DEPOSITION AND DESTRUCTION OF HOLOCENE CALCAREOUS TUFA CASCADES IN THE BOHEMIAN KARST (CZECH REPUBLIC)

1. INTRODUCTION

Over large parts of Europe from the British Isles to the Mediterranean and from Spain to the Czech Republic, Slovakia and Poland, the rates of calcareous tufa deposition were high in the Early and Mid Holocene, but declined markedly thereafter (Weisrock 1986). Over much of Europe, it has been postulated that in the Late Holocene (since ~ 2,500 years B.P.) there was a sharp decline in the deposition of tufa (Goudie et al. 1993). There has been a considerable debate about the causes of this phenomenon, with some authors stressing the importance of natural climatic changes, and others asserting that miscellaneous human activities (e.g., deforestation connected with agricultural activities) were crucial.

Several tens of springs in the Bohemian Karst deposited calcareous tufa from their waters during the Early and Mid Holocene. Tufa deposition continues at a number of localities at present, too (Kadlecová, Žák 1998). As shown by V. Ložek (1992), most of the calcareous tufa bodies of the Bohemian Karst show very similar lithological and biostratigraphic pattern, reflecting Holocene climatic, hydrological and biotic conditions.

2. GEOGRAPHICAL, GEOLOGICAL AND HYDROGEOLOGICAL SETTINGS

Bohemian Karst extends between Praha and Zdice over an area of ca. 200 km². With its NE margin, this karst area reaches to the territory of Prague. With its climatic conditions, the Bohemian Karst is a warm and dry area lying at altitudes of 210–500 m a.s.l. Total annual precipitation is 500 mm with an average annual temperature of 8–9 °C (Quitt 1971).
The Bohemian Karst is located in the central part of the Prague Basin. This basin contains a continuous succession of Ordovician to Middle Devonian deposits accompanied by volcanic activity (Chlupáč et al. 1998). The Bohemian Karst itself, located SW of Prague, is composed of Upper Silurian shales, limestones and basalt lava flows (diabases) plus volcaniclastic rocks (tuffs) and Lower to Middle Devonian limestones and shales. During the Late Paleozoic Variscan Orogeny, sediments of the Prague Basin were folded into large anticlinal and synclinal structures and faulted (Chlupáč et al. 1998).

Groundwaters of the Paleozoic basin fill are issued on many places in the Bohemian Karst: along exposed boundaries between limestones and non-carbonate rocks near bottoms of karstic valleys, and at fault intersections. Most of the karst springs are characterized by relatively stable discharge (between 0.1 and 20 l/s) and temperature, somewhat exceeding average annual temperature in the area in some cases. This is indicative of a deeper karst-water circulation (Kadlecová, Žák 1998; Žák et al. 2001). A typical feature of most springs of the Bohemian Karst is the deposition of calcareous tufa in their proximity, precipitating from the issued karst waters. About 70 localities where
calcareous tufa precipitates or was deposited in the past have been described from the Bohemian Karst (Kovanda 1971; Ložek 1992; Kadlecová, Žák 1998). The most common forms are tufa barriers and cascades, which were growing near karst springs during the Holocene, barring the bottoms of karstic valleys.

Five tufa sections with characteristic development were selected for the correlation of lithological features, variations in molluscan assemblages and time successions of accumulation and subsequent destruction of tufa bodies in the Bohemian Karst. These include (from SW to NE): the cascade at Kotýz, the cascade at Svatý Jan pod Skalou, cascades in the Císařská Gorge near Srbsko, the cascade of “Petránka” in the Karlické Valley, and the cascade on the Čertova Gorge at Malá Chuchle (Fig. 1).

3. METHODS USED

3.1. MALACOZOOLOGICAL ANALYSES

Acquisition of samples for paleomalacological and biostratigraphic analyses followed the unified methodology of Ložek (1964). If permitted so by the character of the sediment, samples of the matrix 3–4 l in volume were taken from all macroscopically distinguishable beds within the studied tufa sections. These were later, after careful drying, washed in laboratory conditions. Individual shells and their fragments were hand-picked from the washing residue under a stereomicroscope and determined. Fragments of shells were recalculated to whole individuals following the standard methodology. For a better orientation in fossil malacocoenoses, the proportions of the registered mollusc species in selected tufa sections were statistically processed into the form of histograms (malacospectra). The malacospectrum of species (MSS) expresses relative proportions of the individual species within the principal ecological groups. Attribution of molluscan species to the principal ecological groups in the histograms follows Ložek (1964).

3.2. DATING ANALYSES

3.2.1. DATING BY THE U-SERIES METHOD (U-SERIES LABORATORY OF THE GEOLOGICAL INSTITUTE OF THE POLISH ACADEMY OF SCIENCES, POLAND)

Samples ca. 1–2 kg in weight were collected in the field and subjected to a careful separation of carbonate cement in the laboratory. Preference was given to portions with pure, crystalline cement with no substantial admixture of clay minerals and other detrital components. Dating of carbonates em-
ployed the \(^{230}\text{Th} ^{234}\text{U}\) method. Uranium and thorium were separated from the carbonate using a standard chemical procedure (Ivanovich and Harmon, 1992). The samples were dissolved in 6 M nitric acid, and uranium and thorium were separated by a chromatographic method using the DOWEX 1 x 8 ion exchanger. The efficacy of chemical separation was controlled by addition of spike \(^{228}\text{Th} ^{232}\text{U}\). Activity measurements (? spectrometry) were taken on the OCTE-TE PC device of the EG&G ORTEC company. Spectral analysis and age calculation were performed with the use of “URANOTHOR 2.5” software (Gorka, Hercman 2002). It was necessary to perform correction of samples for an admixture of detrital thorium. The assumed initial \(^{230}\text{Th}\) / \(^{232}\text{Th}\) activity ratio of detrital contamination was 1.5 ± 0.5. Uncertainty in this ratio results in a larger error of the calculated corrected age.

3.2.2. RADIOCARBON DATING BY THE AMS METHOD (POZNAŃ RADIOCARBON LABORATORY, POLAND)

Small pieces of charcoal were (after treatment with hot solutions of acid, alkali, and acid to remove all carbonate carbon and easily soluble organics) measured by the AMS method. The \(^{14}\text{C}\) data on organic matter have been calibrated for variable initial \(^{14}\text{C}\) concentration using the OxCal v3.5 calibration program (Bronk 2001).

4. CALCAREOUS TUFA CASCADES

4.1. TUFA CASCADE AT KOTÝZ

Tufa cascade at Kotýz (No. 1 in Fig. 1) is preserved in the slope 15 m above the present karst spring. The tufa sequence was exposed by a test hole.

**Lithology**

Tufa body is underlain by slope sediments composed of fragments of dark Silurian shales. The section can be subdivided into 16 beds (Fig. 2).

**Malacozoology**

Although the basal interval (Beds 16–10) is of very low species diversity due to the poor fossilization ability, it occasionally yielded species like *Vertigo substriata*, *Perpolita petronella* and *Vitrea crystallina*, characteristic for early Holocene. This interval completely lacks typical glacial elements, however, the accompanying species *Vallonia costata* and *V. pulchella* indicate the presence of open habitats of dry to mesic character.
The overlying beds 9–1 markedly differ from the above mentioned underlying interval in the fossil malacofauna they contain. The bed of solid structural tufa (Bed 9) already shows a gradual onset of forest species, but the species of open habitats are still maintaining a markedly higher abundance. It was only in this bed that the early Holocene element *Discus ruderatus* was rarely encountered. From Bed 8 upwards, a rapid boom of forest species occurs at the expense of open-landscape elements. Molluscan species in this bed document closed woodland conditions, also persisting in the overlying interval (Beds 7–4). Fossil molluscs from Bed 8 and from the interval of Beds 7–4 indicate environmental conditions of the Holocene climatic optimum, i.e. a massive expansion of woodland molluscan species such as *Bulgarica cana*, *Vitrea diaphana*, *Platyla polita*, *Vertigo pusilla* etc., and high abundance of the hygrophilous element *Carychium tridentatum*, whereas the open-landscape elements and the majority of mesophiles disappeared or became very rare (e.g., *Vallonia pulchella* and *Truncatellina cylindrica* are completely absent from Beds 6–4).

The abundance of open-landscape species increases and that of moist woodland species decreases within Beds 2 and 3. After termination of tufa deposition the cascade was covered by dark brown humic soil sediment with increasing number of rock fragments redeposited from the upper part of the slope. The appearance of modern immigrants (e.g., *Oxychiluscellarius*) is characteristic for this uppermost bed in the section.

**Chronology of tufa deposition**

Charcoal from Beds 8 and 4 was subjected to $^{14}$C dating (Fig. 2). Given on the obtained data and the occurrence of fossil molluscan assemblages, horizons of different age can be distinguished in the tufa accumulation. Tufa deposition started in the Boreal period. Solid tufa with rare shale fragments (Bed 9) contains molluscan fauna indicating moist, light forest environment with decreasing abundance of species *Discus ruderatus*, *Trichia sericea* and *Perpolita petronella*. The underlying Beds 16–10 can be thus generally dated to the late Glacial to Preboreal because of the sporadic occurrence of undemanding molluscan species and the prevalence of Early Holocene elements.

The interval between Beds 8 and 4 is characterized by massive development of woodland communities; the abundance of hygrophilous elements dominated by *Carychium tridentatum* indicates humid climate. This interval can be attributed to the Holocene climatic optimum – Atlantic and Epialtan-
Fig. 2. A section through the spring tufa deposit at Kotýz
1 – dark brown humic Rendzic Leptosol with sporadic limestone and diabase clasts (4 cm in diameter); 2 – dark yellowish brown slightly humic soil sediment with rare limestone clasts (0.5 cm); 2a – very dark greyish brown slightly humic soil sediment; 3 – dark brown slightly humic soil sediment with abundant tufa encrustations; 4 – pale brown fine-grained tufa with coarse encrustations in the upper portion of the bed and dark stains coloured with Fe and Mn oxides; 5 – light yellowish brown tufa; 6 – yellowish brown tufa with coarse encrustations in the upper portion of the bed; 7 – very dark greyish brown tufa with rare, very dark brown Silurian shale clasts; 8 – very dark brown mouldered slightly loamy tufa with rare shale clasts; 9 – dark greyish brown solid tufa with shale clasts; 10 – very dark brown shales (clasts 1 cm in diameter), dark greyish brown loamy matrix; 11 – very dark brown shales (clasts 2 cm in diameter) with tufa encrustations (30%), dark brown loamy matrix; 12 – very dark brown shales (clasts 2 cm in diameter) with sporadic tufa encrustations, very dark grey matrix;
tic, as was also confirmed by $^{14}$C dating to the period 5,070–3,090 years BC (Fig. 2). In Bed 3, the accumulation of tufa is terminated, and the recovered molluscan assemblages from this bed point to a prominent drying and a massive retreat of forests contrasting with a prominent spread of open-landscape elements such as species *Truncatellina cylindrica*, *Pupilla muscorum*, *Vertigo pygmaea* and common representatives of the genus *Vallonia*. This trend continues in the overlying strata. Beds 3–1 must be therefore placed to the late Holocene (Subboreal, Subatlantic and Subrecent – Fig. 10), which is also indicated by incursions of modern immigrants of steppe mollusc *Xerolenta obvia* in Bed 2 and ecologically indifferent *Oxychilus cellarius* in Bed 1.

4.2. TUFA CASCADE AT SVATÝ JAN POD SKALOU

A section in calcareous tufa cascade at Svatý Jan pod Skalou (No. 2 in Fig. 1) represents a significant site for the Holocene stratigraphy and a unique archive of local climate and nature development (Ložek 1967; Kovanda 1971).

The tufa body was partly eroded and quarried in the past. The lower portion of the cascade can be studied in a test-pit excavated in the early 1960s
Fig. 3. Vertical section in the calcareous tufa accumulation at Svatý Jan pod Skalou based on drilling, excavated pit S1 and outcrop above (Žák et al. 2002)

1 – dark brown humic soil with small limestone and tufa clasts, a bed of tufa debris at the base; 2 – brown humic soil with limestone clasts and a bed of limestone scree; 3 – light brown, extremely loose tufa to brown soil with frequent tufa clasts; 4 – fine-to medium-grained limestone clasts with loamy or tufa matrix; 5 – brown sandy soil, with tufa debris and limestone clasts at the base; 6 – brown sandy soil with tufa clasts; 7 – brown-yellow to yellow loose tufa, locally irregular relics of solid tufa; 8 – yellow solid tufa; 9 – medium- to coarse-grained limestone clasts with loamy and sandy matrix; 10 – grey-yellow partly loose tufa; 11 – grey-yellow extremely loose tufa with brown loamy and sandy bed, with a thin bed of limestone clasts at the base; 12 – light grey solid tufa, in places loose; 13 – brown sandy soil with tufa debris; 14 – light grey solid tufa, in places loose; 15 – dark brown sandy and clayey soil; 16 – grey to brown-grey loose loamy tufa with rusty limonite streaks; 17 – grey to brown-grey strongly loose tufa with limonite streaks, 18 – light grey solid tufa, in places loose; 19 – white grey solid tufa with conspicuous limonite streak on the surface; 20 – light grey fine sandy lacustrine tufa; 21 – light grey, locally rusty brown solid tufa; 22 – light grey to yellow, locally rusty brown solid tufa; 23 – light grey strongly loose tufa; 24 – light brown loose tufa with a lenticular bed of sandy gravel in the upper part; 25 – medium- to coarse-grained limestone clasts with sandy matrix; 26 – light brown loose tufa, locally with loamy matrix; 27 – yellow white solid tufa; 28 – grey-yellow to light grey massive solid tufa; 29 – light grey loose tufa, locally with loam admixture; 30 – greyish yellow to light grey massive solid tufa; 31 – light grey to brown loose tufa, locally with loam admixture; 32 – grey-yellow loose tufa; 33 – loose grey-brown tufa; 34 – grey-yellow to brown-yellow massive solid tufa, more porous at the base; 35 – medium-grained limestone clasts with tufa fragments and encrustations in the upper part of the bed, rounded pebbles of Paleozoic and Proterozoic rocks in the lower part of the bed; 36 – fluvial sandy gravel with well rounded pebbles of Paleozoic and Proterozoic rocks and minor presence of limestone clasts; tufa absent

Pionowy przekrój przez osady trawertynowe w Svatý Jan pod Skalou oparty o wiercenia, odkrywkę S1 i szurf powyżej (Žak i in. 2002)

1 – gleba humusowa, ciemnobrązowa z małymi okruchami wapieni i trawertynow, warstwa okruchów trawertynow w spagu; 2 – gleba humusowa, brązowa z okruchami wapiennymi i warstwą zwietrzeliny wapiennej; 3 – trawertyn bardzo luźny, jasnobrązowy; gleba brązowa z licznymi okruchami trawertynów; 4 – okruchy wapienia, drobno- do średnioziarnistych w gliniastym lub trawertynowym matrix; 5 – gleba brązowa, piaszczysta z okruchami trawertynu i wapienia w spagu; 6 – gleba brązowa, piaszczysta z okruchami trawertynu; 7 – trawertyn brazowożółty do żółtego, luźny, lokalnie nierozgładne reliki zwiększego trawertynu; 8 – trawertyn żółty, zwięzły; 9 – okruchy wapienne średnio- do gruboziarnistych z gliniastym i piaszczystym matrix; 10 – trawertyn szarożółty, częściowo luźny; 11 – trawertyn szarożółty, bardzo luźny z brązową gliniasto-piaszczystą warstwą i z cienką warstwą okruchów wapiennych w spagu; 12 – trawertyn jasnoszary, zwięzły, miejscami luźny; 13 – gleba piaszczysta brązowa z okruchami trawertynu; 14 – trawertyn jasnoszary, zwarty, miejscami luźny; 15 – gleba piaszczysta i siasta, ciemnobrązowa; 16 – trawertyn gliniastyc szary do brązowoszarego, luźny z rdawnymi smugami limonitu; 17 – trawertyn gliniasty szary do brązowoszarego, bardzo luźny ze smugami limonitu; 18 – trawertyn jasnoszary, zwięzły, miejscami luźny; 19 – trawertyn, białoszary, zwarty ze smugami limonitu; 20 – trawertyn jeziorny, drobno piaszczysty, jasnoszary; 21 – trawertyn jasnoszary, miejscami rdzawobrązowy, zwarty; 22 – trawertyn jasnoszary do żółtego, miejscami rdzawobrązowy, zwarty; 23 – trawertyn jasnoszary, bardzo luźny; 24 – trawertyn jasnobrązowy, luźny, z soczewkowatą warstwą piaszczystego żwirowi w górnej części; 25 – okruchy wapienne średnio do gruboziarnistych w piaszczystym matrix; 26 – trawertyn jasnobrązowy, luźny, miejscami z gliniastym matrix; 27 – trawertyn żółtobiały, zwięzły; 28 – trawertyn szarożółty do...
and in small cellars excavated in tufa, while the basal portion of the cascade below the groundwater table has been studied by drilling in 1996 (Žák et al. 2001).

**Lithology**

The calcareous tufa cascade consists of a complex of various types of tufas up to 17 m thick (Fig. 3). The tufa cascade is underlain by a sandy gravel fluvial terrace of the near Kačák Stream, characterized by a mixture of rounded pebbles of Upper Proterozoic and Lower Paleozoic rocks and angular limestone clasts. The base of the tufa accumulation lies about 1 m below the present level of the Kačák Stream.

**Malacozoology**

Malacofauna from the tufa accumulation was synoptically described already by Petrbok (1923). The most recent extensive inter-disciplinary study was provided by Žák et al. (2001). This study gives a complex review of molluscan fauna systematically processed since the 1960s. Complete fossil malacocoenoses from this tufa body were also presented by Žák et al. (2002), who – besides the list of species – also provided a careful description of malacocoenology and the reconstruction of palaeoenvironmental changes.

**Chronology**

The lower part of the section between the base of solid tufa (~ -9 m) and the test pit bank (0 m) was deposited between ~ 9500 cal. years B.P. and ~ 6500 cal. years B.P. and corresponds to the Late Boreal and most of the Atlantic. Lithologically, most of this section is characterized by massive structural tufa almost free of clastic material. The fossil molluscan assemblage is characterized by high numbers of open-landscape species (open forest with parklands in some places). Nevertheless, already Bed 30 (-5 m, Fig. 3) provided a demanding thermophilous element *Truncatellina claustralis* with Early Holocene elements, such as *Discus ruderatus* and *Perpolita petronella*, occurring in very low numbers.
Loose beds between the solid tufa and the lower scree horizon (Bed 25) were formed, given on geochronological data, between ~ 6500 and ~ 6200 cal. years B.P. This complex includes very rich malacofauna characterized by the appearance of sensitive woodland species and some aquatic species. The lower scree horizon is characterized by the maximum species abundance (46 molluscan species), high number of aquatic and wetland elements.

The thick complex between the lower and upper scree horizons shows a rather wide variety of lithofacies, but its molluscan assemblages show lower species diversity. Aquatic and wetland species remain important and their diversity reaches its maximum in the intercalation of fine-grained grey limnic tufa (Bed 20). The richest woodland assemblage was recorded in Bed 15 (32 species). This part of the section contains several horizons richer in organic matter (up to 0.5% org. C), which represent fossil soils. The best developed soil horizon corresponds to ~ 4200 cal. years B.P. Red-yellow coloured and narrow black zones paralleling fossil soils are a result of post-depositional mobility of Fe and Mn and their redeposition on redox boundaries.

The upper scree horizon (~ 2800 cal. years B.P.) with humic rendzina matrix contains prehistoric pottery fragments belonging to the Late Bronze Age, late stages of the so-called Knovíz Culture (Ložek 1967). Woodland snails remain dominant.

The woodland character of the malacofauna persists in the uppermost, predominantly clastic intervals. Bed 3 also yielded archaeological artefacts attributed to Early Iron Age, the so-called Bylany Culture, dated to the 7th–6th century BC. The tufa formation was terminated at ~ 2400 cal. years B.P., either because climate changed or the spring was relocated to the base of the tufa deposit and started to erode its base. This could have been supported by erosive activity of the Kačák Stream. As a result of these processes, a cave (called Ivan’s Cave) was formed in the tufa body. An original presence of small cavities and caves cannot be ruled out. Unfortunately, the cave was artificially enlarged several times and its original walls were mostly destroyed.

4.3. TUFA CASCADES IN THE CÍSAŘSKÁ GORGE

The Císařská Gorge is a valley 700 m long and over 100 m deep (Kadlecová, Žák 1998). Tufa is intensively precipitated from waters of a spring in the upper part of the valley. Tufa forms three cascades, marked by numbers I, II and III in the upstream direction. Only Cascades I and II were subjects of this study (No. 3 in Fig.1).
Lithology

Limestone scree cemented by carbonate is deposited on the base of the thickest cascade – Cascade I. Above the scree, a bed of solid structural tufa was deposited, interfingering with slope sediments laterally. A young tufa accumulation is presently growing in the erosive channel transecting the cascade (Figs 4 and 5). Cascade II, lying ca. 130 m from here, has an analogous lithological character (Fig. 6).

Malacozoology

In both cascades, samples corresponding in their level with radiometrically dated beds were selected for malacozoological and malacostratigraphic analysis (see sampling points in Fig. 4 and Fig. 5). Fossil molluscs from the bed of massive porous brownish calcareous tufa from Cascade I (Fig. 4) are markedly dominated by woodland species. Gastropods *Sphyradium doliolum*, *Platyla polita*, *Vertigo pusilla*, *Aegopinella pura*, *Discus rotundatus*, *Macrogastra ventricosa*, *Alinda biciplicata*, *Clausilia pumila* and other species were found to be very abundant. These are accompanied by woodland species of moderate size (*Monachoides incarnatus*, *Urticola umbrosus*, *Heli-

Fig. 4. Tufa cascade I in the Císałská Gorge. 1 – the youngest calcareous tufa; 2 – massive porous brown yellowish calcareous tufa; 3 – limestone scree cemented by brown porous carbonate, angular clasts with average size of 4 cm; clast size up to 10 cm in the upper part; 4 – grey loose limestone scree; 5 – limestone bedrock; 6 – sampling point on fossil molluscs

Trawertyn kaskadowy I z Wąwozu Císałská. 1 – najmłodszy trawertyn węglanowy; 2 – trawertyn węglanowy brązowożółty masywny, porowaty; 3 – zwietrzelina wapienna scementowana przez okruchy węglanowe brązowe, porowane, ostrokrawędziste, o średnicy 4 cm; w górnej części okruchy o średnicy do 10 cm; 4 – zwietrzelina wapienna szara, luźna; 5 – podłoże wapienne; 6 – miejsca poboru próbek kopalnych mięczaków
codonta obvoluta, Cepaea hortensis), again highly abundant. Gastropods with non-specific ecological affinity (ecologic group C) reach higher abundance than open-landscape and forest-free elements, which are considerably less frequent and restricted only to species Vallonia costata and rare Truncatellina cylindrica, probably redeposited from the ambient steep slopes. Fossil malacocoenosis clearly indicates a moist, continuous forest covering valley areas, which was getting lighter towards higher elevations.

A poor molluscan assemblage clearly dominated by Vallonia costata, Punctum pygmaeum and Vitrea crystallina was ascertained in the underlying bed of limestone scree cemented by brown porous carbonate from Cascade I (Fig. 4). These undemanding species were occasionally accompanied by the Early Holocene element of Discus ruderatus and ecologically indifferent Cochlicopa lubrica together with Euconulus fulvus. The proportion of woodland species in this bed was very low: they were limited only to the species of Monachoides incarnatus and Platyla polita. A similar composition of fossil malacoofauna was also observed in the sample collected from the bed of limestone scree cemented by brown porous carbonate from Cascade II (Fig. 6). The common Discus ruderatus and Perpolita petronella are followed by gastropods Vertigo alpestris, Discus rotundatus, Aegopinella minor, Trichia
hispida and Ena montana, accompanied by indifferent species Punctum pygmaeum, Cochlicopa lubrica and Euconulus fulvus. Both of these beds are completely lacking any of the prominent elements of continuous forest characteristic for the Holocene climatic optimum or the youngest Holocene.

**Chronology**

As indicated by molluscan remains in the beds of limestone scree cemented by brown porous carbonate from Cascades I and II, their fill can be dated to the Early Holocene. This is suggested not only by the common occurrence of Early Holocene species Discus ruderatus, Perpolita petronella, Vitrea crystallina and even Vertigo alpestris, but also by the notable absence of elements indicative of a continuous forest of the climatic optimum. The Early Holocene age of the scree is also confirmed by a radiometric age of its carbonate matrix – 9,460 ± 1,200 years BP (sample TMS-1) – Table 1 and Fig. 4.
encountered assemblages rather indicate the Boreal period (sample from Cascade I), or possibly a transition between the Boreal and early phases of the Atlantic (sample from Cascade II – with carbonate matrix dated at 5,920 ± 1,520 years BP – sample TMS-28, see Tabule 1 and Fig. 6), when the landscape had the character of open spaces alternating with small areas of light poor deciduous forests having, however, a different composition than the present ones. Moisture conditions were more favourable already but still did not permit a development of more continuous woodland complexes, as documented by the notable absence of demanding woodland molluscan species or only a low proportion of hydrophilious elements.

In contrast with the underlying beds, malacostratigraphic analysis of a sample from the bed of massive porous brown yellowish calcareous tufa from Cascade I (Fig. 4) yielded malacofauna indicating the Holocene climatic optimum – Atlantic and Epiatlantic (sensu Jäger, 1969). This is evidenced by almost a complete absence of open-landscape elements as well as by the absence of Early Holocene elements or elements from the youngest phases of the Holocene.

In a time succession, the Císařská Gorge was first filled with talus with angular scree fragments in the Early Holocene (Preboreal, Boreal to early phases of the Atlantic). The scree was later overlain by accumulations of structural tufa precipitated during the Holocene climatic optimum (Atlantic, Epiatlantic).

4.4. PETRÁNKA TUFA CASCADE IN THE KARLICKÉ VALLEY

The tufa accumulations (No. 4 in Fig. 1) form relics in the banks of a small gorge 12 m deep, with a karst spring in its closure (Kadlecová, Žák 1998).

Lithology

The basal part of the tufa succession is formed by a bed of coarse limestone clasts, filling a small depression in the underlying dark Paleozoic limestone. The scree is stratified by beds of dark silt with frequent shale clasts. The scree is overlain by a complex of loose tufa with beds and lenses of yellow-brown massive structural tufa. The upper portion of the section is formed by loose grey tufa with Rendzic Leptosol on the surface. For a detailed description of the section – Fig. 7.
Fig. 7. A relic of the tufa cascade exposed near the Petránka Spring in the Karlické Valley. 1 – dark brown humic Rendzic Leptosol; 2 – loose grey tufa, slightly humic; 3 – loose grey tufa; 4 – a complex of light brown loose tufa with thin beds of solid tufa; 5 – lens-like beds of solid tufa with dark stains coloured with Fe and Mn oxides; 6 – loose, light yellow-brown tufa; 7 – a lens-like bed of solid tufa; 8 – loose, light yellow-brown tufa with sporadic limestone and shale clasts (0.5 cm in diameter); 9 – scree horizon formed by shale plates and limestone clasts up to 20 cm large in a silt-sand matrix; 10 – brown sandy silt with rare limestone clasts; 11 – yellow-brown silt; 12 – coarse scree horizon formed by limestone blocks up to 70 cm large in a silt-sand matrix; 13 – limestone bedrock

Relikt trawertynu kaskadowego odsłonięty w pobliżu Źródła Petránka w Dolinie Karlické.
1 – rdzina ciemno brązowa; 2 – trawertyn lekko humusowy, szary, luźny; 3 – trawertyn, szary luźny; 4 – kompleks trawertynu szarobrązowego, luźnego z cienkimi warstwami trawertynu zwartego; 5 – soczewkowate warstwy trawertynu zwartego z ciernymi plamami zabarwionymi tlenkami żelaza i manganu; 6 – trawertyn jasno żółtobrązowy, luźny; 7 – soczewkowata warstwa trawertynu zwartego; 8 – trawertyn jasno żółtobrązowy, luźny z pojedynczymi okruchami wapieni i łupków o średnicy 0,5 cm; 9 – warstwa zwietrzeliny utworzona przez płyty łupków i okruchy wapieni o wielkości do 20 cm w pylaство-piaszczystym matrix; 10 – mulek piaszczysty, brązowy z rzadkimi okruchami wapiennymi; 11 – mulek żółto-brązowy; 12 – warstwa zwietrzeliny utworzona przez bloki o wielkości do 70 cm w pylaство-piaszczystym matrix; 13 – podłoże wapienne
Malacozoology

The basal part of the section (Beds 12, 11 and 9) contains no molluscan fauna.

The first fauna (*Trichia sericea*) was identified in a bed formed by brown sandy silt (Bed 10) overlain by a bed of slope scree (Ložek, Kadlec 2000). Bed 8 (loose light yellow-brown tufa with sporadic limestone and shale clasts) yielded rich fossil malacofauna dominated especially by *Carychium tridentatum*, *Sphyradium dolioiium*, *Aegopinella pura*, *Aegopinella minor*, *Discus rotundatus* and *Columella edentula*, accompanied by frequent *Cochlicopa lubricella* and by aquatic gastropods *Galba truncatula* and *Anisus leucostoma*. Altogether 23 molluscan species were identified in this horizon. Similar malacofauna was also encountered in the overlying tufa horizons, showing only very slight differences in the compositions of fossil malacocoenoses. While Beds 7–5 are characterized by absolute absence of open-habitat and steppe elements, *Vallonia costata* appears in Bed 4 and belongs among the dominant species in Bed 3 already. This indicates partial drying and deforestation during the deposition of this horizon. The uppermost beds are marked by the appearance of *Truncatellina cylindrica* (Bed 2) and the modern immigrant *Oxychilus cellarius* (Bed 1).

The whole tufa interval (Beds 8–2) yielded relatively rich woodland malacofauna, which has not been impoverished to a higher degree but has survived until the present days with only slight species modifications (e.g., gastropods *Sphyradium dolioiium*, *Aegopinella pura*, *Macrogastra ventricosa*, *Choclodina laminata*, *Ailida biplicata*, *Ena montana*, *Urticicola umbrosus*). This molluscan assemblage indicates warm and light forest environment.

Chronology

As indicated by the molluscan assemblages, tufa deposition probably started during the Boreal period and continued to the Atlantic and Epialantic climatic optimum. As indicated by fossil malacocoenoses in Beds 3 and 2, the existing woodland complexes maintaining a closed character up to this level increased the proportion of lighter habitats at this boundary.

The basal beds of limestone scree may represent the Preboreal colder conditions with intensive mass wasting. After the termination of tufa deposition, the cascade was incised by running water down to the underlying limestone.
4.5. TUFA CASDADES IN THE ČERTOVA GORGE AT MALÁ CHUCHLE

A tufa cascade (No. 5 in Fig. 1) was originally barring the Čertova Gorge in the width of 30–40 m. As a result of later erosion, tufa relics now lie at the height of up to 12 m above the present gorge bottom.

**Lithology**

The bottom of the gorge is filled with slope deposits – coarse limestone scree with sandy and silty matrix transported by water and mass movements from the slopes probably during the end of the last glacial stage (Fig. 8). The tufa cascade was deposited on these slope deposits. The studied section is exposed in the northern slope of the Čertova Gorge. Beds of grey to brownish grey, mostly loose tufa form a tufa succession underlain by slope deposits. For a detailed description of section – Fig. 9.

**Malacozoology**

A tufa section on the left valley bank provided malacozoological material of extremely high species diversity consisting of species of broad ecologic range. Woodland species *Monachoides incarnatus*, *Discus rotundatus*, *Sphyrradium doliolum* and *Acanthina aculeata* occur almost continuously in the whole interval, being accompanied by hydrophilous species *Carychium tridentatum* and *Zonitoides nitidus*. The finds of wetland species *Vertigo angustior* and *Vertigo antivertigo* well correspond with the occurrences of aquatic
Fig. 9. A section in the Epiatlantic to Subboreal calcareous tufa exposed in the northern slope of the Čertova Gorge. 1 – brownish grey loose tufa with rusty limonitic stains in the lower portion of the bed; 2 – brownish grey loose fine tufa; 3 – greyish brown partly loose leaf tufa; 4 – light grey medium-grained loose tufa; 5 – yellowish grey, almost solid structural porous tufa with horizons with leaf encrustations; 6 – brownish grey loose tufa with encrustations; 7 – brownish grey, partly loose leaf tufa; 8 – light grey fine-grained loose tufa; 9 – greyish yellow tufa with a rusty limonitic band on the surface; 10 – light grey fine-grained loose tufa with a rusty limonitic band; 11 – dark grey fine-grained loose tufa with dark stains; 12 – dark brown clayey silt with pebbles and rock fragments – slope deposits

Przekrój przez trawertyn weglanowy (późny Atlantyk – Subboreal), odsłonięty w północnym stoku Wąwozu Čertova. 1 – trawertyn brązowawoszary, luźny z rdzawymi plamami limonitu w dolnej części warstwy; 2 – trawertyn drobnoziarnisty, brązowawoszary, luźny; 3 – trawertyn szarobrązowy, częściowo luźny; 4 – trawertyn średniodziarnisty, jasnoszary, luźny; 5 – trawertyn żółtawoszary, prawie zwarty, porowaty z warstwami z inkustowanymi liśćmi; 6 – trawertyn brązowawoszary, luźny z inkrustacją; 7 – trawertyn brązowawoszary, częściowo luźny; 8 – trawertyn drobnoziarnisty, jasnoszary, luźny; 9 – trawertyn szarowoszyty z rdzawymi nalołami limonitu na powierzchni; 10 – trawertyn drobnoziarnisty, jasnoszary, luźny z rdzawym nalotem limonitu; 11 – trawertyn drobnoziarnisty, ciemnoszary, luźny z ciemnymi plamami; 12 – mały ilasty ciemno brązowy z otoczakami i fragmentami skal – osady stokowe
to paludal species *Galba truncatula, Radix peregra* and *Succinea putris*, which indicates local presence of limited wetlands and small pools. These were surrounded to a large degree by continuous woodland formations of small areal extent, as evidenced by the common occurrence of woodland and wetland species. On the other hand, also the common occurrences of woodland species with open-habitat species should be taken into account. Among them, gastropod *Vallonia costata* was repeatedly encountered, being accompanied by *Vallonia pulchella, Truncatellina cylindrica* and *Pupilla muscorum*. Malacocoenological spectra thus show many indications of alternating changes in the appearance of the environment, which is typical for the Epiatlantic and Subboreal periods.

**Chronology**

The oldest portion of the tufa body is preserved in a small relic in the southern slope of the valley as indicated by the molluscan assemblages (Ložek, Jäger 1968). The molluscan assemblage dates tufa deposition to the younger stage of the Holocene – the Epiatlantic and Subboreal (*sensu* Jäger, 1969), dominated by wet forest environment. Younger parts of the tufa cascade are not preserved, maybe due to younger erosion, when running water eroded the tufa cascade. The youngest Holocene incision of the Čertova Gorge reached the underlying Late Pleistocene slope sediments. The spring now resurges near the base of the tufa body due to subrosion.

4. DISCUSSION ON THE DEVELOPMENT AND DESTRUCTION OF TUFA CASCADES IN THE BOHEMIAN KARST

4.1. CASCADE DEVELOPMENT

Holocene development of tufa cascades of the Bohemian Karst shares many common features conditioned by climatic and hydrologic influence. The formation of cascades, which were building on the bottoms of karstic valleys, must have postdated the end of intensive fluvial erosion characteristic for the Glacial/Holocene boundary (Vandenberghe 1993; Vandenberghe et al. 1994, a.o.). The tufa is usually underlain by limestone talus derived from the ambient slopes. Thicknesses of preserved talus depends largely on the character of source Paleozoic rocks forming valley slopes (e.g., stratification and tectonic deformation) and on the erosive potential of the stream at the site the cascade started to develop. Molluscan assemblages found in talus beneath the tufa evidence Boreal age of these colluvia.
Talus in the Císařská Gorge is secondarily cemented by carbonate precipitated from karst waters. Radiometric age of the cement was determined at 9,460 ± 1,200 years BP and 5,920 ± 1,520 years BP – see Table 1 and Figs 4 and 6. The tufa cascade at Svatý Jan pod Skalou also started to accumulate in the Boreal (Žák et al. 2001, 2002). Massive structural tufa with minimum clastic component were deposited on all cascades under climatically favourable condition of the Atlantic. Accumulations of these structural tufas reach up to 2–5 m in thickness (Kovanda 1971; Ložek 1992). Deposition of tufa continued in the late period of the Holocene climatic optimum (Epiatlantic). Short-term climatic oscillations, however, occurred in the Epiatlantic, being characterized by alternation of periods of relative aridity and humidity. These short-term climatic oscillations are indicated by horizons of initial carbonate soils and by talus intercalations in the tufa successions. Climatic oscillations culminated by markedly dry and warm period in the Subboreal (Jäger 1969). As a result, sedimentary record in younger portions of the tufa cascades is lithologically more variable, with alternating beds of friable and compact tufa, colluvio-fluvial sediments and soil horizons (Žák et al. 2001). Principal accumulation stages of tufa cascades in the Bohemian Karst are terminated in the late Subboreal at 2,500 BP (Žák et al. 2002).

Molluscan assemblages detected in the tufa bodies show many common features. Malacospectral analyses of tufas at Kotýz, Svatý Jan pod Skalou a Petráňka in the Karlické Valley revealed the proportions of molluscs of the main ecologic groups (Ecologic group: A – woodland species in general, B – open-landscape species in general, C – indifferent species, D – marsh and aquatic species) – Fig. 10. As the underlying intervals of the tufa bodies at Kotýz (Beds 16–11) and Svatý Jan pod Skalou (Beds 36–31) contain very poor malacozoological material, the ratio between the woodland malacofauna component and open-habitat component or indifferent species is biased to a considerable degree. In contrast, the overlying beds contain high numbers of molluscan species already and are fully eligible for statistical evaluation. As shown by the malacospectra, the overlying beds of the Atlantic–Epiatlantic climatic optimum marked by intensive tufa accumulation are dominated by woodland species in the malacocoenoses, while open-habitat species are scarcely represented (Svatý Jan pod Skalou, Kotýz) or present in very low proportions (Petránka). This indicates continuous woodland formations with prevalence of hydrophilous molluscan species. In the Epiatlantic phase, climatic oscillations culminate with the Subboreal period characterized by suppressed woodland component and the onset of open-habitat elements. This is particularly obvious from the malacospectra of tufas from Svatý Jan pod
Fig. 10. Malacospectra of species (MSS) showing the proportions of the main ecologic groups based on Ložek (1964)


Malacospektra gatunków (MSS) przedstawiające wzajemny stosunek głównych grup ekologicznych na podstawie Ložka (1964)

Skalou and Kotýz. In the Petránka tufa in the Karlické Valley, the Subboreal period is characterized by the abundant occurrence of gastropod *Vallonia costata*, a typical open-habitat species; however, the woodland component still maintains a prominent dominance. Molluscan assemblages from the youngest Holocene phases often share the features of modern communities as evidenced by molluscan occurrences in the neighbourhood of the tufa bodies (Ložek 1974; Hlaváč 2002).

4.2. TERMINATION OF CASCADE DEVELOPMENT

Termination of cascade development was due to the coming dry period, probably manifested in a discharge reduction of the karst springs. Reduced discharges of the issued water could have resulted in subrosion, which created new paths in the basal portions of the tufa bodies. Karst waters ceased to flow on top of the cascade surfaces. The onset of this dry period dates to the Late Bronze Age; it resulted in dramatic changes in vegetation and in molluscan communities, but also in a decrease in the activity of river systems. These phenomena have been documented from many regions of the Czech Republic. A major environmental change dating to the Late Bronze Age has been documented from central and northern Bohemia on the basis of multidisciplinary study of sediments deposited under sandstone rockshelters. Changes in molluscan communities indicate deforestation associated with more intensive agricultural use of land (Svoboda et al. 1996; Cílek et al. 1996). A sudden vegetational change in the Late Bronze Age is also indicated by pollen spectra from sediments filling an ox-bow lake of the Labe River near Tišice (15 km N of Prague). Such a change probably reflects increased anthropogenic stress on the environment (deforestation connected with agricultural activity) controlled by changing climatic conditions (Pokorný, in print). Given on archaeological evidence of settlement on the Klejnárka Stream flood plain (60 km SE of Prague), Pavlí (2002) identified a period of severe floods (3,500–2,500 BP), followed by a period of relative fluvial stability.

4.3. DESTRUCTION OF CASCADES

Erosion responsible for the destruction of all large tufa cascades in the Bohemian Karst must have been associated with a period extremely rich in flash precipitation events. Such period was characterized by increased discharges of streams but also of karst springs. The onset of erosion and cascade destruction is constrained by radiometric ages of carbonate laminae precipitated in a small cavity in limestone talus of Cascade II in the Cisařská Gor-
These laminae were formed at 1,880 – 450 years BP (sample TMS-5, see Table 1 and Fig. 6), prior to erosion, when the cavity was closed. Only a part of the carbonate filling of this cavity has been preserved: on the surface of a dilated fracture formed by detachment of a part of the cascade due to erosion and destruction of the body (Fig. 6).

Tufa cascades of the Bohemian Karst were destructed in the period of anomalous precipitation and increased fluvial activity. This is a characteristic obviously fitting the Little Ice Age (LIA) – one of the coldest periods in the whole Holocene (Bradley et al. 2003). Climate deterioration signalling the onset of the LIA in Bohemia was marked by a lowering of average winter temperatures and an increase of precipitation in the half of the 15th century (Brázdil 1996), and consequently by an increased incidence of flood events as documented by higher incidence of floods on the Berounka River (Ninger, Zelinka 1872), which flows across the Bohemian Karst area (Fig. 1). Increased flood activity of the Labe River in central Bohemia has been documented by radiometric dating of a stump of a tree growing on top of fluvial sediments of the Labe River near Lžovice. The age of the tree was set at 541 years BP (Šilar et al. 1994). It is significant that the tree stump is overlain by flood sands up to 3 m thick dating to the younger period of the LIA (Růžičková, pers. comm. 2003). The period of intensive fluvial erosion, deepening the beds of minor streams by as much as several metres in the LIA and in the 20th century, has been well documented from Great Britain and from Crete (Macklin et al. 1992; Maas et al. 1998). In both studied catchments, the authors give considerable significance not only to the climate deterioration but also to the anthropogenic land-use effect resulting in a weakened ability of land to retain water at extreme precipitation events.

It can be assumed that erosion and destruction of tufa cascades in the Bohemian Karst occurred during several flash precipitation events in the LIA and due to increased precipitation and severe floods in the 20th century. Larger volumes of water flowing through the Cisařská Gorge during the LIA is

Table 1. U-series age data of carbonates from tufa cascades in the Cisařská Gorge.

<table>
<thead>
<tr>
<th>Location</th>
<th>Sample</th>
<th>Lab. No.</th>
<th>U content (ppm)</th>
<th>U error (ppm)</th>
<th>234U/238U error</th>
<th>230Th/234U error</th>
<th>230Th/232Th error</th>
<th>Age (without correction) (ka)</th>
<th>Error (ka)</th>
<th>Corrected age (ka)</th>
<th>Error (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cascade I</td>
<td>TMS-1</td>
<td>W 743</td>
<td>2.363 ±0.042</td>
<td>1.367 ±0.018</td>
<td>0.097 ±0.002</td>
<td>9.7</td>
<td>±0.25</td>
<td>9.46 ±1.20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cascade II</td>
<td>TMS-5</td>
<td>W 744</td>
<td>0.786 ±0.015</td>
<td>1.985 ±0.032</td>
<td>0.020 ±0.001</td>
<td>10</td>
<td>±0.15</td>
<td>1.88 ±0.45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cascade II</td>
<td>TMS-28</td>
<td>W 914</td>
<td>1.162 ±0.021</td>
<td>1.876 ±0.034</td>
<td>0.088 ±0.003</td>
<td>6.4</td>
<td>±0.34</td>
<td>5.92 ±1.52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cascade II</td>
<td>TMS-29</td>
<td>W 917</td>
<td>1.789 ±0.032</td>
<td>1.735 ±0.028</td>
<td>0.008 ±0.001</td>
<td>2.3</td>
<td>±0.09</td>
<td>0.30 ±0.60</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
also indicate by the radiometric age of the carbonate precipitated on plant roots in Cascade II (sample TMS-29, see Table 1 and Fig. 6). The carbonate was precipitated on the root at 300 ± 600 years BP, i.e., at the time of undoubted existence of the fracture destructing the cascade (see above). At that time, however, water must have been still flowing across the upper part of the cascade.

The rate of erosion of sedimentary fill of a valley by running water can be observed on several examples. In 1995, extremely high precipitation resulted in the destruction of tufa layers up to 1 m thick in the valley of the Bubovický Creek 2 km NE of the Císařská Gorge (Žák et al. 1996). Second example of modern erosion is located in a small side valley at Dolní Roblín Village some 300 m N of the spring and the Petránka Cascade. This side valley was barred by an earth dam more than 80 years ago. A small reservoir formed upstream of the dam holding water to run the local mill. The dam was destructed during a severe flood of 1953, and a new channel was formed by headward erosion in the loamy fill of the valley. The new channel was considerably deepened due to the anomalous precipitations preceding the flood of 2002. Now, an erosive cut 3.8 deep is present at the site of the former dam (the stream incised by 2 m in August 2002). Strong erosion associated with the flood of 1953 also altered Cascade I in the Císařská Gorge: the erosive cut in the cascade as shown on a photograph of Petrbok (1955) taken before 1950 has a markedly narrower shape than it has today. Moreover, the young accumulation of tufa now depositing in the streambed (Fig. 5) is missing on the old photograph.

At present, accumulation of tufa prevails over its erosion at most localities in the Bohemian Karst area. New tufa bodies are being formed on eroded cascades in the Císařská Gorge and in the Čertova Gorge at Malá Chuchle. Present tufa formation has been reported from many other places in the Bohemian Karst (Kadlecová, Žák 1998). The rate of present tufa deposition can be observed at Malá Chuchle. An artificial streambed was constructed here, the walls of which were fixed with stone blocks in the late 1980s. Tufa is precipitated from karst water flowing through this channel. Since the time of this reconstruction, a tufa accumulation up to 0.6 m thick was built in the channel. It is, therefore, highly probable that the youngest tufa in the Císařská Gorge cascades was deposited during the last 50 years, thus representing a period of weaker fluvial and erosive activity.
5. CONCLUSIONS

1. Holocene tufa cascades of the Bohemian Karst were growing in the Boreal to Late Subboreal period (9,500–2,500 years B.P.). The end of their formation is marked by the onset of a dry period in the Late Bronze Age. This climatic change accelerated agricultural activity associated with vegetational changes (deforestation). These processes have been documented at many sites in central Bohemia.

2. Erosion and destruction of tufa cascades continued in a period of frequent flash precipitations. The local erosion of some cascades in the Bohemian Karst in the last years makes us to assume that most cascades of the Bohemian Karst were destructed in the recent past – probably during the LIA. In this perspective, LIA seems to be the period of maximum erosion intensity within the whole of the Holocene.

3. The last 50 years (before 1997) in Bohemia were marked by the absence of floods and by a relatively low intensity of fluvial erosion. As a result, new tufa accumulations grew on some of the cascades.

Acknowledgements

This study was supported by GACR grant project 205/02/0449 and is linked with the project of the Institute of Geology AS CR – CEZ Z3-013-912.

REFERENCES


**TWORZENIE I NISZCZENIE HOLOCEŃSKICH KASKAD TRAWERTYNOWYCH W KRASIE CZESKIM (REPUBLICA CZESKA)**

Streszczenie

logicznych. W epoce późnego brązu, w efekcie zmian klimatycznych powodujących spadek wydajności źródeł, tworzenie trawertynów zostało zahamowane. Osuszenie klimatu widoczne w wielu profilach Środkowych Czech przyśpieszone było przez wzrost aktywności rolniczej i przez związane z nim odlesienie terenu. Niszczenie kaskad rozpoczęło się w okresie po 2 000 lat BP. Związane było ono z okresami anomalnie wysokich i gwałtownych opadów i powodowaną przez nie wzmożoną aktywność rzek. Najprawdopodobniej w okresie małej epoki lodowej niszczenie kaskad osiągnęło największą intensywność. W okresie ostatnich 50 lat (przed 1997) w Czechach nie były notowane istotne powodzie i intensywność erozji rzecznej była stosunkowo niska. W rezultacie, lokalnie, nastąpiło wznowienie depozycji trawertynów w badanych stanowiskach. Jednak w wielu stanowiskach obserwować można ślady niszczenia trawertynów w okresach wzmożonych opadów i powodzi z ostatnich lat.

Adres of the Author’s:

Jaroslav Hlaváč, Karel Žák,
Institute of Geology AS CR,
Rozvojová 135, CZ–16502 Praha 6, Czech Republic
e-mail: jhlavac@gli.cas.cz

Jaroslav Kadlec
Czech Geological Survey,
Klárov 3, CZ–11821 Praha 1, Czech Republic
e-mail: kadlec@gli.cas.cz

Helena Hercman
Institute of Geological Sciences, Polish Academy of Sciences,
ul. Twarda 51/55, 00–818 Warszawa, Poland
e-mail: hhercman@twarda.pan.pl