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URANIUM-SERIES DATING OF SPELEOTHEMS FROM DEMÄNOVA ICE CAVE: A STEP TO AGE ESTIMATION OF THE DEMÄNOVA CAVE SYSTEM (THE NÍZKE TATRY MTS., SLOVAKIA)

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Abstract: The Th/U and U/U datings indicate 4 episodes of speleothem growth in Demänova Ice Cave, namely: *ca.* 685–410 ka, *ca.* 170–140 ka, *ca.* 104–70 ka, and < 5.6 ka. The speleothems studied are confined to the IV cave level of the Demänova Cave System. Taking into account the commonly accepted rules of cave level formation, one should accept that the level IV must have been dewatered before its oldest speleothems developed, i.e. before *ca.* 685 ka. Since these speleothems are underlain by fluvial sands of normal magnetic polarity, it is possible to constrain the age of level IV as falling into the time-span of 780–685 ka. It means that this level is older than hitherto supposed and, consequently, that the age of higher levels (V–IX) is older as well.

Abstrakt: Datowania Th/U i U/U dowodzą, że w Demenovskiej Lodowej Jaskini czterokrotnie dochodziło do wzrostu nacieków. Stwierdzone zostały generacje o następującym wieku: ok. 685–410 ka, ok. 170–140 ka, ok. 104–70 ka i młodszym od 5.6 ka. Badane nacieki występowały na IV poziomie jaskiniowym w Demenovskim Systemie Jaskiniowym. Biorąc pod uwagę ogólnie przyjmowane zasady tworzenia się poziomów jaskiniowych należy uznać, że IV poziom został odwodniony przed powstaniem najstarszych nacieków na nim występujących. Stwierdzony U/U wiek tych nacieków wynosi ok. 685 ka. Biorąc pod uwagę, że bezpośrednio pod tymi naciekami znajdują się rzeczne piaski o normalnym namagnesowaniu można określić wiek odwodnienia IV poziomu jaskiniowego na między 780 ka a ok. 685 ka. Dowodzi to, że wiek tego poziomu jest starszy niż dotychczas sądzono. Starszy też musi być wiek wyższych poziomów (V–IX).

Key words: U-series dating, speleothems, cave evolution, Slovakia, Demänova Cave System.

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INTRODUCTION

The Demänova Cave System (DCS; in Slovak "Demänovsky jaskynny systém") has been described in a monograph by Droppa (1957) and in numerous subsequent papers by this author (Droppa, 1963, 1966, 1972) as an example of a multi-level cave system, whose individual levels could be correlated with fluvial terraces (see Fig. 2). This system is a model example of caves of such a type, quoted in textbooks all over the world (*cf.* Sweeting, 1973, pp. 151–154, fig. 72; Warwick, 1976, pp. 112; Bögli, 1980, pp. 118–119, fig. 8.2; Jennings, 1985, pp. 242–244, fig. 89). More recent, detailed studies indicate, however, that the origin of this system is a more complicated one (Hochmuth, 1988, 1993, 1995; Bella, 1993, 1996). The dating of age boundaries of this system by independent physical methods is of crucial importance for further discussion. The most appropriate methods in this respect are palaeomagnetic studies and isotopic datings of speleothems.

The results of numerous studies indicate that speleothems can successfully be dated quantitatively by isotopic methods (*cf.* White, 1988; Ford & Williams, 1989; Ivano-

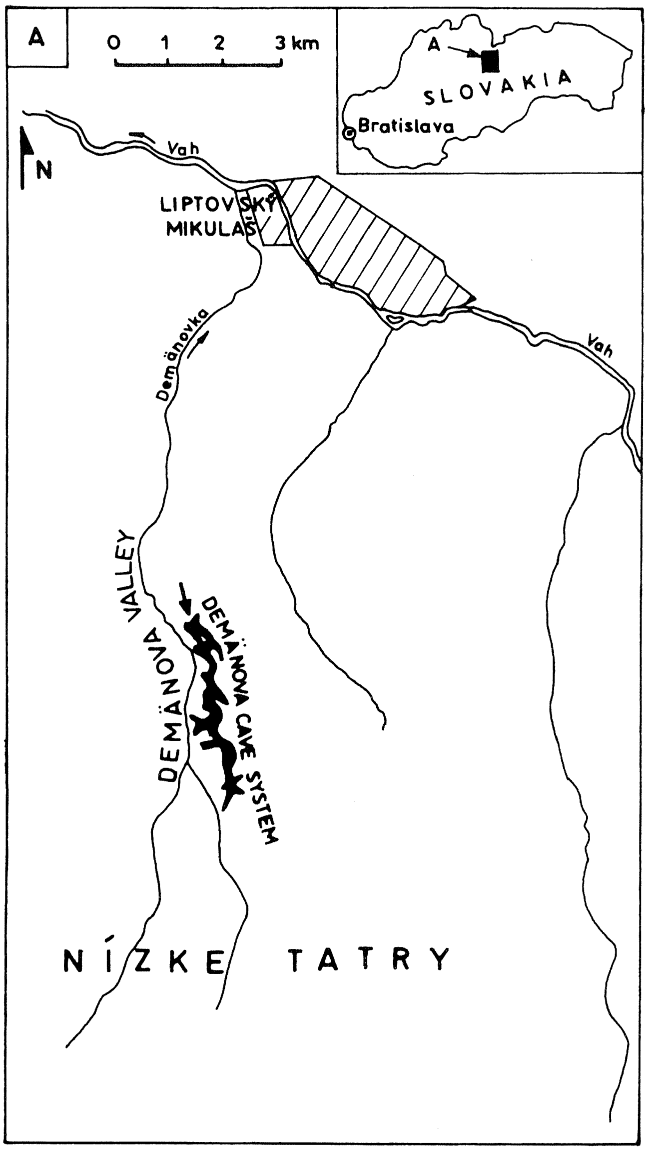

Fig. 1. Location of the Demänova Cave System in the Nízke Tatry Mts., arrow indicates Demänova Ice Cave

vich & Harmon, 1992). Such determinations make it possible to recostruct important environmental changes like, for instance, climatic warmings (Thompson *et al.*, 1974; Harmon *et al.*, 1975; Atkinson *et al.*, 1978; Głazek & Harmon, 1981; Gascoyne *et al.*, 1983; Henning *et al.*, 1983; Gordon *et al.*, 1989; Hercman, 1991; Baker *et al.*, 1993; Lauritzen, 1995). The age of speleothems and palaeomagnetic determinations of cave sediments are also useful in reconstructing episodes of geomorphic evolution of a cave-bearing area (Ford, 1973; Ford *et al.*, 1981; Schmidt, 1982; Williams *et al.*, 1986; Hercman, 1991).

Preliminary results of this studies was presented on 12th International Congress of Speleology (Hercman *et al.*, 1997).

GEOLOGIC AND GEOMORPHOLOGICAL SETTING

The DCS is situated in the Nízke Tatry Mts., on the eastern side of the Demänova Valley (in Slovak "Demänovská dolina"; Droppa, 1957; Fig. 1). The system is developed within Anisian limestones and dolomites of the Gutenstein type. These limestones belong to the allochthonous Križna sequence that constitutes the northern sedimentary cover of the Nízke Tatry Mts. crystalline core, the latter being composed of granitoids (*cf.* Droppa, 1957). The upper part of the Demänova Valley was glaciated at least twice during the Middle Pleistocene. The DCS, however, occurs in a narrow canyon located downstream the glaciated part of the valley and below the preserved till deposits (Droppa, 1972). The total length of DCS attains 24 km and its relief is up to 173 m (Bella, 1993). Droppa (1957) distinguished 9 cave levels in the DCS (Fig. 2). In subsequent papers, this author (Droppa, 1963, 1964, 1966, 1972) correlated these levels with fluvial terraces of the Demänovka stream, as well as with those of the Váh River and its tributaries. He assigned individual cave levels to successive glacial stages, using the classical Alpine morphostratigraphic scheme.

The Demänova Ice Cave (called in this paper DIC; in Slovak "Demänovska ĺadova jaskyňa") forms the northern (resurgence) part of DCS and is developed in three levels: IV, V, and VI (Droppa, 1957, 1972; Fig. 2). The gross part of the cave is occupied by level IV, which is situated *ca.* 45 m above the present-day Demänovka stream. It is important to note that the level IV is clearly discernible both in DIC and in other parts of DCS, and that it is the most distinct from among all the cave levels in that area. Unfortunately,

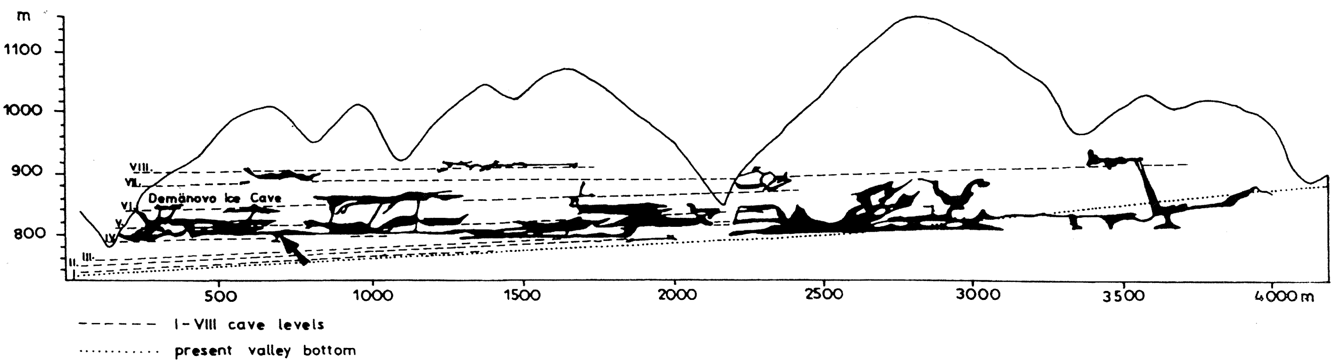

Fig. 2. Longitudinal section of Demänova Cave System, I–IX cave levels are visible (after Droppa, 1966, simplified); arrow indicates the Závrtový dóm chamber – sampling place

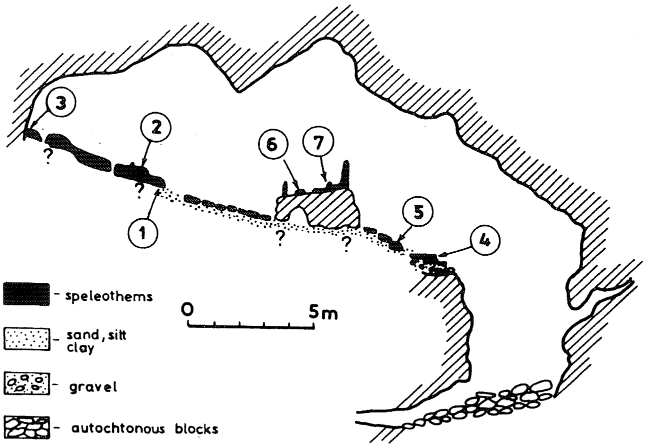

Fig. 3. Cross section of the Závrtový dóm, numbers in circles indicate collection places of particular flowstone samples

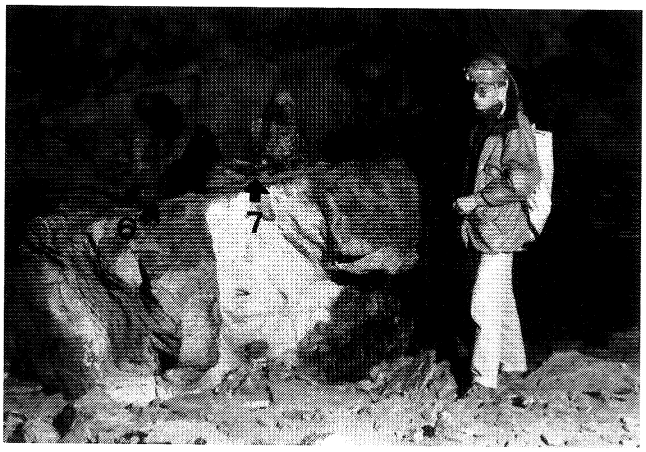

Fig. 5. Block lying in the centre of the Závrtový dóm, numbers indicate collection places of particular flowstone samples

the level cannot be correlated with any preserved terrace of the Demänovka stream. Droppa (1966) relates the origin of this level to the Mindel II glacial stage, basing on a correlation with terraces preserved in valleys of the Váh and other tributaries of Váh River.

MATERIAL

Flowstone samples have been collected in a chamber called Závrtový dóm of DIC, belonging to the IV cave level distinguished by Droppa (1957, 1966). Geologic setting of this chamber is shown in Fig. 3. Seven flowstones, occurring side by side or in superposition have been sampled. These flowstones are intercalated by clastic sediments. Sample 1, 2 and 3 were collected from fractured, rotated and slightly displaced flowstones, which are a very characteristic element of the chamber (Fig. 4). Samples 4 and 5 were taken from flowstones occurring inbetween clastic sediments in the western part of the chamber, whereas samples 6 and 7 were collected from flowstones which drape over a block lying in the middle of the chamber (Fig. 5). All the samples have been labelled in field JLod1 through JLod 7. For simplicity purposes, in the remaining part of this paper, we shall use only sample numbers, without letter codes.

Fig. 4. General view of the Závrtový dóm, numbers indicate collection places of particular flowstone samples

METHODS

Sedimentological analyses included examination of polished slabs and thin sections of specimens. Thin sections have been studied under an Axioskop Carl Zeiss Opton petrographic microscope, coupled with a MC80 photo camera.

For radiometric dating, standard radiometric dating of $^{230}Th/^{234}U$ dates were used (*cf.* Ivanovich & Harmon, 1992). Samples of 15–30 g were dissolved in *ca.* 6 M nitric acid. Uranium and thorium fractions were separated by the chromatography method. The ^{234}U, ^{238}U, ^{230}Th and ^{232}Th activities were measured by using isotope dilution with $^{228}Th/^{232}U$ spike. All measurements were done with alpha spectrometry at the U-Series Laboratory in Bergen University. The ages were calculated by a standard algorithm (*cf.* Ivanovich & Harmon, 1992) using program "Age04" (Lauritzen, 1981). The reported errors are 1 sigma. After dating all the samples by means of the $^{230}Th/^{234}U$ method, the $^{234}U/^{238}U$ method was used to estimate the age of the oldest flowstones from DIC, according to RUBE method (Ivanovich & Harmon, 1992). The calculated initial $^{234}U/^{238}U$ ratios in the younger samples were used for estimation of the initial $^{234}U/^{238}U$ ratio in sample 4. We used the mean value of all the calculated initial $^{234}U/^{238}U$ ratios and obtained estimator of initial $^{234}U/^{238}U$ in the sample 4 equal to 2.62+/-0.38.

Palaeomagnetic analysis included measurements of natural remanent magnetization (NMR) of 11 subsamples (volume *ca.* 24–40 mm^3), cut from sample 4, on a Cryogenic magnetometer (sensitivity 0.02 mAm^{-1}).

RESULTS OF URANIUM SERIES DATING

All the obtained results are reliable due to the high enough uranium content and the lack of detrital thorium contamination (Table 1). The results of $^{230}Th/^{234}U$ dating

Table 1

$^{230}Th/^{234}U$ dating results of flowstone samples

Sample	Conc. U [ppm]	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	Age [ka}
1/1	0.28±0.006	1.408±0.026	0.837±0.041	> 10000	169^{+20}_{-17}
1/3	0.38±0.009	1.416±0.032	0.836±0.029	1015	169^{+14}_{-12}
1/6	0.15±0.004	1.535±0.048	0.791±0.029	> 10000	148^{+11}_{-8}
1/9	0.17±0.005	1.460±0.036	0.764±0.028	> 10000	140^{+10}_{-9}
2/1	2.49±0.08	2.496±0.082	0.548±0.023	> 10000	$78.7^{+4.6}_{-4.4}$
2/2	0.36±0.009	1.989±0.046	0.530±0.019	> 10000	$76.3^{+3.8}_{-3.7}$
2/3	0.22±0.005	2.215±0.045	0.499±0.019	> 10000	$69.9^{+3.5}_{-3.4}$
2/4	0.49±0.011	2.896±0.049	0.042±0.003	> 10000	$4.7^{+0.3}_{-0.3}$
3/1	0.16±0.004	1.967±0.539	0.561±0.022	> 10000	$82.5^{+4.6}_{-4.4}$
3/3	0.19±0.004	1.868±0.044	0.518±0.022	> 10000	$74.2^{+4.3}_{-4.2}$
4/1	0.59±0.014	1.181±0.033	1.008±0.038	> 10000	> 350
4/2	0.28±0.010	1.395±0.058	1.043±0.050	436.5	> 350
5/1	0.30±0.007	2.075±0.041	0.604±0.019	140	$91.4^{+4.2}_{-4.0}$
5/1a	0.37±0.009	2.134±0.046	0.574±0.019	230.6	$84.7^{+4.2}_{-4.0}$
5/2	0.30±0.006	2.078±0.038	0.548±0.015	662	$79.5^{+3.0}_{-2.9}$
6/1	0.48±0.009	1.975±0.035	0.649±0.016	600	$102^{+4.0}_{-3.9}$
6/2	0.44±0.015	2.100±0.076	0.649±0.030	140.3	$101^{+7.4}_{-7.0}$
7/1	0.42±0.008	2.084±0.043	0.661±0.017	> 10000	$104^{+4.2}_{-4.1}$
7/2	0.29±0.010	2.024±0.072	0.609±0.029	> 10000	$92.5^{+6.7}_{-6.4}$
7/3	0.42±0.009	2.657±0.050	0.051±0.004	> 10000	$5.6^{+0.4}_{-0.4}$

are presented in Table 1 (see also Figs. 8–10). Table 2 contains results of $^{234}U/^{238}U$ dating of sample 4 (see also Fig. 7).

Based of the dating results we can distinguish at least four generations of speleothems which developed in individualised periods. The first generation (sample 4) was deposited between *ca.* 685 ka–410 ka, the second (sample 1) between *ca.* 170–140 ka, the third (samples 2, 3, 5–7) between *ca.* 104–70 ka, and the fourth one (upper parts of samples 2, 3, and 7) after 5.6 ka (see Fig. 13).

RESULTS OF PALAEOMAGNETIC ANALYSIS

The top 5 subsamples have intensities close to the noise level of the instrument. No reliable polarity has been obtained from these levels in the speleothem. The lower 6 sub-

Table 2

RUBE dates of sample 4

Sample	234U/238U age [ka]
4/1	+60 685 -40
4,2	+73 410 -46

samples have NMR intensities well above the noise level, and progressive alternating field demagnetization to 40 mT has been performed. The results indicate the presence of a single component magnetization of normal polarity (Fig. 6).

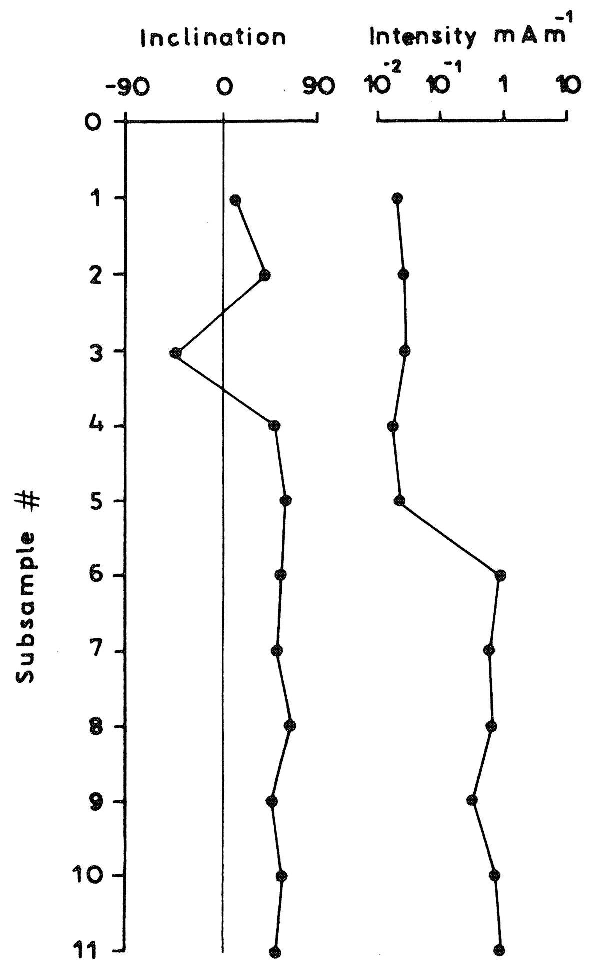

Fig. 6. Stratigraphic plots of natural remnant magnetization inclination and intensity; sample 4, five upper subsamples are calcite flowstone, six lower are cemented clastic deposits

FLOWSTONES

FIRST SPELEOTHEM GENERATION

Description. The first speleothem generation is represented by a 10 cm-thick flowstone (sample 4, Fig. 7), developed upon cave infill whose top, 8 cm-thick part, is cemented by calcite. This infill is composed of siliciclastic material, including grains of quartz, variably weathered biotite, muscovite and feldspars, as well as of carbonate silt. The overlying flowstone is composed in its lower and upper parts mainly of columnar and, subordinately, acicular crystals. Corrosion surfaces are to be found at places. The middle part of the flowstone is occupied by a lense of porous sediment, composed of calcite crystals, 3.5 cm high.

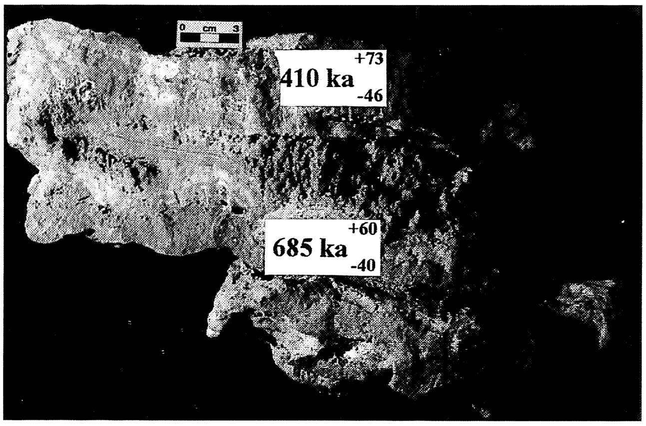

Fig. 7. The sample 4 represents the oldest speleothem generation in Demänova Ice Cave, U/U ages (ka ago) of particular layers are indicated, in the centre of sample the lens filled with macroscopic-size calcite crystals that developed in a small pool, is visible

Interpretation. The first speleothem generation grew under suitable conditions at uninterrupted supply of water, as shown by well-developed columnar calcite crystals (*cf.* Dziadzio *et al.*, 1993; Frisia *et al.*, 1993; Gradziński *et al.*, 1996). Corrosion surfaces point to temporary interruption of the growth and destruction of previously precipitated flowstones; nevertheless, they do not represent – most probably – a profound hiatus in the speleothem growth. The porous sediment that builds a lense-like body in the middle part of the flowstone developed in a small lake, several centimetres deep (*cf.* González & Lohmann, 1988; González *et al.*, 1992).

SECOND SPELEOTHEM GENERATION

Description. The second speleothem generation is a 12 cm-thick flowstone, yellow in colour (sample 1; Fig. 8), developed upon cave infill, whose top part, 1 cm thick, is cemented by calcite. This flowstone is largely composed of columnar calcite crystals and does not show corrosion surfaces. In its middle part a macroscopically distinguishable, lighter layer occurs, showing submicroscopic lamination. Above a distinct corrosion surface on top of the flowstone, a

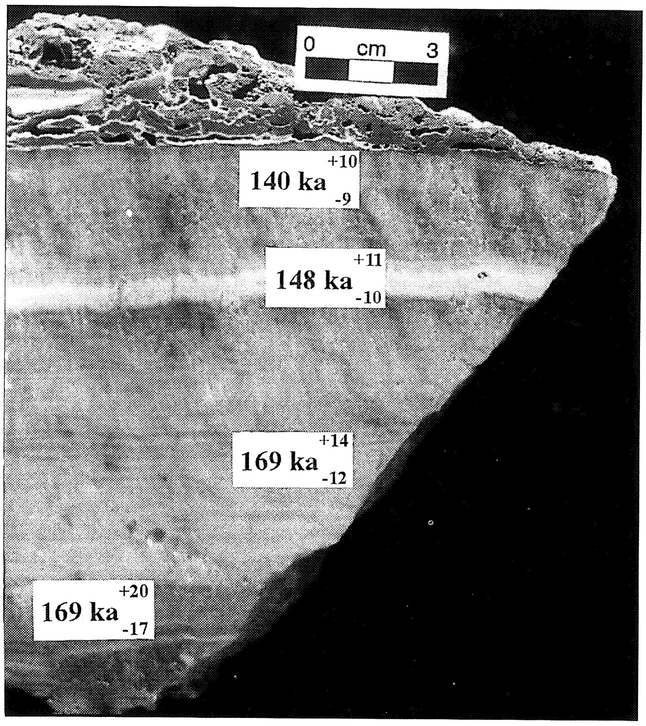

Fig. 8. The sample 1 represents the second speleothem generation in Demänova Ice Cave, U/Th age (ka ago) of particular layers are indicated, the layer built of cemented intraclasts is visible in the upper part of the sample (see text for further explanations)

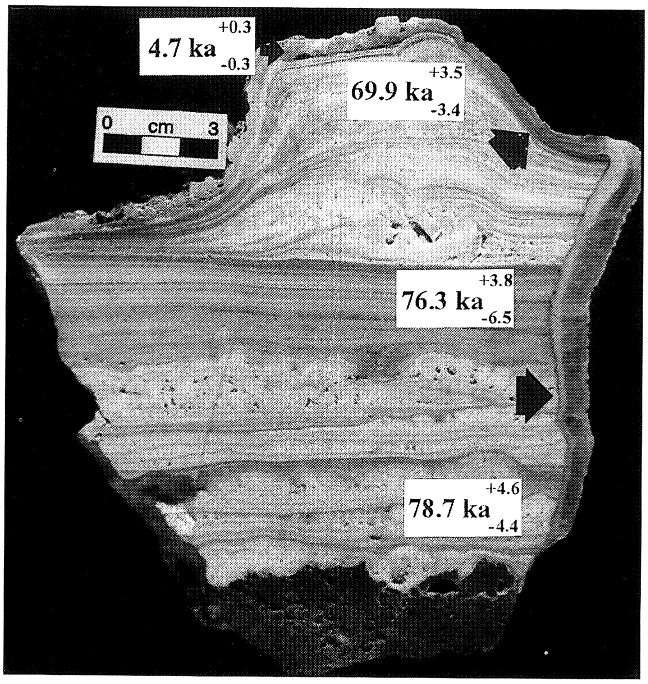

Fig. 9. The sample 2 represents the third and the fourth speleothem generations in Demänova Ice Cave, U/Th age (ka ago) of particular layers are indicated, corrosion surface between both generations is visible (*big arrows*)

3 cm thick layer occurs which is built up by clasts composed of fine-grained sediments, ranging from fine-grained sand to silt. These clasts are fragments of the cemented cave infill; hence, they represent intraclasts. They display internal horizontal lamination. The clasts are rotated, displaced and cemented by spary cement.

Interpretation. Columnar calcite crystals building the flowstone represent the columnar microfacies, distinguished by Dziadzio *et al.* (1993) and Gradziński *et al.* (1996). Their regular development testifies to suitable growth conditions of the flowstone in question (see also Frisia *et al.*, 1993). The lack of corrosion and nucleation surfaces in the log described is indicative of stable hydrodynamic conditions during the flowstone growth. Lamination occurring in the middle part of the flowstone is associated with the cyclic, probably seasonal delivery of alternately clear and contaminated by organic and/or mineral substance solutions (Gradziński *et al.*, 1997a). A distinct corrosion surface at the top records destructive processes that had occurred before the layer composed of intraclasts was deposited. The spatial arrangement of intraclasts resembles that of teepe structures (*cf.* Tucker & Wright, 1990). The presence of such structures is indicative of rapid cementation of clastic sediments, displacement of clasts, most certainly at short distances, and repeated cementation of the reworked sediments in stagnant waters.

THIRD SPELEOTHEM GENERATION

Description. This generation is represented by flowstones of variable thickness, from 2.5 to 15 cm. Individual flowstones show as well different internal structure (samples 2, 3, 5–7; Figs. 9, 10). All of them were growing upon cemented, siliciclastic cave sediments. Samples 2 and 5 represent the infill composed of rounded intraclasts, derived from older cave deposits (Fig. 11). The flowstones in question are composed of acicular and columnar calcite crystals. The acicular crystals usually form macroscopically recognisable, white, dome-like forms. Flowstones of the third generation do also include frequent nucleation surfaces (Fig. 12) which are responsible for macroscopically visible lamination. Sample 3 reveals another character. It shows high porosity and the presence of acicular calcite crystals which grow freely at variable angles to the nucleation surfaces. The topmost parts of all the flowstones bear distinct corrosion surfaces.

Interpretation. The third speleothem generation grew

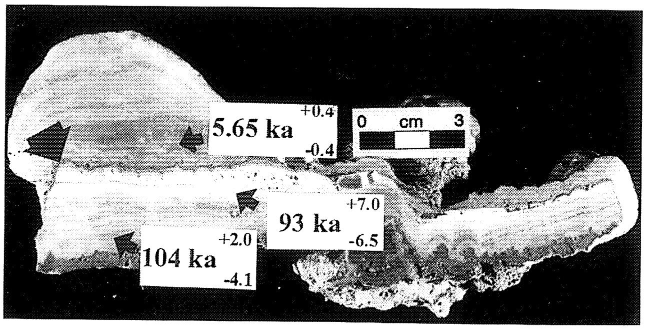

Fig. 10. The sample 7 represents the third and the fourth speleothem generations in Demänova Ice Cave. U/Th age (ka ago) of particular layers are indicated, corrosional surface between both generations is visible (*big arrow*)

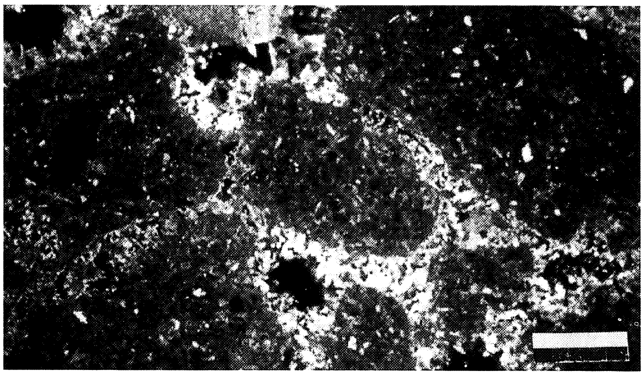

Fig. 11. Intraclasts comprise clastic materials which build lowermost part of sample 2; X nicols, scale bar 0.8 mm

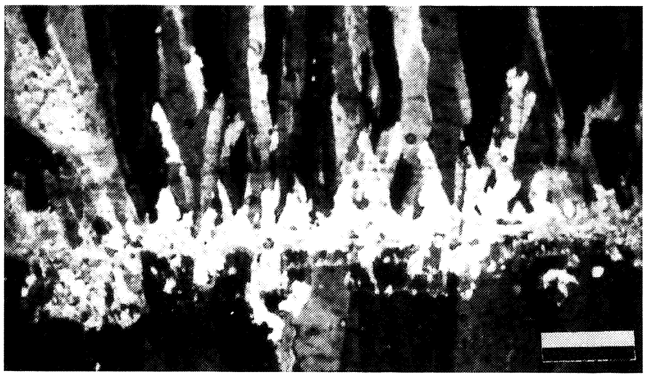

Fig. 12. Nucleation surface well visible due to competitive crystal growth pattern (cf. Sunagawa, 1994), upper part of sample 2; X nicols, scale bar 0.8 mm

under considerably less stable conditions, as compared to the previous one. Acicular calcite crystals, being a common component of this generation, belong to the acicular microfacies, distinguished by Gradziński *et al.* (in press). Such crystals originate under unstable conditions, characterised by the presence of supersaturated solution (see also Given & Wilkinson, 1985; González *et al.*, 1992; Jones & Kahle, 1993). Numerous nucleation surfaces testify to frequent interruptions in the speleothem growth, probably due to drying up of the cave. Comparing the properties and ages of individual flowstones, one can conclude that the growth conditions gradually deteriorated, from relatively suitable ones at the time of development of the oldest flowstone (lower part of sample 7), to the less favourable conditions during the growth of the youngest flowstone, rich in nucleation surfaces (sample 2). The flowstone growth was coeval with the development of small lakes. The infill of one of such lakes is represented by sample 3 (*cf.* González & Lohmann, 1988; González *et al.*, 1992).

FOURTH SPELEOTHEM GENERATION

Description. This generation is represented by up to 1 cm-thick layers, built up of micritic calcite. These layers overlie corrosion surfaces in samples 2 and 3 (Figs. 9, 10). The generation comprises as well a flowstone and a small stalagmite, developed upon a corrosion surface on top of sample 7. Both of them are composed of regularly developed columnar calcite crystals.

Interpretation. The micritic flowstones are probably the products of advanced diagenesis of moonmilk (*cf.* Gradziński *et al.*, 1997b). The properties of the flowstone and stalagmite of sample 7 point to stable and favourable growth conditions (*cf.* Dziadzio *et al.*, 1993; Frisia *et al.*, 1993; Gradziński *et al.*, 1996).

STAGES OF FLOWSTONE GROWTH IN DEMÄNOVA ICE CAVE

It was noted quite early that speleothem deposition, at least in the upper mid-latitudes, is discontinuous with ages clustering into distinct groups that correlate broadly with the known warm and humid stages of the Late Pleistocene (Thompson *et al.*, 1974; Harmon *et al.*, 1975; Atkinson *et al.*, 1978; Głazek & Harmon, 1981; Gascoyne *et al.*, 1983; Henning *et al.*, 1983; Gordon *et al.*, 1989; Hercman, 1991; Baker *et al.*, 1993). Since the speleothem growth is controlled by climatic factors, we can compare the estimated stages of speleothem growth with independent climatic records. We used a geologic time-scale developed by Imbrie *et al.* (1984), based on analyses of isotopic data from five deep-sea cores. It is noteworthy that three of them penetrated the Brunhes/Matuyama boundary. This time-scale covers the last 780,000 years.

The oldest stage of speleothem deposition in DIC can be correlated with the 20–11 ^{18}O stages. The second period is correlated with ^{18}O stage 6, whereas the third one – with ^{18}O stage 5. More precisely, it can be correlated with substages 5c–5a. The youngest, fourth stage is coeval with ^{18}O stage 1 (Fig. 13).

The above comparison indicates that some speleothems grew in DIC at the time of "cold" stages. The best example is provided by flowstones growing during ^{18}O stage 6. Sedi-

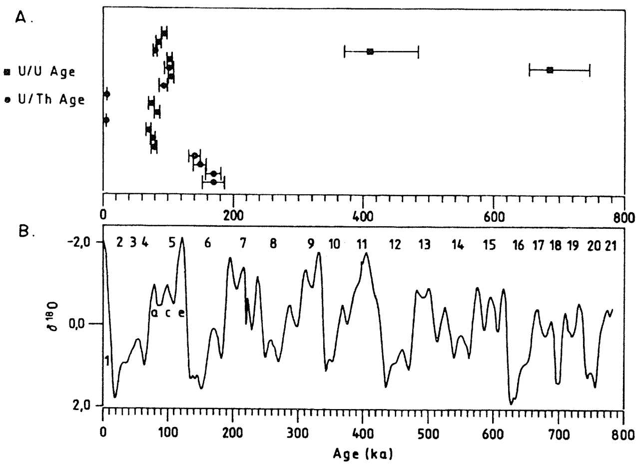

Fig. 13. Correlation of uranium series dating results of speleothems from Demänova Ice Cave and oxygen isotope record: **A** – speleothems dating results, errors 1σ; **B** – the stacked, smoothed oxygen-isotope record as a function of age in SPECMAP time scale. Isotopic variation expressed in standard deviation units around a zero mean (after Imbrie *et al.*, 1984)

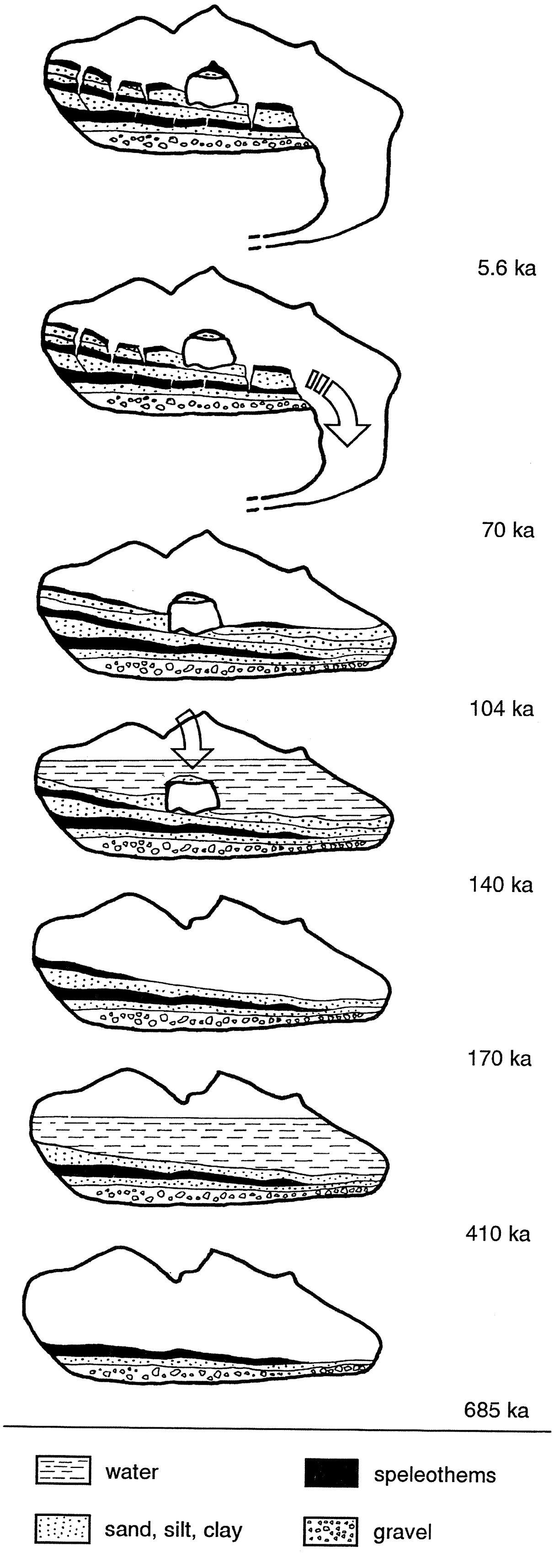

Fig. 14. Scheme of Závrtový dóm development from *ca.* 685 ka to Recent, see text for further explanations

mentological features of the flowstones (see above) prove that they grew in favourable, wet and humid conditions. It suggests that the Nízke Tatry Mts. were situated outside the periglacial zone at that time. On the other hand, the lack of speleothem deposition during the "warm" substage 5e is probably caused by local conditions, because in the other parts of DCS we have dated flowstones that could be correlated with that stage. Uninterrupted flowstone growth during ^{18}O stages 20 through 11 is difficult to understand. This problem requires further work.

EVOLUTION OF DEMÄNOVA ICE CAVE

The analysis of cave passages and their infill makes it possible to reconstruct the evolution of the Závrtový dóm chamber in DIC and, basing on this example, the evolution of the entire IV cave level in DCS (Fig. 14). Age determinations of cave sediments enable us to constrain the ages of individual stages of the cave system development.

The development of the IV cave level should be viewed as proceeding in two stages: (1) enlargement of cave passages, and (2) the subsequent filling of such voids by sediments. The top passages, occurring in the top part of Závrtový dóm, can be either (1) relics of incipient phreatic corridors that were subsequently dissected and remodelled under vadose conditions (*cf.* Bretz, 1942), or (2) an effect of paragenesis (Ford & Williams, 1989). There is no sufficient evidence for cave filling up to the top by clastic sediments, what favours the first option. Owing to subsequent lowering of elevation of the spring position, the Závrtový dóm chamber was placed in the vadose zone, the chamber's floor being systematically lowered. When the present-day position of the floor was achieved, the cave became infilled by clastic sediments, i.e. gravels and sands, as well as by flowstone floors. Basing on sedimentary sequences that fill the chamber, one can distinguish three stages of clastic sediment deposition and four episodes of speleothem crystallisation. The material of clastic sediments was derived from the Nízke Tatry Mts. crystalline core and, probably, from reworked older or coeval glacial deposits, and transported into the cave by surface streams. Therefore, deposition of clastic sediments should be linked with the cave flooding, whereas flowstone formation on the cave floor was associated with periods of cave drying up.

The first stage of cave filling is marked by gravels deposited directly on the rocky floor of the chamber. These gravels are covered by sands (Fig. 14), whose top part was deposited during the Brunhes Chron, i.e. not earlier than 780 ka (*cf.* Baksi *et al.*, 1992; Tauxe *et al.*, 1992). Following the cave dewatering, the oldest, i.e. first speleothem generation was deposited immediately upon sandy sediments. The speleothem growth began *ca.* 685 ka and lasted until 410 ka.

After crystallisation of the oldest speleothem generation, the Závrtový dóm chamber became flooded by waters which laid down sands and silts overlying the pre-existing speleothems. Another episode of speleothem crystallisation took place between *ca.* 170 ka and 140 ka (second generation; Fig. 14). The speleothem growth was terminated by an episode of corrosion, after which the cave witnessed several episodes of flooding by waters bringing in clastic material and reworking older sedimentary infill.

The block, presently lying in the centre of the chamber, probably fell off from the roof, either before or during deposition of these sediments. This is indicated by the presence of 1 cm-thick layer of siliciclastic material draping over the block surface and locally preserved under younger flowstones. This material was deposited in an aquatic environment, after the block fell off from the roof of the chamber. The presence of clastic sediments upon the block shows that the chamber must have been flooded at least up to the upper edge of the block, i.e. the depth of the water basin (a pond?) in the southern part of the chamber must have exceeded 2 m (Fig. 14).

The clastic sediments were covered by another, third generation of speleothems between *ca.* 104 ka and 70 ka (Fig. 14). Their growth proceeded under unstable and gradually deteriorating conditions, associated with the systematic cooling during the advance of the last glacial cycle.

Crystallisation of the third speleothem generation was followed by: the formation of a pitch in the southern part of the chamber, the fragmentation of previously crystallised flowstones, and the displacement of their dismembered fragments (Fig. 14). The last process was caused by erosion and/or gravity sliding of underlying, uncemented clastic sediments.

The fragmented flowstones underwent intensive erosion, producing distinct corrosion surfaces that are developed upon the exposed surfaces of older speleothems. The corrosion surfaces, in turn, were capped in Holocene times by the youngest, fourth generation of speleothems.

AN ATTEMPT AT ESTIMATING THE AGE OF THE DEMÄNOVA CAVE SYSTEM

Horizontal caves of smoothed gradients originate in the epiphreatic zone, i.e. at the level of karst springs or slightly above, depending on hydraulic gradient (Swinnerton, 1932). Ford (1977) and Ford and Ewers (1978) showed that horizontal caves of smoothed gradient, also called ideal watertable caves, tend to develop at the boundary between the phreatic and vadose zones, within highly fractured rocks. The development of such caves proceeds at the time of base level stabilisation. During rapid valley deepening, the cave level is dewatered or cut by vadose canyons. During the next period of base level stabilisation another, lower, cave level develops. In this way, a multiphase cave system is being formed, whose individual levels reflect successive periods of base level stabilisation (Ford & Williams, 1989). Cave levels develop more or less at the former base level horizons, indicating the position of former valley bottoms of those rivers that drained the cave system. The above view is a commonly accepted one, and the one which has recently been confirmed by complex studies by Palmer (1987) of numerous North American caves. It should also be noted that younger, vertical shafts of vadose character could truncate the horizontal, older fragments of cave systems. The origin of such shafts is associated with invasion waters (Ford & Ewers, 1978) which could form, for instance, during glacier melting (*cf.* Głazek *et al.*, 1977).

The age of a particular cave level is difficult to estimate precisely. The best approach is to date sediments that infill the level, whose age is the youngest possible age of the level. The age of speleothems developed in a given cave level, in turn, gives the minimum age of dewatering of such a level. This technique has been applied to the Rocky Mts. caves (Ford, 1973; Ford *et al.*, 1981), the Mammoth Cave system (Schmidt, 1982), caves in Wyandotte Ridge, Indiana (Pease *et al.*, 1994), Yorkishire Dale and Mendip Hills caves in the British Isles (Atkinson *et al.*, 1978), Western Tatra Mts. caves (Hercman, 1991), caves near Guilin (Williams *et al.*, 1986) and caves of the Buchanan Karst in Australia (Webb *et al.*, 1992). The age of speleothems is usually determined by the use of uranium series techniques, whereas that of clastic sediments is determined by the palaeomagnetic method.

The DCS is a typical multiphase cave system. Basing on concepts of Ford (1977) and Ford and Ewers (1978), Bella (1993) assigned individual DCS cave levels, distinguished by Droppa (1957), to the ideal watertable caves or to the mixture of phreatic and watertable levelled caves. Therefore, it is justified to conclude that the age of the oldest speleothems occurring in the IV cave level of DIC is the minimum age of dewatering of this level.

Taking into account that the age of the oldest flowstones of the IV cave level is *ca.* 685 ka (see Table 2), one should accept that the level must have been already dewatered at that time. Fluvial sands underlying the dated flowstone show normal magnetic polarity, indicating that they were deposited during the Brunhes Chron, i.e. not earlier than 780 ka BP (*cf.* Baksi *et al.*, 1992; Tauxe *et al.*, 1992). These data show that the dewatering of the IV cave level occurred between 780 ka and *ca.* 685 ka. Droppa (1966) associated the origin of the IV cave level with the Mindel II glacial stage, basing on correlation with fluvial terraces. A comparison of the estimated age of dewatering of this level with the known age of the Mindel II glacial stage, dated at *ca.* 500 ka (Kukla, 1977), calls for revision of Droppa's (1966) view. One should also bear in mind that the discussed age estimations refer to the period of dewatering of the cave level, hence, the age of the level itself must be older.

Episodes of flooding of the IV cave level in DCS, leaving siliciclastic sediments inbetween the 2nd and 3rd and, probably, also between the 1st and 2nd speleothem generations, should be linked with the delivery of invasion vadose waters into the cave. These waters originated at the time of glacier melting during consecutive glacial stages. It seems likely, therefore, that the clastic sediments were not deposited by subterraneous flows of the Demanovka stream, and that their top cannot mark the valley bottom position at that time. Similar events of clastic material deposition within caves, due to huge flows induced by glacier thawing, have already been described from numerous caves like, e.g. those of the Tatra Mts. (Głazek *et al.*, 1977), the Matlock area in Derbyshire (Ford & Worley, 1977) or Castelguard Cave in the Canadian Rocky Mts. (Schroeder & Ford, 1983).

Moreover, the formation of a pitch in the southern part of the chamber, creeping of clastic sediments and fragmentation of the three older flowstone generations, all resulted from the draining of invasion vadose waters into lower levels of the DCS, most probably at the decline of the last glacial stage.

The above rules governing the development of multilevel cave systems and the estimated age of dewatering of the IV cave level enable us to infer that before the dewatering, i.e. before *ca.* 685 ka, the Demanova Valley bottom was situated not higher than 45 m above its present-day position. Therefore, the rate of fluvial incision in Late Quaternary times must have been smaller than hitherto supposed. The higher situated DCS levels (V through IX) should, hence, be older as well, and cannot be correlated with successive Alpine glaciations, i.e. Mindel I through Donau, respectively, as conjectured by Droppa (1966). We conclude, therefore, that the morphology of the Nízke Tatry Mts. is older than previously supposed.

The above conclusions are of preliminary character. A more detailed reconstruction of the DCS development and its precise dating requires further geomorphological and speleogenetic studies, aided by isotopic datings of speleothems and palaeomagnetic determinations performed in the remaining cave levels.

CONCLUSIONS

1. The IV cave level of Demänova Cave System became dewatered between 780 ka and *ca.* 685 ka; hence, it is older than previously supposed.

2. The age of the remaining cave levels, as well as that of the Nízke Tatry Mts. relief is also older.

3. Demänova Ice Cave bears a record of four episodes of speleothem growth, i.e. *ca.* 685–410 ka, 170–140 ka, 104–70 ka, and after 5.6 ka.

4. Between 410 ka and 5.6 ka, Demänova Ice Cave was flooded at least twice by invasion (proglacial) waters supplied from the melting glaciers.

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Streszczenie

DATOWANIE NACIEKÓW Z DEMENOVSKIEJ LODOWEJ JASKINI ETAPEM W OKREŚLENIU WIEKU DEMENOVSKIEGO SYSTEMU JASKINIOWEGO (NIŻNE TATRY, SŁOWACJA)

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Demenovski System Jaskiniowy (DCS) (Fig. 1) jest powszechnie podawanym w literaturze przykładem wielopoziomowego systemu jaskiniowego. Poszczególne poziomy tego systemu Droppa (1966, 1972) skorelował z poziomami teras rzek powierzchniowych – Demenovki, a także Vagu i innych jego dopływów. Poziomom tym przypisał wiek kolejnych zlodowaceń posługując się klasycznym alpejskim podziałem czwartorzędu (Fig. 2). Demenovska Lodowa Jaskinia (DIC) jest rozwinięta głównie na IV poziomie jaskiniowym ok. 45 m ponad poziom dzisiejszego dna Demenovki. Droppa (1966) wiąże powstanie tego poziomu ze zlodowaceniem Mindel II.

Próby polew naciekowych do badań laboratoryjnych zostały zebrane w sali Závrtový dóm (Fig. 3, 4, 5). Wiek wszystkich polew określono metodą $^{230}Th/^{234}U$, a wiek najstarszych polew metodą $^{234}U/^{238}U$. Zostało określone także namagnesowanie 11 prób z najstarszej polewy. Wykonane zostały również obserwacje mikroskopowe pobranych prób.

Wyniki datowań $^{230}Th/^{234}U$ przedstawia Tabela 1 i Fig. 8–10, a $^{234}U/^{238}U$ Tabela 2 i Fig. 7. Opierając się na wynikach datowania można wyróżnić cztery generacje nacieków o następującym wieku: ok. 685–410 ka, ok. 170–140 ka, ok. 104–70 ka i młodszym od 5.6 ka. Badane próby najstarszej generacji nacieków, i znajdującego się bezpośrednio pod nią scementowanego namuliska silikoklastycznego cechują się normalnym namagnesowaniem (Fig. 6).

Pierwszą i drugą generację nacieków tworzą głównie kolumnowe kryształy kalcytu świadczące o dogodnych warunkach wzrostu tych generacji. Powierzchnie korozyjne są w nich stosunkowo nieliczne. Natomiast generacja trzecia, występująca ponad niewielkiej miąższości osadami klastycznymi (Fig. 11) zbudowana jest z różnorodnie wykształconych kryształów kalcytu z licznymi powierzchniami nukleacji (Fig. 12) i powierzchniami korozyjnymi, co świadczy o niestabilnych warunkach podczas jej wzrostu. Generacja ta jest oddzielona od nadległej, najmłodszej czwartej generacji czytelną powierzchnia korozyjną.

Poszczególne generacje nacieków jaskiniowych zostały skorelowane ze stadiami tlenowymi zapisanymi w osadach głębokomorskich (*cf.* Imbrie *et al.*, 1984; Fig. 13): generacja pierwsza ze stadiami 20-11, druga ze stadium 6, trzecia ze stadium 5c–5a, a czwarta ze stadium 1. Problem wzrostu trzeciej generacji nacieków w czasie "zimnego" stadium 6 i ciągły wzrost nacieków od 20 do 11 stadium jest na obecnym etapie badań trudny do wyjaśnienia.

Osady silikoklastyczne zdeponowane pomiędzy datowanymi polewami naciekowymi, powstanie studni w południowej części sali, spełzywanie osadów klastycznych i pokruszenie trzech starszych generacji polew było spowodowane dopływem do jaskini inwazyjnych wadycznych wód. Wody te związane były z topnieniem kolejnych zlodowaceń.

Otrzymane wyniki datowania nacieków i wyniki badań paleomagnetycznych świadczą, że odwodnienie IV poziomu jaskiniowego nastąpiło pomiędzy 780 ka i ok. 685 ka. Droppa (1966), na podstawie korelacji z terasami rzek powierzchniowych wiązał powstanie IV poziomu jaskiniowego ze zlodowaceniem Mindel II. Z porównania estymowanego wieku odwodnienia IV poziomu jaskiniowego z przyjmowanym obecnie wiekiem zlodowacenia Mindel II, który wynosi ok. 500 ka (Kukla, 1977) wynika, że pogląd Droppy (1966) dotyczący wieku IV poziomu jaskiniowego musi zostać zrewidowany. Dowodzi to, że tempo wcinania się Demenovskiej doliny w młodszym czwartorzędzie było niższe niż dotychczas zakładano, a rzeźba Niżnych Tatr jest starsza niż dotychczas uważano. Odpowiednio starsze są więc również wyższe (tj. V–IX) poziomy jaskiniowe DCS.