi-Minh Gallery at a depth of 700 m is marked as the sample Čr1. In the sample the inverse magnetism was ascertained (Audra 2000), which signifies that these clays are more than 780,000 years old, i.e. they date back to the period of the last inversion of the magnetic field (Brunhes/Matuyama). The sample contains mostly calcite and there is plenty of quartz, while the amount of dolomite is slightly lower. The sample contains also very small amounts of clay minerals (illite/muscovite and chlorite).

A part of glacial-karstic stratified clays ("varves") from a depth of 1000 m is the Čr2 sample. In the sample the presence of inverse magnetism was ascertained (Audra 2000). The sample contains mostly calcite, while the amount of dolomite has increased, and there is a small amount of quartz, whereas clay minerals are present only in traces. The amount of carbonate grains in samples from this cave, when compared to the ratio of quartz and clay minerals, considerably increases as in previous examples with the cave's depth.

Renejevo brezno cave, no. 7090

The entrance into the Renejevo brezno is situated at the crossing between Kaninski podi and southern slope of Kanin mountain at 2260 m above sea level (y = 5380 710, x = 5135 760). In the cave the shafts and meanders exchanging and its currently measured depth is 1071 m (Gabrovšek

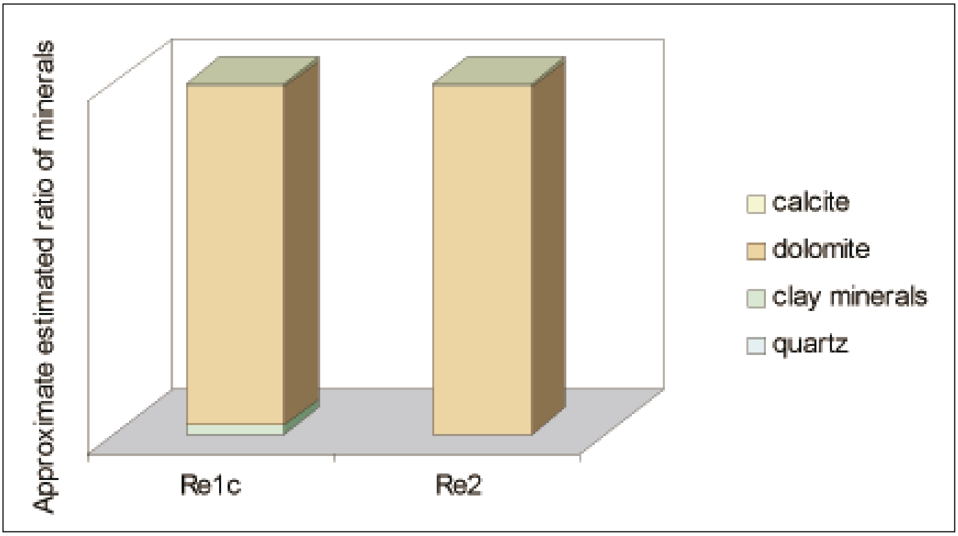

Fig. 8: Mineral composition of samples from Renejevo brezno cave.
Sl. 8: Mineralna sestava vzorcev iz Renejevega brezna.

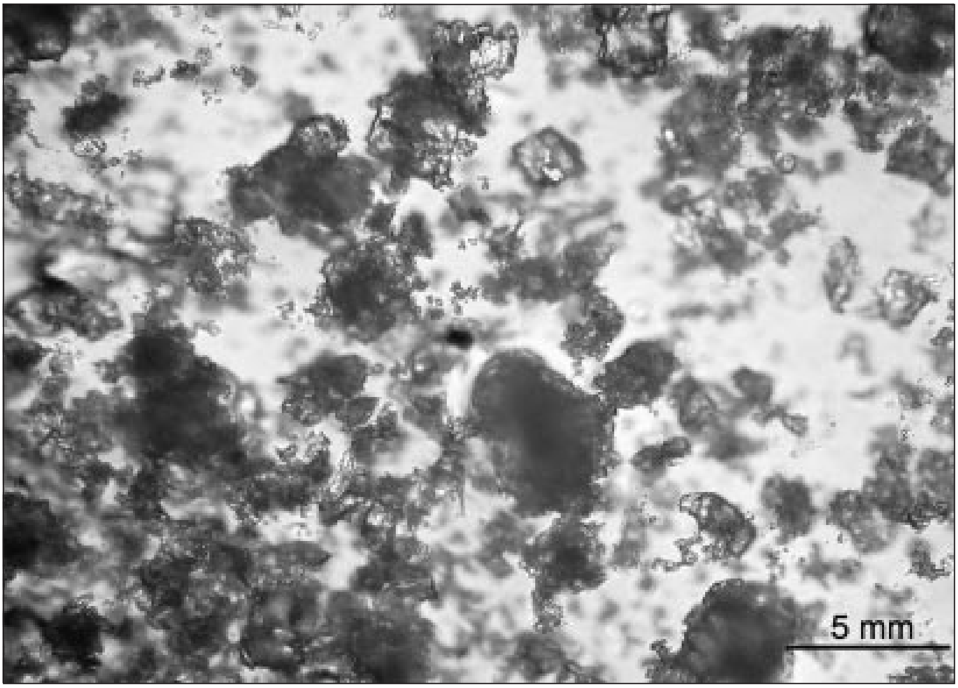

Fig. 9: Carbonate clasts with dolomite rhomboid from sample Re2, Renejevo brezno cave (polarized light II).
Sl. 9: Karbonatni klasti z dolomitnim rombom iz vzorca Re2, Renejevo brezno (polarizirana svetloba II).

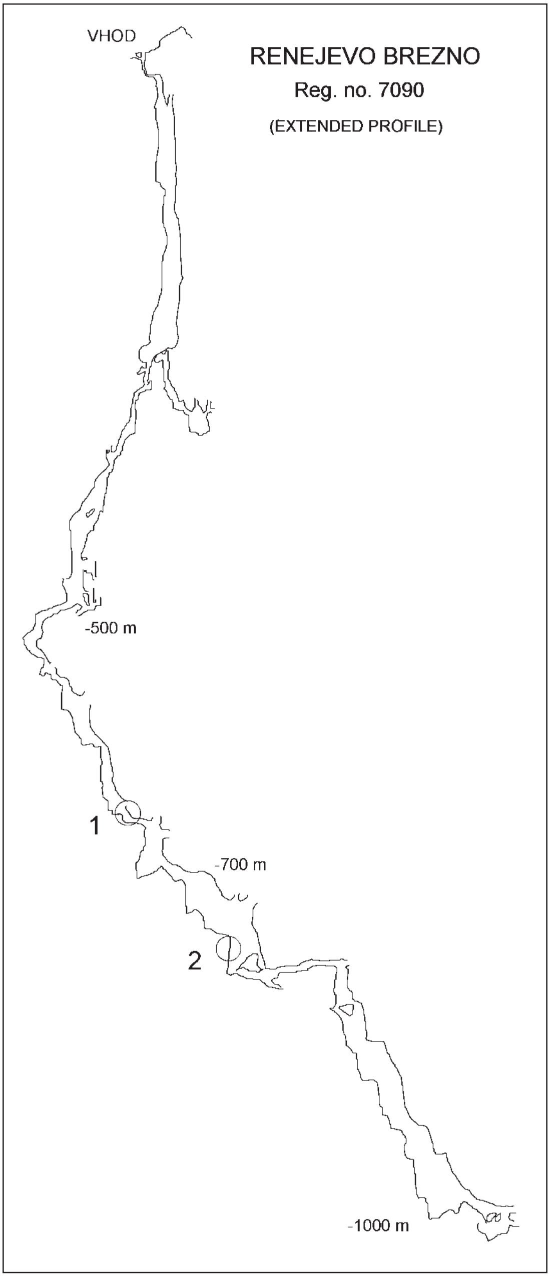

Fig. 7: Renejevo brezno with position of the samples:
1 - sample Re1c, 2 - sample Re2. (Cave map: Renejevo brezno; Gabrovšek 2000)
Sl. 7: Renejevo brezno z označeno lego vzorcev:
1 - vzorec Re1c, 2 - vzorec Re2. (Načrt jame: Renejevo brezno; Gabrovšek 2000)

2000). The position of samples in the cave is indicated in the extended profile (Fig. 7). The mineral composition of samples taken from cave Renejevo brezno was determined by the method of X-ray diffraction (Fig. 8).

Gabrovšek F. provided me with some samples from this cave, which were collected during the research by the Ljubljana caving club (DZRLJ). The sample marked Re1c was removed from the wall of a cave passage called Mokavec at a depth of 650 m and is actually a heavily weathered dolomite.

The Re1c samples are very fine heavily weathered carbonate grains. When dry it is of white colour 10 YR 8/2. The sample is almost entirely composed of dolomite, which contains quite a lot of iron; the calcite exists only in traces. With regard to the position of the main dolomite's peak, which swerves towards the ankerite, I inferred that a part of dolomite's magnesium was replaced by iron.

The brownish silt from the sandbank on the floor of the chamber above Tomovina at a depth of 750 m is in the sample Re2. The sample is finely grained silt with individual grains of quartz and clay minerals (chlorite), wherein individual and larger rhomboid dolomite crystals are to be found (Fig. 9). The sample's colour, when dry, is very light brown 10YR 8/3. The sample predominantly consists of dolomite with a high amount of iron, whereas there is but an insignificant presence of clay minerals. Calcite exists only in traces, whereas the method of X-ray diffraction could not detect any amount of quartz, although the individual grains are visible when observed under the microscope.

I have also calculated the level of the crystal lattice organisation (Goldsmith & Graf 1958) of the dolomite, that contained a large amount of iron, because I wanted to clarify what is happening to the dolomite in the course of its weathering. In the sample of the weathered dolomite - Re1c, the level of organisation was 0.78 whereas in the sediment of the dolomite silt - Re2, the crystal lattice organisation is only 0.54.

Mineral composition and origin of clastic sediments from the caves of Kanin mountine

The mineral composition of clastic sediments, which are of greater age according to their position, differs from the mineral composition of the fine-grained clastic sediments, that are presently accumulating at the bottom of the Kaninsko pogorje shafts. In active shafts the recent autochthonous clastic sediments are piled up at their bottoms in the form of mud and clay, as well as sand. Old horizontal galleries intersect the younger, active shafts. The galleries are in no genetic connection with the present formation of the cave, because they originated in completely different conditions (phreatic origin) and were filled up with sediments of non-carbonate origin. In these, at present mostly non-active parts of caves, we may find allochthonous stratified sands and loams (Manca 1998). According to their mineral composition, which includes predominantly quartz and clay minerals, they differ from those that are being formed at present, which points to their allochthonous origin. The older sediments are at some places washed away by water, which mixes them with recently formed carbonate clastic sediments. In such cases we may detect clastic sediments with mixed mineral composition (occasionally also carbonate clasts added in different time periods).

The amount of carbonate clasts in clastic sediments rises in proportion with depth, which is a consequence of the fact that the amount of the material washed away form the walls increases with depth as well.

Dolomite appears as a constituent part only when we reach deeper and deeper which may, because of the dolomite's position in the base of the Dachstein limestone, be taken for granted. With respect to the predominant dip of strata in the SW direction and the outpouring of water from the mountain region (Čar & Janež 1992), there is a possibility of the inflow of the dolomite particles from some passages and fissures carved in the dolomite or dolomitised limestone located at higher altitudes into those passages that are positioned deeper. The amount of dolomite clasts is thus the greatest exactly in the deepest parts of the cave, where passages were developed in dolomite, and water washes the rock particles from the passage walls.

Samples from the cave very vividly indicate the increasing amount of carbonate grains in relation to the decrease of the amount of the quartz grains. The correlation between the two is negative, yet very significant - the correlation coefficient is almost 1 (Fig. 10).

The mineral composition of recent sediments and older loam points to the fact that the washing away from the cave walls is actively going on also at present and in the same manner as it used to in the past. The washing of cave walls and perhaps also the intensified mechanical erosion of the surface might in certain time periods have been accelerated by the presence of a covering of ice.

The question of the origin of high mountainous silt sediments is too extensive to be explained just with few samples analyses. As one of the possible solutions I may, at this juncture,

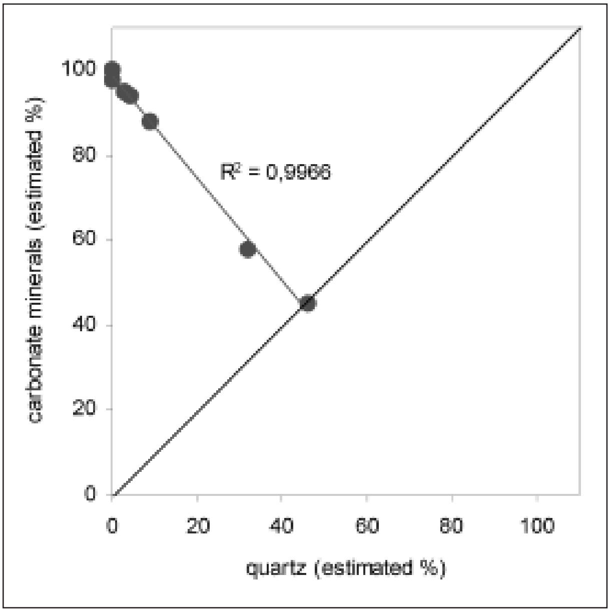

Fig. 10: Correlation of estimated ratio of quartz and carbonate minerals in the samples from Kanin mountain caves.
Legend: trend line, correlation coefficient (R) is negative.
Sl. 10: Primerjava ocenjenih deležev kremena in karbonatnih mineralov v vzorcih iz jam Kaninskega pogorja.
Legenda: trendna črta, korelacijski koeficient (R) je negativen.

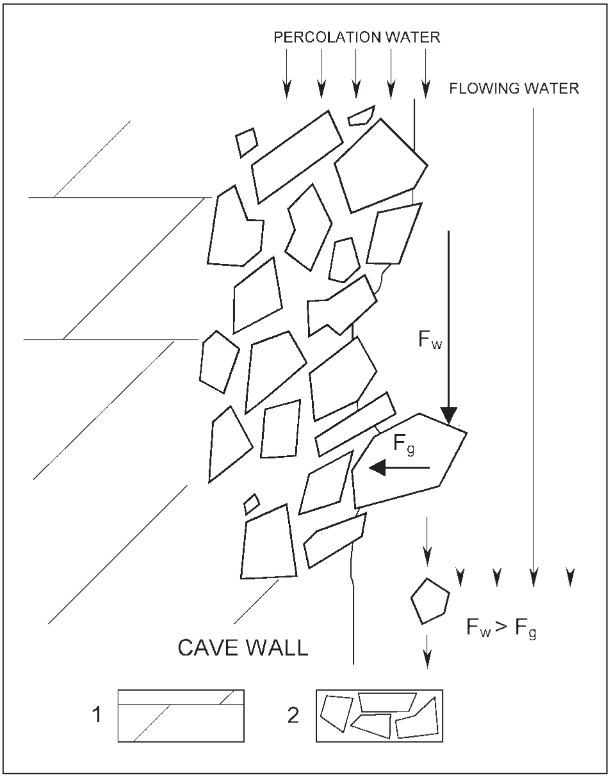

Fig. 11: Conceptual model of mechanical erosion of cave wall by flowing water.
Legend: 1 - dolomite (or limestone), 2 - carbonate grains exposed by corrosion, Fw - flowing water force, Fg - grain's adhesion.
Sl. 11: Shematičen model mehanske erozije jamske stene s tekočo vodo.
Legenda: 1 - dolomit (ali apnenec), 2 - s korozijo izpostavljena karbonatna zrna, Fw - sila tekoče vode, Fg - adhezija zrna.

only suggest the washing away of tiny carbonate clasts from cave walls.

The mineral composition of samples from Renjevo brezno proves the direct formation of dolomite silt during the weathering of the passage wall, because the mineral composition and structure are almost identical in both samples. The amount of dolomite silt, created by its being washed away from the cave wall is quite considerable, as it piles up at the floor of the chamber above Tomovina in veritable sandbanks.

The dolomite's presence in clastic sediments in the cave confirms that it has been washed away from the passages walls by water and was, at the point when water lost its transporting force, deposited. The dolomite in the cave environment does not get precipitated and does not bind the clastic grains, as the cement. For this reason its origin is not related only to the dolomite weathering, which builds the individual parts of cave passages and also not to the mechanical detachment of the particles from the wall surface.

The enrichment of the cave allochthonous sediment with carbonate minerals is excellently indicated in the cases, where water flows faster or is flowing through narrower channels and siphons, and is thus able to mechanically erode passages walls in a more pronounced and effective manner. A part of the enrichment of the cave clastic sediments with autochthonous carbonate clasts should be also ascribed to the washing away of weathered carbonate rock particles from the earth's surface by percolating water through the cave ceiling.

DISCUSSION

The manner in which the carbonate rock is carried away from the place of its origin depends on its properties, as well as on the properties of the water with which it is in contact. Water may erode rock mechanically or chemically. The ratio between both types of erosion is, however, conditioned by numerous local factors (Lauritzen & Lundberg 2000).

For instance, when the rock is tectonically crushed, water may dissolve the rubble much more easily and may mechanically wash it away faster as well, yet when the rock is not tectonically broken down, dissolution is more strongly influenced by its mineral composition and structure.

The chemical weathering of the rock in the cave passage may stop, but the weathered part of carbonate rock remains at its original place, because it is not in contact with the flowing water which could tear the dissolved particles from the passage wall and carry them away.

The dissolution does not only leave in its wake the thick weathered zone, but also the rough surface of the wall. Strongly pronounced roughness of the rock surface is typical of the recrystallized limestones, dolomitized limestones and late-diagenetic dolomites.

In cases when the roughened surface comes into contact with the flow of water, the water will wash the exposed particles from the wall, carry them away and finally accumulate them in the cave sediment. Carbonate particles are deposed either as an independent sediment or they may mix with the allochthonous deposits. The sediments of non-carbonate origin becomes in such cases substantially enriched with carbonate particles (Newson 1971a, Zupan & Mihevc 1988).

The formation of autochthonous carbonate silt and clay depends, of course, on various local factors, on the suitability of the rock which is related to the degree of the weathering of the wall surface, on the inflow of water which after rains washes shafts, or on high floods washing the wall surfaces. At places where water flows through passages fast enough, it may tear those particles, that were already partly dissolved, off from the walls. In case of more weathered rocks, however, a weak flow of water may suffice, for example mere trickling water along the weathered wall. Let me emphasise here that we are not encountering abrasion by quartz pebbles as proposed by Gams (1959) or Newson (1971a) but mechanical erosion by means of flowing water in the vadose or phreatic zone.

The water that streams rapidly along the cave passage walls interacts with the exposed rock to a minimal degree; it reacts only with its laminated and adhesively bound layer. Using its force, rapidly flowing water breaks through the laminar layer and is thus also able to dissolve or tear the exposed grains from the wall surface at a faster rate. The manner in which grains are exposed or how numerous they may be depends on the carbonate rock, whose structure conditions the selective dissolution and thus also the formation of the variously coarsened surface. To explain that process the conceptual model was made (Fig. 11). The grains that jut out from their places and whose ties are weakened by dissolution, are well exposed and inclined to be washed away from the wall by water. The force of flowing water (Fw) which acts upon the exposed grains must be greater than the forces (Fg) that tie the mineral grains to the rock (Fw depends on the water's velocity and on the surface of the grain it acts upon; Fg, however, is proportionate to the grain's adhesion, which in turn depends on the size and the surface of the grain's contact area with its base). It naturally follows that mineral grains whose contacts have been already partly dissolved or exposed to selective dissolution get more easily torn off than grains from the fresh unweathered rock.

For each particle there exists a critical velocity (Briggs 1977), at which it is still able to move, which we also call the critical erosion velocity. In the cases I am describing, the velocity of water flow must exceed this critical velocity to be able to tear the particles from the wall. As the water's velocity and its transporting force falls, the carbonate clasts get deposited as independent clastic sediments or they mix with the allochthonous alluvium.

The ratio between chemical and mechanical erosion of carbonate rock in the cave passages is, besides the flowing water's velocity, decisively influenced also by its structure. It affects the beginning as well as the course of the dissolution. During the weathering of late diagenetic dolomite, dolomite silt is formed (Zogović 1966). The wall surface of the passage in the dolomite is rough, and there are large grains jutting out of it, which are suitable for the formation of autochthonous carbonate silts. Out of the finely grained micrite limestones carbonate clay is formed, whose grains are so small that in most cases they dissolve very rapidly. Dissolution follows the rock's interior structures and in certain particular cases it leaves in its wake a mosaic porosity - strongly porous and weathered rock. Sufficiently fast-flowing water may also erode it mechanically. The more the rock is chemically weathered, the more easily will water tear off its particles.

The ratio between chemical and mechanical erosion is influential especially for the genesis of cave passages through which water flows fast enough to tear grains weakened and exposed by selective corrosion. However, in places where corrosion proves to be strong enough to act frontally it polishes the wall to such an extent that it is not rough any more. In that instance water cannot wash away any exposed particles, for they are absent, so that it just streams through passages or knocks some particles out of the wall by its charge.

One of the greatest dilemmas to be solved is to evaluate the ratio between corrosion and transport erosion in the shaping of the cave passages. In other words, to what extent the chemical disintegration of the rock is active, so that it may enable the beginning of the mechanical washing away of the loosened particles. The field observations demonstrated that the ratio depends on various conditions, such as the location in the cave, on the composition and structure of the rock, on the contact with the cave sediment, on the presence of flowstone crust, on the manner of the inflow of water, its physical and chemical properties and on the manner and the time of the contact with water. With regard to the extent of the carbonate rock's weathering, the water's velocity should be fast enough to tear the rock particles from the cave walls surfaces.

In addition to the rock grains, water tears from cave walls also the crushed rock fragments from tectonic zones and carries the rock particles fallen from the walls, which were previously fractured by tectonic and load-releasing fissures. The flow of water carries the loosened particles away and deposits them as its transport force weakens. This is why the share of carbonate pebbles along the water stream through the cave passages may even increase.

Incomplete dissolution accompanied with the simultaneous washing away of the weathered rock also accelerates the growth of passages. The ties that bind grains together dissolve and water mechanically erodes the remaining grains. By means of this process the passage's enlargement is faster and more intensive. Hindrances to the passage's growth may occur only at a stage when it is still very small and may get filled up by the newly formed carbonate silt or clay. The accelerated enlargement of the passage's dimensions is conditioned by occasional or exceptional washing away of thicker weathered zones of limestone or dolomite which follows extreme abundant floods.

With the acquired knowledge of the composition of the carbonate rocks weathered zones and of the processes that are taking place during dissolution, as well as being acquainted with the manner of the formation of autochthonous carbonate clastic sediments, I call to your attention yet another among the numerous peculiarities, which deserves our special notice when explaining the speleogenetic processes and the formation of karst cave passages. It became manifest that the removal of the limestone from its primary place is not always conditioned merely by dissolution, but is in case, when water washes the exposed carbonate particles from the cave passages walls and mechanically carries them away, limited also by the transportation of particles.

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IZVOR DROBNOZRNATIH KARBONATNIH KLASTOV V JAMSKIH SEDIMENTIH

Povzetek

Nastajanje karbonatnih litoklastov in njihovo izpadanje iz jamskih sten je pogojeno s korozijsko in abrazijsko sposobnostjo vodnega toka ter strukturo kamnine. Učinkovitost raztapljanja kamnine je odvisna od hitrosti reakcije na površini kamnine, prenosa reaktantov in proizvodov raztapljanja, konverzije CO_2 z vodo: $CO_2 + H_2O = H^+ + HCO_3^-$ (Dreybrodt 1988) ter litoloških lastnosti kamnine.

Mehansko delovanje vodnega toka na kamnino delimo na delovanje sile vode in na dolbenje z materialom, ki ga voda prenaša. V primerih, ki jih opisujem, ne gre za izbijanje delcev kamnine z lebdečim tovorom, na primer s kremenovimi zrni (Gams 1959, Newson 1971a), ampak za trganje delcev s površine kamnine zaradi adhezije. Zaradi adhezije med vodo in steno (Trudgill 1985) trga hiter, vrtinčast vodni tok s stene manjše delce, ki jih osami korozija.

Kako karbonatno kamnino odnese z mesta njenega nastanka je, odvisno od njenih lastnosti, kot tudi od lastnosti vode, ki je v stiku z njo. Voda lahko erodira kamnino mehansko in kemično.

Razmerje med obema vrstama erozije je odvisno od mnogih lokalnih dejavnikov.

Kadar je na primer kamnina tektonsko porušena, voda drobir lažje topi in ga tudi hitreje mehansko odplakne, kadar pa kamnina tektonsko ni porušena, na raztapljanje močneje vpliva njena mineralna sestava ter struktura.

Preperevanje, v obravnavanih primerih raztapljanje, kamnine se v jamskem rovu lahko ustavi, prepereli del karbonatne kamnine pa ostane na primarnem mestu zato, ker ni v stiku s tekočo vodo, ki bi natopljene delce trgala s stene rova in jih odnašala.

Raztapljanje za seboj ne pušča le debele preperele cone, ampak tudi hrapavo površino stene. Močno izražena hrapava skalna površina je značilna za prekristaljene apnence, dolomitizirane apnence in poznodiagenetske dolomite. V primeru, da hrapava površina pride v stik z vodnim tokom, ta izpostavljene delce spira s stene, jih odnaša in akumulira v jamskih naplavinah. Karbonatni delci se odlagajo kot samostojen sediment ali pa se mešajo z alohtonimi naplavinami. Naplavina nekarbonatnega izvora se v takih primerih močno obogati s karbonatnimi delci.

Nastajanje avtohtonega karbonatnega melja in gline je seveda odvisno od različnih lokalnih dejavnikov, od primernosti kamnine in s tem načetosti površine stene, do dotoka vode, ki po nalivih spira brezna ali po izjemnih poplavah, ki spirajo stene. Tam, kjer se voda skozi rove pretaka dovolj hitro, z raztapljanjem načete dele kamnine odtrga od stene. Pri bolj preperelih kamninah pa je zadosten že šibek vodni tok, na primer samo mezenje po prepereli steni. Naj poudarim, da to ni abrazija s kremenovimi prodniki v smislu Gamsa (1959) ali Newsona (1971a), ampak za mehansko erozijo s tekočo vodo v vadozni ali freatični coni.

Voda, ki hitro teče mimo sten jamskih rovov, z izpostavljeno kamnino minimalno kemično reagira, reagira samo njen laminarno adhezivno vezani film. Hitro tekoča voda s svojo silo razbije laminarno plast in zato lahko tudi hitreje raztaplja ali pa trga iz površine stene izpostavljena zrna. Kako so zrna izpostavljena in koliko jih je, je odvisno od karbonatne kamnine, ki s svojo strukturo pogojuje selektivno raztapljanje in s tem nastanek bolj ali manj hrapave površine.

Iz okolja štrleča zrna, katerih vezi so oslabljene z raztapljanjem, so izpostavljena in primerna, da jih voda odplakne s stene. Sile tekoče vode (F_w), ki delujejo na izpostavljena zrna, morajo biti večje od sil (F_g), ki vežejo mineralno zrno v kamnino. F_w je odvisna od hitrosti vode in površine zrna na katero deluje; F_g pa je sorazmerna z adhezijo zrna, ki je odvisna od velikosti in površine stika zrna z osnovo. Sledi, da se mineralna zrna, katerih kontakti so bili načeti z raztapljanjem ali izpostavljeni s selektivnim raztapljanjem lažje odtrgajo, kot pa zrna iz sveže, nepreperele kamnine.

Za vsak delec obstaja kritična hitrost, ko je še zmožen gibanja, to je kritična hitrost erozije (Briggs 1977). V tu opisanih primerih mora bi hitrost vode večja od kritične hitrosti, da delce lahko odtrga s stene. Ko vodi pade hitrost in transportna moč, se karbonatni klasti usedajo kot samostojni klastični sedimenti ali pa pomešani z alohtonimi naplavinami.

Na razmerje med avtohtono kemijsko in mehansko erozijo karbonatne kamnine v jamskih rovih poleg hitrosti tekoče vode odločilno vpliva tudi njena struktura. Struktura vpliva na začetek in potek raztapljanja. Iz poznodiagenetskega dolomita med preperevanjem nastaja dolomitni melj (Zogović 1966). Površina stene rova izoblikovanega v dolomitu je hrapava in iz nje štrlijo velika zrna, ki so primerna za nastanek avtohtonih karbonatnih meljev. Iz mikritnih apnencev nastaja karbonatna glina, katere zrna pa so tako majhna, da se v večini primerov zelo hitro raztopijo. Raztapljanje sledi notranjim strukturam v kamnini, za sabo v posebnih pogojih pušča močno porozno in preperelo kamnino, ki jo zadosti hitro tekoča voda tudi mehansko erodira. Bolj ko je kamnina kemično preperela, lažje voda trga njene delce.

Razmerje med kemijsko in mehansko erozijo ima vpliv predvsem na genezo jamskih rovov, skozi katere se voda pretaka dovolj hitro, da lahko trga z selektivno korozijo izpostavljena zrna. Kjer je korozija dovolj močna, da deluje ploskovno, steno tako zgladi, da ni hrapava. Takrat voda ne more spirati delcev, ker ji ni, ampak se skozi rove samo pretaka ali pa izbija iz stene delce s svojim tovorom.

Največji problem je ovrednotiti razmerje med korozijo in transportno erozijo pri oblikovanju jamskih rovov. Z drugimi besedami, do katere stopnje deluje kemijska razgradnja kamnine, da potem lahko nastopi mehansko odplavljanje razrahljanih delcev. Iz terenski opazovanj se je pokazalo, da razmerje zavisi od različnih pogojev, od položaja v rovu, sestave in strukture kamnine, stika z jamskimi naplavinami, prekritostjo s sigo, načinom dotoka vode, fizikalnimi in kemičnimi lastnostmi vode in načinom ter časa stika z vodo (Zupan Hajna 2000). Vsekakor mora biti glede na stopnjo preperelosti karbonatne kamnine hitrost vode zadosti velika, da delce kamnine odtrga s površine jamskih sten.

Voda poleg zrn kamnine trga z jamskih sten tudi porušene dele kamnine iz tektonskih con in odnaša izpadle kose iz sten, ki so predhodno pretrte s tektonskimi in razbremenitvenimi razpokami. Vodni tok razrahljane dele kamnin odnaša, jih preoblikuje in odlaga, ko vodi transportna moč pade. Zato se lahko vzdolž vodnega toka v jamskih rovov delež karbonatnih prodnikov celo poviša (Kranjc 1989).

Mislim, da je v speleogenezi pojav nepopolnega raztapljanja karbonatnih kamnin lahko pomemben dejavnik pri nastajanju prvih kanalov, ker se poroznost karbonatne kamnine povečuje s selektivnim raztapljanjem kalcita in dolomita (Zupan Hajna 2000). Med preperevanjem se pore v apnencu in dolomitu večajo, vzpostavlja se povezava med njimi in s tem povečuje efektivna poroznost. Večanje por in širjenje povezav med njimi vodi v nastanek prvih kanalov. Za nastanek por in povezav med njimi pa v obravnavanih primerih zadostuje raztapljanje z ogljikovo kislino.

Nepopolno raztapljanje pri sprotnem odnašanju preperele kamnine pospešuje tudi rast rovov. Vezi med zrni se raztopijo in voda mehansko odnaša (erodira) preostala zrna. S tem je večanje rova hitrejše in intenzivnejše. Ovira pri rasti rovov se lahko pojavi samo dokler so rovi še zelo majhni in jih nastal karbonatni melj ali glina zamašita. Hitro povečanje dimenzij rova je pogojeno z občasnim ali izjemnim spiranjem debelejših preperelih con apnenca ali dolomita po ekstremnih nalivih ali poplavah.

Da so karbonatni delčki v klastičnih sedimentih res avtohtoni litoklasti nakazuje tudi mineralna sestava recentne naplavine v Renejevem breznu. V naplavini je v glavnem dolomit, ki se praviloma ne izloča kot jamski kemični sediment, dovolj ga je pa preperelega v stenah brezen pred dvorano z akumulirano naplavino. Hkrati s pojavom dolomita v jamski naplavini ovržem tudi možnost, da so karbonatni melji ledeniškega nastanka, ker na površju nad jamo ni dolomita.

Povečanega deleža karbonatnih klastov v jamskih sedimentih ni opaziti v primeru, če jih vodni tok prenaša skozi velike kanale s prosto gladino (Zupan Hajna 1998) in velike zalite kanale, kjer je pretakanje vode počasnejše. Pri transportu sedimentov skozi rove manjših dimenzij in v manjših zalitih rovih, kjer je vodni tok hitrejši in ta spira jamske stene, se delež karbonatov v jamskih naplavinah močno poveča. Največji pa je delež karbonatnih klastov, ko voda v slapovih ali curkih spira stene rovov (Mihevc & Zupan 1988). Najbolj je to izraženo v stopnjastih breznih, kjer voda po nalivih teče z veliko hitrostjo spira jamske stene.

Avtohtone karbonatne klastične sedimente v tu opisanih primerih tako sestavljajo delci matične kamnine, to je litoklasti, ki izvirajo iz preperelih sten jamskih rovov, od koder jih je voda odtrgala.

V nadaljevanju jih voda odloži v zatišnih delih. Lahko same, lahko pa pomešane z materialom, ki ga voda prinaša v jamo iz nekraškega zaledja.

Karbonatni klasti se pojavljajo kot sestavni del klastičnih sedimentov predvsem v dnu aktivnih brezen, kjer stene spirajo vodni hitri vodni tokovi in v občasno zalitih jamskih rovih, kjer se voda pretaka dovolj hitro. Najmočnejše pa je mehansko spiranje sten po nalivih in času taljenja snega, ko se hitrost vode v breznih poveča.

S poznavanjem sestave preperelih con karbonatnih kamnin in dogajanja v kamnini med raztapljanjem ter načinom nastajanja avtohtonih karbonatnih klastičnih sedimentov opozarjam na še eno od številnih posebnosti krasa, na katero moramo biti pozorni pri razlaganju speleogenetskih procesov in oblikovanja kraških rovov.