NA JAVORCE CAVE – A NEW DISCOVERY IN THE BOHEMIAN KARST (CZECH REPUBLIC): UNIQUE EXAMPLE OF RELATIONSHIPS BETWEEN HYDROTHERMAL AND COMMON KARSTIFICATION

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The Na Javorce Cave is located in the Bohemian Karst, Czech Republic, near the Karlštejn castle, about 25 km SW of Prague. The cave was discovered as a result of extensive exploration including cave digging and widely employed capping of narrow sections. Exploration in the cave has already lasted 20 years. The cave is fitted with several hundred meters of fixed and rope ladders and several small fixed bridges across intra-cave chasms. Access to the remote parts of the cave is difficult because of long narrow crawl passages and deep and narrow vertical sections. The Na Javorce Cave became the deepest cave discovered to date in Bohemia with the discovery of its deepest part containing a lake in 2010. The cave was formed in vertically dipping layers of Lower Devonian limestone; it is 1,723 m long and 129 m deep, of which 9 m is permanently flooded (data as of December 2012). The cave is polygenetic, with several clearly separable evolutionary stages. Cavities discovered to date were mostly formed along the tectonic structures of two main systems. One of these systems is represented by vertical faults of generally N-S strike, which are frequently accompanied by vein hydrothermal calcite with crystal cavities. The second fault system is represented by moderately inclined faults (dip 27 to 45°, dip direction to the W). Smaller tube-like passages of phreatic morphology connect the larger cavities developed along the two above-mentioned systems. The fluid inclusion data obtained for calcite developed along both fault systems in combination with C and O stable isotope studies indicate that the hydrothermal calcite was deposited from moderately saline fluids (0.5 to 8.7 wt. % NaCl equiv.) in the temperature range from 58 to 98 °C. The fluids were NaCl-type basinal fluids, probably derived from the deeper clastic horizons of the Barrandian sedimentary sequence. The age of the hydrothermal processes is unknown; geologically it is delimited by the Permian and Paleogene. The hydrothermal cavities are small compared to cavities formed during the later stages of karstification. The majority of the known cavities were probably formed by corrosion by floodwater derived from an adjacent river. This process was initiated during the Late Oligocene to Early Miocene, as was confirmed by typical assemblage of heavy minerals identical in the surface river sediments and in clastic cave sediments. The morphology of most cavities is phreatic or epiphreatic, with only local development of leveled roof sections ("Laugdecken"). The phreatic evolution of the cave is probably continuing into the present in its deepest permanently flooded part, which exhibits a water level close to that of the adjacent Berounka River. Nevertheless, the chemistry of the cave lake differs from that of the river water. The cave hosts all the usual types of cave decoration (including locally abundant erratics). The most interesting speleothem type is cryogenic cave carbonate, which was formed during freezing of water in relation to the presence of permafrost during the Glacial period. The occurrence of cryogenic cave carbonate here indicates that the permafrost of the Last Glacial period penetrated to a depth of at least 65 m below the surface.

1. Introduction and history of the cave exploration

Two small cave entrances, located high in the eastern slope of the Javorka Hill, close to the famous Karlštejn castle, already attracted attention at the end of the nineteen forties and beginning of the nineteen fifties. Jaroslav Petrbok, a well-known karst researcher, archaeologist and zoologist focusing on terrestrial mollusks, performed excavations in both entrances. Radvan Horný and Jiří Kovanda helped him during this work (both later became well-known geologists). Only a few meters of the entrance sections were explored, with finds of several ceramic fragments of the Hallstatt culture and an iron spear point dated to the Middle Ages (Petrbok and Horný 1950; Petrbok 1955). Allegedly Mesolithic finds, fragments of antlers, were later suggested not to be artifacts by Fridrich and Sklenář (1976) and Sklenář and Matoušek (1992). This stage can be considered not to be important from the viewpoint of cave exploration.

A new exploration phase was initiated by the members of the Czech Speleological Society, Unit 1-11 Barrandien (who are also the authors of this paper), in the upper entrance in March 1993. Clay sediments, with only small open spaces near the roof, filled the passages of the upper entrance behind the section explored archaeologically. The excavated material was transported using a special suspended mini-railway. The excavation performed in the complicated space of karstified tectonic structures with large unstable blocks of rock reached a length of 49 m in 1997. The work was interrupted here because of the instability of the walls of the excavated space. The next effort was focused on the lower entrance after an interruption of 3 years, again using a similar mini-railway suspended near the roof of the passage. Narrow sections had to be widened using capping. After 15 m of difficult work, the first open cavities with attractive decorations were reached in 2001 (Fig. 1).

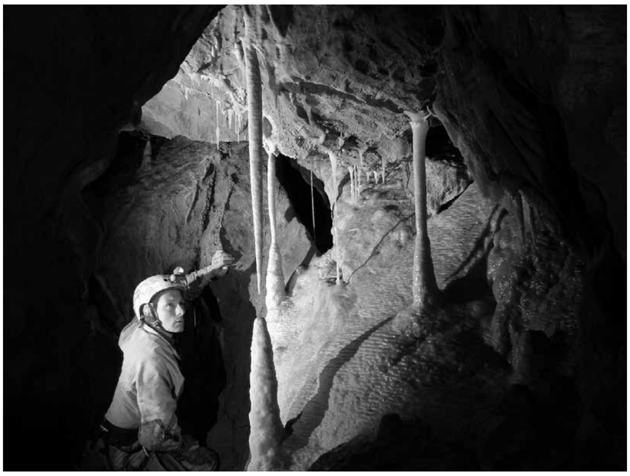

Figure 1. Speleothem decoration in the cavities of the lower entrance (a cavity called Digital Chimney) discovered in 2001. Photo by J. Novotný.

The discovery initiated more intensive work, which enabled further uncovering of this morphologically complicated cave, which is very difficult to explore. It became clear that the cave developed in a structurally complex space, affected by low-temperature hydrothermal activity with deposition of calcite crystals in cavities.

The cave generally consists of several types of cavities. The first type is represented by narrow, flat cavities developed along the N–S faults with calcite veins. The cavities are up to 1–2 m wide (frequently only 0.3–0.4 m), but up to several tens meters long and commonly several tens of meters high in the direction along the faults. The second important type of cavities is represented by both narrow and larger corridors that developed along faults moderately dipping to the W. The two systems of cavities are interconnected by narrow, tube-like phreatic channels.

Further exploration resulted in the interconnection of the upper and lower cave entrances in 2005. Together with further minor discoveries, the cave was explored to a length of 500 m that year. Difficult access to the above-mentioned connecting tubes between the vertical cavities required the construction of small hanging platforms, from which further exploration was possible. Difficult digging at the bottom of a narrow shaft called Zubatá finally resulted in penetration into larger open spaces in 2006. The cave was explored to a depth of 104 m in that year (Figs. 2, 3).

Further exploration was more rapid in the following several years. After cleaning of another connecting tube, a high parallel cavity was reached and, following difficult climbing up this chimney (in 2007), the upper levels of the cave have been gradually explored. This upper part of the cave also has rich decoration, including long soda straws and abundant erratics (Fig. 4). Any work in this distant cave section requires long access, which was facilitated by the construction of small bridges across the chasms. Cave digging in the narrow passages of the upper part of the cave enabled further discoveries in 2008 and 2009. The largest cavity, an inclined irregular passage called Sešup, was discovered in this period. Exploration of vertical cavities in this part resulted in the discovery of the deepest cave section with a lake in 2010.

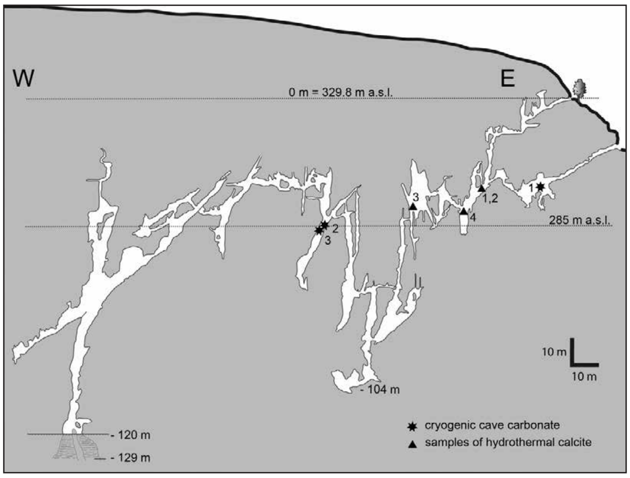

Figure 2. Simplified longitudinal E-W section (side view) of the Na Javorce Cave. The horizontal line at 285 m a.s.l. corresponds approximately to the base of the Neogene river terraces, and simultaneously to the base of the oldest Early Pleistocene river terraces in the adjacent valley. The sites of sampling of cryogenic cave carbonates (stars) and of hydrothermal vein fill (triangles) are also depicted. Based on mapping of J. Dragoun, J. Vejlupek and J. Novotný in 2010.

Figure 3. Typical appearance of vertical cavities of the Na Javorce Cave. The photo is taken in a vertical cavity above the point of -104 m (cf. Fig. 2). Photo by J. Novotný.

The water level of the lake has lies at 120 m below the upper entrance (Fig. 5). Measurement of the water depth and first diving explorations demonstrated a water depth of 9 m, which corresponds to a total cave depth of 129 m. The cave became the deepest one discovered in Bohemia. Further cave exploration performed at several locations within the cave since 2010 did not result in new discoveries. Altogether, 498 one-day or two-day work shifts have been spent in the cave during the last 20 years. The cave became not only the deepest discovered in Bohemia, it is also the third longest cave discovered in the Bohemian Karst.

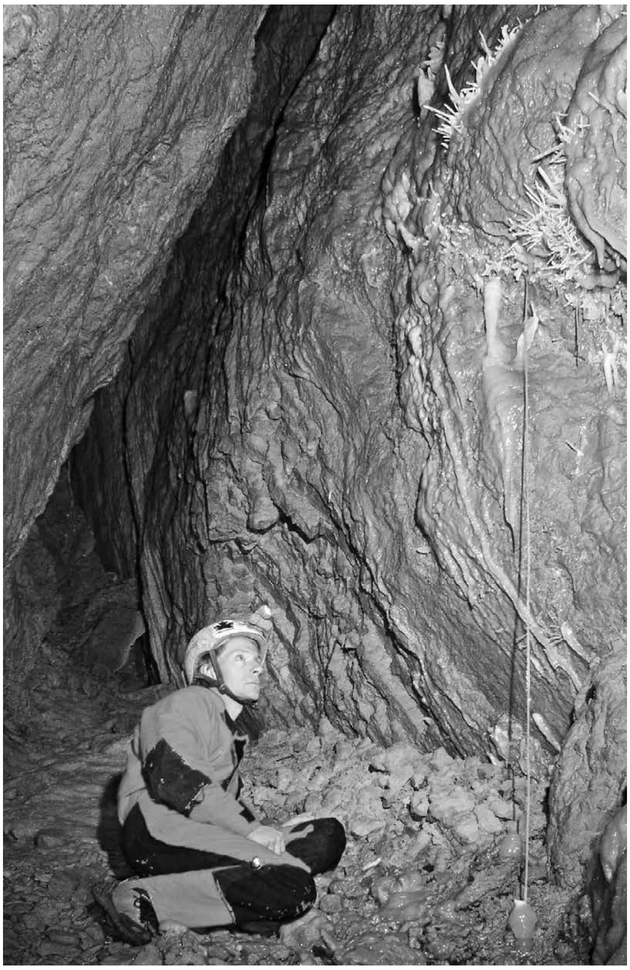

Figure 4. Speleothem decoration in the Radvanská Passage (distant upper part of the cave) with erratics and long soda straw. Photo by J. Novotný.

Figure 5. Lake in the deepest part of the Na Javorce cave. Photo by J. Novotný.

2. Cave location, geology, hydrothermal calcite and cave decoration

The two cave entrances are located in the steep eastern slope of the Javorka Hill at elevations of 329.8 and 313.3 m a.s.l. The upper entrance opens 120 m above the water level of the Berounka River flowing at a distance of several hundred meters (the usual water level in the river is at 209.5 m a.s.l.). The cave is located below the S and SE slopes of the hill close to its summit. This results in only a small geographical catchment of the cave under the present-day topography. The major lithology hosting the cave is Lower Devonian Kotýs Limestone, especially pure limestone layers in the upper part of the Lochkovian Stage. Nevertheless, cavities frequently also penetrate to the lower lithology, Kotýs Limestone with siliceous chert lenses and layers, and rarely also to the upper Loděnice Limestone and Dvorce-Prokop Limestone, both of which already belong to the Pragian Stage. Layers of all types of limestone dip almost vertically in this part of the Javorka Hill (the strike of the layers is almost E–W, 80 to 85°; the layer dip is around 90°). The main Hercynian folding, producing a complicated structure including abundant large overthrusts, occurred in the Late Devonian and Early Carboniferous in the area.

The vertically dipping sedimentary sequence is affected in the cave area by the faults of two main systems. Vertical faults of N–S strike (the whole range of strikes is 155 to 180°), represent the most important fault system. The limestone layering had a small effect on the cave morphology. The layering is roughly parallel to the E–W simplified section (Fig. 2), while the N–S faults and cavities developed along them are perpendicular to this section. The second fault system is represented by moderately inclined faults (dip 27 to 45°, dip direction 240 to 270°). Both entrance passages and the large Sešup Passage developed along the faults and joints of this second system (Fig. 2).

Calcite veining and crystal cavities were formed especially along the structures with N–S strike. Locally they also penetrated into inclined faults. Calcite is coarsely crystalline, with scalenohedrons and rhombohedra with sizes up to 10 cm, of white, yellowish or brownish color. The evolution of calcite veins was irregular. Locally, they reach a thickness of several tens of cm, while at other places they are completely absent on the faults. Hydrothermal calcite was more resistant to corrosion during the later cave evolution, so that the calcite veins locally protrude out of the cavity walls, producing typical boxwork. Limestone alteration (inter-granular corrosion) locally produced rock with sandy disintegration and small accumulations of carbonate sand at several places. Cavities of tectonic and hydrothermal origin represent only a small portion of the known cavities. Most cavities developed during the later stages by common corrosion in the phreatic karst zone. Corrosion occurred along all the types of faults and calcite veins, so that the extent of earlier hydrothermal corrosion (if present) cannot be evaluated. Phreatic corrosion, a dominant process shaping the cave, is well-recorded in the morphology of the cavities. A small section of leveled roofs (“Laugdecken”), indicating long-term stagnation of the water level, developed only locally.

There are several types of clastic cave sediments. The most interesting are quartz-dominated gravels with well-rounded pebbles and quartz-dominated sands of white to grey color. They occur in the upper part of the cave in a small quantities (up to several m^3), especially in sections located close to the lower entrance. They represent the lowermost part of the cave sedimentary filling here. Since they show lithological similarity to the surface sediments of a river flowing not far from the cave during the Late Oligocene to Early Miocene, they have been subjected to study of the heavy mineral assemblage (see below). Quaternary speleothems can be found in the cave in a variety of morphological types, including long soda straws and locally abundant erratics (Fig. 4). Several chambers and corridors are well decorated, while the majority of the cave does not have any speleothems. Cryogenic cave carbonates formed by crystallization accompanied by water freezing occur at several sites (see the star symbols in Fig. 2; cf. Žák et al. 2012). They occur as accumulations of free crystals and crystal aggregates loosely deposited on the bottom of the cavities (Fig. 6 and the discussion below).

3. Analytical methods

New analytical research in the cave included study of the hydrothermal processes using fluid inclusion and stable isotope data on hydrothermal calcite, study of pre-Quaternary clastic sediments in the cave using the assemblage of heavy minerals, research on specific types of speleothems – cryogenic cave carbonates (cf. Žák et al. 2012), and a pilot study on the chemistry of the lake water.

Microthermometric analyses of fluid inclusion entrapped in hydrothermal vein calcite and calcite crystals in cavities were performed on cleavage chips (of about 300 μm thick) using Chaixmeca apparatus (Poty et al. 1976). The apparatus was calibrated in the temperature range -100 to +400 °C using Merck chemical standards, the melting point of distilled water, and phase transitions in natural pure CO_2 inclusions. The reproducibility of temperatures of homogenization up to +200 °C was ±3.0 °C; the reproducibility of the temperatures of ice melting in fluid inclusions below 0 °C was ±0.2 °C. The salinity of fluids was calculated according to Bodnar and Vityk (1994) and the composition of the salt system was evaluated after Borisenko (1977).

C and O stable isotope composition of hydrothermal calcite was determined using the standard method of McCrea (1950). The isotopic composition of the CO_2 gas produced by decomposition of samples was measured using a Finnigan MAT 251 mass spectrometer. The heavy minerals were separated from a sieved 0.2 to 0.6 mm fraction of the cave sands using tetrabromethane with a density of 2.95 g.cm^{-3}. Methods used for the study of cryogenic cave carbonates are contained in Žák et al. (2012). Minerals were determined by X-ray powder diffraction using a Bruker D8 apparatus. The chemistry of water in the cave lake was determined using standard analytical methods (AAS, HPLC).

4. Results and discussion

4.1. Fluid inclusions in hydrothermal calcite

The Jav1, Jav2 and Jav3 samples (see Fig. 2 for the sample location) contained relatively small amounts of primary fluid inclusions in 3D distribution. The inclusions were of irregular shape, from 5 to 60 μm in diameter, and with variable liquid to vapor ratios (LVR = L/L+V). The most common (about 80 %) were liquid-only inclusions, followed by liquid-rich two-phase inclusions with LVR of about 0.9 (about 15 %), and inclusions with prevailing vapor phase were relatively rare. In a contrast, the Jav4 sample contained a very large number of tiny primary inclusions with variable LVR ratio in 3D distribution (“sponge texture”). The inclusions were of oval to irregular shape and from 5 to 20 μm in diameter.

Only fluids of the H_2O-type were found in primary inclusions of all the studied samples. No fluid inclusions with a gaseous phase, such as CO_2 or CH_4, were recorded. Due to the variable LVR, the homogenization temperatures (Th) were measured in clusters of inclusions with LVR of 0.90 to 0.95. The values of Th of the primary inclusions fluctuated from 58 to 91 °C; the salinity of an aqueous solution, calculated from the melting temperature of the last ice crystal (Tm), varied from 0.5 to 7.0 wt.% NaCl equiv. The eutectic temperature (Te = -22.0 to -23.2) indicated that NaCl was the major component of the aqueous solution (Tab. 1).

Table 1. Fluid inclusion data. FIA – fluid inclusion assemblage; Th – temperature of homogenization; Tm – temperature of melting of the last ice crystal; Te – eutectic temperature.

No.	FIA generation	FIA type	Th (°C)	Tm (°C)	salinity (wt.% NaCl eq.)	Te (°C)
Jav1	primary	H_2O	58–68	-2.1 to -4.4	3.6–7.0	-23.2
	pseudosec.	H_2O	79–98	-1.2 to -2.1	2.1–3.6	
	secondary	H_2O	65–94	-0.1 to -0.4	0.2–0.7	
Jav2	primary	H_2O	84–91	-1.1 to -3.3	1.9–5.4	
	pseudosec.	H_2O	72–86	-0.7 to -0.8	1.2–1.4	-21.5
	secondary	H_2O	75–112	-1.2 to -2.1	2.1–3.6	
Jav3	primary	H_2O	–	-0.3 to -1.2	0.5–2.1	-22.0
	pseudosec.	H_2O	–	–	–	
	secondary	H_2O	85–112	-0.8 to -3.4	1.4–5.6	
				-12.6 to -13.9	16.5–17.7	-21.5
Jav4	primary	H_2O	58–74	-1.4 to -3.5	2.4–5.7	-22.5
	pseudosec.	H_2O	74–94	-2.6 to -5.6	4.3–8.7	
	secondary	H_2O	–	–	–	

Pseudosecondary fluid inclusions were observed in the studied samples along short healed microfractures. The inclusions were mostly of oval shape, up to 20 μm in diameter, and exhibited consistent LVR ratios from 0.90 to 0.95. The Th values yielded valuable data in the range from 72 to 98 °C, the salinity of the aqueous solution was calculated between 1.2 and 8.7 wt.% NaCl equiv., and NaCl was assumed to be the major compound of the aqueous solutions (Te = -21.5 °C).

Two generations of secondary inclusions were found in the studied calcite samples. They were observed either along longer healed microfractures, where they are of oval shape, up to 20 μm in diameter, and with consistent LVR from 0.90 to 0.95, or along cleavage planes, where they are of irregular shape, from 10 to 200 μm in diameter, and with variable LVR. The obtained Th values in the inclusions of the first generation ranged between 65 and 112 °C, and the salinity of the solution was found to be from 0.2 to 5.6 wt.% NaCl equiv. The Th value of the second generation of secondary fluid inclusions was not determined because of variable LVR. The obtained Tm values yielded two intervals of salinity, from 1.9 to 1.9 wt.% NaCl equiv., and from 16.5 to 17.7 wt.% NaCl equiv.

4.2. Carbon and oxygen stable isotopes in hydrothermal calcite and origin of fluids

The carbon isotope data of the hydrothermal calcite ($\delta^{13}C$ from -6.37 to -3.33‰ vs. VPDB) and the oxygen isotope data ($\delta^{18}O$ from -10.74 to -9.20‰ VPDB) were obtained on identical hydrothermal calcite cleavage chips, which were also used for the fluid inclusion study. This enabled recalculation of the mineral C and O isotope data to the stable isotope parameters of the fluids. HCO_3^- was assumed to be the dominant carbonaceous component of the fluids. The fluids depositing the calcite had $\delta^{13}C$ values in the range from -8.1 to -4.8‰ VPDB and $\delta^{18}O$ values in the range from 0 to +5‰ VSMOW. These characteristics are typical for basinal fluids. Meteoric waters of shallow circulation cannot be considered for the deposition of hydrothermal calcite because of the fluid $\delta\ ^{18}O$ values and also their temperature and salinity.

4.3. Pre-Quaternary clastic cave sediments and the evolution of cavities in the phreatic zone

Well size-sorted, white to gray, quartz-dominated sands from the passages of the lower cave entrance are locally accompanied by white to light-gray clays. The heavy mineral assemblage of the sands (2–5 % andalusite, 5–15 % secondary Fe-minerals, 30–40 % ilmenite, 5 % kyanite, 2–10 % leukoxene, 1–5 % magnetite, 10–15 % rutile, 3–5 % turmaline and 10–15 % zircon) contained only stable minerals typical in the studied area for Late Oligocene and Early Miocene river sands. In contrast, minerals typical for Quaternary river terraces (amphiboles, pyroxenes, garnets, etc.) were completely missing in the studied cave sands. The relationship of the studied cave sands to an Oligocene/Miocene river can be considered as proved. The mineralogy of the spatially related light-colored clays (kaolinite, illite/muscovite) supports the pre-Quaternary origin of the cavities hosting these clastic sediments.

We assume that these clastic sediments penetrated into the cave together with floodwater injection from the Oligocene/Miocene river. The cavities were rapidly enlarged by corrosion by the river water, possibly with a contribution from mixing corrosion during mixing of the river and karst waters. As the Quaternary valley network started to develop, the upper parts of the cavities became drained, and the phreatic zone moved deeper and deeper.

4.4. Cryogenic cave carbonates and permafrost during the Glacial

Freezing of mineralized karst water is inevitably accompanied by cryogenic mineral precipitation. The cryogenic cave carbonates exhibit typical modes of occurrence, morphology and geochemistry. The low-ventilation caves can be cooled to freezing temperature only as a result of formation of permafrost. The occurrence and dating of cryogenic cave carbonates in these caves can be used for estimation of the permafrost depth of former glacials (Žák et al. 2012). The low ventilation of the Na Javorce Cave is reflected in the elevated content of CO_2 in the cave atmosphere (around 2 %) and by its almost constant temperature. The occurrences of cryogenic cave carbonates in the Na Javorce Cave (stars in Fig. 2) have been studied and dated in detail by Žák et al. (2012). Site 1 yielded U-series ages of 50.04±0.39 and 28.56±0.17 ka BP, Site 2 an age of 14.98±0.17 ka BP and Site 3 an age of 9.19±0.07 ka BP. The data show that the rock massif and the cave were in a permafrost zone down to at least 65 m below the surface during the Last Glacial.

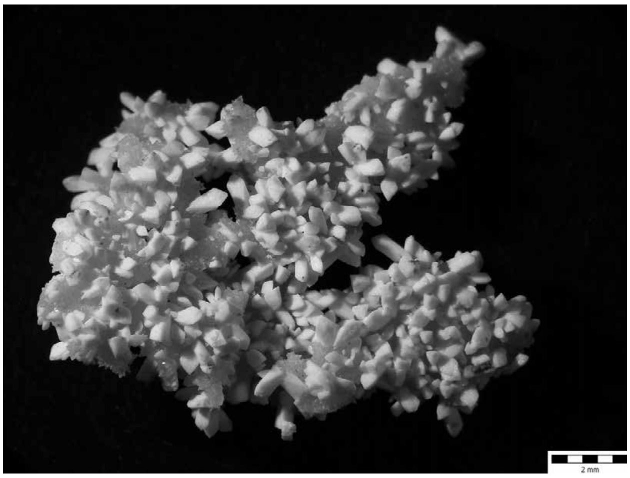

Figure 6. Cryogenic cave carbonate of raft type with two generations of crystals, Na Javorce Cave, location 1 in Fig. 2. Photo by M. Filippi.

4.5. Present-day cave hydrogeology

The cave lake (Fig. 4) contains low-mineralized karst water (sampling on 27 December 2010; composition in $mg.L^{-1}$: Li^+ 0.0042; NH_4^+ <0.02; Na^+ 7.00; Mg^{2+} 29.94; Al <0.20; K^+ 2.34; Ca^{2+} 71.9; Mn^{2+} 0.015; Fe 0.11; Zn^{2+} <0.005; HCO_3^- 311.2; NO_3^- 13.6; F^- 0.09; SO_4^{2-} 20.2; Cl 15.84; pH 7.42; conductivity 503 $\mu S.cm^{-1}$). This water chemistry differs from that of the adjacent Berounka River (which exhibits a higher content of sulfate and chloride). It also differs from the water of karst springs with deep circulation, and from the water of a polluted creek flowing through the village of Karlštejn. The water in the cave lake is therefore local infiltration water derived from the forested Javorka Hill itself. The present-day hydrogeological behavior of the lake is unknown. Detailed studies in the past few years clarified the hydraulic relationships between the river and adjacent caves (Vysoká et al. 2012). Nevertheless, the cave lake in the Na Javorce Cave is farther away from the river than any of the lakes studied by Vysoká et al. (2012).

5. Conclusions – overview of the cave evolution

The cave evolution was initiated by tectonic processes. The inclined structures of western dip are probably older than the vertical tectonic structures of approximately S-N strike. Movements on these vertical structures locally opened small tectonic cavities. These cavities were later filled by hydrothermal calcite, containing abundant crystal cavities. Neither the tectonic phases nor the hydrothermal phase have been precisely dated. Dating is lacking for any of the abundant calcite veins of the Bohemian Karst. Geological observation indicates that the movement along vertical faults could have occurred from the Carboniferous to the