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RECONSTRUCTION OF PALAEOCLIMATIC CHANGES IN CENTRAL EUROPE BETWEEN 10 AND 200 THOUSAND YEARS BP, BASED ON ANALYSIS OF GROWTH FREQUENCY OF SPELEOTHEMS

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Abstract

The present study is an attempt to utilise the uranium-thorium dates of speleothems as a source of palaeoclimatic data. The clue is that the changing climate influenced intensity of speleothem deposition, which is reflected in clustering of U-Series dates of speleothems in certain time intervals. This work discusses and improves various methods of combined presentation of dates, with a special attention to the presentation in form of growth frequency ('pdf') curves. Using the 'bootstrap' method the confidence intervals of the 'pdf' curves could be determined. Also the algorithm, originally developed to determine parameters of arbitrarily chosen maxima in the curve, has been modified. Due to that an assessment of number of maxima has been possible. This method enables objective distinction of phases of speleothem growth, which cannot be done 'by eye' when the 'pdf' curve is smooth. The statistical tests show that the reliable 'pdf' curve should contain more than 150 dates.

Basing on 308 U-series dates of cave speleothems from southern Poland and other regions of central Europe, the growth frequency curves for the Carpathians and Uplands have been constructed. Comparison of phases of speleothem growth, distinguished by various authors for several regions of Europe, indicates that the climatic changes were synchronous over the whole region. However, different shapes of the 'pdf' curves reflect increasing continuity of speleothem growth in the N–S transect southwards. This may be connected with the N–S climatic gradient in Europe. Using the 'pdf' curves from caves of Tatra and Low Tatra Mountains the most probable timing of development phases of mountain glaciers has been delimited.

Key words: U-series dating, speleothems, palaeoclimatology, speleothem growth frequency

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INTRODUCTION

Climatology, which investigates physical processes controlling the climate and influence of geographical factors on the course of these processes, utilises direct observations and measurements. Using instrumental records, climatologists can derive information about variations of climatic parameters in the past. However, the time span covered by such records is rather short.

Investigation of natural processes and their dependence on climatic conditions enables us to understand relationships between them, and to use fossil records in palaeoclimatic studies. The climate-related (or climate-controlled) processes may provide records of past climatic changes. The more detailed the record is, and the more we know about its relationship to particular climatic factors, the better is our chance to obtain reliable palaeoclimatic reconstruction. In such a work, it is of basic importance to realise which type of data we possess, and which are the methods of their analysis. It is necessary to consider specific problems of physico-chemical methods used in gaining palaeoclimatic data, of the adopted assumptions, and of statistical analysis of obtained data. Only then the reconstructions obtained from different archives may be comparable with one another, which gives a possibility for their synthetic elaboration.

The present work is an attempt to demonstrate the possibilities of using the uranium-thorium dates of cave speleothems as a source of palaeoclimatic data. The relation of speleothem crystallisation intensity to climate has been realised long ago. As the number of collected results increased, the possibility to use the frequency of dates has been pointed out (Harmon *et al.* 1975, Atkinson *et al.* 1978). The methodology of results collation and analysis has been then gradually developed.

During five years of activity of the Uranium-Thorium Laboratory, Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, and during my practice in the Laboratory of Institute of Geology in Bergen (Norway), I performed U-series dating of a few hundred of speleothems from Poland, Slovakia and Czech Republic. The obtained results, besides information on development of particular cave systems, may be used in reconstruction of climatic changes in the past. This stimulated me to test and to improve the methods of construction and analysis of growth frequency records of cave speleothems. In view of the range of the U-series method, that analysis concerns the last 200 thousand years. It

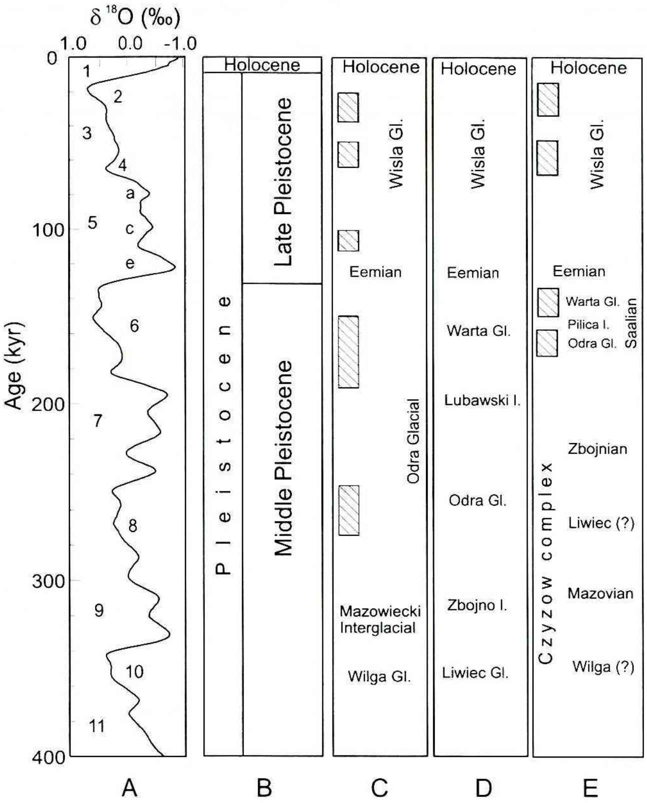

Fig. 1. Schematic diagram of stratigraphic division of younger Quaternary (the last 400 thousand years). A – The stacked, smoothed oxygen-isotope record as a function of age in SPECMAP time scale with the oxygen stages. (Imbrie *et al.* 1984); B – main stratigraphic units; C – stratigraphic division according to Mojski (1991); D – stratigraphic division according to Lindner (1992); E – stratigraphic division according to Krzyszkowski (1995). The periods of ice sheet development in territory of Poland are marked with hatched rectangles.

seems that the obtained results may become valuable information for geologists dealing with that period of the Earth's history.

The range of U-series dating covers two glacial/interglacial cycles. As different authors use different climatostratigraphic divisions (Fig. 1), an unequivocal correlation and temporal ordering of events is difficult. For that reason, in this work the results obtained from analysis of cave speleothems will be correlated with global records of climatic changes represented by the oxygen isotopic composition curve, and in particular, with the oxygen isotopic stages.

Records of palaeoclimatic changes in cave speleothems

Course of many natural processes depends on prevailing climatic conditions. If the available archives enable determination of the course of such processes, we may try to reconstruct past environmental conditions.

Main types of data used in the palaeoclimatic studies are listed in Table 1. Each of them provides somewhat different information. They utilise different materials, and carry information on different time periods. Part of them is only indicative for an existence of specific conditions (*e.g.* occurrence of end moraines indicates an extent of a glacier), while the other ones enable an assessment of intensity of some features. For example, variability of isotopic composition of oxygen enables us to assess the changes of temperature or the volume of the ice sheet.

Among terrestrial sediments, cave speleothems are quoted. This type of cave deposits has fascinated people for long. Description of diverse speleothem forms were one of the earliest scientific information obtained in caves. The possibility to draw many valuable informations on depositional environment, basing on analysis of calcite (the main constituent of speleothem), has been pointed out quite early. At the moment of speleothem crystallisation, various trace elements are incorporated in the crystal lattice, and/or are fixed on the grain surface. They can be then used to derive different type of information. Trace admixtures of uranium isotopes, and of carbon-14 enable us to date the moment of speleothem crystallisation. The principles of methods of dating speleothems and the related problems are discussed in the later sections of this work.

Information on climatic conditions is often derived from the analysis of isotopic composition of oxygen (Hendy, Wilson 1968, Fantidis, Ehhalt 1970, Hendy 1971, Schwarcz *et al.* 1976, Harmon *et al.* 1978, Lauritzen, Kihle, 1996, Różański, Duliński 1988, Kucharczyk, Zieliński 1999), carbon (Cerling 1984, Schwarcz 1986, Holmgren 1996), and hydrogen. Quite frequently, speleothems comprise grains of plant pollen, which entered the cave with percolating water and were entrapped into crystallising structure. They may bring information about vegetation cover at the surface (Geurts 1976, Bastin 1979, Bastin, Gewelt 1986, Ford, Williams 1989, Brook *et al.* 1990, Lauritzen *et al.* 1990). In some cases, analysis of amount and composition of organic matter enabled determination of the type of soils at the surface above the cave (Lauritzen *et al.* 1994). Different content of organic matter in different growth layers of a speleothem is pointed out as a cause of differentiated microluminescence of calcite (Baker *et al.* 1993a, Shopov *et al.* 1994, Genty, Quinif 1996, Gradziński *et al.* 1997, White 1997, Fleitman *et al.* 2000). The trace admixtures of many elements have also been studied, but their palaeoclimatic meaning is still unclear (Harmon 1975, Gascoyne 1983, 1992, Goede, Vogel 1991). Also the occurrence of speleothems itself is an indication of conditions favourable for crystallisation. The evaluation of climatic conditions basing on frequency of speleothem crystallisation is the main subject of this work.

Rate and frequency of speleothem crystallisation

The question of rate of speleothem crystallisation had been raised for long. As usual, a solution of such an apparently simple problem is rather difficult. The relationship between factors controlling growth of speleothem and rate of its formation (usually expressed in millimetres per thousand years) is not straightforward. The growth rate depends not only on ambient conditions, but also on the type of speleothem, abundance of detrital material carried with the water, on amount of water and its chemical composition, and on many other factors. It has even been succeeded to observe seasonal changes of speleothem crystallisation rate. In the

Table 1

Sources of palaeoclimatic data

Type of data and type of material			Source of data	Measured quantities	Related climatic factors	Possibilities of dating
Glaciological	Ice cores		Stable isotope composition	$\delta^{18}O$ $\delta^{13}C$ ^{10}Be	Temperature, composition of atmosphere, production rate of cosmogenic isotopes, insolation	^{14}C in macrofossils, ice flow model, correlation of individual records
			Physical parameters of ice	Conductivity Structure of ice		
			Trace elements and dust content	Chemical composition Dust content		
Geological	Marine sediments	Organogenic	Isotopic composition of oxygen	$\delta^{18}O$	Overall volume of ice sheets, temperature and salinity of oceanic water, temperature and circulation patterns of deep oceanic water, wind strength and wind directions	^{14}C, correlation of records, Ar-K in tufa and volcanic dust, Th/U in organic fossils
			Amount of fossils			
			Morphological variability of fossils			
		Inorganic	Structure and texture of sediments			
			Accumulation rate and content of fraction of continental and glacial origin			
			Geochemical indicators			
	Terrestrial sediments		Sediments and traces of glacial erosion Periglacial structures Sea level changes Eolian sediments Lake sediments Fossil soils		Humidity, amount of precipitation, temperature, intensity of vegetation	Th-U, ^{14}C, Ar-K, TL, ESR, chemical methods, corelation of records, palaeomagnetism
			Speleothems	$\boldsymbol{\delta^{18}O}$ $\boldsymbol{\delta^{13}C}$ **Admixture of trace elements** **Microluminescence** **Amount and composition of pollen** **Frequency of crystallisation**		
Biological			Tree rings Pollen grains Plant macrofossils Insect remnants Geographical differentiation of populations		Temperature, amount of precipitation, types of plant assemblages	^{14}C, Th-U, dendrochronology, Ar-K, correlation of records
Historical			Written archives			

Postojna Cave (Slovenia), growth rate of speleothems during summer appeared twice as high as in winter (Gams 1965). The growth rates of speleothems forming in different climatic (from glacial to interglacial) conditions, and in different geographical regions, are very diverse (*cf.* Ford, Williams 1989). For that reason, it is very difficult to indicate possibility of direct application of the growth rate data as a source of palaeoclimatic information.

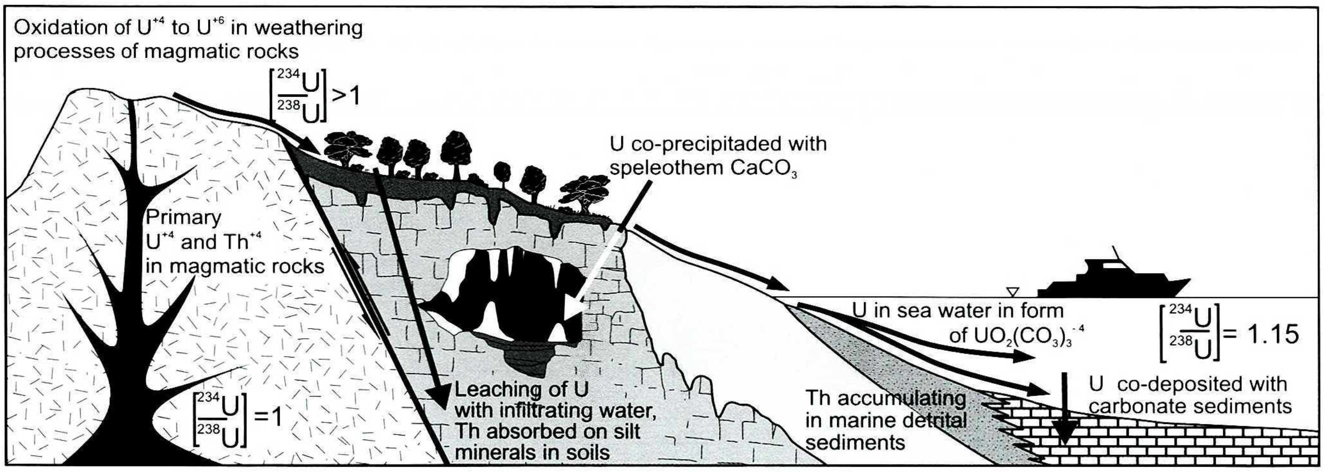

Fig. 2. Simplified scheme of uranium and thorium circulation in hypergenic processes.

Also an information itself about speleothem growth in particular period has palaeoclimatic implications. Crystallisation of speleothems is controlled by climatic factors, mainly by temperature, amount of precipitation and intensity of vegetation. In warm and humid periods, characterised by development of thick vegetation cover above the cave, crystallisation of speleothems is intensive. On the other hand, in periods of cold and dry climate, deposition of speleothems may be inhibited or totally terminated, and older speleothems may be destroyed. The record of deposition and decay phases preserved in the structure of speleothem, in connection with possibility of their dating, offers information on climatic changes. On the other hand, statistical analyses of large populations of dates enable us to distinguish periods favourable and unfavourable for the growth of speleothems. The methods of building the curves showing frequency of speleothem crystallisation and the methods of their analysis will be described in details in further sections of this work.

METHODS OF DATING OF SPELEOTHEMS

In the literature, one can find results of speleothem dating obtained with many different methods. The most popular is the uranium-thorium method. For speleothems the radiocarbon (^{14}C), thermoluminescence (TL) and electron spin resonance (ESR) methods are applicable, too.

Uranium-thorium method

Uranium series disequilibrium dating of cave calcite deposits (speleothems) is based on a fact that various daughter nuclides of the ^{238}U series are, in part, different chemical elements that behave differently in the meteoric weathering system (Fig. 2). During oxidising weathering of old, uranium-bearing deposits, U isotopes are easily mobilised as $(UO_2)^{2+}$ (often as a carbonate complex), whilst Th is highly insoluble under these conditions and it becomes absorbed onto clay minerals. In consequence, the percolation water that precipitates calcite speleothems, contains ^{238}U and ^{234}U and is essentially free from their daughter nuclide, ^{230}Th. After deposition, formation of ^{230}Th can be described by the equation:

$$\frac{^{230}Th}{^{234}U} = \frac{^{238}U}{^{234}U}(1-\exp(-\lambda_{230}t))+ \\ +\frac{\lambda_{230}}{\lambda_{230}-\lambda_{234}}\left(1-\frac{^{238}U}{^{234}U}\right)(1-\exp(-(\lambda_{230}-\lambda_{234})t)) \qquad (1)$$

where $^{230}Th/^{234}U$, $^{238}U/^{234}U$ are the measured activity ratios of the nuclides in the samples, λ_{230} and λ_{234} are the decay constants of ^{230}Th and ^{234}U respectively, and 't' is the elapsed time in years. In this way, the ^{230}Th-^{234}U disequilibrium method determines the time since the mineral phase (calcite) was precipitated. However, applicability of the method using eq. (1) is based on three assumptions:

a) initial conditions are well defined (*i.e.* the sample must have been free from ^{230}Th at the moment of deposition);

b) the sample must have behaved as a geochemical closed system since deposition;

c) the sample contains sufficient uranium for analysis of nuclide concentrations.

The assumption a) is fulfilled only when the sample is free from detrital matter. Detrital particles contain both ^{230}Th and ^{232}Th, so that contamination can be detected by the appearance of ^{232}Th peak in the radiation spectra. Within the analytical precision that is available with α-spectrometry technique, contamination of up to 5% (*i.e.* $^{230}Th/^{232}Th \geq 20$) has no significant effect on the sample age, and therefore can be neglected. However, for the $^{230}Th/^{232}Th$ ratios distinctly smaller than 20, the amount of ^{230}Th that was brought into the sample at t=0 must be taken into account, and the age appropriately corrected. This can be done in several ways (Schwarcz 1980, Ivanovich, Harmon 1982, Schwarcz, Latham 1989, Przybyłowicz *et al.* 1991). In most cases, the age is corrected by replacing the left-hand side of eq. (1) with:

$$\frac{^{230}Th}{^{234}U} - \frac{^{232}Th}{^{234}U}B_0\exp(-\lambda_{230}t) \qquad (2)$$

where the term B_0 represents the $^{230}Th/^{232}Th$ activity ratio in the detritus at t=0 (Schwarcz 1980). Although B_0 should be determined for local detrital fraction, an empirically derived average value of 1.5 is commonly used for this purpose (Ivanovich, Harmon 1982). Much better approach is to construct isochron plots ($^{230}Th/^{232}Th$ *vs.* $^{234}U/^{232}Th$ and $^{234}U/^{232}Th$ *vs.* $^{238}U/^{232}Th$), from which corrected $^{230}Th/^{234}U$ and $^{234}U/^{238}U$ activity ratios can be determined. However, in this method, several analyses are required to obtain single date.

The assumption b) is satisfied for non-porous, macrocrystalline speleothems, which are the most suitable materials for dating. The condition c) is more critical, because the U-content of a speleothem is dependent on the host rock, and on the percolation system above the cave. This factor can vary both between and within regions and caves. Generally, U concentrations greater than about 0.05 ppm is required for α-spectrometric measurements, but using large sample mass and long counting times, samples with as little as 0.01 ppm U can be dated. The quoted error of dates is based solely on counting statistics, and is therefore a direct function of the sample size, its U-content and the yield of chemical preparation.

Radiocarbon method

Dating of speleothems by means of the ^{14}C technique was introduced in the early years of application of the radiocarbon method. The most important question in the dating of speleothems and other carbonates precipitated from bicarbonates dissolved in groundwater, concerns the knowledge of initial ^{14}C concentration (Fig. 3). It has been shown by several authors that this value might be assumed equal to *ca.* 85% of ^{14}C concentration in contemporary land vegetation (of the so-called 'modern carbon'; Bastin, Gewelt 1986, Gewelt 1985, Talma, Vogel 1992). Actually, initial ^{14}C concentration in speleothems ranges from 50% to more than 100% of modern carbon (Gewelt 1986, Geyh, Henning 1986, Hercman 1991). Hence the radiocarbon age of speleothem calculated by means of equation:

$$T_c = 8033 \cdot \ln \frac{S_o}{A} \qquad (3)$$

where S_o is ^{14}C activity of an international standard of modern carbon and 'A' is ^{14}C activity in the sample, must be corrected to account for that initial ^{14}C activity of the speleothem significantly differs from S_o. This effect is known as the 'reservoir effect', and it results in the so-called 'apparent age' of the speleothems and other freshwater calcite samples. Denoting:

$$A_0 = \alpha \cdot S_o \qquad (4)$$

where 'α' is termed 'reservoir dilution factor', and substituting it into eq. (3) we obtain:

$$T_c = 8033 \cdot \ln \frac{A_0}{\alpha \cdot A} = 8033 \cdot \ln \frac{A_0}{A} - 8033 \cdot \ln \alpha = T + T_{app} \qquad (5)$$

The first term 'T' denotes the real age of the speleothem, while the second one, 'T_{app}' is called 'apparent age' and means systematic correction, which should be evaluated separately. It should be noted that because $\alpha<1$, the sign of T_{app} is positive.

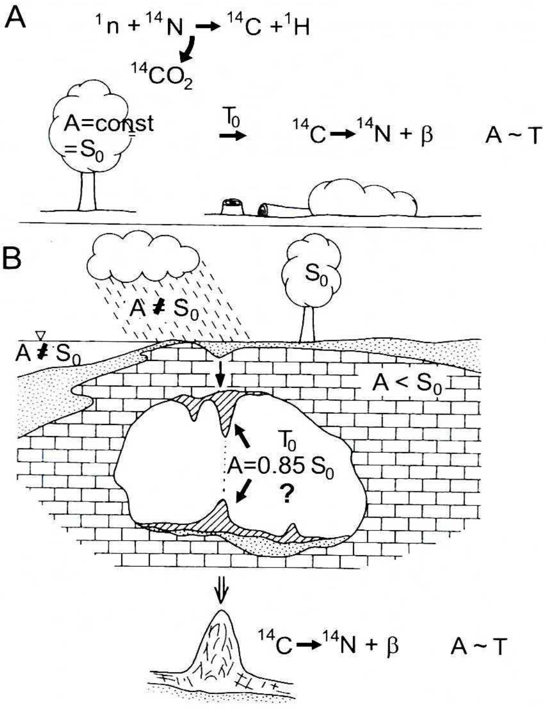

Fig. 3. Simplified illustration of fundamentals of radiocarbon dating of terrestrial organisms (**A**) and speleothems (**B**).

TL and ESR methods

Both electron spin resonance (ESR) and thermoluminescence (TL) methods of dating Quaternary sediments deal with radiation defects produced in some crystalline grains by natural nuclear radiation. The intensities of the ESR or TL signals are proportional to the concentration of these defects, or, more precisely, to the total dose of absorbed radiation – the so-called 'effective' or 'equivalent dose' (ED). The ED received by a speleothem is composed of internal α, β and γ doses from the decay of natural radioactive isotopes in the speleothem itself, and of the external dose from cosmic rays and environmental radiation.

In both TL and ESR dating methods the age of a dated sample is calculated from the relation:

$$AGE = \frac{ED}{D} \qquad (6)$$

where D is the dose rate (annual dose). The annual dose can be represented as a sum of internal (D_{int}) and external (D_{ext}) doses *i.e.*:

$$D = D_{int} + D_{ext} = D_U + D_{Th+K} + D_{ext} \qquad (7)$$

where D_U and D_{Th+K} denote contributions to D_{int} from the U-series and the Th-series+^{40}K, respectively.

Comparison of dating results

The results of dating of speleothems, obtained with different methods, differ sometimes significantly from one another.

Comparison of the TL, ESR and U-series dates

Comparison of TL, ESR and U-series ages obtained by the author has been done for *ca.* 15 speleothem samples. The TL and ESR dates were obtained in the Gliwice Laboratory, Poland (Hercman 1991). The U-series dates were obtained in Bergen Laboratory, Norway, and in Warsaw Laboratory.

Comparison of dates (Fig. 4) shows no correlation between the results of the TL, ESR and U-series dating. Usually the TL/ESR ages are older than the U-series ages. The most important reason of this discrepancy is variation of the dose rate in the past. For the age calculation, the dose rate measured in the cave or in the laboratory is used. One, however, does not know if the external dose rate was constant in the past. The effect of the external dose rate variations may be quite strong because the internal dose rate for the speleothem calcite is usually low. Uranium concentrations in speleothems usually range between 0.01 and several ppm. Concentrations of thorium and ^{40}K are low too.

Detailed measurements of the external dose rate were performed in selected caves in Tatra Mountains (Southern Poland). The results from the Kasprowa Niżnia Cave (Fig. 5) show high variability of the dose rate, and reveal significant correlation of the D_{ext} with the presence of sediment (silty sands) and water level.

The external dose rate in the cave passages depends on presence of sediments and/or water. If the passage is partly or completely filled with water, the effective dose rate is lower. In passages filled up with sediments the dose rate is usually higher. Consequently, removal of sediments or water from the passage alters the external dose rate. If the differences between the TL/ESR and real (*e.g.* the U-series) ages were entirely produced by variations of D_{ext}, knowing (or assuming) the magnitude of the dose rate changes connected with the presence of sediment and/or water we could calculate the time of their appearance in the cave. One should, however, keep in mind that the history of the dose rate changes could be quite complex, and rather unique for each sample.

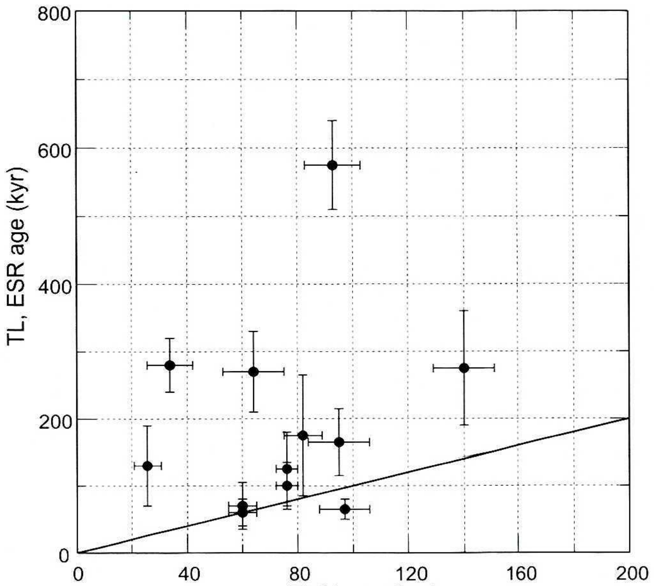

Fig. 4. Comparison of TL/ESR and U-series dates of speleothems.

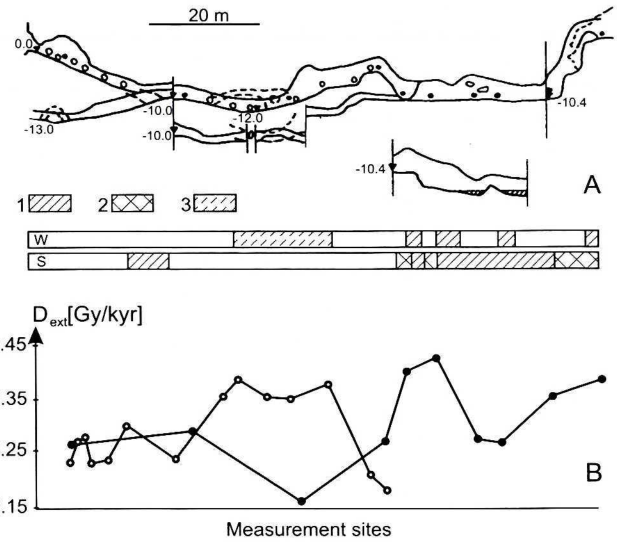

Fig. 5. **A** – schematic cross section of the introductory part of Kasprowa Niżnia Cave and water (W) and sand (S) distribution in the cave passages: 1. Permanent presence of water or sand, 2. Permanent presence of large volume of sand, 3. Temporary presence of water; **B** – results of *in situ* measurements of D_{ext} *versus* distance from the cave entrance. Open circles show the results obtained in winter (no water in the cave); solid circles – results obtained in summer (parts of the cave filled with water).

Comparison of the radiocarbon and U-series dates

Comparison of ^{14}C and U-series ages for *ca.* 65 speleothems gives us completely different picture from that obtained for the TL/ESR ages (Goslar *et al.* in print). Here, significant correlation between dates is noted (Fig. 6).

For the samples younger than 20 kyr (U-series age; "kyr' denotes "thousand years') the correlation is similar to that obtained for corals (Bard *et al.* 1990, 1993). For the samples older than 20 kyr, difference between ^{14}C and U-series dates is still not less than 4–5 kyr. The speleothem dates seem thus to confirm that the deviation between ^{14}C and absolute time scales did not disappear between 35 and 45 kyr BP ('BP' means 'before present'). All pairs of U-series and ^{14}C dates of speleothems suggest that this deviation was probably not less than 4 thousand years. Similar effect was reported for the samples from other areas (Vogel 1983, Vogel, Kronfeld 1997, Holmgren *et al.* 1994, Goede, Vogel 1991).

Completely different method of comparison of the U-series and ^{14}C dates uses the speleothem crystallisation frequency curves (Goslar *et al.* in print). Here, all available dates published till now have been collected, and two curves of crystallisation frequency have been constructed, separately for the U-series and the ^{14}C dates. Assuming that deposition of speleothems is controlled by climatic factors, one

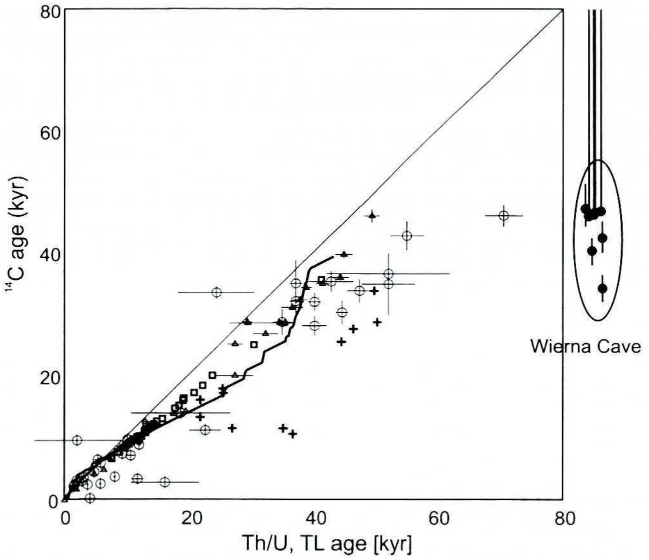

Fig. 6. Comparison of pairs of ^{14}C and U-series dates of speleothems: open circles (Goslar *et al.* in print), black triangles (Vogel 1983, Vogel, Kronfeld 1997), crosses (Holmgren *et al.* 1994) and corals (open squares; Bard *et al.* 1990, 1993). Black circles at the right side of graph represent the results of dating of stalagmite from Wierna Cave (see text). Thick line: transfer function of radiocarbon time scale obtained from comparison of frequency distribution of ^{14}C and U-series ages (see text).

could expect both records similar to each other, independent of the dating method. The results of analyses are presented in Fig. 7. The two records have quite similar shape but different time scales (Fig. 7A). Correlation of records is much better after transformation of the ^{14}C-time scale (Fig. 7C). The transform function is presented in Fig. 7B.

The results obtained with both methods of comparison are quite similar (Fig. 6). This means that the discrepancy between ^{14}C and U-series dates has a global character.

Assessment of reliability of results

In the literature on dating cave speleothems one can find results obtained with different methods. The Uranium-Thorium method dominates definitely, but other methods are in use too. These are the following: protactinium-uranium (^{231}Pa/^{235}U), uranium (^{234}U/^{238}U), radiocarbon (^{14}C), thermoluminescence (TL) and electron spin resonance (ESR) methods. Some attempts to apply the fission track (FT) method have been also made. Each method has specific parameters, the main ones being shown in Fig. 8. The first parameter, which differentiates the mentioned methods, is the time range (Fig. 8A). Potentially the largest range is offered by the FT method, however its use has been abandoned because of serious problems with distinction of fission tracks from other defects revealed after etching the sample. Additionally, low concentrations of uranium in speleothems limits applicability of the FT method only to very old samples. In theory, the sample with highest U concentrations ever found in speleothems, should be at least 100 thousand years old to be datable. Relatively large range is offered by the TL and ESR methods. It depends mainly on concentration of radionuclides in calcite and in the surrounding of speleothem.

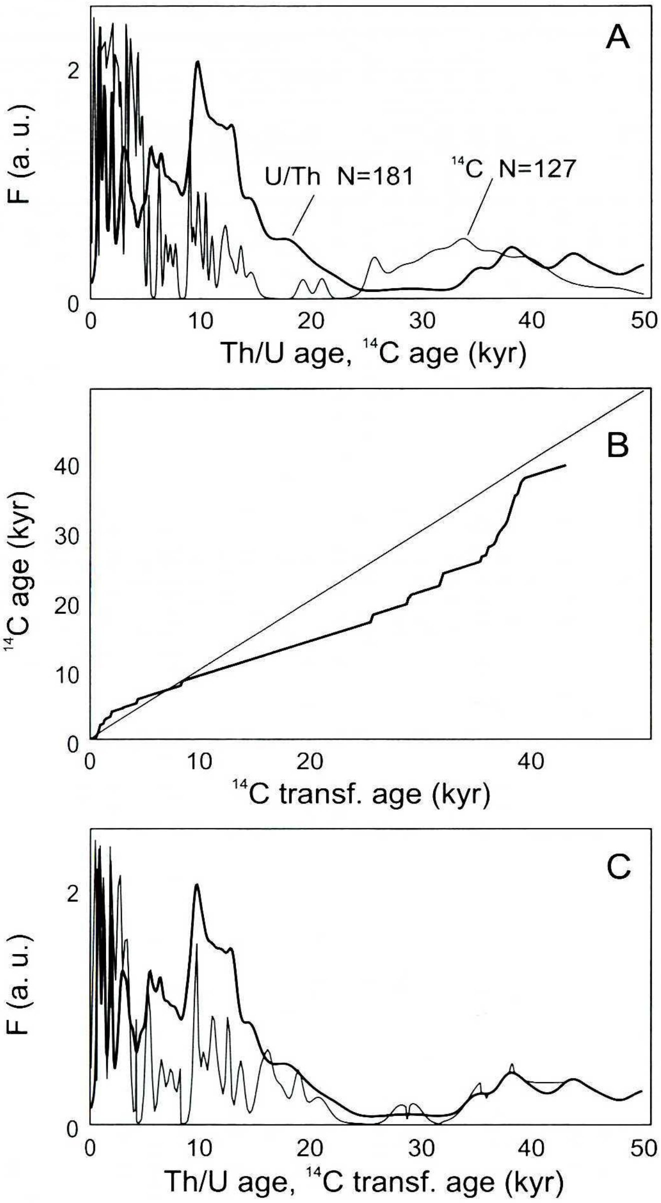

Fig. 7. **A** – comparison of frequency distributions of ^{14}C (thin line) and U-series (thick line) ages of speleothems, selected from literature; **B** – relationship between ^{14}C and U-series time scales (transfer function) which explains the time lags between distributions from part A; **C** – comparison of distributions as in part A, with the ^{14}C time scale modified according to the transfer function (after Goslar *et al.* in print).

Relatively low uranium concentrations in speleothems allow us to estimate the range of the TL and ESR methods to 1–5·10^{6} years. However, in old speleothems one has to expect an increasing effect of thermal vacation of electron traps. This effect is stronger in higher temperatures, but even in caves in middle latitudes, where the temperatures range between 4 and 10°C, the thermal escape of electrons becomes significant at the time scale of hundred thousands of years. The shortest range is that of the radiocarbon method (40–50 thousand years). With the protactinium-uranium method one can date samples up to 100 thousand years old, and with the uranium-uranium method – up to 1.2 million years. Applicability of both methods is however limited because of prob-

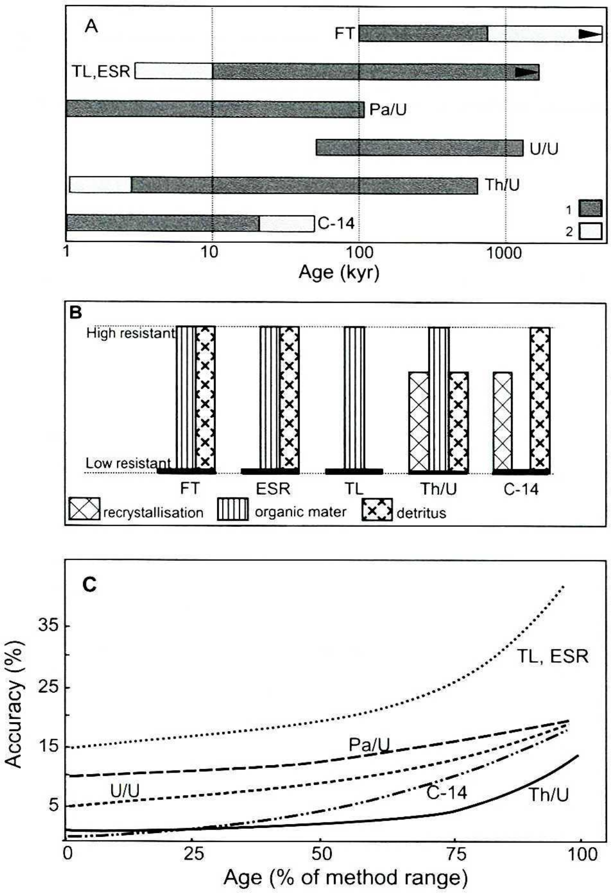

Fig. 8. Characterisation of selected methods of dating. **A** – range of method: 1. Typical range, 2. Dating possible in favourable conditions (high content of particular isotopes); **B** – sensitivity of the methods to selected perturbing factors; **C** – relative accuracy of dating.

lems with determination of initial activity ratios of appropriate isotopes.

The most frequently mentioned factors, which can affect results of dating of cave speleothems, are contamination with detrital material, and recrystallisation of calcite (Fig. 8B). Contamination with detrital material does not affect dates obtained with the radiocarbon, ESR or FT methods. In the uranium-thorium method, detrital contamination causes problems due to non-radiogenic thorium introduced in speleothem. Luckily, in this method, the contribution of non-radiogenic thorium can be estimated, and the appropriate corrections included. The detrital component makes difficult application of the TL method, since the thermoluminescence of calcite cannot be distinguished from that of *e.g.* quartz. Contamination with organic material affects the results of radiocarbon dating, but is insignificant in case of other methods. Recrystallisation of calcite precludes application of the FT, TL and ESR methods. It may also become a problem in the case of the radiocarbon and uranium-thorium methods, as it causes opening of the system and post-depositional migration of isotopes.

The next question is the potential precision of dating. Fig. 8C shows typical relative precision (in per cent) as a function of samples age (expressed in per cent of the range of method). For the youngest samples, the best potential precision is offered by the ^{14}C method. One has however to remember the 'reservoir effect', that causes the initial ^{14}C activity not exactly known. This is an important problem, especially as the quoted error of ^{14}C dates usually takes into account only 'laboratory components', assuming initial ^{14}C activity in speleothem well known (most frequently 0.85 of modern carbon). Slightly poorer is the precision of the uranium-thorium method, though for high concentrations of uranium (several ppm) it becomes quite comparable, and for older samples even better than that of ^{14}C. In recent years, occurrence of non-radiogenic thorium in modern speleothems has been reported (Whitehead *et al.* 1999). Initial thorium (^{230}Th) content has been equivalent to 1–3 kyr of 'initial age'. For dozen years of research only a few such cases have been met. In such speleothems, ^{230}Th was also accompanied with ^{232}Th. Precision of the TL and ESR ages is usually lower than 15%.

One of the most frequently raised problems of the ^{14}C dating of speleothems is that of the dilution factor and related 'apparent age'. This causes uncertainty of the 'zero point' of the radiocarbon time scale. It happens quite rarely, that the dilution factor can be determined by dating of contemporary organic and carbonate samples. From available bibliographic data one can conclude that the 'apparent age' usually ranges from 1000 to 2000 years. For that reason, one should realise that the uncertainty of 'zero point' of the radiocarbon time scale may reach as much as 2000 years. It should be taken into account in the error of radiocarbon age.

For old samples, more serious problem is high sensitivity of the ^{14}C age to sample contamination with modern carbon. The significance of that problem is exhibited in the case of stalagmite from the Wierna Cave (Fig. 6). The series of uranium-thorium analyses gave ages older than 350 thousand years. Only the youngest sample appeared 200 thousand years old. On the other hand, radiocarbon dating gave 'finite ages' (between 35 and 45 thousand years) for as much as four samples from that stalagmite. The calcite in this stalagmite has fine crystalline structure, with relatively high porosity. It thus seems that so large discrepancy between the uranium-thorium and ^{14}C ages is caused by crystallisation of younger calcite in pores of the stalagmite. An admixture of one percent of young material makes ^{14}C-activity detectable and radiocarbon age finite. The uranium-thorium method is distinctly less susceptible to contamination. Influence of contamination with young material on both radiocarbon and uranium-thorium age is shown in Fig. 9. The activity ratios ^{230}Th/^{234}U and ^{14}C/^{14}C$_{atm}$ (where ^{14}C$_{atm}$ means activity of radiocarbon in the atmosphere at the moment of speleothem crystallisation) are depicted with thick lines. Dotted lines show effects of contamination with ''dead' (^{14}C-free) carbon and with non-radiogenic thorium, respectively. These impurities alter the activity ratios only slightly. Thin lines illustrate effects of 5% contamination with modern material. The original speleothem 35-kyr-old would contain very little ^{14}C, and admixture of 5% of modern carbon makes the radiocarbon age younger by as much as 15 thousand years. Same contamination alters the uranium-thorium age by *ca.* 5 kyr. The effect is even stronger for speleothem 100 kyr old. Such an age is beyond the range of the radiocarbon method but the

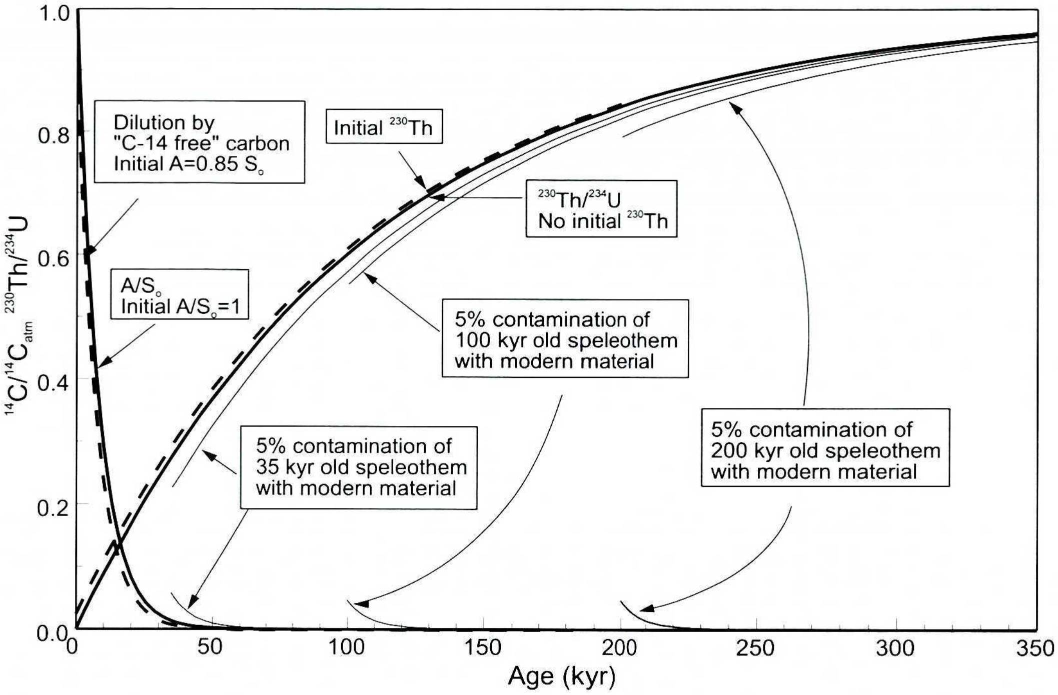

Fig. 9. Influence of contamination with the young material on fine projection of ^{14}C activity and $^{230}Th/^{234}U$ activities ratio in the speleothems.

contamination makes the ^{14}C age younger by several tens of kyr. That was the case of the stalagmite from the Wierna Cave. The corresponding shift of the uranium-thorium age is much smaller *i.e.* by *ca.* 10 thousand years. In such a situation, all radiocarbon ages of speleothems older than 20–25 thousand years should be treated with caution. The examples in Fig. 9 show additionally, that the choice of material for dating is a crucial question. The speleothems with any traces of porosity, corroded and cracked are definitely not suitable for radiocarbon dating, and require special attention by interpretation of dates obtained with the uranium-thorium method.

METHOD OF CONSTRUCTION AND ANALYSIS OF GROWTH FREQUENCY CURVES OF CAVE SPELEOTHEMS

A growth of individual speleothem may be disturbed by local factors *e.g.* changes of water circulation, burying with sediments, which may be completely random in their effects. Averaging, however, growth rates of speleothems from a certain cave, we eliminate influence of local effects, and gain an information on changes of global conditions controlling crystallisation. Analysing sufficiently large population of dates we may estimate distribution of ages of speleothems (frequency curve, often called as 'pdf curve'), which represents past variations of amount of calcite crystallising in caves. After first attempts to construct such curves, one realised that crystallisation of speleothems in caves in middle latitudes was not continuous process. It has also been noted, that the dates from the upper Pleistocene clustered within interglacials and within warm and humid interstadials. For that reason, speleothems have been accepted as a very good tool for studies of past climatic changes.

Mechanism of speleothem growth and its relation with climatic conditions

Speleothems formed in deep parts of caves have become important material in the Quaternary research long ago. This is due to a possibility of their precise dating (see Ivanovich, Harmon 1982), and due to number of types of palaeoclimatic data they record (Atkinson *et al.* 1978, Harmon *et al.* 1977, Gascoyne 1992, Gascoyne *et al.* 1983). The main process leading to crystallisation of speleothem is an escape of gaseous CO_2 when the solution saturated with carbonates enters the cave (White 1976). It is caused by a difference between partial pressures of CO_2 in soils and in cave's air. The major source of CO_2 in infiltrating water is decomposition of organic matter and root respiration in soils. The content of CO_2 in water infiltrating to a cave depends on mean annual temperature in the region (Drake, Wigley 1975). It is because intensity of biological processes at the surface is mostly controlled by temperature (Drake 1980). Brook *et al.* (1983) did show a role of general humidity and pointed out possibility of model simulation of soil CO_2 content in relation to intensity of modern evapotranspiration. The content of CO_2 in soils depends also on type of vegetation cover (Grunn, Trudgill 1982). Hence the cave water infiltrating from forested surface contains more CO_2 than that infiltrating from meadows. Therefore, in mountain regions infiltrating waters recharged in areas situated below the upper tree line, are richer in CO_2 than the waters recharged on alps (Ford 1971).

The above mentioned relationships have become the basis for considering frequency of speleothem growth as a palaeoclimatic indicator. During cold and dry climatic periods, the production of soil CO_2 declines due to weakening or extinction of biological processes (Van Cleve, Sprague 1971, Poole, Miller 1982), and it may cease totally when the area is

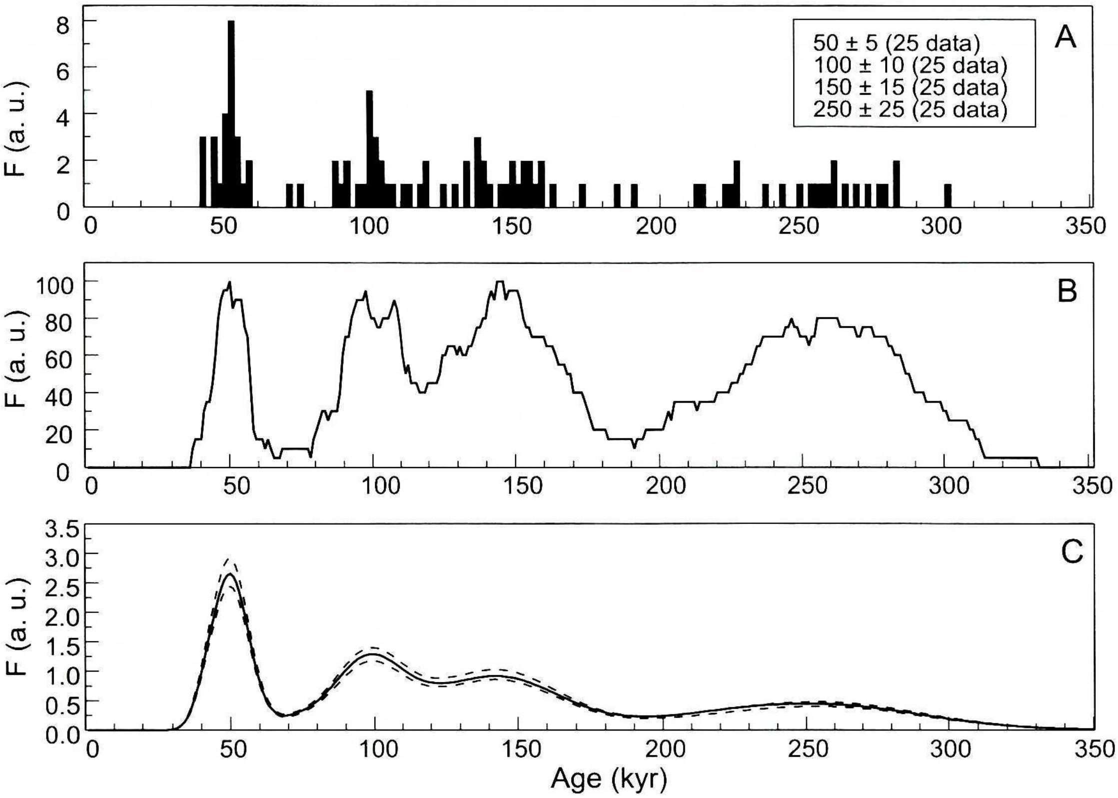

Fig. 10. Comparison of different modes of graphical presentation of dates – an example for the test data set. **A** – histogram; **B** – method of weighted distributions (Hennig *et al.* 1983); **C** – frequency curve.

covered by ice. Simultaneously, development of permafrost may disable inflow of water to a cave. In effect, growth of speleothems is slowed down or it ceases completely. On the contrary, in warm and humid periods biological activity is intensified, which increases production of soil CO_2, and stimulates rapid growth of speleothems.

First attempts to use the growth frequency of speleothems as a palaeoclimatic indicator were not meaningful, because of small number of available results of dating (Harmon *et al.* 1975, Atkinson *et al.* 1978). The quality of results was then improving with increasing number of accumulated dates, and with progress of methods of their analysis.

The test data: generation of random dates of known probability distribution

The various methods of construction and analysis of speleothem growth frequency curves will be described in further sections of this chapter. To facilitate their comparison, they will be illustrated with exemplary results of analysis of test data. The sets of test data have been created by random generation of dates of known probability distribution.

Using generator of random numbers of normal distribution the set of 100 dates has been created. These dates came from four sub-populations:

- 25 random dates from sub-population 50±5 kyr,
- 25 random dates from sub-population 100±10 kyr,
- 25 random dates from sub-population 150±15 kyr,
- 25 random dates from sub-population 250±25 kyr.

Accuracy of dating has been set to 10%. For each randomly generated 'age', the $^{230}Th/^{234}U$-activity ratio has been calculated, together with corresponding error. The $^{234}U/^{238}U$-activity ratio has been set to 1.000±0.004 (the typical accuracy of measurement). In case where problems required illustration with real data (*e.g.* when different accuracy of dates was desirable), the results from the Carpathian caves were used as an example.

Methods of graphical presentation of results of dating

Histogram

In first works describing variations of growth frequency of speleothems, Geyh (1970) analysed histogram of radiocarbon dates. At that time this was a standard method of comprehensive analysis of such data, used not only for dates of speleothems. After great number of uranium-thorium dates has been collected, similar analyses covered the whole period of the last 350 thousand years. Consequently, in many works, analyses of such histograms were used to reconstruct climatic changes (Harmon *et al.* 1977, Hennig *et al.* 1983, Gascoyne 1980). In construction of histogram, each individual date is represented by bar of the same area and shape. Exemplary histograms of the test set of data are shown in Fig. 10A. Histogram of the set of real results is presented in Fig. 11B. As one can see, regardless its accuracy, each result is represented by an equal surface. It means, that the dates 100±10 kyr and 100±50 kyr have the same contribution to the combined histogram, though their significance is much dif-

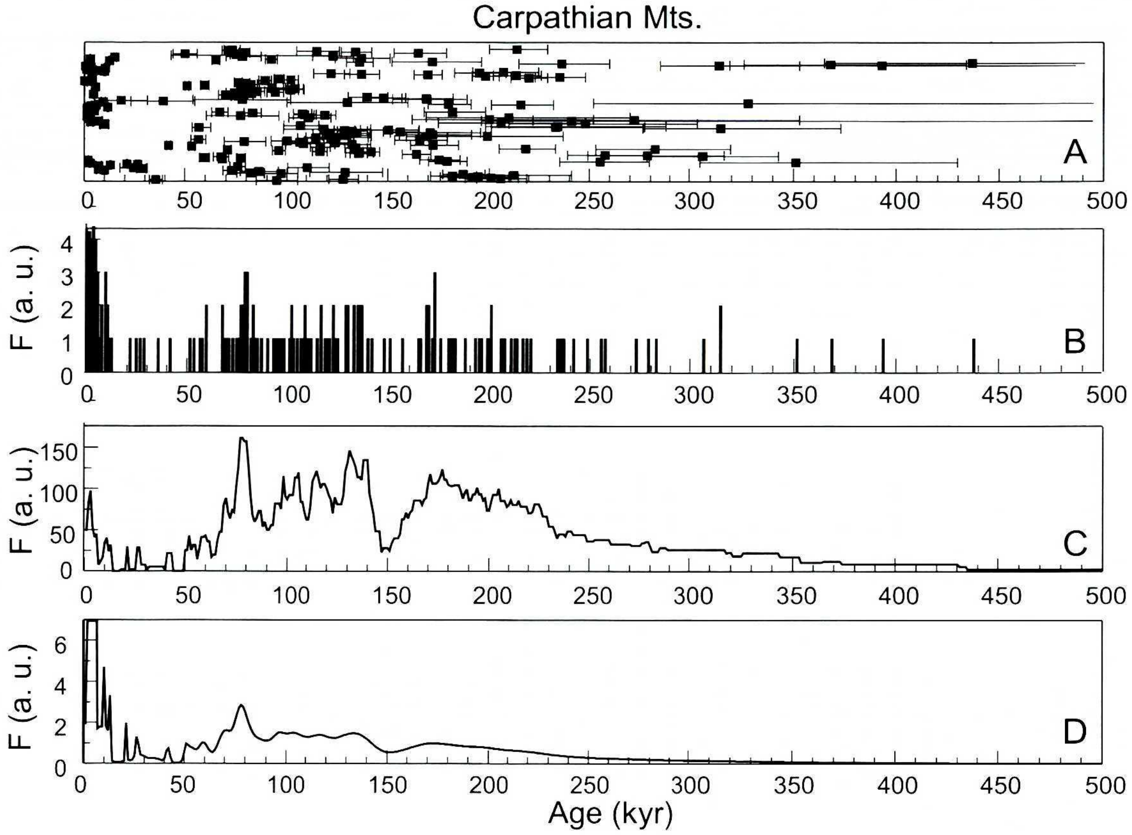

Fig. 11. Graphical presentations of ages of speleothem from the Carpathians, using different presentation modes. **A** – results and error bars; **B** – histogram; **C** – weighted ditributions (Hennig *et al.* 1983); **D** – frequency curve.

ferent. In some works, the results with different errors were marked with different hatches. That, however, had not helped much, and another methods of presentation have been searched for.

Weighted distributions

First attempt to take into account the accuracy of date in construction of combined growth frequency distribution has been made by Hennig *et al.* (1983). These authors collected all available results of uranium-thorium dating of cave speleothems and travertines. They analysed 805 dates: 664 from cave speleothems and 141 from travertines. Each individual date was represented by a rectangle with a base comprised in the range: age±error and a height dependent on relative accuracy of the date (age/error). An example of combined distribution of frequency of dates, obtained for randomly generated results, is shown in Fig. 10B. The combined distribution for the real set of dates is shown in Fig. 11C.

The obtained distributions strongly differ from the 'classical histograms' presented by Hennig *et al.* (1983). The histograms indicate high frequency of dates for relatively young ages, and distinct decline of frequency for old samples. On the contrary, the weighted distribution shows low frequency of dates for young ages. This discrepancy has been raised by Gordon and Smart (1984), who pointed out, that the triangle area representing single date was set proportional to sample age, an effect which overestimates significance of older dates.

Composing of probability distributions

Gordon and Smart (1984), besides demonstrating errors in the Hennig *et al.*'s (1983) method of weighting dates, raised also the question of proper probability distribution of the date. According to them, instead of uniform bar, one should use realistic probability distribution of age. As the simplest approach, they proposed to approximate it with the normal (*i.e.* gaussian) distribution. Moreover, Gordon and Smart (1984) realised, that real probability distribution of age determined with the uranium-thorium method differs from the gaussian one. Indeed, the distribution of really gaussian shape is that of $^{230}\mathrm{Th}/^{234}\mathrm{U}$ activity ratio, *i.e.* the variable which is directly measured. Consequently, distribution of the uranium-thorium age is skewed, and its deviation from normal distribution additionally depends on the $^{234}\mathrm{U}/^{238}\mathrm{U}$-activity ratio. Therefore, the gaussian distribution of activity ratio should be converted into distribution of age. Such a procedure is to be applied for each date, and then the construction of summary distribution is possible. If distribution for each date is normalised to equal area, the summary distribution may be interpreted as distribution of growth frequency of speleothems, expressed as number of dates per time unit. Examples of summary frequency distributions of dates are shown in Fig. 10C (for the set of randomly generated dates) and in Fig. 11D (for real dates).

The approach of Gordon and Smart (1984) has become a standard method of presentation of crystallisation frequency of cave speleothems dated with the uranium-thorium method, and it has been used in many following works.

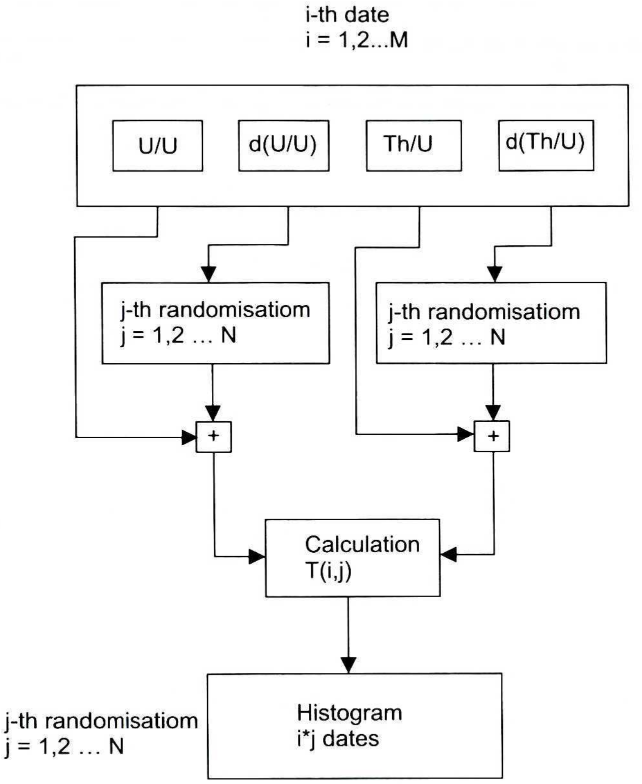

Fig. 12. Scheme of the algorithm for construction of histograms using the randomisation method.

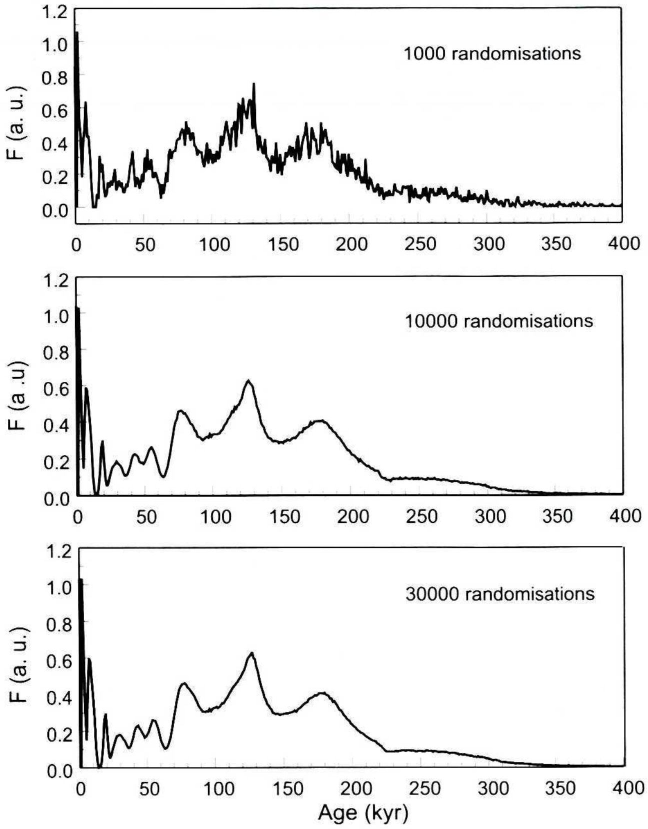

Fig. 13. Illustration of dependence of histogram's smoothness on number of randomisations.

Randomisation

Gordon and Smart (1984) found, that because of non-linear relationship between ^{230}Th/^{234}U activity ratio and age, approximation of age distribution with the normal distribution is not recommended approach. The method proposed by Gordon and Smart (1984) requires complicated calculations, in order to convert the distribution of ^{230}Th/^{234}U-activity ratio into distribution of age. That transform needs the ^{234}U/^{238}U-activity ratio to be known. Of course, distribution of age depends on uncertainty of the measured activity ratios. Unfortunately, the algorithm of Gordon and Smart (1984) does not take into account the uncertainty of the ^{234}U/^{238}U ratio. In fact, all computer programs for construction of curves of growth frequency of speleothems, which have been made accessible to me, used just the certain value of the ^{234}U/^{238}U ratio, and its uncertainty was being neglected.

Simultaneous taking into account uncertainties of determined activity ratios is possible when the growth frequency curves are constructed with the Monte-Carlo randomisation method (Hercman, Walanus 1996). That method somewhat refers to the construction of histogram. However, in this case the histogram is constructed for each individual result of dating. It represents the set of numbers (=ages) determined for large number (*e.g.* 10–50 thousand) of pairs of ^{230}Th/^{234}U and ^{234}U/^{238}U activity ratios. These ratios have normal distributions with parameters determined by the measurement.

The age of sample is calculated basing on measurements of ^{230}Th/^{234}U (denoted as Th/U in Fig. 12) and ^{234}U/^{238}U ratios (U/U in Fig. 12). The uncertainties of both values (errors of measurements) are denoted by d(Th/U) and d(U/U) respectively. The true value of activity ratio is not known exactly; we only know its probability distribution, which is normal, with the expected value equal to the result of measurement (*e.g.* Th/U) and the dispersion equal to the error of measurement (*e.g.* d(Th/U)). Due to that, we can produce large number of pairs (Th/U, U/U) using generator of random numbers of normal distribution. Such pairs are then transformed into large number of ages, and histogram of these ages is an approximation of real distribution of age of single sample. Repeating that procedure for all results of dating we obtain final histogram, which describes the growth frequency of speleothems. Due to normalisation of distributions for individual samples we may still interpret the final result as the number of dates per time unit. The degree of 'smoothing' of histogram (Fig. 13) depends on the number of generated pairs Th/U and U/U ('N' in Fig. 12). Using sufficiently large number of generations we may obtain the histogram which is comparable with curves obtained with other methods.

Comparison of growth frequency curves obtained with different methods

Differences between the growth frequency curves constructed with the most common methods are shown in Figs. 11 and 14. Fig. 14 presents curves obtained for the set of test data. There, the curves obtained for different errors (5%, 10% and 20%) were compared.

On the frequency curve shown in Fig. 14C one can see

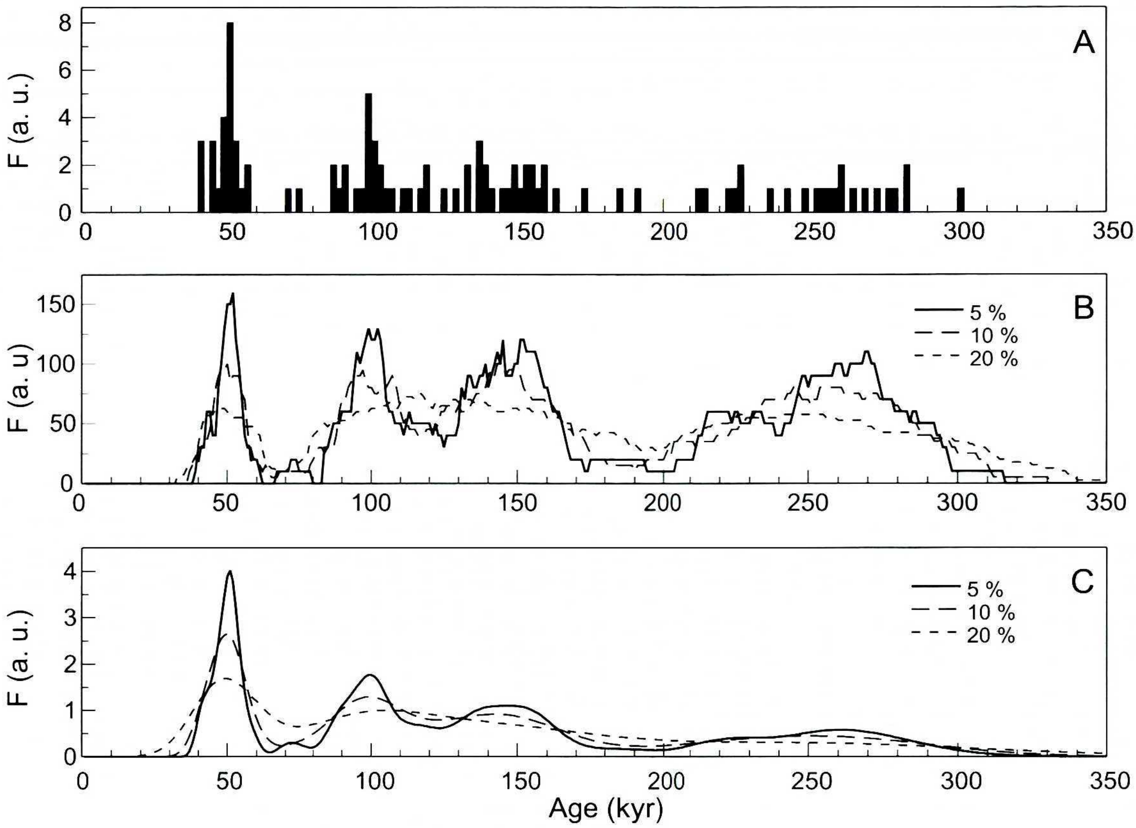

Fig. 14. Graphical representation of populations of dates (the test data) of different accuracy. **A** – histogram; **B** – method of weighted distributions (Hennig *et al.* 1983); **C** – frequency curve.

the relationship between accuracy of result and its representation. The dispersions of individual distributions differ from one another, but the areas of all distributions are the same (the 'heights' and 'widths' of distribution are inversely proportional to each other). With lower accuracy of dates, the record becomes less readable, or completely indistinct when individual dates do not differ from each other significantly (*cf.* the fragments of curves in Fig. 14C for older age and lower accuracy).

In the presentation proposed by Hennig *et al.* (1983) the area representing individual result is proportional to the age (Fig. 14B). This overestimates influence of older samples on the overall course of the curve. In the histogram (Fig. 14A) all rectangles representing dates are identical, irrespectively of accuracy of the results. The effects discussed above are also visible from comparison of curves obtained for the real set of dates (Fig. 11).

Analysis of the crystallisation frequency curve

Before using the growth frequency curve as a record of palaeoclimatic changes, one must consider several questions. First, one should decide whether to use all available dates or to select them before curve construction (*e.g.* according to accuracy of dating). Second, one has to ensure that the features of the curve are not an artificial effect of improper selection of samples. Last, one should assess the significance of features (maxima and minima) of the obtained curve. All these questions are the matter of analysis of the growth frequency curves.

The question of sample selection

The first question concerns selection of samples for dating and construction of the curve. Each result of dating can be presented in form of probability distribution of the age. However, the distribution obtained for single date does not carry information on growth frequency of speleothems. One can only say, that in a given period and in the particular area the conditions were suitable for crystallisation of speleothems. No information on the duration of that period is available.

Population of dates, which can be used in construction of the 'pdf' curve recording palaeoclimatic changes, must fulfil several conditions. Among others, the dates must cover the whole time range of interest. It is of course impossible to conclude about the events from 150 kyr ago, if one dated only speleothems younger than *e.g.* 60 kyr. Additionally, number of available dates must be sufficiently large. In case of too few dates, the features on the 'pdf' curve reflect just the selection of samples, and do not record changing climatic conditions. The question if we dispose sufficient number of dates, can be checked by comparison of 'pdf' curves obtained after elimination of significant number of data from the original set.

If we randomly eliminate *e.g.* 40% of dates from the original data set, and compare the resulting 'pdf' curve with the curve for the full set, we may ascertain if the maxima of the curves are stable. If the maximum is not preserved after elimination, we may guess that the number of dates is insufficient, or our data do not cover the whole time range densely enough. An example of comparison of the 'pdf' curves for

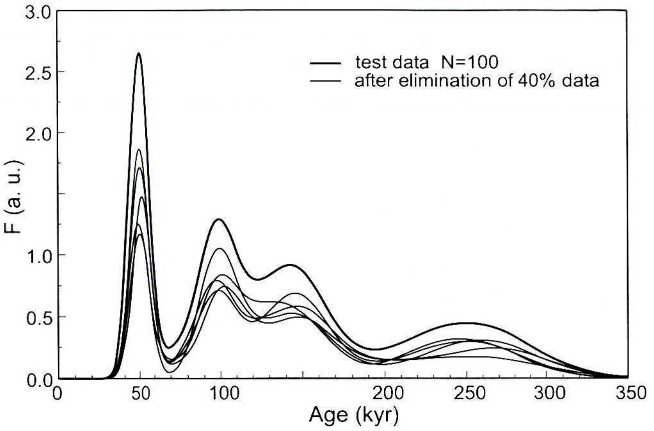

Fig. 15. Frequency curves obtained for the full set of test data (thick line), and after elimination of 40% of data (thin lines).

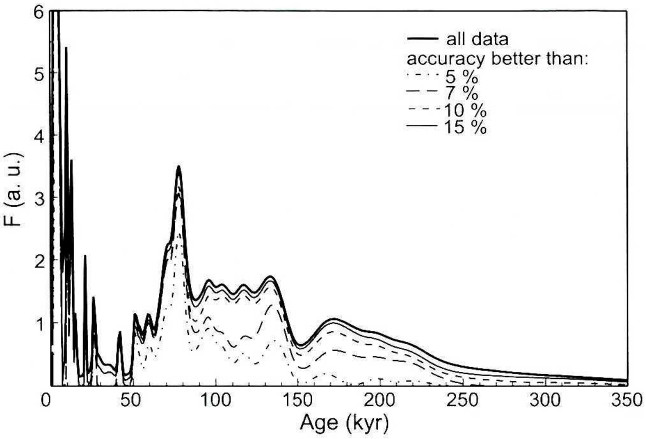

Fig. 16. Frequency curves obtained using selection of dates according to their uncertainties.

the test data is shown in Fig. 15. Here, the growth frequency curve for the full set of dates is compared with 5 curves obtained after random elimination of 40% of dates. As one can see, after the elimination the maxima are still preserved. This allows us to say that the used set of test data is sufficiently large.

The random elimination of part of the dates should be repeated many times. In the analysis of the growth frequency curves described in further sections of this work, 20 eliminations were performed.

Selection of samples

In construction of the growth frequency curves of speleothems from given region, we may deal with very diverse data. It is thus important to determine the criteria of eventual data selection.

As it has been shown in the earlier sections of this work, different methods of dating provide results of different reliability and accuracy. Therefore, in construction of the 'pdf' curve one should use the dates obtained with one method only. However, even when the results obtained with only one method are considered, they may have quite different uncertainties. If we select the data according to accuracy of dates, we obtain curves with similar positions, but different distinctness of particular maxima and minima (Fig. 16). Sample selection may be used in an initial estimation of boundaries of periods favourable for speleothem growth.

Problem of significance of wiggles of the 'pdf' curve – testing deviation from uniform distribution

The main question in palaeoclimatic interpretation of the speleothem growth frequency curve is significance of the wiggles of the curve. One should be able to distinguish significant maxima from those caused by limited accuracy of dating. One should also determine confidence interval of the obtained curve. These questions are very important, but also pretty difficult. The first attempt to solve them was made by Baker *et al.* (1993b), for analysis of growth frequency of speleothems from Northwest Europe. Baker *et al.* used *ca.* 520 dates of speleothems from caves located in Great Britain, Belgium and Germany. In order to determine significance of particular maxima and minima in the 'pdf' curve, they performed Monte-Carlo experiment. This experiment was based on analysis of random sets of dates. The number of generated dates and their uncertainties were the same as in the set of original dates.

Using random numbers' generator of uniform distribution Baker *et al.* (1993b) created 40 sets of 500 ages each. These authors assumed accuracy of each age equal to 7.5% (usual accuracy of uranium-thorium dating with the α-spectrometry technique). For each data set they constructed growth frequency curve. Using 40 such curves the authors determined 95% confidence intervals for particular maxima and minima. The periods, where the 'pdf' curve built for original dates passed beyond the confidence interval, were accepted as favourable (when the curve passed above the interval) or unfavourable (below the interval) for crystallisation of speleothems. The result of analogous experiment with the test data is shown in Fig. 17 (solid thin line).

Actually, the experiment above gives no information about significance of particular maxima and minima. The only thing we can state is that the distribution of crystallisation frequency of speleothems differs significantly from uniform distribution. If some fragments of the curve lie beyond the interval determined with the Monte-Carlo experiment, we may only say that in these periods distribution of frequency of speleothems dates was not uniform. That confirms that the climatic conditions varied in the past, and that the changing environmental parameters had significant influence on intensity of speleothem crystallisation.

One may try to perform Monte-Carlo experiments using random numbers generators of distributions different from those discussed above. However, such a method will not provide the most important – information about significance of maxima and minima on the 'pdf' curve.

Problem of significance of wiggles of the 'pdf' curve – confidence intervals of the growth frequency

Significance of particular maxima and minima of the 'pdf' curve may be assessed when confidence intervals of the growth frequency are estimated. This may be done with the 'bootstrap' (or 'bootstraping') method. In this method, simu-

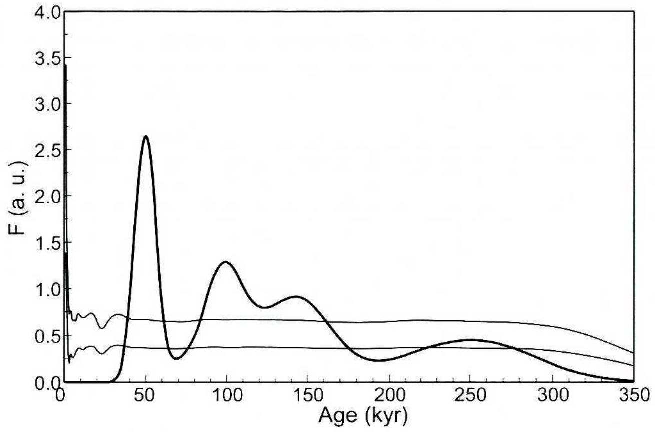

Fig. 17. 95% confidence interval determined in Monte-Carlo experiment using generator of uniformly distributed random numbers (thin solid line) for the 'pdf' of test data.

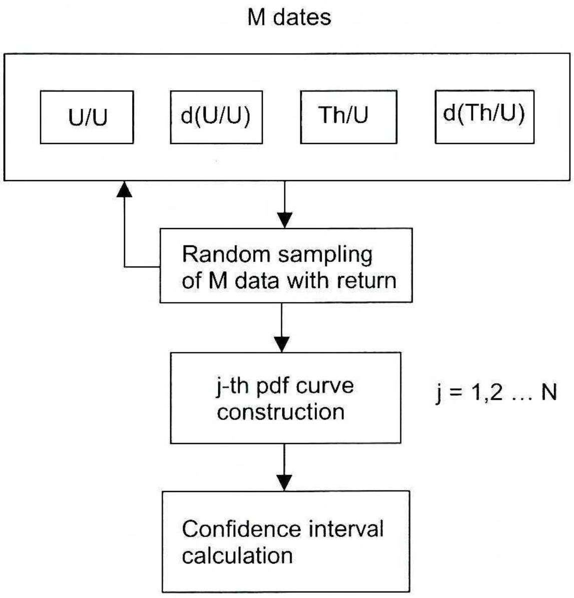

Fig. 18. Scheme of the algorithm for calculations of confidence intervals.

lations are based on original data (Fig. 18). Using the set of original dates, we create the set of 'bootstrapped data'. That set contains the dates randomly sampled from the original set. The number of samplings is equal to the number of dates in the original set, and each date is sampled from the whole set of original dates. Therefore in the 'bootstrapped' set some dates may be repeated many times, while other dates from the original set may be completely lacking (Fig. 18). For such a set we construct the 'bootstrapped pdf curve'. Repeating that procedure, one may receive large number of 'bootstrapped pdf curves', which may be used to determine the 95% confidence interval of the original curve (Fig. 19). One may interpret, that any 'pdf' curve constructed for random set of dates (of the same size) descending from the same distribution as the original data do, would fall in the confidence interval with a probability of 95%. One may then conclude that all maxima and minima in Fig. 19 are significant, as they are revealed by any curve passing within the 95% confidence interval.

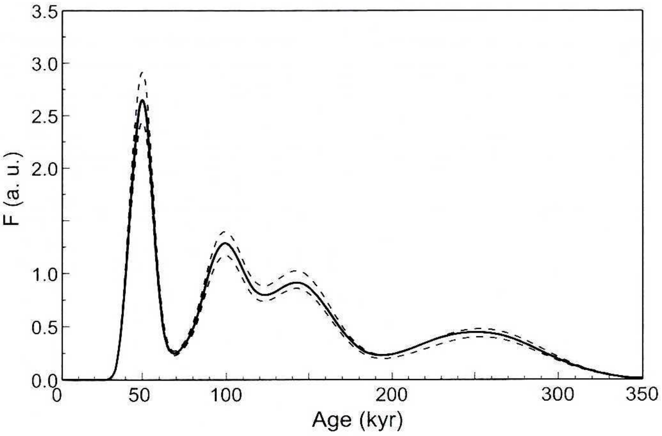

Fig. 19. 95% confidence interval of the 'pdf' curve, determined for the test data using the 'bootstraping' method.

Analysis of modality

Some other information may be obtained from analysis of modality of the 'pdf' curve. If in the past the periods favourable for growth of speleothems alternated with the non-favourable ones, one may assume that the dates should cluster in the favourable periods, with the maximum frequencies in the climatic optima of each period. Receding from the optimum, the frequency should decline until certain minimum, or complete extinction of crystallisation in the climatic pesimum. In a first-order approximation, frequency distribution of dates within individual crystallisation-favouring period may be described with the normal distribution. If so, the 'pdf' curve might be approximated as a sum of normal distributions describing growth frequency of speleothoems in the growth-favourable periods. The parameters of such distributions may then be used for description of those periods *i.e.* they estimate the most probable date of the optimum, together with its accuracy. Deconvolution of the growth frequency curve into sub-populations with the parameters well determined, has been first applied by Smart and Richards (1992). They utilised that method to determine the ages of the high sea-level periods using the uranium-thorium ages of corals. They used the method, which has been developed since the sixties (Hasselblad 1966, Titterrington *et al.* 1985).

The composite probability density function 'g' can be described as:

$$g = \sum_{j=1}^{k} \alpha_j f_j \qquad (8)$$

where: 'f_j' is the gaussian density function of j-th (= 1, 2, ... k) population, and 'α_j' is the weight of population ($0<\alpha<1$, $\Sigma(\alpha_j)=1$).

The expected values, standard deviations and weights of individual sub-populations were determined with the algorithm described by Agha and Ibrahim (1984). Using an iterative procedure, one searches for the maximum of the best-fit function 'L';

$$L = \sum_{i=1}^{m} n_i \ln g_i \qquad (9)$$

where: 'n_i' and 'g_i' denote the frequencies read from the 'pdf' curve and from the distribution given by eq. (8), respectively. To allow numerical calculations, the time span covered by distributions (10–200 kyr) is uniformly divided into 'm' intervals, and the curves are sampled with time resolution of 190/m. In practice, this method requires number of sub-populations and their initial parameters to be stated. The number of sub-populations and their approximate parameters may be read from the 'pdf' curve, and the recommended maximum difference between 'L' values in consecutive iterations is $1 \cdot 10^{-9}$. The algorithm is quick and guarantees finding of maximum of the 'L' function. The results of analysis for the test data are listed in Table 2. Here, as little as 35 iterations were sufficient to reach the difference between consecutive 'L' values $<1 \cdot 10^{-9}$.

As one can see, this algorithm may be applied to determine parameters of sub-populations in the composed 'pdf' curve. Comparison of the original curve with that combined from derived sub-populations for test data is shown in Fig. 20.

The described method has serious limitations. Here, one has to state number of sub-populations prior to the analysis. This requires an assessment of significance of individual maxima.

However, number of sub-populations can be determined with the so-called analysis of modality (Fig. 21). In that analysis we run the iterative algorithm successively for 1, 2, ... sub-populations and compare the original 'pdf' (after normalisation) with 'pdf_i' constructed basing on results of analyse. We plot the 'SERR' (sum of squared differences of 'pdf' and 'pdf_i') value as a function of number of sub-populations (k). Of course, the quality of fit improves (the 'SERR' value decreases) with increasing number of sub-populations. However, above certain number of sub-populations, further increase becomes insignificant. Moreover, the expected values of consecutive sub-populations often duplicate. As one can see, for the test data one should assume finding of 4 sub-populations (Fig. 22), in agreement with the structure of the test data. In the next step, the parameters of sub-populations can be determined.

Table 2

Results of analysis of modality for the test data set[1]

Sub-pop.	Parameters	x_0	σ_0	α_0	x	σ	α
1	50±5	30	10	0.15	50.06	5.01	0.25
2	100±10	110	10	0.35	100.00	10.00	0.25
3	150±15	140	10	0.35	150.05	15.01	0.25
4	250±25	220	10	0.15	249.98	25.00	0.25

[1] x_0, s_0, α_0 – initial values of parameters; x, σ, α – determined values of parameters

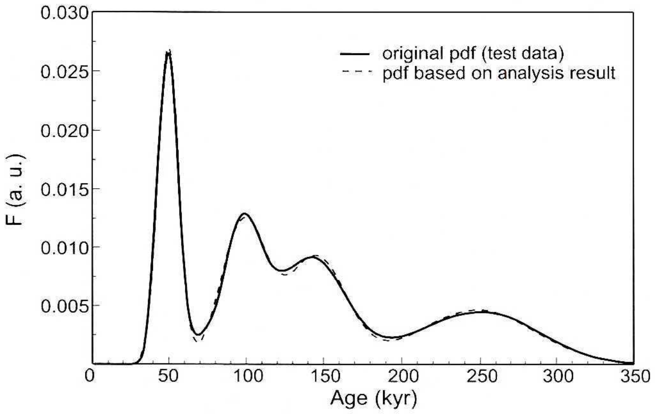

Fig. 20. Comparison of original distribution of the test data (solid line) with the frequency curve built using the determined parameters of sub-populations (dotted line).

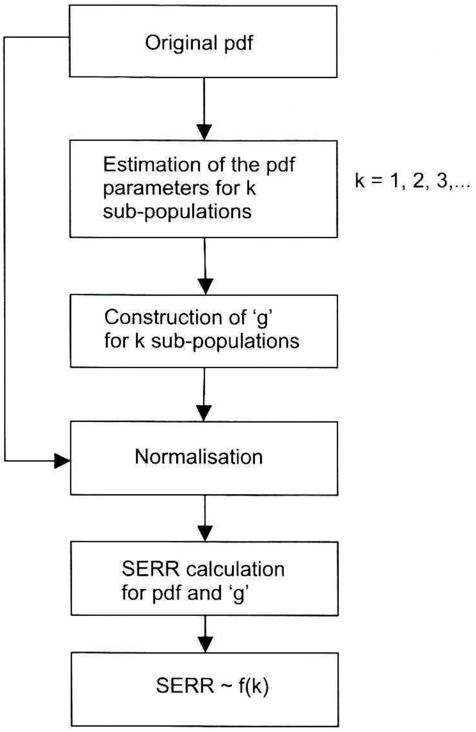

Fig. 21. Scheme of analysis of modality of the 'pdf' curve.

Another approach has been proposed by Bluszcz and Michczyński (1999). They used the 'bootstraping' method for analysis of frequency of TL dates from Polish loess. Application of 'bootstraping' for assessment the number of maxima of the curve has been described by Efron and Tibishirani (1993). The 'bootstraping' is definitely more time-consuming than the method described above.

Limitations and problems

To summarise this part, one has to stress once again that many requirements must be fulfilled by a data set, intended to be used for construction of a 'pdf' curve which would record palaeoclimatic changes. Some of these requirements have been already discussed. The importance of the others we will learn in the following sections of this work.

First, the data set must cover the whole time period under study. Moreover, number of samples in each time interval should be sufficiently large. One has to realise that the reliability of the 'pdf' curve is primarily dependent on the number of samples. When the number of samples is too small, the course of the 'pdf' curve may be influenced by se-

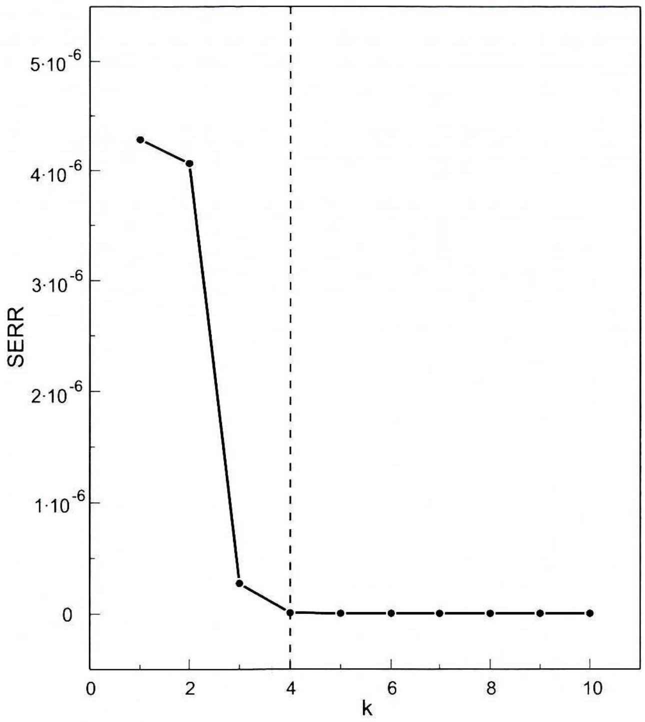

Fig. 22. Sum of squared deviations (SERR) between the original 'pdf' curve and the curve built using the determined parameters of sub-populations, as a function of assumed number of sub-populations (test data).

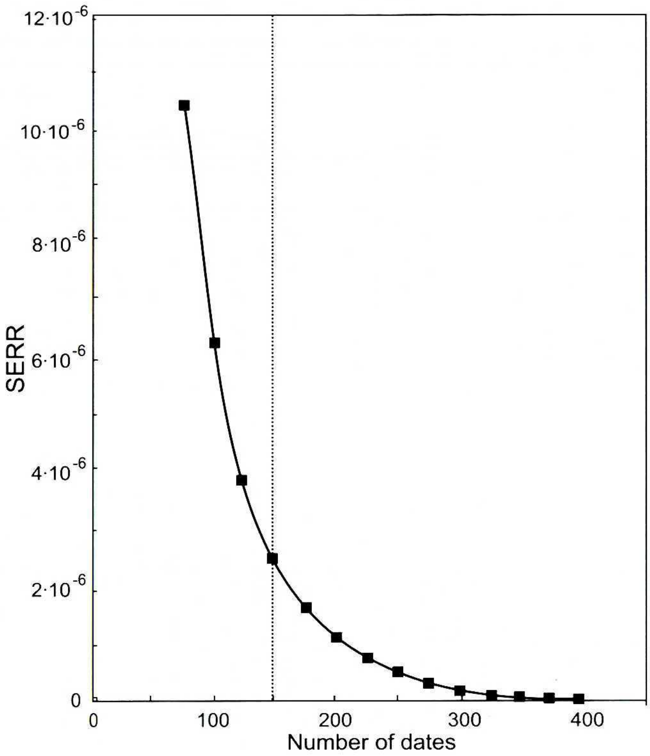

Fig. 23. Sum of squared deviations (SERR) between the test 'pdf' curve and the curve built using the different number of dates randomly selected from test data.

lection of samples itself. The minima of the curve, instead of indicating climate deterioration, would just reflect the periods the samples have not been collected from. Also the maxima might reflect just the periods where most of the selected samples come from. The 'pdf' curve describes the growth frequency of speleothems basing solely on samples physically collected. So, selection of representative samples, and sufficiently large number of samples are crucial for getting reliable record.

In order to estimate minimum number of dates needed for construction of a reliable frequency curve, a set of 1000 dates was created. The 'pdf' curve built for that set was then regarded as real distribution of growth frequency. From that set, one performed certain number of random samplings. The population selected that way was used to construct the frequency curve, and then the mean deviation (SERR) between the original (*i.e.* that constructed for 1000 dates) and secondary (constructed for the selected population) curves was calculated. The relationship between that deviation and the number of sampled dates is shown in Fig. 23. Of course, the higher the number of dates, the smaller is deviation between both curves. Somewhat arbitrarily, the minimum size of population has been chosen by a condition, that addition of 25 new dates should not decrease the deviation by more than $1 \cdot 10^{-6}$. With such a condition, the minimum number of dates has been established to 150.

The way of sample selection may cause other problems, too. Quite often, from one generation of speleothem (*e.g.* of continuously growing flowstone) two samples are taken for dating, *i.e.* from the top and from the bottom part. This, with no pre-selection of dates, may lead to appearance of artificial, not realistic bimodality. In such a case, the two maxima do not correspond to climatic optima, but they rather reflect the onset and termination of period favourable for deposition of speleothems. The trough between the maxima may then occur at climatic optimum itself. Such a risk is especially significant if one uses published data, the full documentation of which is not always available.

At the end, one more aspect of sample selection must be raised. If the 'pdf' curve is intended to reflect palaeoclimatic changes, for its construction only samples descending from region of uniform 'climatic history' can be used. As we shall see, regions situated relatively close to each other may have quite different palaeoclimatic records.

ANALYTICAL MATERIAL

In 1993 an idea to compare the growth frequency curves of cave speleothems in the North–South transect of Europe has been raised. This idea was a motive of my practice in the Uranium-Thorium Laboratory, Bergen University in Norway. I had there a possibility to learn the procedure of dating, and to perform first U-Th analyses of speleothems from Poland and Slovakia. My main goal was to create the growth frequency curve of speleothems from Polish territory. During the practice in Bergen, and during three-years of work in the Uranium-Thorium Laboratory, Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, I performed substantial number of analyses of cave speleothems. The main regions of my interest were the karst areas of Poland, Slovakia and Moravia (Czech Republic). At the moment of writing this work, the data set consisted of 442 uranium-thorium dates of cave speleothems from Poland, Slovakia and Czech Republic (Table 3). Thirty four 'finite' dates have

Table 3

Numbers of U-Series dates of speleothems used in the growth frequency analysis

Region	Performed analyses	Dates used in construction of the frequency curves				
		All dates	Age 10-200 kyr	Own dates (obtained by the author)		Collected from literature
'Uplands'	138	105	92	Holy Cross Mountains	18	1
				Kraków–Częstochowa Upland	59	16
				Sudetes	20	1
				Total	87	18
Tatra and Pieniny Mountains	123	117	97		101	16
Low Tatra Mountains	98	73	62		73	
Moravian Karst	83	47	27		47	
Total	442	342	278		308	34

been published by other authors (Głazek 1984, 1985, Duliński 1988). These results have been recalculated myself, with the procedures included in the program 'UranoTor' routinely used in the U-Th Laboratory in Warsaw.

From the set of all dates, I rejected the results beyond the range of the uranium-thorium method, the results with low yield of chemical separation of uranium or thorium, and the results with significant content of non-radiogenic thorium. The obtained set of dates has been used for construction of crystallisation frequency curves of selected regions.

When making regional division, two conditions have been considered:

a) number of results from single region could not be lower than 150 (cf. the section concerning methodology of construction and analysis of 'pdf' curve. With further accumulation of dates, more detailed analysis for smaller areas will become possible;

b) the selected region should have rather uniform 'climatic history' during the last 200 thousand years (*i.e.* during period covered with the analysed dates).

The full analysis has been performed according to the following scheme:

a) test of random elimination of 40% of dates;

b) determination of confidence interval of the 'pdf' curve;

c) analysis of modality of the 'pdf' curve;

d) determination of parameters of sub-populations (maxima of the 'pdf' curve), corresponding to periods favourable for deposition of speleothems;

e) correlation of distinguished periods with other palaeoclimatic records.

As the initial parameters of sub-populations, used in the detailed analysis of maxima, one adopted the values giving the best fit, except for the standard deviations and weights, which were set equal for all sub-populations.

Basing on analysis of stability of the record, performed by means of elimination of 40% of data, the time period of frequency analysis has been constrained to the interval 10–200 thousand years. An attempt to analyse the climatic variability in the Holocene would require accumulation of much more dates from that period. In turn, low accuracy of dates of samples older than 200–250 kyr makes particular features of the 'pdf' curve not readable.

Global palaeoclimatic records used for correlation

In view of lack of generally accepted division of younger Quaternary in Poland, I decided to correlate the 'pdf' records with the global climatic records, represented by oxygen isotope curves. I used the SPECMAP curve (Imbrie *et al.* 1984, Martinson *et al.* 1987), and the record of oxygen isotopic composition of calcite from Devils Hole (USA) (Winograd *et al.* 1992). Additionally, I used the data on insolation (July, 52°N) (Berger, Loutre 1991), and the records of palaeotemperatures and precipitation derived from palynological studies in France (Fauquette *et al.* 1999). The latter ones cover only the last 140 kyr. The course of these curves for the last 300 thousand years is shown in Fig. 24. In general, all curves are similar to one another. One may observe correlation between main maxima and minima of the curves. However, in a more detailed comparison a few differences should be pointed out. Despite one can demonstrate correlation between maxima in the insolation curve and in the other records (Fig. 24) the variations of the latter ones are much smoothed. Climatic variations are a reaction to a complex set of factors, the insolation being only one of them. In the oxygen curves (Figs. 24A and 24B) one can see periods of 'better' and 'worse' conditions, which usually encompass a few insolation cycles. Within those periods, some fluctuations occur, which have similar length but distinctly smaller amplitude than the insolation changes. Differences between reaction to the climatic changes in the oceanic and terrestrial areas also

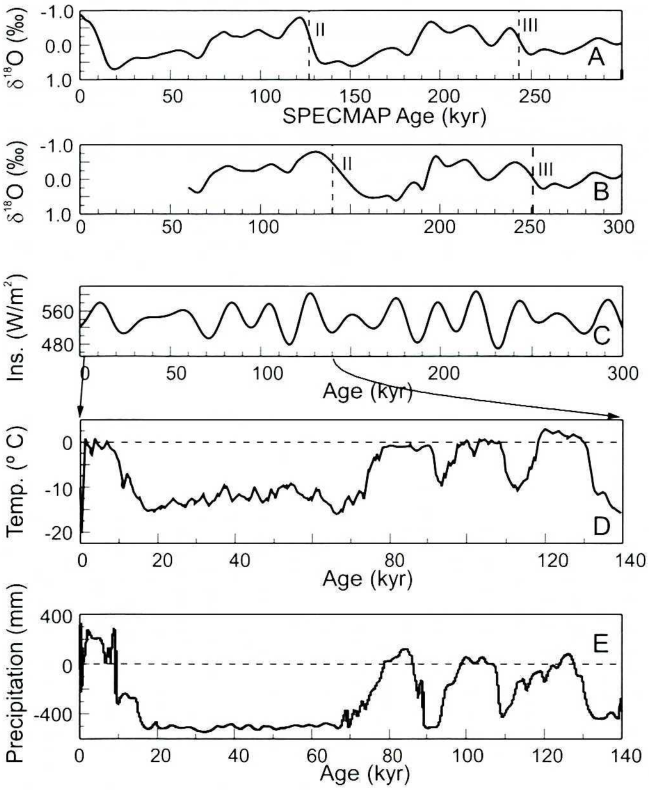

Fig. 24. Comparison of records of climatic changes for younger Quaternary. **A** – oxygen isotopic composition in shells of foraminifera (Martinson *et al.* 1987); **B** –oxygen isotopic composition of calcite from Devils Hole (Winograd *et al.* 1992); **C** – insolation of July at 52° N (Berger, Loutre 1991); **D** – temperature (with respect to the present value) based on palynological research (Fauquette *et al.* 1999); **E** – annual precipitation (with respect to the present value) (Fauquette *et al.* 1999).

occur. They are visible from comparison of the oxygen isotope curves with the records of palaeotemperatures (Fig 24D) and precipitation (Fig. 24E) from western and central Europe, which show much stronger fluctuations than the oxygen curves. The double climatic deterioration within the 5th oxygen isotopic stage (at *ca.* 90 and 115 kyr BP) is more distinctly reflected in the terrestrial records than in the oceanic records.

The next problem is the differences between the two oxygen curves (Figs. 24A and 24B). These curves have been obtained in completely different ways.

The SPECMAP curve is interpreted as a record of the ice-sheet volume changes. It has been obtained from measurements of oxygen isotopic composition in the shells of benthic foraminifera. The time scale for that curve does not rely on direct dating on the analysed marine cores. That scale has been created by correlation of 3 levels of known (= assumed) age in 5 cores, and by interpolation in between. The detailed time scale has been established by iterative fitting of the oxygen records to the well-known record of Earth's surface insolation.

The curve DH11 describes changes of the oxygen isotopic in the incrusted calcite from Devils Hole in Nevada, USA. For the core 36-cm long, the oxygen isotope analyses have been performed in 285 samples, situated 1.26 mm apart from each other. The time scale has been based on 21 uranium-thorium dates, obtained with the mass-spectrometry technique. Additionally, 14 analyses with the alpha-spectrometry technique have been made. Variability of oxygen isotopes reflects changes of isotopic composition of meteoric waters. They may be interpreted as the changes of winter-spring mean temperatures (that is the season of maximum precipitation in this area).

Both oxygen curves demonstrate relatively rapid transitions between glacials and interglacials (Fig. 24). The transitions between interglacials and glacials were more gradual and usually they had a multistage character. However, the detailed record of these changes is different in both curves. In the time interval of interest (the last 200–300 thousand years), a few differences are worth pointing out. The transition between the penultimate glacial and the last interglacial (correlated with the beginning of the 5th oxygen isotope stage, the so-called Termination II), is dated on the SPECMAP curve to 128±3 thousand years ago, while the DH11 curve dates that event to 140±3 kyr BP. Also the onset of the earlier interglacial (Termination III) is dated differently by the both curves: 244±3 (SPECMAP) and 253±3 (DH11) kyr BP. According to SPECMAP, the Termination II correlates with the maximum insolation, while the same Termination at the DH11 curve coincides with declining insolation. The maximum of the insolation curve is correlated with the period of the most rapid ice melting. According to the SPECMAP curve, the climatic pessimum of the 6th stage occurred at *ca.* 135 thousand years ago. However, reconstruction of the sea-level changes (being an effect of development and extinction of the ice-sheets) claims, that at that time the sea level was already similar to the modern one. According to the DH11 curve at that time (*i.e.* 135 kyr BP) interglacial conditions have already prevailed. Also the length of the 5e isotopic stage (Eemian interglacial) is different in both curves. According to the SPECMAP curve the Eemian lasted 11 thousand years, while the DH11 record determines its duration to *ca.* 20 thousand years. The glaciohydroisostatic model (Lambeck, Nakada 1992) suggests that the 5e stage was at least 15 thousand years long.

Direct comparison of time scales of the both oxygen curves is shown in Fig. 25. The largest time lags occur in periods between 110–200 kyr, 320–400 kyr, and 420–560 kyr BP (Fig. 25B). These time lags are significant, so I decided to correlate speleothems growth frequency records with both oxygen curves, independently. Since the DH11 curve covers the interval between 60 and 560 thousand years ago, correlation for the youngest period (*i.e.* between 10 and 60 kyr) was possible with the SPECMAP curve only.

Crystallisation frequency curves of speleothems from the caves in southern Poland

At first, I made an attempt to construct the growth frequency curve for Poland (Fig. 26A). The dated speleothems descended from all the karst regions in southern Poland. Because one the main regions is that of the Tatra Mountains, where local glaciers are formed, I compared the records from Tatra and from the other regions (Kraków–Częstochowa Upland, Holy Cross Mountains, Sudethes). It appeared that the curve obtained for the other regions (called below as 'upland

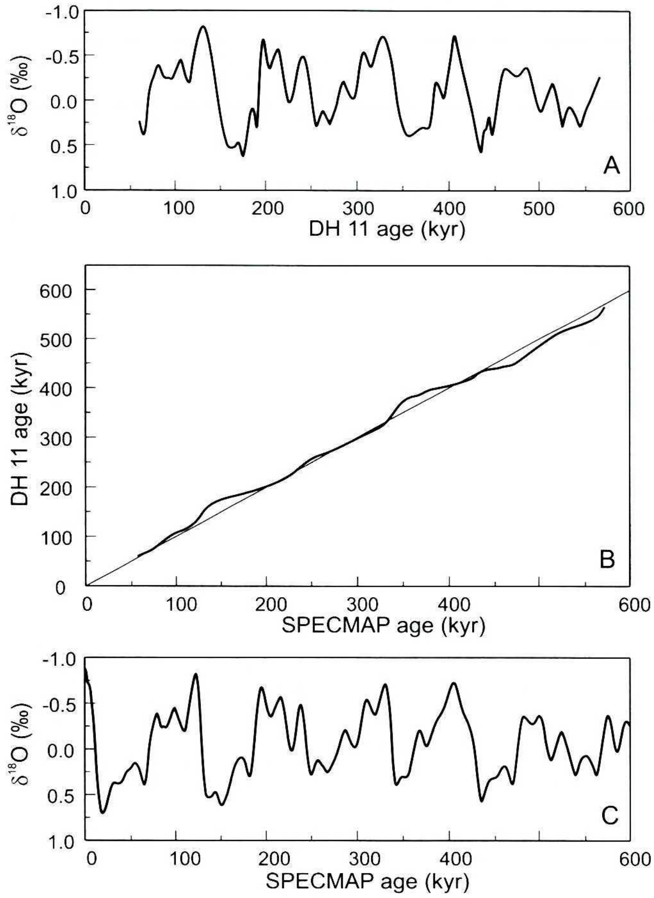

Fig. 25. Comparison of records of oxygen isotopic composition in marine cores (**C**) and in calcite from Devils Hole (**A**) for the last 600 thousand years. Direct comparison of the time scales of both records is shown in part **B**.

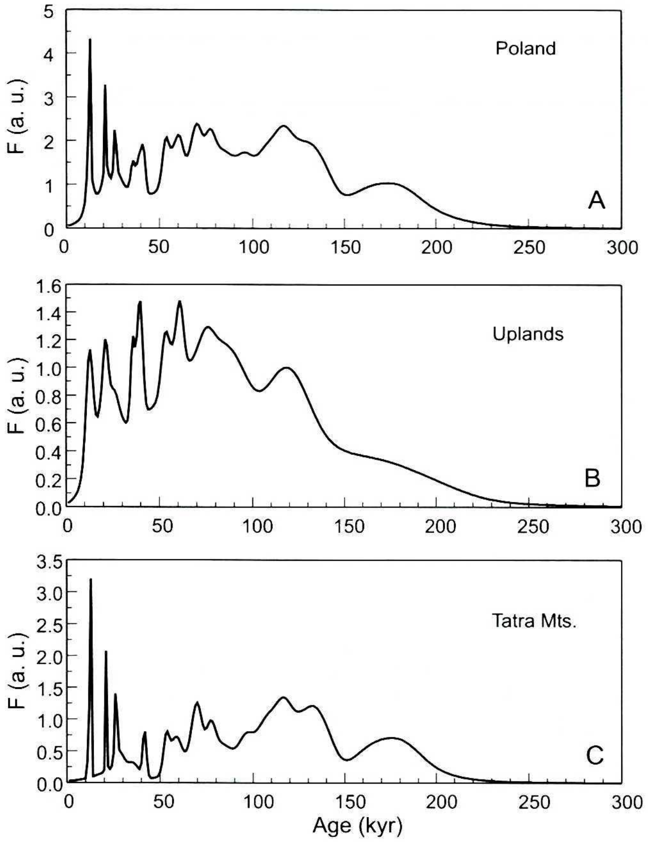

Fig. 26. Curves of crystallisation frequency of speleothems from whole Poland (**A**), Polish karst areas excluding Tatra Mts (**B**), and the Tatra Mountains (**C**). Only the dates between 10 and 200 kyr were considered.

curve') deviates from the summary record for Poland and Tatra (Fig. 26). The upland record is distinctly less clear than the Tatra one. The Tatra curve indicates larger diversity of speleothem crystallisation conditions; especially the periods non-favourable for deposition are expressed more distinctly. The difference between the Tatra and Upland records may be caused by two reasons.

First, it may be due to different accuracy of dating of speleothems from different regions. Lower accuracy makes the record smoother. Mean uncertainty of speleothem dates from the uplands is ca. 17%, while for Tatra it is only 9% (Fig. 27). Here, the main factor limiting accuracy of dating was concentration of uranium, usually very low in the uplands (in order of a few hundredths of ppm). Quite often, low uranium concentrations made the speleothems not worth dating. Minimum level of uranium concentration, which warrants reliable dating, is estimated to 0.03 ppm. In the speleothems from the uplands, especially from the Kraków–Częstochowa Upland, concentrations lower than that level are encountered quite often. This requires high caution during the chemical preparation, and long alpha counting times. Consequently, accuracy of dates is lower than for the other regions.

The second reason of disagreement of the frequency curves might be differences of climatic conditions. The karst regions of southern Poland, during the last 200 thousand years, were situated far from the Scandinavian ice-sheet margin, even in periods of its maximum extent (minimum 200–300 km). That distance was large enough to provide relatively mild climatic conditions, mere weakening of speleothem growth, and producing local short lasting breaks in crystallisation, even during the glacial maxima. That made the record continuous, and there the climatic pessima are marked with gentle minima in the frequency curve. In the Tatra Mountains, influence of the distant ice-sheet was superimposed on effects of local glaciers. These effects would have distinctly stronger influence on speleothem crystallisation, reflected in sharper features of the curve.

The summary curve for Poland is dominated with the distinct record from Tatra Mountains. This is visible from comparison of parameters of the deposition favourable periods (Table 4).

The example from Poland clearly shows the necessity of thorough consideration of region characteristics, where the samples to be combined in one curve come from. One of basic requirements, pointed out earlier, is that the speleothems should descend from regions of similar climatic history. In case of Poland, this excludes combination of speleothems from Tatra and from the other regions into one curve.

The problems discussed above stimulated deeper consideration of regional diversity of crystallisation frequency records of cave speleothems. As the minimum number of dates required for construction of reliable 'pdf' curve has

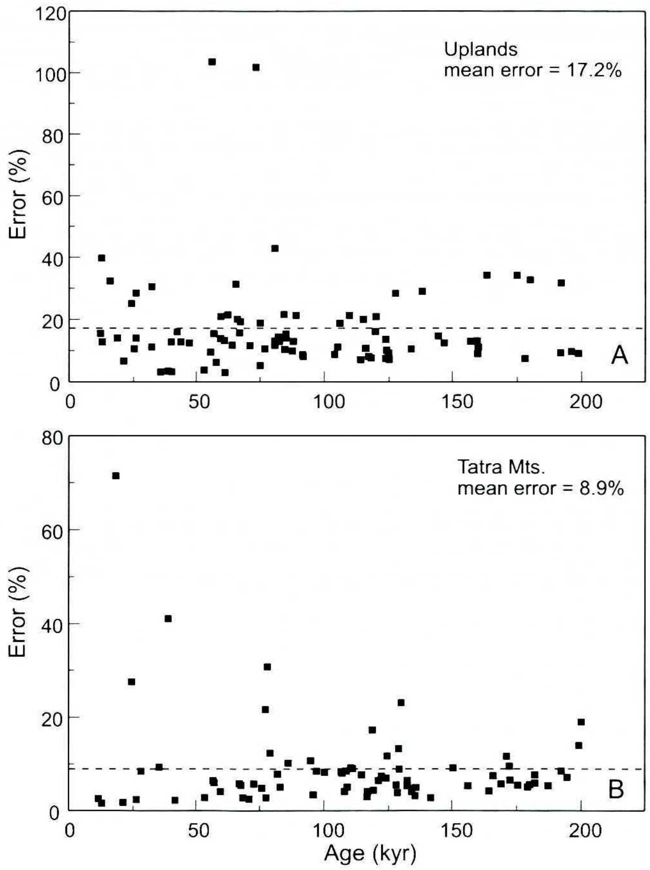

Fig. 27. Relative accuracy of U-series dates of speleothems: **A** – from Polish karst areas excluding Tatra Mountains; **B** – from the Tatra Mts.

been assessed to 150, the necessity to enlarge the data set appeared.

Regarding climatic conditions in Europe, it seems possible to distinguish 3 roughly parallel zones. The first zone encompasses North-European lowlands. That is the region, into which the Scandinavian ice-sheet extended during glacial maxima. Unfortunately, no karst area exists in that region, so it is excluded from analysis. The next zone is the belt of uplands and low mountains of Central Europe, including also the karst areas of Southern Poland (except of Tatra Mountains). The third zone is the Carpatho-Alpean massif, which probably constituted a climatic barrier in the Quaternary. That massif underwent local glaciations, what distinguishes it from other regions. The dates of speleothems from the above-mentioned zones were collected from literature. Only dates accompanied with complete data on U and Th isotope concentrations, and on sample localisation, were used. In such cases it was possible to recalculate the dates using uniform procedures of age determination, to assess reliability of results and to avoid using of multiple dates from the same samples. So collected dates, joined with own results constitute the basis to construct the regional curves. Numbers of results from particular regions are shown on a map in Fig. 28.

The results from Poland, Slovakia and Czech Republic have been divided into 2 groups (Table 3). The first one encompasses analyses of speleothems from caves in the Western Tatra and Low Tatra Mountains. The frequency curve built from these dates will further be called the 'Carpathian curve'. It would be interesting to compare conditions at the northern and southern slopes of the Tatra massif. Perhaps it would give a basis for assessment of the role of the climatic barrier, which the Tatra massif constituted in the past. However, small amount of available dates precludes, for the moment, separate analysis of crystallisation frequency in both areas. One may hope that growing amount of data will enable such comparison in the near future.

The second group encompasses analyses of speleothems from regions situated north of the barrier assigned with the Carpatho-Alpean massif, *i.e.* from Kraków–Częstochowa Upland, Holy Cross Mountains, Sudetes, Moravia, Germany and Belgium. The frequency curve built from these samples

Table 4

Results of analysis of crystallisation frequency curves of speleothems from Southern Poland

Poland (combined)			'Uplands'			Tatra Mountains		
X	σ	w	X	σ	w	X	σ	x
12.5	2.0	0.039	12.7	3.4	0.045	12.8	0.4	0.030
23.5	4.2	0.069	23.6	4.8	0.081	24.7	3.3	0.028
34.8	3.6	0.031	38.5	3.8	0.086	28.2	10.6	0.067
41.1	3.2	0.041	48.0	2.3	0.023	41.7	0.9	0.011
53.2	3.4	0.054	53.3	2.2	0.037	53.6	2.0	0.025
60.8	2.9	0.047	60.7	3.6	0.077	59.5	2.8	0.037
69.5	3.4	0.065	74.0	5.8	0.108	69.1	3.0	0.061
78.8	4.4	0.074	89.5	6.9	0.099	78.2	4.4	0.071
93.7	7.4	0.113	116.3	11.1	0.121	96.6	7.7	0.109
113.4	7.3	0.135	140.9	45	0.322	115.4	7.1	0.170
131.4	7.0	0.091				133.5	6.8	0.140
167.7	27.6	0.240				174.0	19.8	0.250

X: expected value of age of climatic optimum (kyr BP); σ: standard deviation of X (kyr BP); w: weight of particular sub-population in the total curve

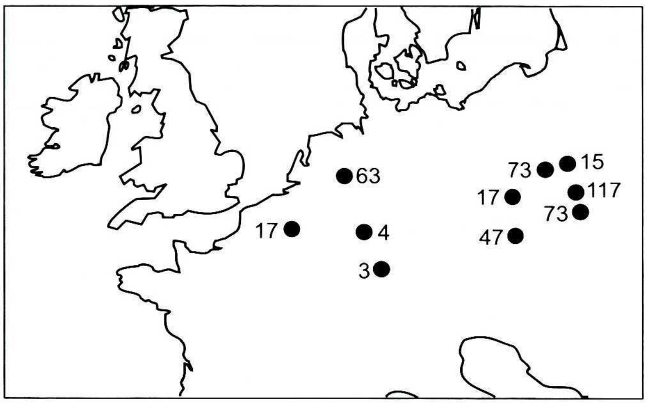

Fig. 28. Map showing the areas where the cave speleothems used in analysis came from. Numbers of dates obtained for speleothems from particular areas are denoted.

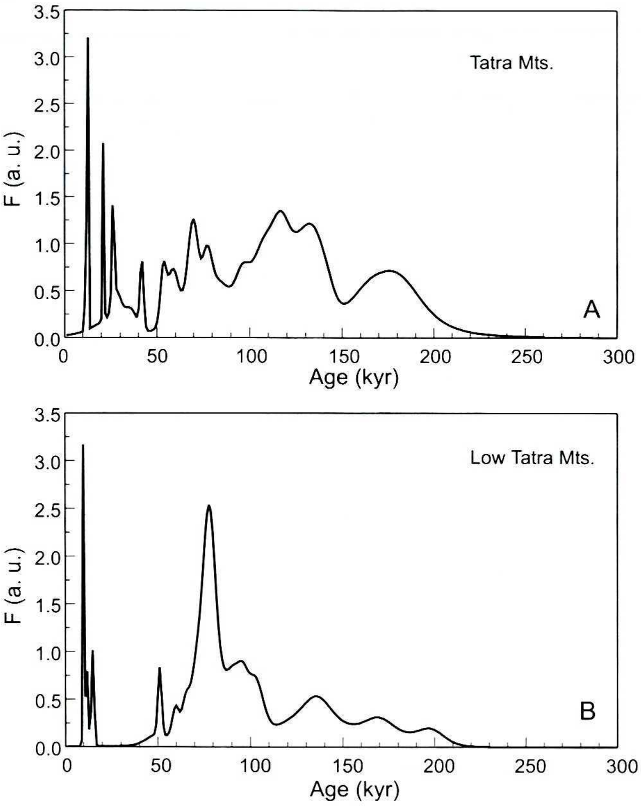

Fig. 29. Curves of crystallisation frequency of speleothems from Tatra and Low Tatra Mountains.

is then called the ‘upland curve’. The large number of collected results, and regional distribution of caves, the dated speleothems come from, enabled an attempt to analyse differentiation of the growth frequency in the North–South transect, *i.e.* in dependence on distance from the margin of the Scandinavian ice-sheet. An attempt to analyse changes in the growth frequency record in the East– West profile has been also made. That analysis would enable us to control eventual influence of distance from the Atlantic, and climate continentality on the ‘pdf’ records.

CRYSTALLISATION FREQUENCY CURVE OF SPELEOTHEMS FROM THE CARPATHIAN CAVES

The dated speleothems descended from three main karst areas of inner Carpathians: from Pieniny Mountains (14 analyses) Western Tatra (103 analyses) and Low Tatra (73 analyses). Numbers of results from particular regions were too low to allow for independent analysis of growth frequency curves. Therefore, I decided to build one, composite curve for the Carpathian region. The overall number (190) of dates guarantees construction of reliable curve. However, it was necessary to check if the records do not indicate drastic differences of climatic history of particular regions. The speleothems from the Pieniny Mountains were of Holocene age, so only the synchronism of the records from the Western and the Low Tatra has been checked.

Comparison of the frequency curves from the Western and the Low Tatra (Fig. 29) indicates similar character of both records. In the Low Tatra, the speleothems of age between 20 and 40 thousand years have not been found so far. The small number of dates, however, does not allow us to determine, whether the speleothems were not formed at that time or this is purely an effect of bias in sampling. The increase of crystallisation frequency correlative with the Holocene occurred in both regions at similar time, also the crystallisation maxima between 50 and 140 kyr BP are synchronous within the error limit. Comparison of parameters of distinguished periods favourable for speleothem crystallisation is shown in Table 5.

One may hope that further accumulation of data from Tatra and Low Tatra will allow independent analysis of crystallisation frequency of speleothems of both regions in the near future. Comparison of these curves with the curve from the karst regions situated north of the Tatra, will solve the question of the role of the Tatra massif in formation of climatic conditions in Europe during the late Pleistocene. Unfortunately, for the moment we may possess only the data averaged for the whole massif of the Inner Western Carpathians.

Therefore, I decided to construct only one curve for the whole Carpathian area. The results of dating, and the crystallisation frequency curve built accordingly, are depicted in Fig. 30. In the curve, a few interesting, characteristic features are visible. After the period of speleothem growth at 250–160 kyr BP, deterioration of conditions occurred, with the pessimum at *ca.* 150 kyr BP. That period corresponds probably to the pre-Eemian glacial. The following period is characterised by an enhanced growth of speleothems, and it lasted from *ca.* 140 till *ca.* 70 thousand years ago. The conditions at that time varied, which is indicated by several maxima, more or less readable on the ‘pdf’ curve. It is interesting that the most intensive growth of speleothems occurred at the closing part of that time interval (around 80 kyr BP). The subsequent period, between 60 and 20 kyr BP, was in general not favourable for crystallisation of speleothems. Here, only short lasting phases of improved conditions are expressed with clear maxima around 60, 50, 40 and 25 kyr BP. The periods least favourable for speleothem growth occurred between 50 and 43, and between 20 and 15 kyr BP. The late-glacial intensification of speleothem crystallisation occurred at *ca.* 15 thousand years ago.

Table 5

Results of analysis of crystallisation frequency curves of speleothems from Tatra and Low Tatra Mountains

Low Tatra Mountains			Tatra Mountains		
X	σ	w	X	σ	w
11.8	2.2	0.07	12.8	0.5	0.03
			24.7	3.3	0.03
			28.2	10.6	0.07
			41.7	0.9	0.01
50.9	0.9	0.02	53.6	2.0	0.03
61.6	11.0	0.08	59.5	2.8	0.04
72.1	5.2	0.10	69.1	3.0	0.06
78.7	3.4	0.20	78.2	4.4	0.07
90.9	4.7	0.12	96.6	7.7	0.11
102.1	4.7	0.10			
118.3	6.8	0.04	115.4	7.1	0.17
136.8	8.8	0.13	133.5	6.8	0.14
166.7	9.8	0.09	174.0	19.8	0.25

X: expected value of age of climatic optimum (kyr BP); σ: standard deviation of X (kyr BP); w: weight of particular sub-population in the total curve

Table 6

Results of analysis of crystallisation frequency curve of speleothems from the Carpathians

X	σ	w	Phase of deposition
12.0	1.8	0.05	VIII
24.2	3.6	0.02	VII
36.7	13.2	0.05	
51.8	1.5	0.01	VI
59.0	3.6	0.04	
69.5	3.5	0.07	V
78.0	3.4	0.10	
92.9	12.2	0.15	IV
102.9	13.0	0.02	
103.8	13.1	0.02	
104.5	13.1	0.02	
105.5	13.1	0.02	
108.8	13.8	0.01	
109.6	12.5	0.02	
120.2	8.1	0.08	III
135.6	6.9	0.10	II
172.9	19.9	0.21	I
230.3	24.5	0.00	

X: expected value of age of climatic optimum (kyr BP); σ: standard deviation of X (kyr BP); w: weight of particular sub-population in the total curve

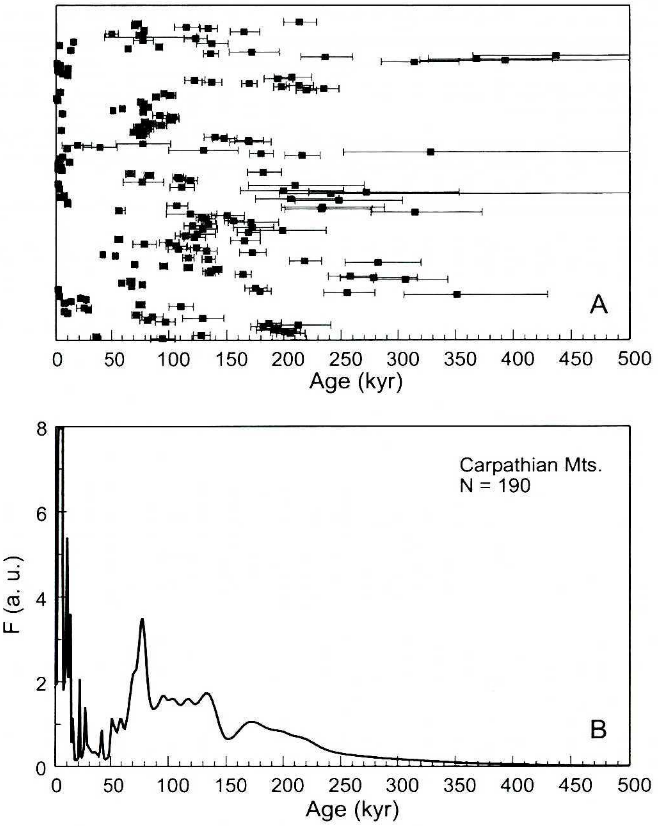

Fig. 30. Results of dating (**A**) and crystallisation frequency curve (**B**) of speleothems from the Carpathians.

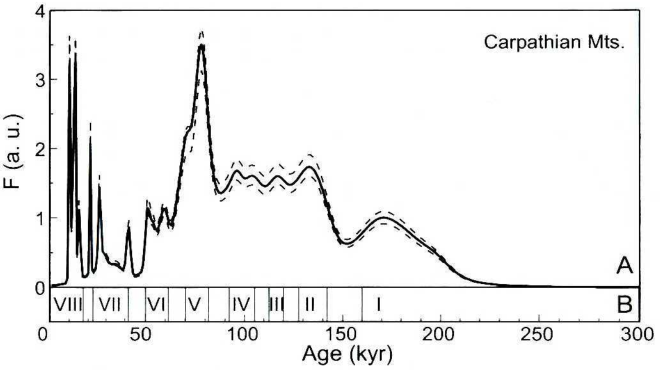

Fig. 31. **A** – curve of crystallisation frequency of speleothems from the Carpathians, with the 95% confidence band determined with the 'bootstraping' method; **B** – phases of speleothem deposition, determined from the frequency curve.

According to the rules discussed earlier, the detailed analysis was made for the curve built from the dates within the range between 10 and 200 thousand years. This curve, with the confidence interval determined with the 'bootstraping' method, is shown in Fig. 31. The parameters of distinguished periods favourable for speleothem deposition are collected in Table 6. Basing on analysis of modality of the 'pdf' curve, and on its confidence interval, 8 phases of speleothem deposition have been separated. The boundaries of phases have been arbitrarily set at the half-distance between adjacent extrema (Fig. 31).

In the earlier period (before 200 kyr BP), several phases of speleothem crystallisation occurred in the Carpathians. There are numerous speleothems of age beyond 250 kyr, and also of age in the range between 300 and 200 kyr (Fig. 30 – upper part). However, determination of timing of those older phases is problematic in view of relatively large errors of the dates.

Concerning the last 200 thousand years, the oldest phase of speleothem formation (I) lasted till *ca.* 160 thousand years ago. At that time, an intensive growth of speleothems took place in the Tatra as well as in the Low Tatra Mountains. The speleothems of this generation often form stalagmites and flowstones of large size. Characteristic is a yellowish-brown tint of calcite of this generation. Most frequently, such a tint is caused by a substantial amount of organic matter, which would evidence well-developed vegetation at the surface.

The subsequent phase (II) lasted between *ca.* 142 and *ca.* 128 kyr BP. It was preceded by a period of distinct deterioration of climatic conditions, which was marked by a break in deposition, and decay of older speleothem generation. At the boundary, a clear layer of silt often occurs, which suggests enhanced water inflow to caves. The intensive supply of silt material took part at the initial period of that crystallisation phase. Later on, the conditions stabilised, and speleothems were formed from pure, middle-crystalline calcite, frequently of a yellowish tint.

The next phase of crystallisation (III) lasted from 120 till 113 kyr BP. The speleothems formed at that phase are represented in the whole area of interest. They are separated from older generations by clear zones of crystallisation slow down and break of calcite deposition. Sometimes, at the boundary between phases, traces of increased water inflow are visible, indicated by higher content of silt material. That material could be supplied with waters intensively percolating to the cave (as a rule, this is indicated by an increased amount of silt impurities in calcite without break in calcite deposition, and after exceeding of certain, critical level of detrital contamination, by a break of crystallisation). Alternatively, it could be transported with waters periodically flowing through a cave (in such a case, the calcite deposition is usually interrupted and the speleothem destroyed, and silt material is deposited in the initial phase of cave drainage, at the surface, of the destroyed speleothem).

The following crystallisation phase (IV) is also represented in the whole area under investigation, and it covered the interval between 105 and 92 kyr BP. The speleothems formed in that phase are separated from the older generations by distinct surfaces of discontinuity with traces of decay of older speleothems. Between phases III and IV, at least in some part of the Carpathians the collapses happened in caves. At that time, a huge collapse in the area of Ślepa Komora in the Szczelina Chochołowska Cave was formed (Hercman *et al.* 1998). Also the collapse in Stalagnatowa Galeria in the Slobody Cave (Low Tatra) could arise in that period, as the speleothems accumulating directly on the blocks of the so-called 'Cintorin Zawał' represent IVth phase of crystallisation. The course of the 'pdf' curve within the phase IV suggests its possible dichotomy. However, that needs confirmation by more material.

Also the next phase (V), between *ca.* 82 and *ca.* 70 kyr BP, may be bipartite. The pessimum between phases IV and V is marked weaker than the former ones. In places, crystallisation was only slowed down or interrupted, but intensive decay of older generations did not occur. The phase V is represented on the whole area. It is marked as the most distinct maximum of the whole growth frequency curve.

The period following the Vth phase is generally less favourable for deposition of speleothems. It is characterised by unstable conditions. Only in short periods the conditions improved enough to make the intensive growth of speleothems possible. The speleothems formed in that period can be found in the whole area, however, macroscopic characteristic of the calcite indicates worse crystallisation conditions. These speleothems are built from fine-crystalline calcite with substantial admixture of silt material. Their crystallisation is often interrupted, and microscopic structure of calcite suggests the growth inhibition by droughts (Hercman *et al.* 1997). In this period, two phases of speleothem deposition can be distinguished. The older one (VI) is presumable bipartite, and covers the interval between 62 and 50 kyr BP. During the following phase (VII), between 42 and 22 thousand years ago, the conditions varied even more. The ephemeral periods of speleothem growth were interrupted with periods, when formation of speleothems was largely inhibited or even impossible.

The youngest phase (VIII) of speleothem growth began around 18 thousand years ago. The speleothems of this phase are isolated by distinct surfaces of discontinuity with traces of deterioration of older generations. These speleothems commonly occur in the whole area. At least in some places, crystallisation of that phase began earlier. In the Szczelina Chochołowska Cave, on the slightly decayed flowstone of the VIIth phase *ca.* 26 kyr old, above clear depositional gap and thin layer of moonmilk, the stalagmite started to grow as early as *ca.* 21 kyr BP (Hercman *et al.* 1998). The growth of that stalagmite was uninterrupted till *ca.* 3 thousand years ago.

Correlation with other palaeoclimatic records

The phases of enhanced crystallisation of cave speleothems indicate warm and humid climatic conditions. Comparing the crystallisation frequency record with the oxygen isotope curves one may correlate distinguished phases of speleothem deposition with the oxygen isotope stages (Table 7).

In Table 7 one can see differences between time scales from the SPECMAP and DH11 (Devils Hole) oxygen curves (*cf.* Fig. 25). As discussed earlier, the largest discrepancies between time scales of both curves occured between 110 and 200 kyr. Relying on the timing of speleothem crystallisation phases, and of the stages 5 and 6 on the SPECMAP curve, one should correlate phases I, II with the stage 6 (Fig. 32). It seems, however, that the phase II is a beginning of period clearly favourable for crystallisation of speleothems. The transition between pessimum I/II and phase II appears then to mark the onset of the last interglacial (Termination II). If we set that boundary at the half-distance between extrema of the 'pdf' curve, the timing of so determined 'Termination II' agrees well with the data from Devils Hole (Fig. 32). The first phase of speleothem crystallisation would then correspond to the initial period of stage 5. Comparison of the oxygen curves with the growth frequency curve of speleothems points to distinct differences of climatic conditions within stage 5. Unlike for the oxygen curves, where the stage 5e, correlative

Table 7

Correlation of distinguished crystallisation phases of speleothems from the Carpathians with the oxygen isotope stages from SPECMAP and Devils Hole

Crystallisation phase		Period (kyr)	SPECMAP		DH 11	
I		>160	7-6		6	
	I/II	160-142	6			
II		142-128	6			5e
	II/III	128-120	5			
III		120-113		5e		5e
	III/IV	113-105				
IV		105-92		5c		5c
	IV/V	92-82				
V		82-70		5a		5a
	V/VI	70-62	4		4	
VI		62-50	3			
	VI/VII	50-42				
VII		42-22				
	VII/VIII	22-18	2			
VIII		<18	2-1			

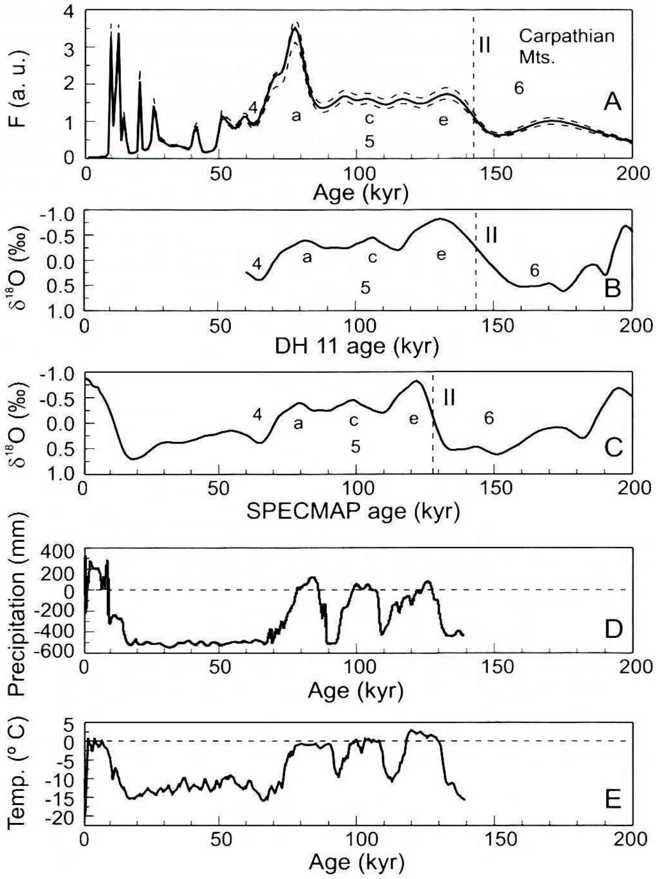

Fig. 32. Correlation of crystallisation frequency curves of speleothoems from the Carpathians (**A**) with the Devils Hole (**B**) and SPECMAP (**C**) oxygen isotope records, and reconstructions of precipitation (**D**) and temperatures (**E**) derived from palynological data (Fauquette *et al.* 1999).

with the Eemian interglacial, is the warmest period, the optimum conditions for growth of speleothems in the Carpathians prevailed in the stage 5a. Perhaps, amount of precipitation in particular periods of the stage 5 played an important role here. Mean sums of precipitation and temperatures, determined from palynological studies in France and from their correlation with Western and Central European sites (Fig. 32) suggest similar humidity and temperature in the stages 5a, 5c and 5e. The maximum for the stage 5a is even slightly higher than for the other stages. The role of humidity seems to be implied by comparison of the oxygen, 'pdf', and precipitation curves in the stages 4–2. Though according to the oxygen curve, the conditions in stage 3 were similar to those in the stage 6 (where intensive deposition of speleothems occurred) the whole period of stages 4–2 seems not favourable for crystallisation of speleothems. This period is characterised by low precipitation, which in all probability is the reason of lowered intensity of speleothem growth.

Climatic coolings not favourable for speleothem deposition had different intensity. Distinct deterioration of climatic conditions, connected with local development of mountain glaciers, should induce considerable decline of speleothem crystallisation intensity, and in some circumstances (cut off the water supply due to freezing) even extinction of growth. Release of large amount of water during melting of the glaciers might cause inundation of caves, decay of speleothems, and sometimes filling the cave with clastic sediments. Thus the periods least favourable for speleothem deposition are the intervals of potentially most intensive development of mountain glaciers in the Carpathians. The most probable periods of intensified glacier development are marked in Fig. 33 (the areas denoted with skewed hatch under the frequency curve). Their timing has been determined from the course of the curve, and from intensity of particular phases not favourable for crystallisation. They are these phases, where breaks in crystallisation were accompanied with decay of older speleothems by enhanced inflow of waters.

Comparison with stratigraphic division of the Youngest Pleistocene in the Carpathians

The detailed stratigraphic division of the youngest Pleistocene in the Carpathian region has been elaborated for the Tatra Mountains (Lindner *et al.* 1990, 1993, Lindner and Marks 1996, see also Fig. 33). The main source of data for construction the time scale of that division were the TL dates of fluvioglacial sediments at the Tatra foreground, and TL, ESR and ^{14}C dates of cave speleothems. Basing on these results, particular interstadials have been distinguished. The TL, ESR and ^{14}C methods, however, are not the best for dating speleothem material (see the section about methods of dating). The published earlier dates obtained with these methods should be treated with caution, especially that the reasonably estimated confidence intervals of these results are comparable (or even wider) to the duration of particular interstadials. For the moment, one should agree that they have only historical meaning. The time scale for the youngest part of the Pleistocene must be then re-established (Fig. 33).

Wójcik (1979) describes moraines of the older glaciation

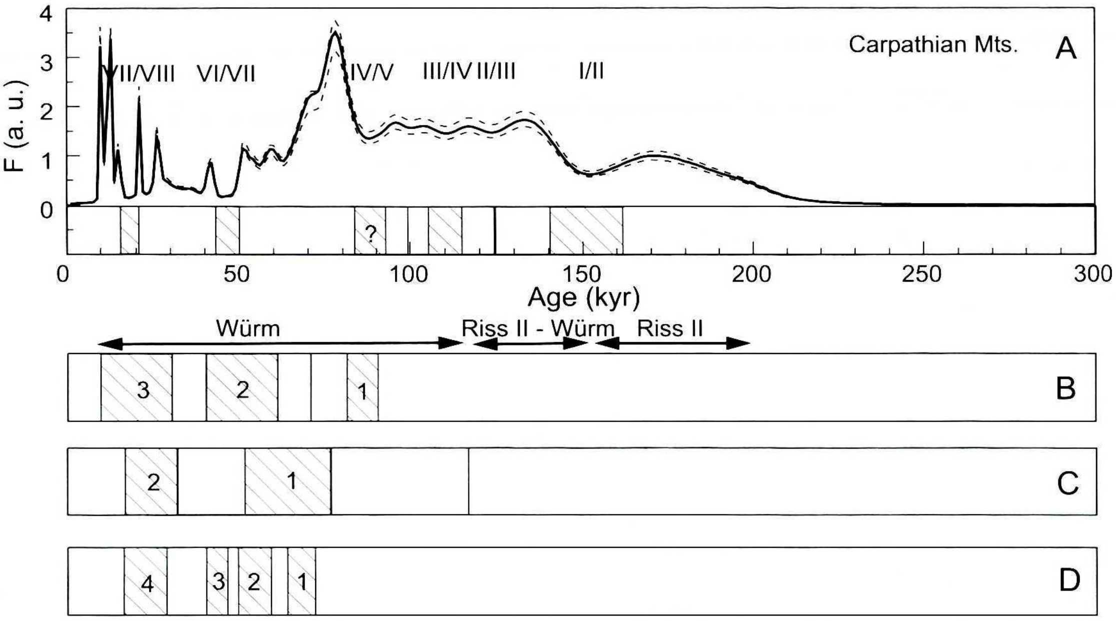

Fig. 33. The most probable periods of mountain glaciers' development in the Carpathians derived from the frequency curve of speleothem crystallisation (marked with hatched rectangles in part **A**), and their correlation with different schemes of stratigraphic division of the younger Quaternary: **B** – according to Lindner *et al.* (1990, 1993), **C** – according to Starkel (1980), **D** – according to Luknis (1964) and Halouzka (1977).

situated in the Bystra Valley, and their connection with the sediments filling the Kalacka Cave. According to this author, the cave has been filled with the sediments washed out from these moraines. In the niche *ca.* 50 m away of the entrance, fragments of flowstone covering that filling have been preserved. This flowstone was forming during the phase II of speleothem deposition (dates: 130±30 and 120±22 thousand years). It seems thus, that the penultimate glaciation (Riss II) occurred around 160–140 kyr BP (I/II). The Sucha Woda Stadial ('1' in Fig. 33B) could then correspond to the period between 113–105 kyr BP (III/IV) or between 92–82 kyr (IV/V). The correlation with the III/IV period seems to be supported by the record left in the speleothems. That period signed up itself considerably stronger than the subsequent one (IV/V). The Bystra Stadial ('2' in Fig. 33B) should then be situated at *ca.* 50–42 kyr BP (VI/VII), and the Białka Stadial ('3' in Fig. 33B) around 22–15 kyr BP (VII/VIII). The Bystra Stadial ('2' in Fig. 33B) lasted longer than the Białka Stadial. Both of them were characterised by definite deterioration of climatic conditions.

An attempt of climatostratigraphic division for the Carpathians, based on palynological, lithological and palaeomorphological data has been made by Starkel (1980, Fig. 33B). Starkel distinguished 2 periods that were especially cold, with ocurrence of permafrost, and forests of a tundra type in the older pleniglacial (marked with '1' in Fig. 33C) and in the younger pleniglacial (marked with '2' in Fig. 33C). These periods should coincide with the intervals least favourable for deposition of speleothems within the Vistulian. The older pleniglacial would then correspond to the interval around 50–42 kyr BP (VI/VII), and the younger pleniglacial, to the phase between 22 and 18 thousand years kyr BP (VII/VIII). In such an interpretation, the early glacial would encompass the period before 50 thousand years ago, its final section being definitely colder than the earlier part. Interpleniglacial would then be dated to 42–22 kyr BP.

Less recognised is the situation in the southern part of Tatra and in the Low Tatra Mountains. The division of the youngest Pleistocene in this area relies merely on lithological and palaeomorphological data. There is no results enabling creation of an independent time scale for these records. Their timing was established only by correlation with the records from the Northern Europe and the Alps. The results of speleothems dating can give, for the first time, possibility to determine to timing of particular stadials, distinguished using lithological data from the Slovakian Tatra Mountains. Basing on lithological and palaeomorphological data the Slovak authors (Luknis 1964, Halouzka 1977) distinguished 4 stadials within the Vistulian. The oldest Rakytovec Stadial (marked with '1' in Fig. 33D), and subsequent Stosy being the maximum stadial ('2' in Fig. 33D) have been roughly situated at 70–63 and 47–57 kyr BP. The following stadials: Lomnica ('3' in Fig. 33D) and Veza ('4' in Fig. 33D) and the Stadials D–E (not marked), were the subsequent stages of deglaciation. The Veza Stadial lasted from *ca.* 28 till *ca.* 15 kyr BP.

It seems, that the maximum stadial, Stosy, should be coincided with the period 50–42 kyr BP (VI/VII). The Rakytovec Stadial would most probably correspond to the period IV/V or V/VI. In turn, the Łomnica Stadial should be correlated with the period between 22 and 18 thousand years ago (VII/VIII). The deglaciation (stadials D–E), similarly as the deglaciation of the youngest Glacial at the northern side of the Tatra, had a multistage character.

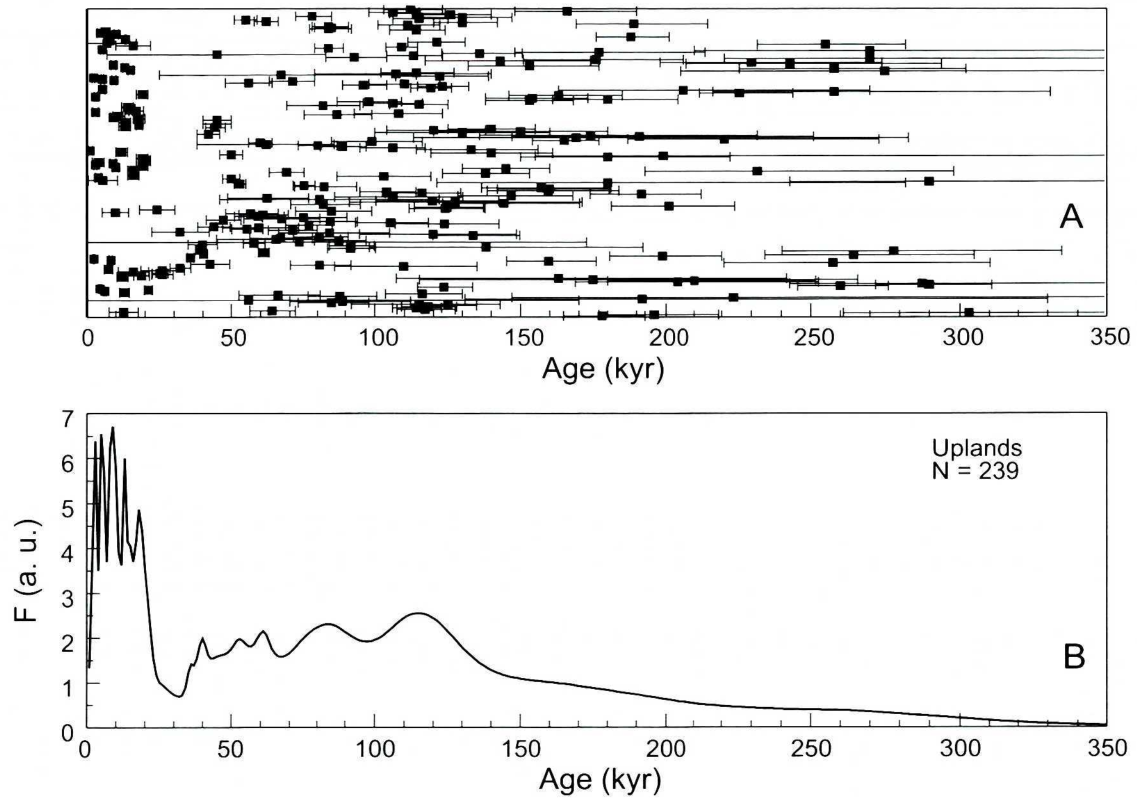

Fig. 34. U-series dates (**A**) and crystallisation frequency curve (**B**) of cave speleothems from uplands and foothills of Central and Western Europe.

CRYSTALLISATION FREQUENCY CURVE OF SPELEOTHEMS FROM THE FOOTHILLS AND UPLANDS OF CENTRAL AND WESTERN EUROPE

The tests (*cf.* the section describing the methods) demonstrated, that the minimum number of dates needed for construction of the crystallisation frequency curve of speleothems was 150. Therefore, the data sets obtained myself were supplemented with the data found in literature. From those published by various authors, only dates accompanied with full additional data (accurate localisation of the cave, relative positions of dated fragments of speleothem, full data on measured isotopic ratios) were selected. In effect, a set of 239 dates of speleothems from foothills and low mountains situated north of the Alps and Carpathians has been created. In this set there is 105 dates from the Kraków–Częstochowa Upland, Holy Cross Mountains and Sudetes, 47 results from the Moravian Karst region (Czech Republic), 70 dates from Germany (regions of Dortmund, Stuttgart and Frankfurt), and 17 dates from Belgium (Fig. 28). Using this set, the crystallisation frequency curve of speleothems has been constructed (Fig. 34).

In the curve, four sections can be distinguished. The oldest section covers the time interval before 145 thousand years ago. It is characterised by a relatively low frequency, consequently increasing towards the younger end. One may suspect a few wiggles in the curve, however, they are not clear. Some traces of intensified speleothem growth are visible around 150–160 kyr, but its position is difficult to determine.

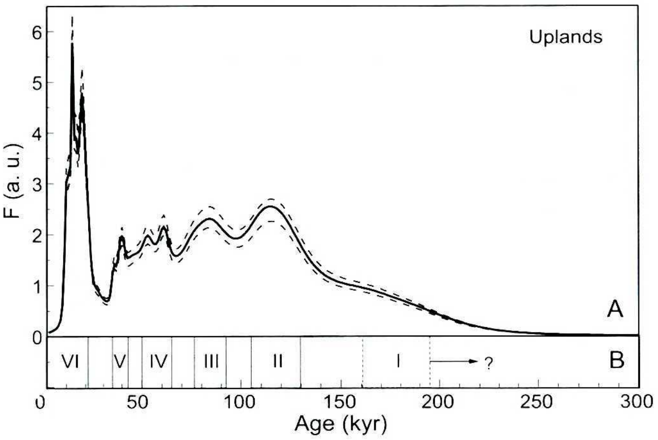

Fig. 35. **A** – curve of crystallisation frequency of speleothems from uplands and foothills of Central and Western Europe, with the 95% confidence band determined with the 'bootstraping' method; **B** – phases of speleothem crystallisation determined from the frequency curve.

The second section encompasses the interval between 145 kyr and *ca.* 35 kyr BP. Generally, this is a period of intensive growth of speleothems (high frequency). The conditions at that time were variable. One may point out 5 phases of enhanced growth: around 115, 85, 62, 53 and 41 kyr BP. These are separated with periods of deteriorated conditions, clearly marked though not very strong.

The third section is short. It includes the phase of strongest aggravation of climatic conditions between 35 and 23 kyr BP. It is marked as the most distinct minimum on the 'pdf'

Table 8
Results of analysis of the crystallisation frequency curve of speleothems from the uplands and foothills of Central Europe

X	σ	w	Phase of deposition
16.0	4.6	0.17	VI
41.8	9.2	0.11	V
59.0	6.6	0.07	IV
80.3	9.5	0.10	III
106.3	24.9	0.03	II
107.6	25.3	0.23	
115.6	16.2	0.04	
116.2	9.6	0.05	
117.7	26.7	0.02	
166.2	25.2	0.11	I
177.3	45.2	0.06	

X: expected value of age of climatic optimum (kyr BP); σ: standard deviation of X (in kyr BP); w: weight of particular sub-population in the total curve

curve. The transition from the older phase favourable for speleothem deposition was rather abrupt. This phase lasted shortly, and after *ca.* 23 thousand years ago a very rapid increase of crystallisation frequency occurred.

The curve built on dates from interval 10–200 kyr has been analysed in detail. Its course, together with the confidence interval determined with the 'bootstraping' method is shown in Fig. 35. The parameters of distinguished periods favourable for speleothem deposition are listed in Table 8. Basing on analysis of the curve and on its confidence interval, one distinguished 6 phases of speleothem deposition within the last 200 thousand years. The decision on separation of particular phase was made using the results of the curve analysis and its confidence intervals. Additionally, indicators of conditions visible in the dated speleothems were considered: the speleothems of a given phase should occur in the whole area, and at least in some places the boundaries between phases should be recorded by breaks in deposition. The boundaries of phases have been arbitrarily set at the half-distance between adjacent extremes of the curve.

In general, one may say that the 'upland' frequency curve has much more continuous character than the record from the Carpathians. The boundaries between phases are markedly weaker, often merely as declines of crystallisation rate. Distinct breaks in deposition, with visible traces of decay of the older layer occur substantially scarcer. Especially in the older periods one may find speleothems continuously growing throughout 2 subsequent phases.

Similarly as in the Carpathians, the oldest speleothems collected in the research area were older than the analysed time interval. The ages of many dated samples were beyond the range of the method *i.e.* >350 kyr. In all probability, a few phases of speleothem deposition before the last 200 thousand years occurred. This is evidenced by frequent occurrence of old speleothems with traces of gaps visible in the cross sections, and by their position in profiles of sediments filling the caves.

The oldest phase of speleothem growth within the last 200-kyr (I) seems to be finished at *ca.* 150–160 kyr BP. Most frequently, breaks in speleothem deposition of that age occur at about 160 kyr BP. However, the speleothems growing till *ca.* 150 thousand years ago occur too. The deterioration period after this phase (I/II) is marked only slightly. In some caves of the Kraków–Częstochowa Upland (the Deszczowa and Grzmiączka Caves), speleothems were growing continuously, and only some decline of the deposition rate has been marked. In the other regions, breaks of deposition occurred, however the traces of decay of older layers are usually only slight.

The following phase of speleothem growth (II) lasted between 130 and 105 kyr BP. The speleothems of such age are common in the whole area of research. Beside the youngest period, this was the phase of the highest frequency of crystallisation. Deterioration of conditions (II/III) after termination of the phase II is marked more distinct than the former one, but the conditions appear not much worse. Also in this period occur speleothems growing continuously, where the climatic aggravation is recorded only as a distinct slowing down of crystallisation rate. The breaks in speleothem deposition are rather frequent, too. Sometimes, traces of destruction of older layers are visible (*e.g.* in the Zbraszowska Cave – Czech Republic; in the Bez Nazwy Cave and the Dziewicza Cave – Kraków–Częstochowa Upland, or in the Radochowska Cave – Sudetes). However, the breaks in the growth of speleothems were short.

The subsequent phase (III) lasted from *ca.* 91 till *ca.* 75 kyr BP. Speleothems formed then commonly and they are numerously represented in the caves of the investigated area. Aggravation of conditions after this phase (III/IV) seems to be slightly stronger than the former one. As a rule, it caused breaks in growth of speleothems. One has found only two samples, in caves of the Kraków–Częstochowa Upland, where the calcite crystallised at that time. It is however, developed in facies indicating very slow crystallisation.

The next phase (IV) of speleothem growth covered the period between 63 and 50 kyr BP. The course of the 'pdf' curve suggests bipartite character of this phase. This hypothesis will be verified after accumulation of more dates from this area. The aggravation period after the phase IV (IV/V) is usually recorded as a break in speleothem deposition or as an ultimate end of the growth. At the surface, the traces of decay are visible. For speleothems, which have no increments after phase IV, one cannot exclude that their surface was destroyed later. The speleothems growing continuously throughout this period have not been found.

The following phase of deposition (V) lasted from *ca.* 42 till *ca.* 35 kyr BP. The speleothems of this generation, when growing on older layers, cover destroyed surfaces of older formations. Deterioration of conditions after the end of phase V (V/VI) had rather abrupt character. No speleothems grown at that time has been found. This period is marked by a break in speleothem growth, and frequent decay of older layers. However, it lasted relatively shortly. The abrupt decline of crystallisation frequency is almost immediately followed by gradual, and after 23 thousand years, rapid increase.

The youngest phase of speleothem deposition (VI) lasted since *ca.* 21 kyr BP. Spelothems, after the break caused by

Table 9

Correlation of distinguished crystallisation phases of speleothems from uplands and foothills of Central and Western Europe with the oxygen stages

Crystallisation phase		Period (kyr)	SPECMAP		DH 11	
I		<160	7-6		6	
	I/II	160-130	6			
II		130-105	5	e	5	d
	II/III	105-91		b, c		b, c
III		91-75		a		a
	III/IV	75-63	4		4	
IV		63-50	3		Not recorded	
	IV/V	50-42				
V		42-35				
	V/VI	35-21				
VI		<21	2-1			

not favourable conditions in the period V/VI, started to grow rather rapidly. In Germany, their crystallisation began around 20–18 thousand years ago. In the Kraków–Częstochowa Upland, the oldest speleothems of this phase have an age of *ca.* 24 kyr. In the Moravian territory, crystallisation of speleothems started only about 16 kyr BP. Crystallisation of speleothems in this phase is intensive, and they are numerously represented in the whole area of research.

Comparison with other palaeoclimatic records

Comparing the crystallisation frequency record with the oxygen isotope curves one can correlate the distinguished phases of speleothem deposition with the oxygen isotope stages (Table 9).

Correlation of the frequency record from the uplands and foothills of Central and Western Europe with the oxygen SPECMAP curve is, unlike for the record from the Carpathians, quite fine (Table 9, Fig. 36). The oldest phase of deposition may be correlated with the 6th oxygen isotope stage. As one can see, the conditions within that stage were sufficiently mild to allow for crystallisation of speleothems. The beginning of the Eemian Interglacial, defined at the half-distance between curve breakdown at the period I/II and the maximum of phase II appears at *ca.* 128 kyr BP, which coincides very well with the SPECMAP data (stage 5e). Within the phase II, correlative with the stage 5e, the best climatic conditions of the whole stage 5 prevailed. This agrees with records visible in the oxygen curves. Stage 4, which can be correlated with the period III/IV, is marked less distinctly than the stage 6 (I/II), however the growth of speleothems in that period has not been stopped, either. The strongest deterioration of climatic conditions, reflected in the largest minimum of the crystallisation frequency curve in phase V/VI, may be correlated with the declining period of stage 3, and the onset of stage 2. An improvement of climatic conditions is noted as early as at 23 kyr BP. Since *ca.* 16 kyr BP, speleothems grew intensively, their deposition prolonging continuously till today in many regions.

Comparison with stratigraphic divisions of the Youngest Pleistocene

As it has been mentioned already, lowered crystallisation frequency of speleothems suggests cool and dry climatic conditions. The history of development of the Scandinavian ice sheet, which controlled climatic conditions in Europe during the analysed period (the last 200 thousand years), is well recognised. Stratigraphic schemes of that period, proposed by numerous authors, rely on wide range of data. These schemes use lithology of sediments, analyses of glacial relief, and analyses of remnants of flora and fauna. The time scale is usually based on TL dates of sandy and dusty sediments, and in the youngest section, on radiocarbon dates of organogenic deposits. Analysis of crystallisation frequency of cave speleothems may provide additional data on climatic conditions in that period. One should remember that the karst regions, where the analysed samples come from, were rather distant from the front zone of the Scandinavian ice. That distance (100–200 km) caused softening of influence of the ice sheet. However, even at such a distance, the climatic fluctuations were distinctly marked.

The oldest period of disturbed speleothem growth (I/II), and locally, of breaks in speleothem deposition, presumably corresponded to the Warta Stadial (Fig. 1). It is not too distinctly marked on the curve, so its boundaries are difficult to determine. Most probably, this was caused by two factors. First, far from the margin of the Scandinavian ice sheet, climatic deterioration was not strong enough to stop crystallisa-

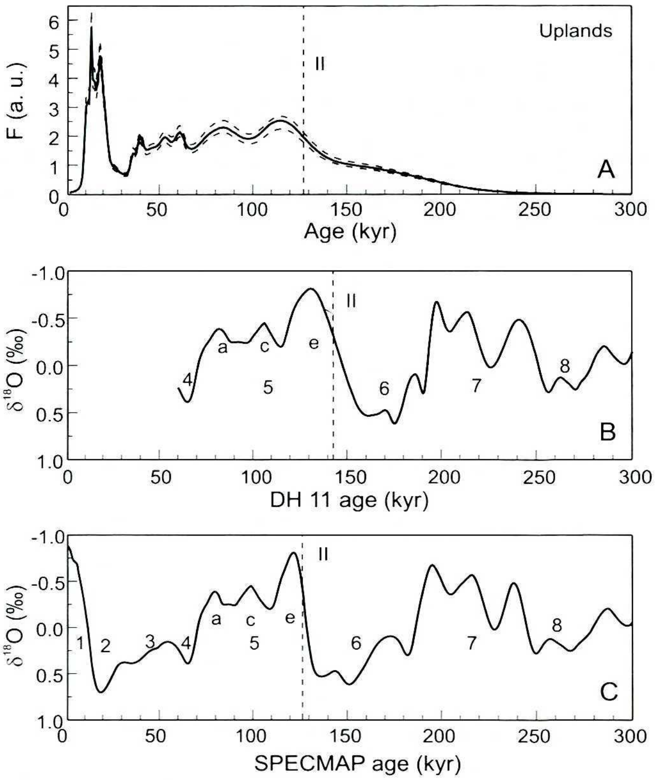

Fig. 36. Correlation of crystallisation frequency curve of speleothems from uplands and foothills of Central and Western Europe (A) with the Devils Hole (B) and SPECMAP (C) oxygen isotope records

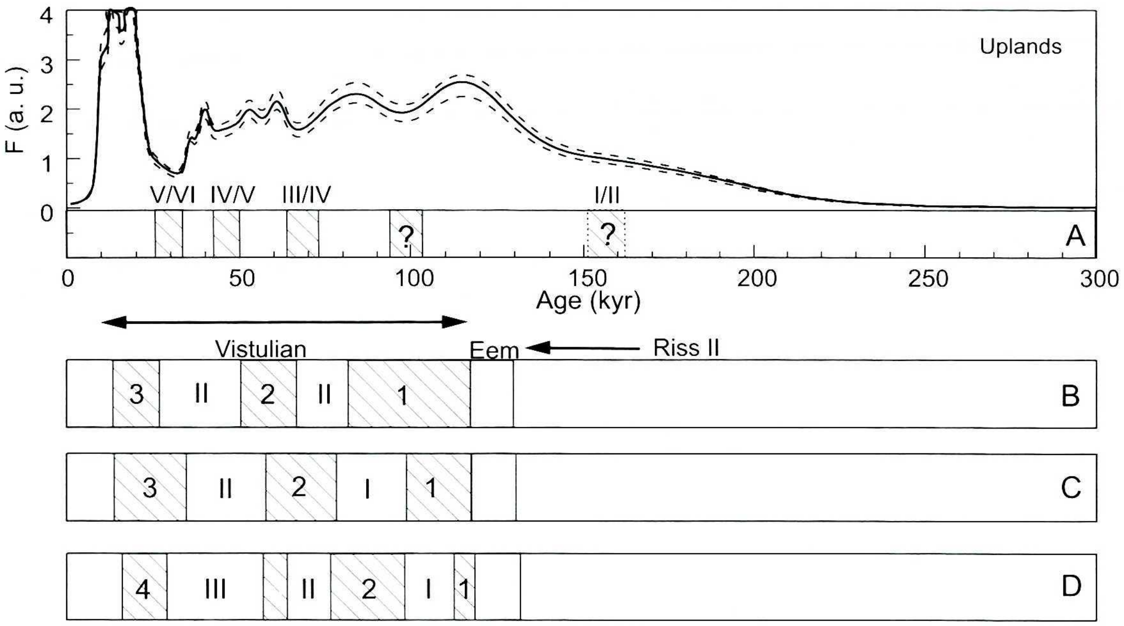

Fig. 37. The most probable periods of glaciers development derived from the frequency curve of speleothem crystallisation (marked with hatched rectangles in part **A**), and their correlation with the schemes of stratigraphic division of the younger Quaternary according to: **B** – Mojski (1988); **C** – Lindner (1992); **D** – Stankowski (1996).

tion in caves completely – that is evidenced by the cases of continuous growth of speleothems. Simultaneously, errors of dates of older speleothems are rather large. This causes flattening of the curve, and makes the record less readable. In such a situation, analysis of modality might be useful (*cf.* the section describing methods of curve analysis). Results of that analysis unequivocally demonstrate existence of phase of enhanced crystallisation at *ca.* 170–180 thousand years ago. Basing on TL dates, the maximum of the Warta glaciation is determined as younger than 230 and older than 150 kyr (Stankowski 1996). The conditions prevailing at that time have been also recorded in clastic sediments of Nietoperzowa Cave, where the field and laboratory studies enabled reconstruction of sedimentation processes, and their relationship with climatic conditions (Madeyska 1969, 1982). The oldest described layers from that cave, indicate strong influence of mechanical weathering. The cool conditions are confirmed by the presence of cold-resistant fauna.

Climatic changes during the last glaciation (Vistulian, North-Polish Glaciation) were rather complex. The climatic units distinguished by different authors are represented in Fig. 37. In the upper part of figure, the frequency curve is shown, with periods of climatic deterioration marked. The lower part shows the position of particular units, distinguished by Mojski (1988), Lindner (1992) and Stankowski (1996).

In general, all authors agree concerning the age of the last interglacial – the Eemian. It is commonly accepted that it lasted between 130 and 115 thousand years ago (Fig. 37B, C and D). The corresponding phase of speleothem growth persisted until *ca.* 105 kyr BP. It is regarded as the warmest period in the analysed section of Pleistocene. It is also characterised by the highest frequency of speleothem crystallisation (phase II). Basing on reconstruction of vegetation assemblages, average July temperatures at the optimum is estimated *ca.* 2–3°C higher than present (Stankowski 1996). Simultaneously, influence of the Atlantic Ocean on European climate was in Eemian stronger than today, as well in summer as in winter (Mojski 1988). Moreover, the decline of the Eemian was characterised by a gradual cooling, though it was rather humid. These data agree with the results of analyses of cave sediments (Madeyska 1969, 1982). In sediments formed during the Eemian optimum the remnants of thermophilous fauna occur, while the structure of sediments and character of debris in the overlying layers suggest rather high humidity and advanced development of soils at the surface. In these sediments, artefacts of the Middle Palaeolithic have been found. Traces of warm and humid climate in the Eemian are also visible in loess profiles of Southern Poland, where the well-developed forest soil is found (Maruszczak 1991). The climatic conditions enabled continuous deposition of speleothems till 105 kyr BP, and in places, much longer.

The Vistulian began with a cooling. Mojski distinguishes the Kaszubski Stadial lasting from *ca.* 115 till *ca.* 80 kyr BP (marked with '1' in Fig. 37B). Lindner calls that cooling the Toruń Stadial (Vistula I) and determines its timing to *ca.* 115–94 kyr BP ('1' in Fig. 37C). Stankowski writes about the Toruń "glaciation' of bipartite character, lasting between 115 and 75 kyr BP (coolings '1' and '2' separated with warming 'I' in Fig. 37D). In cool periods, mean annual temperature was about 0±1°C. In clastic sediments of caves of the Kraków–Częstochowa Upland formed at that time, fragments of fauna characteristic for temperate climate with arctic elements was found (Madeyska 1969, 1982). However, there are also indications of high humidity, a probable reason why that cooling was not distinctly marked in the growth frequency curve (II/III). In most cases, only some decrease of crystallisation rate occurred in that period.

The subsequent warming is termed by Mojski (1988) as Konin Interstadial; its timing being estimated to 80–65 kyr

BP ('I' in Fig. 37B). Lindner (1992) calls that warming as Gniew Interstadial (V1/V2), dating it to 94–74 kyr BP ('I' in Fig. 37C). Stankowski (1996) describes a warming corresponding to that of Brörup and perhaps of Odderade interstadials ('II' in Fig. 37D), and determines its decline to 70, or more probably (as it is implied from further author's comments) to 60 kyr. This warming would correspond to phase III of speleothem deposition. In cave sediments, arctic elements of fauna definitely extinct, and artefacts of Middle Palaeolithic are found (Madeyska 1969). In the loess of Southern Poland, a soil of chernozem type occurs.

The next period is characterised by deterioration of climatic conditions. This, according to Mojski (1988) is the Pre-Grudziądz Stadial ('2' in Fig. 37B) located at 60–50 kyr. The author stresses, that the ice-sheet extent was then larger than in the preceding stadial. Lindner (1992) calls that period as Świecie Stadial (V2), and determines its age to 74–53 kyr ('2' in Fig. 37C). When describing that period, Stankowski (1996, '3' in Fig. 37D) points to occurrence of frost-formed structures, *e.g.* of ice wedges in Southern Polish loess. Age of deposits from that period is estimated with the TL method to 67–55 kyr. In the cave sediments, sharp-edged debris is abundant, and remnants of arctic fauna are found (Madeyska 1969, 1982). In Southern Poland, deposition of loess took place (Maruszczak 1991). This stadial corresponds to the period of lower frequency of speleothem crystallisation (III/IV). In the speleothems, climatic aggravation was recorded stronger than in the preceding periods. As a rule, deposition was interrupted, and slowing of crystallisation without break of continuity is noted only scarcely (2 samples).

The subsequent period of improved climatic conditions is termed by Mojski as Grudziądz Interstadial ('II' in Fig. 37B). According to him, that interstadial covered time interval between 50 and 25 kyr BP. Lindner uses the same name ('II' in Fig. 37C), and quotes the date 53–33 kyr. Stankowski, when describing the same period ('III' in Fig. 37D) stresses substantial variability of climatic conditions at that time. Poland was situated then in a periglacial zone, covered with discontinuous permafrost. In the territory of Southern Poland, accumulation of loess was non-stable, being evidenced by intercalations of weakly developed, often bipartite, soil horizons (Maruszczak 1991). According to Stankowski (1996) the period of variable climatic conditions lasted since *ca.* 55 till 30, and even till 22 kyr BP. In cave sediments, after initial warming, influence of relatively high humidity is visible in the middle part of the discussed period. Also the remnants of thermophilous fauna were being found. The conditions improved in the younger part of the described period. In sediments of this period, archaeological findings of Upper Palaeolithic were met (Madeyska 1969, 1982). Variable climatic conditions in this time interval are also visible on the curve of crystallisation frequency of speleothems. Two phases of enhanced crystallisation (IV and V) are separated with a spell of worse conditions. It has marked out distinctly, usually as a break, or even termination of speleothem deposition. Moreover, the phase IV may be bipartite itself.

The following cold period is termed by Mojski as Leszno (= Main) Stadial, and is dated to 22–12 thousand years ago ('3' in Fig. 37B). Also Lindner calls this stadial as the 'Main', and attributes its age of 33–12 kyr ('3' in Fig. 37C). Stankowski uses the name 'Stadiał Leszczyńsko-Pomorski' ('4' in Fig. 37D). The authors consistently determine the age of maximum extent of the Scandinavian ice sheet to *ca.* 20 thousand years. In sediments deposited in caves, a sharp-edged debris is accumulated, which evidences strong frost-induced weathering (Madeyska 1969, 1982). In Southern Poland, loess was accumulated continuously (Maruszczak 1991). It is interesting, that the minimum of crystallisation frequency in this period falls at *ca.* 33 kyr BP. The drop of crystallisation frequency after phase V was very abrupt, and from *ca.* 23 kyr on, the frequency began to rise again.

The last phase of speleothem growth (VI), the boundary of which has been set to 21 kyr, corresponds to Late Glacial and Holocene.

REGIONAL DIFFERENTIATION OF CLIMATIC CONDITIONS DURING THE LAST 200 THOUSAND YEARS, RECONSTRUCTED FROM CURVES OF CRYSTALLISATION FREQUENCY OF SPELEOTHEMS

The stratigraphy of the Quaternary is mainly based on climatostratigraphic research, using recurring alternation of coolings and warmings. In Europe, with the climatic changes, the consecutive stages of development and extinction of the Scandinavian ice sheet are connected. The success of attempt to establish universal stratigraphic division for European territory depends on answer to several questions. First, were the climatic changes synchronous over the whole continent? Second, how did the distance from the ice-sheet front influence the regional climatic conditions? The following question is, which influence on climate in given region had the distance from the Atlantic Ocean? Was the Atlantic Ocean significantly tempering the conditions, and if so, did its influence vary in the Quaternary? These are not the questions, one can easily resolve. They require comparison of climatic records, reconstructed for different regions of the continent, using data of the same type. Assuming that the course of processes used for palaeoclimatic reconstruction did not depend on region, but on climatic factors only, and comparing the records from different regions, we may hope to observe differences and hints helpful to resolve the questions stated above.

Differentiation of climatic conditions in the N–S transect of Europe

Comparison of records of climatic conditions in regions situated at different latitudes may indicate, if any relationship between distance from the margin of the ice-sheet and regional climate exists. The region where the curve of crystallisation frequency of speleothems has been built earliest, were British Islands (Gordon *et al.* 1989). There were used 341 dates of speleothems from different karst regions of British Isles, situated between 54°N and 51°N. The authors analysed in detail the section of the frequency curve between 250 and 20 thousand years. They distinguished 10 maxima of growth frequency (Fig. 38). The oldest maximum (at *ca.* 180 thousand years) has been attributed to the penultimate glacial (the

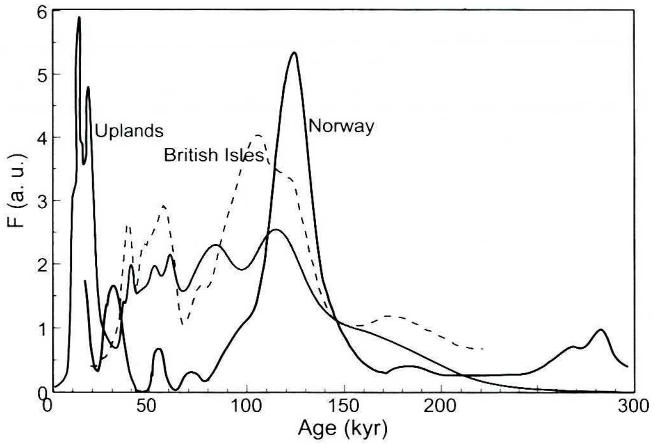

Fig. 38. Comparison of crystallisation frequency curves of speleothems from Northern Norway (Lauritzen 1991, 1993), Great Britain (Gordon *et al.* 1989) and uplands and foothills of Central and Western Europe.

Table 10

Distinguished phases (in kyr BP) of enhanced speleothems crystallisation and their correlation with the oxygen isotope stages. Sources: England – Gordon *et al.* (1989); Norway – Lauritzen (1993); NW Europe – Baker *et al.* (1993b)

England 58-51°N	Norway *ca.* 66.5°N	NW Europe 58-51°N	'Uplands' (this work) ca. 52-50°N	Oxygen isotope stages
29	30	28-31		2
36		35-42	35-42 (V)	3
45				
50		49-56	50-63 (IV)	
57	55	56-62		
76	70	72-78	75-91 (III)	5a
90	90	87-98		5
105	120	98-115	105-130 (II)	
124	140	115-133		5e
180	185		>160 (I)	6

equivalent of the Warta Glacial). The following maxima, at *ca.* 124, 105 and 90.5 thousand years ago, have been accepted as three warm and humid periods within the oxygen stage 5. The youngest 6 maxima, according to the authors, mark periods of warm and humid climate within the last glacial. The authors pointed out variable conditions within that glacial. Moreover, in comparison with other terrestrial sediments, the cave speleothems appeared the material suitable for the best (the most detailed) reconstruction of climatic changes (Gordon *et al.* 1989).

Lauritzen (1993) compared crystallisation frequency curve of cave speleothems from Northern Norway with the mentioned curve for Britain (Fig. 38). He pointed out differences in both curves. For construction of the "Norwegian' curve, only 100 dates of speleothems from the karst regions situated close to the polar circle (66.5°N) were used. In the "Norwegian' curve Lauritzen (1991, 1993) distinguished maxima at *ca.* 30, 55 and 70 kyr BP, and prominent maximum about 120 thousand years ago with marked phases about 90 and 140 kyr. On that curve, also the periods of raised frequency about 185 kyr and above 250 kyr are visible. The author (Lauritzen 1993) stressed differences between both curves. The "Norwegian' curve indicates more rare and shorter periods of ameliorated conditions and intensified crystallisation of speleothems than the British one. As the potential cause of these differences, the author suggested different geographical situation of both regions. In the karst regions of Northern Norway, there were only short periods where the conditions ameliorated distinctly enough to be recorded in the enhanced deposition of speleothems. At the territory of Great Britain, situated farther south, these periods lasted longer, and they appeared more often. That is the reason, why the British record is more continuous (Lauritzen 1993).

One must however stress, that the territory of British Isles is located not only south, but also distinctly further west of Northern Norway. Many authors claim, that this is the region of the strongest influence of the Atlantic Ocean, which causes the climate milder and more humid. So, better continuity of the British record may result not only from the N–S climatic gradient, but it may also reflect the past W–E gradient of climatic continentality. Moreover, in the British curve, strong fluctuations occur during the last glacial, with the Last Glacial Maximum marked very heavily. Perhaps, the sharper record of crystallisation frequency changes within that period was caused by seasonal freezing of North Sea and North Atlantic, which caused some shift of climate towards continentality.

Much better test of influence of the N–S gradient on crystallisation frequency is provided by comparison of the Norwegian curve with that obtained for the foothills and uplands situated north of the Carpathian massif (Fig. 38). The character of both curves is quite different. The record for 'uplands' of Central and Western Europe is essentially more continuous. The periods of climatic deterioration, completely interrupting speleothem growth in Northern Norway (*ca.* 65°N) caused only some lowering of crystallisation frequency in the Central European regions (*ca.* 52–50°N).

Comparison of distinguished phases of enhanced crystallisation of speleothems in territories of Northern Norway, British Isles, and the upland and foothill belt of Central and Western Europe is shown in Table 10. From that comparison one may conclude, that there is a clear difference between the record of climatic conditions in Northern Norway and in the two other regions. Differences between British Islands and European uplands are smaller, nevertheless, also here differences are visible, especially in the period between 70 and 30 kyr BP. The 'upland' curve is more continuous in this period. Due to development of ice sheet during the Last Glacial, large part of British Isles was covered with ice. Some part of investigated caves has been buried under ice, and the other ones found themselves close to the ice-sheet margin. The uplands and foothills, despite similar latitude, did lie substantially farther from the ice margin. The additional effect was freezing of the North Sea and North Atlantic, which could act towards continentalisation of British climate. More information about the magnitude of 'oceanic' effect will be derived after completing comparison of oxygen isotopic composition in speleothems growing at similar latitude, but at different distances from the Atlantic coast.

Table 10 contains also the results of analysis of the 'pdf' curve constructed from 520 dates of secondary carbonates (cave speleothems and travertines), coming from regions of British Isles, Ireland, Belgium and Germany (Baker *et al.* 1993b). Comparing these results with the 'upland' curve, one may point to some differences. The maximum occurring at *ca.* 28–31 kyr BP in the British curve is absent from the 'upland' record. Similarly, in the section correlative with the 5th oxygen isotope stage, a strong influence of data from the British region is reflected. The above-mentioned differences between British Islands and European uplands and foothills have been 'averaged' in the curve for NW Europe published by Baker *et al.* (1993b). However, as in the earlier described case of the data from Southern Poland, it seems that the data from British Islands and continental Europe should not be mixed in one curve.

The next problem is a question of synchronism of climatic changes over the Europe. Comparison of phases of enhanced deposition of speleothems distinguished by different authors (Table 10), gives no argument to claim that the climatic variations were significantly lagged in different regions of Europe. However one must stress, that intensity of these variations was different, depending on localisation of the region. It seems that intensity of climatic variations was mostly latitude-dependent, which might be connected with a distance from the ice-sheet margin. Such a mechanism was superimposed on an effect of elevation a.s.l. which was manifested by development of local glaciations in high mountains, leading to stronger changes than in the non-glaciated areas of similar latitude. Additionally, crystallisation frequency of speleothems may depend on humidity, controlled by the water balance. The periods warm but dry, are characterised with relatively low frequency of speleothem growth. It seems, that the dominant factors controlling crystallisation frequency of cave speleothems are temperature, humidity, and degree of vegetation development. Determination of influence of particular factors on crystallisation frequency needs further research. Here, accumulation of more dates, which would allow for comparison of reliable 'pdf' curves from particular karst regions (a detailed regional analysis), is needed. Simultaneous analysis of stable isotopic composition of oxygen and carbon will enable determination of relative temperature changes, and perhaps will allow us to get an information on development of vegetation on the surface. Additionally, an attempt to build semi-quantitative or quantitative model of speleothem crystallisation in dependence on climatic and environmental conditions would be necessary.

CONCLUSIONS

To summarise the results of the present work, one may draw conclusions of two types. The first-type conclusions concern the methodological questions.

1. The obtained results show, that the curves of crystallisation frequency of speleothems are reliable records of changes of climatic conditions, being an additional tool in the palaeoclimatic studies;

2. The performed tests have demonstrated that the minimum number of dates, enabling construction of reliable 'pdf' curve is 150;

3. When combining results of dating from different karst regions into one curve one needs to consider, if these regions were characterised by similar climatic conditions;

4. Analysis of modality of the 'pdf' curve may be particularly useful for analysing curve sections characterised with high degree of continuity. In this situation, it may be helpful in separation of depositional phases, the boundaries of which are difficult, or even impossible to determine by eye.

The second group of conclusions concerns geological meaning of obtained results. Beside the detailed conclusions on characteristics and changes of climatic conditions, which have been discussed by description of results from particular regions, some main, general conclusions deserve special attention.

1. Relying on analysis of crystallisation frequency curves of speleothems from caves in Tatra and Low Tatra Mountains, one may indicate the most probable timing of development phases of local mountain glaciers;

2. By comparison of crystallisation frequency curves from different regions one may find increasing degree of continuity of speleothem growth, from the north to the south of Europe, which should be connected with the N–S climatic gradient;

3. Comparison of phases of enhanced speleothem deposition distinguished by various authors for different regions of Europe does not show significant time lags between the regions. This claims for synchronism of climatic changes in the whole Europe.

Additionally, directions of future research need to be indicated, which should be performed to specify the results obtained till now, and/or to answer the questions arising at the present stage of investigation. In majority, such a research has been already taken on or its initiation in the near future is planned.

1. Accumulation of more dates will make reliable the comparison between records of climatic changes in different regions. Comparison of records from regions situated north and south of the Tatra massif will allow for studying of eventual role of the Tatra massif as a barrier controlling climatic conditions in Europe in the youngest Quaternary. Comparison of results from other regions should allow for separation of palaeoclimatic records for the northern and the southern part of Central and Western European uplands. This will make possible better assessment of an influence of the N–S climatic gradient on the records of crystallisation frequency of speleothems.

2. The next direction of research, leading to better understanding of an influence of various climatic and environmental factors (*e.g.* temperature, humidity, type of vegetation cover at the surface) on intensity of speleothem formation, should constitute an attempt to create semi-quantitative or quantitative model of speleothem crystallisation. The conceptual models constructed till now show general relationships but do not give quantitative information.

3. Systematic comparison of oxygen isotopic composition in speleothems descending from particular phases of

deposition and regions will enable detailed characterisation of climatic changes within the crystallisation phases, and pointing out the boundaries between phases in the speleothems, which grew continuously in periods of climatic deterioration. This should also allow for observation of influence of the Atlantic Ocean on climatic conditions in Europe.

4. More precise determination of duration of particular deposition phases will become possible after application of mass spectrometric technique in the U and Th isotopic measurements. Additionally, this will give a possibility to extend the time interval of reconstruction (till *ca.* 500 kyr). One may expect the construction of reliable frequency curve encompassing at least 300–400 thousand years. By the way, dating of smaller samples will become possible, which will improve the time resolution of the method, and will allow for more precise dating of speleothem crystallisation phases.

The results obtained till now are so interesting, that this study appears worth continuing. One should hope, that the results of further research will help us to better understand and utilise the information stored in curves of crystallisation frequency of cave speleothems.

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