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Holocene and Late Pleistocene climate in the sub-Mediterranean continental environment: A speleothem record from Poleva Cave (Southern Carpathians, Romania)

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Abstract

The PP10 stalagmite from Poleva Cave provides a Late Pleistocene and Holocene isotopic record characteristic for the SW of Romania, a sub-Mediterranean climatic region. The speleothem was dated by eight TIMS and one alpha U-series dates which showed that it was precipitated between ~75 ka and ~2 ka with at least two hiatuses. The basal sector of the stalagmite showed a slow-growing regime of ~0.26 cm/ka, while the upper one grew relatively fast with about 5 cm/ka. The temporal resolution for the isotopic sampling is thus ~2 ka/sample for the lower sector, and ~150 years/sample for the upper one. The relationship between $\delta^{18}O$ and temperature was found positive. The isotopic record of the lower sector shows two marked cold intervals during ~67 and 58 ka and ~40–35 ka, respectively, which correlate well with the Villars and Soreq records. The upper sector record is so far the most detailed Holocene isotopic record in Romania and the only one available for the regions located at the exterior of the Carpathians Range. The signal shows a gradual warming after the GS1 event punctuated by several cold events at ~8, 7.2 and 4.2 ka and also by warm oscillations centered at about 5.2 and 3.3 ka. The results seem to indicate that if the North-Atlantic first-order signals may extend well to the south-eastern Europe, their amplitude and general trend may be diminished by the interferences with the Mediterranean circulation.

Keywords: Speleothem; U-series datings; Isotopes; Holocene; Late Pleistocene; Paleoclimate; Romania

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1. Introduction

In recent years, an increasing number of papers have been dedicated to the use of speleothems as paleoclimatic indicators by measuring the stable isotopic (usually $\delta^{18}O$ and $\delta^{13}C$) variations along their axes. These are considered to reflect, for example, changes in mean annual surface temperature (e.g. Gascoyne et al., 1980), and/or changes of the continental ice volume or long-term shifts in moisture sources (Lauritzen and Lundberg, 1999; McDermott et al., 1999; see also Dorale et al., 2002; McDermott, 2004 and references therein). The refinement of the U-series TIMS dating techniques has allowed very accurate time-calibrations of such profiles, thus enabling direct correlations with both marine oxygen isotopic stages (MIS) and continental records of the global climate change.

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Since the supply of percolation water (and thus, speleothem deposition) is generally curtailed both during very cold or very dry climatic episodes, often speleothems formed at northern (e.g. the sub-Arctic) or southern latitudes (e.g. the Mediterranean realm) only preserve incomplete records of the climatic variations. Our studies have focused recently on speleothems collected from caves located in the *sub-Mediterranean region of SW Romania*, reasonably far from the influence of the NW Europe (Atlantic) circulation and also from the arid conditions of the SE Mediterranean and which may therefore preserve longer isotopic records.

Continental climate records of the Upper Pleistocene and Holocene in Central and Eastern Europe are generally scarce and, in many cases, have low temporal resolution (Willis, 1994; Onac and Lauritzen, 1996; Carbonnel et al., 1999; Cârciumaru, 1999; Farcas et al., 1999; Lauritzen and Onac, 1999). However, in the last few years new data have emerged from a wide range of well-dated proxies such as pollen (Feurdean et al., 2001; Wohlfarth et al., 2001; Björkman et al., 2002, 2003), lake and marine sediments (Grafenstein von et al., 1999; Denèfle et al., 2000; Onac et al., 2001; Veski et al., 2004; Bahr et al., 2005; Esterhues et al., 2005), loess deposits (Panaiotu et al., 2001, 2002) and speleothems (Constantin et al., 2001a,b; Onac et al., 2002; Spötl and Mangini, 2002; Tămaş et al., 2005).

In Romania, the only isotopic profile of an Upper Pleistocene speleothem published so far is that of the stalagmite LFG2 (Litophagus Cave, Pădurea Craiului Mountains, NW Romania) (Lauritzen and Onac, 1999). However, this profile, which covers the time period between ca. 130 and ca. 60 ka is hampered by the low resolution of the alpha-spectrometric dates. Better data are available for the Holocene, for which a TIMS-dated isotopic profile covering the time-span ~7–1 ka BP was measured in the stalagmite PU2 (Urşilor Cave, Pădurea Craiului Mountains, NW Romania) (Onac et al., 2002) and from two stalagmites covering the time span ~13.5–5.6 ka, coming from Bihor Mountains (Tămaş et al., 2005). Another stalagmite (PP9), collected from Poleva Cave (Locvei Mountains, SW Romania), yielded a detailed isotopic profile, also TIMS-dated, which covers the last 10 ka (Constantin et al., 2001a; see also this paper). In the present paper we report the isotopic profile of PP10, another stalagmite collected from Poleva Cave which grew between ca. 75 ka BP and ~2.5 ka BP.

2. Geographical and geological setting

Poleva Cave is located in SW Romania, in the southern part of Locvei Mountains, ~10 km north of the Danube Gorge (Fig. 1). The cave is entirely carved into massive reef limestones (locally called *The Plopa Limestones*) of Barremian (Lower Cretaceous) age (Constantin, 2003). This cave is a typical fluvio-karstic network that forms an underground meander of the small creek of Poleva (Fig. 2). The waters of this creek

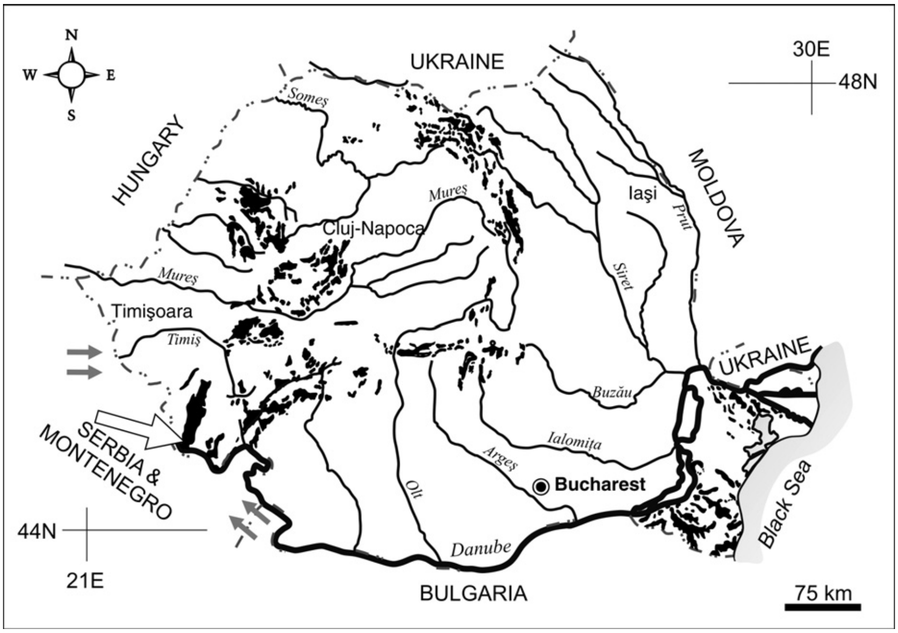


Fig. 1. The map of karst rocks (solid black shading) outcropping in Romania and location of Poleva cave (indicated by the large white arrow). The small gray arrows show the directions of the main directions of atmospheric circulation.

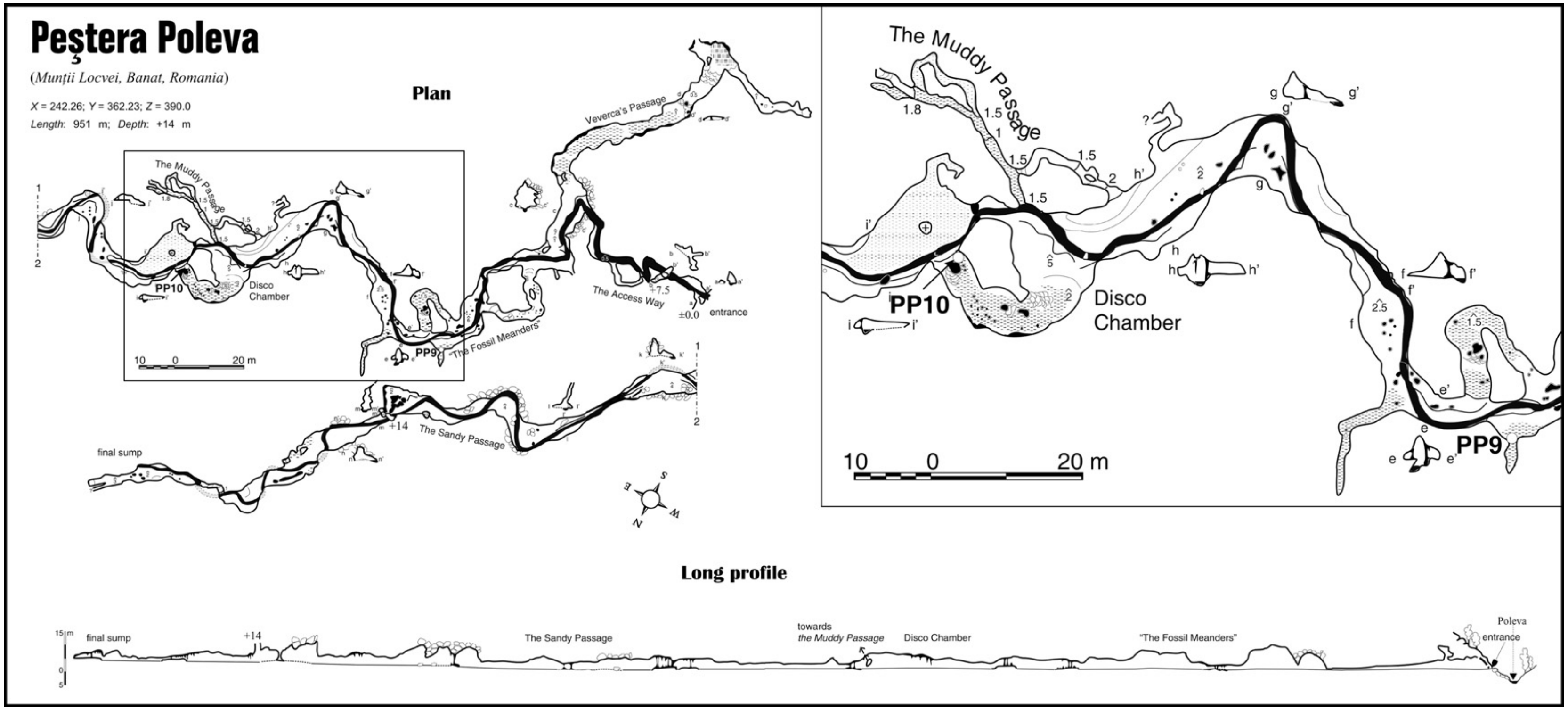


Fig. 2. The map of Poleva Cave and the position of stalagmites PP10 and PP9 (see detail view of the suspended meander).

(average flow rate ~20 l/s) sink into a swallet at the contact between the granite basement (Sicheviţa Granite) and the overlying limestones, reappear into the "final sump" of the cave, flow through a meandering trunk-passage and rejoin the surface-valley through the cave's main entrance (390 m a.s.l.).

With a total length of explored passages exceeding 950 m, Poleva Cave is one of the most important caves of the area and also one of the most abundantly decorated with speleothems. The main passage consists of a streamway incised at a depth of 1–1.8 m with respect to the underground terrace sediments and suspended ("fossil") meanders (Fig. 2). U-series dates of more than 70 speleothem samples from this cave have shown that the incision of the small "underground canyon" occurred following the underground catchment of the stream through the "Access Way", at least 32 ka BP (Constantin, 2003). Except for the entrance area, the cave shows no marked air circulation and in the fossil meanders the air relative humidity was measured at 98–99‰.

The regional climate pattern is typical for the low-mountainous areas of SW Romania, with an annual precipitation of 700–800 mm/year and temperature of 10–11 °C. These values are interpolated from the multi-annual mean values quoted for Moldova Nouă weather station by Munteanu and Bălănescu (1999) and the records of Gîrnic weather station (A. Iurkiewicz, personal communication, 2000). The temperature measured in 1997–1999 in the deep sections of the cave was 10.5–11 °C. The climate includes mild, wet winters and warm, dry summers (mean monthly temperature in July: 20.5–21.5 °C; Mihalca and Stanciu, 1999), with the main atmospheric circulation coming from the Mediterranean (ESE). The vegetation in the region above the cave ('sub-Mediterranean' vegetation) also shows clear climatic influences and includes sub-Mediterranean oak trees, such as *Quercus pubescens* and *Quercus ceris*, and thermophylous shrubs such as *Syringa vulgaris*, *Padus mahaleb*, *Cotinus coggygria* and *Fraxinus ornus* (Iana and Petcu, 1976). The xerophytes are generally known to follow the C4 photosynthetic cycle (Park and Epstein, 1960; Bender, 1968; Clark and Fritz, 1997), therefore we may consider that the present plant association in south-western Romania includes more C4 species than in any other regions of the Carpathians, although the relative percentage of the C4 plants versus C3 ones is currently hard to assess.

3. Site and samples description

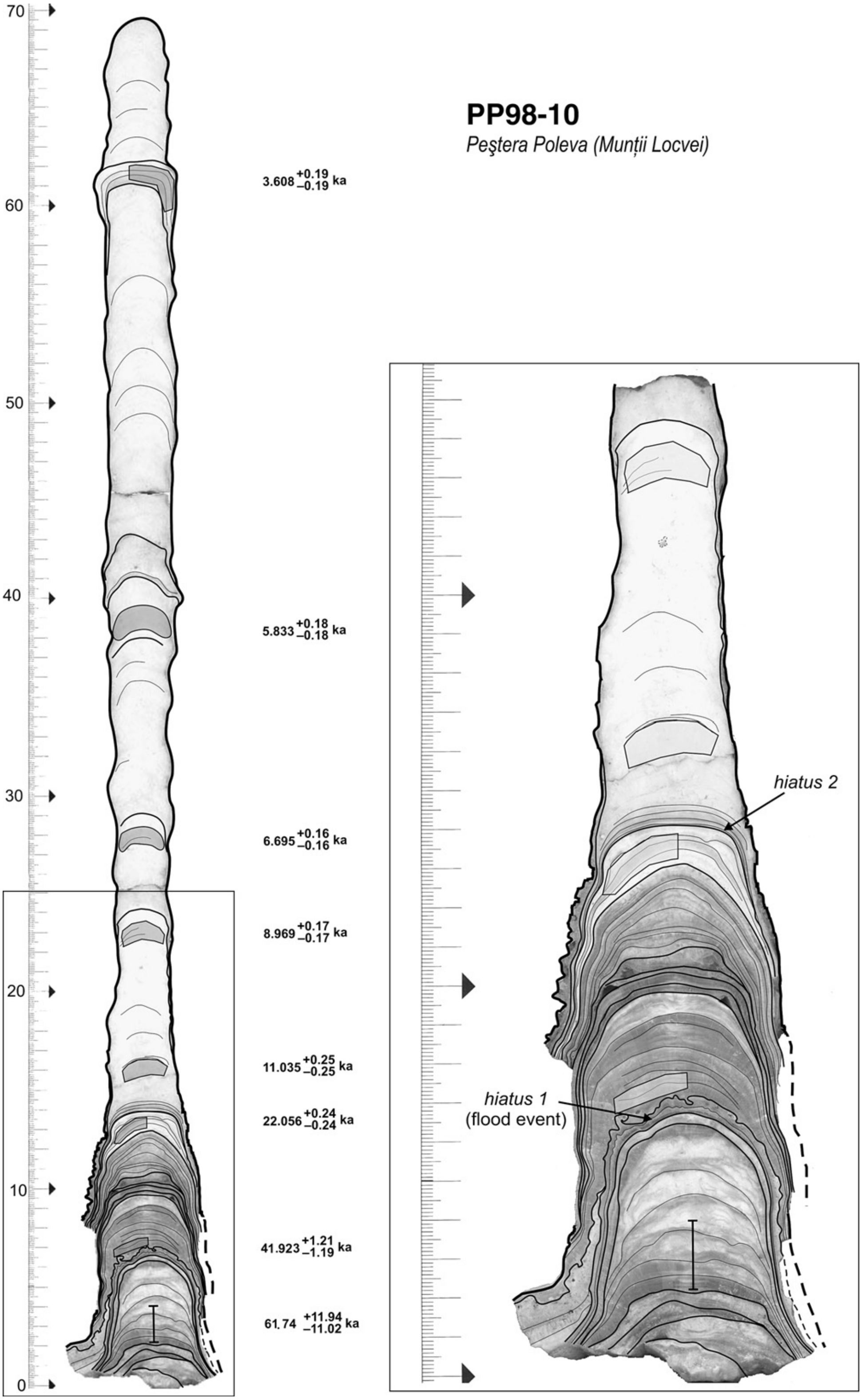
Stalagmite PP10 was collected from one of the suspended meanders of the cave (see Fig. 2), located about 1.3 m above the subterranean streambed. Its basal 3 cm were buried in a red clay deposit. It is a "candlestick" stalagmite, approximately 70 cm long, decreasing in diameter from some 7 cm at the base, to some 2–2.5 cm after the first 18 cm (Fig. 3).

Based upon optical and crystallographic features, the stalagmite was divided into two sectors which will be further discussed separately. The first ~14 cm, the "thick" *lower sector,* is composed of greenish, translucent calcite laminae and, in the upper part, by brown-opaque ones. The calcite within this sector displays mainly microcrystalline fabrics and subordinately columnar ones (*sensu* Frisia et al., 2000). At ~6.5 cm from the base, the stalagmite displays a brown, 2–3 mm thick layer which was interpreted as a clayey inclusion deposited during a massive flood episode. However, the microcrystalline structure of the calcite below and above this discontinuity does not suggest a long interruption in calcite deposition. Two other porous levels located at some 10 cm from base may also indicate brief episodes of speleothem growth interruption. At the end of the first sector a clearly visible, hardened surface makes the transition between the microcrystalline-fabric calcite (MFC) and the dendritic-fabric calcite (DFC). This surface was considered to represent a significant change in the regime of calcite precipitation and assigned to a depositional hiatus.

The second, *upper sector* is thin, "candlestick"-like and is mainly composed of white-opaque calcite with a dendritic crystal fabric showing several thicker "knots" of translucent, slow-growing calcite. In this sector the laminae are almost exclusively precipitated at the tip of the speleothem with little or no precipitation towards the sides.

A second stalagmite, PP9, was collected in the vicinity of PP10, from a small side-passage located at about 1.6 m above the underground stream (see Fig. 2). This stalagmite was first discussed by Constantin et al. (2001a); we also describe it below because it was used for the replication test presented further on. It is a very thin (2–3 cm) candlestick stalagmite with a length of 32 cm. The calcite within PP9 is white-opaque displaying a microcrystalline fabric, with several areas of columnar, translucent, calcite.

One of the most distinct features of both stalagmites is their *small diameter* (the upper sector of PP10 and the entire PP9) which is very close to (or sometimes even smaller than) the theoretical "minimum diameter" of 2–2.5 cm for stalagmites as postulated by Curl (1973) or Dreybrodt (1988). Such "small-diameter" stalagmites are frequent in Poleva and many other caves from SW Romania where often specimens as thin as 0.8–2 cm have been formed. Their occurrence is thought to be


PP98-10
Peştera Poleva (Munții Locvei)
70
60
50
40
30
20
10
0
3.608 +0.19 −0.19 ka
5.833 +0.18 −0.18 ka
6.695 +0.16 −0.16 ka
8.969 +0.17 −0.17 ka
11.035 +0.25 −0.25 ka
22.056 +0.24 −0.24 ka
41.923 +1.21 −1.19 ka
61.74 +11.94 −11.02 ka
hiatus 2
hiatus 1
(flood event)

related to several parameters such as: (i) a slow drip-rate; (ii) a low dripping height; (iii) rapid calcite precipitation possibly indicating slightly evaporative conditions (low relative humidity) (see Dreybrodt, 1988; Constantin, 2003). However, the presence of the evaporative conditions is not necessarily implicit for the formation of the "small-diameter stalagmites" — in fact, such speleothems are actively growing now at some experimental points located in high-stability-meroclimate sectors of Cloşani Laboratory Cave (Romania) (Constantin et al., work in progress). The possibility of evaporative conditions affecting the precipitation of PP10 might cause concern about the validity of the isotopic data for paleoclimatic interpretation. That this fact is not of concern, it is discussed at length below.

4. Dating and stable isotopes analysis

A preliminary U-series alpha-spectrometric date of the basal 2.5 cm of stalagmite PP10 was done at the U-series Geochronology Laboratory, Bergen University, Norway. The sub-sample was cut from what seemed to be, optically, the most suitable (translucent) calcite but, due to the low U-content known for the speleothems in the region, the amount of calcite used was quite high (ca. 2.5 cm of axial extension, between 1.5 and 4 cm from the base). The sample yielded a corrected age of ca. 61.7±11 (1σ error) ka (see Table 1). Given the good chemical yields, this relatively high uncertainty (>18% at 1σ) may be mainly assigned to the low Uranium content (~0.05 ppm) of the sample.

Seven TIMS-dates on subsamples (of 2.5–3 g each) taken along the speleothem were done at the TIMS Laboratory, Bergen University (Fig. 3 and Table 2). (Subsamples taken below the first "hiatus" and of the topmost layer were not successful.) All samples were composed of pure white and/or translucent calcite containing no visible detritus. They yielded ages in correct stratigraphical order, ranging from ~42 ka, at ~7 cm from base, to ~3.5 ka at ca. 5 cm below the top, with typical analytical errors of 1–2% (2σ) for ages younger than 15 ka (Table 2).

The analytical procedures for alpha-spectrometry dating followed those described in Lauritzen and Onac (1999) and the spectra were processed by tailored software (Lauritzen, 1993). For TIMS dating, the chemical preparation and TIMS runs followed the procedure described in Lauritzen and Lundberg (1999). Mass abundances of ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{229}Th, ^{230}Th and ^{232}Th were measured on a Finnigan 262 RPQ instrument in dynamic mode.

Subsamples for stable isotope analysis (80–90 µg each) were typically taken at 5-mm intervals along the growth axis of the stalagmite. In total, 154 samples were analyzed, including 19 supplemental samples taken at 2.5-mm intervals in order to clarify unusual or doubtful isotopic variations. CO_2 was extracted from calcite at 70 °C by reaction with H_3PO_4 (McCrea, 1950) using a Finnigan MAT Kiel II preparation line. Data were corrected for fractionation using the carbonate-phosphoric acid fractionation factors for calcite (Swart et al., 1991). The δ^{18}O values are given in permil relative to SMOW and the δ^{13}C values relative to PDB. The standard deviations are 0.06% for δ^{13}C and 0.1% for δ^{18}O (1σ) based on replicate measurements of an internal carbonate standard.

The Hendy test (Hendy, 1971) is often used as a check for possible kinetic fractionation although numerous studies (e.g. Lauritzen and Lundberg, 1999; Dorale et al., 2002) have point out that in practice the "Hendy traverses" may not represent exactly the same calcite growth layer and therefore a negative Hendy test may not be relevant for kinetic fractionation conditions. Considering also the structure of the stalagmite (low-diameter, apical deposition) and the presence of DFC which makes the sampling of individual laminae even more problematic, we have decided not to perform any Hendy test and have chosen instead to apply the "replication test" using the coeval PP9 stalagmite (discussed below).

5. Results and discussions

5.1. Dating results; corrections

For all samples the uranium content was very low, but very constant, averaging 0.044 ppm. No visible detrital contamination was apparent during chemical preparation but the low ^{230}Th/^{232}Th ratios (between 3 and 12) suggest the presence of some detrital thorium. There is a marked shift between the lower sector of the stalagmite, with ^{230}Th/^{232}Th ratios of 10–12, and the thin upper sector with ratios of 3–4. This geochemically different behavior suggests that the 'thin' part of PP10 may have been precipitated under slightly evaporative conditions accompanied by an airborne influx of detrital

Fig. 3. Photo of the PP10 sampling slice showing the positions of alpha-dated sample (vertical bar, base) and TIMS-dated samples (gray polygons). Errors are 2σ except for the alpha date which is 1σ. The two hiatuses and the other limits between different calcite fabrics are indicated by thick black lines. The second hiatus marks the limit between the "lower", slow-growing and the "upper", fast-growing sectors. Note the irregular limit of the first hiatus due to the clay shrinking features.

Table 1
Alpha-spectrometry U-series dating result of the base subsample of stalagmite PP10

Lab. no.	cm from base	U conc. (ppm)	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	Calculated age (ka)	Corrected age (ka)
2279	1.5–4	0.046±0.004	1.52±0.15	0.48±0.06	13.8	67.12 (+11.2; −10.2)	61.7 (+11.9; −11.0)

Note: the age was corrected for detrital content assuming an initial $^{230}Th/^{232}Th$ of 1.5.
All uncertainties are 1σ.

Th. Thus a correction of the calculated dates for detrital ^{230}Th was required.

The problem of ‘age correction’ for calcite samples is often difficult to deal with. One option is to use isochron dating of many coeval samples with varying levels of contamination (e.g. Richards and Dorale, 2003). Considering the low diameter of PP10 stalagmite, the isochron technique could not be applied. Onac et al. (2002) counted annual calcite laminae between consecutive samples to assess the correction factor needed. This technique could not be applied to PP10 because annual laminae are not apparent. For old samples, low $^{230}Th/^{232}Th$ ratios are generally indicative of detrital contamination. However Lauritzen and Lundberg (1999) and Linge et al. (2001) suggest that young samples with low ^{230}Th levels but no detrital contamination will do have low $^{230}Th/^{232}Th$ ratios. Thus, they suggest a new test for contamination: samples with absolute ^{232}Th content above 1 ppm and $^{234}U/^{232}Th$ ratios below ~60 are likely to be contaminated and must be corrected. Applying this test to PP10 confirms detrital contamination: although the ^{232}Th content is below 1 ppm in all cases, the $^{234}U/^{232}Th$ ratio is also low (19–60).

Considering the theoretical possibility of a *weak* detrital contamination suggested by (a) the theoretical models of ‘low-diameter stalagmites’ formation, (b) the moderate ^{232}Th concentrations measured and (c) the low $^{234}U/^{232}Th$ ratios, we decided to use in this study the correction technique of an assumed initial $^{230}Th/^{232}Th$ ratio for the detritus of 1.5 (Gascoyne, 1979).

In order to test the validity of this corrected-age model we have compared it with those of other two low-diameter stalagmites from the same cave. Fig. 4 shows the age vs. stratigraphy model of three thin, candlestick stalagmites: PP10, PP9 and PP7. The dating results for stalagmite PP9 were first reported by Constantin et al. (2001a), while those of PP7 are so far unpublished (Constantin, 2003) (Table 3). For all these stalagmites the calculated ages were corrected if $^{230}Th/^{232}Th$ ratios were lower than 30, using an initial $^{230}Th/^{232}Th$ ratio of 1.5. For four sub-samples showing $^{230}Th/^{232}Th = 30–120$ no correction was applied and for all sub-samples dated below 8 ka the $^{230}Th/^{232}Th$ ratios were decreasing below 6. The graph shows for all stalagmites a rapid growth regime which commenced at the onset of the Holocene with average growth rates between 3.7 and 7.7 cm/ka—at least one order of magnitude higher than the growth rates known for pre-Holocene stalagmites from the same cave or elsewhere (e.g. Lauritzen and Onac, 1999; Spötl and Mangini, 2002). The Holocene growth rate is also sensibly higher than the 3–4 cm/ka reported by various authors for ‘regular-diameter’ stalagmites (e.g. Baker et al., 1998; Linge et al., 2001; Onac et al., 2002) but this fact is not surprising for the thin ‘candlestick’ stalagmites from SW Romania where exceptionally high growth rates (up to 200 cm/ka) were recorded (Constantin, 2003).

5.2. Stalagmite's structure and age model

The morphologic and structural analysis of the stalagmite’s structure indicates that the speleothem has experienced a brief episode of growth cessation, at ~42 ka, most probably due to a massive flood of the inactive meander that led to the deposition of a 1–3 mm

Table 2
TIMS U-series datings results of the stalagmite PP10

Lab. no.	cm from base	U conc. (ppm)	^{232}Th conc. (ppm)	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	$^{234}U/^{232}Th$	Calculated age (ka)	Corrected age (ka)
260	6.5–7	0.0585±0.0003	0.67	1.50±0.02	0.360±0.001	10.0±0.2	27.0±0.7	48.0 ±1.2	41.92±1.20
261	12.5 –13	0.057±0	0.31	1.12±0.002	0.205±0.002	12±0.13	57.71±0.8	24.91±0.24	22.06±0.24
263	15–15.8	0.04±0	0.66	1.114±0.003	0.170±0.002	3±0.037	18.554±0.294	20.16±0.24	11.04±0.25
265	22–23	0.037±0	0.3	1.114±0.004	0.116±0.001	4±0.055	38.01±0.641	13.33±0.16	8.97±0.17
273	27–28.3	0.041±0	0.67	1.117±0.002	0.133±0.001	3±0.028	19.33±0.264	15.45±0.14	6.70±0.16
274	38–39.5	0.037±0	0.43	1.097±0.002	0.106±0.001	3±0.42	26.225±0.517	12.22±0.17	5.83±0.18
276	56.5–58	0.035±0	0.18	1.121±0.003	0.057±0.002	3±0.103	60.463±2.544	6.34±0.19	3.61±0.19

Note: all ages were corrected for detrital content assuming that an initial $^{230}Th/^{232}Th$ of 1.5.
All uncertainties are 2σ.

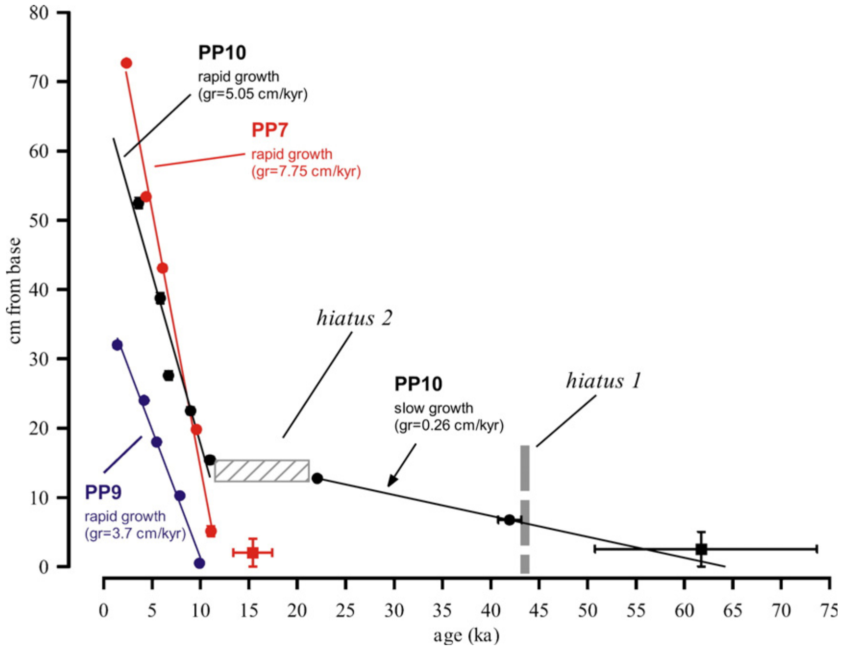


Fig. 4. Age vs. stratigraphy model and mean grow rates (gr) calculated for three thin, 'candlestick' stalagmites from Poleva Cave. Bars show the alpha-dated samples (PP10 base and PP7 base) and circles the TIMS-dated samples. Age error bars are 1σ for alpha-dates and 2σ for TIMS-dates (in most cases smaller than the symbol). Some of the dates were corrected using an assumed initial ^{230}Th/^{232}Th activity ratio of 1.5 (see text). Note the good coincidence of the rapid growth of all stalagmites at the onset of the Holocene.

thick layer of red clay (Fig. 3). The upper level of this clay horizon is markedly irregular and, in places, its morphology suggests typical clay-shrinking effects. The attempt to date a sub-sample located right below this layer failed due to its high Th content. However, based on comparative mineralogical observations of the calcite layers below and above this hiatus, we believe that this hiatus did not imply a major change in the dripping regime or cave microclimate. Further evidence in favor of a relatively short hiatus comes from the ^{238}U systematics (Tables 1 and 2), which shows no notable difference between the subsamples 2279 (alpha-dated, at the base of the stalagmite) and 260 (TIMS-dated, above the hiatus).

Recent dating results (Trinkaus et al., 2003; Zilhão et al., in press) from *Peştera cu Oase,* a cave located some 40 km north of Poleva, seem to confirm the theory

Table 3
TIMS U-series datings results for the stalagmites PP9 and PP7

Lab. no.	cm from base	U conc. (ppm)	^{232}Th conc. (ppm)	^{234}U/^{238}U	^{230}Th/^{234}U	^{230}Th/^{232}Th	^{234}U/^{232}Th	Calculated age (ka)	Corrected age (ka)
PP9									
PP9/1	0.25–0.75	0.125	3.87	1.35	0.10	15.70±0.22	163.68±2.29	10.92 ±0.1	**9.90 ±0.12**
PP9/2	10–10.5	0.081	0.28	1.30	0.07	119.77±0.89	1713.37±12.73	**7.86±0.04**	
PP9/3	17.8–18.2	0.082	1.86	1.29	0.05	17.61±0.24	329.21±4.49	5.97±0.06	**5. 46±0.07**
PP9/4	23.8–24.2	0.079	5.84	1.30	0.05	5.99±0.08	120.50±1.61	5.54±0.48	**4.17±0.64**
PP7									
284	4.4–5.8	0.071	0.08	1.26±0.002	0.097±0.001	30±0.39	306.06±5.63	**11.07±0.15**	
285	19.4–20.2	0.056	0.02	1.25±0.001	0.084	89±0.86	1055.64±11.9	**9.57±0.06**	
286	42.7–43.5	0.056	0.29	1.230±0.001	0.076	5±0.066	65.77±1.11	8.57±0.09	**6.08±0.1**
300	53–53.8	0.047	0.22	1.220±0.002	0.059±0.001	4±0.141	72.79±3.33	6.63±0.22	**4.37±0.22**
301	72.4–78	0.047	0.16	1.223±0.001	0.036	4±0.07	103.11±2.71	3.93±.0.07	**2.35±.07**

Note: ages with ^{230}Th/^{232}Th < 30 were corrected for detrital content assuming that an initial ^{230}Th/^{232}Th of 1.5. Dates given in bold were used to construct the age-models in Fig. 4. PP9 datings done at the Gif-sur-Yvette (France) laboratory; PP7 datings done at the Bergen University Laboratory. All uncertainties are 2σ.

of some sort of severe flood episodes prior to 42 ka in this area. In *Peştera* cu Oase, a massive accumulation of fossil bones, sediments and speleothems was discovered and is currently under study. Preliminary results indicate that this deposit was probably generated by a series of massive floods that occurred between ~45 and ~42 ka (the calibrated ^{14}C ages of several dated cave bear bones). Subsequently, no evidence of floods appears and the youngest dated remains are the human bones at ca. 40.5 (±0.97) ka (calibrated ^{14}C age of Trinkaus et al., 2003). If we compare this tentative scenario with the PP10 available dates, the coincidence of the evidence for pre-42 ka floods is striking. In Poleva cave, with a different topography and located at a lower elevation than Peştera cu Oase, this flood(s) did not have the same large-scale effects leading only to the deposition of a clay deposit on the floor and the top of the stalagmites.

A second, longer, depositional hiatus was revealed by both mineralogical observations and U-series dates at ~14 cm from the base of the stalagmite. A hardened surface clearly marks the difference between a zone of MFC and the beginning of the 'thin sector' of the stalagmite consisting of alternating DFC and MFC zones. Subsample 261 (5 mm below the hiatus) was dated at ~22 ka, while subsample 263, taken at approximately 1 cm above the hiatus, yielded a date of only ~11 ka. This hiatus corresponds to the Last Glacial Maximum (LGM) a period when speleothem growth in Romania shows a significant decrease (Onac and Lauritzen, 1996) and to the Post-Glacial when the scarcity of dated speleothems (even at southern latitudes of the SW Romania karst) suggests a slow soil recovery after periglacial conditions (Constantin, 2003 and unpublished data). The remaining part of the stalagmite does not show notable hiatuses, although some variations of the growth rate may be inferred from the variations in diameter, the few thicker sections indicating temporarily slower growth.

Taking into account the dating results and the internal structure of PP10, we assumed the following growth model for the stalagmite:

(i) a slow-growth regime for the lower sector, interrupted by at least one brief (probably not longer than 1–2 ka) flooding episode. Based upon the calculated theoretical growth rate of 0.26 cm/ka, this regime started at least ~65 ka ago and lasted until ~22 ka ago (the age of subsample 261. If we assume that the growth rate of 0.26 cm/ka (Fig. 4) also applies to the 0.6 cm between subsample 261 and the hiatus, then the hiatus occurred at ~20 ka);

(ii) an interruption of calcite precipitation followed until some time before 11 ka ago when the deposition resumed (if we assume that the growth rate of 5.05 cm/ka operated between the hiatus and the 11 ka layer, then the hiatus lasted until ~11.4 ka);

(iii) a rapid-growth regime for the upper sector between ~11 ka and ~2.4 ka ago (the topmost age extrapolated using the mean growth rate of 5.05 cm/ka).

5.3. Isotopic sampling resolution, equilibrium testing and climatic interpretation

Along speleothem axis, 154 stable isotopes samples were collected, typically at 0.5 cm intervals; in selected sectors this resolution was increased to 0.25 cm in order to clarify the isotopic trends or suspicious results. The time-resolution of the basic isotopic profile (0.5 cm) corresponds to ~2 ka/sample for the lower (slow-growing) sector of the stalagmite and to ~40–150 years/sample for the upper (fast-growing) part. However, this theoretical resolution may be misleading, since it is generally higher than the uncertainty of the dating results. Therefore, for all isotopic variations discussed in this paper we must accept a time-uncertainty of at least 250 years, regardless of the theoretical resolution of the isotopic profile.

As mentioned above, the 'Hendy' test could not be applied in order to test the isotopic equilibrium of calcite deposition. Instead, we applied the so-called "replication test" (Dorale et al., 2002) which compares two (or more) coeval isotopic profiles from speleothems from the same cave or from closely located caves. Since the chemical and physical parameters of the percolation waters seeping into a cave are likely to be highly different, if such profiles may be correlated, then either: (i) the parameters that control the kinetic fractionation are similar (which is highly improbable), or (ii) the contribution of such processes to the isotopic composition is very low, therefore they may be considered as formed under isotopic equilibrium.

In many cases the replication test is difficult to apply, since it is impossible to appreciate *in situ* the age of speleothems and therefore, the chances of collecting two coeval samples are low. However, we have benefited from a second, partially coeval stalagmite, PP9, which have grown between ~10 ka and the present-day. This stalagmite was TIMS U-series dated at the Laboratory of Gif-sur-Yvette (France) and its isotopic content was measured with a theoretical time resolution of ~60 years (0.25 cm) at the Stable Isotopes Laboratory in Bern University (Constantin et al., 2001a). For the common time-interval, the two $\delta^{18}O$ isotopic profiles are shown super-imposed in Fig. 5. The excellent coincidence of the isotopic values is clearly demonstrated. Along the whole profile, the differences between the δ^{18}O isotopic values never exceed 1‰, while some significant peaks have very close values. We consider the good coincidence of the two δ^{18}O profiles as a strong argument that the calcite was deposited in isotopic equilibrium and therefore the two profiles have paleoclimatic significance.

As an alternative test for the reliability of the isotopic data we have also compared the δ^{18}O and δ^{13}C profiles in the upper sector of PP10, where the DFC is present. Since dendritic fabrics are considered to form under disequilibrium conditions, it has been suggested (McDermott et al., 1999; Frisia et al., 2000) that the carbon isotope signal may not be a reliable proxy for past climate changes (and, if covariant, the oxygen isotope signal as well). In PP10 stalagmite the two signals show no correlation (Fig. 6), at least in the first-order trends. Therefore, we consider that, although the δ^{13}C signal may not be significant for paleoclimate interpretations, at least in the upper sector of the speleothem where DFC is present, the oxygen record of PP10 may be considered reliable and the paper will further focus on its analysis.

Once the isotopic equilibrium (or quasi-equilibrium) deposition is proven by the replication test throughout (at least) the upper sector of PP10 stalagmite, it may be inferred that the δ^{18}O signal is related to cave temperature and isotopic composition of the fluid. Rainout effect usually causes variations for inland locations (typically overwhelming any signal from variations in the source region of the evaporating water and the small shifts caused by rainfall amount variations). Changing regional and/or cave temperatures then show a positive relationship of δ^{18}O with temperature (Fricke and O'Neil, 1999). The present-day δ^{18}O composition of calcite in Poleva cave is −8.63‰ — an average based on three soda-straw tips collected just above the PP9 stalagmite (Constantin et al., 2001a). No data are available for δ^{18}O of precipitation in SW Carpathians or in the neighborhood and, due to the remoteness of this cave site the isotopic composition of drip water in the cave could not be monitored. In order to test whether the relationship of δ^{18}O is positive or negative with respect to temperature, we compared the trend of the δ^{18}O time-series with known, dated, climatic events from Europe. Such episodes, when the temperatures were lower than present-day ones occurred at ~11.5 ka and about 8.2 ka (Alley et al., 1997; Grafenstein von et al., 1999; Alley and Ágústsdóttir, 2005). However, the GS1 (Younger Dryas) oscillation is not represented in our speleothem and at 8.2 ka the δ^{18}O profile shows only a rather broad decrease, in contrast to the usual sharp oscillation reported in most references for the 8.2 ka event.

While it may not be possible to isolate individual controls on the isotopic composition of the calcite, it is common to find an empirical relationship with temperature for time periods when general temperature trends are

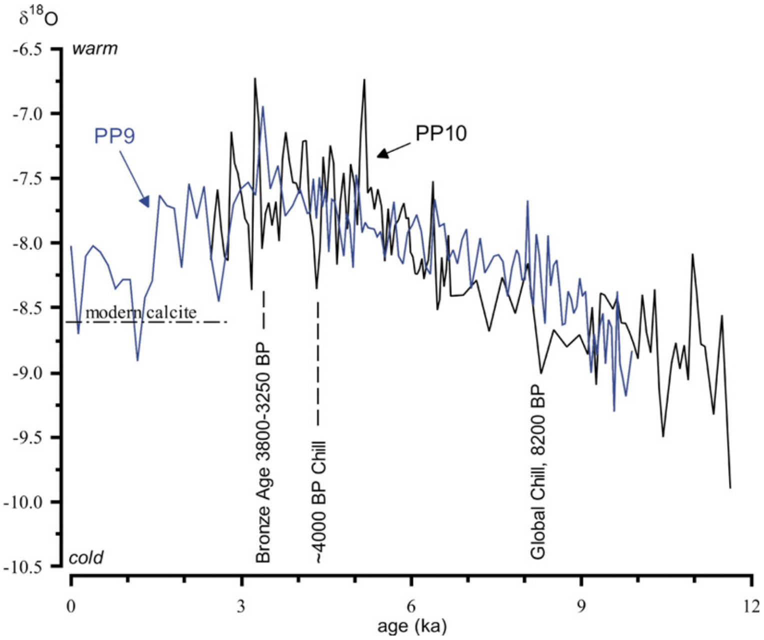


Fig. 5. The δ^{18}O profiles of speleothems PP10 (black line; 123 samples) and PP9 (blue line; 118 samples) for the last ~12 ka. Note the very good coincidence of the first-order trends as well as that of several second-order spikes (e.g. the 3.3 ka warm-spike). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

known from other proxies. Here, the trend of the post-glacial isotopic record can be compared with general trends in regional climate known from the literature. In the upper sector of PP10, the record starts with depleted oxygen and enriched carbon isotopic compositions, concomitant with documented cool regional climate (~11.5–10 ka) (e.g., Grafenstein von et al., 1999; Mayer and Schwark, 1999). The general rise in isotopic values up to the mid-Holocene (from ~10 ka to 5 ka) mirrors the general rise to warmer temperatures (e.g. Onac et al., 2002); although the record terminates at 2.5 ka, the beginning of the drop to modern values can be seen, again mirroring the general trend towards late Holocene cooler temperatures (e.g. Perry and Hsu, 2000). Thus, at least for the post-glacial period, this site does appear to follow the normal pattern for inland caves in temperate regions of a positive relationship of δ^{18}O with temperature (as expected for inland caves in temperate regions, e.g. Onac et al., 2002, or, more generally, for calcite cements formed from meteoric waters; Hays and Grossman, 1991). In the absence of any indication to the contrary, the same relationship is presumed for the earlier part of the record, for MIS 4 and 3.

The carbon isotope record is typically an indication of soil biological activity. In the simplest cases, with no changes in photosynthetic pathways, carbon isotope shows an inverse relationship to biological activity (Tămaş et al., 2005). Therefore in the lower sector of the PP10, we can interpret the increasing carbon isotopic values toward the LGM as indicating reduction of the biological activity. The post-glacial carbon signal is more complex: the first half seems to suggest the expected rise in biological activity paralleling the rise in temperature; there is a step-wise shift around 7.5 ka, and then the parallel relationship once again established by about 6 ka. Considering the present-day δ^{13}C composition of −8.79‰, the shift in the oxygen–carbon relationship may be interpreted as a possible shift in the vegetation type, with more Mediterranean succulents (C4 plants) becoming more common during the warmest part of the Holocene. We must however emphasize once again that the presence of DFC along the upper sector of the speleothem makes the δ^{13}C signal problematic and therefore the safe approach is to consider only the δ^{18}O signal as reliable for the upper sector of PP10.

5.4. Interpretation of the oxygen isotopic profile of the lower sector of PP10 (MIS 4–3)

The isotopic profile of the *lower sector* was constructed differently for the stalagmite zones located above and below the first hiatus. Above the first hiatus we used a theoretical growth rate of 0.3 cm/ka calculated from the ages of subsamples 260 and 261. For the sector located below the first hiatus, which was not TIMS-dated, the growth rate was estimated taking as a tie-point the alpha-spectrometric age of 61.7 ka of the base sample (#2279, Table 1; also Fig. 4), and running several age-models with different durations of the hiatus 1 ranging from 1 to 5 ka. The resulting isotopic profiles were then compared with the LFG9 profile of a stalagmite from the Western Carpathians (Lauritzen and Onac, 1999) in order to establish a “best fit” value for the duration of the hiatus. The best model, which both fits the general trend shown by the LFG9 stalagmite and the “short hiatus” and “constant growth rate” assumptions was calculated considering a hiatus estimate of ~2 ka (Fig. 6). The calculated theoretical growth rate in this case was of ~0.23 cm/ka — the same order of magnitude as the one calculated above the hiatus from the high-resolution dates.

Without question, the isotopic model for the lower sector of PP10, between ~70 and 22 ka, is limited by the very few dated points and the low resolution of the isotopic sampling (theoretical isotopic resolution is 1.5–2 ka per sample). Consequently, we consider that this isotopic profile shall be considered only as a ‘big picture’, within which short-lived climatic oscillations may not be accurately outlined. The first part of the profile shows a broad correlation of both δ^{18}O and δ^{13}C with the ocean core record of Bassinot et al. (1994) and with the first-order trends of the “SFCP2004” modified GRIP curve (Shackleton et al., 2004) displaying two peaks at ~57 ka and ~69 ka which may be broadly correlated with Greenland Interstadials (GIS) 17 and 19, respectively (Fig. 6). These are separated by a ‘trough’ with δ^{18}O values that are ~1‰ lower between ~67 ka and 58 ka which corresponds to the low δ^{18}O values recorded also in the GRIP profile during MIS 4. In addition, this trough correlates remarkably well with the D3 hiatus (“Villars Cold Phase”) dated to 61.2±0.6–67.4±0.9 by Genty et al. (2003). In the Villars cave (SW France) profile, an increase in the δ^{13}C was interpreted to reflect a cooling event — in the PP10 stalagmite, during approximately the same time-period a δ^{13}C increase of ~1.5‰ may also be noticed. The opposite trends of both δ^{13}C and δ^{18}O isotopic profiles, together with the expected positive relationship between temperature and oxygen isotopes composition for the Poleva site, strongly suggest a temperature decrease during this episode. The same oscillation may be observed in the composite oxygen record of Soreq cave, Israel (Bar-Matthews et al., 2003; McGarry et al., 2004).

After reaching the highest δ^{18}O isotopic values at ~57 ka, the δ^{18}O values then decrease to ca. −9‰ at ca.

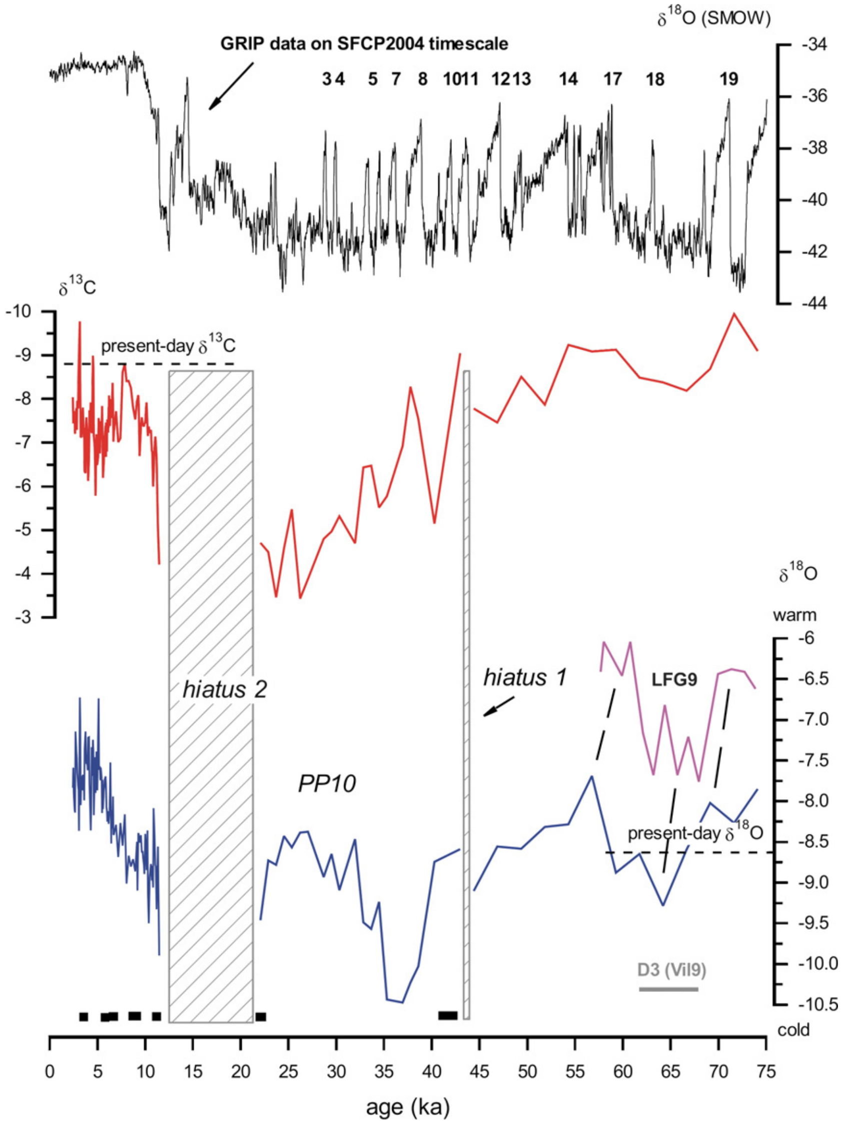


Fig. 6. The δ^{18}O profiles for the speleothems PP10 (bottom, blue line) and LFG9 (after Lauritzen and Onac, 1999) (middle, magenta line), and the δ^{13}C profile for PP10 (red line), compared with the GRIP data on SFCP2004 timescale (Shackleton et al., 2004) (5x running average, top, black line). Note that the δ^{13}C scale is inverted. The numbers on top of SFCP2004 curve indicate Greenland Interstadial (GIS) events. The D3 (Vil9) horizontal gray line at the bottom of the figure marks the extension of the 'Villars cold phase' (Genty et al., 2003). The thin, sub-vertical, dashed lines indicate tentative correlations between the PP10 and LFG9 records. The black bars at the bottom indicate the TIMS ages uncertainties (2σ). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

42–44 ka when the first hiatus is encountered. Taking into account the dating uncertainties and the inherent model flaws, this hiatus (probably flood-induced) might be correlated with either GIS 10 or 11, but it may also represent a delayed effect of the more severe GIS 12 event.

The second part of the record, from ~45 ka to ~23 ka, covering MIS 3 and the general cool-down leading to LGM, is not so clearly correlated with the ocean and ice core records. The carbon record does show a simple slope paralleling the ocean record, which can be interpreted as a steady reduction in biological activity. The oxygen record does not show a simple pattern nor any relationship with the ice core. Above Hiatus 1, the δ^{18}O values decrease abruptly from −8.5‰ to −10.5‰ beginning at ~40 ka and continuing for ca. 5 ka. This trough, defined by four data points, appears to record a severe stadial, which may be also found in the Soreq Cave isotope record, where the δ^{18}O values at 35 ka are comparable to those during the Last Glacial Maximum (LGM), although in this profile the oscillation is rapid (Bar-Matthews et al., 2003). If the controls on δ^{18}O assumed for the warmer times continue to operate during the approach to the full glacial, then the obvious dip around 38–35 ka must be interpreted as a cold phase. However, there is no matching cold phase in the ice core record and these light isotopic values are, for now, hard to explain.

For the next part of the PP10 profile, the first-order trend shows a δ^{18}O increase of about 1.5‰, with peaks at ca. 33 ka and ca. 27 ka. This suggests a moderate warming indicative of MIS3. The abrupt decrease in δ^{18}O values towards the LGM starts at ~25 ka and is ended by the second (major) hiatus at ~21 ka.

5.5. Interpretation of the oxygen isotopic profile of the upper sector of PP10 (Holocene)

The upper part of the stalagmite has an oxygen isotopic profile that spans over the time interval 11.5–2 ka, recording several important rapid oscillations that may be correlated globally (Fig. 7). This is, so far, one of the most detailed δ^{18}O profiles for the Holocene of Romania with 115 isotope measurements. The stalagmite resumed its growth during the deglaciation that followed the GS1 (Greenland Stadial 1) event (Younger Dryas) (Björck et al., 1998), at ~11.5 ka. The presence of DCF calcite in the upper sector of the stalagmite indicates warm conditions with a low drip rate and perhaps also a slight evaporation, possibly due to the opening of the main entrance of the cave (Constantin, 2003).

The oxygen isotope record shows an overall trend of gradual δ^{18}O increase from −9.9‰ at 11.5 ka to −6.7‰ at 5.2 ka which may be interpreted as representing the Holocene postglacial warming. The first marked spike at ca. 11 ka probably correlates with a temperature-high recorded in the SFCP2004 profile. This was followed in both records by a rapid cooling, the δ^{18}O values in PP10 dropping ~1.5‰ by 10.3 ka. In the next 2000 years the PP10 profile recorded several minor oscillations but the general trend shows some degree of stability around an average value of −8.75‰, close to the one measured for modern calcite. The following trend is indicative for a cooling that peaks at ~9.2 ka and ~8.2 ka. Although the '8.2 ka Event' (Alley et al., 1997; Grafenstein von et al., 1999) is not as well-defined as in the Greenland ice-cores profiles, it shows some of the most depleted δ^{18}O values since the GS1 event. The low δ^{18}O at ~8.2 ka contrasts with the S22 stalagmite profile (Tămaş et al., 2005) (see Fig. 7), and also with the PP9 record (Fig. 5) where the "8.2 ka Event" cannot be recognized possibly due to the lower resolution of the isotope records. The described pattern for PP10 would confirm the short duration of the known "8200 years BP cold event" in Europe (Magny et al., 2003; Veski et al., 2004; Bahr et al., 2005).

From 8.2 ka to ca. 5.2 ka PP10 exhibits a general trend of δ^{18}O increase with several short-lived minor oscillations (a couple of hundreds years or even less). The first notable oscillation during this time-period appears at ~7.1 ka following the post-"8.2 ka Event" warming phase. This is consistent with a similar trough recorded in the PU2 stalagmite from Ursilor Cave, Romania (Onac et al., 2002) where it was interpreted as reflecting a wet and cold period. It is the last moment in the PP10 profile when the isotopic values are lower than the modern calcite ones and also coincides with the first "Sahara aridity period" (Perry and Hsu, 2000). Further on, during the so-called "Holocene Climate Optimum" (Bell and Walker, 1992; Huntley and Prentice, 1993), the warming tendency is obvious and shows several notable peaks at ~6.3 ka and ~5.9 ka. This is also confirmed by several pollen analyses of sites from northwest Romania (Feurdean et al., 2001; Wohlfarth et al., 2001; Björkman et al., 2002) that show a mixed *Corylus* and *Picea* forest indicating warm conditions until ~5.2 ka when a maximum isotopic value of −6.7‰ was measured.

Although defined by only a few data points, this "warm 5.2 ka-event" is also recorded in another Holocene stalagmite from Romania: CB3 from Cioaca cu Brebenei cave (Mehedinţi Mountains, ca. 150 km toward north-east) shows the same isotopic values (Constantin, 2003). In PP10, it is followed by a period of rapid oscillations around a mean isotopic value of −7.5‰. Within this overall trend, decreasing isotopic values between 5.2 and 4.2 ka possibly reflect the temperature decline and precipitation increase documented in the Carpathians by Magyari et al. (2001) based on pollen and mollusk records. In many parts of the Northern Hemisphere this time period is recorded as cold and dry (the '4000 BP Event'; Perry and Hsu, 2000) but in Romania the pollen spectra (as well as the CB3 stalagmite record) indicate instead a cool and humid climate (Boşcaiu and Lupşa, 1967; Magyari et al., 2001).

After this, the general climatic amelioration of the middle Holocene resumed and peaked at 3.3 ka which coincides strikingly with similar peaks recorded by both PU2 (Onac et al., 2002) and PP9 stalagmites (Fig. 5). This event seems to have had a regional extent since it is clearly recorded, with roughly the same amplitude, in both stalagmites from Poleva cave and in the PU2 stalagmite from Western Carpathians — a region that lies under the Atlantic climatic influence. This is considered to have been a warm and relatively wet phase which corresponds with the beginning of the Bronze Age according to

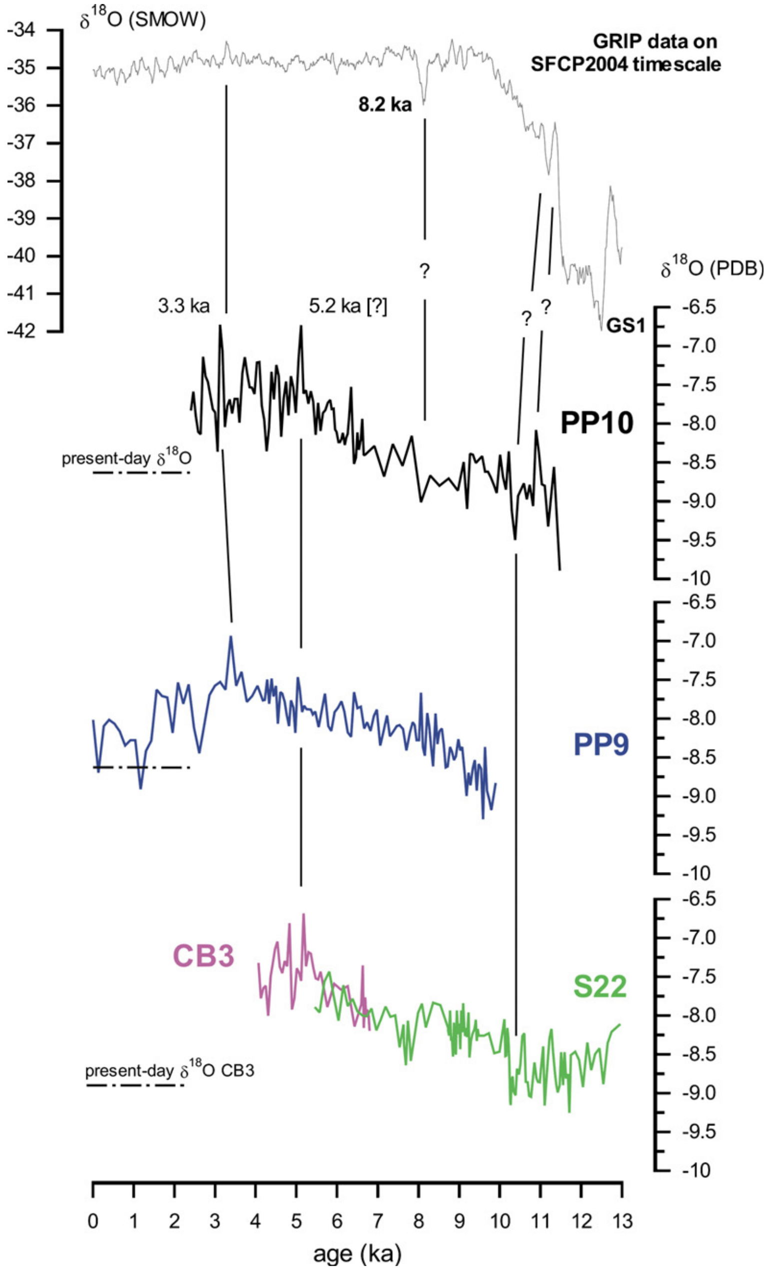


Fig. 7. The δ^{18}O profiles of the upper sector of PP10 speleothem (black line) compared with the GRIP data on SFCP2004 timescale (Shackleton et al., 2004) (5x running average, top), the PP9 data (blue line) (Constantin et al., 2001a), and the S22 (bottom, green line) (Tămaş et al., 2005) and CB3 (bottom, magenta line) (Constantin, 2003) data. The thin, sub-vertical, solid lines indicate tentative correlations of climatic events between various speleothems in Romania and possible correlation with known events on the GRIP-SFCP profile. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

archaeological evidence from Romania (Motzoi-Chicideanu, 1986). After the warm 3.3 ka event, the isotopic profile recorded a slight decrease until ~2.4 ka when the speleothems growth ceased.

Compared with the Greenland ice-cores profiles, the PP10 record shows a different behavior during the Holocene deglaciation. Both GRIP and GISP2 signals show an abrupt increase of δ^{18}O values between ca. 12.5 ka and ca. 10 ka followed by a "plateau" between ~10 and 2 ka. In North Norway, the stalagmite SG93 (Lauritzen and Lundberg, 1999) shows a general gradual increase until about 7.5 ka. Further south and east, the PP10 stalagmite (and also PP9) shows a general trend of *gradual* increase of δ^{18}O values with ca. 1.5–2‰ between ~11.5 ka and 5.2 ka when the values seem to stabilize. In a continental region located at middle latitude, such as southwestern Romania, 'sheltered' by the Carpathians Range, receiving only distal influences of the North Atlantic Oscillation and supposedly more influenced by the Mediterranean circulation the isotopic signal may reflect better the regional temperature changes than in coastal sites. The "8.2 ka cold event", for example, can be hardly noticed in PP10 and seems to be absent in PP9 and S22 profiles, as opposed to sites from coastal settings (e.g. Lachniet et al., 2004), which may be an indication that the signal mostly (or only) reflects temperature changes in a continental setting.

In the Eastern Mediterranean, in the Soreq Cave record (Bar-Matthews et al., 1999, 2003) a negative correlation between temperature and δ^{18}O signal was recorded. Here, the gradual δ^{18}O increase during the last 7000 years is considered to reflect mainly a drop of the rainfall amount and possibly also a change in the δ^{18}O and the sea surface temperature of the Mediterranean Sea. The gradual increase of the oxygen signal in the PP10 stalagmite suggests that in some continental settings the Holocene warming may have been less abrupt than in coastal areas perhaps due to an attenuation of the influence of the oceanic air masses. This seems to be proved also when comparing the isotopic records of stalagmites PP10 and PP9 and the one of S22 (Tămaş et al., 2005) stalagmites (Figs. 5 and 7). Although PP10 and PP9 stalagmites were collected from the Southern Carpathians and S22 from the Western Carpathians, ca. 500 km northward, all three show a remarkable coincidence of the first-order isotopic trends. The fact that stalagmites collected from caves located in different climatic settings (i.e. distal North-Atlantic vs. distal Mediterranean) show similar δ^{18}O values and trends and that their isotope signals are dampened with respect to the ones from coastal areas may indicate a lower sensitivity to changes in vapour sources which may prevail in coastal settings.

6. Conclusions

The stalagmite PP10 is assumed to have been precipitated under isotopic (quasi)equilibrium between ~75 ka and ~22 ka (with at least one brief interruption) and between 11.5 and ~2 ka. The δ^{18}O signal is considered to reflect mainly the regional changes of the average temperatures following a positive relationship, i.e. heavier δ^{18}O values are interpreted as reflecting warmer conditions.

Although the lower sector of the speleothem has a relatively poor date-control and a low isotopic resolution the first-order isotopic trends show low δ^{18}O values between ~58 and 67 ka which correlate well with the cooling episode recorded by the Villars 9 stalagmite record. The well-defined and more depleted trough at ~40–35 ka seems to be indicative of a stadial period that can also be correlated with a record from Soreq Cave in Israel.

The upper sector of the PP10 stalagmite is indicative of the climatic conditions of SW Romania after the GS 1 event and shows a gradual warming with several notable events such as the ones at ~5.2 and ~3.3 ka which are considered to reflect warm conditions, while the depleted values at ca. 8, 7.2, and 4.2 ka reflect colder episodes.

The correlation of the PP10 oxygen record with other speleothems from Romania is very good; the correlation with other proxy records throughout Europe and the Middle East shows at least a good correspondence at the levels of first-order trends and some marker-events. However, the isotopic signal of the PP10 speleothem seems to be more attenuated than the one recorded in the North-Atlantic indicating either a certain degree of dampening of the oceanic vapor-masses response over Central Europe or a possible interference with the Mediterranean isotopic signal.

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