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THICKNESS OF CAP ROCK AND OTHER IMPORTANT FACTORS AFFECTING MORPHOGENESIS OF SALT KARST

DEBELINA KROVNINE IN DRUGI POMEMBNI DEJAVNIKI, KI VPLIVAJO NA MORFOGENEZO KRASA V SOLI

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Jiří Bruthans & Jakub Šmíd & Michal Filippi & Ondřej Zeman: Debelina krovnine in drugi pomembni dejavniki, ki vplivajo na morfogenezo krasa v soli

Debelino krovnine je mogoče razporediti v 4 razrede. Za vsakega so značilne posebne površinske in podzemeljske kraške oblike: 1. solni izdanki; 2. tanka krovnina (0,5 - 2 m); 3. zmerno debela krovnina (5 - 30 m); 4. zelo debela krovnina (preko 30 m). Najpomembnejši dejavniki, na katere vpliva debelina krovnine, so: gostota mest, skozi katera prodira voda; količina vode, ki ponika na posameznem mestu; hitrost zniževanja površja solnega telesa; »korozijska« sposobnost vode in velikost ter količina tovora, ki ga prenašajo podzemeljske poplavne vode. Debelina krovnine nad jamo ne vpliva neposredno na jamo. Kaže, da je bolj pomembna debelina kamnine v njenem zaledju in tip dotoka na solno telo. Drugi pomemben dejavnik je debelina krovnine v smislu teže, ki je obratnosorazmerna z udiranjem. Široki rovi v nekaterih jamah so nastali zaradi odlaganja sedimenta v strugi, kar je prisililo vodo, da je tekla vzdolž sten in jih tako pospešeno korodirala v pasu, visokem nekaj decimetrov.
Ključne besede: kras v soli, jama, kamnina, solna doma, speleogeneza, Iran, JV Zagros.

Abstract UDC: 551.44(55)

Jiří Bruthans & Jakub Šmíd & Michal Filippi & Ondřej Zeman: Thickness of cap rock and other important factors affecting the morphogenesis of salt karst

Four classes of different thickness of cap rock can be distinguished, each with its special superficial and underground karst forms: 1. salt outcrops, 2. thin cap rock (0,5-2 m), 3. cap rock of moderate thickness (5-30 m), 4. cap rock of great thickness (more than 30 m). The most important factors affected by cap rock thickness are as follows: the density of recharge points, the amounts of concentrated recharge which occur at each recharge point, the rate of lowering the ground surface of salt karst, the dissolution capacity of water and the size and amount of load transported by underground flood-streams into cave systems. The thickness of cap rock above the cave does not influence the cave itself; more important seems to be the thickness of cap rock in the recharge area of the cave and the type of recharge into the salt environment. Another important factor is the thickness of overburden above the cave, which negatively correlates with intensity of breakdown. Wide passages in some caves are developed as result of intensive deposition of bedload, which expel the stream into the side of the passage and are due to enhanced corrosion in the few decimetres high zone above the bottom of passage.
Key words: karst in salt, cave, cap rock, salt plug, speleogenesis, Iran, SE Zagros Mts.

INTRODUCTION

Only a few studies of factors important for evolution of salt karst have been made until now. An exception is the salt karst on plug Mt. Sedom in Israel, which was studied very intensively from the point of karstogenesis, hydrogeology, rate of karst processes, etc. (Frumkin;1994a, b, 1996; Ford and Frumkin 1995). The salt karst on Mt. Sedom is very young; its evolution started only during the Holocene (Frumkin 1996). Unfortunately the variety of environments is relatively low. The whole of Mt. Sedom is covered by cap rock of great thickness.

Karst forms of about 70 salt plugs in a coastal region of the Persian Gulf were briefly described by Bosák (1993) and Bosák et al. (1998, 1999a, b). Nevertheless notes on superficial karst forms and on existence of caves can have been dated since the second half of the 19th century (e.g., Winklehner 1892; Fürst 1970, 1976).

Four student expeditions were organised in 1997 to 2000 into the salt karst of the SE Zagros Mountains in Iran. The following members, students of geology at Charles University in Praha, took part in expeditions: Jiří Bruthans, Michal Filippi, Lukáš Palatinus, Tomáš Svoboda, Jakub Šmíd, and Michal Vašíček. The results of the first three expeditions were published previously (Bosák et al. 1999a, b). Results of research indicated that Iranian salt karst is much older than karst in Israel. Karst forms are various, frequently abundant, from initial and mature ones to residual forms. A broad variety of environments favour the evaluation of the importance of karstogenetic factors (in the area, there are many tens of salt plugs with different morphology, activity of salt uplift, geological history, climate, thickness of cap rocks, etc.). Three plugs, situated in the broader vicinity of port of Bandar-Abbas, were studied in detail: the plug on Hormoz Island (low activity), Namakdan plug on the Queshm Island (passive plug) and the Khurgu (high activity). For detailed description of geological situation and karst forms see Bosák et al. (1998; 1999a).

THICKNESS OF CAP ROCK

The surface of the studied salt plugs is covered by a broad variety of semi-consolidated deposits in regard to their structure and origin. The most common are as follows: thin cover of recent reddish gypcrust, alluvial and marine terraces and several tens of meters thick residues produced by subrosion. These different deposits act in most cases as impermeable cover and prevent karstification of the underlying salt. All these type of rocks with similar function will be summarised later in the text into the term ”cap rock”. Also large blocks of exotic rocks (up to 1,5 km long fragments of sedimentary and igneous rocks transported by halokinesis from depth; Bosák et al. 1998) act similarly as impermeable cover.

Irrespective of the plug activity and type of environment, specific karst forms are linked to a certain thickness of cap rock. Four classes of different thickness of cap rock can be distinguished, each with its special superficial and underground karst forms: (1) salt outcrops; (2) thin cap rock; (3) cap rock of moderate thickness, and (4) cap rock of great thickness. A relatively close relationship exists among the thickness of cap rock and type and size of superficial karst forms. The relationship between the thickness of cap rock and character of underground karst forms is more obscure. As to caves, the cap rock thickness above the cave is not important, but the cap rock thickness in the recharge area of the cave and type of recharge into the salt environment are important factors. The most important factors affected by cap rock thickness are as follows:

(a) the density of recharge points, which has negative correlation with thickness of cap rock. The thicker the cap rock the lower is the density of permeable fractures which enable infiltration of water into salt environment. Thin cap rock is permeable for water at numerous places and therefore a very dense net of small dolines can develop. On the contrary, thick cap rock is impermeable and rare fractures enable evolution of thinly distributed but huge dolines (Bosák et al. 1999a).

(b) the volume of concentrated recharge, which occur at each recharge point (closely related to previous aspect).

(c) the rate of lowering the surface of salt karst. There is almost no lowering of surface in categories 3 and 4; all salt dissolution is concentrated into cave passages. On the contrary, the lowering of ground surface in categories 1 and 2 is very fast and could exceed the rate of halokinesis.

(d) the dissolution capacity of water. In category 4, huge catchments enable the creation of flood-streams with discharge of several hundreds litres per second or containing almost no dissolved NaCl when going underground. On the contrary, the water flowing in forms as thin films on salt outcrops and in shafts under doline bottoms reaches the NaCl saturation very quickly (Frumkin 1994a).

(e) size and amount of particles transported by underground flood-streams into cave systems.

SALT OUTCROPS, NO SEDIMENTARY COVER

Outcrops of rock salt occur only on steep slopes (more than 50°) and also at the bottom of steep canyons and gullies, where residuum after salt dissolution has been repeatedly washed out by precipitation events. Salt outcrops occur predominantly on highly active salt plugs, where the vertical distance between the top and foot of the plug can reach up to 700 m and slopes are very steep (Khurgu). On Hormoz and Namakdan plugs, salt outcrops form also the border of the quaternary marine terraces and sides of deeply entrenched valleys.

On salt outcrops, there is only superficial outflow. Sharp rillenkarren and steep gullies are typical for this environment (Fig. 4).

THIN CAP ROCK (thickness 0.5-2 m)

Thin reddish ferruginous cap rock occurs on moderate to gentle slopes, where thicker sedimentary deposits were previously removed by erosion. This cap rock is the result of current salt dissolution. Insoluble particles from rock salt have been transported by overland flow to close depressions. After deposition, it was cemented into semi-consolidated cap rock. The cap rock prevents the underlying salt from corrosion and former depressions filled by cap rock retreat into hills by dissolution of surrounding salt during the time (Bosák et al. 1999a). Cap rock covering the top of the hills is slowly eroded by overland flow and underlying salt has been consequently rapidly dissolved. This repeating process led to continuous lowering of the whole surface (chemical denudation), which is a relatively fast process. Deepening of the uvala-like depressions progresses in many cases at a rate comparable with the rate of salt mass uplift. Due to fast deepening of their

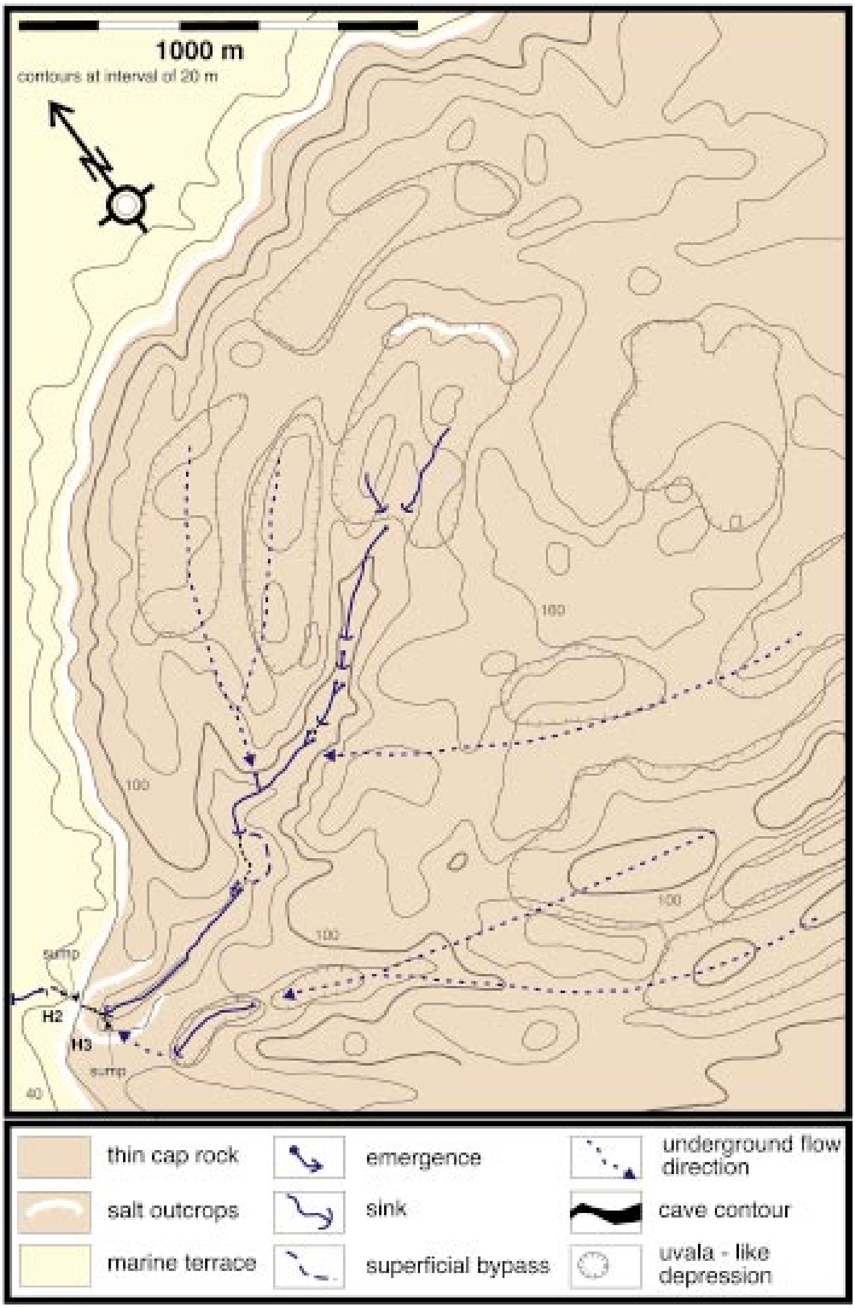

Fig. 1: Cave of Tří Naháčů (5010 m) and drainage pattern typical for the area with cap rock of great thickness (SE margin of the Namakdan salt plug, Queshm Island).

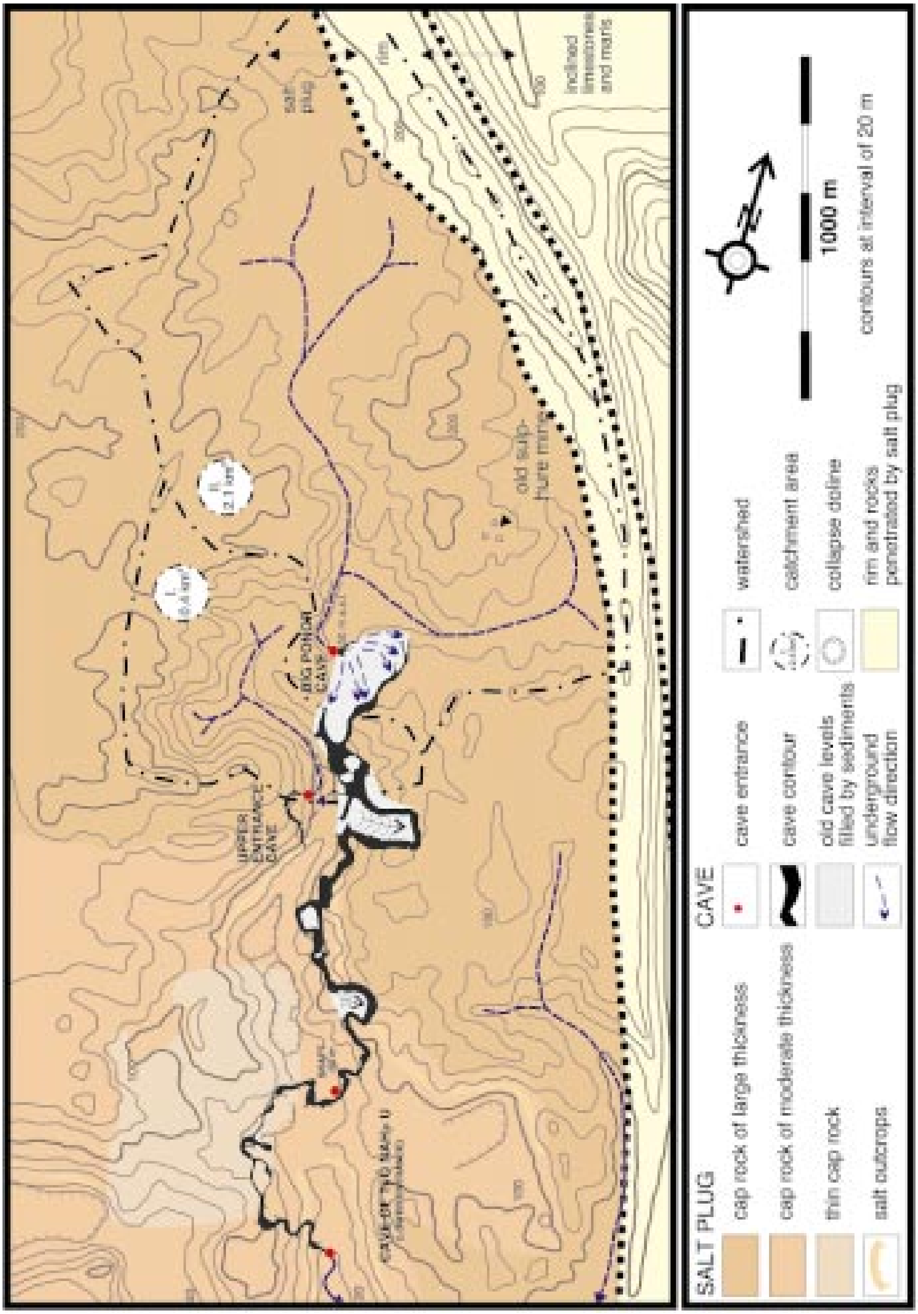

Fig. 2: Karst landscape and drainage pattern connected with thin cap rock (N margin of plug on the Hormoz Island).

bottoms, a part of uvala-like forms reached the underground water table level and cave drainage was consequently replaced in these parts by superficial streams (Fig. 1). Areas with thin cap rock cover the whole central part of Hormoz Island, small-enclosed SE part of the Namakdan plug and many scattered areas on Khurgu plug.

The drainage pattern is underground, superficial segments of streams occur only on the bottoms of some uvala-like depressions. The major part of recharge passes through the dense network of dolines and small inaccessible cavities and feeds the main drainage routes.

Small funnel-shaped dolines (diameter 2-8 meters) terminating in vertical shafts (depth 1-5 m) in rock salt cover as dense net nearly the whole area of the second category. Their density can reach up to several thousand dolines per 1 km^2. Dolines are concentrated in flat uvala-like depressions (diameters: 100 - 500 m, depths: 10 - 30 m). Some of uvala-like depressions have steeper sides and their bottoms are traversed by episodic or perennial streams.

Caves formed by flood-streams collected on thin cap rock are relatively short, with lengths of 10 to 300 m. They are interrupted by several hundreds meters long segments of superficial streams. Caves are commonly bypassed several meters above the current level by superficial entrenchment. Passages have small and rather circular cross-sections (from 0,5 up to 10 m^2), despite the fact that the catchment areas in some cases have similar extent to the catchment of large caves (Cave of Tří Naháčů). Maze patterns and sumps occur. Meander notches are scarce. Caves related to that environment differ considerably from those formed by sinking flood-streams collected on cap rock of great thickness. Following factors have the highest responsibility for shape of caves.

A great part of residual particles from salt dissolution remains trapped in impenetrably small channels and cavities immediately under dolines. Caves accessible for man (which, only, could be studied) are formed by flood-streams draining the cavities and channels below dolines. Flood-streams rising from channels have a relatively low amount of bedload and large particles are almost lacking. As a consequence, sumps are protected from filling by sediments. Water is partly saturated with the respect to NaCl, due to the contact with rock salt in channels beneath dolines. Dissolution capacity of water is considerably lower compared with water collected on areas with thick cap rock. The maximum discharge during flood events is much lower than in a case of flood-streams collected on cap rock of great thickness, because of the retardation effect of small channels and cavities. The relatively high storage capacity of these cavities had been observed in March 1998, several days after a strong precipitation event.

CAP ROCK OF MODERATE THICKNESS (thickness 5-30 m)

The cap rock with a thickness of more than 2 m mostly results from previous fluvial and marine activity (accumulation terraces, insoluble residuum created by subrosion). Such environment occurs on the SE margin of the Namakdan plug, on a summit part of the Khurgu plug and at marginal parts of Hormoz Island.

Drainage is completely underground. The surface is covered by a dense net of dolines, and small blind valleys occur too.

Dolines have similar shape to those in the previous case, but they are noticeably larger (diameter about 20 to 50 m). Their density is considerably lower. Doline bottoms are terminated by vertical shafts with diameter of 2 to 10 m and depth up to 60 m.

CAP ROCK OF GREAT THICKNESS (more than 30 m thick)

The central parts of Namakdan and Khurgu plugs are covered by several tens of meters thick cap rock. The cap rock probably resulted from long-lasting subrosion beneath alluvial or marine environments. On Hormoz Island, marine terraces and thick alluvia occur at marginal parts.

The drainage pattern is almost completely superficial. In areas formed by thick cap rock, karst forms are generally absent. Huge collapse dolines occur only very scarcely (diameter 20-70 m, depth 30-50 m). Around these dolines, 50 to 300 meters long entrenchments are developed feeding dolines during precipitation events. Areas covered by thick cap rock are very favourable for the evolution of extensive cave systems, because it enables collection of pure water from large catchments (up to 2 km^2).

Caves formed by flood-streams collected on cap rock of large thickness could be quite long (Ghár-e Daneshju Cave 1909 m, Cave of Tří Naháčů 5010 m). Also catchments of the world's longest cave in salt in Israel and other long caves in that area are situated on thick cap rock (Frumkin 1994b).

Cross-sections of cave passages are large (up to 100 m^2) and wide but low, if not affected by breakdown. Flat slightly inclined roofs and meander notches are typical. On the contrary, superficial bypasses, maze character and sumps are missing. Caves developed by flood-streams collected on the surface of large exotic blocks show similar features (Cave of Dragon Breath, Hormoz Island).

Huge amounts and the size of particles transported by sinking flood-streams represent the most important factor influencing cave character here. All particles eroded by flood upstream have been transported into caves in the case of thick cap rock. Bigger particles start to settle down nearly immediately in cave entrance. Cobbles with diameter 0,1- 0,5 m are common in upstream part of the Big Ponor Cave and Upper Entrance Cave. Comparably large particles were not found in or below Cave of Tří Naháčů representing downstream part of both previous caves (Fig. 2). Also other observations proved that all particles bigger than 0,2 m and probably also major part of smaller particles remained trapped within the cave. Proximal parts of caves could be compared to alluvial fans or braided rivers with intensive sedimentation.

High dissolution capacity of water represents another important factor. Water is collected outside the contact with rock salt and therefore the concentrated flow enters the salt environment with almost no NaCl dissolved.

MEANDER NOTCHES AND EQUILIBRIUM PROFILE

Meander notches (flat inclined roofs) occur in salt caves in Iran and also in caves on Mt. Sedom, Israel (Frumkin 1994b). This form has similar shape to horizontal notches but a completely different origin. The main differences are depicted in Fig. 3. Horizontal notches (laugdecken) originate by corrosion in standing water with slow convection generated by density difference between saturated and unsaturated water (Kempe et al. 1975). Meander notches are created by corrosion and abrasion of quickly flowing flood-streams. On Mt. Seldom (Israel), Ford and Frumkin (1995) proved by measurements that the retreat of surface of cave passages was restricted to the region of 0 to 0,3 m above the bottom of the passage, although the maximum level of flood reached 0,5 - 1 m above

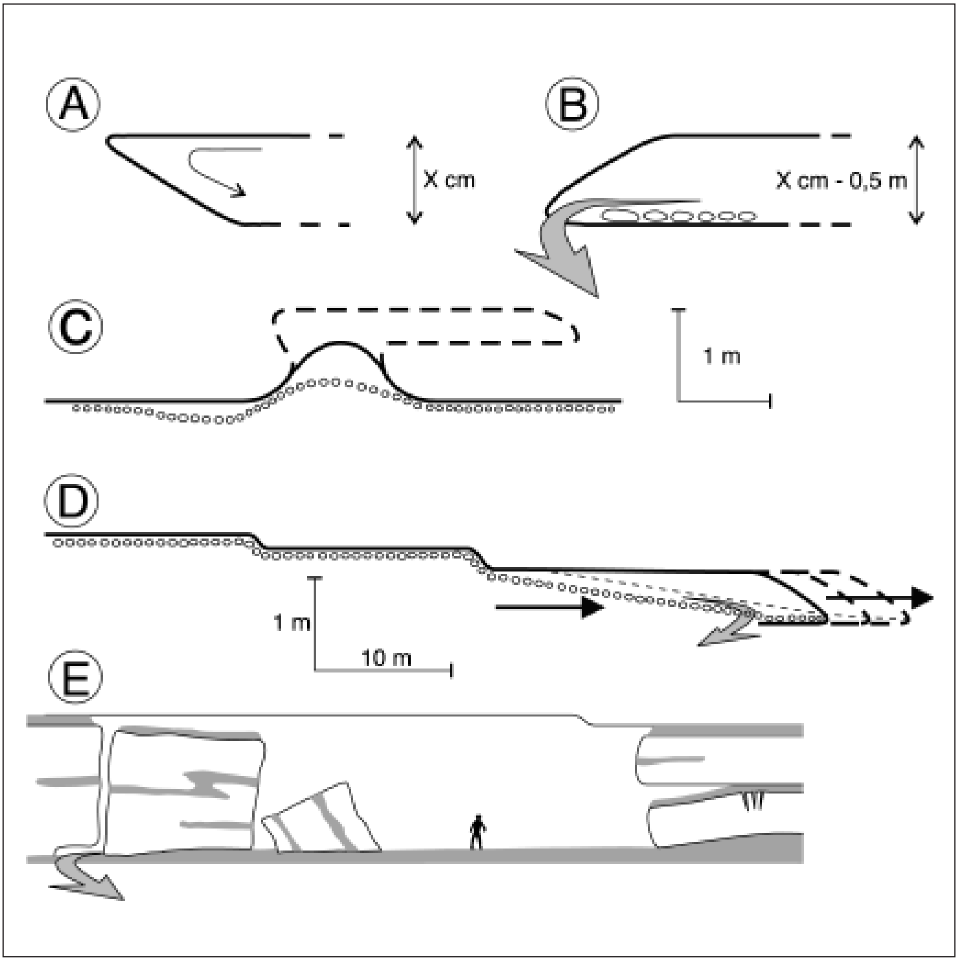

Fig. 3: Cross-sections representing main differences between:
A) "laugdecken" (horizontal roof above sloping sidewall) and B) "meander notches" (roofs inclination of 0,3- 11 % in direction of flow, roofs in detail slightly sloping to the sides, flat bottom with alluvium).
Cross-sections showing development of meander notches:
C) Paragenetic cycle. The ceiling half-tube is result of rapid full-pipe flow.
D) Erosion cycle, in meander bend. The retreat of passage side is restricted to outer side of meander, on the inner side the bedload is deposited, filling the whole space. The extensive (230 m wide) meander in the northern part of the Cave of Tří Naháčů (Fig. 2) was created during the recent erosion cycle.
E) The extensive passages (width up to 40 m, height up to 6 m) in northern part of Cave of Tří Naháčů have been developed during the recent erosion cycle by undercutting of roof blocks which consequently collapsed along old levels of meander notches.

passage bottom. This fact could be probably ascribed to the important influence of bedload transport as an enhancement factor in the retreat of the surface of passages and also in the evolution of meander notches (due to abrasion?, enhanced corrosion?).

All caves with recent meander notches have already reached equilibrium profile, e.g., minimum gradient allowing the transport of coarse sediment load. Equilibrium profile was stated by Frumkin (1994b) as a time independent longitudinal cave profile adjusted to the base level of erosion below which the cave passagge cannot degrade and at which neither erosion nor deposition occur. In caves with intensive deposition of coarse bedload (Cave of Tří Naháčů and related caves) the equilibrium profile was also reached, but only for particles of small grain-size. The main definition of equilibrium profile (stability during time) is still valid there as the sedimentation occurs along a very wide front, but nearly at the same level along the profile.

The longitudinal section of salt caves, which have reached the equilibrium profile (Ghár-e Danešjú, Big Ponor Cave - Cave of Tří Naháčů) is commonly convex, the slope of the passage decreasing downwards along longitudinal profile of the cave (*cf.* Frumkin 1994b). The research in Iranian salt karst showed that this deflection resulted from two main factors:

(a) decreasing size and amount of particles transported by flood-streams along passage due to their deposition in the cave. The smaller diameter of particles and the lower velocity of the underground stream is necessary for their transportation and as a consequence, the lower slope of the equilibrium profile is necessary to assure such velocity.

(b) decrease in minimum inclination of passage necessary for transportation of bedload of a certain size along the flow route. This is the result of increasing discharge rate of flood water (coming from tributaries) and simultaneous decreasing of friction due to enlarging of wetted perimeter. In the salt caves in Iran, there is the negative relationship between discharge of flood-flows and the inclination of cave passages, which reached the equilibrium profile (Bosák et al. 1999a).

The intensive sedimentation in the upper parts of caves disturbs the balance established by equilibrium profile. The underground flood-stream is therefore permanently expelled into the sides of passages. The results are represented by very broad (in places more than 100 m wide) passages, which are predominantly filled by sediments. The best example is the Cave of Tří Naháčů. Here, many levels of meander notches were found, both from paragenetic cycle and from erosion cycle (Fig. 2, 3, 7). Figure 2 shows only minimum (apparent) extent of old levels of meander notches; their actual extent is probably considerably larger.

THICKNESS OF OVERBURDEN

The thickness of overburden above caves strongly affects the intensity of breakdown and collapse of passages and rooms in studied salt karst in Iran. This fact can be clearly demonstrated in the Cave of Tří Naháčů (Fig. 2). The largest rooms and corridors are concentrated below the 80-150 m thick overburden in the northern part of the cave. Breakdown is relatively rare, although passages are wide (up to 40 m). Old corrosion forms are preserved in sides and roofs of passages.

The southern part of the cave is situated mostly 20 - 60 m below the ground surface. It is strongly affected by breakdown, despite the relatively small width of passages (Fig. 2). Cross-

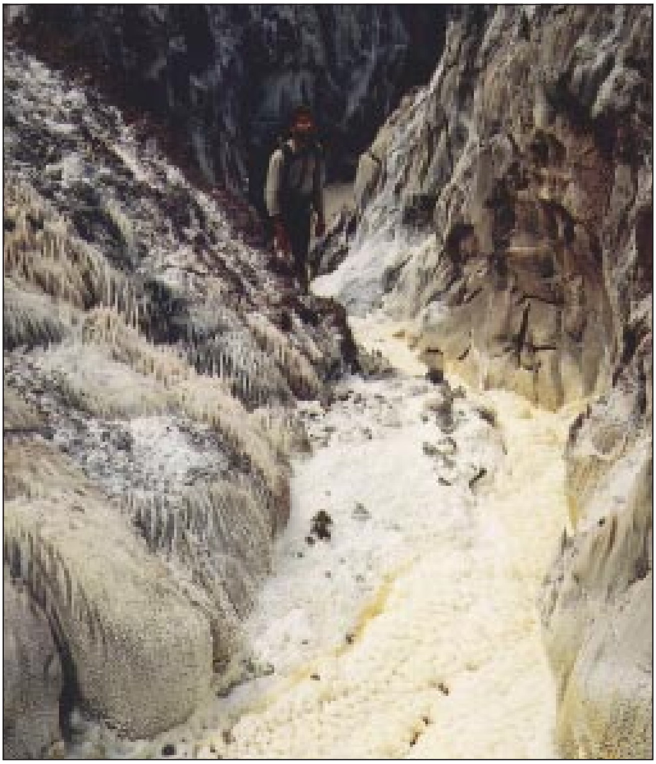

Fig. 4: Rillenkarren and gully entrenched into rock salt, typical karst forms of salt outcrops (Khurgu plug). The bottom of the gully is covered by 5-20 cm thick layer of salt sinters.

Fig. 5: Uvala-like depression covered by hundreds of small dolines, typical karst forms of an area with thin cap rock (central Hormoz Island). The width of the middle part of picture is about 300 m.

Fig. 6: Large dolines developed on cap rock of moderate thickness (SE Namakdan). The width of the middle part of picture is about 200 m.

Fig. 7: Meander notches developed during paragenetic cycle in the side of "Megadomes", the northern part of the Cave of Tří Naháčů. The salt layering is steeply inclined.

section of passages below overburden of low thickness show a predominantly parabolic shape, due to breakdown along a tension dome, with no traces of primary corrosion forms.

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DEBELINA KROVNINE IN DRUGI POMEMBNI DEJAVNIKI, KI VPLIVAJO NA MORFOGENEZO KRASA V SOLI

Povzetek

Debelino krovnine je mogoče razporediti v 4 razrede. Za vsakega so značilne posebne površinske in podzemeljske kraške oblike: 1. solni izdanki; 2. tanka krovnina (0,5 - 2 m); 3. zmerno debela krovnina (5- 30 m); 4. zelo debela krovnina (preko 30 m).

Debelina krovnine nad jamo ne vpliva neposredno na jamo. Kaže, da je bolj pomembna debelina kamnine v njenem zaledju in tip dotoka na solno telo.

Najpomembnejši dejavniki na katere vpliva debelina krovnine, so:

a) Gostota mest, skozi katera prodira voda; ta je obratnosorazmerna z debelino krovnine.
b) Količina vode, ki koncentrirano prenika na posameznem mestu.
c) Hitrost zniževanja površja solnega telesa. V razredih 3 in 4 skoraj ni zniževanja površja, pač pa je raztapljanje soli osredotočeno v jamskih rovih. Nasprotno pa je zniževanje površja v prvih dveh razredih zelo hitro in lahko celo preseže hitrost halokineze.
d) »Korozijska« sposobnost vode. V četrtem razredu nastajajo zaradi velikih zaledjih poplavni tokovi, ki lahko dosežejo več sto litrov pretoka v sekundi in ki ob vstopu v podzemlje skoraj ne vsebujejo raztopljenega NaCl. Nasprotno pa se voda, ki teče v obliki tanke prevleke preko solnih izdankov in v brezna pod dnom vrtač, zelo hitro zasiči z NaCl.
e) Velikost delcev ter količina tovora, ki ga prenašajo podzemeljske poplavne vode po jamah.

Široki rovi v nekaterih jamah so nastali zaradi na debelo odloženega sedimenta v strugi, kar je prisililo vodo, da je tekla vzdolž sten in jih tako pospešeno korodirala v pasu, visokem nekaj decimetrov.

V iranskem krasu v soli je debelina krovnine nad jamami obratnosorazmerna z intenzivnostjo podiranja rovov in dvoran. Te podori močno prizadevajo celo globlje od 60 m pod površjem.