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Climate-induced changes in Holocene calcareous tufa formations, Bohemian Karst, Czech Republic

Karel Žák[a,*], Vojen Ložek[b], Jaroslav Kadlec[b], Jana Hladíková[a], Václav Cílek[b]

[a] *Czech Geological Survey, Klárov 3, 118 21 Praha 1, Czech Republic*
[b] *Institute of Geology, Czech Academy of Sciences, Rozvojová 135, 165 00 Praha 6, Czech Republic*

Abstract

About 70 localities where Holocene calcareous tufa is formed recently and/or was formed in the past are known in the Bohemian Karst, a small karst area located SW of Prague. All known tufa accumulations display a very similar pattern of lithological and biostratigraphic evolution, reflecting climatic changes, erosion events and biota succession. A 17 m thick tufa accumulation at Svatý Jan pod Skalou was selected and thoroughly studied as a typical, well developed representative of local tufa deposits. Tufa formation started at about 9500 BP, on a flat fluvial gravel terrace of Late Glacial/Early Holocene age. Deposition of lithologically uniform, pure hard porous tufa continued until about 6500 BP. From that time, a more unstable climate with several dry periods and erosion events produced a lithologically varied complex of loose tufa alternating with embedded soils and scree layers. Termination of the tufa deposition occurred about 2500 BP, and was followed by partial erosion connected with relocation of the spring below the tufa body. Holocene climatic changes were recorded in lithology, molluscan assemblages, and oscillations of oxygen and carbon stable isotope ratios in carbonate. The observed patterns are in good agreement with the evolution of calcareous tufa deposits throughout Central Europe. © 2002 Elsevier Science Ltd and INQUA. All rights reserved.

1. Introduction

The Bohemian Karst, formed by limestones of Paleozoic age and located in the central part of Bohemia between Praha and Zdice, is an area with numerous deposits of calcareous tufa of Holocene age. In this karstic area (approx. 200 km^2) about 70 localities where calcareous tufa precipitates or was deposited in the past are known (Kovanda, 1971; Ložek, 1992; Kadlecová and Žák, 1998). In general, the following three morphogenetic types of tufa accumulations can be distinguished (using terminology of Ford and Pedley, 1996):

- *valley-side*, with perched spring accumulations on slopes, with small extent but locally large thickness (a very frequent type, but carbonate precipitation is usually limited for this type under present-day conditions),
- *fluvial* accumulations in surface streams, usually braided but rarely small barrage types (with less or more intensive active deposition under present-day conditions), and
- *lacustrine and paludal* accumulations (inactive under present-day conditions, deposited in flat valleys of the southern part of the area, typically during the climatic optimum of the Holocene).

Very little information about these calcareous tufa localities exists in the international literature, though regional, usually Czech- or German-language literature is voluminous and lists almost 100 papers (see Kovanda, 1971 or Žák et al., 2001, for a review). Some 20 tufa bodies of the area were studied using lithological and especially biostratigraphical methods (assemblages of *Mollusca*) over the past decades. Detailed study, based on application of geological, biostratigraphical and geochemical methods combined with dating was still missing. A combination of biostratigraphical study with stable isotope data can be especially useful, since both methods can decipher different aspects of past climatic changes. Holocene tufa accumulations were generally shown to contain a stable isotope record of paleoclimatic change (Pazdur et al., 1988; Andrews et al., 1994, 1996).

The calcareous tufa body at Svatý Jan pod Skalou was selected as a case section for detailed study of tufa deposition in the Bohemian Karst. This section exhibits

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*Corresponding author.

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the largest thickness of Holocene calcareous sediments of the whole area and was frequently studied in the past (e.g., Babor, 1901; Petrbok, 1923, 1956; Němejc, 1928; Ložek, 1955, 1959, 1964, 1967a; Jäger and Ložek, 1968; Kovanda in Šibrava et al., 1969; Kovanda, 1971; Horvatinčić et al., 1989; Šilar et al., 1990; Bouzek, 1993; Ložek and Cílek, 1994, 1995; Benková and Čtverák, 1998; a full list of all references related to the locality is given in Žák et al., 2001), is well accessible for study, and represents a unique archive of Holocene development of the whole area.

As already shown by Ložek (1992), most of the Holocene calcareous tufa accumulations of the Bohemian Karst show very similar biostratigraphical and lithological pattern, reflecting Holocene climatic and biota changes. The tufa section at Svatý Jan pod Skalou fulfills requirements for a type locality with record spanning a major part of the Holocene.

2. Site description

Svatý Jan pod Skalou (literally St. John under Rock) is a village located 25 km SW of Prague in a deep valley of the Kačák stream incised into Silurian and Devonian sedimentary sequences. A karstic spring (mean discharge of about 20 l/s) resurges near the valley bottom above the boundary between limestone and underlying volcanic rock. The resurgence site is controlled by longitudinal and transverse faults. Detailed 3 yr monitoring of the present-day spring (Buzek et al., 1998; Žák et al., 2001) concluded that water with long residence time (approximately 20 yr based on ^{3}H data) dominates. The temperature of the spring water oscillated between 10.5°C and 11.6°C with an average of 11.4°C, which is significantly higher than the annual mean temperature of the area (approximately 8.5°C), and indicates deep and slow groundwater circulation. The spring shows limited discharge variability. The maximum observed discharge during local floods was only about twice of the observed discharge minimum during an extended drought period. Present-day mean annual precipitation of the area is slightly above 500 mm.

The studied calcareous tufa body can be morphologically classified as valley-side-sited, perched spring accumulation with relatively small lateral extent (about 5000 m^2), large thickness (up to 17 m), a steep frontal cascade, and almost horizontal strata behind the cascade.

The existence of a permanent source of drinking water attracted man's attention to this place very early. Several caves of the area were inhabited as early as Late Paleolithic, and a large fortified settlement of Late Bronze/Early Iron Age was discovered during field studies on a hill above the spring. According to medieval and Baroque legends, the hermit St. Ivan lived in a cave inside the tufa body in the 9th century AD. The tufa cave is mentioned in a manuscript dated 1205. The hard tufa was quarried as early as the 12–13th century, as indicated by the tufa portal of the Romanesque church in nearby Tetín. The spring and tufa became one of most important places of pilgrimage during the Baroque period. Some of the early descriptions of the site and karstic processes date back to Renaissance court of emperor Rudolf II. Almost half of the tufa body was extracted for building material, but on the other side artificial profiles including large cellars made the profiles accessible for detailed studies. The location and extent of the calcareous tufa body at Svatý Jan pod Skalou are shown in Fig. 1.

The internal structure of the accumulation is best seen in an artificial longitudinal cut through the tufa body, about 70 m long. The outcrop starts at the steep frontal part of the deposit adjacent to the church in the NW, continues as an 8 m high artificial cut ca. 30 m long to the SE, then extends to the E and continues for ca. 45 m along the shallow gully (Fig. 2). At the spot where this longitudinal profile changes its direction, an excavated 6 m deep test pit is located. The total thickness of calcareous Holocene deposits is nearly 17 m here. This vertical section was selected for an integrated study (see Fig. 3).

A dry karstic valley, Propadlé vody (Sunken Waters), is located east of the tufa body. The ephemeral, episodic stream transported clastic material through this valley during strong precipitation events. The layers of clastic deposits are preserved especially in the upper portion of the tufa body. An increasing volume of limestone scree

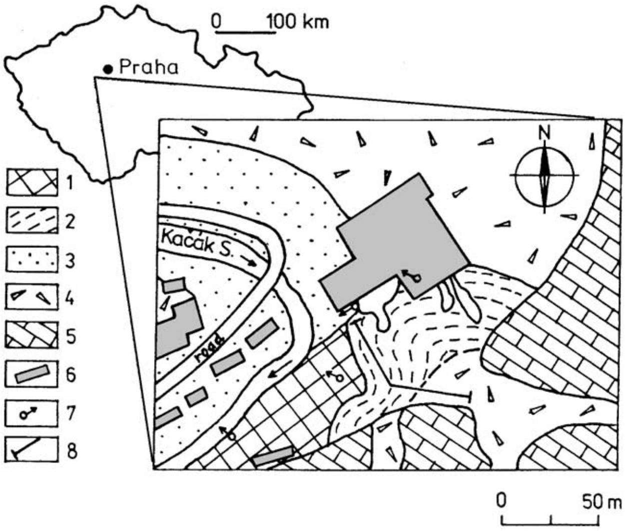


Fig. 1. Sketch-map of the calcareous tufa accumulation at the Svatý Jan pod Skalou. (1) anthropogenic deposits, (2) calcareous tufa body including natural and artificial cavities, (3) fluvial deposits, (4) slope deposits, (5) Paleozoic limestones, (6) buildings including the monastery and church complex in the centre, (7) karst spring, (8) longitudinal profile through tufa body (see Fig. 2).

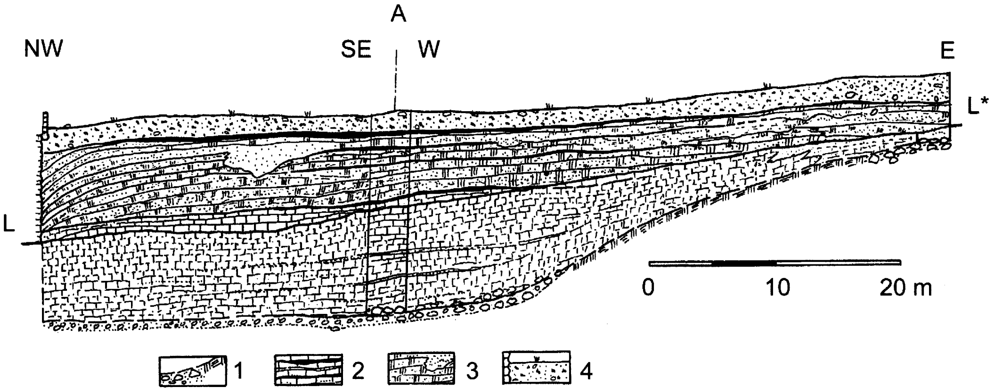


Fig. 2. Longitudinal profile of the calcareous tufa accumulation at the Svatý Jan pod Skalou: idealized and simplified profile through tufa accumulation. The line L—L* represents the level of erosional gully bottom and axis A a bend of the profile. Only the left upper part of the profile is accessible to direct observation. The other parts are either compiled from former unpublished sources (especially Kovanda and Ložek in Žák et al., 2001) or deduced from a pit and bore hole located along A axis, outcrops in nearby cellars of the monastery and in Cave of St. Ivan, and by earth radar results. The actual stratigraphy is very complex and besides climatic factors it reflects different tufa facies such as pool-rim transitions. It can be simplified into four basic complexes: (1) Underlying sediments are formed either by rock scree (local Paleozoic limestones and volcanites) or by fluviatile sediments (gravels). (2) The massive phytohermal tufa used as building material occurs as a flat body in the lower part of the profile. Several loose to sandy tufa intercalations were observed. (3) The main body of tufa exposed above the gorge bottom consists of highly heterogeneous strata where massive layers alternate or form facial transitions into loose tufas that sedimented in pools. Notice the "cascade" inclination of layers close to the left end of profile. The profile is interrupted there by the church wall. The horizontal dark layers represent humic soils, calcified soil sediments and intercalations of rock scree. (4) The uppermost part is formed by anthropogenic sediments associated with construction of monastery, prehistoric cultural layers, soils and different slope sediments.

in the sections under the outlet of the Propadlé vody gorge was reported by Kovanda in Šibrava et al. (1969) (see Fig. 2). However, the massive tufa of the lower part of section contains almost no scree or fallen boulders from the high cliff above the tufa body. Rock disintegration had to be limited during the first half of the Holocene, possibly because the rocks were partly covered and thus protected by vegetation and because the mild oceanic-type climate limited the number and intensity of freeze-thaw cycles.

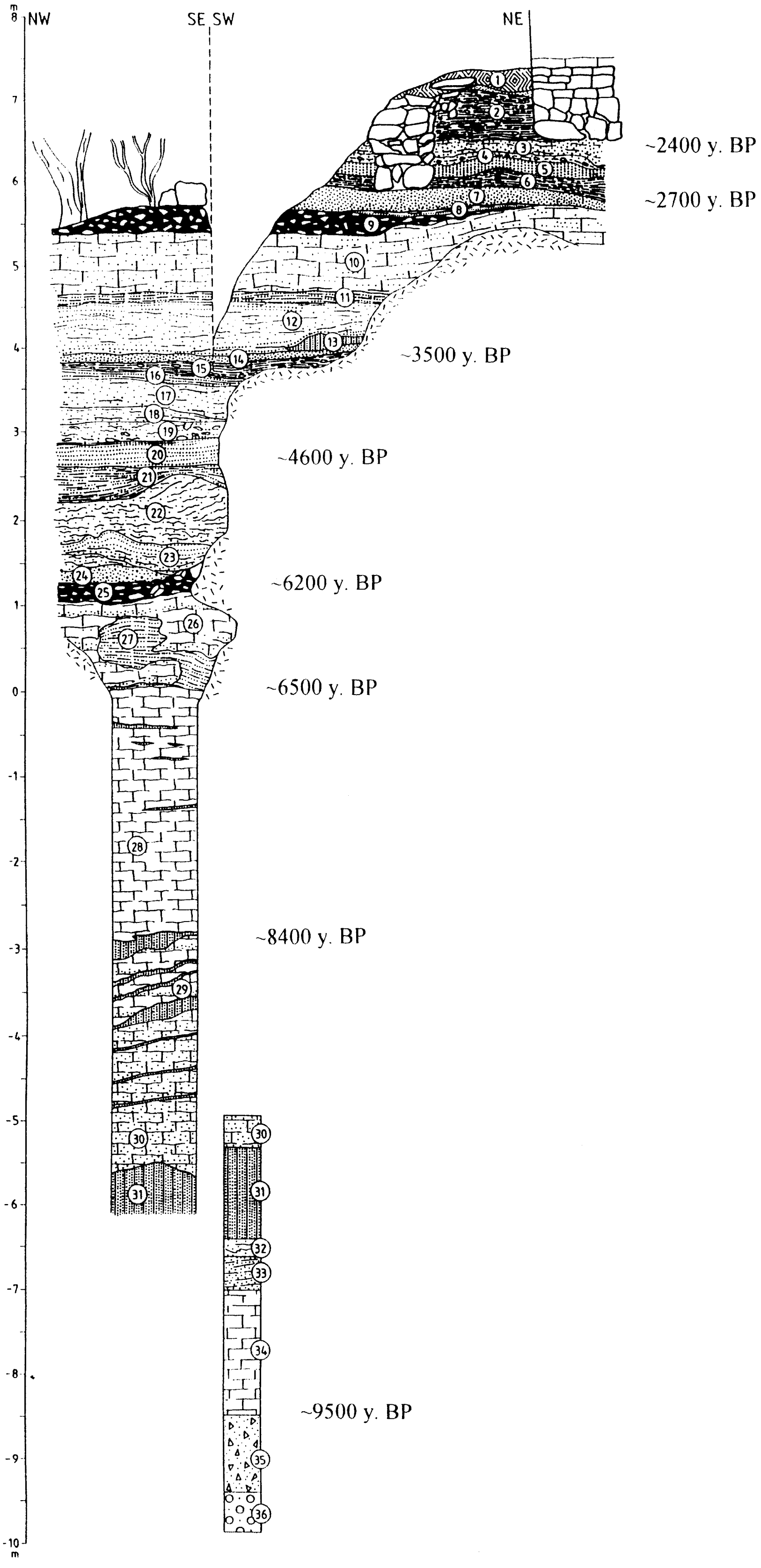
The spring resurges now at the base of the tufa accumulation. The position of the original resurgence point is unknown, but it is generally believed that it was located either somewhere in the upper part of the tufa body or not far above in the Propadlé vody gorge. It is evident that the position of the resurgence orifice was not stable during tufa formation. As indicated by drillings below the church and at the bottom of the test pit, most of the tufa accumulation is underlain by the fluvial terrace of the Kačák stream formed by pebbles of Upper Proterozoic graywackes, shales and silicites.

Lithology of the calcareous tufa deposits is variable both laterally and vertically. The frontal cascade is formed by hard porous phytohermal (structural) tufa across the whole thickness of the deposit. Behind the frontal cascade, where individual sedimentary layers are horizontal or sub-horizontal, two lithologically different complexes can be defined, with the boundary between them roughly equivalent to the test pit top, i.e. level 0 m in Fig. 3:

(i) the lower lithologically uniform sequence of hard porous tufa with only a few intercalations of loose tufa containing a very limited amount of clastic material, and
(ii) the upper lithologically varied complex of layers of porous phytohermal tufa, oncoidal tufa and even lacustrine-like tufa intercalated with several horizons of buried soils and horizons of limestone scree.

The uppermost portion of the sequence contains numerous fragments of prehistoric pottery (especially beds No. 3–9 in Fig. 3) produced in the Late Bronze or Early Iron ages (approximately 8th–5th century BC, Benková and Čtverák, 1998).

Based on micromorphological study, the soil horizons preserved in the upper part of the sedimentary sequence are autochthonous (or semi-autochthonous) rendzina-type soils, with minor admixture of quartz, mica and feldspar grains, indicating transport of clastic material on the surface of the tufa accumulation during soil evolution (Žigová in Žák et al., 2001). The scree horizons are dominated by angular limestone fragments but also contain quartz clasts and pebbles, indicating transport of sedimentary material derived from Mesozoic karst infillings and Tertiary fluviatile terraces from the upper segment of the gorge.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Tufa mineralogy is very uniform, dominated by low-Mg calcite with minor admixture of clay minerals and quartz grains in the upper portion of the sequence. Yellow, red and black strips of Fe- and Mn-hydroxides (MnO_2 type) precipitated on the contacts between soils and tufa due to the influence of geochemical barriers.

Some authors (e.g., Ložek, 1963; Kovanda, 1964) have suggested diagenetic changes of calcareous tufa resulting in significant solidification of the tufa by filling of open spaces and recrystallization of calcite (so called "travertinization of tufa"). Detailed study of hard tufa from the lower portion of the sequence has shown that even small cavities around decomposed roots or stems remained unfilled by secondary carbonate. The diagenetic processes were therefore of minor importance or were restricted to partial recrystallisation of the already precipitated material. Petrological study suggests that tufa diagenesis which took place probably almost immediately after tufa deposition should have no significant effect on the isotopic record. We observed that the hardening and diagenesis of modern tufa deposits frequently happens within a few years after deposition, and subsequently the carbonate system remains "locked" to secondary changes.

Fig. 3. The studied section. Lithology: (1) dark brown humic soil with small limestone and tufa clasts with a layer of tufa scree at the base, (2) brown humic soil with limestone clasts and a layer of limestone scree, (3) light brown extremely loose tufa mixed with brown soil with frequent tufa clasts, (4) limestone scree with silty and tufa matrix, (5) brown sandy soil with tufa scree 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) limestone scree with silty and sandy matrix, (10) grey–yellow partly loose tufa, (11) grey–yellow extremely loose tufa with brown silty and sandy layers, thin layer of limestone scree at the base, (12) light grey solid tufa, loose in places, (13) brown sandy soil with tufa clasts, (14) light grey solid tufa, loose in places, (15) dark brown sandy and clayey soil, (16) grey to brown–grey strongly loose tufa with rusty limonite streaks, (17) grey to brown–grey strongly loose tufa with limonite streaks, (18) light grey solid tufa, loose in places, (19) whitish grey solid tufa with conspicuous limonite streak at the top, (20) light grey 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 lenticular layer of sandy gravel in the upper part, (25) limestone scree with sandy matrix, (26) light brown strongly loose tufa, locally with silty matrix, (27) yellowish white solid tufa, (28) grey–yellow to light grey massive solid tufa, (29) light grey strongly loose tufa, locally with silty admixture, (30) grey yellow to light grey massive solid tufa, (31) light grey to brown strongly loose tufa, locally with silty 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) limestone scree with tufa fragments and incrustations in the upper part, pebbles of Paleozoic and Proterozoic rocks in the lower part of the layer, (36) sandy fluvial gravel with pebbles of Paleozoic and Proterozoic rocks and minor presence of limestone scree.

3. Methods

3.1. Malacozoology

Samples for the study of molluscan assemblages were taken in several sampling campaigns from 18 levels in the section, including the test pit S1 and core obtained by drilling at the bottom of the test pit. Samples with volume 5–10 L were dried and wet-sieved before separation of the molluscan shells. The techniques of sampling and shell separation were described by Ložek (1964).

3.2. Dating

For radiometric dating of the calcareous tufa, a combination of several dating methods was applied. The only method for which a sample can be collected anywhere in the studied section is ^{14}C dating of carbonate. By this method 11 samples covering 14.3 m of the thickness have been dated by conventional counting method in the Environmental Isotope Laboratory, Department of Earth Sciences, University of Waterloo, Canada. Organic matter, either small pieces of charcoal or sedimentary organic matter of buried soils, 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 in the Rafter Radiocarbon Laboratory, Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand. The ^{14}C data on organic matter have been calibrated for variable initial concentration of ^{14}C using published calibration curves. In the intervals between dated samples, ages of individual depth levels were calculated assuming constant accumulation rates. In the interval between the deepest sample of organic matter dated by AMS ^{14}C (-2.95 to -3.05 m) and the base of tufa accumulation (i.e., -9.65 m) the age difference was estimated based on carbonate ^{14}C data, which indicates an age difference of about 1000 yr between these two horizons. Several samples of tufa were dated also by ^{230}Th/^{234}U (α-particle counting) method in the Centre d'Etudes et de Recherches Appliquées au Karst, Faculté Polytechnique de Mons, Belgium, and in the Institute of Geological Sciences of the Polish Academy of Sciences, Warszawa.

3.3. Stable isotope study

Samples for geochemical study were collected by the channel method, each sample representing an average of a section segment about 0.2 m thick. Altogether 83 samples were collected in two sampling campaigns. After drying coarse clastic material was removed by combination of sieving and hand-picking, with special care given to the removal of any clasts of

Paleozoic limestones. Samples were then homogenized, and carbonate content, organic matter content, carbonate $\delta^{13}C$ and $\delta^{18}O$ and organic matter $\delta^{13}C$ were determined.

3.4. Other methods

Many other methods were used to determine the tufa mineralogy and petrology (electron microprobe JEOL-JXA-50A, difractograph Philips), to describe local karst hydrology (water chemistry, tracing experiments, $\delta^{18}O$ and ^{3}H study of water, $\delta^{15}N$ study of dissolved nitrate), and the geology of tufa deposit (ground-penetrating radar). All three important outlets of the karst spring were monitored for 3 yr with respect to temperature and discharge. The prehistoric finds were collected at several places and examined by an archaeological team. Analyses of slope sediments, soils, cave infillings was conducted. The results of these interdisciplinary studies are described in a monograph (Žák et al., 2001), but in this paper we focus on climatic and environmental analysis only.

4. Biostratigraphical record

Molluscan shells are present in all layers of the studied section. They are much more abundant in loose sediments than in solid phytohermal tufa. The malacofauna from this site was described previously by Petrbok (1923) and this first list of species was repeatedly supplemented (see Petrbok, 1956, for a review). Petrbok attributed all molluscan records from Svatý Jan to the "Atlantic Littorinian", a moist phase in which a great majority of tufa deposits of the Bohemian Karst were formed. The malacofauna described by Petrbok consists predominantly of demanding woodland species and includes no elements of Early Holocene *Discus ruderatus*-fauna, because the Early Holocene layers were not exposed at that time. Of particular interest is a rather high number of aquatic species reported by Petrbok, for instance the presence of *Bathyomphalus contortus (L.)*; among terrestrial species even the alpine element *Neostyriaca corynodes (Held)* is cited, whose occurrence in the Holocene of the Bohemian Karst is unlikely.

New investigations were initiated in 1960 when K.-D. Jäger and V. Ložek cleaned and documented the section which was later connected with the excavated research pit (see Fig. 1 for location, Fig. 3 for a section drawing). During the recent period earlier studies were complemented by more precise analysis of molluscan assemblages from the test pit and research drilling. The results are given in Table 1 including information on ecology and biostratigraphy of each species.

The entire section is dominated by a well-developed woodland malacofauna, which includes a number of species with high temperature and moisture requirements, i.e., an assemblage corresponding to the climatic optimum. The number of shells transported from various habitats surrounding the tufa deposit, particularly from xerothermic rock cliffs, remains very low throughout the sequence. Changes in the occurrence of several species as well as in the presence of particular ecological groups enable the tufa sequence to be subdivided into several units characterized by the presence/absence of certain elements.

The number of species and specimens obtained from the lowermost section of the accumulation using the research drilling (layers 31–36) was very small. The occurrence of individual species did not differ significantly from the overlying complex of solid tufa studied in more detail.

The basal complex of solid tufa in the excavated test pit (layers 30 to 28) is characterized by high numbers of two open-country species—*Truncatellina cylindrica* and *Vallonia costata*—which suddenly disappear in horizon 28. This layer is characterized by abrupt decrease in species richness. *Carychium tridentatum* is abundant. *Trichia sericea,* characteristic of the older half of Holocene, occurs in layers 30 to 28. The lowermost horizon 30 contained the demanding thermophilous element *Truncatellina claustralis* associated with Early Holocene elements, such as *Discus ruderatus* and *Perpolita petronella* that occur in very small numbers. Interesting is the occurrence of *Laciniaria plicata* and the appearance of neoendemic *Bulgarica nitidosa* in the loose interlayer 29. Some species characteristic of the younger half of the Holocene, particularly *Helicodonta obvoluta*, and aquatic species are absent.

Loose layers between the complex of solid tufa (28–30) and lower scree horizon (25) include a very rich malacofauna characterized by the appearance of sensitive woodland species, such as *Platyla polita*, *Bulgarica cana,* and *Cochlodina orthostoma*. Early Holocene elements are represented by *Clausilia cruciata*, whereas *Trichia sericea*, *Vallonia costata* and *Truncatellina cylindrica* disappear. Of interest is the find of one specimen of *Chondrina avenacea*, a rupestral epilithic species, and the strong occurrence of aquatic species *Radix ovata* and *Pisidium* spp. The woodland species show a marked increase in the assemblage. Early Holocene elements, for example *Discus ruderatus* and *Perpolita petronella*, decline and disappear in the loose layers 26 and 27. All these data suggest a rather open forest with denser parklands in some places under very favorable soil and moisture conditions, which corresponds to the late Atlantic phase.

The lower scree horizon (25) is characterized by maximum species richness (46 species), high numbers of aquatic and wetland elements, as well as by the appearance of *Isognomostoma isognomostomos*. The genus *Aegopinella* is here probably represented even by the hygrophilous species *Ae. nitens*. This horizon provided the only specimens of *Vertigo alpestris,* and the last occurrence of *Discus ruderatus*. Even though the scree indicates transport of clastic material from the surroundings, the horizon includes no rupestral species coming from the cliffs situated in the neighborhood of the tufa deposit.

The thick complex (layers 24 to 10) between the lower and upper scree horizons is characterized by a wide variety of lithofacies reflecting the alternation of tufa wetlands, small pools and short dry periods, but its assemblages are less diverse. Aquatic and wetland species remain important and their representation attains its maximum in the intercalation of fine limnic tufa (layers 21 and 20), largely dominated by *Radix ovata* with subordinate *Pisidium casertanum*. Only this horizon contained the wetland element *Oxyloma elegans*. In layer 17, *Arianta arbustorum* and *Helicigona lapicida* appear, whereas the first record of a species characteristic of the younger part of Holocene, *Helicodonta obvoluta*, comes from the layer 12. The richest woodland assemblage was recorded in layer 15 (32 species).

The upper scree with humic rendzina matrix and prehistoric pottery (layers 9 to 7), archaeologically dated to the declining Bronze Age and Early Iron Age at about 800–500 BC, includes again species-rich (34 and 38 species) assemblages, in which woodland snails remain dominant. Even here, thermophilous *Truncatellina claustralis* appears in association with *Ena obscura*.

Table 1
Assemblages of *Mollusca* in individual layers of calcareous tufa in Svatỳ Jan pod Skalou. Layer numbers relate to Fig. 3

Ecological-biostratigr. characteristics				List of species	Layer No.																	
					36	35 B	35 A	33	31	30	29	28	26/27	25	20/21	17	15	12	9	7	4	2
A	1		!	*Acanthinula aculeata (Müller)*	-	-	-	-	-	+	+	-	+	+	+	+	+	+	+	+	-	-
			!	*Aegopinella nitens (Michaud)*	-	-	-	-	-	-	-	-	-	+?	-	-	-	-	-	-	-	-
			!	*Aegopinella pura (Alder)*	-	-	-	-	-	+	+	+	+	+	+	-	+	+	+	+	-	+
			!	*Bulgarica cana (Held)*	-	-	-	-	-	-	-	-	+	+	-	-	-	-	-	-	-	-
				Clausilia cruciata (Studer)	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-
			!	*Cochlodina laminata (Montagu)*	-	-	-	-	+	-	+	-	+	+	-	+	+	+	+	+	+	+
			!	*Cochlodina orthostoma (Menke)*	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-
			(G)	*Discus ruderatus (Férussac)*	-	-	-	-	-	+	-	-	-	+	-	-	-	-	-	-	-	-
			!	*Ena montana (Draparnaud)*	-	-	-	-	-	+	-	-	-	+	-	-	-	-	-	+	+	+
			!	*Ena obscura (Müller)*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	-	-
			!	*Helicodonta obvoluta (Müller)*	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+	+	+
			!	*Isognomostoma isognomostomos (Schröter)*	-	-	-	-	-	-	-	-	-	+	-	-	-	-	+	-	-	+
			!	*Macrogastra plicatula (Draparnaud)*	-	-	-	-	-	+	-	-	+	+	-	-	+	+	+	+	+	-
			!	*Monachoides incarnatus (Müller)*	+	+	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
			(G)	*Oxychilus depressus (Sterki)*	-	-	-	-	-	+	-	-	-	+	-	-	-	-	-	-	-	-
			!	*Petasina unidentata bohemica (Ložek)*	-	-	-	-	+	+	+	+	+	+	-	-	+	+	+	+	-	+
			!	*Platyla polita (Hartmann)*	-	-	-	-	-	-	-	+	+	+	-	+	+	+	+	-	-	+
				Semilimax semilimax (Férussac)	-	-	-	-	+	+	+	+	+	+	+	+	+	+	-	-	-	-
			!	*Sphyradium doliolum (Bruguiere)*	-	-	-	-	-	+	+	+	+	+	-	+	+	+	+	+	+	+
			(!)	*Vertigo pusilla Müller*	-	-	-	-	-	+	+	-	+	+	-	-	+	+	+	+	+	-
	2	W (M)	!	*Alinda biplicata (Montagu)*	-	-	-	-	-	+	+	-	+	+	+	+	+	+	+	+	+	+
			(+)	*Arianta arbustorum (Linné)*	-	-	-	-	+	-	-	-	-	-	-	+	+	+	+	+	+	-
			!	*Cepaea hortensis (Müller)*	-	-	-	-	+	-	+	-	+	+	-	-	-	-	-	+	-	+
			!	*Discus rotundatus (Müller)*	-	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+
			!	*Limax sp. (cf.cinereoniger Wolf)*	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-
		W (S)	!	*Aegopinella minor (Stabile)*	-	+	-	+	+	+	-	+	+	+	+	+	+	+	+	+	+	+
			(!)	*Fruticicola fruticum (Müller)*	+	-	+	+	+	+	+	+	+	+	-	+	+	-	-	+	-	+
			!	*Helix pomatia Linné*	-	-	-	+?	-	+	+	-	+	+	-	+	+	+	-	-	-	+
		W (H)	(+)	*Vitrea crystallina (Müller)*	-	-	-	-	+	+	-	+	+	+	+	+	-	+	-	-	-	-
	3		(G)	*Clausilia pumila C.Pfeiffer*	-	-	-	-	-	-	+	-	+	+	-	-	+	-	+	+	+	-
			!	*Macrogastra ventricosa (Draparnaud)*	-	-	-	-	+	+	+	+	+	+	+	+	+	+	-	+	+	-
			!	*Urticicola umbrosus (C.Pfeiffer)*	-	-	-	-	+	-	-	-	+	+	+	+	+	-	+	+	+	-
B	4	S	M	*Cecilioides acicula (Müller)*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+
			(+)	*Granaria frumentum (Draparnaud)*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	+	+
		Ca		*Chondrina avenacea (Bruguiére)*	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-
		S (W)	!!	*Truncatellina claustralis (Gredler)*	-	-	-	-	-	+	+	-	+	-	-	-	-	-	+	-	-	-
	5		+	*Pupilla muscorum (Linné)*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+
			(!)	*Truncatellina cylindrica (Férussac)*	-	-	-	-	-	+	+	-	-	-	-	-	-	-	-	-	-	-
			(+)	*Vallonia costata (Müller)*	-	-	-	+	-	+	+	-	+	+	-	-	-	+	+	+	+	+
			G	*Vallonia pulchella (Müller)*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-

Ecological-biostratigr. characteristics				List of species	Layer No. 36	35 B	35 A	33	31	30	29	28	26/27	25	20/21	17	15	12	9	7	4	2
C	6		!	*Bulgarica nitidosa (Ulicný)*	-	-	-	+	-	-	+	-	+	+	-	-	+	+	+	+	+	+
			(!)	*Cochlicopa lubricella (Porro)*	-	-	-	-	-	+	+	-	-	+	-	-	-	-	+	+	-	+
			(!)	*Euomphalia strigella (Draparnaud)*	-	-	-	+	+	+	+	-	-	+	-	-	-	+	+	+	-	+
			!	*Tandonia rustica (Millet)*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-
	7	Me	(+)	*Cochlicopa lubrica (Müller)*	-	-	-	-	+	+	+	+	+	-	-	+	+	+	-	-	-	+
			(+)	*Euconulus fulvus (Müller)*	-	-	-	-	-	+	+	+	+	+	+	-	+	+	-	+	-	-
			(+)	*Limacidae /Agriolimacidae*	-	-	-	-	+	-	+	+	-	+	-	+	+	+	+	+	+	+
			(+)	*Perpolita hammonis (Ström)*	-	-	-	-	-	+	+	-	-	+	-	-	-	-	-	-	-	-
			(+)	*Punctum pygmaeum (Draparnaud)*	-	-	-	-	-	+	+	-	+	+	-	+	+	-	+	+	-	-
			+	*Trichia hispida (Linné)*	-	+	-	+	-	-	-	+?	+	-	-	+	-	-	+	-	-	-
			(+)	*Trichia sericea (Draparnaud)*	-	-	-	-	-	+	+	+	-	-	-	-	-	-	-	-	-	-
			!	*Vitrea contracta (Westerlund)*	-	-	-	-	-	+	+	-	+	+	-	-	+	-	-	-	-	-
			(G)	*Vitrina pellucida (Müller)*	-	-	-	-	-	-	-	-	-	-	+	-	-	-	+	-	-	-
		Wp	(+)	*Clausilia dubia (Draparnaud)*	-	-	-	-	-	-	-	-	+	+	-	-	-	-	-	-	+	-
			!	*Helicigona lapicida (Linné)*	-	-	-	-	-	-	-	-	-	-	-	+	+	+	+	+	+	+
			!	*Laciniaria plicata (Draparnaud)*	-	-	-	+	-	+	-	-	-	-	-	-	-	-	-	-	+	-
			G	*Vertigo alpestris Alder*	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-
	8		!	*Carychium tridentatum (Risso)*	-	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-
			(!)	*Columella edentula (Draparnaud)*	-	-	-	-	+	+	+	+	+	+	+	+	-	-	-	+	-	-
			(G)	*Perpolita petronella (L.Pfeiffer)*	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-
			+	*Succinella oblonga (Draparnaud)*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-
D	9		G	*Carychium minimum Müller*	-	-	-	-	-	-	-	-	+	+	-	-	-	-	+	-	-	-
			(G)	*Oxyloma elegans (Risso)*	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
			(+)	*Succinea putris (Linné)*	-	-	-	-	-	+	+	+	+	+	-	-	-	-	+	+	+	+
			G	*Zonitoides nitidus (Müller)*	-	-	-	-	-	+	+	-	+	+	+	-	+	+	+	+	-	-
	10		(+)	*Aplexa hypnorum (Linné)*	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-
			(+)	*Galba truncatula (Müller)*	-	-	-	-	-	-	-	-	-	-	-	+	+	-	-	+	+	-
			(+)	*Pisidium casertanum (Poli)*	-	-	-	-	+	-	-	-	+	+	+	-	+	-	-	-	+	+
			(+)	*Pisidium obtusale (Lamarck)*	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-
				Pisidium personatum Malm	-	-	-	-	-	-	-	-	+	+	+	+	+	+	+	+	+	-
				Pisidium supinum A. Schmidt	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+
			(+)	*Radix ovata (Draparnaud)*	-	-	-	-	+	-	-	-	+	+	+	+	+	-	-	-	-	+
			G	*Radix peregra (Müller)*	-	-	-	-	-	-	-	-	-	-	+	-	-	-	+	+	-	-
number of species					2	3	1	10	19	35	32	19	42	46	21	25	32	28	34	38	27	29

Ecological characteristics: General ecological groups: A—woodland (in general), B—open country, C—woodland/open country, D—water, wetlands. Ecological groups: 1—woodland (*sensu stricto*); 2—woodland, partly semi–open to open habitats [W(M)—mesic, W(S)—xeric, W(H)—damp]; 3—damp woodland; 4—xeric open habitats [S—in general, Ca—limestone rocks, S(W)—partly shaded habitats]; 5—open habitats in general (moist meadows to steppes); woodland/open country: 6—predominantly dry; 7—mesic or various (Me—mesic in general, catholic, Wp—mesic rocks, scree woodland); 8—predominantly damp; 9—wetlands, banks; 10—aquatic habitats.

Biostratigraphic characteristics: +—loess species, (+)—local or occasional loess species, !—species characteristic of warm phases, (!)—eurythermic species of warm phases, !!—index species of warm phases, G—species surviving the Glacial out of the loess zone, (G)—ditto as relics, M—modern immigrants (Late Holocene index species)

Presence in layers: +—present, +?—only approximate determination, ––absent.

Cochlicopa lubricella and *Vallonia costata* in high amounts as well as the appearance of *Granaria frumentum* (layer 7) reflect partial clearance of forests. Importantly, the woodland character of the malacofauna is preserved, although higher numbers of such species as *Cochlicopa lubricella*, *Vallonia costata* and the admixture of *Granaria frumentum* reflect a clearance of the adjacent forest complex.

In the uppermost, predominantly clastic layers (6 to 2) the woodland character of malacofauna continues, the species richness slightly decreases and several elements indicating further clearance in the surroundings appear (*Vallonia pulchella*, *Pupilla muscorum*, *Cecilioides*). However, *Platyla polita*, a sensitive woodland species is still present, *Laciniaria plicata* re-appears (at present extinct in the Bohemian Karst) and even in the subsurface layer 2 *Helicodonta obvoluta* remains important. By contrast, modern immigrants are represented only by the terricolous *Cecilioides acicula,* which penetrates into deeper soil horizons. The assemblages of the youngest layers converge to present-day conditions. Today's environment is characterized by fully developed woodland biocenoses including rich forest snail communities. It is obvious that neither prehistoric nor historic human activities were sufficiently intensive to lead to depopulation of woodland ecosystems and expansion of species characteristic of cultivated areas.

5. Chronology and the stable isotope record

Since ^{14}C dating of carbonate is plagued by a number of uncertainties (unknown initial activity because of mixing of organic matter-derived carbon and limestone-derived carbon, a possibility of post-depositional changes because of tufa diagenesis, infilling of pores, etc.), small pieces of charcoal or sedimentary organic matter from selected horizons were also ^{14}C dated using AMS. Nevertheless, ^{14}C dating of carbonate is the only method for which a sample can be collected anywhere in the section, which was the reason why both methods were applied. The data are given in Table 2.

In Fig. 4, calibrated ^{14}C data of organic matter and ^{14}C model ages of carbonate are plotted against depth in the section. The carbonate ^{14}C model ages were calculated assuming constant initial ^{14}C activity of carbonate carbon equal to 80% of modern carbon (80 pmc). This selected value is slightly lower than the ^{14}C activity of HCO_3^- of the present-day spring water, which was determined several times (83 pmc in 1987, Horvatinčić et al., 1989; between 80.5 and 83.9 pmc during 1997–1998 period, Šilar and Záhrubský, 1999). This selected value gives an identical age for both methods at the uppermost level in the section, where both carbonate and organic matter were dated. The agreement between model carbonate ^{14}C ages and organic matter ^{14}C ages in the deeper part of the section is not satisfactory. Application of the calibration curve to the carbonate ^{14}C data would improve this discrepancy only partly. It follows that the initial activity of deposited carbonate changed significantly through time and/or that the carbonate was partly influenced by post-depositional changes. This is why organic matter ^{14}C data were taken as a basis for calculation of ages for individual depth levels. Constant accumulation rates were assumed between individual dated levels. A problem arose in the basal portion of the section formed by pure tufa, where collection of organic matter for dating was impossible. Based on the difference in carbonate ^{14}C activity, it was roughly estimated that the segment between the deepest dated sample of organic mater (−3.00 m) and the carbonate layer base (−9.65 m) corresponds to approximately 1000 yr. Under this assumption, the base of calcareous tufa layer was set at 9500 yr BP. Based on calibrated ^{14}C data of organic matter and the assumptions mentioned above, a model age was attributed to each carbonate sample used for obtaining of the stable isotope record.

The $^{230}Th/^{234}U$ dating method was applied to verify the ^{14}C dating. All samples had suitable U contents (0.263–0.761 ppm U), but an admixture of clastic Th component adsorbed on clay minerals was too high and the $^{230}Th/^{232}Th$ was lower then 10. Moreover, variable $^{234}U/^{238}U$ ratio indicated disturbed isotopic systems. Even the sample with the highest $^{230}Th/^{232}Th$ ratio (−5.40 to −5.50 m, 0.761 ppm U) indicated an unrealistically high age of 10.6 ± 0.4 ka. After finishing the drilling into the deepest part of the accumulation, $^{230}Th/^{234}U$ dating was applied once on a selected sample of solid pure tufa with limited number of pores (sample location: −8.30 m). The sample contained 0.50 ± 0.01 ppm U and the $^{230}Th/^{232}Th$ ratio was again low. The sample yielded an uncorrected age of 10.39 ± 0.24 ka. Since this sample was the most suitable for the $^{230}Th/^{234}U$ dating, a rough correction to subtract the detrital thorium was applied on the raw data. The corrected age of 8 ± 1 ka is in rough agreement with other dating methods.

The radiometric dating is in good agreement with both biostratigraphic dating and with dating of archaeological finds. The molluscan assemblages indicate that the tufa sequence does not cover the initial phases of the Holocene, since typical faunal assemblages of the Late Glacial/Early Holocene transition are not well developed here. The ^{14}C dating of organic matter derived from layer No. 6 with pottery fragments of the Knovíz culture (generally dated from approximately 8th to 6th century BC, Benková and Čtverák, 1998) yielded a corrected age within an interval 2876 to 2483 yr BP (95% confidence interval).

Carbonate content and carbonate $\delta^{13}C$ and $\delta^{18}O$ data plotted against the model age are shown in Figs. 5 and 6. The highest carbonate contents were recorded in the profile section with model ages between 8800 and 8600 yr BP. Near the level of around 8500 yr BP, there are several distinct horizons enriched in clastic material (mostly clay minerals, organic matter, quartz and feldspar grains). The most stable climatic conditions (so-called climatic optimum of Holocene) with very limited transport of any clastic material and with deposition of relatively pure calcareous tufa occurred between depths −3.00 and +0.07 m (corresponding model ages of 8400 and 6700 yr BP). In the second part of the Atlantic (since about 6700 yr BP) the carbonate content decreased and the proportion of clastic material irregularly increased. The first maximum of clastic material transport into the studied section occurred around 6200 yr BP. The overlying lithologically variable sequence contains numerous horizons very rich in clastic material and also horizons of buried soils. The lowest carbonate content was recorded in a buried soil horizon at +3.50 to +3.75 m (layer 15 in Fig. 3). The upper scree horizon at +5.05 to +5.20 m corresponds roughly to 3100 yr BP and above it the deposition of calcareous tufa was discontinued.

The oxygen isotopic composition of freshwater carbonates is influenced by several partly interdependent factors, the two most important being temperature-controlled oxygen isotope fractionation calcite-water and temperature-controlled variability of oxygen isotopic composition of meteoric waters (Gascoyne, 1992;

Table 2
^{14}C dates from carbonate and organic matter

Laboratory No.	Meters in the profile (m)	Sample description	Preparation and measurement method	^{14}C activity % MC	Conventional ^{14}C age years BP	Calibrated ^{14}C age (95% confidence interval) years BP
Rafter Radiocarb. Lab., New Zealand NZA 5877	+6.00 to +6.10	Charcoal pieces separated from layer No. 6 containing Late Bronze Age pottery (Knovíz Culture). Dated material—charcoal	A–A–A leaching + AMS	71.61 ± 0.60	2639 ± 67	2876 to 2693 2653 to 2483
Univ. of Waterloo, Canada 55465	+4.20 to +4.30	Larger massive block of hard pure tufa within layer No. 12. Dated material—carbonate	Acid decomposition + conventional counting method	54.00 ± 0.47		
Rafter Radiocarb. Lab., New Zealand NZA 5878	+4.00 to +4.10	Isolated charcoal pieces separated near boundary of layer No. 13 and 14. Dated material—charcoal	A–A–A leaching + AMS	64.41 ± 0.61	3489 ± 77	3935 to 3555
Rafter Radiocarb. Lab., New Zealand NZA 5879	+2.60 to +2.65	Isolated charcoal pieces separated from upper part of layer No. 20. Dated material—charcoal	A–A–A leaching + AMS	56.20 ± 0.51	4585 ± 74	5467 to 4997
Univ. of Waterloo, Canada 55466	+1.95 to +2.05	Hard porous "structural" tufa, central part of a large block within layer No. 22. Dated material—carbonate	Acid decomposition + conventional counting method	50.10 ± 0.46		
Univ. of Waterloo, Canada 55467	−0.35 to −0.45	Hard porous "structural" tufa, upper part of layer No. 28. Dated material—carbonate	Acid decomposition + conventional counting method	45.00 ± 0.40		
Univ. of Waterloo, Canada 55468	−2.55 to −2.65	Hard porous "structural" tufa, lower part of layer No. 28. Dated material—carbonate	Acid decomposition + conventional counting method	42.70 ± 0.41		
Rafter Radiocarb. Lab., New Zealand NZA 7772	−2.95 to −3.05	Loose light brown tufa with soil admixture. Dated material—organic matter in the soil admixture	A–A–A leaching + AMS	38.26 ± 0.32	7673 ± 68	8551 to 8325
Univ. of Waterloo, Canada 55469	−5.40 to −5.50	Hard porous "structural" tufa, lower limit of layer No. 30. Dated material—carbonate	Acid decomposition + conventional counting method	34.40 ± 0.34		
Univ. of Waterloo, Canada 74030	−7.05 to −7.10	Hard porous "structural" tufa, upper part of layer No. 34 (from drilling). Dated material—carbonate	Acid decomposition + conventional counting method	30.54 ± 0.30		
Univ. of Waterloo, Canada 74031	−8.25 to −8.35	Hard porous "structural" tufa, lower part of layer No. 34 (from drilling). Dated material—carbonate	Acid decomposition + conventional counting method	30.08 ± 0.30		

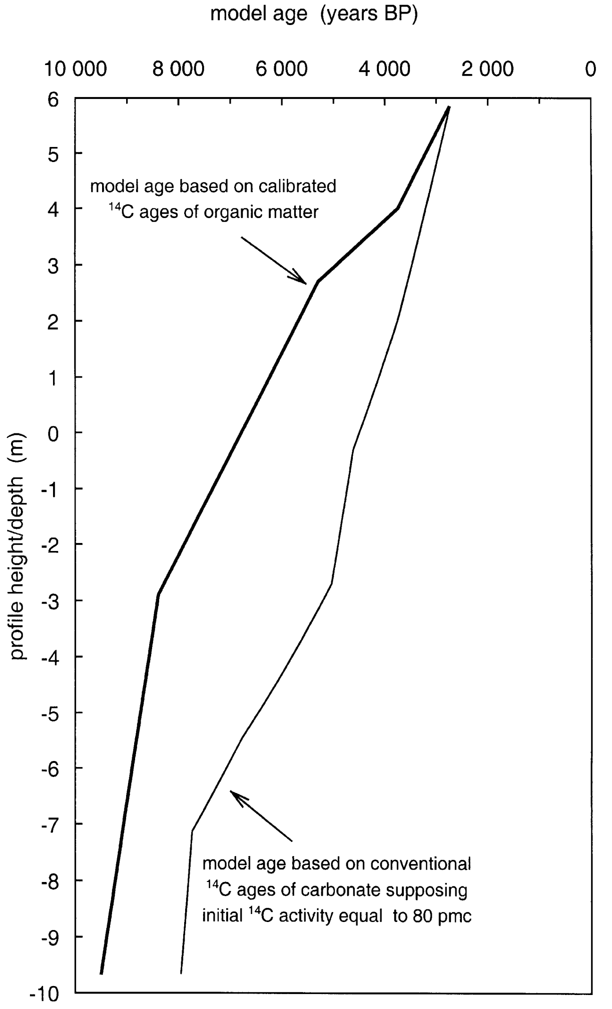

Fig. 4. ^{14}C ages based on calibrated data of organic matter and also the ^{14}C carbonate ages, calculated assuming identical initial activity of carbonate carbon of 80 pmc vs. depth.

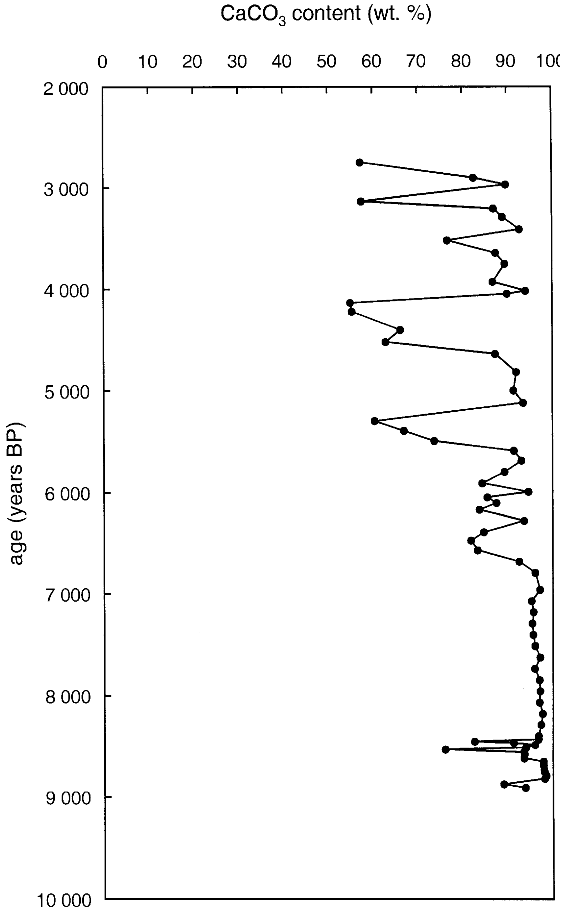

Fig. 5. Carbonate content vs. model age.

Dorale et al., 1992). These two factors have an opposite influence on the carbonate δ^{18}O data, with the effect of temperature-controlled variability of oxygen isotopic composition of meteoric waters usually being the more important factor in the mild climatic zones.

With respect to the large discharge of the spring, long underground residence time of the spring water and almost constant spring temperature, and with regard to the location of the tufa deposit near the spring, any significant water temperature changes and/or isotopic effects connected with water evaporation at the site of deposition probably can be neglected. Changes in the δ^{18}O values of meteoric waters were the most important factor controlling changes in δ^{18}O of the deposited carbonate. A similar conclusion about freshwater tufa deposits of British Isles was drawn by Andrews et al. (1993). Under these conditions higher carbonate δ^{18}O values should indicate higher temperatures and vice versa.

The carbonate δ^{18}O record obtained from the Svatý Jan section was compared with ice δ^{18}O in the Greenland GISP 2 (Fig. 7; data for GISP 2 after Grootes et al., 1993; Stuiver et al., 1995; GISP 2 dating after Sowers et al., 1993; Meese et al., 1997). With respect to dating uncertainty at Svatý Jan, the oscillations of both curves can be viewed as similar. A significant temperature increase marking the onset of Holocene is clearly not recorded at the Svatý Jan. This is in good agreement with both the results of dating of the tufa section and with the biostratigraphic analysis of molluscan assemblages.

Carbonate δ^{13}C values at Svatý Jan show higher variability than δ^{18}O values. Moreover, it was found that the carbonate δ^{13}C data are probably controlled by different mechanisms in the lower series of hard pure tufa with high carbonate content and in the upper varied sedimentary series. While in the lower portion of the section the δ^{13}C and δ^{18}O of carbonate change independently, in the upper portion there is a significant correlation between oscillations of the δ^{13}C and δ^{18}O data. With respect to the fact that differences between the δ^{13}C values of carbonate and organic matter are almost constant throughout the section ($\delta^{13}C_{\mathrm{carb}}$ are in the range from -10.54‰ to -7.92‰, $\delta^{13}C_{\mathrm{org}}$ in the range -30.6‰ to -26.3‰, $\Delta^{13}C_{\mathrm{carb-org}}$ in the range 18.8–20.7‰), the kinetic effect of CO_2 escape from the water at the site of deposition had probably only a

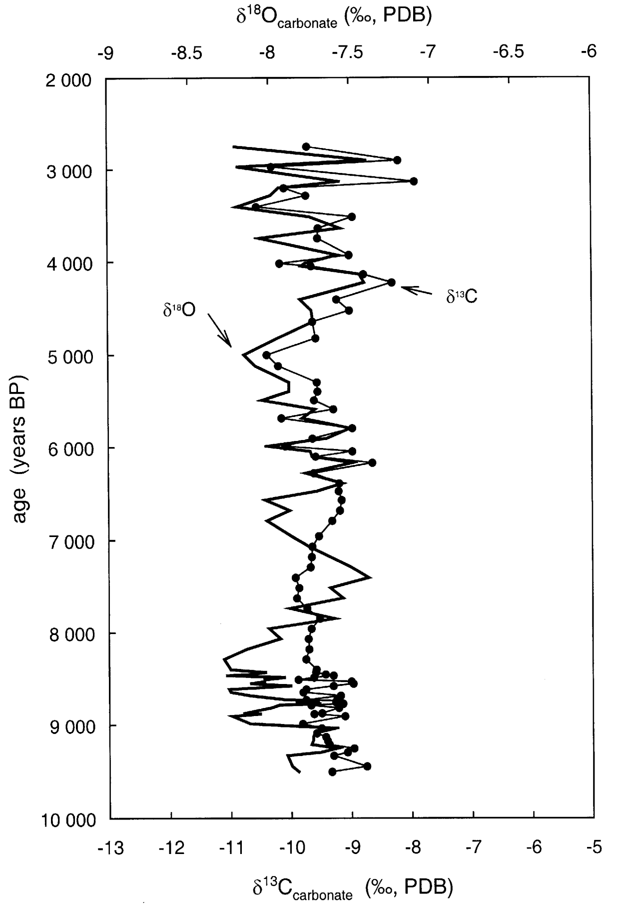

Fig. 6. The carbonate δ^{13}C and δ^{18}O data vs. model age.

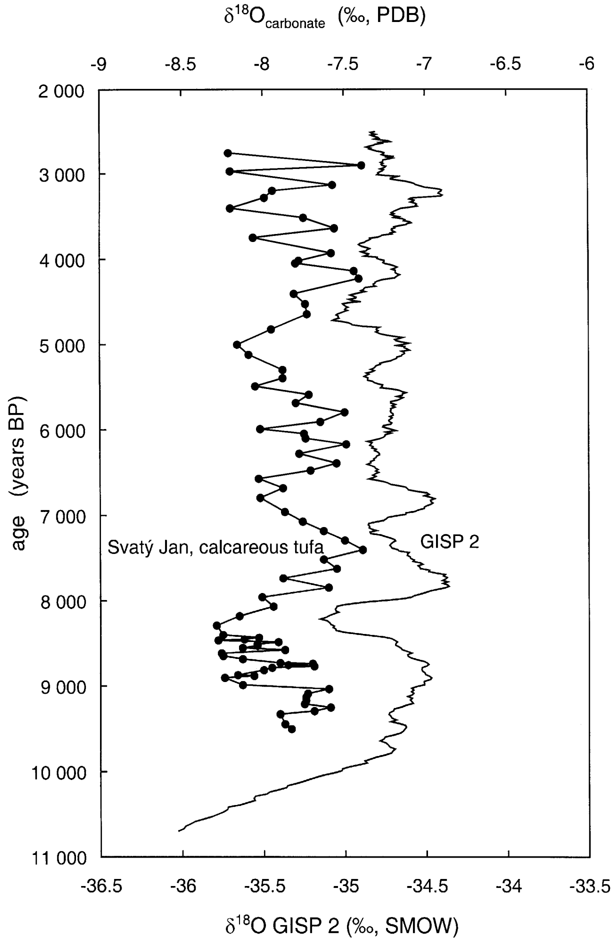

Fig. 7. Comparison of the carbonate δ^{18}O data from Svatý Jan and GISP 2 δ^{18}O record.

minor influence on the carbonate δ^{13}C systematics. The environmental and climatic impacts on soil processes in the recharge area were probably more important. We can speculate on the nature of these processes. They could be caused by human activities associated with more intensive pasture and deforestation, enhanced sheet erosion, changed microbial conditions of soil edaphon, gradual decalcification of soils or oceanity/continentality shifts. The field observations from Central Bohemian region support all these hypotheses, but some contradictory evidence appears—e.g. tufa formation ceased even in nearby Křivoklát region at sites located at steep slopes which were never affected by human influences and where the mollusc assemblages prove the continuous existence of forest.

6. Discussion

6.1. Onset of tufa deposition—comparison with other tufa bodies

The calcareous tufa section at Svatý Jan pod Skalou is the one of few sites within the Bohemian Karst where biostratigraphic analysis was combined with an extensive application of geochronological methods. During the Late Glacial any deposits of calcareous tufa at the Svatý Jan pod Skalou (if formed) were destroyed due to increased fluvial erosion. The rock floor of the Kačák Valley was at this time up to 8–9 m deeper than is the surface level of the recent floodplain. The tufa accumulation at the Svatý Jan pod Skalou is underlain by river terrace probably of Late Glacial/Early Holocene age. For the onset of calcareous tufa formation two controlling factors were of prime importance:

- decrease in fluvial activity of the Kačák stream, and
- an increase in dissolved load of spring water connected with expansion of plant communities and evolution of soil profiles in the recharge area.

Both geochronological dating and assemblages of *Mollusca* indicate that the basal tufa layer at Svatý Jan pod Skalou was deposited around 9500 yr BP; i.e. the transition Late Glacial/Holocene is not represented by carbonate sediments nor here. These results are in good agreement with studies of fluvial sediments of the largest Bohemian Labe River (Růžičková and Zeman, 1994), where the formation of Early Holocene floodplain also was dated around 9500 yr BP.

Other tufa deposits of the area, studied by biostratigraphic methods only, reflect very similar evolutional patterns (Ložek, 1992). Tufas containing molluscan assemblages typical of the transition from the Late Glacial to Holocene are rare within the Bohemian Karst. One of such accumulation was found by Ložek (1967b, 1968) in the valley of Švarcava Creek, 12 km east of Svatý Jan pod Skalou. An approximately 3 m thick accumulation of tufa of braided fluvial type forms a low creek terrace incised by younger erosion. The basal sandy and muddy sediments at Švarcava contained three Late Glacial elements—*Columella columella*, *Vallonia tenuilabris* and *Vertigo parcedentata*—while the overlying loose tufa layer was rich in typical Early Holocene *Discus ruderatus*-assemblage with *Perpolita petronella*, *Clausilia cruciata*, *Vertigo substriata* and abundant *Vallonia costata* (Ložek, 1967b, 1968; Ložek in Žák et al., 2001). Surprisingly, carbonate δ^{13}C and δ^{18}O data from the lower portion of this section were within the range of data from the lower portion of the Svatý Jan pod Skalou tufa. One ^{14}C AMS date of sedimentary organic matter of fossil soil from the basal part of the calcareous tufa layer from Švarcava yielded a corrected ^{14}C age within an interval 8954–8554 yr BP (sample ref. no. NZA 7702, 37.05 ± 0.41 pmc, Žák et al., 2001), excluding the possibility that intensive carbonate tufa deposition occurred at this locality at the Late Glacial/Holocene transition. This ^{14}C date supported the idea of almost synchronous onset of intensive tufa formation in the whole Bohemian Karst. In the case of the Švarcava section, either some shells of *Mollusca* were re-deposited under fluvial conditions or a relic assemblage survived for some time in a narrow, inversion valley of Švarcava.

6.2. Phase of humid stable climate in the Atlantic

During the phase of humid and stable climate, intensive calcareous tufa growths are evident at most sites. Massive accumulations of solid phytohermal tufa with very limited quantities of clastic material were formed during this period. Based on results obtained from the Svatý Jan pod Skalou section, the maximum growth of massive structural calcareous tufa occurred between 8 400 and 6500 yr BP. In the surrounding areas brown decalcified rendzina-type soils were formed with some residual corroded clasts of limestone. Transport of slope scree was very limited. Based on the δ^{18}O record, the temperature reached its maximum around 7500 yr BP. Generally, the mean annual temperatures of this period were only slightly higher than during the later period. More importantly, annual precipitation was higher and oceanic-type climate prevailed with smaller temperature differences between winters and summers. The landscape was almost continuously covered by forests inducing increased evapotranspiration and steady stream discharge conditions.

6.3. Phase of oscillation between dry and wet climate

The start of next phase is limited approximately to 6500 yr BP in the Bohemian Karst. The phase is characterized by short rapid oscillations of dry and wet periods, which resulted in alternation of structural tufa and loose tufa with intercalations of soil and scree horizons. In several sections located in the Bohemian Karst, up to 5 dry oscillations can be identified. The duration of these dry oscillations is not precisely known. The phase spans about 4000 yr. Based on paleopedological analysis, the buried soils preserved at Svatý Jan pod Skalou were classified as autochthonous or semi-autochthonous. The lithological characteristics of the more than 6 m thick upper portion of the studied section indicate that dry periods probably were not longer than several hundreds of years.

Based on the study of peat profiles in Denmark, Aaby (1976) concluded that climatic oscillations occurred each 260 or, less frequently, each 520 yr. An 800-yr periodicity was found as dominant in peat sections in N England (Barber et al., 1994). Similar periodicities with several hundred-years order also were recorded through study of glacier movements (Grove, 1979). The δ^{18}O record from the Svatý Jan pod Skalou shows that changes in precipitation quantity were more important during these climatic oscillations than changes in temperature. In addition to dry periods, this phase is characterized also by flash-floods that transported clastic material through karstic valleys which are dry at present.

Local deforestation that can be probably attributed to both climate and expanding pasture can be documented biostratigraphically during the younger part of this time period. This feature, together with irregular precipitation during the year, produced a distinct flood event around 3100 yr BP, recorded at Svatý Jan pod Skalou by the limestone scree horizon overlain by the calcareous tufa dated both archaeologically and by ^{14}C to approximately 2700 yr BP.

Wet and cooler climate with frequent temperature oscillations around 0°C is generally more effective for scree formation below the slopes and overhanging cliffs (Ložek and Cílek, 1995). At the same time, a significant increase in precipitation was recorded biostratigraphically in lake sediments in the Šumava Mountains (Veselý, 1998) and by expansion of wetlands in low-elevation areas (e.g., around 2650 BP in the Netherlands, Geel et al., 1996).

6.4. Termination of tufa formation

Not only the synchronous start of the tufa formation of the area is expected on the basis of the same lithological and biostratigraphical pattern, but the termination as well. The formation of calcareous tufa bodies was terminated at numerous localities in central Europe between 2500 and 2200 yr BP. This stage is characterized by several short dry periods, indicated by spreading human settlement across river floodplains (Bouzek, 1993). During the Subatlantic period, the deposition of calcareous tufa almost ceased in the Bohemian Karst. The Late Holocene decline of calcareous tufa formation in central Europe was probably connected with a decrease in the quantity of infiltrating precipitation and/or with changes in soil processes as discussed above.

Thick valley-side-sited spring accumulations were later typically cut by younger erosion that often incised them down to the bedrock. Precise dating of these erosion events is not available: some could occur as late as in the Middle Ages, when enormous floods were recorded on Bohemian rivers. The karstic springs often moved and started to discharge at the base of individual tufa bodies. There still exist karst springs that precipitate present-day tufas, but their total number is diminished significantly when compared with the situation some 3000 yr ago. We believe that tufa termination could be caused by a complex interplay of prehistoric man and natural factors entering a new phase of environmental co-evolution, but the precise evidence is lacking.

6.5. Regional comparisons and Holocene climatic provinces

The biota evolution influenced by Holocene climatic changes in central Europe has been reviewed several times (e.g. Ložek and Cílek, 1995). These studies concluded that the temporal evolution of calcareous tufa bodies has numerous similar features in a large territory limited by the Danube River in the south, by German and Polish lowlands in the north, by Slovak Karst in the east, and by Thuringia in the west. These similarities indicate that regional climatic factors were the main control on calcareous tufa formation, while local factors were of only minor importance. The same roughly synchronous processes were involved in Late Holocene erosion and destruction of tufa bodies (Jäger and Ložek, 1968; Hennig et al., 1983; Pazdur, 1988; Ložek and Cílek, 1995; Ložek, 1997; Cílek, 1997). A similar pattern of calcareous tufa formation has been observed over much of Europe. It has been postulated that in the Late Holocene (since ca. 2500 BP) there was a marked decline in the deposition of tufa (see Goudie et al., 1993, for a review of available data).

The Central European Holocene strata developed in tufas, slope sediments and in the cave entrances provide certain patterns where the individual layers are usually well defined, with distinct terminations and characteristic fossil contents. The Central European Holocene stratigraphy was thus proposed on the basis of this similar observable stratigraphic pattern. However, it was proposed for the western part of Europe several times (see Roberts, 1998) that stratigraphic subdivision of the Holocene is artificial, because the Holocene consists of numerous oscillations. The question deserves more attention, but we propose according to Jäger (personal communication, 2000) the possibility that several Holocene stratigraphic provinces exist. The oscillating divide between Central and Western European Holocene Provinces could be indicated by prevailing continental climate in contrast to more oceanic western climates. The general features of Holocene climates seem to be alike throughout the modern European temperate zone, but regional differences must be taken into account when we are dealing with secondary oscillations.

7. Conclusions

The tufa body of Svatý Jan pod Skalou represents an exceptionally large body of Holocene fresh water limestone and probably the site where interdisciplinary studies of geology, paleoclimatology, malacozoology, karst hydrography, archaeology and some related disciplines have provided the most detailed results from all studied Central European tufa bodies. K.-D. Jäger, the Coordinator of INQUA Holocene Group proposed recently (2000) the profile as the International Stratigraphic Point for the continental Holocene, and called for publication of basic characteristics, as given in this paper. The tufa formation started at about 9500 BP, on a flat fluvial gravel terrace of Late Glacial/Early Holocene age. Deposition of lithologically uniform, pure hard phytohermal tufa continued until about 6500 BP. From that time more unstable climate with several dry periods (see stable isotope results in Figs. 4–6 and Table 1) and erosion events produced a lithologically varied complex of loose tufa alternating with embedded soils and scree layers (Figs. 2 and 3). Termination of tufa deposition occurred about 2500 BP and was followed by partial erosion connected with relocation of the spring below the tufa body.

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