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ISOTOPIC STRATIGRAPHY OF A LAST INTERGLACIAL STALAGMITE FROM NORTHWESTERN ROMANIA: CORRELATION WITH THE DEEP-SEA RECORD AND NORTHERN-LATITUDE SPELEOTHEM

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LFG-2, a 39.5 cm tall stalagmite from northwestern Romania, has been dated by U-series α-spectrometric dating, and analyzed for stable isotope variations ($\delta^{18}O$, $\delta^{13}C$) along its growth axis. The sample grew all the way through oxygen isotope stage 5(a-e), and perhaps for some time into stage 4. In spite of a rather low uranium content and therefore imprecise chronology, the sample provides an interesting stable isotope record with high temporal resolution that correlates favorably with other speleothems and with the deep-sea record. Termination II is well defined in the record as a rapid shift from light (cold) to heavier (warm) $\delta^{18}O$ values, when C3 vegetation seemed to dominate. The $\delta^{13}C$ in a slow growth zone, corresponding to oxygen isotope stage 5d, as well after the stage 5/4 transition, suggests that C4 plants possibly dominated the surface environment. The $\delta^{18}O$ record also correlate quite well with the α-dated FM-2 record from northern Norway.

Speleothems are important paleoclimatic and chronological archives because they are continental deposits and well-suited for uranium series disequilibrium dating. Besides the dating potential by U-series methods (Schwarcz 1986), which yield data about climate-controlled growth range (Gascoyne *et al*. 1983) and growth frequency (Gordon *et al*. 1989; Baker *et al*. 1993b; Lauritzen 1993b; Onac & Lauritzen 1996), speleothems also carry a vast range of paleoclimatic proxies, like stable isotopes (Lauritzen & Lundbergdi 1998; Rowe *et al*. 1998), growth laminae (Baker *et al*. 1993a; Shopov *et al*. 1994; Genty & Quinif 1996), natural organic matter (NOM) Lauritzen *et al*. 1986; Ramseyer *et al*. 1997), microfossils, such as pollen (Bastin 1978; Lauritzen *et al*. 1990). Finally, speleothems preserve paleomagnetic signals (Latham *et al*. 1979, 1989; Perkins & Maher l993), which can be accurately dated.

Karst areas are regionally widespread, and speleothems can yield consistent paleoclimatic proxy data from large geographic areas. Therefore, the Speleothem Pole-Equator-Pole Project (SPEP) has been launched under the PEP activities (Lauritzen 1998). In the SPEP-III project, which aims at comparing speleothem data along a north-south transect from Spitzbergen and Norway (Lauritzen 1995; Lauritzen & Lundberg 1998) to South Africa (Holmgren *et al*. 1994, 1998), Romania, situated well beyond the limits of the Scandinavian glaciations, plays an important role with its continental climate. Our results so far have revealed that time-dependent speleothem growth frequency is less sensitive to climatic change at this location than at higher latitude areas, such as the British Isles and North Norway (Baker *et al*. 1993b; Lauritzen 1993b; Lauritzen *et al*. 1996; Onac & Lauritzen 1996). In this paper we present the results of detailed chronostratigraphic studies of a *single* speleothem, the LFG-2 stalagmite from Lithophagus Cave in northwestern Romania.

MATERIAL AND METHODS

THE LITHOPHAGUS CAVE

The Lithophagus Cave is located in the Middle Basin of Iada Valley, within the eastemmost part of the Pãdurea Craiului Massif (Apuseni Mountains, Transylvania, Fig. 1). More than 250 caves and potholes are distributed on 5 different karstification levels with a vertical extent of 350 m (Tamas & Vremir, 1997). The most important cavities in this region were discovered during intensive mining and hydroelectric tunneling.

The cave, which is formed in Upper Jurassic (Tithonian) limestone, opens on the southern side of the valley at a relative altitude of 55 m (545 m msl) (Vremir 1994). It consists of several isolated phreatic and vadose galleries and chambers totaling 620 m in length, interrupted in a few places by mining galleries (collapses, storage spaces, etc). The name, Lithophagus

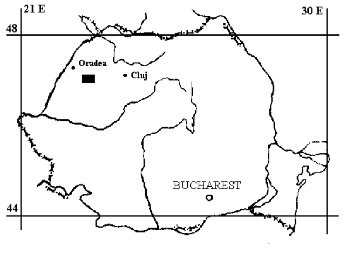

Figure 1. Key map of Romania with the investigated area.

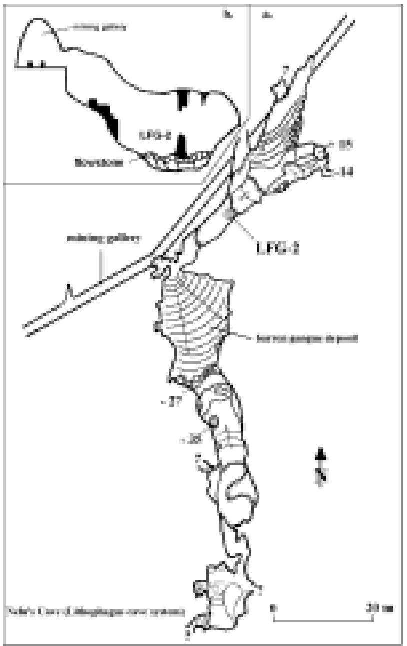

Figure 2. Plan map of Nelus cave in the Lithophagus Cave system (a), with inset (b) showing passage cross-section with sample site.

("stone eater"), comes from the fact that more than 7000 m³ of barren gangue were consumed or "eaten" by the cave. The cave has no natural entrances, and it is likely that it has stayed as a closed cavity for a very long time in the past.

The LFG-2 stalagmite was collected from a 30 m long side passage in Nelus Cave (part of the Lithophagus Cave system), just below the mining gallery (Fig. 2a) (Onac 1996). The speleothem grew on top of a 3 to 4 cm thick flowstone that itself covered collapsed limestone boulders (Fig. 2b).

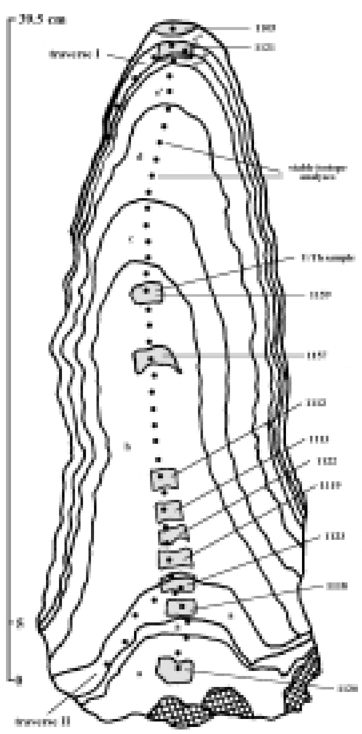

Figure 3. Longitudinal section of stalagmite sample LFG2 with location stable isotopes (black spots), $^{230}Th/^{234}U$ dating (grey boxes), and (a-e). a: fine laminae of length-slow calcite; b & c: translucent to numerous abrupt changes; d: length-fast, palisade calcite; e: a white calcite (e'), and clear columnar calcite (e").

SAMPLES

The stalagmite (LFG-2) is 39.5 cm high. The lowest samples for U-series dating and isotopic analysis were extracted from 1.5 cm above the base of the speleothem (Fig. 3).

The outside part of the stalagmite is randomly covered by millimeter-sized botryoidal or coral-like calcite speleothems that were presumably formed by splashing or rapidly dripping water rebounding from the gravel floor or from neighboring speleothems.

The speleothem was cast in plaster for stabilization and cut into several 1 cm thick slices parallel with the growth axis. Each slice was briefly etched in dilute HCl, washed, ground and polished. The cross-section (Fig. 3) exhibits several growth zones visible to the naked eye. The most important ones were analyzed microscopically on six thin sections. This revealed that boundaries between growth layers represent 1) linear concentration of gas or liquid inclusions, 2) impurity-rich layers, 3) changes of the calcite crystal habit during growth, and 4) layers of micritic calcite crystals.

Thus, we have divided the sample into 5 morphological zones labeled a, b, c, d and e in Fig. 3:

Zone «a» (0 to 75 mm): Very fine laminae made up of length-slow calcite (Folk & Assereto 1976), outlined by abundant gas/liquid inclusions;

Zones «b» & «c» (75 mm to 290 mm): Translucent to clear calcite laminae, slightly similar in fabric to zone «a» but with fewer inclusions. Most of the growth-layering within zones «b» and «c» is defined by abrupt changes in either inclusion density or crystal morphology. The «b/c» boundary is given by a clear brown impurity layer at 265 mm from base. The length-slow calcite crystals are replaced by length-fast crystals as they approach the boundary to zone «d»;

Zone «d» (290 mm to 350 mm): This zone consists of ordinary length-fast calcite crystals that build clear columnar crystals (palisade fabric) (Kendall & Broughton 1978). It is difficult to estimate the width of the crystals as they are nearly parallel to each other and show semicomposite to weakly undulose extinction. Just above the lower boundary, the *c-axes* of the calcite crystals tend to lie subhorizontally (at an angle between 40° to 85° from the vertical), but further up, due to geometrical selection (Grigor'ev 1965; Dickson 1993), the *c axis* becomes perpendicular to the growth surface. The calcite crystals in this zone are transparent to translucent and have very few inclusions;

Zone «e» (350 mm to 395 mm): The upper part of the stalagmite consists of two sub-zones of white opaque calcite laminae, very porous and full of inclusions (Fig. 3, «e_1») and two other sub-zones of clear to translucent layers made up of columnar calcite crystals (Fig. 3, «e_2»).

Length-slow calcite crystals began their growth on a disconformity surface, and due to variable flow rate (i.e local 'wetness' in the cave), the calcite crystals composing zone «a» are of unequal size and form a porous fabric. Normal length-fast calcite that prevails in zones «b», «c» and «d» suggests a wet (local) environment with no significant changes in the chemistry of the dripwater (which would otherwise have precipitated different types of calcite crystals), although there are intervals when calcite precipitation rate was attenuated or even ceased. For instance, changes in the $\delta^{18}O$ values below and above the «b/c» zone boundary (295 mm from base), where a layer of brown calcite was precipitated, would indicate such an event marked by changes in calcite crystal fabric from length-slow (just above this brown layer) to length-fast for the rest of the zone. Therefore, zone «b» probably experienced slow growth under mostly wet conditions. In zone «c», the precipitation commenced at a slow rate under wet conditions and increased as it approached the boundary with zone «d». Zone «d» is made up of length-fast calcite crystals which developed under wet conditions, but the crystallization rate was rather slow. Within zone «e», there are 2 sub-zones («e_1») that indicate mostly dry and fast growth (very porous material) while the other 2 sub-zones («e_2» are characteristic for slow growth under non-drying conditions.

URANIUM-SERIES DATING

Uranium-series disequilibrium dating can be performed on speleothems provided sufficient U is present (> 0.02 ppm) and that the system was initially free from non-authigenic ^{230}Th, as monitored with the $^{230}Th/^{232}Th$ index (Latham & Schwarcz 1992). Fourteen subsamples (10-15 mm thick, 10-60 g) were removed at regular stratigraphic levels for U-series dating, of which 11 contained sufficient U for dating (Fig. 3). The samples were digested in excess nitric acid, spiked ($^{228}Th/^{232}U$) and equilibrated by H_20_2 oxidation and boiling for several hours. U and Th were pre-concentrated by scavenger precipitation on ferric hydroxide. Iron was then removed by ether extraction in 9M hydrochloric acid, and U and Th separated by ion exchange chromatography on Dowex 1 resin. The purified, carrier-free fractions of U and Th were then electroplated onto stainless steel disks and counted for alpha particle activity *in vacuo* on an Ortec Octéte unit with silicon surface barrier detectors for 2-4 days. Each spectrum was corrected for background and delay since chemical separation and processed by tailored software (Lauritzen 1993a). All dates were performed at the Uranium-Series Geochronology Laboratory at the Department of Geology, University of Bergen.

STABLE ISOTOPES IN SPELEOTHEMS

The oxygen isotopic composition of speleothem carbonate, $\delta^{18}0_c$, precipitated in isotopic equilibrium with the dripwater (Hendy 1971; Gascoyne 1992), may be expressed as the *Speleothem Delta Function* (Lauritzen 1995,1996):

$$\delta^{18}O_c = e^{\left[\frac{a}{T}-b\right]}\left[F(T,t,g)+10^3\right]-10^3 \qquad \textbf{[1]}$$

where T is absolute temperature, t is time and g is geographical position of the site. Equation **[1]** has two terms. The first (exponential) term with constants a and b represents the *thermodynamic fractionation* factor (α_{c-w}) between calcite and water (later called $\mathbf{T_{fr}}$). The second term contains the *dripwater function*, F(T,t,g*)*. Here, the T-dependence relates to the atmospheric precipitation at a site, while the t- and g-dependence represent the transport history of rain and various properties of the weather system producing the rainfall. (It is also assumed that the cave temperature equals the annual mean of the surface temperature). This sensitivity is further modulated by storage and mixing of the percolation water above the cave. There might also be a seasonal interception bias in aquifer recharge above the cave, dependent on the fraction of precipitation that actually enters the epikarst (Lauritzen 1995).

The components $\mathbf{T_{fr}}$ and F(T,t,g) have different temperature sensitivities. $\mathbf{T_{fr}}$ always has a negative response to temperature (i.e. shifts to heavier $\delta^{18}O_c$ values imply decreasing cave temperature), whilst F(T,t,g) may respond either positively or negatively, depending on regional meteorology, like rain-out effects. Consequently, the temperature response of speleothem carbonate is entirely dependent on the relative magnitude of $\mathbf{T_{fr}}$ and F(T,t,g). The *temperature response* (μ) of **[1]** is, in mathematical terms, its T-derivative (Lauritzen, 1995) defined as:

$$\mu = \frac{\partial}{\partial T}\left(\delta^{18}O_c\right) \qquad \textbf{[2]}$$

which can, in principle, be negative, zero or positive. This can be further discussed with respect to the relative magnitudes of the T-responses of its components, $\mathbf{T_{fr}}$ and F(T,t,g):

1. when $\mu > 0$, the F(T,t,g) response is positive and large enough to dominate over $\mathbf{T_{fr}}$.
2. when $\mu = 0$, the $\mathbf{T_{fr}}$ and F(T,t,g) responses cancel and
3. when $\mu < 0$, the F(T,t,g) response is negative or positive (if positive, it has a smaller absolute effect than $\mathbf{T_{fr}}$).

In the cases of $\mu > 0$ or $\mu << 0$ variations in $\delta^{18}O_w$ of the precipitation dominate. The temperature sensitivity and therefore the interpretation of speleothem $\delta^{18}O_c$ is by no means straightforward and often ambiguous.

However, this ambiguity may be overcome in several ways that either aim at estimating F(T,t,g), or the sign of μ:

First, F(T,t,g) at a given point in time and space can be estimated from fluid inclusions within the calcite, which are actual samples of the original dripwater at the time of precipitation. Here, $\delta^{18}O_w$ = F(T,t,g) must be estimated from δ^2H_w, via the so-called 'meteoric water line', or its local equivalent (Craig 1961; Gat 1980):

$$\delta^{18}O_w = \tfrac{1}{8}\delta^2H_w - \tfrac{10}{8} \qquad \textbf{[3]}$$

Then, temperature can be calculated directly from the thermodynamic term of **[1]** (Schwarcz & Yonge 1983; Rowe *et al*. 1998).

Second, independent evaluation of paleowater $\delta^{18}O_w$ may be extracted from other sources, such as fossil aquifers (Talma & Vogel 1992).

Third, given that some temperature estimates exist together with calcite $\delta^{18}Oc$ values for both present and past conditions, like today and well-defined historic thermal events, (e.g. the Little Ice Age), the dripwater function may be calibrated by using a simple linear relationship between temperature and isotopic composition (Dansgaard 1964). Assuming that the values of the two constants are valid for timespans beyond the calibration range, the $\delta^{18}O_c$ record may then be transformed to absolute temperature (Lauritzen 1996; Lauritzen & Lundberg 1998).

Finally, by comparing trends in the $\delta^{18}O_c$ time-series with present-day $\delta^{18}O_c$ of stalactite tips (i.e. Holocene, non-glacial conditions) and known climatic changes in the past, the sign of (m) may be judged and assumed valid for the rest of the time-series (Schwarcz 1986).

At present, the carbon isotope signal in speleothem is much more difficult to interpret than for oxygen, because shifts in $\delta^{13}C$ values are dependent on several variables that cannot be measured. Variations of $\delta^{13}C$ in speleothem carbonate are determined by the metabolic processes that control the composition of the soil CO_2, the drip rate of the cave water, the amount of bedrock carbonate that goes into solution, and the rate of outgassing and precipitation (Schwarcz 1986; Dulinski & Rozanski 1990). In regions where a change between C3 and C4 vegetation is possible, speleothem carbonate with $\delta^{13}C$ values of about -13‰(PDB) reflects an environment dominated by C3-vegetation, whereas carbonates with $\delta^{13}C$ values of approximately +1.2‰ reflect a pure C4-biomass. C4 grasses are adapted to drought stress and grow preferentially where temperatures in the growing season are above 22.5°C and minimum temperatures never go below 8°C, as for example in South Africa and Israel (Talma *et al*. 1974; Holmgren *et al*. 1995; Bar-Matthews & Ayalon 1997).

At northern latitudes, C4 vegetation is lacking, so that variations in $\delta^{13}C$ may be interpreted as changes in soil productivity and amount of bedrock interaction, which in part is governed by temperature. Northwest Romania does not have any present-day C4 vegetation, although the loess steppes that expanded in central Europe (e.g. Hungary) during glacial maxima, might have had a proportion of C4 grasses. The only Romanian evidence for climatic changes during the last interglacial was presented by Diaconeasa *et al*. (1976) showing a mixed C3 and C4-type vegetation community from the central part of the Transylvanian basin. More detailed proxy records are available from the Middle Danubian Basin (Hungary), 100 to 200 km west of our cave. Pollen analysis data indicated that during the last interglacial short periods of climatic changes can be recognized as the C3 vegetation was replaced by steppe communities dominated by C4-type vegetation (Urban 1984; Jarai-Komlodi 1991). Furthermore, several loess cores from the central and eastern parts of Hungary show evident changes from forest soils to forest-steppe and steppe soils during isotope stage 5 (Pécsi 1993). From the vegetational point of view this means a shift from C3 to C4-type plants, a fact that agrees well with the rest of Central-Eastern Europe (Willis 1994).

Often, $\delta^{13}C$ and $\delta^{18}0$ display some covariation along the growth axis of a speleothem, suggesting that they both depend of the same external parameter, i.e. temperature. Shopov *et al*. (1997) suggested one possible explanation for this kind of effect but it is too elaborate to be included here.

Samples for stable isotopes were taken (100-200 µg each) at 10 mm intervals along the growth axis by means of a dentist's drill (Fig. 3). Also, two traverses for testing the Hendy (1971) criteria (*vide infra*) were made along growth layers at 50 mm and 375 mm above basis datum (Fig. 3). Yet another four analyses were made on crystal growth surfaces of stalactite tips sampled in the cave ceiling directly above LFG 2, in order to obtain values of recent calcite. All samples were analyzed for oxygen and carbon isotopes in CO_2 expelled in a hot H_3PO_4-line on a Finnigan 251 mass spectrometer at the GMS Laboratory, Department of Geology, University of Bergen.

RESULTS AND DISCUSSION

URANIUM SERIES DATES

Three analyses out of 14 were rejected because of low chemical yields and poorly resolved spectra; the remaining 11 dates are considered to be analytically correct (Table 1). The consistently low U content of LFG 2 (0.045-0.089 ppm U) makes it difficult to perform precise dates, hence the relatively wide age errors. However, in spite of variable errors, the central values of the dates are all in correct stratigraphic order, which permit us to make a tentative age calibration curve by linear interpolation through each dated zone (Fig. 4). This

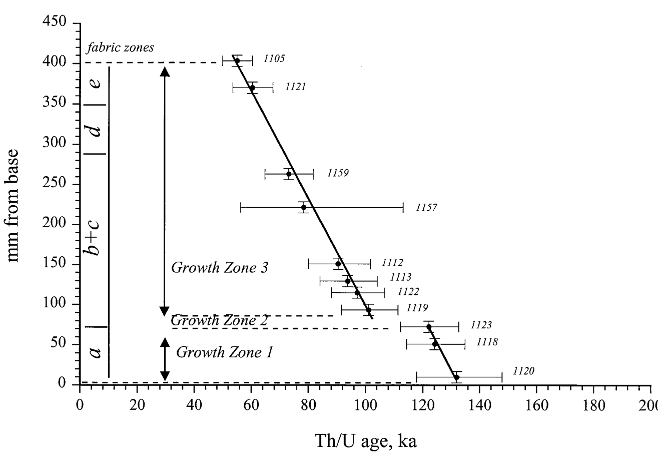

Figure 4. Age-stratigraphy calibration of LFG2. Because there is an apparent break in growth rate, coincident with fabric zone boundary (a/b), the sequence is divided into 3 growth zones. See text for further discussion.

Table 1. Uranium-series dates of stalagmite LFG-2.

Lab No.	Sample	mm from base	(ppm)	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	age (ka)		Corrected age (ka)	
1120	LFG 2d	0-20	0.072	1.768 ±0.084	0.754 ±0.048	> 1000	131.98	+15.88 -14.14		
1118	LFG 2b	45-55	0.078	1.52 ±0.062	0.718 ±0.034	> 1000	124.21	+10.72 -9.87		
1123	LFG 2h	65-75	0.084	1.66 ±0.073	0.717 ±0.035	> 1000	122.13	+10.66 -9.83		
1119	LFG 2c	85-95	0.085	1.811 ±0.076	0.641 ±0.041	> 1000	101.11	+10.35 -9.58		
1122	LFG 2g	105-115	0.089	1.796 ±0.12	0.624 ±0.04	> 1000	97.10	+9.70 -9.02		
1113	LFG 2f	125-135	0.066	1.725 ±0.156	0.608 ±0.043	> 1000	93.73	+10.42 -9.63		
1112	LFG 2e	145-160	0.072	2.025 ±0.27	0.6 ±0.05	> 1000	90.43	+11.37 -10.46		
1157	LFG 2k	210-230	0.062	1.457 ±0.105	0.65 ±0.073	4	106.01	+20.66 -17.67	78.34	+24.79 -22.03
1159	LFG 2l	250-270	0.045	1.723 ±0.06	0.612 ±0.03	5	94.77	+7.26 -6.87	73.04	+8.69 -8.34
1121	LFG 2x-1	365-375	0.08	2.837 ±0.2	0.448 ±0.041	> 1000	60.33	+7.14 -6.78		
1105	LFG 2x	385-395	0.068	3.63 ±0.27	0.418 ±0.032	> 1000	54.98	+5.33 -5.14		

curve has, of course, rather large errors; we estimate the average error (1 σ) in each age estimate to be ±10-15 ka.

The time span covered by the speleothem growth is the interval (130 ± 15) to (55 ± 15) ka, covering all of oxygen isotope stage 5 (a-e), and some time into stage 4. The marked offset of the graph between 100 and 120 ka suggests a strong growth attenuation or hiatus somewhere within this time interval, which may coincide with the transition between fabric zones «a» and «b» (Fig. 3). We have therefore divided the sample into 3 growth zones (1-3) (Fig. 4). Even when the chronological error is taken into account, Growth Zone 1 corresponds roughly to the Last Interglacial, (Eemian Stage Se), which occupies only the first 70 mm of the sample. However, the longest growth interval (Growth Zone 3, about 300 mm), corresponds roughly to the remainder of the Early Weichselian (Stage 5a-d) (Mangerud 1989). The growth rates of Zones 1 and 3 appear to be about the same (~7 mm/ka), although the chronological errors do not permit any closer comparison.

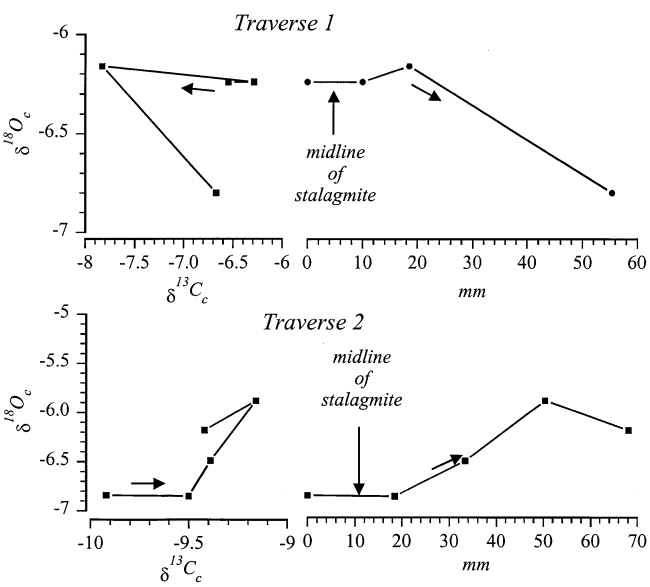

Figure 5. Results of Hendy test on two growth layers (Traverse 1 and 2, Fig. 3). The left diagrams display the covariation of δ18O and δ13C, whereas the diagram on the right side shows progressive changes in δ18O along the growth layer from the apex and down the side of the stalagmite. Arrows indicate the direction from the apex down the sides of the stalagmite. The 20-30 mm wide zone around the apex appears to have grown in isotopic equilibrium, whilst non-equilibrium fractionation might have occurred down the sides of the specimen.

HENDY CRITERIA

The Hendy criteria for testing if calcite was precipitated in isotopic equilibrium or not require that there is both no correlation between $\delta^{18}O$ and $\delta^{13}C$ of successive samples taken along the same growth layer, and that $\delta^{18}O$ does not change significantly along the growth layer when traversed across the apex and down the side of the sample. The theory is that, if kinetic fractionation (i.e. non-isotopic equilibrium) occurred during precipitation, $\delta^{18}O$ and $\delta^{13}C$ would both change in concert as the water film ran off the sides of the stalagmite. If precipitation occurred under isotopic equilibrium, $\delta^{18}O$ would largely remain constant, whilst $\delta^{13}C$ would change progressively with the traversed path. Since nature is never ideal, a pertinent question is how large tolerance that can be allowed before 'kinetic fractionation' is deduced and the sample regarded as 'useless'. Here, we have followed the standard set by Gascoyne (1992, Fig. 8), i.e. up to about 0.8 per mil change in $\delta^{18}O$ is accepted as 'constant' along a single growth layer.

Results of the Hendy test are shown in Figure 5. Neither of the two traverses exceeds 0.8 per mil change in $\delta^{18}O$ along each single growth layer traverse. Also, the largest changes

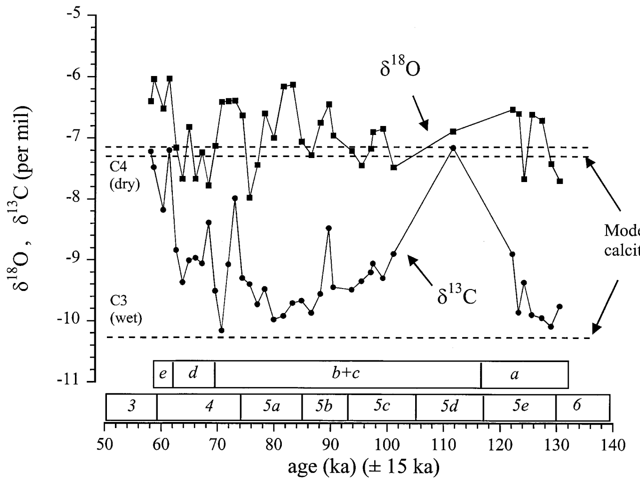

Figure 6. Time-series of oxygen and carbon isotopes in LFG-2 compared to modern values. See text for further discussion. Upper horizontal bar: crystal fabric zones of Figure 3. Lower horizontal bar: oxygen isotope stages.

occur down along the sides of the sample. This is also mirrored in the $\delta^{18}O$ /$\delta^{13}C$ plot. We may therefore conclude that the sample appears to have been precipitated in isotopic equilibrium within 20-30 mm of the apex, but that some fractionation occurred along the sides of the growing stalagmite. The isotopic time-series (which is taken along the growth axis) is thus assumed to represent an equilibrium deposit since it was taken along a line close to the apex where kinetic fractionation effects could not be detected.

OXYGEN AND CARBON ISOTOPE TIME-SERIES

Along the growth axis, $\delta^{18}O$ and $\delta^{13}C$ vary in the range of [-6 - -8] and [-7 - -10] per mil (VPDB), respectively, which could now be compared with recent isotopic values. Since the sample was no longer growing actively, the isotopic composition of present-day calcite was assessed from four stalactite tips that were taken at the site and analyzed (Table 2). Three of them, which consist of solid, translucent crystals at the apex, have values of $\delta^{18}O$ = -7.21 ±0.11 and $\delta^{13}C$ = -10.3 ±0.04 per mil. The fourth sample, which had a powdery, opaque surface and rather deviant isotopic composition, was rejected.

The age-calibrated time-series of the axial $\delta^{18}O$ and $\delta^{13}C$ profiles are shown in Figure 6. There is some covariation between the two records. For instance, the isotopically lightest values occur within growth zones 1 and 3. Moreover, both records become isotopically heavier at the top of the sequence (after 50-60 ka), as well as during growth zone 2 (100-120 ka), when deposition ceased or was halted for some time. At the commencement of growth (>130 ka), the $\delta^{18}O$ sequence rises from isotopically lighter to isotopically heavier values than present-day calcite. Also, between 100 and 120 ka, in the slow-growing zone 2, the values drop back to isotopically lighter values than present. Since growth zone 2 represents a period when growth was slow, or even halted, it is reasonable to assume that the climate became cooler and/or drier. These various features of growth and isotopic behavior are taken as roughly corresponding to the rise and fall in temperatures through isotope stage 5e, to the colder stage 5d. Hence, the isotopic response is so that the calcite becomes heavier with increasing temperature, i.e. $\mu > 0$ (equation **[2]**), and we may infer that $\delta^{18}O_w$ variations are dominated by the meteoric signal ($\delta^{18}O_c$) in precipitation.

Table 2. Stable isotope values of recent calcite at LFG-2.

Sample (soda straws)	$\delta^{18}O$(VPDB)	$\delta^{13}C$(VPDB)
LFG2-1 (white, fresh)	-7.34	-10.34
LFG2-2 (white, fresh)	-7.22	-10.25
LFG2-3 (white, fresh)	-7.07	-10.29
LFG2-4 (brown, dry)	-6.31	-8.71
Mean (1-3) ± 1σ	-7.21 ±0.110	-10.20 ±0.037

CORRELATION WITH THE DEEP-SEA RECORD

Due to the large chronological errors, there is, of course, some freedom in the correlation of LFG2 with other records. Also, speleothem records tend to display great temporal resolution, i.e. a rather spiky record of short-term events that are not necessarily present in the smoothed deep-sea curves. Our comparison is therefore somewhat conformistic, i.e. we have tested whether the data, within the freedom given by the time-scale, can be brought into harmony with other, known records. For instance, assuming that $\mu > 0$, there is a temperature rise at the beginning of the sequence (120-140 ka) which is in harmony with Termination II, the end of the Penultimate Glaciation (Broecker & van Dunk 1970).

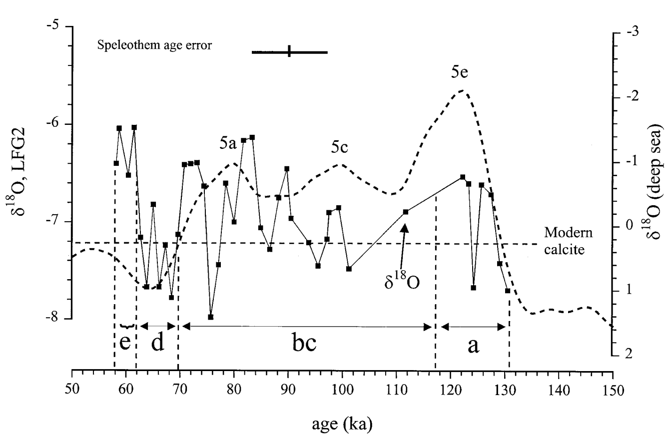

Figure 7. Calibrated isotope time-series of LFG 2 compared with the deep-sea curve of Martinson *et al.* (1987) (thick, dashed curve, oxygen isotope stages 5a, 5c and 5e labeled). The positions of the fabric growth zones of Figure 3 are shown with letters and arrows below the two curves. See text for further discussion.

In Figure 7, we have plotted a deep-sea isotope curve that reflects global ice-volume (Martinson *et al*. 1987) and compared it with the LFG2 record. The Last Interglacial, the Eemian (Stage 5e), is recorded within growth zone #1. Albeit represented by only one sample, the record may suggest an intra-Eemian instability (a cold spike at about 122 ka), which is also reported from other speleothem records (Lauritzen 1995; Roberts *et al*. 1998). After about 110 ka, the LFG-2 sequence displays several peaks and troughs, which are difficult (if not impossible) to correlate with corresponding wiggles of the Martinson *et al*. (1987) curve. However, both curves display a distinct drop (cooling and increase in global ice-volume) around 70 ka, which is the Stage 5/4 boundary.

CARBON ISOTOPES AND THE PALEOENVIRONMENT.

During Stage 5b, $\delta^{13}C$ and $\delta^{18}O$ appear to be anticorrelated, while they both show a strong shift towards heavier values at the onset of the Weichselian Glaciation at the Stage 5/4 transition (Fig. 6). If the $\delta^{13}C$ record is interpreted as reflecting changes in the composition of C3 and C4 plants on the surface above the cave, then the 5e/5d transition (growth zone 2) may (shown by only one sample!) represent a period with a higher proportion of C4 plants, i.e. there were drier conditions. Also, at the termination of the sequence (the Stage 5/4 transition), the isotopic record displays a similar C3-C4 shift, but the corresponding oxygen isotope shift suggests that it also became warmer as well as drier.

CORRELATION WITH OTHER SPELEOTHEM RECORDS

In Figure 8, we have compared the LFG2 record with the FM2 record from northern Norway (Lauritzen 1995). There is a remarkable correlation between the two series. Both display a rapid rise in $\delta^{18}O$ at Termination II (*ca*. 130 ka). Both sequences display a cold spike, although the imprecise chronology does not permit us to determine if the spikes are exactly the same age. It is, however, interesting to note that after FM2 ceased to grow at 70 ka and displayed a cooling signal, LFG-2 continues to grow while its stable isotope record suggests a warmer and drier climate in northwest Romania. This is compatible with the expansion of the Scandinavian ice sheets in concert with the dry, glacial steppe environment in central and southern Europe.

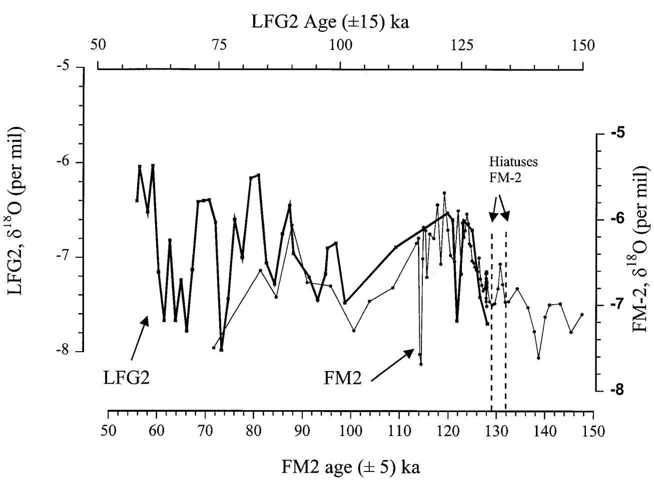

Figure 8. The oxygen isotope record of LFG6 (thick curve) compared with the α-dated last interglacial (thin curve with dots) from Northern Norway, FM2 (Lauritzen 1995). The main isotopic warming in the Eemian, around 120 ka, is present in both sequences, and demonstrates that speleothem climatic signals can be correlated over large latitudinal distances.

CONCLUSIONS

The LFG-2 stalagmite from northwest Romania grew through oxygen isotope Stage 5-4, and possibly also some time into Stage 3. Albeit a rather low uranium content and, thus, imprecise chronology, the stable isotope signal correlates quite well with speleothem record (FM-2) from northern Norway and broadly with the marine record. Termination II is well defined in the record, and during oxygen isotope Stage 5e (the Eemian, or the last Interglaciation in Europe), the temperature was higher than today. Less abundant data suggests that during Stage 5d, cooling occurred, accompanied with slow or no speleothem growth, as well as $\delta^{13}C$ shifts that may indicate a C4 vegetation (i.e. drier). Near the end of the sequence, probably after the isotope Stage 5/4 transition, temperature increased, growth slowed down, and C4 plants dominated. This might be interpreted as commencement of warmer and drier conditions at the onset of the Weichselian glaciation. These events are summarized in Table 3.

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Table 3. Summary of climatic changes during the growth of LFG-2.

Isotope stage	Response in LFG-2	FM-2 (North Norway)	Scandinavian Glaciation
6	No growth	Growth commenced	Saalian glaciation
6/5e	rapid warming	rapid warming	Termination II
5e	warm, unstable	warm, unstable	The Eemian
5d	cold, dry, slow growth/hiatus?	slow growth	Cold, glacier expansion
5a-5c	rapid growth	slow growth	Brørup/Odderade interstadials
4	warm, dry, then hiatus	corrosional hiatus	Middle Weichselian glaciation

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REFERENCES.

Baker, A., Smart, P.L., Edwards, R.L. & Richards, D.A. (1993a). Annual growth banding in a cave stalagmite. *Nature 364*: 518-520.

Baker, A., Smart, P.L. & Ford, D.C. (1993b). Northwest European palaeoclimate as indicated by growth frequency variations of secondary calcite deposits. *Palaeogeography Palaeoclimatology Palaeoecology 100*: 291-301.

Bar-Matthews, M. & Ayalon, A. (1997). Late Quaternary paleoclimate in the eastern Mediterranean region from stable isotope analysis of speleothems at Soreq Cave, Israel. *Quaternary Research 47*: 155-168.

Bastin, B. (1978). L'analyse pollinique des stalagmites: Une nouvelle possibilité d'approche des fluctuations climatiques du quaternaire. *Annales de la Societé Geologique de Belgue 101*: 13-19.

Broecker, W.S. & van Dunk, J. (1970). Insolation changes, ice volumes, and the 180 record in deep-sea cores. *Reviews of Geophysics and Space Physics 8*: 169-198.

Craig, H. (1961). Isotopic variation in meteoric waters. *Science 133*: 1702-1703.

Dansgaard, W. (1964). Stable isotopes in precipitation. *Tellus 16*: 436-468.

Diaconeasa, B., Clichici, O. & Dragos, I. (1976). Quelques renseignements sporopoffiniques concernant le passé de la vegetation Quarternaire de Transylvanie. *Contributii botanice*: 193-196.

Dickson, J.A.D. (1993). Crystal growth diagrams as an aid to interpreting the fabrics of calcite aggregates. *Journal of Sedimentary Petrology 63*: 1-17.

Dulinski, M. & Rozanski, K. (1990). Formation of $^{13}C/^{12}C$ isotope ratios in speleothems: A semi-dynamic model. *Radiocarbon 32*: 7-16.

Folk, R. & Assereto, R. (1976). Comparative fabrics of length-slow and length-fast calcite and calcitized aragonite in a Holocene speleothem, Carlsbad Caverns, New Mexico. *Journal of Sedimentary Petrology 56*: 486-496.

Gascoyne, M. (1992). Palaeoclimate determination from cave calcite deposits. *Quaternary Science Reviews 11*: 609-632.

Gascoyne, M., Schwarcz, H.P. & Ford, D.C. (1983). Uranium- series ages of speleothem from northwest England correlation with Quaternary Climate. *Philosophical Transactions of The Royal Society of London Series B 301*: 143-164.

Gat, J.R. (1980). The isotopes of hydrogen and oxygen in precipitation. In Fritz, P. & Fontes, J.C. (eds.) *Handbook of Environmental Isotope Geochemistry*. Elsevier Scientific Publishing Company, Amsterdam: 21-48.

Genty, D. & Quinif, Y. (1996). Annually laminated sequences in the internal structure of some Belgian stalagmites - importance for palaeoclimatology. *Journal of Sedimentary Research 66*: 275-288.

Gordon, D., Smart, P.L., Ford, D.C., Andrews, J.N., Atkinson, T.C., Rowe, P.J. & Christopher, N.S.J. (1989). Dating of late Pleistocene interglacial and interstadial periods in the United Kingdom from speleothem growth frequency. *Quaternary Research 31*: 14.26.

Grgor'ev, D.P. (1965). *Ontogeny of Minerals*. Israel Program for Scientific Translations, Jerusalem: 250p.

Hendy, C.H. (1971). The isotopic geochemistry of speleothems. Part 1. The calculation of the effects of different modes of formation on the isotopic composition of speleothems and their applicability as paleoclimatic indicators. *Geochimica et Cosmochimica Acta 35*: 801-824.

Holingren, K., Lauritzen, S.-E. & Possnert, G. (1994). $^{230}Th/^{234}U$ and ^{14}C dating of a late Pleistocene stalagmite in Lobatse II Cave, Botswana. *Quaternary Geochronology 13*: 111-119.

Holmgren, K., Karlén, W. & Shaw, P.A. (1995). Paleoclimatic significance of the stable isotope composition and petrology of a late Pleistocene stalagmite from Botswana. *Quaternary Research 43*: 320-328.

Holingren, K., Karlén, W., Lauritzen, S.-E., Lee-Thorp, J., Partridge, T.C., Piketh, S., Repinski, P., Stevenson, C., Svanerd, O. & Tyson, P.D. (in review). A high-resolution reconstruction of the palaeoclimate of the north-eastern summer rainfall region of South Africa over the last three millennia. *The Holocene*.

Jarai-Komlodi, M. (1991). Late Pleistocene vegetation history in Hungary since the last interglacial. In Pecsi, M. and Schweitzer, F. (eds.) *Quaternary Environments in Hungary, Studies in Geography in Hungary, 26.* Akademiai Kiado, Budapest: 5-46.

Kendall, A.C. & Broughton, P.L. (1978). Origin of fabrics in speleothems composed of columnar calcite crystals. *Journal of Sedimentary Petrology 48*: 519-538.

Latham, A.G. & Schwarcz, H.P. (1992). Carbonate and sulphate precipitates. In Ivanovich, M. & Harmon, R.S. (eds.). *Uranium-series Disequilibrium: Applications to Earth, Marine, and Environmental Sciences*. Clarendon Press, Oxford: 423-459.

Latham, A. G., Schwarcz, H.P. & Ford, D.C. (1979). Palaeomagnetism of stalagmite deposits. *Nature 280*: 383-385.

Latham, A.G., Ford, D.C., Schwarcz, H.P. & Birchall, T. (1989). Secular variation from Mexican stalagmites: their potential and problems. *Physics of the Earth and Planetary Interiors 56*: 34-48.

Lauritzen, S.-E. (1993a). *"Age4U2U". Program for reading ADCAM energy spectra, integration peak-correction and calculation of ^{230}Thorium/^{234}Uranium ages*. Computer Program Turbo Pascal Code, 5,000 lines, Department of Geology, Bergen.

Lauritzen, S.-E. (1993b). Natural Environmental Change in Karst: The quaternary record. *Catena Supplement 25*: 21-40.

Lauritzen, S.-E. (1995). High-resolution paleotemperature proxy record during the last interglaciation in Norway from speleothems. *Quaternary Research 43*: 133-146.

Lauritzen, S.-E. (1996). Calibration of speleothem stable isotopes against historical records: A Holocene temperature curve for north Norway? *Karst Waters Institute Special Publication 2*: 78-80.

Lauritzen, S.-E. (1998). "SPEP": the speleothem record in the Pole-Equator-Pole transects. In Gasse, F., Kroeplin, S. & Oldfield, F. (Eds.) *PEP III: The Pole-Equator-Pole transect through Europe and Africa ["Coordinating paleoenvironmental research along the PEP III transect" Bierville (France), September 12-15 1996]*. PAGES, Bern: 37-43.

Lauritzen, S.-E. & Lundberg, J. (1998). Rapid temperature variations and volcanic events during the Holocene from a Norwegian speleothem record. *PAGES Open Science Meeting, University of London, April 20-23, 1998*: 88.

Lauritzen, S.-E., Ford, D.C. & Schwarcz, H.P. (1986). Humic substances in speleothem matrix- Paleoclimatic significance.

Proceedings, 9th International Speleological Congress. Barcelona 1: 77-79.

Lauritzen, S.-E., Løvlie, R., Moe, D. & Østbye, E. (1990). Paleoclimate deduced from a multidisciplinary study of a half-million-year-old stalagmite from Rana, northern Norway. *Quaternary Research 34*: 306-316.

Lauritzen, S.-E., Hercman, H. & Glazek, J. (1996). Preliminary comparison between Norwegian and Polish speleothem growth frequencies. *Karst Waters Institute Special Publication 2*: 81-83.

Mangerud, J. (1989). Correlation of the Eemian and the Weichselian with deep sea oxygen isotope stratigraphy. *Quaternary International 3/4*: 1-4

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C. & Shackleton, N.J. (1987). Age dating and the orbital theory of the Ice Ages: Development of a high-resolution 0 to 300,000 yr chronostratigraphy. *Quaternary Research 27*: 1-29.

Onac, B.P. (1996). Mineralogy of speleothems from caves in Padurea Craiului Mountains (Romania), and their palaeoclimatic significance. *Cave and Karst Science 23*: 109-124.

Onac, B.P. & Lauritzen, S.-E. (1996). The climate of the last 150,000 years recorded in speleothems: preliminary results from north-western Romania. *Theoretical and Applied Karstology 9*: 9-21.

Onac, P.B. & Lauritzen, S.-E. (1996). Pleistocene and Holocene climate in north-western Romania as indicated by growth frequency variations of speleothems. In: Horoi, V. & Constantin, S. (Eds.) *The XIVth International Symposium on Theoretical and Applied Karstology. Baile Herculane - Romania, May 26- June 1, 1996*. Institul de Spéologie “Emil Racovita”, Bucarest: 42.

Pécsi, M. (1993). *Quaternary and Loess Research Akadémiai.* Kiadó, Budapest: 20-36.

Perkins, A.M. & Maher, B.A. (1993). Rock magnetic and palaeomagnetic studies of British speleothems. *Journal of Geomagnetism and Geoelectricity 45*: 143-153.

Ramseyer, K., Miano, T., D’Orazio, V., Wildberger, A., Wagner, T. & Geister, J. (1997). Nature and origin of organic matter in carbonates from speleothems, marine cements and coral skeletons. *Organic Geochemistry 26*: 361-378.

Roberts, M.S., Smart, P.L. & Hawkesworth, C.J. (1998). Evidence for an intra-Eemian cooling event from TIMS $^{230}Th/^{234}U$ dating of a British stalagmite (Abstract). *PAGES Open Science Meeting, University of London, April 20-23, 1998*: 109-110.

Rowe, P.J., Dennis, P.F., Atkinson, T.C., Lauritzen, S.-E. & Lundberg, J. (1998). A high resolution deuterium record from fluid inclusions in a late Holocene speleothem from S.W. Britain. *PAGES Open Science Meeting, University of London, April 20-23, 1998*: 112.

Schwarcz, H.P. (1986). Geochronology and isotope geochemistry in speleothems. In Fritz, P. & Fontes, J., (eds.) *Handbook of Environmental Isotope Geochemistry*. Elsevier, Amsterdam: 271-303.

Schwarcz, H.P. & Yonge, C. (1983). Isotopic composition of paleowaters as inferred from speleothem and its fluid inclusions. In *Paleoclimates and Paleowaters; a Collection of Environmental Isotope Studies*. International Atomic Energy Agency Vienna Austria.

Shopov, Y., Ford, D.C. & Schwarcz, H.P. (1994). Luminescent microbanding in speleothems: High-resolution chronology and paleoclimate. *Geology 22*: 407-410.

Shopov, Y., Tsankov, L.T., Yonge, C.J., Krouse, H.P.R. & Jull, A.J.T. (1997). Influence of the bedrock $C0_2$ on stable isotope records in cave calcites. *Proceedings of the 12th International Congress of Speleology 1*: 65-68.

Talma, A.S. & Vogel, J.C. (1992). Late Quaternary paleotemperatures derived from a speleothem from Cango Caves, Cape Province, South Africa. *Quaternary Research 37*: 203-213.

Talma, A.S., Vogel, J.C. & Partridge, T.C. (1974). Isotopic contents of some Transvaal speleothems and their palaeoclimatic significance. *South African Journal of Science 70*: 135-140.

Tamas, T. & Vremir, M. (1997). Karstological investigations in the Middle Basin of Lada Valley (Padurea Craiului Mountains, Romania). *Proceedings of the 12th International Congress of Speleology, La Chaux-de-Fonds, Switzerland 1*: 413-416.

Urban, B. (1984). Palynology of Central European loess-soil sequences: 229-248. In Pecsi, M. (ed.) *Lithology and Stratigraphy of Loess and Paleosols*. Geographical Research Institute, Hungarian Academy of Science, Budapest.

Vremir, M. (1994). Pesteri descoperite prin lucrari industriale în bazinul Mijlociu al Vaii Iadei (Muntii Padurea Craiului). *Ardealul Speologic 4*: 30-57.

Willis, K.J. (1994). The vegetational history of the Balkans. *Quaternary Science Reviews 13*: 769-788.

ERRATUM

The editor wishes to correct a typesetting error in the paper by Toth in the December issue (v. 60, n. 3) of the *Journal of Cave and Karst Studies*. On page 169, first paragraph, the first full sentence should read: “These fast flow rates (1.67×10^{-3} m/sec for the first test and 1.67×10^{-2} m/sec for the second)….” The parenthetical statement in the last sentence of the same paragraph should read: “(4.32×10^{-3} m/sec through 70 m of overburden).” We thank Bill Mixon for noting our error.