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THE EVOLUTION OF KARST AND CAVES IN THE KONĚPRUSY REGION (BOHEMIAN KARST, CZECH REPUBLIC), PART II: HYDROTERMAL PALEOKARST

RAZVOJ KRASA IN JAM V KONĚPRUSIH (ČESKÝ KRAS, ČEŠKA REPUBLIKA), II. DEL: HIDROTERMALNI PALEOKRAS

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Pavel Bosák: Razvoj krasa in jam v Koněprusih (Česki kras, Češka republika), II. del: hidrotermalni paleokras

Nastanek hidrotermalnih kraških jam je povezan z variskičnimi hidrotermalnimi procesi. Nastali votli prostori so bili zapolnjeni s kristaliničnim kalcitom. Proces je spremljala močna dolomitizacija. Mlajša faza hidrotermalnega zakrasevanja pa ni bila povezana z zapolnjevanjem žil, ampak z globokim kroženjem kraške vode, najbrž v zvezi z "neovulkansko" dejavnostjo v Češkem masivu. To potrjujeta pelod in razpadli vulkanski pepel v kapnikih, ki so nastali po vodilni speleogenetski fazi. Jame v Koněpruskih devonskih kamninah so domnevno nastale v ujetem vodonosniku v freatičnih in batifreatičnih okoliščinah. Termalne okoliščine so se pojavile, ko se je zaradi močne "neovulkanske" dejavnosti povečala paleogeotermična stopnja. Hidrotermalno zakrasevanje je deloma spremenilo obliko jam. Na podlagi velikih kalcitnih kristalov, ki so se odložili v freatičnih in globokih freatičnih okoliščinah, je mogoče sklepati, da je bila največja temperatura 60-70^0 C. Piezometrični nivo je bil nad apnenci v silikaklastih zgornjekredne platforme, na kar navajajo številne skoraj navpične freatične cevi ("depresije"), zapolnjene s krednimi in terciarnimi sedimenti, ki so zdrsnili vanje, ko se je pritisk vode zmanjšal. Pokovki podobne silificirane "Koněpruske rozete" so lahko nastale zaradi znižanja gladine termalne vode in mešanja s prenikajočo padavinsko vodo. Zunanji del velikih kalcitnih kristalov, ki se je izločal pri temperaturah okoli 40^0 C, bi lahko kazal na postopno ohlajanje celotnega sklopa.
Ključne besede: paleokras, hidrotermalno zakrasevanje, razvoj jam in krasa, Koněprusy, Češki kras, Češka republika.

Abstract UDC: 551.44(437.1)

Pavel Bosák: The evolution of karst and caves in the Koněprusy region Bohemian Karst, Czech Republic), Part II: Hydrothermal paleokarst

The origin of hydrothermal karst cavities was connected with the Variscan hydrothermal process. The cavities were formed and filled by crystalline calcite. The process was accompanied by the intensive dolomitisation. Younger phase of hydrothermal karstification was not connected with vein-filling, but with the deep circulation of groundwater, probably associated with neovolcanic activity in the Bohemian Massif. This is supported by pollen grains and decomposed volcanic ash in speleothems which were formed after the major phases of speleogenesis. It is supposed that caves in the Koněprusy Devonian were formed in confined aquifer under phreatic and batyphreatic conditions. Thermal conditions appeared when paleogeothermic gradient was increased due to intensive neovolcanic activity. Hydrothermal karstification partly changed the morphology of caves. The maximum temperatures were stated to 60-70^{0}C from large calcite crystals precipitated under phreatic and deeply phreatic conditions. The piezometric level was situated above limestones in Upper Cretaceous platform siliciclastics as indicated by numerous subvertical phreatic tubes („depressions") filled with sunkened Cretaceous and Tertiary sediments after the water buyoancy support decreased. Popcorn-like silicified Koněprusy Rosettes can be result of decrease of thermal water level and mixing with infiltrating meteoric waters. Outer zones of large calcite crystals with precipitation temperatures of about 40^{0}C can indicate the gradual cooling of the whole system.
Key word: paleokarst, hydrothermal karstification, cave and karst evolution, Koněprusy region, Bohemian Karst, Czech Republic.

INTRODUCTION

The Koněprusy region with a special development of Lower Devonian sequences is situated in the south-western closure of the Siluro-Devonian core of the Barrandian (Prague) Basin between villages of Koněprusy, Suchomasty, Vinařice and Měňany (Fig. 1). The region is known as the Koněprusy Devonian. The dominant part of the region is built by massive organodetrital and, in the upper part, reefal Koněprusy Limestones (Pragian) in the thickness up to 350 m. They are underlain by Kotýz Limestones (finely organodetrital with intercalation of marsltones and fine-grained siliciclastic often with densely packed chert nodules; about 60 m, Lochkovian) and by the Požáry Formation composed of shales with thin limestone intercalations (30-80 m, Late Silurian, Přídolí). In the present geological configuration, the Koněprusy Limestones are overlain only partly in a narrow strip along the northern tectonic boundary of the Koněprusy Devonian, i.e. by the Suchomasty Limestones (20 m, uppermost Zlíchovian to Dalejan), Acanthopygae Limestones (20 m, Eifelian) and by siliciclastics of the Srbsko Formation in small denudation relics (Givetian; *cf.* Chlupáč et al. 1992; Fig. 1). Koněprusy Limestones are well lithified, structurally homogeneous and brittle. They are folded into the system of open synclines and squeezed anticlines, often with overthrusts. Tectonisation by faults and fissure systems is dense. The Lower Devonian sequences form irregularly ovate synclinal basin-like structure isolated by underlying Silurian formations and tectonics from other occurrences of limestones. The NNE limit of the Koněprusy Devonian is formed by major line of the Očkov Overthrust

The evolution of caves in Koněprusy Devonian and in the whole Barrandian Basin were connected exclusively with the evolution of the terrace system of main rivers, i.e. the Berounka and Litava Rivers and their paleoequivalents (*cf.* Hromas 1968; Hromas & Kučera 1974). Cílek (1989) introduced the idea of polycyclic exhumation model of the relief which was repeatedly buried and exhumed from thick fluvial sequences since Upper Cretaceous. Bosák, Cílek & Tipková (1992), and Bosák, Cílek & Bednářová (1993) expected the origin of main cavern systems below the piezometric level within the phreatic regime by the mixing corrosion of karst groundwater with infiltrated surface water (rivers, precipitation). The evolution was connected with repeated development of very broad alluvial plains. Their model resulted from the general character of many caves in the Barrandian Basin, i.e. irregular mazes to sponge-works and labyrinths, often isolated without known continuation and connection to nearby caves. In the Koněprusy Devonian, Bosák (1996a-c) proposed the new paleohydrogeological model of cave origin based on one-cycle upwelling of groundwater from the depth in the contrary to old view of formation of caves levels dependant to river terrace levels by per descendum of piezometric levels. This idea represents the basis also for presented model of hydrothermal karstification.

THE PROBLEM

Cílek, Žák & Dobeš (1994) firstly stressed the connection between North-South trending Variscan hydrothermal veins and karstification, however the connection is indirect. Calcite veins are highly tectonised enabling deep circulation of groundwater. Suchy, Zeman & Dobeš (1997) and Suchy et al. (1997) studied calcite veins which were connected with extensive solution of the host-rock. The origin of cylindrical-shaped depressions filled with complicated sequence of sunkened Cretaceous

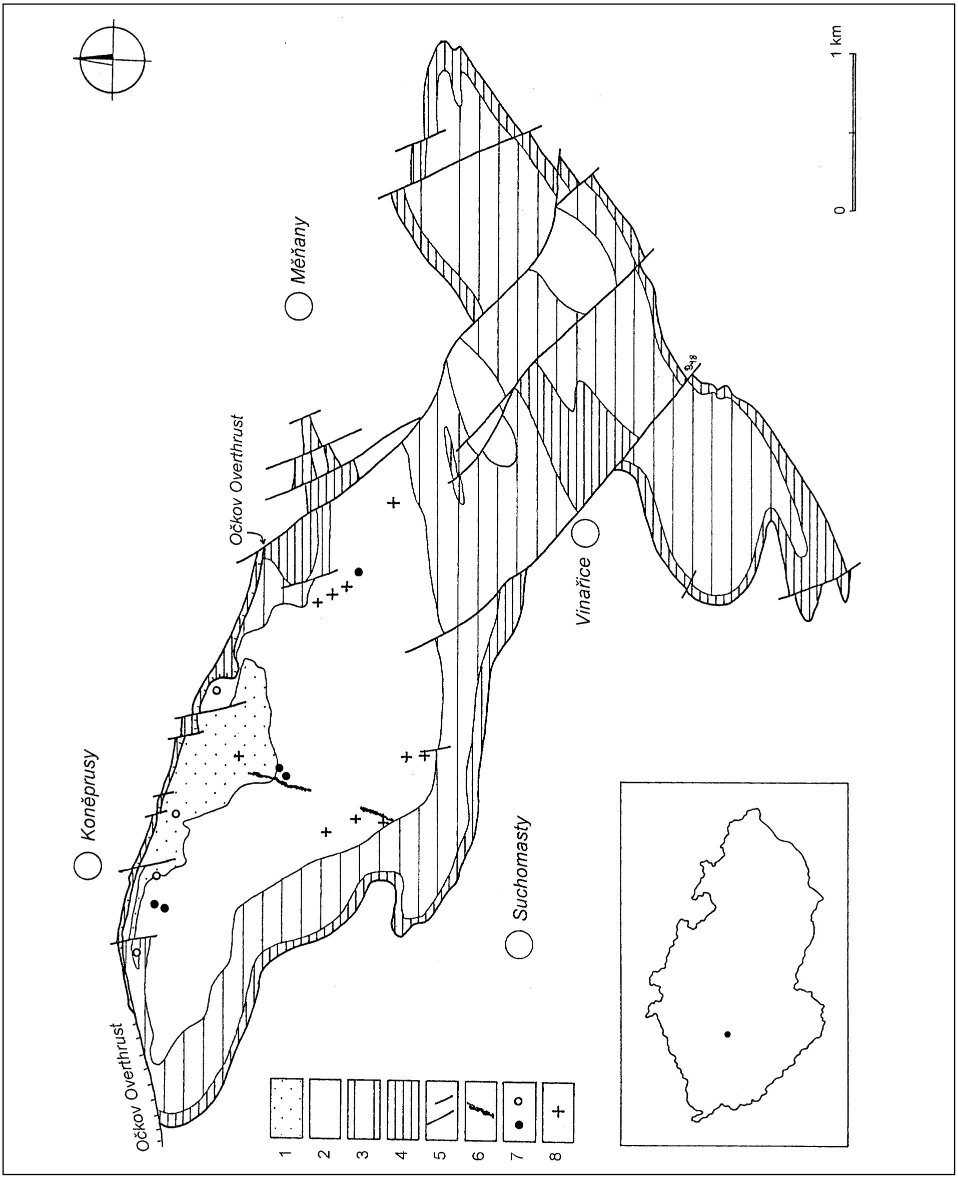

Fig. 1: Koněprusy Devonian, simplified geological map without young cover (completed and modified from Klein et al. 1989).
1. Srbsko Formation, Acanthopygae and Suchomasty Limestones, 2. Pragian limestones, 3. Lochkovian Limestones, 4. Požáry Formation, 5. faults, 6. calcite vein, 7. caves with calcite crystals (full circles=clear position of calcite crystals, free circles=unclear position of calcite crystals), 8. boreholes with small cavities with calcite crystals.

and ?Tertiary sediments they connected with the process. They supposed that „at least some caves" in Barrandian carbonate sequences have hydrothermal origin as resulted from precipitation of popcorn-like speleothems (so-called Koněprusy Rosettes) supposedly from warm mineralised solutions. Later they detected (Zeman et al. 1997) todorokite in thick calcite vein in the Koněprusy area. The crystallisation temperatures of calcite were stated to 55-84^{0}C. The space association of North-South trending calcite veins and subvertical corrosional depressions they explained by the hydrothermal process of veining. Walls of subvertical cavities are covered by a sequence of dark-coloured crusts containing manganese minerals (Figs. 3 and 4), and todorokite, which is, for them, the evidence of hydrothermal origin of dark crusts (Zeman, Suchy & Melka 1997), rather than of exogenic infiltration origin proposed by Cílek & Fábry (1989) and Cílek & Kloušek (1990). Finally, Suchy & Zeman (1998a, b) linked the origin of many large caves within the western part of the Bohemian Massif with hydrothermal process of veining and carbonate dissolution. The main evidence for them is the irregularity of shape of some caves with common cupola-form cavities, i.e. forms often generated during common „cold" phreatic speleogenesis. Rests of completely fossilised hydrothermal paleokarst of Variscan age associated with the origin of thick calcite veins were detected by Bosák (1998b) in the centre of the Koněprusy Devonian.

Without any doubts, hydrothermal paleokarst occurs in the Koněprusy Devonian. Calcite veins have been usually connected with late stages of Variscan Orogeny (Žák et al 1987; Cílek, Dobeš & Žák 1994; Suchy et al. 1997). Associated paleokarsts are completely filled with coarse-crystalline calcite (Bosák 1998b). However, forms documented e.g. by Suchy et al. (1997), i.e. cylindrical subvertical depressions and irregular cavities, are filled with sequence of Upper Cretaceous and post-Cretaceous sediments showing distinct traces of subsidence into them (*cf.* e.g. Cílek, Tipková & Kvaček 1992; Suchy, Zeman & Bosák 1996). More, interpretation of detailed geophysical measurements and control boreholes on the Koněprusy deposit did not proved the presence of collapse breccias at the bottom of such depressions (Bosák 1997). Some blind cavities are also filled by Upper Cretaceous sediments (Bosák, unpubl.).

Nevertheless, in the Koněprusy Devonian there are existing number of problems especially connected with the dating of individual processes of the hydrothermal activity. Several caves with walls covered by large calcite crystals were discovered and documented during the quarry operations and in some exploration boreholes. Calcite crystals (up to 12 cm in size) are sometimes connected with crusts of microcrystalline quartz. Such caves represent an integral part of network described by Bosák (1997) and they are genetically connected with the largest caves of the region - the open-to-public Koněprusy Caves. There, the Koněprusy Rosettes (silicified popcorn-like speleothems) are supposed to be precipitated from warm solutions (Suchy, Zeman & Dobeš 1997; Suchy, Zeman & Dobeš 1997; Zeman et al. 1997). Rests of Oligocene to Early Miocene pollen grains and volcanic ash were detected in fine speleothems of aerosol origin younger than the Koněprusy Rosettes. Pollen grains date the end of speleogenesis, indicating that in this time the cave was open to the surface and air exchange of caves with external atmosphere was active through three former openings to the surface (Halbichová & Jančařík 1982-1983; Jančařík 1986).

VARISCAN HYDROTHERMAL PALEOKARST

Calcite veins

Calcite veins with a common thickness of 0.5 to 3 m (max. 8 m) are found on numerous locations in the Bohemian Karst (*cf.* Žák et al. 1987; Cílek, Dobeš & Žák 1994; Cílek, Žák & Dobeš 1994). Within the Koněprusy Devonian, they are occurring especially in huge limestone quarries and their foreland (Velkolom Čertovy schody - Giant Quarry of Devils Steps; Fig. 2), in slopes of Kotyz Hill, in abandoned Kobyla Quarry, etc. They show dominant NNS-SSW and NNW-SSE trends, locally they follow W-E structures predisposed by Lower/Middle Devonian neptunic dykes. They are steeply dipping (70 to 90^0). They are filled with extremely coarse-grained calcite of milky to light brown colour. Their internal structure is banded, symmetrical or asymmetrical. Individual bands are composed of perpendicularly arranged coarse-columnar calcite crystals. The centres of veins are sometimes hollow with calcite druses. Traces of repeated injections can be observed, sometimes resembling telescoping veins. Walls of veins are often brecciated, cemented by brown ankerite. Limestone host-rock is highly tectonised in vein surroundings with dark veining and abundant fine veinlets of ochreous iron-stained sacharroidal dolomite. Vein walls are also often syngenetically corroded. The zone around thick veins is highly disturbed and tectonised by pressure action of penetrating thermal waters.

Hydrothermal paleokarst

Irregular corrosion cavities were uncovered by the limestone exploitation in the Velkolom Čertovy schody Quarry (Fig. 2). They were mostly flat, sometimes with triangular sections. The largest cavity was 2.5 m high, 4 to 9 m wide and about 20 m long. Other forms were smaller. They were filled with sequence of milky to light brown calcite, often with zonal crystals. Crystals were blocky to coarse-columnar. The surroundings of cavities were often impregnated by ochreous sacharoidal dolomite. In some places crystalline calcite encircled ovate dolomitic structures. Corrosional cavities were always directly connected with calcite veins of different thicknesses. The largest cavity was cut by small fault (Fig. 2).

Dolomites

Dolomites occur in the surroundings of calcite veins as net of veinlets. Veinlets are usually only several millimetres thick and they pinch out for a larger distance. Dolomite also forms irregular nests of decimetric to metric sizes, usually directly associated with thicker calcite veins. „Epigenetic“ dolomitisation reported by Cmuntová (in Ovčarov et al. 1972, 1977) with dolomite expressed by concentrated hydroxidic iron compounds can be identified with dolomites reported here. Saddle dolomite in the centre of vein was recently found by Suchy (1997, pers. comm.) who supposed temperatures of oil window during its growth. Migrated hydrocarbons were found during exploration drillings in this region (Ovčarov et al. 1972; Bosák 1997).

Interpretation

Calcite veins in the whole core of the Barrandian Basin have their source in the depth outside limestones as indicated by stable isotopic data (Žák et al. 1987). Upwelling mineralised waters were represented, most probably, by deeply circulating meteoric and karst waters mixed with connate waters expelled from underlying carbonate and non-carbonate sequences during late state of

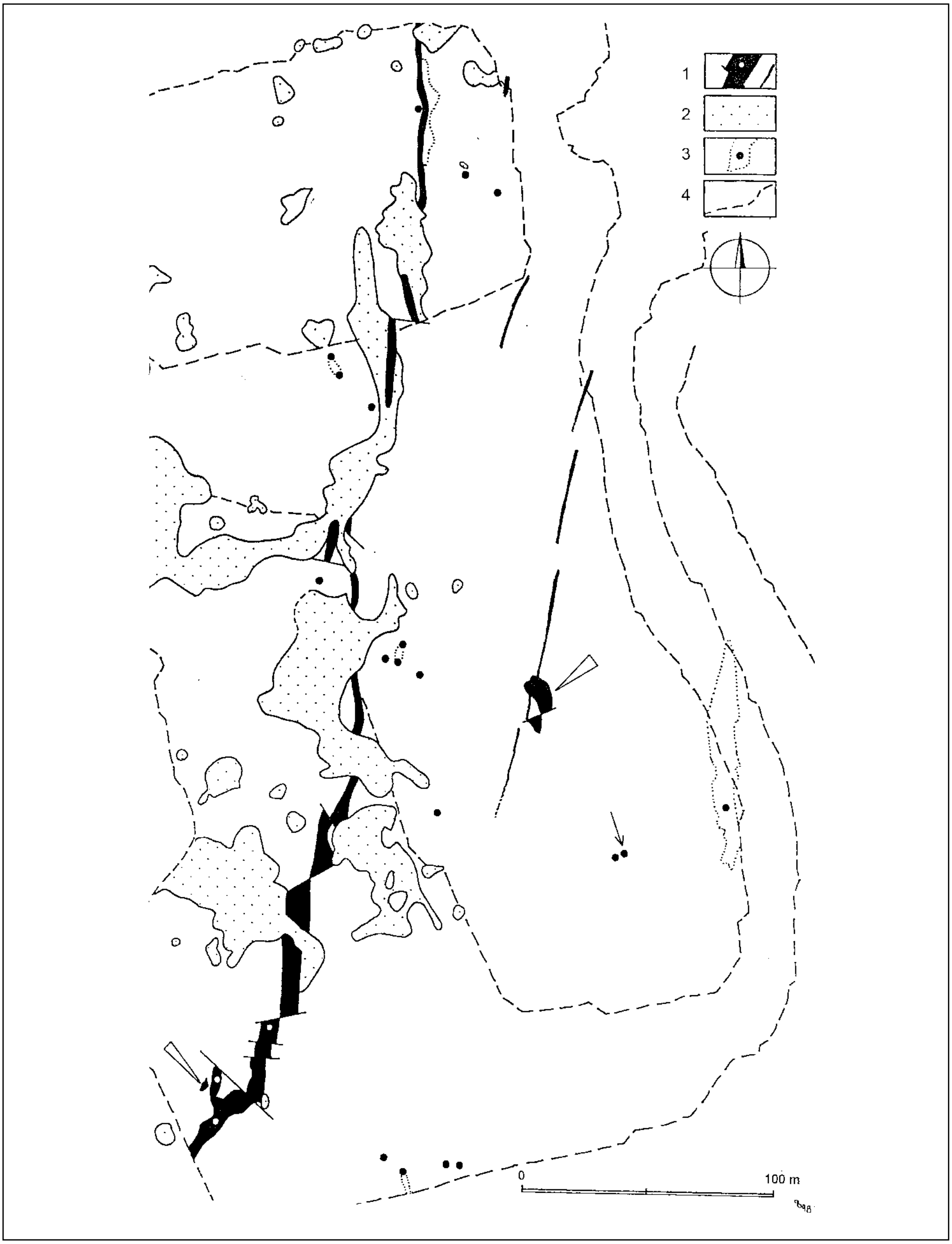

Fig. 2: Part of the Velkolom Čertovy schody-Quarry East (modified from Bosák 1998a). 1. Calcite vein with younger caves (white circle), arrows indicate Variscan paleokarst cavities, 2. Karst depressions with Cretaceous-Tertiary sedimentary fill, 3. Caves (dotted line the contour of larger caves, arrow - samples for fluid inclusions), 4. Approximate limit of exploitation benches.

burial and tectonic stress during the orogeny (Cílek, Žák & Dobeš 1994; Cílek, Dobeš & Žák 1994). Calcite crystallised from 50 to 115^0 C, mostly between 55 and 84^0 C (Suchy, Zeman & Dobeš 1997). The process could be connected with late phases of the Variscan Orogeny (Žák et al 1987; Cílek, Dobeš & Žák 1994; Suchy et al. 1997) correlated with one important interval of metallogeny within the Bohemian Massif dated to 360-230 Ma, i.e. Upper Carboniferous to Middle Triassic (Vanìček et al. 1985).

The invasion of hydrothermal solutions caused pressure veining of the Koněprusy Limestones in a broad zone around upwelling route. As indicated by solution cavities around veins, the invasion of hot waters was connected with hydrothermal solution of limestones, at least during early stages. From detailed documentation of quarry walls it resulted, that walls of calcite veins are intensively corrosionally carved in places, with curved and semi-circular forms (Bosák 1997, 1998b). Primary pressure veining of upwelling routes was probably connected with intensive corrosion only in early stages of the vein evolution. It was accompanied with tectonic movement along fissures controlling veins, as indicated by enormous thickening of vein from common 1.5 to 3 m up to 10 m in some limited places. Solutional cavities with coarse-crystalline hydrothermal calcite are without any doubts directly connected with calcite veins although sometimes occurring in some distance from them.

Nevertheless, the hydrothermal process itself has been poorly studied. The invasion of solutions was connected by Cílek, Žák & Dobeš (1994) and by Cílek, Dobeš & Žák (1994) with some of late phases of Variscan Orogeny. Data of Suchy & Rozkošny (1996) and Suchy et al. (1996), based on the reflectance study of organic matter, the increased diagenetic temperatures accompanied by the origin of calcite veins, quartz, dolomitisation had to be connected purely with temperature increase during burial. It indicates, without doubts, that the deposition in Middle Devonian (Givetian) had to continue and sediments could reach thickness of about 1.000 m and more (*cf.* also Suchy et al. 1997). Those sediments were completely eroded before the deposition of continental Westphalian C, as indicated by rests of red-beds overlying Lower Ordovician and Proterozoic sequences in small tectonically limited basins close to Beroun.

The hydrothermal process acted in the depth under the thick cover of impermeable siliciclastics of flyshoid Srbsko Formation. Therefore, there existed conditions for extensive thermal karstification in massive and thick sequence of pure Koněprusy Limestones. It cannot be excluded, that warm solutions utilised pre-existed macroporosity developed during early diagenesis and connected with the oscillation of halocline during repeating emersions of Koněprusy Limestones and overlying limestone units (Bosák 1997, 1998b). As cavities are filled with the same filling as calcite veins, it could be possible to consider that the hydrothermal karstification took place during early stages of the hydrothermal process.

Dolomites associated with calcite veins are very similar to ore dolomites from many polymetallic deposits in carbonate rocks of the Mississippi Valley Type, which hydrothermal origin is proved (*cf.* eg. Dżułyñski & Sass-Gustkiewicz 1989). Similar type of dolomitisation of biodetrital horizons of the Přídolí Formation in the Barrandian Basin was the result of hydrothermal activity of warm Mg-rich brines selectively circulating through porous media (Suchy 1995).

The dolomitisation was connected, most probably, with hydrothermal processes of circulation of basinal pore and diagenetic waters (*cf.* Cílek, Žák & Dobeš 1994; Cílek, Dobeš & Žák 1994). The upwelling of warms solutions from the depth is proved by the intensive dolomitisation of the Kotyz and Radotín Limestones underlying the Koněprusy Limestones (Bosák 1997, 1998b). The invasion of connate basinal waters from the depth was caused by squeezing during folding. The invasion routes could be located along tectonic structures active already during the deposition of Pragian carbonate sequences. On the contrary, the dolomitisation is missing in the Suchomasty Limestone overlying the Koněprusy Limestones. It indicates, that the Suchomasty Limestones formed a certain type of the aquitard limiting the space distribution of dolomitisation.

YOUNGER PHASE(S) OF HYDROTHERMAL KARSTIFICATION

The occurrence of caves with walls covered by large calcite crystals is the most striking feature indicating the possibility of younger hydrothermal process than the Variscan one. Caves were formed by the process described by Bosák (1996a-c) during Paleogene to lowermost Miocene which was supposed to be connected with an ordinary cold phreatic/bathyphreatic speleogenesis. Dense net of exploration boreholes uncovered also some examples of smaller caves with walls covered by calcite crystals, some of such occurrences were situated closely to later discovered caves with crystals (Fig. 1).

Caves with calcite crystals

Caves with calcite were uncovered mostly during limestone exploitation in several quarries of the region (Fig. 1). Calcite crystals cover even large areas on cave walls and they reach the size up to 15 cm. They are developed as rhombohedrons, often with short crystallographic axis *c* (flat rhombohedrons, nailhead spar, *cf.* Dublyansky & Bosák 1999), less often as scalenohedrons. The most typical calcite covered caves were discovered in the Velkolom Čertovy schody Quarry: Krystalová (Crystal) Cave (calcite on all walls and ceilings); Velká Krystalová (Large Crystal) Cave (calcite crystals up to 7 cm large on walls and ceilings), and Jezerní (Lake) Cave (crystals up to 12 cm in size on large areas of walls; Figs. 1 and 5). During mining in December 1996, phreatic channel covered by large crystals (up to 15 cm) was uncovered in the close vicinity of the Jezerní (Lake) Cave. Crystals were sampled. Krystalová (Crystal) Cave in the Plešivec Quarry showed calcite crystals on walls and ceiling covered by younger speleothems. Also in other caves, there were noted calcite crystals, but their character and positions are not clear (e.g. Renáta Cave, Alke Cave, Zlomená sluj Cave). Succession of speleothems in the largest cave system of the area - Koněprusy Caves - is also specific, i.e. popcorn-like forms containing laminae of microcrystalline quartz known as the Koněprusy Rosettes in places coated by honey-coloured columnar calcite (Lysenko and Slačík 1975, 1977a, b). Some authors associate their precipitation with hydrothermal process (e.g. Suchy et al. 1997; Suchy, Zeman & Dobeš 1997) and with the presence of waters rich in H_2S (Suchy & Zeman 1998b). Koněprusy Rosettes, both calcite and silica laminae „contain low-salinity fluid inclusions, possibly with a small admixture of higher hydrocarbons“ (Dobeš in Suchy & Zeman 1998b, p. 160).

Fluid inclusion study

Samples of calcite crystals from phreatic channel close to the Jezerní (Lake) Cave in the Eastern Quarry of the Velkolom Čertovy schody Quarry were taken in late 1996. The channel was about

1.5 m in diameter of ovate shape, steeply descending in the direction of the Jezerní (Lake) Cave (Figs. 1 and 5). The walls were covered by calcite crystals, flat rhombohedrons, with size of 4 to 12 cm. Samples were delivered to Dr. Yuri N. Dublyansky of Novosibirsk who kindly performed first fluid inclusion study (*cf.* also Dublyansky & Bosák 1999).

Luminescence. The sample was irradiated in darkness by powerful photographic flash and its luminescence was registered on the visual basis (*cf.* Shopov in Hill & Forti 1997). Calcite exhibited short (~1/3 s) orange-red glow which is indicative for hydrothermal calcite with fluid inclusion temperatures over ~60^0 C.

Thermometry. The lowest temperatures were measured in inclusions apparently secondary or primary-secondary in origin that were formed by healing microfissures and cracks. Some of inclusions are aligned along the cleavages planes and they are typically flat and having irregular shape. Some of the higher-temperature inclusions are also aligned along inclined planes which may represent either healed fractures or trails of crystal edge propagation. Inclusions which gave temperatures of 60 to 70^0 C typically have good „equilibrated“ shape, often showing fragments of „negative crystal“ facing. They exhibit random and three-dimensional distribution in the matrix, which suggests their primary (i.e. growth-related) character. In several cases, for higher-temperature inclusions temperatures were recorded not by single inclusions, but by fluid inclusion associations (FIAs). There are groups of inclusions of similar habit, having similar degree of filling (gas-to-liquid ratio), and showing similar, within 2 to 3^0 C, homogenisation temperatures. The data, obtained by FIAs are considered to be most reliable in the fluid inclusion studies (Goldstein & Reinolds 1994). Fluid inclusion thermometric data suggest hydrothermal origin of the calcite studied that occurred at temperatures of about 70-80^0 C. This episode was followed by cooling of the system or, alternatively, by several episodes occurring at lower temperatures.

Hydrocarbon inclusions. Primary inclusions of dark hydrocarbons (presumably, oil or bitumen) are present in crystals. They might be judged primary as they are aligned along plane surfaces (growth facies) with one side of inclusion being flat and another side - convex. This indicates that these inclusions were trapped at an interface between solid growing crystal (flat surface) and mineral-forming media (Goldstein & Reinolds 1994). Calcite was subjected to bulk gas chromatographic analysis. A setup of two coupled chromatographs: regular LHM8 and one, specially tuned to discriminate hydrocarbons was employed. Gas for analysis was released by means of heating of the sample to 500^0 C. Calcite removed from the heater lost its bright white colour and acquired greyish tinge. This suggests decomposition („burning“) of hydrocarbons occurring either as inclusions or as disseminate admixtures. The total content of hydrocarbons was 3 to 4.5 ppm (CH_4=1.0 ppm, C_2H_2=0.5 ppm, C_2H_4+C_2H_6=0.2, C_3=0.4 ppm, C_4=0.3 ppm, C_5=0.4 ppm, C_6=0.2 ppm, and about 0.5 to 1.5 ppm of 3 to 4 more heavy hydrocarbons which were not identified).

Interpretation

Precipitation of large calcite crystals is usually connected with thermal water systems due to slow and stable CO_2 degasation (Ford & Williams 1989; Forti 1996) and slow water exchange (Ford & Williams 1989). The crystallisation occurs usually below the water table at depths up 6 to 30 m, rarely deeper (-130 m; Ford & Williams 1989, pp. 340-342). Palmer and Palmer (1997, pers. comm.) suppose that the crystallisation of larger crystals represents the product of thermal system stable for longer time periods in which the growth of euhedral crystals is more rapid. Forti (1996) stated that if thermal waters have lower temperature, silica would precipitate as amorphous and/or cryptocrystalline speleothems, commonly as botryoidal opal, which could be the case of the Koněprusy Rosettes.

As large calcite crystals, usually rhombohedrons and flat rhombohedrons (nailhead spar) cover relatively large areas in caves, it could be stated that caves are the product of hydrothermal karstification, i.e. degasation and cooling of warm waters close to water table. Cores of large crystals are connected with waters with temperatures from 60 to 80^0 C and their marginal zones indicate the cooling of the system within one or several episodes occurring at lower temperatures. This fact can prove eventual mixing with descending meteoric waters (*cf.* Forti 1996; Martini & Marais 1996).

The distribution of caves with crystals show the concentration in a narrow strip along the Očkov Overthrust in the North although in distinct distance form it, i.e. the feature corresponding with the distribution of all caves in the area (*cf.* Bosák 1996a-c). Such distribution of caves was caused by paleohydrogeological and paleohydraulic features connected with two major factors. The first one can be seen in a closed character of fissures under pressure conditions in a immediate foreland of the overthrust (J. Glazek 1995, pers. comm.). The second feature was connected with considerably less permeable formations (Suchomasty and Acanthopygae Limestones) overlying Koněprusy Limestones and tapering waters in a confined and/or partially confined aquifer (*cf.* Klimchouk 1994; Forti 1996; Martini & Marais 1996). The water tapering was probably also enhanced by the presence of an overlying meteoric aquifer (*cf.* Forti 1996) in shallow subsurface zone, which could result in the mixing of meteoric and warm waters. This situation was favourable for the origin of stable thermal stratification of warm water resulting in the formation of two-dimensional maze caves (*sensu* Forti 1996) and also for the precipitation of large calcite crystals (Palmer and Palmer 1997, pers. comm.). The altitude position of caves somewhat differs, which corresponds to phreatic and bathyphreatic character of original conduits, nevertheless altitudes of caves with crystals are more or less equivalent in individual structurally limited blocks of the Koněprusy Devonian.

As major caves in the area developed before Early Miocene when the Koněprusy Caves were already open to the surface (Oligocene to Early Miocene pollen grains and volcanic ash in aerosol speleothems distinctly younger than popcorn-like Koněprusy Rosettes, Halbichová & Jančařík 1982-1983; Jančaěřík 1986), the source of thermal waters have to be connected with Paleogene to Early Miocene deep karst water circulation and/or eventual invasion of thermal waters from the depth. It could be stated relatively strictly, that such process was clearly post-Variscan in age. Owing to the history of speleogenesis presented by Bosák (1996a-c), the process can be connected with so-called „main phase of cave formation“ in the Bohemian Massif (Bosák 1990) dated back to Paleogene/Early Miocene. The speleogenesis is supposed to act below the cover of platform Upper Cretaceous sediments (Bosák 1996a-c) in deep phreatic and bathyphreatic conditions.

The origin of thermal waters either by the heating due to deep circulation of karst water and/or meteoric water or eventual invasion of thermal waters of deep origin could be connected most probably only with neoalpine phases of the Alpine Orogeny, i.e. with the Laramide phase (Cretaceous/Paleogene boundary), and/or Styrian phase (Eocene/Oligocene boundary), and/or young Pyrenees and Savian phases (upper Oligocene/lower Miocene; *cf.* Roth 1980). The Laramide phase produced the oldest neovolcanic activity in the Massif, i.e. origin of subvolcanic intrusions (67 to 60 Ma; Kopecky 1978). Younger phases (Eocene to Early Miocene) were connected with the main phase of neovolcanic activity dated to 35-17 Ma (Kopecky 1978) with abundant surface volcanoes. Medaris et al. (1998) calculated the heat flow during the main volcanic phase. According to his thermometric calculation, the heat flow was about 3 times higher than the recent one. This fact can explain the origin of thermal waters only from the heating of deeply circulating meteoric and karst waters without the introduction of thermal waters of deep origin. Assuming that the thickness of the Upper Cretaceous cover was more than 200 m after marine regression, the thickness of Pragian and younger limestone formations was nearly 400 m and Zlíchovian with Late Silurian carbonate formations attained nearly 150 m, than water circulating to the depth of about 700 m below surface up to the top of „impermeable" Silurian formations would be heated to about 60^{o}C plus actual surface temperature of water, during Paleocene to Middle Eocene supposed to be the equivalent of average annual tropical temperatures (i.e. higher than 20^{0} C).

REVISED MODEL OF SPELEOGENESIS

The paleohydrogeological model of the evolution of caves in the Koněprusy Devonian was presented by Bosák (1996a-c) and it represents the basis for our interpretations. It is based on following postulates, in general: (1) the destruction of Upper Cretaceous platform sediments in wet and hot climates during Paleocene to Oligocene was connected with the evolution of infiltration routes under a cover of permeable Cenomanian sediments and of eventual ponors on bare limestone formations; (2) the speleogenesis was connected with deep phreatic and bathyphreatic zone; (3) the main hydraulic barrier was represented by the Očkov overthrust which caused the upwelling of the waters, the increase in piezometric level connected with the formation of maze to labyrinth-like caves with irregular morphology of shallow phreatic nature in a confined or partly confined aquifer and later also of vadose lake-filled rooms, and (4) the evolution of lower deep phreatic cave horizons was later dependent on the decrease of piezometric level as a consequence of the change of regional base level. Complete removal of Cretaceous platform cover led to formation of carbonate outcrops and resulted in the retreat of limestone slopes and shift of ponors in the centripetal manner.

The model is still valid, as all data available are in the agreement. The new factor, the hydrothermal process, can be inserted to the idea, although there is some uncertainty with dating. Lower time limit for such process is given by the fact that supposed pre-Cenomanian cavities were fully fossilised, filled with sediments after the marine transgression (*cf.* Bosák 1997, 1998a). The upper time limit is given by opening of the Koněprusy Caves to the surface as proved by the presence of pollen grains of Oligocene/Early Miocene age in speleothems of arerosol origin (Jančařík 1986). At that time, the speleogenesis had to be finished, as aerosol speleothems were formed during air exchange between cave air and external atmosphere.

The thermal process was not connected with the origin of calcite veins but with another process (Žák 1999), which is proved by the perforation of calcite veins by caves connected with the younger process (Fig. 6). Younger hydrothermal karstification was probably associated with periods of increased geothermic gradient connected with increased heat flow due to active volcanic activity. Meteoric and karst waters could be easily heated during deep circulation through Cretaceous platform cover, and Lower Devonian and Late Silurian limestone formations. North-South trending fissures, often with Variscan calcite veins, with the tension regime for long-lasting time periods could serve as an ideal routes for such circulation (*cf.* Cílek, Žák & Dobeš 1994).

Two scenarios could be opened now. The first could assume that the post-Cretaceous and pre-Early Miocene thermal circulation is responsible for the origin of a majority of caves in the Koněprusy

Devonian. As rests of calcite crystals were found only in several from all known caves of the region, this speculation is less acceptable, at least for me. More interpretation of Žák (1999) strictly excludes the possibility that the Koněprusy Rosettes and related silicification could be of real hydrothermal origin.

The second scenario is a little bit complicated, assuming first normal „cold" speleogenesis in conditions of confined phreatic regime later invaded by hot waters. The confinement was caused by aquitard of less permeable Middle Devonian limestones and partly by Upper Cretaceous platform cover. According to the paleohydrological model presented earlier (Bosák 1996a-c) a network of phreatic and deep phreatic cavities formed. In a certain evolution stage, the heat flow increased owing to the intensive neovolcanic activity and the system started to develop in hydrothermal conditions of deeply circulating groundwaters. Thermal waters brought entropy to the system and caves developed rapidly, changing partly their morphologies, some of them resembling real thermal speleogens. This process was especially developed along and below the water level, as indicated by the morphology of the middle level of the Koněprusy Caves, i.e. in the surroundings of the Prošek´s Dome. There, rests of original phreatic tubes are visible within the irregular two-dimensional maze cave. This fact could also indicate, that invasion of warm waters occurred in later stages of the evolution of the whole karst system.

Large calcite crystals precipitated on walls of phreatic channels under real hydrothermal temperatures (60-80^0 C). Channels constituted the main water conduits from ponor areas towards the area of the Očkov Overthrust, where the maximum amount of caves appears, including caves with crystals. Caves with crystal occur always in relatively great depth below surface, below or at the level of lower level of the Koněprusy Caves. The mixing of waters originally enhanced corrosion along the top of permeable Koněprusy Limestones at their contact with less permeable overlying limestones. Later the drop of water table associated with the inrush of cold meteoric waters caused cooling of the system (outer zones of crystals with precipitation temperature of about 40^{o}C) and popcorn-like Koněprusy Rosettes precipitated in cooled lakes.

The character of abundant depressions filled with Cretaceous and Tertiary sediments (e.g. Suchy, Zeman & Bosák 1996) which have been very often uncovered by limestone exploitation in quarries can provide another data specifying the character of karstification. Depression are commonly tube-like, steeply inclined, with diameter of 2 to about 25 m. They are composed of single tube (chimney) or they show more complicated morphology composed of several parallel tubes separated by sharp pinnacles and ridges (Fig. 3). Geophysical measurements (Puffr 1991; Jungbauer, Puffr & Bosák 1993; Bárta, Hrubec & Beneš 1996), drilling operations and mining did not discover rests of collapses at the base of such depressions, as assumed earlier by Bosák (1996c, 1997). Walls of some of depressions show phreatic speleogens (scallops, wall niches, wall copulas, overhanging walls, etc.; Fig. 4). Sequences of Upper Cretaceous, Tertiary and ?pre-Upper Cretaceous rocks exhibit mostly chaotic arrangement with steeply inclined lithological boundaries, parallel with walls of depressions. Cases when sediments are only gently sunkened (*cf.* Suchy, Zeman & Bosák 1996) are exceptional. The genesis of some of depressions can be connected with the speleogenesis in Koněprusy Limestones within shallow phreatic conditions. Limestones were perforated up to their top, as water table was lying above their interface with overlying Upper Cretaceous sediments. After buoyancy support of water decreased, overlying siliciclastics collapsed to open steeply inclined forms. The presence of metahalloysite in basal parts of siliciclastics originally interpreted as stress-derived product from slow movement of sediments into the depression (Cílek & Šťastny 1996) could represent the product of hydrothermal alteration of clay minerals. The problem of black crusts on walls of some of depressions supposed to be hydrothermal in origin (Zeman, Suchy & Melka 1997) is relatively simple. Authors assuming the hydrothermal origin did not realised that depressions far (about 50 m) from main calcite vein of the region are without crusts. It is relatively clear, that manganese-bearing crusts are connected with weathering on manganese minerals occurring in the centre of thick calcite vein and with later mobilisation and precipitation of manganese compounds during exogenic infiltration (*cf.* Cílek & Fábry 1989; Cílek & Kloušek 1990). Black crust therefore cannot serve, unfortunately, as direct evidence of hydrothermal origin of depressions.

CONCLUSIONS

Two phases of hydrothermal karstification were detected in the Koněprusy Devonian. The older one was connected with the late phases of the Variscan orogenic cycle (about 360-230 Ma) and the younger one with tectonic unrest and intensive volcanic activity of neoalpine orogenic phases (67-60 and 35-17 Ma), i.e. after about 200 Ma.

During older phase, thick calcite veins originated. They were accompanied by the dolomitisation, quite similar to ore-forming process of the Mississippi Valley type of deposits. Relatively large caverns of hydrothermal origin were formed. They are completely fossilised by coarse-crystalline hydrothermal calcite similar to vein fill. Caves were relatively large. Some of them are cut by later tectonics.

Younger phase of hydrothermal karstification was not connected with vein-filling, as older calcite veins are perforated by caves originated during the younger process. It was connected with the deep circulation of groundwater during increased heat flow associated probably with the main phase of neovolcanic activity in the Bohemian Massif (35-17 Ma). This idea is supported by the finds of Oligocene/Early Miocene pollen grains and decomposed volcanic ash in aerosol speleothems in the Koněprusy Caves. Aerosol speleothems were formed after cave spaces were connected with external atmosphere, i.e. after the major phases of speleogenesis. It is supposed that caves in the Koněprusy Devonian were formed within confined aquifer under phreatic and bathyphreatic conditions. Confinement was caused by less permeable overlying limestone formations and siliciclastic platform cover. Thermal conditions appeared when paleogeothermic gradient was increased due to intensive neovolcanic activity. Thermal waters invaded cold water caves and changed partly their morphology, leaving two-dimensional mazes with rests of original phreatic tubes along the boundary of permeable and less permeable formations, and phreatic morphologies in the depth. The maximum temperatures were stated to 60-80^0 C from large calcite crystals precipitated under phreatic and deeply phreatic conditions. The piezometric level was situated above limestones in Upper Cretaceous platform siliciclastics as indicated by numerous subvertical phreatic tubes („depressions“) filled with sunkened Cretaceous and Tertiary sediments after the water buoyancy support decreased. Popcorn-like silicified Koněprusy Rosettes making irregular horizon in two-dimensional maze caves can be result of the drop of thermal water level and mixing with infiltrating meteoric waters. Outer zones of large calcite crystals with precipitation temperatures of about 40^0 C can indicate the gradual cooling of the whole system.

Fig. 3: Large karst depressions filled with Upper Cretaceous sediments, note the black crusts on walls, Velkolom Čertovy schody-Quarry East (Photo by P. Bosák, September 1995).

Fig. 4: The shape of walls of karst depression after fill was removed, note overhanging walls, Velkolom Čertovy schody-Quarry East (Photo by P. Bosák, September 1994).

Fig. 5: Opening of inclined phreatic channel with calcite crystals sampled for fluid inclusions, Velkolom Čertovy schody-Quarry East (Photo by P. Bosák, December 1996).

Fig. 6: Cave perforating Variscan calcite vein, Velkolom Čertovy schody-Quarry East (Photo by P. Bosák, March 1996).

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RAZVOJ KRASA IN JAM V KON ĚPRUSIH (ČESKÝ KRAS, ČEŠKA REPUBLIKA), II. DEL: HIDROTERMALNI PALEOKRAS

Povzetek

Kot posledica variskičnih hidrotermalnih procesov je nastala mreža pretežno sever-jug usmerjenih, do 8 m debelih kalcitnih žil. Nastanek kraških votlin (do velikosti 20 x 9 x 3 m) je najbrž povezan z zgodnjimi stadiji hidrotermalnih procesov. Nastali votli prostori so bili zapolnjeni z zelo debelozrnatim kristaliničnim kalcitom, enakemu tistemu, ki je zapolnjeval žile. Hidrotermalni proces je spremljala močna dolomitizacija okoliških žil in votlin, ki so po nastanku primerljive z dolomitnimi orudenji tipa "Mississippi Valley". Dolomitizacija je bila povezana s prodiranjem konatne in diagenetske vode, ki so jo iztiskali pritiski, nastali zaradi gubanja vzdolž predisponiranih struktur.

Mlajša faza hidrotermalnega zakrasevanja se je pričela po okoli 200 milijonov let dolgem mirovanju in ni bila povezana z zapolnjevanjem žil, saj so te prekinjene z jamami, nastalimi kot posledica mlajših procesov. To je bilo povezano z globokim kroženjem kraške vode ob naraščajoči temperaturi, verjetno povezano z "neovulkansko" dejavnostjo v Češkem masivu (35 - 17 milijonov let). To misel potrjujejo najdbe oligocenskih oziroma zgodnje miocenskih pelodnih zrn in razpadlega vulkanskega pepela v "aerosolnih" kapnikih Koněpruskih jam. Ti kapniki so nastali, ko so bili jamski prostori že povezani z zunanjim ozračjem, to je po glavnih speleogenetskih fazah. Jame v Koněpruskih devonskih kamninah so domnevno nastale v ujetem vodonosniku v freatičnih in batifreatičnih okoliščinah. Vodonosnik je bil ujet s krovnimi manj prepustnimi apnenčevimi formacijami in silikoklastičnim pokrovom. Termalne okoliščine so se pojavile, ko se je zaradi močne "neovulkanske" dejavnosti povečala paleogeotermična stopnja. Termalne vode so zalile jame, do tedaj zapolnjene s hladno vodo in deloma spremenile njihovo morfologijo tako, da je nastal dvodimenzionalni labirint z ostanki freatičnih cevi vzdolž meje med bolj in manj prepustnimi formacijami. V globljih delih pa se je obdržala freatična morfologija.

Na podlagi velikih kalcitnih kristalov, ki so se odložili v freatičnih in globokih freatičnih okoliščinah, je mogoče sklepati, da je bila največja temperatura 60-70^0 C. Piezometrični nivo je bil nad apnenci v silikaklastih zgornjekredne platforme, na kar navajajo številne skoraj navpične freatične cevi ("depresije"), zapolnjene s krednimi in terciarnimi sedimenti, ki so zdrsnili vanje, ko se je pritisk vode zmanjšal. Pokovki podobne silificirane "Koněpruske rozete", ki so v odložene v nepravilnem horizontu v dvodimenzionalnem jamskem labirintu, so lahko nastale zaradi znižanja gladine termalne vode in mešanja s prenikajočo padavinsko vodo. Zunanji del velikih kalcitnih kristalov, ki se je izločal pri temperaturah okoli 40^0 C, bi lahko kazal na postopno ohlajanje celotnega sklopa.