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Lateglacial-Middle Holocene stable isotope records in two coeval stalagmites from the Bihor Mountains, NW Romania

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Oxygen and carbon stable isotope records of two stalagmites from NW Romania provide a continuous climatic record between 14.8 and 5.6 ka BP. The chronology is established by 21 TIMS uranium series ages. Uncertainties in the isotope chronology range between ±20 and ±100 yr. The $\delta^{18}O$ values are positively correlated with temperature, whereas $\delta^{13}C$ fluctuations suggest changes in soil CO_2 production. Lateglacial deposition of both stalagmites started at ~14.8 ka BP. The $\delta^{18}O$ records subsequently show a slow decline in temperatures until 12.6 ka BP. Three warmer periods with increased soil productivity occurred at 14.5–13.9 ka BP, 13.6–13.2 ka BP, and 12.9–12.6 ka BP. Lower $\delta^{18}O$ and high $\delta^{13}C$ values between 12.6 and 11.4 (11.7) ka BP indicate a cold and dry climate during the Younger Dryas (GS-1). During the Early Holocene, three short cold intervals are marked on the $\delta^{18}O$ profiles at 11.0–10.6, 10.5–10.2 and 9.4–9.1 ka BP. For the remainder of the Holocene sequence, the $\delta^{18}O$ records show less variation between 9 and 7.8 ka BP and gradual warming from 7.6–5.6 ka BP. The speleothem records correlate with the Greenland ice core records and with other proxies throughout Europe and the North Atlantic region.

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Key words: NW Romania, Lateglacial-Middle Holocene, stalagmites, stable isotopes, uranium-thorium TIMS dating.

INTRODUCTION

Calcium carbonate deposits from caves, such as stalagmites or flowstones, provide information on the nature of past climates and environments. Changes of climatic conditions were shown to influence stable isotope geochemistry during speleothem deposition (Hendy and Wilson, 1968; McDermott, 2004). The timing of past climatic shifts in such continental records is important for comparisons with marine or ice core records and for reconstructions of climate variability.

U-Th TIMS dating of speleothems provides good precision of results in terms of radiometric ages and sample stratigraphy (Li *et al*., 1989; Richards and Dorale, 2003). Speleothems dated by TIMS provide valuable palaeoclimatic information when associated with other proxies such as $\delta^{18}O$ and $\delta^{13}C$ isotopic composition of calcite (Dorale *et al*., 1998; McDermott *et al*., 1999; McDermott, 2004; Williams *et al*., 2005).

In this study we present a reconstruction of Lateglacial-Mid-Holocene climate changes based on continuous stable isotope profiles on two stalagmites from northwestern Romania. The $\delta^{18}O$ and $\delta^{13}C$ speleothem records show similarities with the Greenland ice core records (Dansgaard *et al*., 1989; Johnsen *et al*., 1997) and are correlated with pollen records, lake sediments and vegetation dynamics (Wohlfarth *et al*., 2001; Björkman *et al*., 2002; Bodnariuc *et al*., 2002; Feurdean and Bennike, 2004; Magny, 2004).

SITE DESCRIPTION

The V11 Cave is located in the southeastern part of Vărăşoaia Glade (Bihor Mountains, NW Romania), at 1254 m a.s.l. (Fig. 1A). The area is a typical karst plateau with sinkholes and ponors and the vegetation consists mainly of spruce stands and alpine herbs (Bodnariuc *et al*., 2002). The mean annual temperature is 5°C and the mean annual precipitation exceeds 1200 mm at the Stâna de Vale winter resort (1102 m a.s.l), 11 km NW from the cave. The present-day climate of the

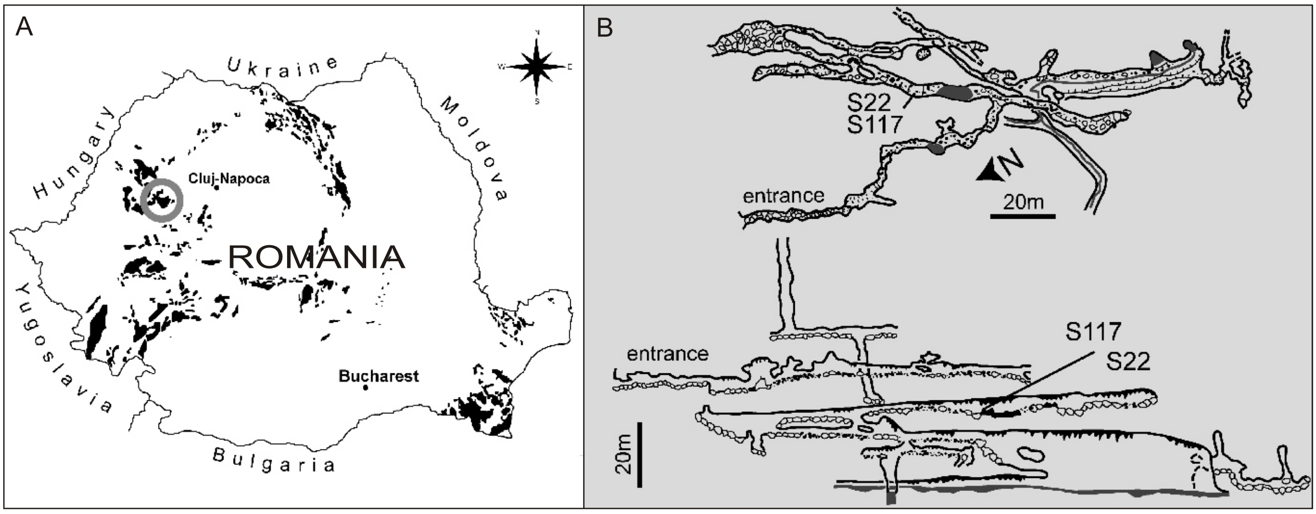

Fig. 1. A — geographical location of the V11 Cave; karst areas are marked in black, the gray circle marks the Bihor Mountains; B — plan and longitudinal section of the V11 cave showing the sampling site of stalagmites S22 and S117

area is predominantly influenced by west-northwest oceanic air masses, with the Southern Carpathians acting as a barrier against Mediterranean influences.

The V11 cave formed in Anisian carbonate rocks: black limestones (Guttenstein facies) and grey dolostones. The cave has 1166 m of surveyed passages, a vertical extension of 67 m (–37 m; +30 m), and it developed as a dendritic maze on four main karstification levels (Damm, 1993; Fig. 1B). The speleothems are restricted to a few sectors and consist of calcite stalagmites, stalactites, old (fossil) flowstones and some aragonite crystal aggregates and crusts. Present-day calcite deposits occur as soda straws and small active stalagmites.

The two stalagmites (S22 and S117), both inactive when sampled, were collected 200 m away from the cave entrance, at about 60 m below the surface (Fig. 1B). The first one grew on a breakdown block and the second on clay deposited on the passage floor. Several active soda straws from their close vicinity were sampled for recent calcite and drip water isotopic analyses. The mean annual temperature and the relative humidity of the cave air, measured between 2003 and 2004, are 6.5°C and 97–98%, respectively.

SAMPLE DESCRIPTION AND ANALYTICAL PROCEDURES

SAMPLE DESCRIPTION

Sample S22 is a 34 cm-tall stalagmite consisting mostly of dense, yellow-brown, low-Mg calcite laminae, composed of large prismatic crystals, continuously grown from one level to another and oriented oblique to the outer surface (Fig. 2A). The first 8 cm-thick interval from the base consists of alternating thin transparent and opaque levels, which ends with a well-marked corrosional hiatus, after which growth was continuous over the last 26 cm to the top. Between 10.5 and 5.8 cm from the top, there is a highly porous white opaque level made up of calcite microcrystals.

Sample S117 (Fig. 2B) is 48 cm in height (measured along the growth axes) and is very different from S22 in terms of shape and stratigraphy. The repeated displacement of its growth axis was probably produced by sliding over the clayey substratum. On the basis of macroscopic observations, the sample could be divided into 4 zones with 10 different growth axes (Tămaş and Causse, 2001):

I. 0–9 cm: from the base to a fracture line covered by subsequent deposition (growth axes A10–A8); thin growth levels, slightly porous dark brown calcite;

II. 9–29.5 cm (A7–A5); light brown to white compact calcite lamina, with a small growth hiatus at 25 cm, marked by a thin film of clay. This sequence ended when the stalagmite broke (not shown in Fig. 2B);

III. 29.6–36.4 cm (A4–A2); deposition resumed and younger growth layers covered the fracture separating zones I and II; yellowish white, transparent, alternating compact and porous calcite levels;

IV. 32.5–48 cm (A1). The stalagmite slipped once more over the substratum and the younger growth layers partly covered zone III, inducing a hiatus of ~0.6 ka.

U-Th DATING

The U and Th ratios were measured in peak jumping mode on a *Finnigan-MAT 262* thermal ionization mass spectrometer at the Laboratoire des Sciences du Climat et de l'Environnement, Gif sur Yvette, France. Details of the research and chemical procedure are given by Tămaş and Causse (2001). A total of 21 samples (12 from S22 and 9 from S117) from the uppermost parts of the two stalagmites (15 to 5.6 ka) were selected for this study (Table 1). About 1 to 2.5 g of calcite was extracted from *ca.* 3 mm thick levels for each analysis. The uranium content ranged between 0.23 and 0.68 ppm. The U-Th ages cover the time intervals of 14.5–5.6 ka BP for S22 and 13.5–6.1 ka for S117 (Table 1 and Fig. 2A, B). A basal age of 14.8 ka BP for the beginning of the Lateglacial was obtained on S117 by linear extrapolation.

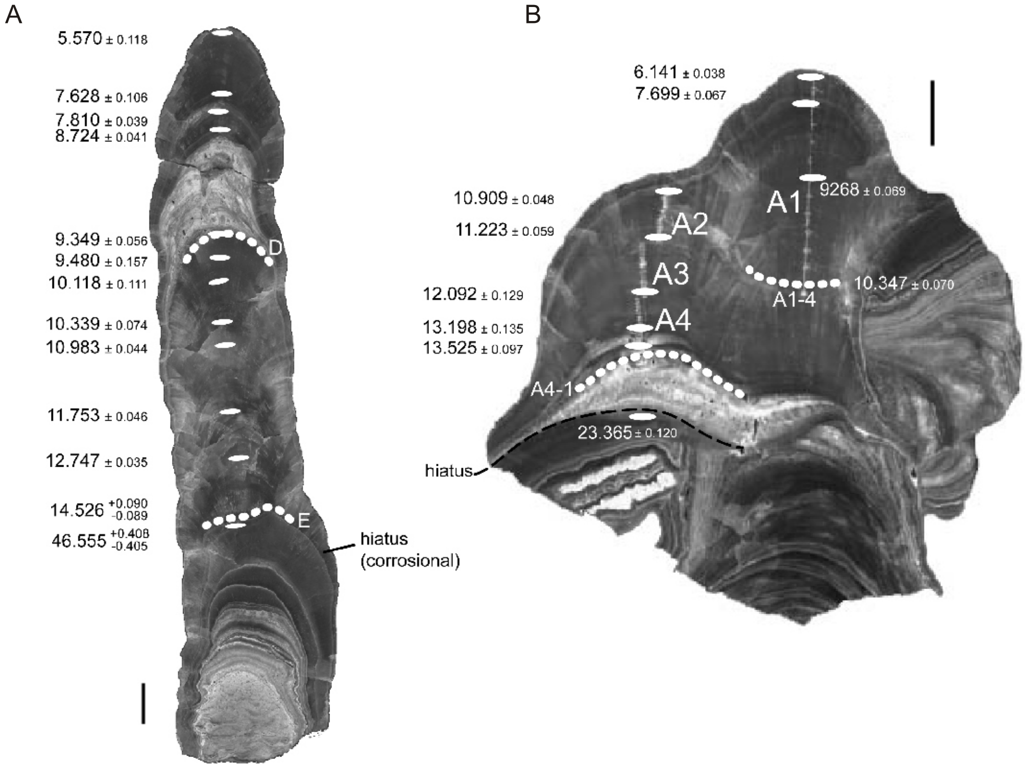

Fig. 2. Sampling profile along the two stalagmites

A — S22; B — S117; A1–A4 on S117 show directions of growth axes; white ellypses show the position of samples taken for U-Th dating; white dots along the growth levels indicate positions of samples checked for 'Hendy' tests (D, E on S22; A4-1, A1-4 on S117); scale bars are 2 cm

STABLE ISOTOPE ANALYSES

Oxygen and carbon stable isotope analyses were performed on the upper part of the stalagmites S22 and S117 (the upper 25 cm for S22 and the upper 13 cm for S117), corresponding to the interval between 15 and 5.6 ka BP. A total of 306 samples (147 from S22, and 159 from S117) were drilled out at 2 mm intervals for S22 and 1 mm intervals for S117, along the central axes of the stalagmites, using 0.5 and 0.3 mm diameter drills. These intervals were considered convenient, as the length and average growth rates of S117 generally represent half the values recorded for S22. The ages were assigned to each stable isotope sampling point by linear interpolation between neighbouring TIMS dates. Two tests for isotopic equilibrium were done on "individual growth layers" for each stalagmite (Fig. 3). A minimum of 7 samples at 5 mm apart was analysed for each growth level.

The isotopic analyses were performed on whole-rock samples using an automatic *Kiel II* preparation line and a *Finnigan MAT Delta Plus* mass spectrometer at the Institute of Earth Sciences, Karl-Franzens University (Austria). Carbon dioxide was released by reaction with phosphoric acid at 70°C. The isotopic values are presented in per mil relative to PDB. NBS-19 and an internal laboratory standard were analysed continuously for accuracy control, and the standard deviation was 0.1‰ for $\delta^{18}O$ and 0.06‰ for $\delta^{13}C$.

Two present-day calcite samples from active soda straw tips and two from a stalagmite top from the same cave, dated at 52±3 yr. BP (Tămaş, 2003), were analysed as well. Drip water from two soda straws was collected from July 2003 to June 2004. However, the high amount of snow during the winter of 2003 made the access to the cave impossible from December 2003 to May 2004 so the water sample collected in May represents an average of these five months. Drip rates are much lower during the winter months. The isotopic composition of the dissolved inorganic carbon (DIC) as well as the isotopic composition of oxygen in water were done at Joanneum Research Graz, Department of Hydrogeology, using automatic preparation lines and a *Finnigan MAT Delta Plus* mass spectrometer. The isotopic values of water samples are given in ‰ relative to SMOW for $\delta^{18}O$ and to PDB for $\delta^{13}C$.

RESULTS

U-Th DATING

The ages and isotope ratios obtained by U-Th dating are presented in Table 1. In S22, an age of 14.5 ka at 8.4 cm from the base follows a level dated at 46.5 ka, from which it is separated by a hiatus (Fig. 2A). Considering its shape, we assumed this hiatus was corrosional, formed by undersaturated drip water that dissolved a part of the calcite formerly deposited (Tămaş and Causse, 2001). In S117, an age of 23.4 ka was obtained for the level below the hiatus (Fig. 2B) (Tămaş and Causse, 2001). The age obtained for the level just above the hiatus in S117 (Fig. 2B)

Table 1

U-Th ages and isotope ratios obtained on the two stalagmites (details in text and in Tămaş and Causse, 2001)

S22							
d* [cm]	U [ppm] ± 2σ	^{234}U/^{238}Ua ± 2σ	^{234}U/^{238}Ui ± 2σ	^{230}Th/^{234}U ± 2σ	^{230}Th/^{232}Th	Age [ka BP]	± 2σ [ka]
33.7	0.407	0.993±0.021	0.992±0.018	0.050±0.001	27.5	5.570	0.118
30.2	0.446	0.970±0.003	0.969±0.003	0.068±0.001	189	7.628	0.106
29.4	0.417	0.981±0.003	0.980±0.002	0.069±0.001	505	7.810	0.039
28.5	0.371	1.001±0.002	1.000±0.002	0.077±0.001	282	8.724	0.041
23.0	0.450	0.927±0.003	0.925±0.002	0.082±0.001	851	9.349	0.056
21.8	0.440	0.927±0.003	0.925±0.002	0.083±0.002	371	9.480	0.157
20.8	0.411	0.929±0.005	0.927±0.004	0.089±0.001	283	10.118	0.111
19.8	0.344	0.930±0.002	0.928±0.002	0.092±0.001	779	10.536	0.141
18.9	0.403	0.921±0.002	0.918±0.002	0.091±0.001	775	10.339	0.074
15.9	0.493	0.921±0.003	0.918±0.002	0.096±0.001	193	10.983	0.044
12.0	0.549	0.905±0.002	0.901±0.002	0.102±0.001	263	11.753	0.046
10.0	0.520	0.919±0.003	0.916±0.002	0.110±0.001	137	12.747	0.035
8.4	0.609	0.885±0.002	0.880±0.001	0.125±0.001	100	14.526	0.090
S117							
47.8	0.283	0.953±0.003	0.952±0.002	0.055±0.001	86	6.141	0.038
47.1	0.447	0.923±0.008	0.922±0.006	0.068±0.001	311	7.699	0.067
44.5	0.446	0.904±0.002	0.901±0.002	0.082±0.001	429	9.268	0.069
41.4	0.333	0.930±0.003	0.928±0.003	0.091±0.001	838	10.347	0.070
40.8	0.345	0.881±0.002	0.877±0.002	0.095±0.001	490	10.909	0.048
39.3	0.378	0.870±0.002	0.866±0.002	0.098±0.001	943	11.223	0.059
38.0	0.655	0.882±0.002	0.878±0.002	0.105±0.001	1376	12.092	0.129
35.9	0.519	0.863±0.003	0.858±0.002	0.114±0.001	874	13.198	0.135
35.5	0.467	0.867±0.002	0.862±0.002	0.117±0.001	650	13.525	0.097
34.6	0.513	0.819±0.002	0.810±0.001	0.1365±0.001	29	16045**	0.089

*d — distance from base; ** — rejected due to detrital contamination

was 16 ka, but it was rejected due to its low ^{230}Th/^{232}Th ratio (Table 1). By extrapolation from the neighbouring age of 13.5 ka to the hiatus, an age of 14.8 ka was obtained for the basal level of this growth interval. Two other dates were obtained with low ^{230}Th/^{232}Th ratios, located at the top of the two stalagmites (Table 1). Corrections for detrital content were not applied in this case because the corrected ages would still fall within the uncertainty limits of the isotopic records.

The average growth rates of the two stalagmites for the whole Lateglacial-Mid Holocene growth interval are 28.2 mm/ka for S22 and 14.3 mm/ka for S117. The growth rates between any two successive U-Th ages vary between 11.2 and 91.6 mm/ka for S22, and between 7.0 and 82.8 mm/ka for S117. Temporal resolutions for the isotope records are thus between 20 and 190 yr/mm for S22 (for isotope sampling points at 2 mm) and 12 and 142 yr/mm for S117. These give a maximum shift of ±100 yr in the stable isotope chronology.

The minimum growth rates are related to the warming phase at the beginning of the Lateglacial (14.5–12.7 ka in S22) and during the final growth interval, from *ca.* 7.7 ka until growth cessation (17.2 mm/ka for S22 and 7.1 mm/ka for S117). Apart from that, S117 has fairly constant growth rates, except for a maximum of 82.8 mm/ky at the beginning of the Holocene (*ca.* 200 years) followed by a hiatus of *ca.* 560 years, due to a change in the growth axis position. S22 has a more complicated growth record, with faster rates within the GS-1 (Younger Dryas) and during the first part of the Boreal (46.6–90.5 mm/ka) and around the Boreal-Atlantic transition (88.0–91.6 mm/ka), separated by slow-growth intervals (15.7 mm/ka, between 10.1 and 9.5 ka, and 11.0 mm/ka, between 8.7 and 7.8 ka). A short, fast growth interval of less than 200 years is recorded between 7.8 and 7.6 ka. This latter interval and the one between 9.3–8.7 ka are also marked by changes in calcite petrography, white porous zones made up by calcite

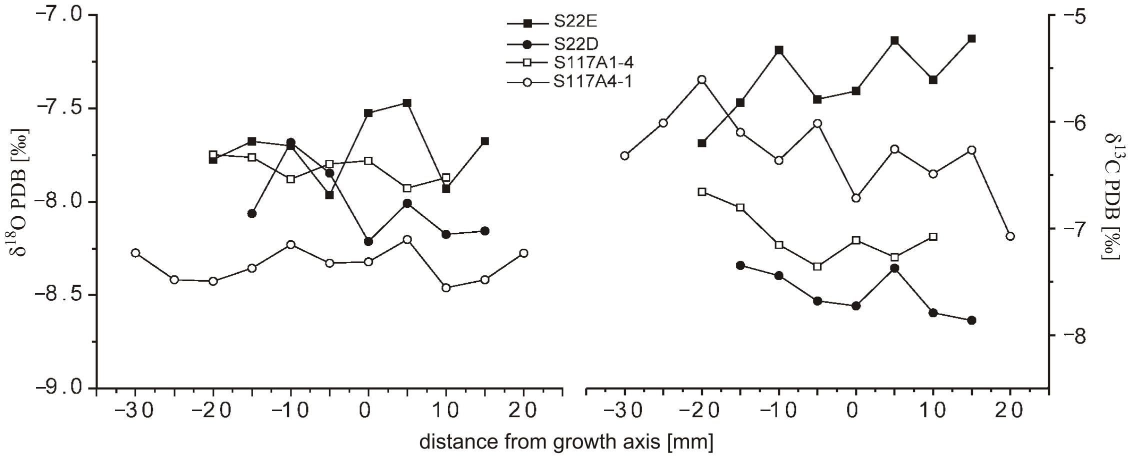

Fig. 3. **$\delta^{18}O$ and $\delta^{13}C$ profiles along growth layers of S22 and S117**

microcrystals replacing the compact palisadic fabric. Such fabrics can also be observed during the Bøling-Allerød in S117, but they are not associated with changes in growth rates.

STABLE ISOTOPE ANALYSES

Speleothems are precipitated in isotopic equilibrium with their drip water when the CO_2 from water degasses slowly, at stable cave temperatures without air currents. Two conditions have to be tested to establish the isotopic equilibrium: first, that the $\delta^{18}O$ values of a single growth layer show no significant variation (Hendy, 1971), and second, that the $\delta^{18}O$ and $\delta^{13}C$ values measured along the growth axis are not correlated. The tests for isotopic equilibrium done on the two stalagmites show little or no correlation between the oxygen and carbon records. The two layers tested from S117 show $\delta^{18}O$ maximum variations of 0.26‰, which is close to twice the analytic error; in the case of S22, the maximum variation is of 0.53‰ (Fig. 3). The ‘Hendy' tests suggest that kinetic effects were not significant during deposition. Also, no correlation exists between $\delta^{18}O$ and $\delta^{13}C$ values along the growth axes of the two stalagmites (Fig. 4). There is, however, a good correlation between the two $\delta^{18}O$ records (Fig. 6 B, C), proving they are suitable for palaeoclimatic interpretations (Dorale *et al.*, 1998, 2002).

The seasonal $\delta^{18}O$ variations in drip water samples collected from the cave are up to 1.4‰ (Fig. 5A), with slightly lower values during the summer months. The amplitude of seasonal temperature variation inside the cave does not exceed 1°C. Using the equation of Friedmann and O`Neil (1977), the calculated $\delta^{18}O$ values of modern calcite have a mean of 22.5‰, which is ~0.8‰ lower than the isotopic composition of present-day calcite (23.3‰). Dissolved inorganic carbon (DIC) values for the collected drip water show pronounced seasonal variation (Fig. 5B), with higher values during winter. The variations are interpreted to reflect different sources of DIC between the winter-summer months, with a higher contribution of bedrock and atmospheric carbon in the cold season. Using the fractionation factors between HCO_3–CO_2 gas (Mook *et al.*, 1974) and CO_2 gas–calcite (Bottinga, 1968), the calculated mean $\delta^{13}C$ of calcite is –7.5‰, only with 0.2‰ lower than the measured carbon isotopic composition of the present-day calcite (–7.3‰). The measured and the calculated values support the view that precipitation of the calcite at the sampling site is near isotopic equilibrium with the drip water.

For speleothems precipitated in isotopic equilibrium with the drip water, the $\delta^{18}O$ isotopic composition is dependent on composition of precipitation, and the temperature-dependent fractionation between drip water and carbonate. The average $\delta^{18}O$

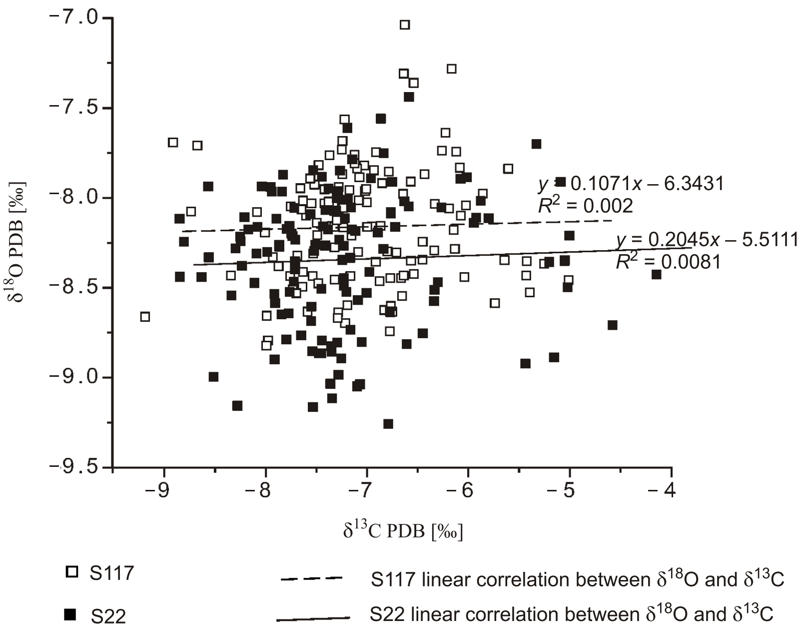

Fig. 4. **$\delta^{18}O$ *vs.* $\delta^{13}C$ values of samples taken along the growth axes of the stalagmites**

R^2 — squared correlation coefficient

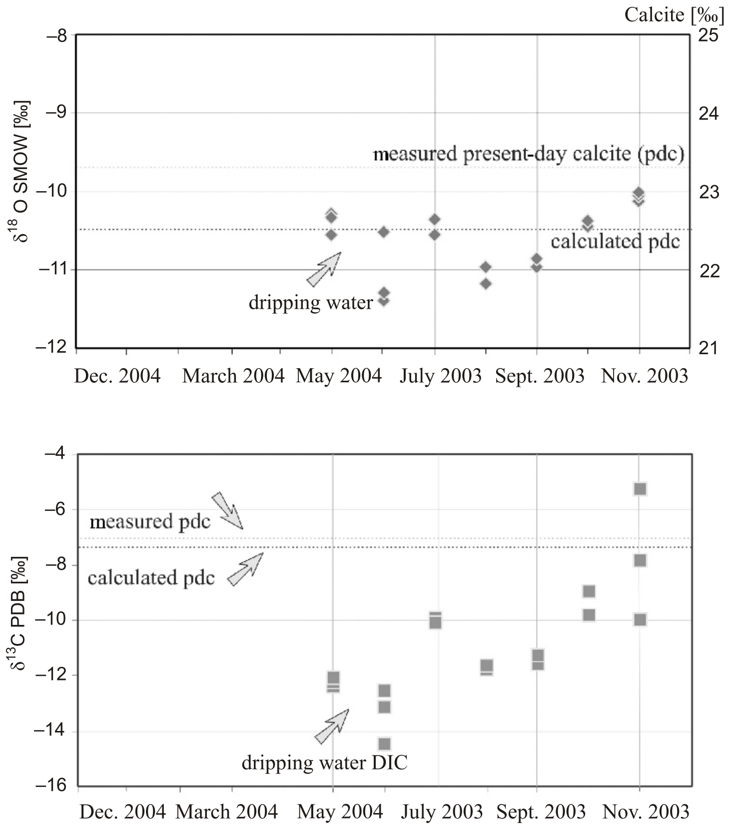

Fig. 5. Monthly variation of $\delta^{18}O$ and dissolved inorganic carbon (DIC) values for drip water plotted with the calculated $\delta^{18}O$ and $\delta^{13}C$ isotopic composition of calcite (continuous line) and the measured $\delta^{18}O$, and $\delta^{13}C$ of present-day calcite (pdc)

value of the drip water collected in the cave during 2003–2004 is –10.6‰, close to the –10.5 ‰ value measured for precipitation at the Urşilor Cave, 12 km SW from our site, during 1997–1998 (six months missing). In Europe, the $\delta^{18}O$ composition of rainwater shows a positive correlation with temperature, with a coefficient of ~0.6‰°C^{-1} (Rozanski *et al*., 1992). Given that the speleothems studied were deposited close to isotopic equilibrium with the drip water, a positive correlation is assessed between the $\delta^{18}O$ record and temperature variations.

The carbon from speleothems has three main sources: atmospheric CO_2, soil CO_2 and carbon from limestones (Schwarcz, 1986; Genty *et al*., 2001). The $\delta^{13}C$ values in speleothems may be influenced by several factors as: type of photosynthesis (C_3 or C_4), soil biogenic activity, carbonate dissolution and precipitation, and drip rate (Schwarcz, 1986; Lauritzen and Lundberg, 1999). At the V11 site the vegetation consisted only of C_3 plants at least since 15 ka BP (Bodnariuc *et al*., 2002). For the temperate regions, soil CO_2 represents the most important source for carbon in speleothems (Genty *et al*., 2001). The present day $\delta^{13}C$ from V11 cave drip water shows heavier values during winter, when biogenic activity is low, and lower values in summer, when more soil CO_2 is produced. Rightmire (1978) studied seasonal variations of soil P_{CO_2} and isotopic composition, showing that during winter, the soil $\delta^{13}C_{CO_2}$ is close to the atmospheric values. In contrast, during the summer period, soil $\delta^{13}C_{CO_2}$ decreases to values of –21.5‰, parallel to an increase in P_{CO_2}. In this study we have shown that the present day calcite precipitates in equilibrium with the DIC. Using the fractionation factor of Mook *et al*. (1974) and the measured $\delta^{13}C_{DIC}$ for May, when the vegetation starts to grow, the calculated composition of soil $\delta^{13}C_{CO_2}$ is ~ –22‰. The value is close to the one measured by Rightmire (1978), and in the range of soil $\delta^{13}C_{CO_2}$ in C_3 dominated landscapes (Bender, 1968). Similarly, using the measured $\delta^{13}C_{DIC}$ of ~ –7‰ for November, the calculated value of $\delta^{13}C_{CO_2}$ is higher (~ –17‰) showing a larger participation of atmospheric CO_2 with $\delta^{13}C$ ~ –7‰. Accordingly, colder/dryer climate conditions in the past would imply increased $\delta^{13}C$ values, due to a higher participation of atmospheric CO_2. During warmer periods, the higher proportion of soil CO_2 from the seepage water would induce lower $\delta^{13}C$ values.

Figures 6 B and C present the $\delta^{18}O$ and $\delta^{13}C$ profiles of the two stalagmites. The general patterns of both oxygen and carbon isotopic profiles show higher amplitudes for the Lateglacial and Early Holocene. $\delta^{18}O$ values range between –7.0‰ and –9.3‰ during the Lateglacial–Early Holocene (14.8–10.2 ka BP) and between –7.5‰ and –8.5‰ for the rest of the Holocene record. Higher average values, of –7 to –8‰, occur between 14.7 and 13.2 ka, at 11.2 ka and between 8 and 5.6 ka BP. The minimum $\delta^{18}O$ values occur between 13.2 and 12.8 ka and between 12.5 and 10.2 ka. The $\delta^{13}C$ values vary between –4.1‰ and –9.2‰. The highest values (–6 to –4.1‰) occur between 12.6 and 11.7 ka and between 11.2 and 10.9 ka. Relatively lower values, of –6.5 to –9‰ characterize the interval 14.7–12.7 ka BP. Holocene $\delta^{13}C$ variations are between –6.5 and –8.7‰, with lower amplitudes after 8.8 ka BP.

LOCAL AND REGIONAL PALAEOCLIMATE CORRELATIONS

Comparing the isotope profiles from the V11 stalagmites with the $\delta^{18}O$ records of the Greenland ice cores, a good overall correlation is observed for the studied sequence (Fig. 6). The differences in chronology, in the order of 50–100 years, are linked to the reduced growth rates and consequently, to the lower temporal resolutions of the stalagmites.

After Termination I, the warming phase from 14.8 to 14.4 ka is recorded in the S117 oxygen isotopic composition as a positive shift of ~1.2‰. The age estimated for the beginning of deposition in S117 at 14.8 ka BP corresponds with the age of 14.7 ka BP determined for the postglacial warming in the Greenland ice cores (Björck *et al*., 1998) and with the high-resolution record of Wohlfarth *et al*. (2001) from Preluca Ţiganului, NW Romania, who obtained an age of 14.7–14.6 calibrated ka BP for the beginning of lake sedimentation. For this stage, the study of Wohlfarth *et al*. (2001), as well as our isotope record, sustain the synchronicity between the climatic transitions in the North Atlantic and Eastern Europe. The $\delta^{13}C$ record of S117 shows a progressive decrease (–6.1 to –7.4‰) between 14.8–14.2 ka, indicating the development of soil and vegetal cover.

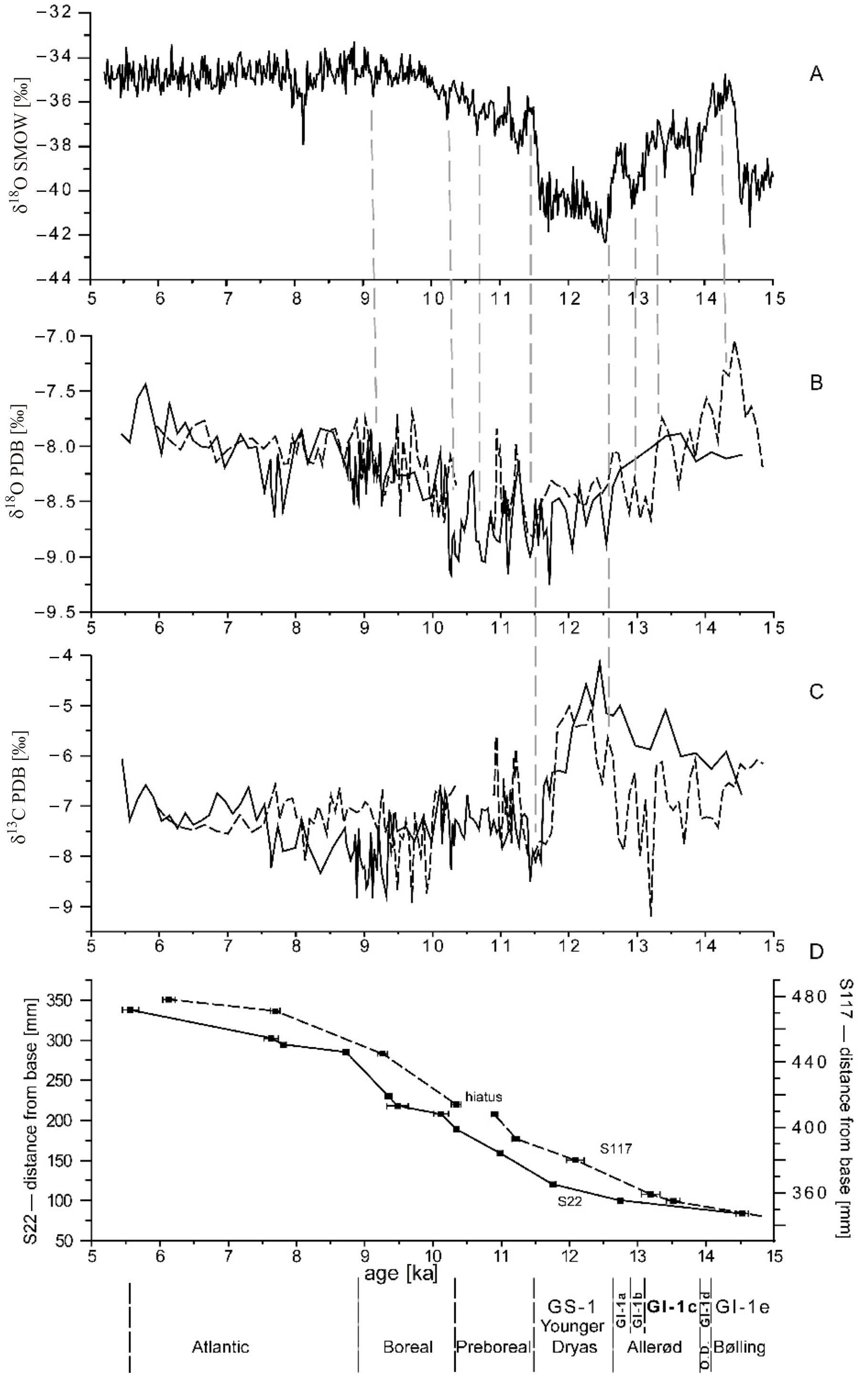

Fig. 6. A — δ^{18}O ice record from GRIP at a 20-year resolution (original data from the Greenland Summit Ice Cores CD-ROM, 1997); B and C— δ^{18}O and δ^{13}C profiles along the growth axes of the two stalagmites; D — thickness-age model for the two stalagmites

lines — S22; dashed lines — S117; dashed grey lines indicate correlative events in GRIP and the stalagmite records; O.D. — Older Dryas

From 14.4 ka on, the decreasing trend in the δ^{18}O record of S117 indicates gradual climate cooling. A similar trend is observed for S22 from 13.6 ka. While the S22 profile has too low resolution to register shorter-term climatic oscillations between 14.5 and 12.7 ka, several maxima on the S117 oxygen profile are interpreted as warmer periods with higher soil productivity. These intervals, dated at 14.5–13.9 ka BP, 13.6–13.2 ka BP, and 12.9–12.6 ka BP, corresponding to minima on the δ^{13}C record, are assigned to Bølling (GI-1e in the ice core event stratigraphy of Björck *et al.*, 1998), and to GI-1c–GI-1a (Allerød). In NW Romania, similar climate conditions for this first part of the Lateglacial were determined by Wohlfarth *et al.* (2001) and Feurdean and Bennike (2004) from pollen, macrofossil and lake sediment studies. A cold/wet event, recorded between 13.2 and 12.8 ka BP in the speleothem δ^{18}O profiles is correlated with an intra-Allerød cold period or GI-1b and has a duration comparable with the one in the GRIP record.

The oxygen profiles of the two stalagmites show a drop of 0.6–1‰ at 12.6 ka BP, interpreted as a change to colder climate. This interval, with a duration of ~1.2 ka, approximates well the Younger Dryas, or GS-1 in the GRIP stratigraphy. The mean δ^{18}O value for the GS-1 is –8.7‰ PDB at this site, whereas the measured present-day calcite has a δ^{18}O value of 23.1‰ (SMOW) or –7.3‰ (PDB), showing a ~1.4‰ enrichment with respect to GS-1. The rapid increase of δ^{13}C to values of –4.5 to –5‰ at 12.7–12.6 ka BP points to a drastic decrease of soil activity, as a consequence of lower temperatures and precipitation. It is interesting that from these values, using the fractionation factors of Mook *et al.* (1974) and Bottinga (1968), the calculated $\delta^{13}C_{DIC}$ value of ~ –8‰ is similar to the DIC value measured in November for drip water in the cave. This would suggest that the δ^{13}C composition of soil CO_2 during GS-1 was similar to the one of modern winters. Pollen and palaeovegetation data from other sites in Romania show reductions of the forest cover (Fărcaş *et al.*, 1999; Tanţău, 2003) and gradual replacement of forest by herb and shrub-dominated vegetation coexisting with barren areas (Björkman *et al.*, 2002, 2003; Feurdean and Bennike, 2004).

A somewhat different trend of the δ^{18}O and δ^{13}C records is noticed between 11.7 and 11.4 ka BP. The carbon values decrease rapidly at 11.7–11.6 ka BP, suggesting increasing wetness and soil productivity, whereas superposed $\delta^{18}O$ shifts towards heavier values (warmer climate) on both stalagmites are recorded some 200 years later. At sites from NW Romania, the replacement of open vegetation by an open *Betula*, *Pinus* and *Picea*-dominated forest around 11.5 ka BP indicate warm and moist climatic conditions at the beginning of the Holocene (Björkman *et al*., 2002; Bodnariuc *et al*., 2002). Our data for the onset of GS-1 and for the GS-1/Holocene transition is also consistent with other proxies from western/central Europe (Von Grafenstein *et al*., 1999; Walker *et al*., 1999; Ammann *et al*., 2000).

Speleothem deposition in the V11 cave was continuous during the whole GS-1 interval, a less common situation within temperate karst regions (Denniston *et al*., 2001; Niggemann *et al*., 2003; Wurth *et al*., 2004). Although this cold interval had a major influence on the vegetation, our dataset may point to a less pronounced cooling than in Western Europe (Walker, 1995; Renssen *et al*., 2000; Shotyk *et al*., 2002).

Another cooling is marked by lower $\delta^{18}O$ during the Preboreal, with two short-term intervals (11.0–10.7 and 10.5–10.2 ka) when $\delta^{18}O$ values reached –9‰, close to the ones recorded throughout GS-1. Both these intervals correlate with lower $\delta^{18}O$ in the Greenland ice core records (Dansgaard *et al*., 1989; Johnsen *et al*., 1997; Björck *et al*., 2001). The latter interval is associated with the first re-expansion of *Corylus*, an indicator of cooler and drier climate around 10.3 ka in several Romanian pollen records (Fărcaş *et al*., 1999; Rösch and Fischer, 2000; Fărcaş, 2001; Bodnariuc *et al*., 2002; Tanţău *et al*., 2003; Feurdean, 2005)) and in other proxies around the North Atlantic region (Nesje *et al*., 2001; Seppä *et al*., 2002).

The beginning of the Boreal is marked by an ascending trend of the $\delta^{18}O$ profiles (10.2–9.5 ka BP) and by a pronounced decrease of growth rates, but in this period, as well as from 9.5 to 7.6 ka BP, the $\delta^{13}C$ records are less well correlated. The $\delta^{18}O$ trend suggests a warming phase at the beginning of the Boreal. Climate warming is also documented from central European lake sediments by Stockhausen and Zolitschka (1999) and from Romanian peat deposits by Feurdean and Bennike (2004), which also indicate a drier period in NW Romania. This phase approximately coincides with the appearance and expansion of the deciduous forests at several Romanian sites (Fărcaş *et al*., 1999; Rösch and Fischer, 2000; Björkman *et al*., 2002, 2003; Bodnariuc *et al*., 2002).

At 9.5– 8.9 ka (10.5–5.8 cm from top), the S22 stalagmite has a zone with a porous fabric, composed of small fast-growth calcite crystals, for which the growth rate reaches the maximum values recorded. Carbon oscillations have an amplitude of 2‰, with a minimum of –9‰, while the oxygen profiles show oscillations around –8‰. This sequence probably was deposited in isotopic disequilibrium, triggered by the higher drip rates, which may have affected the $\delta^{13}C$ signal, but the average $\delta^{18}O$ values are consistent in the two stalagmites. $\delta^{18}O$ records may indicate a short cooling centered at 9.3 ka BP, correlated with lower $\delta^{18}O$ in the Greenland ice core records. This short-term event is present at around 9.5 ka BP in central European lake sediments (von Grafenstein *et al*., 1999) and North Atlantic marine sediments (Bond *et al*., 2001). In Romania, palaeovegetation data also suggest a colder period, marked by the decline of thermophilous tree taxa (*Tilia*, *Quercus* and *Fraxinus*) around 9.3 ka BP, along with a re-expansion of *Corylus* (Björkman *et al*., 2003). We may only infer that the higher growth rates during this period were driven by local causes. As for most of the Holocene, no clear climatic signal can be inferred from the stalagmite $\delta^{13}C$ record for this period, but other studies in NW Romania indicate drier conditions at least until 8.2 ka (Tanţău *et al*., 2003; Feurdean and Bennike, 2004).

Between 9 and 7.8 ka, fairly constant $\delta^{18}O$ values (–7.5 to –8‰) indicate relatively stable average temperatures and the low resolution of the isotopic record does not allow a more detailed climate reconstruction.

The interval with decreased $\delta^{18}O$ values (–8.5‰) between 7.8 and 7.6 ka BP in S22 is associated with a porous deposition facies, where the oxygen and carbon records are covariant, and this probably represents another short episode of deposition in isotopic disequilibrium. The S117 isotopic records, which are more reliable, suggest that no significant temperature change occurred during this period.

After 7.8 ka BP, the oxygen profiles of S22 and S117 show a slight increasing trend to the level of the modern value. This final growth interval of the two speleothems corresponds with an interval of reduced growth frequency for the Romanian speleothems (Onac and Lauritzen, 1996) and with a Mid-European lower lake level phase (Magny, 2004). A drier period in the region of the V11 cave might be indicated by the pollen data and by the strong decrease of sedimentation rates at two peat sites in the Bihor Mountains (Bodnariuc *et al*., 2002).

Between 7.8 and 5.7 ka, during the period known as the "Holocene climatic optimum" (Bell and Walker, 1992; Huntley and Prentice, 1993), the climate of northeastern Europe was characterized by temperatures and amounts of precipitation higher than present ones. With the uncertainties imposed by the reduced sampling resolutions of the two stalagmites in this growth interval, we may only infer that the oxygen profiles of V11-22 and V11-117 imply a gradual rise of the average temperatures to the level of the present-day values. Since ~8 ka BP, the $\delta^{13}C$ has almost constant values around –7‰, similar to the ones measured for the present-day calcite. The growth cessation of the two stalagmites, at 6.1 and respectively 5.6 ka BP, was most probably driven by local causes, such as changes in the paths of the drip water or another change in position, as previously seen in the stratigraphy of S117.

CONCLUSIONS

Two stalagmites from the V11 Cave, NW Romania show consistent overlapping stable isotope records for most of their growth period between the Lateglacial and Middle Holocene. The $\delta^{18}O$ isotopic record is interpreted to be positively correlated with temperature variations, while the $\delta^{13}C$ record appears to be mainly controlled by variations in soil CO_2 production at least during the Lateglacial. Within the limitations imposed by the low growth rates and sampling resolution of the two stalagmites, the Lateglacial–Early Holocene part of the $\delta^{18}O$ and $\delta^{13}C$ profiles is consistent with the Greenland ice core records. The GI-1e (Bølling) and GI-1c–GI-1a (Allerød) intervals are well defined on the $\delta^{18}O$ and $\delta^{13}C$ records of S117. The GS-1 (Younger

Dryas) cold event is reflected in both oxygen and carbon records, but it is better marked on the $\delta^{13}C$ profiles, which indicate an abrupt termination at 11.7–11.6 ka, well correlated with ice-core data and other proxies. The continuous speleothem deposition in the V11 cave during the GS-1 may point to a less pronounced climate cooling than in Western Europe.

In the early part of the Holocene, three short-term shifts towards lower $\delta^{18}O$ in the stalagmite records, dated at 11.2–10.6, 10.5–10.2 and 9.4–9.1 ka BP, correspond with cold events marked in the ice-core $\delta^{18}O$ records. Between 9 and 7.6 ka BP, the $\delta^{18}O$ values indicate stable mean temperatures, but the record is less detailed due to reduced growth rates. From 7.6 ka BP until the end of deposition, $\delta^{18}O$ gradually increases to the present-day value. Overall, the Lateglacial-Middle Holocene climate deduced from the isotopic profiles of the two stalagmites may be correlated with the ice core records and with palaeoclimatic data from other proxies such as pollen, lake sediments and other speleothem records, suggesting the influence of the North Atlantic climate system over southeastern Europe.

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