ACTA CARSOLOGICA	31/3	3	51-74	LJUBLJANA 2002

COBISS: 1.08

BLOW HOLE CAVE: AN UNROOFED CAVE ON SAN SALVADOR ISLAND, THE BAHAMAS, AND ITS IMPORTANCE FOR DETECTION OF PALEOKARST CAVES ON FOSSIL CARBONATE PLATFORMS

BLOW HOLE CAVE (SAN SALVADOR, BAHAMI): BREZSTROPA JAMA IN NJEN POMEN PRI PREPOZNAVANJU PALEOKRAŠKIH JAM FOSILNIH KARBONATNIH PLATFORM

PAVEL BOSÁK[1] & JOHN E. MYLROIE[2] & JINDŘICH HLADIL[1] & JAMES L. CAREW[3] & LADISLAV SLAVÍK[1]

[1] Institute of Geology, Academy of Sciences of the Czech Republic, Rozvojová 135, CZ-165 02 PRAHA 2, CZECH REPUBLIC, e-mail: bosak@gli.cas.cz

[2] Department of Geosciences, Mississippi State University, MISSISSIPPI 39762, U.S.A., e-mail: mylroie@geosci.msstate.edu

[3] Department of Geology and Environmental Geosciences, College of Charleston, CHARLESTON, SC 29424, U.S.A., e-mail: carewj@cofc.edu

Prejeto / received: 30. 8. 2002

Izvleček UDK: 551.44:539.1.08(729.6+437.2)

Pavel Bosák & John E. Mylroie & Jindřich Hladil & James L. Carew & Ladislav Slavík: Blow Hole Cave (San Salvador, Bahami): Brezstropa jama in njen pomen pri prepoznavanju paleokraških jam fosilnih karbonatnih platform

Prispevek obravnava podobnosti v razvoju krasa kvartarne karbonatne platforme na otoku San Salvador in devonske karbonatne platforme na platoju Krásná na Moravskem. Za obe območji so značilne jame, katerih nastanek lahko razložimo s »flank margin« modelom in so nastale v območju sladkovodnih leč med obdobji relativno visoke morske gladine, v času relativno stabilne haloklinе, kar potrjujejo različne študije jamskih zapolnitev. V obeh primerih so jamske sedimentne zapolnitve genetsko primerljive - obalni in eolski sedimenti ter breče.
Ključne besede: karbonatne platforme, »flank margin« jame, brezstrope jame, spektrometrija z gama žarki in karotaža vrtin, zgornji devon, kvartar, otok San Salvador, Bahami, Severna Moravska, Češka republika.

Abstract UDC: 551.44:539.1.08(729.6+437.2)

Pavel Bosák & John E. Mylroie & Jindřich Hladil & James L. Carew & Ladislav Slavík: Blow Hole Cave: An unroofed cave on San Salvador Island, the Bahamas, and its importance for detection of paleokarst caves on fossil carbonate platforms

The comparative study of a Quaternary carbonate platform (San Salvador Island, the Bahamas) and a Devonian Carbonate Platform (Krásná Elevation, Moravia) indicates a great similarity in karst evolution. Caves on both sites are interpreted as flank margin caves associated with a freshwater lens and halocline stabilised during sea-level highstands. The sedimentary fill of both caves is genetically comparable - beach and aeolian sediments with bodies of breccias.
Key words: carbonate platforms, flank margin caves, unroofed caves, gamma-ray spectrometry and well-logging, Upper Devonian, Quaternary, San Salvador Island, Bahamas, North Moravia, Czech Republic.

INTRODUCTION

Depositional and/or local karst (*sensu* Choquette & James 1988) on recent emerged parts of carbonate platforms has been intensively studied to obtain criteria for identification of fossil counterparts in the rock record (e.g., Longman 1980; James & Choquette, 1988; Wright & Smart 1994; Moore 2001) and to know the velocity of speleogenesis (Mylroie & Carew 1986, 1987). The evolution of karst processes during emergences of a carbonate platform have been usually connected with special facies of diagenesis (Esteban & Klappa 1983), especially when studying the Caribbean type of the karst (Esteban 1991). The study of modern subaerial diagenetic processes, including freshwater and mixed-water diagenetic settings offer a tool for recognition of porosity distribution important in petroleum exploration (*cf*. e.g., Moore 2001; James & Choquette, 1988; Tucker & Wright 1990).

Recent and fossil carbonate platforms show numerous identical features of cyclicity, amalgamation of unconformities, time record in sedimentary sequences, porosity distribution and karst evolution, especially when studying extensive carbonate platforms on passive continent margins. Our comparison of karst on San Salvador Island (the Great Bahama Bank; GBB) and Devonian Carbonate Platform in Moravia (DCPM, Czech Republic) is based on similar paleotectonic settings, significant thickness of carbonate sequences, and well defined unconformity surfaces of various ranks (*cf*. Hladil et al. 2002). Karst on the GBB was studied directly on outcrops and in caves, while the karst in the DCPM has been known only from boreholes (cores) and well logging (Hladil 1993, 1999; Hladil et al. 1994).

METHODS

Gamma-ray spectrometry

Spectral gamma-ray measurements were carried out on relatively fresh and continuous rock faces. A calibrated gamma-ray spectrometer was used in the direct display of computed contents of K [%], U and Th [ppm] mode. The highest resolution GS-256 spectrometer produced and adapted by Geofyzika Ltd. Brno was used. The most reliable measurements on outcrops were obtained using the 0.5 m step with the probe axis parallel to bedding and in full contact perpendicular to the rock wall, and a sufficiently stabilised gain of counts after 240 s. Natural gamma-ray (GR) and gamma-ray spectrometry (GRS) logging of drilled wells were used in the past, but the use of characteristic time series of the GRS patterns has become common since it was introduced by Ruffell & Worden (2000). The total GR well logs were used only in the Devonian rocks, because of the absence of appropriate cores on San Salvador Island. In wells, the data were digitised using 0.1 m steps.

Sampling and laboratory measurements of magnetic susceptibility

Fresh rock samples were taken at 0.1 m intervals, using a hammer and chisel. The parts damaged by tools or having other defects were removed using a cooled diamond-copper saw. The average weight of the samples was 20 g. After the documentation of volume and weight (and density), the proper measurements were carried out (Laboratory of Paleomagnetism, Institute of Geology AS CR, Praha-Průhonice) using the most sensitive commercially available laboratory kappabridges for measuring bulk magnetic susceptibility KLY-3 (produced by Agico Ltd. Brno).

SAN SALVADOR ISLAND, THE BAHAMAS

The San Salvador Island is a part of the Bahamian Archipelago. It represents a detached promontory of the Great Bahama Bank (GBB) facing the Atlantic Ocean. From the GBB it is separated by deep channel with two another small islands (Fig. 1). It is located along the eastern flanks of the Bahama Platform, some 600 km ESE of Miami (Florida, USA) and about 350 km N of Cuba. The island is about 19 km long and max. 8 km wide, with the area of about 100 km^2. The island is surrounded by relatively deep Atlantic Ocean, with depth of more than 2,000 m.

The surface of the island is composed of fossil aaeolian ridges arranged according to prevailing wind directions. Lakes of highly variable salinities are located between the ridges. The highest point of the island is about 37 m a.s.l.

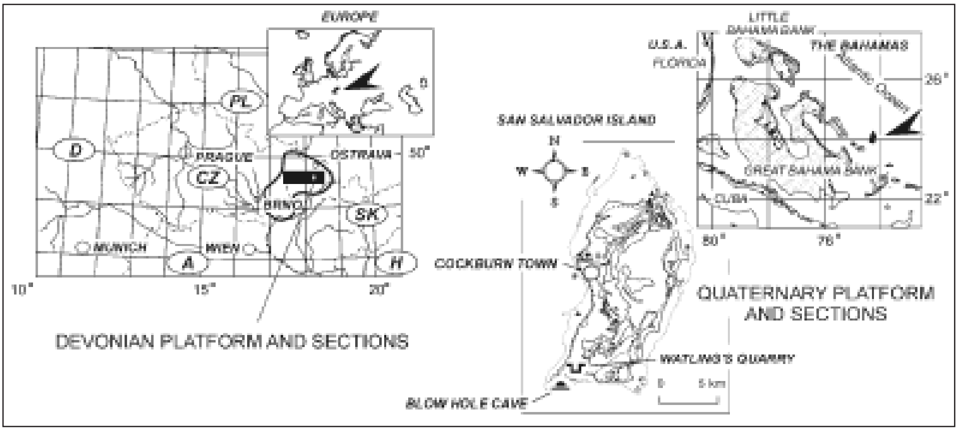


Fig. 1: Location of the studied sites.

Geological setting

The GBB is a tectonically stable platform whose major boundaries are defined at great depth by tectonic fractures (Mullins & Lynts 1972). The great relief of the banks and steepness of their margins is related both to depositional process and to erosion of the intervening channels (Hooke & Schlager 1980). The carbonates of Cretaceous to Holocene age sediments overly poorly known pre-Triassic basement in a total thickness of more than 4,000 m. The GBB was divided into several platforms during the Miocene (Eberli & Ginsburg 1987). Since the Cretaceous, the isostatic subsidence was calculated to 1 to 4 cm.ka^{-1} and during the past few million years, subsidence has been about 2 cm.ka^{-1} (Pierson 1983). It can be expected that the subsidence also reflects deep-seated inter- and intrastratal pressure dissolution of carbonate rocks.

Quaternary stratigraphy

The Quaternary depositional history of the shallow banks and islands of the Bahamas was controlled by glacio-eustatic sea-level changes. Significant production of carbonate grains and mud occurred only during brief (~10 ka) high stands of sea level, such as that of the present time, flooding the bank tops (above minus10 m). During those times carbonate material is produced by members of the coral reef community that precipitate carbonate shells or mud. Other common components of Bahamian calcareous sands are spherical ooids. During the last highstand of sea level, circa 125 ka, oolitic sediment was much more widespread, and formed massive aaeolian calcarenites. Between the relatively short depositional intervals, there were long periods (~10^5 years) when sea level was at least 10 meters below its present position, and only subaerial erosion and fallout of atmospheric dust occurred on the Bahamian banks and islands. During those long intervals of exposure, the dominant geological processes included dissolution of the limestone (local karst) and formation of soils. Terra rossa paleosols developed on the exposed surfaces, and they now form the sequence boundaries between deposits formed during separate interglacials. The stratigraphy of the island consists of three Quaternary rock units (Fig. 2), which are generally separated by a paleosol, which marks an unconformity that represents an extended time of low sea level and subaerial exposure (Carew & Mylroie 1995, 1997).

The oldest rocks exposed on San Salvador are referred to as the *Owl's Hole Formation*. Those rocks consist of aeolian calcarenites that are capped by a terra rossa paleosol, is overlain either by subtidal deposits or by a younger highly oolitic aeolianite that is also capped by a terra rossa paleosol (Carew & Mylroie 1995). The age of the sea-level highstand(s) during which the Owl's Hole aeolianites were deposited most likely represents one or more of the Pleistocene highstands

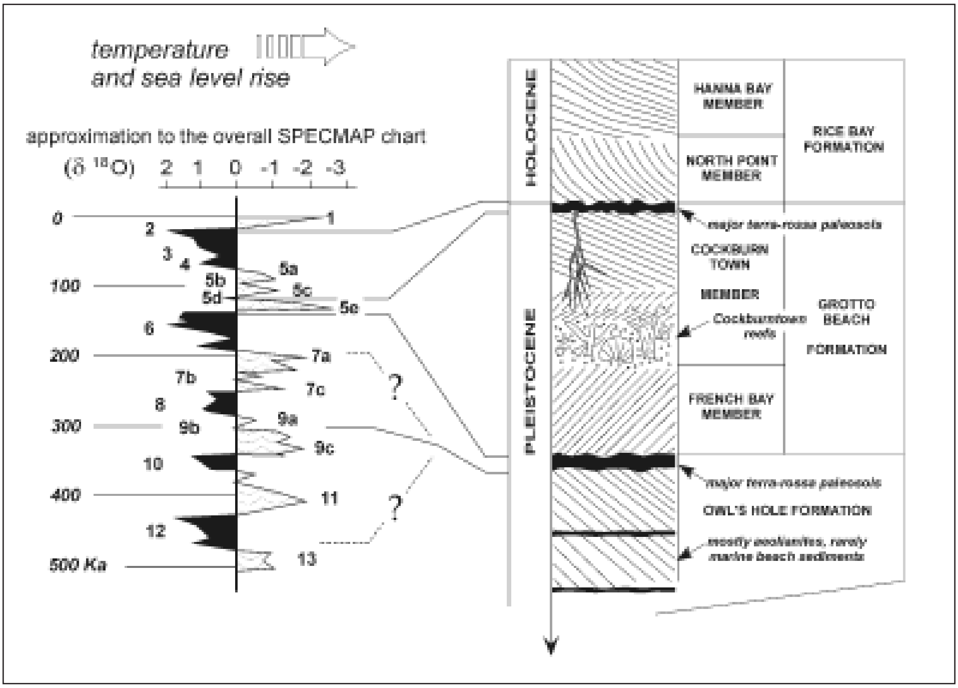


Fig. 2: Graphic representation of the composite lithostratigraphy of the Quaternary limestones on San Salvador Island (modified from Carew & Mylroie 1995) and comparison with oxygen isotope stages.

(from ~220 to ~410 ka; Fig. 2). Owl's Hole aeolianites are fossiliferous pelsparites or peloidal biosparites (fossiliferous peloidal grainstones). The grains are cemented by sparry calcite that formed in the vadose zone. Owl's Hole rocks are often extensively micritised (i.e. altered to microcrystalline carbonate after deposition) along the exposure surface, but interior portions remain relatively weakly cemented and are often little altered by diagenesis (Bain 1991; Schwabe, Carew & Mylroie 1993; Carew & Mylroie 1995, 1997).

The major depositional unit exposed on San Salvador, and all Bahamian islands, is the *Grotto Beach Formation* (Fig. 2). This unit consists of aeolianites and beach through subtidal marine limestones. In some places, this formation can be subdivided into members (French Bay Member, Cockburntown Member). The Grotto Beach Formation is capped by a terra rossa paleosol, except where it has been removed by later erosion. The Grotto Beach Formation contains subtidal facies that are exposed above modern sea level, so it must have been deposited during the substage-5e sea-level highstand (~132 to119 ka; Chen et al., 1991). The age was proved by paleomagnetic and U/Th dating of paleosol and overlying aeolianite in Watling's Quarry. Paleosol contained inverse polarised zone (Blake event = 112-118 ka) and overlying aeolianite was dated to about 104 ka (Bosák, Hladil & Slavík 2001). Throughout the Bahamas, the transgressive-phase aeolianites (deposited as sea level rose to a high stand) and stillstand-phase aeolianites of the Grotto Beach Formation contain abundant well-developed ooids. Most of the subtidal facies of this formation also contain appreciable ooids, except close to a source of bioclastic (shell) debris, such as a reef. Regressive-phase aeolianites (deposited as sea level fell from a high stand to a low stand) of the Grotto Beach Formation are dominantly peloidal and bioclastic, but they also may contain some ooids.

The *Rice Bay Formation* was deposited during the last 6 ka of the Holocene Epoch. On Bahamian Islands, this formation comprises all rocks above the paleosol that caps the Grotto Beach Formation (Carew & Mylroie 1995). The Rice Bay Formation consists of aeolianites and beach-facies rocks that have been deposited during the transgressive and stillstand phases of the current sea-level highstand (oxygen isotope stage 1). In some places, two members (North Point Member, Hanna Bay Member) can be recognised by differences in bedding character, grain composition, and their position relative to current sea level. Although there is some limited early development of thin calcretes (< 1 mm thick) on some rocks of the Rice Bay Formation, terra rossa paleosols are absent. Rocks of the Rice Bay Formation generally have few or no ooids, are dominated by peloids and bioclasts, exhibit limited diagenetic micritisation, and are weakly cemented by meniscus-style low-magnesium calcite cements that formed in the vadose zone.

THE BLOW HOLE CAVE

Blow Hole Cave occurs along the southwestern coast of San Salvador (Fig. 3), it was mapped by Mylroie (1988). The geology of that area is a very complex mixture of subtidal deposits and interspersed aeolianites with calcarenite protosols and terra rossa paleosol. The cave is developed in subtidal and beach deposits of the Grotto Beach Formation. The lower walls of the cave exhibit herringbone cross bedding that is indicative of rock formation on a subtidal shoal. At the sample locality there are about 3 meters of outcrop that is capped by a terra rossa paleosol that also extends down into the cave entrance.

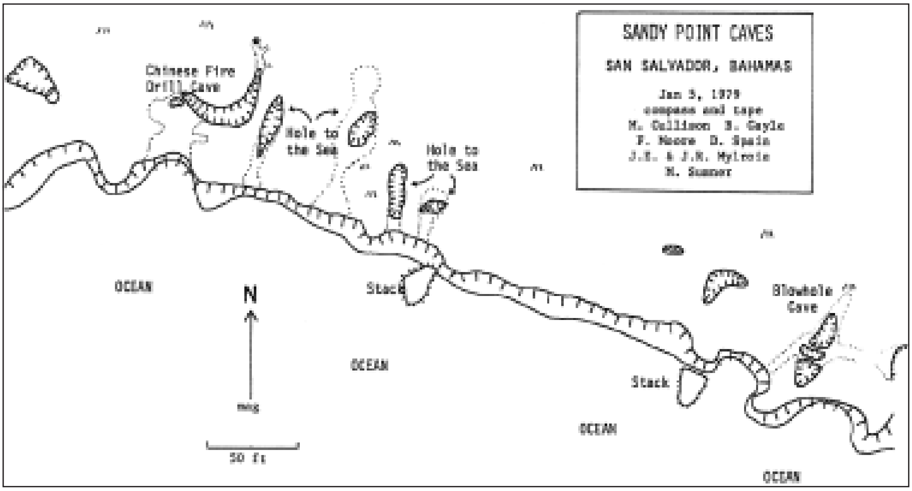


Fig. 3: Map of Sandy Point with location of flank margin caves (after Mylroie 1988).

Limestone is highly hardened to very hard duricrust in the near-surface part. The thickness of the crust is 20 to 60 cm, silicification cannot be excluded (smell of crust after the use of hammer). The duricrust base is uneven, but relatively very sharp.

Description

The cave (Fig. 4), in fact, represents an oval phreatic tube with minor vadose entrenchments in the form of relatively narrow vadose canyons (Photo 1). During our visit, only the entrance part of the cave was accessible, with the width of max. 2.8 m and the height of max. 1 m. The cave channel is slightly inclined to the indistinct rocky cliff, which slope is covered by loose recent beach calcarenites. The cave roof is partly destroyed. In the deeper part of the

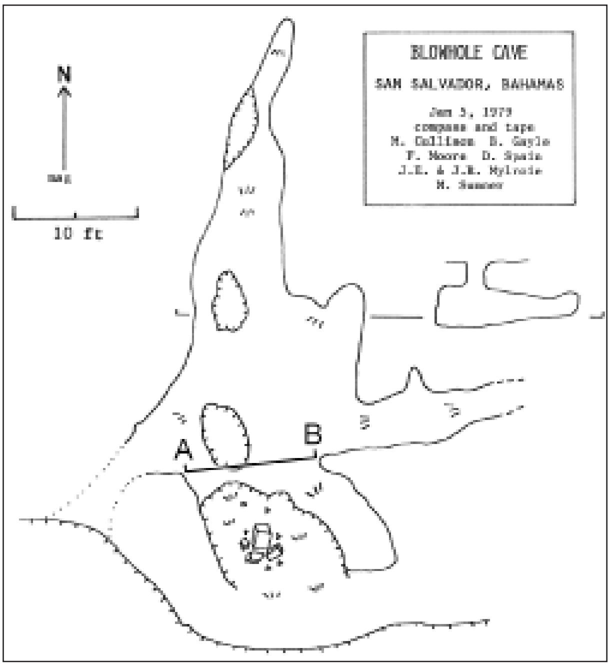


Fig. 4: Map of the Blow Hole Cave (after Mylroie 1988) with profile A-B (Fig. 5).

Photo 1: Blow Hole Cave: phreatic tunnel with small vadose canyon filled by recent sand dunes (photo by P. Bosák).

Photo 2: The fill of the Blow Hole Cave: breccia with blackened pebbles (layer No. 2) and cross-bedded calcarenites (layer No. 1) in the centre, recent dune sand (layer No. 4) and cavernous duricrust behind (photo by P. Bosák).

cave, oval windows perforating hardened carbonate rock are developed to the surface. Above the cave, a narrow shallow trench continues landwards in which the oval windows are developed. The width of shallow trench is equal to the diameter of windows. In the entrance area, the roof is destroyed nearly completely, forming a trench. Towards the sea, the ceiling and walls of the channel are missing, only cave fill can be traced in the rock for about 10 m (Photo 2), where it is completely eroded away together with the host rock. The cave can be classified as unroofed/ denuded cave (*sensu* Mihevc, Slabe & Šebela 1998).

The walls of the cave are covered by a thin film of speleothems (about 1 to 2 mm). The highly indurated duricrust in a thickness up to 5 mm is developed under the speleothem film, in higher thicknesses in wall niches. The duricrust is covered by a thin film of light brown warnish.

Cave fill

The cave is filled by a sequence of sediments (Fig. 5): (1) cross-bedded calcarenites, porous, sometimes containing small clasts of black pebbles and hardened limestone (duricrust), fossil beach sediments; (2) breccia to conglomerate, matrix-supported at the base with low content of small and rather suboval clasts; chaotic clast-supported rock forms the rest of the layer, some clasts are blackened pebbles (black on Fig. 5); the matrix is reddish brown and composed of carbonate allochems with indistinct indications of cross bedding; (3) calcarenite, cross-bedded, whitish, cemented, and (4) calcarenite, recent beach. Layers Nos. 1, 2 and 3 are separated by distinct erosion boundaries. Layer No. 2 fills the erosional trench in layer No. 1. Layer No. 3 overlies layer No. 2 by an irregular erosional boundary with small pockets and karren-like forms with the depth up to 20 cm. Layer No. 1 is covered by a thin speleothem layer (flowstone) and small speleothem columns in places, where not eroded by layer No. 2. It is probable that the speleothems can be older than layer No. 2.

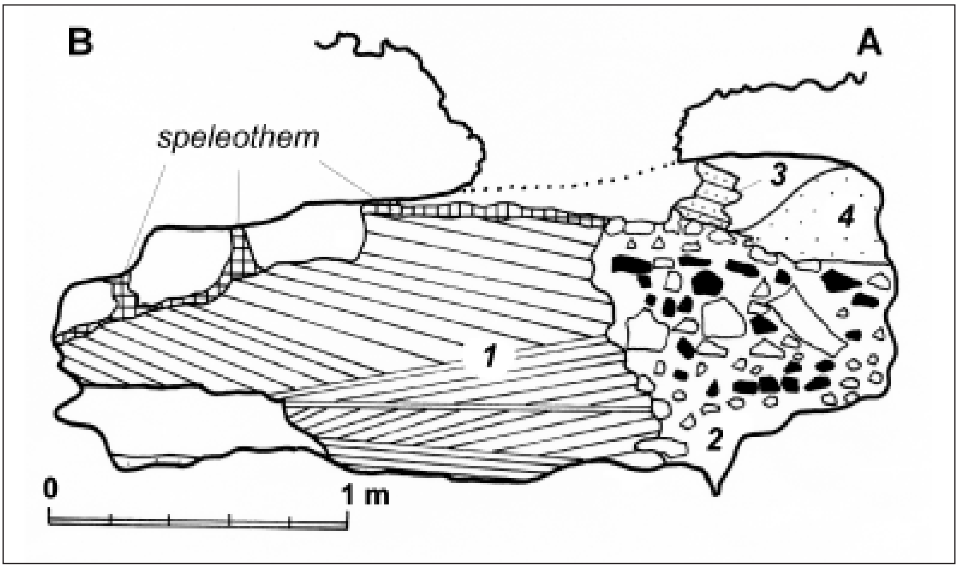


Fig. 5: Fill of the Blow Hole Cave (for explanation see the text; location of the profile in Fig. 4).

Speleothems

The ceiling of the cave contains lot of small bell-like rounded hollows partly filled by small popcorn-like or cauliflower-like formations with diameter up to 2 cm. The aggregates were creamy or yellowish white, at the base pale green, soft and porous. Green colour at the base was probably due to green algae. X-ray analysis identified gypsum as the dominant mineral of the aggregate (Laboratory of Physical Methods, Institute of Geology, Academy of Sciences of the Czech Republic, analyst: K. Melka, Philips X´Pert). The bell-like form can represent products of condensation corrosion, gypsum being precipitated after vadose infiltration from the surface of sulfates from marine spray.

Gamma-spectrometric and magnetosusceptibility patterns

The GSR and magnetosusceptibility (κ) patterns were studied along a transect from the cave bottom, through the cave fill to the cave roof (Fig. 6). The cave fill is marked by increased contents of uranium. This abrupt increase up to 4.3 ppm in average contents is very different from regular background values in the host limestone (about 2.7 ppm; Bosák, Hladil & Slavík 2001). A remarkable increase of thorium values was found in the black-pebble cave breccia. Surprisingly, another increase is related to the porous aeolianites in the lower wall of the cavity, not to a thin layer above the cave floor or aeolian fill in this cave. The bulk magnetic susceptibility (κ-values) is expressed in three maxima (about 1,500; 800, and $800 \cdot 10^{-6}$ SI units) corresponding to a zone just below the cave floor (2 lower maxima) and to cave fill.

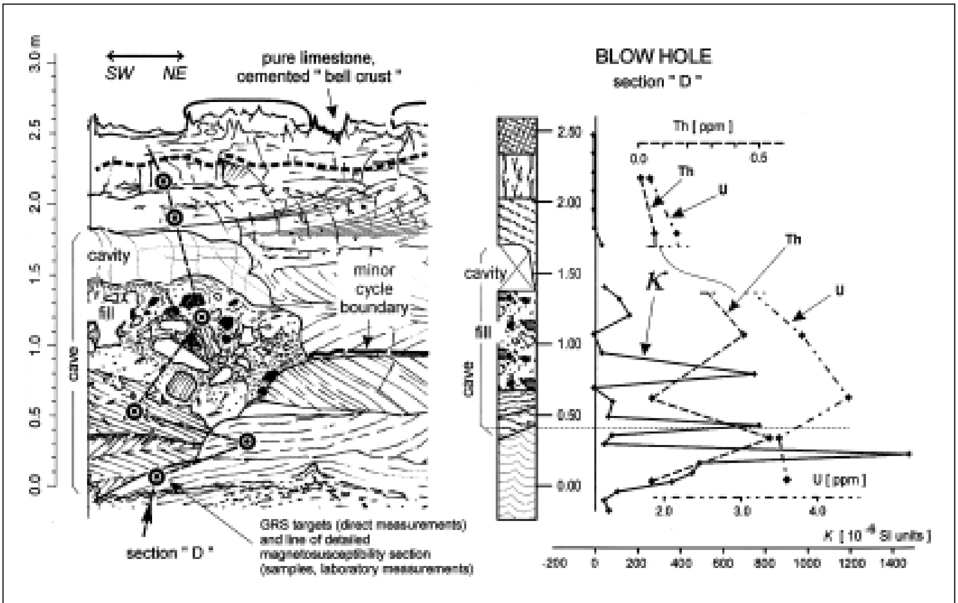


Fig. 6: Diagram of the Blow Hole Cave Section showing the targets of the gammaspectrometric measurements. The magnetosusceptibility κ-measurements were made alongside that line. U = uranium, Th = thorium, κ = magnetic susceptibility values. Potassium was below detection level.

Interpretation

Blow Hole Cave was in existence before the development of the paleosol covering the Grotto Beach Formation and extending down to the cave. The idea is consistent with the cave's development as a flank margin cave formed in the fresh-water lens during the last interglacial sea-level highstand.

Uranium data confirm the general idea that weathering and sedimentary carbonate cave fills would be co-indicated or directly indicated by relatively high uranium concentrations in rocks that otherwise show only generally low background values. An elevated radioactive signal forms broadened, head-shaped, peaks on the GRS curve.

A remarkable increase of thorium values in the black-pebble cave breccia has to come from the extremely fine-grained siliciclastic silty material, which was transported in as atmospheric dust or re-concentrated from the rock residues during hiatuses. The cave is the site for concentration of natural insoluble residues, and the fine particles of non-carbonate material became trapped in the limestone cave fill or penetrated into still porous rocks of the cave floor, where a narrow zone of the "lower cave corona" developed close below the rocky cave floor. An infiltration of ultra-fine-grained particles and colloids may be hypothesised as a possible mechanism for emplacement of the highly insoluble thorium into the porous host rock.

The existence of these communicating pores with reducing microenvironments can be deduced also from the existence of the lowest positive peak of the bulk magnetic susceptibility (κ-values), because this "lower cave corona" close below the cave floor has a strong ferrimagnetic response that is based, at least in part, on the microbially produced magnetite/maghemite (in spite of generally low iron content; *cf*. McNeill et al.1988). The next higher peak marks the basal to lateral margins of the cave fill. This level may be correlated with the paramagnetic and ferrimagnetic silt grains, which are also marked by the maximum concentrations of thorium. However, it is also possible that microbial production of magnetite-maghemite is an additional source for this heightened κ anomaly at the cave floor. Both mechanisms (infiltration and microbially induced crystallisation) are probably valid for the situation in Blow Hole Cave, although the relative contribution of each may vary on the micro scale.

DEVONIAN CARBONATE PLATFORM IN MORAVIA

Geological setting

Krásná Elevation represents the object with evolution features broadly comparable to San Salvador, the Bahamas. The site lies in the northeastern part of Moravia (Czech Republic; Fig. 1). The region is a part of Middle Devonian/Lower Carboniferous carbonate platform Zukalová & Chlupáč 1982). The platform covered a Neoproterozoic microcontinent, which was amalgamated to the eastern boundary of the Bohemian Massif only during Variscan Orogeny. The carbonate platform was later partly overthrusted by Late Paleozoic (Early Carboniferous flysch) and Carpathian nappes (Cretaceous-Paleogene flysch), and covered by Late Carboniferous coal-bearing sequences and Carpathian Foredeep (Miocene-Pliocene), especially along both platform margins. The Middle Devonian/Lower Carboniferous exists primarily as subcrops (e.g., the region was intensively explored for oil and gas. The region under interest is situated within the so-called Drilling Sector Moravia-North (Figs. 1, 7).

Stratigraphy and facies

The large and thick complex of carbonate platform limestones originated during the Eifelian to Frasnian. Substantial areas of the platform became extinct since the Frasnian-Famennian events. The surface was periodically exposed to Famennian-Early Visean erosion, weathering and karstification. Repeated episodes of subaerial exposures were caused by considerably low sea-level stages, particularly during Tournaisian, when climate was rapidly oscillating and a mass of continental ice was accumulated in the circumpolar zone (Isaacson et al.1999; Streel et al. 2000). Paleokarsts of the DCPM were briefly summarised by Hladil (1983), Bosák, Horáček & Panoš (1989), and Bosák (1997).

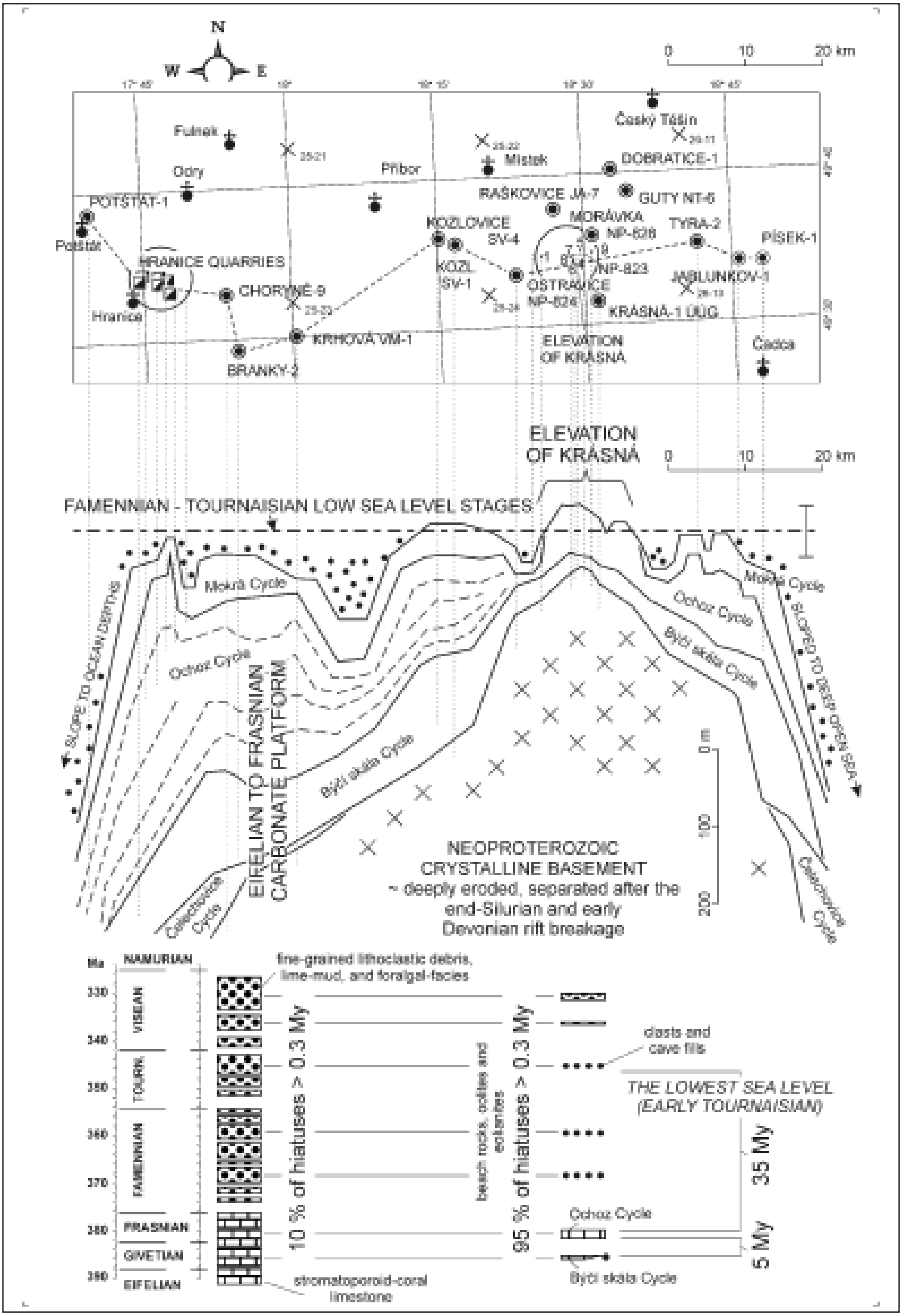
Several hundred meters thick carbonate sediments covered a deeply eroded, Neoproterozoic crystalline segment of the Moravian Block. Thick platform sediments were only sporadically underlain by relicts of terrestrial siliciclastics with rare marine intercalations (Vendian to Early Cambrian, ?Silurian, and Early/Middle Devonian; *cf*. Zukalová et al. 1983; Jachowicz & Přichystal 1997; Vavrdová & Bek 2001).

The facies architecture and composition of the carbonate platform were studied in detail, with respect to requirements of the oil and gas exploration, in numerous boreholes and reflection seismics (Hladil et al. 1990; Hladil 1994, 2002). Slow but continuous subsidence of the Moravian Block was combined with rapidly rising sea-level stages during the Givetian-Frasnian interval. The first platform units separated by remarkable erosion disconformities rank to the *Čelechovice Cycle* (Eifelian to lowermost Givetian), when the carbonates occupied only the margins of the block. However, the carbonate banks of the overlying *Býčí skála Cycle* (Middle Givetian) covered this block entirely. The basal limestones of this cycle were impure, dark-coloured, dolomitic, and gastropod and brachiopod-bearing transgression facies, but these rapidly evolve into thick series of regularly bedded *Amphipora* wackestones, packstones, bafflestones and floatstones. The Býčí skála Cycle terminated with regularly developed stromatoporoid-coral reef banks or patch reef levels, which were slightly emerged, weathered and karstified before the subsequent, massive onlap of the Frasnian reef stages.

The major limestone volumes were deposited within the *Ochoz Cycle*. Whereas the late Givetian sediments are usually very thin or absent in the central elevated area, the tetrad of the Lower and Middle Frasnian partial cycles is very thick, involving all facies of slope, reef margin, lagoon and intra-lagoon, as well as bioconstructions and sediments dispersed in adjacent areas (Fig. 7). The Early and Middle Frasnian reef banks successively covered also the least subsiding and most elevated centre of the platform, e.g., the Elevation of Krásná (Fig. 8).

An evident trend of strongly prograding shoreline with all post-reef remodelling of the surface was set as early as during the Late Frasnian (in the *Mokrá Cycle*), but it culminated much later on, during the Tournaisian. The partial sea-level drops of Early Famennian and particularly Early Tournaisian ages were significant (Figs. 7, 8), with deflections of 30-40 m from the even

Fig. 7: Section across the Devonian carbonate platform on the Moravian Block, Drilling Sector North, S of Ostrava town. Vertical arrangement of segments corresponds to Tournaisian situation. The section starts on the west from Potštát (below Variscan nappes of flysch rocks) and ends on the east, close to Slovak and Polish boundary (below Carpathian nappes of flysch rocks).
(on page 63)


N
W
E
0 10 20 km
Český Těšín
Fulnek
Místek
DOBRATICE-1
Odry
Příbor
RAŠKOVICE JA-7
GUTY NT-6
POTŠTÁT-1
MORÁVKA
NP-828
TYRA-2
PÍSEK-1
Potštát
KOZLOVICE SV-4
HRANICE QUARRIES
KOZL SV-1
NP-823
JABLUNKOV-1
CHORYNĚ-9
OSTRAVICE NP-824
KRÁSNÁ-1 ÚUG
Hranice
KRHOVÁ VM-1
ELEVATION OF KRÁSNÁ
Čadca
BRANKY-2
ELEVATION OF KRÁSNÁ
0 10 20 km
FAMENNIAN - TOURNAISIAN LOW SEA LEVEL STAGES
Mokrá Cycle
Ochoz Cycle
Býčí skála Cycle
SLOPE TO OCEAN DEPTHS
SLOPE TO DEEP OPEN SEA
EIFELIAN TO FRASNIAN CARBONATE PLATFORM
NEOPROTEROZOIC CRYSTALLINE BASEMENT
~ deeply eroded, separated after the end-Silurian and early Devonian rift breakage
Čelechovice Cycle
0 m
100
200
Ma
NAMURIAN
VISEAN
TOURN.
FAMENNIAN
FRASNIAN
GIVETIAN
EIFELIAN
330
340
350
360
370
380
390
fine-grained lithoclastic debris, lime-mud, and foralgal-facies
10 % of hiatuses > 0.3 My
beach rocks, ooliths and eolianites
95 % of hiatuses > 0.3 My
clasts and cave fills
THE LOWEST SEA LEVEL (EARLY TOURNAISIAN)
35 My
5 My
Ochoz Cycle
Býčí skála Cycle
stromatoporoid-coral limestone

strongly depressed sea level averages of these times. The time interval of significant periodical exposures between the last flourishing reef-banks of the Ochoz Cycle and the Early Tournaisian sea level lowering was about 35 Ma (Fig. 7). However, the top of the platform was probably exposed during the Early Visean times, i.e., until the first Middle and Late Visean marine ingressions flooded the platform, which wandered in close proximity of the Variscan orogenic front. The platform was broken and drowned beneath Variscan flysch.

The significance of this major and long series of unconformities (from Famennian to Early Visean) for development of karst of abandoned Devonian reef banks was repeatedly indicated in numerous papers since the early 1980's (e.g., James & Choquette, 1988; Bosák et al.,. 1989; Bosák 1997). The Tournaisian karst morphology occurs in Belgium (Poty 1982; Quinif 1989) and Moravia (J. Dvořák, pers. comm. 1986).

The Krásná Elevation, setting and facies

The Krásná Elevation represented a place of minimum subsidence during the whole Paleozoic history (Fig. 7). The reason of this buoyancy is unknown but it can be expected that periodically increased heating (or low rate of cooling) or presence of low-density rocks in deep crystalline basement may explain this repeatedly elevated position (Hladil 1999; Hladil & Jansa 2000).

In contrast to stratigraphic reefs (porosity < 1 or 0.5%), the condensed parts of the platform (like Krásná) bear much increased porosity (up to 5 or 15%). Increased porosity was connected with inhomogeneous composition of shallow marine sediment, often brecciated, selectively dolomitized-dedolomitized and silicified-desilicified. Those diagenetic features were completed in numerous hiatuses, karst cavities and neptunian dykes (Hladil et al. 1994).

The topmost part of the elevation was reached by the Middle Givetian onlaps (Býčí skála Cycle), but sediments were eroded on several places. On other places, the Býčí skála sediments are known only from pebbles in siliciclastic beds undelying the Early/Middle Frasnian recrystallised pelletal carbonate (e.g., in KS-7 well; Fig. 7). Late Frasnian carbonates of Mokrá Cycle are mostly absent (Fig. 7), because these shallow-subtidal and beach grainstones deposited in rudimentary form and were easily erosionally stripped from the flanks of the elevation. At least 2/3 of drilled carbonate sections are roofed by a few meters of contrasting alternation of porous and strongly cemented levels (Hladil et al., 1994). The correlation of preserved facies on the elevation top in closely neighbouring wells (e.g., KS-7 vs. KS-8) suggests that surface was considerably grooved with differences up to first several tens of meters. The data on vertical and lateral evolution of facies, erosions and alterations of rocks (Hladil 1998) allows the reconstruction of the Krásná Elevation during Tournaisian (Fig. 8).

The Krásná Elevation, cave in boreholes

Caves discovered during the cored drilling in 1980s display various characters. They are developed in several generations, generally cumulated into two principal hiatuses (Fig. 7). Narrow caves, fissures and caverns having rough surfaces of walls that were formed by crystal aggregates or their corroded skeletons, and surrounded by large patchy alteration aureolas represent special feature. The vents were associated either with dedolomitization or dolomitization of the host-rocks. They are expected to be controlled by thermal circulation of fluids by mechanisms proposed by Kohout (1965) or Rougerie & Wauthy (1993; see Hladil 1999) and they are not associated with breaks in deposition, in general. On the steep western upper slope of the elevation

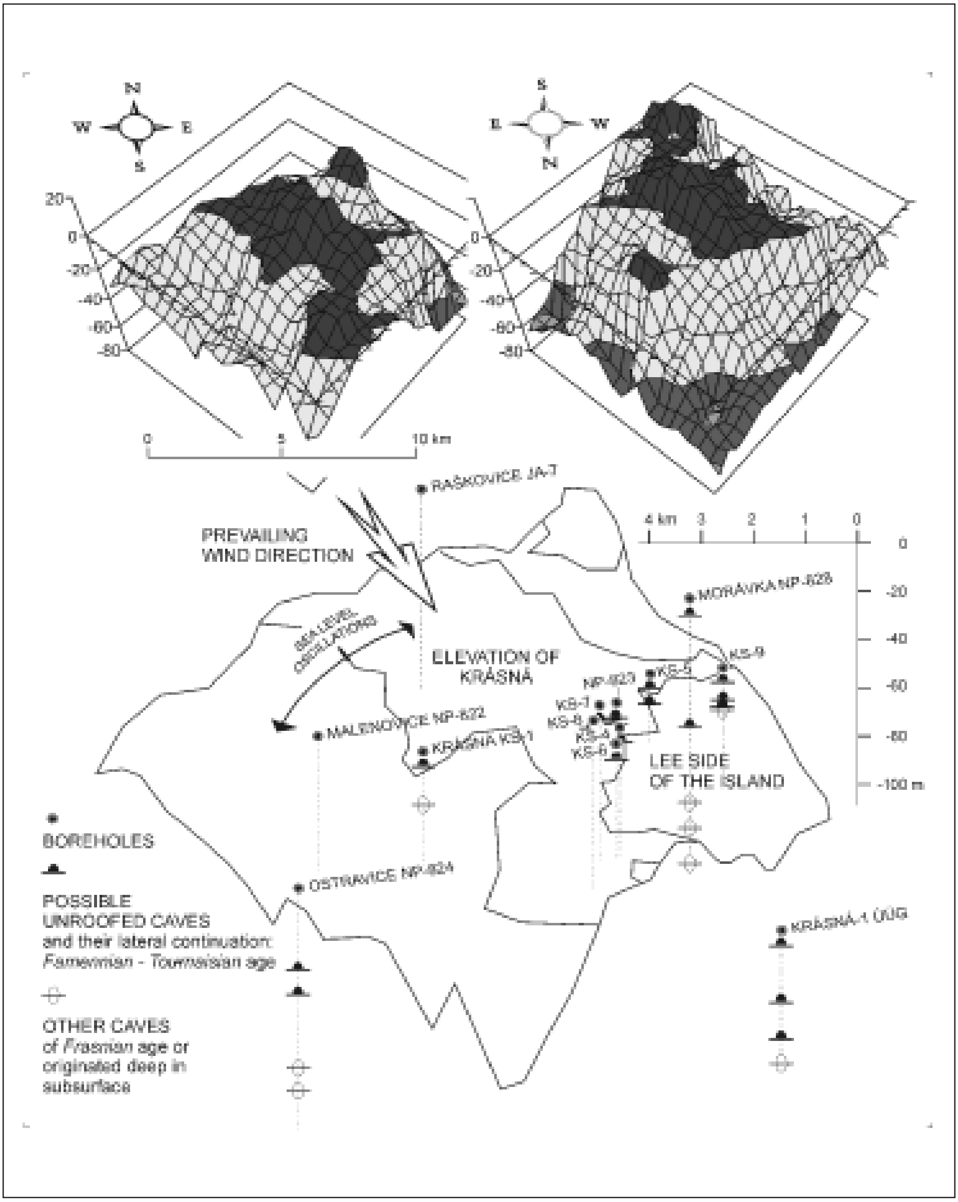


Fig. 8: A tentative 3-D reconstruction of the Krásná Island during Tournaisian times, based on the data on facies, alteration and erosion by Hladil (1998). Moderate slopes on the south and steep slopes on the north are seen in views from south and north, respectively. The most significant boreholes with encountered caves are displayed in scale. Densely spaced caves are concentrated in SE lee side of the island, whereas the Malenovice group of boreholes (on the west, e.g., NP-822) is deficient in number of cave indications.

(e.g., in KS-1 or KS-4; Fig. 7) such caves and fissures irregularly penetrate recrystallised reef-rim.

Caves associated with the lower unconformity are relatively rare. They display smooth walls and fill composed of green fine-grained, calcareous quartz sandstones. Caves and fills originated in lagoonal strata of Býčí skála Cycle during the sea-level drop between the Býčí skála and Ochoz cycles (Givetian; e.g., the lowermost caves in the KS-9, NP-824 or NP-828).

The cave in Krásná-1 ÚÚG (2133-2137 m; Figs. 8, 9) borehole differs from other older caves with carbonate fill. It may serve as an example of the oldest unroofed caves in the area. The cave lies in the latest meters of the Býčí skála Cycle, covered only with thin layer of silicified limestone. The cave fill, according to relevant drilled chips, consists of irregularly dolomitized breccias, poorly fossiliferous peloidal facies and light-grey and variegated carbonates of Middle Frasnian and younger age. Compact limestone overlies the fill and compact dolomite constitutes the cave floor. Distinct erosion unconformity between the Býčí skála and Ochoz cycles was lithologically and biostratigraphically determined. It suggests that the cave originated during approximately 5 Ma long interval of nondeposition between Middle Givetian and Middle Frasnian stromatoporoid-coral rubbles. The vertical position of the cave on a reconstructed island corresponds to the lowermost level of Tournaisian groundwater (ca. 30 m below the log-term average for these times). Possible Tournaisian rejuvenation of the cave can be also assumed.

A considerable number of caves were concentrated in the uppermost part of the moderately eroded Devonian limestones, particularly in lee part of the Krásná Elevation, close below the Tournaisian-Early Visean erosion surface. Caves perforate the limestone complex with unusual density (KS-4, 6, 7 and 8, or NP-823, KS-5, 9 and NP-828). The caves are filled with speleothems, carbonate breccias and rarely also by marine sediments of post-Frasnian age. Several branching offsets from these caves were found in the boreholes on the S and SE periphery of the island, in position several tens meters deeper than these shallowest aggregates of caves. These deep or distant caves persisted as holes until the complex was re-opened along the old cemented neptunian dykes and filled by injections of overlying Namurian sandstones. The deepest injection of Namurian siliciclastics was found in NP-828, about 200 m below the surface of the carbonate complex.

Fossil unroofed caves, their geophysical and geological evidence

Numerous caves were concentrated in the uppermost part of carbonate complex on the lee side of Krásná Elevation. Some of them were unroofed. A large number of wells drilled in this place found caves and cavities filled with breccias and lateral projections of post-Frasnian beach sediments. Unroofing the caves and sedimentation of this fill was possible due to oblique erosion on successively rounded and backstepping flanks and shores of the island and similarly on elevations in close neighbourhoods.

A typical natural GR well-log pattern shows a nearly symmetrical, widened maximum, which corresponds to the cave fill. The upper termination of this anomaly is marked with non-oscillating interval of low values. Oscillating but still depressed level of natural GR emission on carbonate rocks characterises relicts of cave roof, if preserved (Fig. 9). Examples of partly unroofed but subsequently buried caves in depths of several to first several tens of meters are perfectly scanned using the GR well-logging (e.g., Krásná-1 ÚÚG borehole, a large cave in depth 2133-2137 m). However, the caves aggregated close below the surface of the carbonate complex have not always perfect reflection in well logs. It is because of the fact, that the last Paleozoic porous structures on

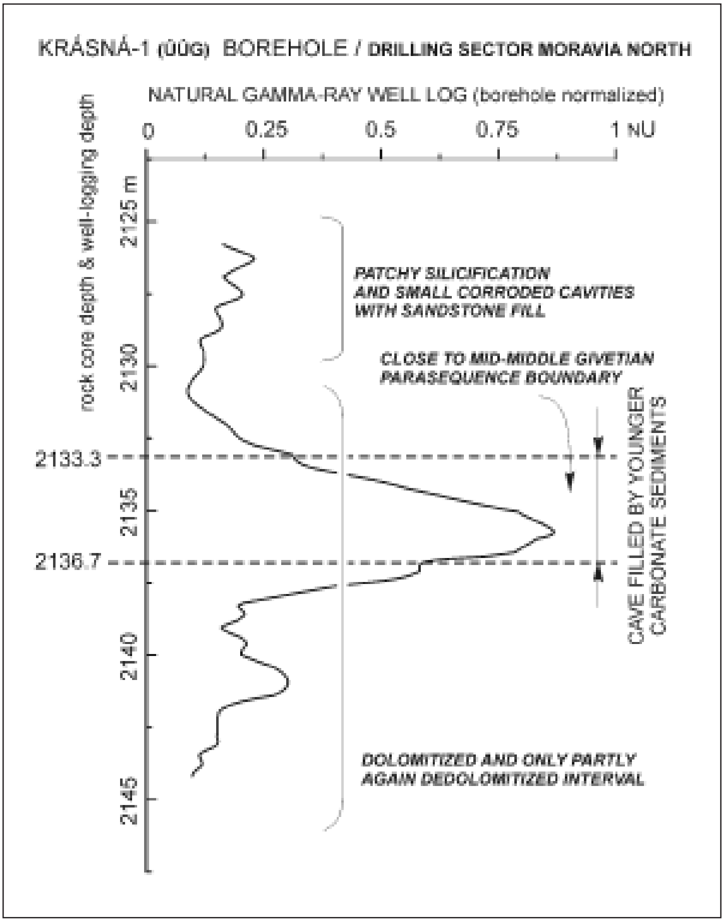


Fig. 9: A typical anomaly in gamma-ray well-log, which marks a fill of unroofed cave, or more generally, any cave filled by weathering products, karst breccias and ingressions of carbonate beach sediments. Example from Krásná-1 ÚÚG borehole (preparation of data by A. Těžký and K. Helešicová).

the surface of carbonate complex were considerably modified due to circulation of Tertiary fluids. Migrating and/or trapped Tertiary oil and associated brine substances are normal (lateral loading by Carpathian nappes). Strongly neomorphic structures were found in KS-4, whereas a low degree of Tertiary alterations can be exemplified by KS-5 and 9.

The original explanation of these strong geophysical anomalies within the uppermost part of the carbonate complex suggested an existence of vertically alternating but laterally continuous diagenetic zones of leaching and cementation, perchance to be on the boundary between vadose diagenetic zone and groundwater (Hladil et al. 1994). Dissolution in the vadose zone had to be so strong that it enabled origin of collapse breccias. However, this model faced many problems with reliable present analogues to such a thickly stratified diagenetic structure.

In addition, the originally belittled rock core indications about non-tectonic alternation of Frasnian and post-Frasnian rocks, as well as the presence of undisputed karst breccia fills, has resulted in a new context for these structures that has substantiated a search for other explanations.

DISCUSSION

Examples of karst and cave development on carbonate platforms of different ages indicate high similarity, although in different time limits and subsidence intensity. While the region of the GBB has been subsiding regularly since Cretaceous times with relatively stable velocity of 1-4 $cm.ka^{-1}$ (Pierson 1983), the region of the Krásná Elevation showed minimum subsidence during the whole Paleozoic (Hladil 1999). The subsidence history resulted in different ranks of unconformities and time available for meteoric diagenesis and karstification. On the Bahamas, short depositional events in duration of 10^1 ka were separated by hiatuses lasting about 10^2 ka (e.g., Carew & Mylroie 1995, 1997; Fig. 2), i.e., separated by unconformitries of the 4th order (parasequence boundary; *cf*. Esteban 1991). On the DCPM the deposition events lasted in 10^3 ka and breaks can be expected in duration of 10^2-10^3 ka, in general (Fig. 7). The Krásná Elevation shows only very short depositional events in time rank of 10^2-10^3 ka interrupted by long breaks in duration of about 10^3-10^4 ka (Fig. 7), i.e., breaks are comparable with unconformities of the 3rd to 2nd orders (regional unconformity and superunconformity *sensu* Esteban 1991). On San Salvador Island, time recorded in sediments represents less than 10% of Quaternary duration, which is comparable with the emerged part of the Krásná Elevation, where only about 5% time is recorded in sediments and/or cave fill (Fig. 7). In spite of difference in a rank of unconformities, we believe that the geological model from San Salvador Island can be highly useful for detection of fossil counterparts.

San Salvador Island, the Bahamas, and the emerged part of Krásná Elevation, the DCPM, have comparable size, i.e., 19x8 km and 10x6 km, respectively. Also the general character of facies architecture is highly similar.

Cave evolution on San Salvador Island and on other islands of the Bahamian Archipelago and Caribbean region, has depended, in general, on glacio-eustatic sea-level changes and steady subsidence during the whole Quaternary history (Harmon, Schwartz & Ford 1978; Gascoyne et al., 1979; Mylroie & Carew 1990; Lundberg & Ford 1994). Caves developed according to flank margin model proposed by Mylroie (1983; *cf*. also Mylroie & Carew 1990 and Mylroie, Carew & Vacher 1995). Caves have been developing in coastal zone in flanks of aeolianite dunes in relation to the freshwater lens and mixing capacity of mixed freshwater and seawater along the halocline. The process is rapid (from 15 ka) and functions even in very small freshwater lens (Mylroie & Carew 1994). On San Salvador Island, there are several flank margin caves, not only the Blow Hole, but also the Lighthouse Cave (NE part of the Island) and Major's Cave (NE of Cockburn Town Airport). It seems that the process of origin of flank margin caves is associated with the present sea-level position; in North Point, there are small karst springs of freshwater at the seacoast. There are also other types of caves on Bahamas, especially so-called blue holes comparable to fossil neptunian dykes and largely controlled by tectonic fissures (e.g., Smart et al. 1988).

Caves of the island of the Krásná Elevation, are concentrated along the fossil shore line, especially on the E and SE (Fig. 8). The fill of some of those caves resemble the fill of the Blow Hole Cave on San Salvador Island, i.e., beach and aeolian sediments with bodies of breccias and speleothems. The fill indicates the close proximity of the shoreline at the time of cave filling (fossilisation). Those characteristics can result in the general conclusion that most of caves discovered by drilling can be connected with the flank margin model. Caves developed in a phreatic regime along the water table of a freshwater lens and along a halocline.

Figure 7 illustrates, that the fill of caves was generated during several short ingressions in Famenian, Tournaisian and Visean. The fact can indicate repeated origin of flank margin caves at different altitudes dependent on different sea-level positions and/or progressive unroofing by intensive chemical denudation, erosion and shore retreat during prolonged breaks.

Except for the flank margin caves, blue holes (San Salvador Island) and neptunian dykes (Krásná) associated with fissuration of carbonate sequences are developed. Their origin is connected both with tectonic lines or slope deformations, and with corrosional modification in phreatic and vadose, freshwater or mixing zone diagenetic environments (cf. Smart et al., 1988; Carew, Mylroie & Schwabe 1998). On Krásná Island, cavities connected with the deep circulation of heated groundwater can be identified by a number of alterations (aureolas) of host carbonate rocks (Hladil 1999).

In summary, the GSR data from the Blow Hole (Fig. 6) show that the Th-anomaly is stratigraphically most closely aligned with the black-pebble breccia (and speleothem-cave fill material as a whole). In contrast, the iron-related anomalies indicated by the κ-values are shifted downward somewhat from the position of the Th-anomalies. Additionally, a strong downward smearing of the peak on the U-curve is observed where the elevated values exist below the highest (lowermost) κ-value peaks. In general, a broad radioactivity enhancement marks the whole cave fill. However, it is important to mention that the upper part of the cave may have reduced values of all measured elements (Fe in magnetic minerals; Th, and U).

A typical natural gamma-ray well-log (GR) pattern in fossil cave of the Krásná Elevation shows a nearly symmetrical, widened maximum indicating the cave fill (Fig. 9). The upper termination of this anomaly is marked with non-oscillating interval of low values. Oscillating but still depressed level of the natural GR emission on carbonate rocks characterises relicts of the cave roof.

The natural gamma-ray record from Krásná well-logging is comparable with the GRS data from the Blow Hole. On both records, there are undulations in intensity at the bottom of cave fill, maximum in lower third of the fill and smoothed decrease of intensities towards the cave roof. The distinct lower undulations can be related to the greater mobility of U^{6+}, its leaching and concentration at or just below host-rock/cave fill interface and to increased Th contents. Decreased values of radioactivity at cave roofs, with intensities even lower than in the laterally comparable host rocks can be connected with leaching of bell holes on the ceilings of phreatic caves.

CONCLUSIONS

The comparative studies on Quaternary carbonate platform (San Salvador Island, the Bahamas) and Devonian Carbonate Platform (Krásná Elevation, Moravia) indicates a great parallel in karst evolution connected with unconformities. Both sites show a similar tectonic/paleotectonic setting at passive margins of continents, high thickness of cyclically arranged carbonate sequences and influences of glacio-eustatic sea-level changes. On both platforms, preserved stratigraphic sequences record less than 10% (the Bahamas) and about 5% (Moravia) of time of evolution.

Nevertheless, there is difference in the character of subsidence and rank of unconformities. The GBB has subsided with relatively constant rate since Cretaceous, but the Krásná Elevation was typified by minimum subsidence during the whole Paleozoic. Breaks in Quaternary of the Bahamas can be compared with unconformities of the 4^{th} order (parasequence boundaries) while hiatuses on the Krásná Elevation are unconformities of the 3^{rd} to 2^{nd} order (regional unconformities and superunconformites). Also the time of sediment accumulation differs, on Bahamas sediment was deposited during periods lasting 10^1 ka, in Moravia depositional events had 10^2 to 10^3 ka in duration. Nevertheless, the evolution model of carbonate platforms and karst/caves is easily comparable in principles.

The alternation of deposition and nondeposition led to creation of the freshwater lens during depositional gaps. The concentration of caves in boreholes along the fossil shoreline of the Krásná Island and their fill indicate origin as phreatic flank margin caves, which easily developed during the relatively short time of individual sea-level highstands. Complicated geomorphic agents (erosion, chemical denudation, abrasion) during periods of prolonged hiatuses led to cave unroofing. Unroofed caves contain preserved fill of minor marine ingressions.

The GSR pattern of the fill of the Quaternary Blow Hole Caves (Bahamas) shows striking similarity with the natural GR well-log from the Devonian Krásná site. The sedimentary fill of both caves is genetically comparable - beach and aeolian sediments with bodies of breccias. The magnetic susceptibility study on the fill of the Blow Hole Cave indicates the dependence on the aeolian delivery of fine-grained silt concentrated in the trap of the cave and its combination with microbial production of magnetic minerals. Uranium data confirm the general idea that weathering and sedimentary carbonate cave fills would be co-indicated or directly indicated by relatively high uranium concentrations in rocks that otherwise show only generally low background values. An elevated radioactive signal forms broadened, head-shaped, peaks on the GRS or GR curves.

ACKNOWLEDGEMENT

This comparative study on unroofed caves was developed in the framework of the grant of the Grant Agency of Academy of Sciences CR, No. GAAVČR A3013809 Recognition of eustatic sea-level changes on Devonian carbonate platform on the SE margin of the Bohemian Massif and completed within the frame of the succeeding project No. GAAVČR A3013209: Products of weathering trapped in pure limestone on carbonate platforms: climatic and early-diagenetic record. The authors gratefully appreciate the assistance provided by the Gerace Research Centre (formerly the Bahamian Field Station), particularly to the research centre executive director Kenny Buchan. We also thank R. Laurence Davis, Joan R. Mylroie, and other co-operative experts. Special thanks belong to the Ministry of Agriculture of the Commonwealth of The Bahamas (Director Eric Carey) for granting the scientific research permit G-102 under which the fieldwork on San Salvador Island was carried out (December 2000 - January 2001). Appreciated is the co-operation by the Brno Team for Well-logging in Carbonates (K. Helešicová, A. Těžký and J. Hrubanová) and the Paleomagnetic Laboratory Praha Průhonice of the Institute of Geology AS CR (P. Pruner, D. Venhodová and M. Chadima).

REFERENCES

Bain, R. J., 1991: Distribution of Pleistocene lithofacies in the interior of San Salvador Island, Bahamas, and possible genetic models. - In: Bain, R.J., Ed., Proceedings of the 5th Symposium on the Geology of the Bahamas 1990, 11-21, Bahamian Field Station, San Salvador, Bahamas.

Bosák, P., 1997: Paleokarst of the Bohemian Massif in the Czech Republic: an overwiev and synthesis. - International Journal of Speleology, 24, 1995, 1-2, 3-40, L'Aquila.

Bosák, P., D.C. Ford, J. Głazek I. Horáček, Eds., 1989: Paleokarst. A Systematic and Regional Review, 725 pp., Elsevier-Academia, Amsterdam-Praha.

Bosák, P., J. Hladil & L. Slavík, 2001: Report on research in the San Salvador Island, Bahamas. - MS, Inst. Geol., AS CR, 1-32, Praha.

Bosák, P., I. Horáček & V. Panoš, 1989: Paleokarst of Czechoslovakia. - In: Bosák, P., D.C. Ford, J. Głazek I. Horáček, Eds.: Paleokarst. A Systematic and Regional Review, 107-135, Elsevier-Academia, Amsterdam-Praha.

Carew, J. L. & J.E. Mylroie, 1995: Depositional model and stratigraphy for the Quaternary geology of the Bahama islands. - In: Curran, H.A. & B. White, Eds., Terrestrial and shallow marine geology of the Bahamas and Bermuda, Geological Society of America Special Paper, 300, 5-32.

Carew, J. L. & J.E. Mylroie, 1997: The Bahamas. - In Vacher, H. L. & T. Quinn, Eds., Geology and Hydrogeology of Carbonate Islands, Developments in Sedimentology, 54, 91-139, Elsevier, New York.

Carew, J. L., J.E. Mylroie & S.J. Schwabe, 1998: The geology of South Andros Island, Bahamas: A reconnaissance report for the Ninth Symposium on the Geology of the Bahamas Field Trip. - Bahamian Field Station, 30 pp., San Salvador, Bahamas.

Chen, J. H., H.A. Curran, B. White & G.J. Wasserburg, 1991: Precise chronology of the last interglacial period: ^{234}U-^{230}Th data from fossil coral reefs in the Bahamas. - Geological Society of America Bulletin, 103, 82-97.

Choquette, P.W. N.P. James, 1988: Introduction. - In: James, N.V. P.W. Choquette, Eds., Paleokarst, 1-21, Springer, New York.

Eberli, G.P. & R.N. Ginsburg, 1987: Segmentation and coalescence of Cenozoic carbonate platforms, northwestern Great Bahama Bank. - Geology, 15, 75-79.

Esteban, M., 1991: Palaeokarst: Practical Applications. - In: Wright, V.P., M. Esteban P.L. Smart, Eds., Palaeokarsts and Palaeokarstic Reservoirs, P.R.I.S. Occassional Publication Series, 2, 89-119, Reading.

Esteban, M. & C.I. Klappa, 1983: Subaerial exposure environments. - In: Scholle, P.A., D.G. Bebout & C.H. Moore, Eds., Carbonate depositional environments, 1-54, Amer. Assoc. Petroleum Geologists, Tulsa.

Gascoyne, M., G.J. Benjamin, H.P. Schwartz & D.C. Ford, 1979: Sea-level lowering during the Illinoan Glaciation: evidence from a Bahama "Blue Hole". - Science, 205, 806-808.

Harmon, R.S., H.P. Schwartz & D.C. Ford, 1978: Late Pleistocene sea level history of Bermuda. - Quaternary research, 9, 205-218.

Hladil, J., 1983: Cyclic sedimentation in Devonian carbonates of the Macocha Formation. - Zemní Plyn Nafta, XXVIII, 1, 114, Hodonín.

Hladil, J., 1994: Moravian Middle and Late Devonian Buildups: evolution in time and space with respect to Laurussian shelf. - Courier Forschungsinstitut Senckenberg, 172, 111-125, Frankfurt am Main.

Hladil, J.,1998: Paleozoic on E borders of the Bohemian Massif. Part 5. The 3-D data and parameters of possible non-structural traps. - MS, Ministry of Environment CR,CD Rom.

Hladil, J., 1999: Philosophy of the Devonian insular elevations DIE and evolution of porosity in the Macocha Formation. - Geol. Research Moravia Silesia, 6, 80-84, Brno. (in Czech)

Hladil, J., 2002: Geophysical records of dispersed weathering products on the Frasnian carbonate platform and early Famennian ramps in Moravia, Czech Republic: proxies for eustasy and palaeoclimate. - Palaeogeography, Palaeoclimatology, Palaeoecology, 181 (in press).

Hladil, J., P. Bosák, L. Slavík, J.L. Carew, J.E. Mylroie & M. Geršl, 2002: A pragmatic test of the early origin and fixation of gamma-ray spectrometric (U, Th) and magneto-susceptibility patterns (Fe) related to sedimentary cycle boundaries in pure platform limestones. - Carbonates and Evaporites.

Hladil, J., F. Chmelík, D. Ďurica, A.B. Čepeljugin & J.G. Namestnikov, 1990: Prospect of the Paleozoic reef structure survey within the SE slope of the Bohemian Massif. - Mineralia slovaca, 22, 289-302. Košice. (in Czech)

Hladil, J., K. Helešicová, J. Hrubanová, P. Müller & M. Ureš, 1994: Devonian Island Elevations under the Scope: Central Europe, Basement of the Carpathian Mountains in Moravia. - Jahrbuch. Geol. Bundesanstalt (Wien), 136, 4, 741-750.

Hladil, J. & J.F. Jansa, 2000: Tilting of Devonian Carbonate Platform along Eastern Borders of the Bohemian Massif: Evidence and Possible Explanations. - Geolines, 10, 26-29, Praha.

Hooke, R. LeB. & W. Schlager, 1980: Geomorphic evolution of the Tongue of the Ocean and Bahamas. - Marine Geology, 35, 343-366.

Isaacson, P.E., J. Hladil, J.W. Shen, J. Kalvoda & G. Grader, 1999: Late Devonian (Famennian) glaciation in South America and marine offlap on other continents. - In: Feist, R., J.A. Talent & A. Daurer, Eds, IGCP 421 North Gondwana: Mid-Palaeozoic Terranes, Stratigraphy and Biota, Abhandlungen Geol. Bundesanstalt (Wien), 54, 239-257.

Jachowicz, M. & A. Přichystal, 1997: Lower Cambrian sediments in deep boreholes in south Moravia. - Bulletin Czech Geol. Survey, 72, 4, 329-332.

James, N.V. P.W. Choquette, Eds., 1988: Paleokarst. - Springer, 416 pp, New York.

Kohout, F.A., 1965: A hypothesis concerning the cyclic flow of salt water related to geothermal feating in the Floridan aquifer. - Transactions New York Academy of Sciences, Ser. 2, 28, 249-271.

Longman, M.W., 1980: Carbonate diagenetic textures from near-surface diagenetic environments. - American Association of Petroleum Geologists Bulletin, 63, 4, 461-487, Tulsa.

Lundberg, J. & D.C. Ford, 1994: Late Pleistocene sea level changes in the Bahamas from mass spectrometric U-series dating of submerged speleothems. - Quaternary Science Review, 13, 1-14.

McNeil, D.F., R.N. Ginsburg, S.-B.R. Chang & J.L. Kirschvink, 1988: Magnetostratigraphic dating of shallow-water carbonates from San Salvador, Bahamas. - Geology, 16, 8-12.

Mihevc, A., T. Slabe & S. Šebela, 1998: Denuded caves-an inherited element in the karst morphology; the case from Kras. - Acta Carsologica, 27, 1, 165-174.

Moore, C.H., 2001: Carbonate Reservoirs. Porosity Evolution and Diagenesis in a Sequence

Stratigraphic Framework. - Developments in Sedimentology, 55, 444 pp., Elsevier, Amsterdam.

Mullins, H.T. & G.W. Lynts, 1972: Origin of the northwestern Bahama Platform: Review and reinterpretation. - Geological Society of America Bulletin, 88, 1447-1461.

Mylroie, J. E., 1983: Caves and karst of San Salvador. - In: Gerace, D. T. et al., Eds., Field guide to the geology of San Salvador Island, CCFL Bahamian Field Station, 67-96, San Salvador, Bahamas.

Mylroie, J.E., 1988: Caves and Karst Features of Sandy Point, San Salvador Island, Bahamas. - In: Mylroie, J.E., Ed., Field Guide to the Karst Geology of San Salvador Island, Bahamas, Dept. Geol. Geogr., Mississippi State Univ. and CCFL Bahamian Field Station, 83-96, Ft. Lauderdale, Florida.

Mylroie, J.E. J.L. Carew, 1986: Minimum duration for speleogenesis. - Comunicacions 9° Congreso Internacional de Espeleologia, I, 249-251, Barcelona.

Mylroie, J.E. J.L. Carew, 1987: Field evidence of the minimum time for speleogenesis. - National Speleological Society Bulletin, 49,2, 67-72, Huntsville.

Mylroie, J.E. J.L. Carew, 1990: The flank margin model for dissolution cave development in carbonate platforms. - Earth Surface Processes and Landforms, 15, 413-424.

Mylroie, J.E. J.L. Carew, 1994: A field trip guide book of Lighthouse Cave, San Salvador Island, Bahamas. - Bahamian Field Station, 10 pp., San Salvador, Bahamas.

Mylroie, J.E., J.L. Carew & H.L. Vacher, 1995: Karst development in the Bahamas and Bermuda. - In: Curran, H.A. & B. White, Eds., Terrestrial and shallow marine geology of the Bahamas and Bermuda, Geological Society of America, Special Paper, 300, 251-267.

Pierson, B.J., 1983: Cyclic sedimentation, limestone diagenesis, and dolomitization in Upper Cenozoic carbonates of the Southeastern Bahamas. - MS, PhD Thesis, 343 pp., Univeristy of Miami, Coral Gables.

Poty, E. 1982: Paleokarst et brèches d'effondrement dans le Fransien moyen des environs de Visé. Leur influence dans le paléogéographie Dinnantienne. - Annales Société Géol. Bélgique, 105, 315-337.

Quinif, Y., 1989: Paleokarst of Belgium. - In: Bosák, P., D.C. Ford, J. Głazek I. Horáček, Eds.: Paleokarst. A Systematic and Regional Review, 35-50, Elsevier-Academia, Amsterdam-Praha.

Rougerie, F. B. Wauthy, 1993: The endo-upwelling concept: from geothermal convection to reef reconstruction. - Coral Reefs, 12, 1, 19-30, Berlin.

Ruffel, A. & R. Worden, 2000: Palaeoclimate analysis using spectral gamma-ray data from the Aptian (Cretaceous) of southern England and southern France. - Palaeogeography, Palaeoclimatology, Palaeoecology, 155, 265-283.

Schwabe, S. J., J.L. Carew & J.E. Mylroie, 1993: Petrology of Bahamian Pleistocene aeolianites and flank margin caves: Implications for Late Quaternary island development. - In: B. White, Ed., Proceedings of the 6th Symposium on the Geology of the Bahamas (1992): Bahamian Field Station, 149-161, San Salvador, Bahamas.

Smart, P.L., R.J. Palmer, F. Whittaker & V.P. Wright, 1988: Neptunian dikes and fissure fills: An overwiev and account of some modern examples. - In: James, N.V. P.W. Choquette, Eds., Paleokarst, 149-163, Springer, New York.

Streel, M., M.V. Caputo, S. Loboziak & J.H.G. Melo, 2000: Late Frasnian-Famennian climates based on palynomorph analyses and the question of the Late Devonian glaciations. - Earth-

Sci. Review, 52, 121-173.
Tucker, M.E. V.P. Wright, 1990: Carbonate Sedimentology. - Blackwell, 482 pp, Oxford.
Vavrdová, M. & J. Bek, 2001: Further palynomorphs of Early Cambrian age from clastic sediments underlying the Moravian Devonian (borehole Němčičky-3). - Bulletin of the Czech Geological Survey, 76, 2, 113-124.
Wright, V.P. P.L. Smart, 1994: Paleokarst (Dissolution Diagenesis): Its Occurrence and Hydrocarbon Exploration Significance. - In: Wolf, K.H. G.V. Chilingarian, Eds., Diagenesis, IV, Developments in Sedimentology, 51, 489-502, Elsevier, Amsterdam.
Zukalová, V. & I. Chlupáč, 1982: Stratigraphic classification of unmetamorphosed Devonian of the Moravo-Silesian region. - Časopis pro mineralogii a geologiii, 27, 3, 226-241, Praha. (in Czech)
Zukalová, V., J. Hladil, J. Kalvoda, A. Galle, F. Řehoř, M. Řehořová, E. Purkyňová, O. Friáková & J. Zikmundová,1983: Biostratigraphy of carbonates in the sector North and their regional correlation. - MS, Unpublished report, Central Geol. Inst., 260 pp., Praha.

BLOW HOLE CAVE (SAN SALVADOR, BAHAMI): BREZSTROPA JAMA IN NJEN POMEN PRI PREPOZNAVANJU PALEOKRAŠKIH JAM FOSILNIH KARBONATNIH PLATFORM

Povzetek

S primerjalno študijo kvartarne (San Salvador, Bahami) in devonske karbonatne platforme (Krásná plato, Moravska) je bila ugotovljena velika podobnost v razvoju njunega krasa. V tektonsko/paleotektonskem smislu pripadata obe območji pasivnemu obrobju celine, kjer sta se pod vplivom glacio-evstatičnih nihanj morske gladine usedli debeli karbonatni zaporedji ciklično urejenih karbonatnih sekvenc. Na Bahamih predstavljajo ohranjena stratigrafska zaporedja manj kot 10 %, na Moravskem pa manj kot 5 % celotnega časovnega razpona evolucije platforme. Kvartarne stratigrafske vrzeli Bahamov so primerljive z nekonformnostmi četrtega reda (parasekvenčne meje), medtem ko predstavljajo hiatusi na območju platoja Krásná nekonformnosti tretjega in drugega reda (regionalne nekonformnosti in supernekonformnosti). Za obe območji so značilne jame, katerih nastanek lahko razložimo s »flank margin« modelom in so nastale v območju sladkovodnih leč med obdobji relativno visoke morske gladine, v času relativno stabilne halokline.

Krivulja spektometrskih meritev gama-žarkov, opravljenih v jamskih zapolnitah kvartarne Blow hole jame (Bahami), kaže podoben vzorec, kot krivulje karotažnih meritev naravne aktivnosti gama-žarkov v zgornje devonskih karbonatih platoja Krásná. V obeh primerih so jamske sedimentne zapolnitve genetsko primerljive - obalni in eolski sedimenti ter breče. Študija magnetne susceptibilnosti jamskih zapolnitev v Blow hole jami je pokazala, da je le-ta odvisna od eolsko prinešenega drobno-zrnatega melja, ki se je kopičil v jami ter magnetnih mineralov, nastalih s pomočjo mikroorganizmov. Podatki meritev urana potrjujejo splošno sprejeto mnenje, da so lahko preperinske in jamske karbonatne sedimentne zapolnitve posredno ali neposredno nakazane z relativno visokimi koncentracijami urana, ki je torej povišan tudi v kamninah, ki kažejo sicer le nizke vrednosti ozadja. Povišan radioaktivni signal povzroči razširjene vrhove kopučastih oblik tako na spektrometerskih kot na karotažnih krivuljah.