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# Holocene climate fluctuations in the Alps as reconstructed from speleothems

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ABSTRACT - High-resolution climate changes for the Holocene have been reconstructed through U-series dating, stable isotope, trace element and calcite fabric profiles of a stalagmite removed from a cave in the Trento Province. The Holocene was characterized by many shifts in climate trends, which occurred at both decadal and millennial scale. The detected decadal shifts allow the reconstruction of different scenarios for pollen-based climates of Holocene chronozones such as the Atlantic. At about 6000 BP, the Trento Province climate was affected by a global change in atmospheric circulation.

*Key words:* Paleoclimate, Holocene, Trentino, Northern Italy, caves, speleothems,.
*Parole chiave:* Paleoclima, Olocene, Trentino, Italia settentrionale, grotte, speleotemi.

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## 1. INTRODUCTION

With the rapidly accumulating climate change records, archaeologists will have a better idea of how much history can be laid at the feet of climate change (Kerr, 1998). Several proxy data detect past natural climate variability at decadal to annual scale (Alverson & Oldfield, 2000; Cane *et al.*, 2000), and, in particular, temperature and moisture balance changes. In continental settings, high-precision climate variability in the past can be reconstructed at annual scale through tree-ring density (Briffa *et al.*, 1992) and speleothem annual growth layers (Gascoyne, 1992). With respect to tree-ring density, speleothems, that is secondary mineral deposits, can preserve very long, continuous, paleoclimate records, which are not affected by the "segment length" curse typical of long tree-ring chronologies (cf. Cook *et al.*, 1997). Speleothems can be precisely dated through U/Th Thermal Ionisation Mass Spectrometry (TIMS) (Edwards *et al.*, 1987) and annual lamina counting. The oxygen and accompanying carbon isotope time-series give records of relative (and even absolute) temperature changes and timberline fluctuations. Trace element and carbonate fabrics are good indicators of moisture balance changes and isotopic equilibrium precipitation (Frisia, 1996, Fairchild *et al.*, 1996, 2000; McDermott *et al.*, 1999; Frisia *et al.*, 2000).

Climate changes have been identified as probable causes of rise and fall of human civilization in Northern Africa, the Middle East and the Black Sea region (Hassan, 1986; Kerr, 1998; Ryan & Pitman, 1999). In the Alps, there are still a few well-dated records of temperature and moisture balance, which may enable to interpret the archaeological scene in terms of climate changes. Here, we present a novel approach to Alpine archaeoclimatology, which compares carbon and oxygen isotope records with Mg/Ca ratio and calcite fabric time-series data extracted from U/Th-dated Holocene stalagmites, which were associated with the prehistoric site of Grotta di Ernesto, in Valsugana (North East Italy). The present paper extends the data shown at the IIPP congress held in 1997 at Trento, and, thus, provides a better insight on alpine paleoclimatology.

## 2. CAVE SETTING

Grotta di Ernesto, located at 1167 m.a.s.l. in Valsugana (Trentino, NE Italy), consists of a single downdipping gallery, 72 m long. The cave entrance was unearthed in 1983 and, subsequently, blocked by a door to prevent both looting, and exchanges with the outer atmosphere that alter the pysico-chemical parameters of cave air and dripwater. The gallery develops < 50 m below the surface, and most of the water seeps into the cave through fissures. This allows the quick response of driprate to rainfall rate variations.

The climate at Grotta di Ernesto site is sub-continental, with mean annual precipitation ranging from 1000 to 1500 mm. Snowfall occurs from December to March, and snowmelt takes place between mid-March and early-April (Borsato, 1995). The vegetation above the cave consists exclusively of a C3-type association, which includes *Fagus*, *Larix decidua* and *Abies alba* (Gafta, 1994).

The 45m$^2$ Mesolithic surface excavated in the cave yielded *Capra Ibex* and red deer bones with butchering marks. A single camp fireplace was found in the first chamber, and charcoals yielded 8140 ± 80 $^{14}$C years BP noncalibrated (Dalmeri, 1985; Awsiuk *et al.*, 1994), which correspond to about 9000 years BP calibrated. The cave contains several animal bones at various layers, however, it is probable that hunters used it only once as temporary shelter (Dalmeri, personal communication, 1997). There is no evidence of human activity in the cave from 9000 years BP up to 1983.

## 3. METHODS

One active stalagmite (ER 76), 368 mm long, was removed from Sala Grande, where water temperature is 6.5 +/-0.1°C (Borsato, 1997). The stalagmite was sliced along the axis and mapped to allow the precise correlation of the samples used for all analytical methods. High-precision U-Th dating (4 dates) were carried out by TIMS U/Th method on samples (0.2-2 g) drilled along the axis. Unlike radiocarbon dating, U-Th technique yields ages directly in calendar years. Petrographic observations were carried out using optical microscopy, Scanning and Transmission Electron Microscopy (SEM, TEM). These techniques allowed to recognize fabrics as related to environmental parameters such as driprate, supersaturation and outgassing (Frisia *et al.*, 2000), including recognition of the presence of air currents. Stable isotope measurements were carried out on samples drilled at 2 mm intervals along the stalagmite axis. The $^{13}C/^{12}C$ and $^{18}O/^{16}O$ are reported as $\delta^{13}C$ and versus VPDB. Analytical precision was typically < 0.2‰ (2s). Cation analysis was by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) on dissolved carbonates. Analytical errors was typically 0.1 ppm for Mg, Ca and Si. Oxygen isotope composition of bone phosphate was determined according to the procedure reported by Longinelli (1965). Analytical error is 0.2‰ (1s).

## 4. RESULTS

ER76 stalagmite has continued to grow since 8581 ± 120 years BP with only minor interruptions between 3000 and 300 years BP (Fig. 1). Petrographic observations excluded diagenetic modifications, therefore, the geochemical values extracted from ER 76 calcite are primary, and related to the environmental conditions existing at the time of formation. Calcite fabrics were listed in Figure 1 according to their "degree of deviation from the equilibrium form", that is from calcite with flat faces and low density of crystal defects to calcite with stepped faces, branching crystals and high density of crystal defects. The resulting fabric order is as follows: 1 Columnar, 2 columnar to microcrystalline, 3 microcrystalline, 4 microcrystalline to dendritic, 5 dendritic.

The $\delta^{13}C$ varies between -6.2 to - 10.4 ‰ and the $\delta^{18}O$ fluctuates between -8.04 to - 6.22 ‰. The time-series oxygen isotope vary independently of the textural and carbon isotope variations, with the exception of the bottom part of the stalagmite (Fig. 1). The molar Mg/Ca ratio varies between 0.00162 to 0.00377 and identifies the followings: (1) low Mg/Ca ratio before ~5400 years BP, high Mg/Ca ratio from ~5400 to ~1000 years B.P, low Mg/Ca ratio from ~1000 BP to present-day. Measurements of cave dripwater $\delta^{18}O$, which were the baseline for the interpretation of the $\delta^{18}O$ of ancient calcite, show a narrow range of values centred about $\delta^{18}O$ = -8.8‰ (McDermott *et al.*, 1999).

Two radiocarbon AMS dates were carried out on *Capra Ibex* bones from the mesolithic layers associated with the camp fireplace. The analyses yielded 9200-9038 years BP and 9542-9489 years BP respectively. The same two bones were also analysed for $\delta^{18}O$ of bone phosphate, which is related to the $d^{18}O$ of the meteoric water at the time when the animal lived. The resulting $\delta^{18}O$ value for Early Holocene rainwater is –9.5‰.

## 5. DISCUSSION: PALEOCLIMATIC SIGNIFICANCE OF SPELEOTHEM PROXY DATA

### 5.1. *Mg/Ca ratio*

The cave host rock consists of both calcite, $CaCO_3$, and dolomite, $CaMg(CO_3)_2$. Because dolomite dissolves much slower than calcite (FAIRCHILD *et al.*, 1996), the Mg/Ca ratio of the seepage waters increases when water/rock interaction time is longer, that is during dry periods (FAIRCHILD *et al.*, 2000). The calcite that forms at Grotta di Ernesto when the parent water has high Mg/Ca is also enriched in magnesium. A rise in Mg/Ca ratio in ER 76 calcite is, therefore, indicative of dry climate conditions, and the abatement of the Mg/Ca ratio is indicative of humid climate (cf. FAIRCHILD *et al.*, 1996).

### 5.2. $\delta^{18}O$

The $\delta^{18}O$ in temperate cave dripwaters, such as Grotta di Ernesto, is related to the $\delta^{18}O$ of meteoric water. At present, the $\delta^{18}O$ of meteoric water decreases across Europe with increasing distance from the N Atlantic (ROZANSKI *et al.*, 1993) as a consequence of the mass-fractionation of moisture precipitated from clouds and air temperature. For European sites, the present-day temperature dependence of $\delta^{18}O$ in rainfall averages +0.59 ± 0.09 ‰/°C (ROZANSKI *et al.*, 1993). The incorporation of $\delta^{18}O$ in speleothem calcite (fractionation) is temperature-dependent, and is -0.23 ± 0.02 ‰ per °C (FRIEDMAN & O'NEIL, 1977). Theoretically it would be possible to calculate mean annual paleotemperatures from the $\delta^{18}O$ of speleothem calcite precipitated in stable isotopic equilibrium, if the $\delta^{18}O$ of the past meteoric water were known. Unfortunately, the $\delta^{18}O$ of the past meteoric/seepage water is commonly unknown. The $\delta^{18}O$ of speleothem calcite is, therefore, used to extract past temperature trends, and not absolute values. Since the +0.59 ± 0.09 ‰ per °C, that is the temperature dependence of $\delta^{18}O$ in rainfall, exceeds the calcite-water fractionation of -0.23 ± 0.02 ‰ per °C, a positive correlation between $d^{18}O$ and temperature is to be expected. Thus, when the $\delta^{18}O$ curve of ER 76 shifted to more positive values, climate was warmer, when it shifted to more negative values, climate was cooler (MCDERMOTT *et al.*, 1999).

### 5.3. $\delta^{13}C$

The $\delta^{13}C$ values of speleothem carbonates records the carbon isotopic composition of seepage water, which is influenced by the uptake of soil $CO_2$. The $\delta^{13}C$ values of seepage waters and speleothem calcite depends on whether the soil $CO_2$ is derived from C3-type vegetation (soil $CO_2$ $\delta^{13}C$ typically -27 ‰) or from C4 type vegetation (soil $CO_2$ $\delta^{13}C$ typically -14 to -12 ‰) (CERLING & QUADE, 1993). At Grotta di Ernesto, C3 vegetation dominated throughout the Holocene, as documented by pollen analyses in the same area (MARTELLO, 1995). Calcite formed from seepage water which percolated through a soil that supports C3 plants has $\delta^{13}C$ of about -11‰ (CERLING, 1984). The $\delta^{13}C$ value of calcite formed from waters that took their carbon dioxide from a soil supporting only C3 plants shifts to more positive or negative values as a response to relative humidity (RH) and temperature. The $\delta^{13}C$ of the soil $CO_2$ is, in fact, related to the rate of soil turnover and the original $\delta^{13}C$ sensitive to humidity and temperature, which play a fundamental role in controlling both the $\delta^{13}C$ values of the organic matter (trees and grass). Commonly the rate of soil turnover and the $\delta^{13}C$ of wood and leaves is more sensitive to humidity rather than temperature (cf. EDWARDS *et al.*, 2000). As a consequence, the $\delta^{13}C$ of soil $CO_2$ becomes more negative under higher RH. Furthermore, the rate of soil turnover depends on the nature of the organic matter that is being degraded. URBANC *et al.* (1997) demonstrated that, at the same RH, the degradation of C3 grass yields $CO_2$ with more negative $d^{13}C$ values with respect to that derived from the degradation of C3 trees. Given these considerations, we infer that, in ER 76, calcite $\delta^{13}C$ values of about -11‰ are indicative of degradation of C3 grass under relatively high RH conditions (URBANC *et al.*, 1997). Calcite $\delta^{13}C$ values of about -8‰ suggest that soil $CO_2$ derived from degradation of deciduous forest organic matter, and RH conditions relatively similar to the present-day. Calcite $\delta^{13}C$ values of about -7 ‰ should be indicative of soil $CO_2$ derived from the degradation of conifers under RH conditions higher o similar to the Present. Calcite $\delta^{13}C$ higher than -7 ‰ indicate $CO_2$ derived from scarce vegetation, under a relatively cool and dry climate.

5.4. *Calcite fabrics*

The spatial arrangement of the calcite crystals (fabric) is related to fluid flow and supersaturation of the thin film of fluid wetting the tip of ER 76. Fabric 1, characterized by crystals with straight boundaries and uniform extinction, formed at low supersaturation and constant flow (the stalagmite was always wet). Fabric 3, composed of defective crystals arranged in layers separated by organic laminae formed under strong seasonal contrast. During the wet season, input of organic particles from the soil caused mismatch of crystallites. Fabric 5, characterized by branching crystals, formed at high supersaturation during long, dry time intervals, and, possibly, under the influence of air current (McDermott *et al.* 1999; Frisia *et al.*, 2000).

## 6. HOLOCENE CLIMATE RECONSTRUCTION

Correlation of the Mg/Ca ratio with the other proxy data allowed us to recognize that shifts in climate trends during the Holocene could occur in less than 50 years (Fig.1). Short-lived (hundred-year scale) cool, warm, or dry transients, characterized long-lasting (millennial scale) trends. Sudden, short-lived shifts of climate to dry or cool conditions are expected to have had a strong impact on human behaviour.

The climate in the Trento Province can be reconstructed with confidence from speleothem proxy data. Before 8500 cal. yr. BP, when mesolithic hunters took refuge in the cave, the vegetation above the cave must have been very scarce. As a consequence, stalagmites did not form because the seepage waters were unsaturated. The meteoric water $\delta^{18}O$ signal at 9000 BP, as derived from the analysis of bone phosphate is about 1‰ lower than the present-day mean $\delta^{18}O$ value recorded for the Trento meteoric waters ($\delta^{18}O$ = -8.4‰) and about 0.7‰ lower than the present Grotta di Ernesto water $\delta^{18}O$ value. This means that the mean annual temperature was as much as 2°C lower than at Present. Alternatively, there was a stronger "continental effect", and the air masses had a different trajectory (Rozanski *et al.*, 1993). From 8500 to 8000 BP the Mg/Ca ratio in ER 76 was lower than 2.5, the $\delta^{18}O$ was lower than the present-day value, the $\delta^{13}C$ was relatively high and the fabric was dendritic and very porous (Fig. 1). We infer that the basal dendritic fabric formed under the influence of air current. The cave entrance, therefore, was still open, and was probably blocked at about 8200-8300 BP. This datum is confirmed by the radiocarbon ages of animal bones, which do not exceed 9000 calibrated years BP. Oxygen isotopes apparently indicate conditions similar to, or slightly cooler than at present-day. The RH was higher than at present (low Mg/Ca), and the $\delta^{13}C$, therefore, can be interpreted as reflecting the presence of little vegetation above the cave. At about 7900 calendar yr. BP, the Mg/Ca ratio suddenly reaches a value of about 3 (Fig. 1), which indicates very dry conditions. The onset of aridity occurred in less than 50 years and lasted for about 100 years. Aridity increased evaporation at the soil and, therefore, shifted the $\delta^{18}O$ to more positive values. The parallel shift to higher $\delta^{13}C$ is also indicative of little water availability. The $\delta^{18}O$ curve shows a peak towards more negative values, which can be interpreted as cooling. The dry spell centred at 7900 year BP coincides with low lake levels in the Alps (Magny, 1992; Guiot *et al.*, 1993).

The dry spell was followed by a sudden shift to humid conditions. In fact, from 7800 to 5600 calendar yr. BP the Mg/Ca ratio was low, the $\delta^{18}O$ reached the lowest values of the entire Holocene, the $\delta^{13}C$ fluctuated about -9.5‰, the fabric was microcrystalline. During the 7800 to 5600 year BP period, temperatures were apparently as much as 2.5°C lower than at Present. Such estimate holds true if the meteoric water $\delta^{18}O$ signal was similar to the present-day value. However, if the precipitation water $\delta^{18}O$ was the same as that recorded at 9000 BP (-9.5‰), temperatures during the coldest transients between 7800 to 5600 BP were about 1 to 0.5°C lower than at Present. Three warm transients occurred at 7000 BP, 6200-6400 BP, and at 5800-6000 BP. The 7000 BP transient was probably also relatively dry (increasing Mg/Ca and dendritic fabric). The $\delta^{13}C$ values, lower than - 9.5‰, probably indicate that conifers, and then the broadleaf forest, reached Grotta di Ernesto between7800 and5400 BP. The dominant microcrystalline fabric indicates strong seasonal contrast.

The 8600 to 5600 cal. year BP period coincides with the Atlantic chronozone (Orombelli & Ravazzi, 1996), according to the calendar $^{14}C$ age BP calibrated with the program Calib 3.0 (Stuiver & Reimer, 1993). The Atlantic chronozone is still commonly considered as a markedly stable period, the "Holocene optimum"or Hypsithermal (Orombelli & Ravazzi,1996). Our data demonstrate that the Atlantic was characterized by sudden climate changes, from cool and humid to arid, to warm and moist. At Grotta di Ernesto, the most remarkable change recorded with respect to the preceding Boreal chronozone is the rising of the timberline, which reached well above 1200 m a.s.l. This phenomenon, and the severe dry spell at 7900 BP, followed by a drop in mean annual temperatures, may explain why the high mountain sites were momentarily abandoned. The 7800 to 5600 year BP period was definitely humid. Between 5600 and 5500 BP a dramatic change occurred, as demonstrated by the rising Mg/Ca ratio values: climate became dryer.

From 5,500 to 3,500 cal yr. BP, the Mg/Ca ratio was >2.5, the $\delta^{18}O$ shifted to higher values, the $\delta^{13}C$ started to shift to lower values, and the dominant fabric was microcrystalline (Fig. 1). These trends are probably indicative of warm and dry conditions, and strong seasonal contrast. Dry conditions probably reflect a major shift in air mass circulation, whereby the $\delta^{18}O$ of rainfall reached today values. Temperatures, therefore, can be calculated with confidence from calcite $\delta^{18}O$. Cooler transients occurred at about 5400 BP, 5200 to 5000 BP, 4800 BP, and 3700 BP. Temperatures reached as much as -1°C with respect to the Present. The cool spells that occurred between 5400 and 5000 BP coincide with the time of the Iceman's death (PRINOTH-FORTWANGNER & NIKLAUS, 1994), which BARONI & OROMBELLI (1996) related to the onset of the Neoglaciation. The data extracted from Grotta di Ernesto stalagmite, however, indicate that between 4600 and 2400 BP temperatures were similar, or higher, than at present-day. Furthemore, climate was relatively arid. We, therefore, believe that there is no evidence of a "Neoglaciation" (BARONI & OROMBELLI, 1996; OROMBELLI & RAVAZZI, 1996) in the speleothem data (cf. MCDERMOTT *et al.*, 1999).

From 3500 BP to the Present, Mg/Ca ratio decreases, with the exception of a peak value >3.5 between 2000 and 1400 BP. The parallel occurrence of dendritic fabric at the same time span indicates arid conditions centred at about 900 AD. The $\delta^{18}O$ and $\delta^{13}C$ values are low, fabrics tend to columnar. The shift towards low $\delta^{18}O$ in the last three millennia of the Holocene may be interpreted as a combination of cooler and wetter conditions, which were interrupted by a dry transient during Imperial Roman to Early Medieval times. The $d^{13}C$ values trend to a pure C3-derived signal, much lower than at present-day, is here interpreted as due to deforestation (cf. WICK & TINNER, 1997) and presence of C3 grass above the cave. The negative $\delta^{18}O$ spike between 150 and 300 BP, indicates sudden cooling, probably related to the Little Ice Age (LIA) cold phase. The parallel, more positive shift of $\delta^{13}C$ values is related to lower soil turnover rate during cool summers.

## 7. CONCLUSIONS

Speleothem high-resolution palaeoclimate record provides good time constraints for short-lived climate changes, which can be hardly detected by other methods. Alpine speleothem record is, therefore, very useful to understand possible connections between rapid climate shifts and cultural events in the alpine region. Our data from Grotta di Ernesto indicate that the "Atlantic" was not a uniform, warm and moist period. A severe dry spell at 7900 BP followed by a drop in mean annual temperature possibly triggered the abandonment of high mountain sites. Between 5600 to 5400 BP a dramatic climate change shifted the whole climate trend to increased aridity, a trend which is still ongoing. Climate was, therefore, dry throughout the whole Roman domination in the Trento Province. Our data indicate that the Iceman find does not necessarily correspond to the onset of a "Neoglaciation" in the Alps, as the period between 5400 BP to 1000 BP was relatvely dry and characterized by temperatures similar to present day values. Consequently, we suggest archaeologist to refer findings and events to radiocarbon calibrated ages or calendar ages, because the framing of events within pollen chronozones could be a source of confusion.

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SUMMARY - The stalagmite ER 76 (Grotta di Ernesto, N. Italy) high-resolution, Holocene palaeoclimatic record detects short-lived climatic changes occurred in the Alps, which can be hardly detected by other methods. These climate-related paleoenvironmental changes allow to interpret cultural events in terms of climate changes. Climate proxy series extracted from Grota di Ernesto stalagmite allowed to recognize that the Atlantic pollen chronozone, which is still considered to have been uniform, warm, and humid, was characterized by rapid climate changes. An arid spell occurred at 7900 BP, followed by a cooler and moist phase, and the rise of the timberline, possibly triggered the abandonment of high mountain sites. Our data also indicate that the Iceman find is not unequivocal proof of climate cooling in the last 5500 years. Starting from 5400 BP, in fact, climate became dry, and temperatures were similar to the Present. The coldest Late Holocene event took place between 300 and 150 BP (Little Ice Age). Following these considerations, archaeologists should always refer findings and events to calendar years or radiocarbon calibrated ages. In conclusion, palaeoclimate series extracted from speleothems are important tools to solve controversies in archeology and prehistory which may be related to global and regional climate changes.

RIASSUNTO - Il *record* paleoclimatico ad alta risoluzione temporale ricavato dallo studio dei parametri fisico-chimici della stalagmite ER 76 (Grotta di Ernesto, N. Italy) ha permesso di identificare cambiamenti climatici improvvisi avvenuti durante l'Olocene, che, in genere, non vengono registrati da altri metodi. Questi cambiamenti climatici modificarono l'ambiente Alpino e, di conseguenza, é probabile che esercitassero pressioni sulle culture preistoriche. A differenza delle serie polliniche, I dati paleoclimatici ricavati dallo studio di speleotemi (in tutta Europa) indicano che il periodo "Atlantico", tuttora erroneamente considerato come uniformemente caldo e umido, fu contrassegnato da rapide inversioni climatiche, con temperature fino a 0.5°C inferiori a quelle attuali. L'innalzamento del limite della foresta, e un evento arido a 7900 BP, seguito da aumento di piovosità tra 7800 to 5400 BP furono probabilmente una delle la cause del cambiamento culturale avvenuto tra Mesolitico e Neolitico. Inoltre, le serie paleoclimatiche estratte dalla stalagmite ER 76 indicano che non esiste una vera e propria Neoglaciazione alpina a partire da 5400 BP, come fu ipotizzato sulla base del ritrovamento della mummia del Similaun. Gli ultimi 5400 anni furono contrassegnati da clima arido e da temperature simili a quella attuale, fatta eccezione per il periodo tra 300 e 150 anni fa (Piccola Età Glaciale). In conclusione, le informazioni ricavabili dagli speleotemi sono molto accurate, e possono contribuire nell'interpretazione di eventi culturali in termini di cambiamenti climatico-ambientali.

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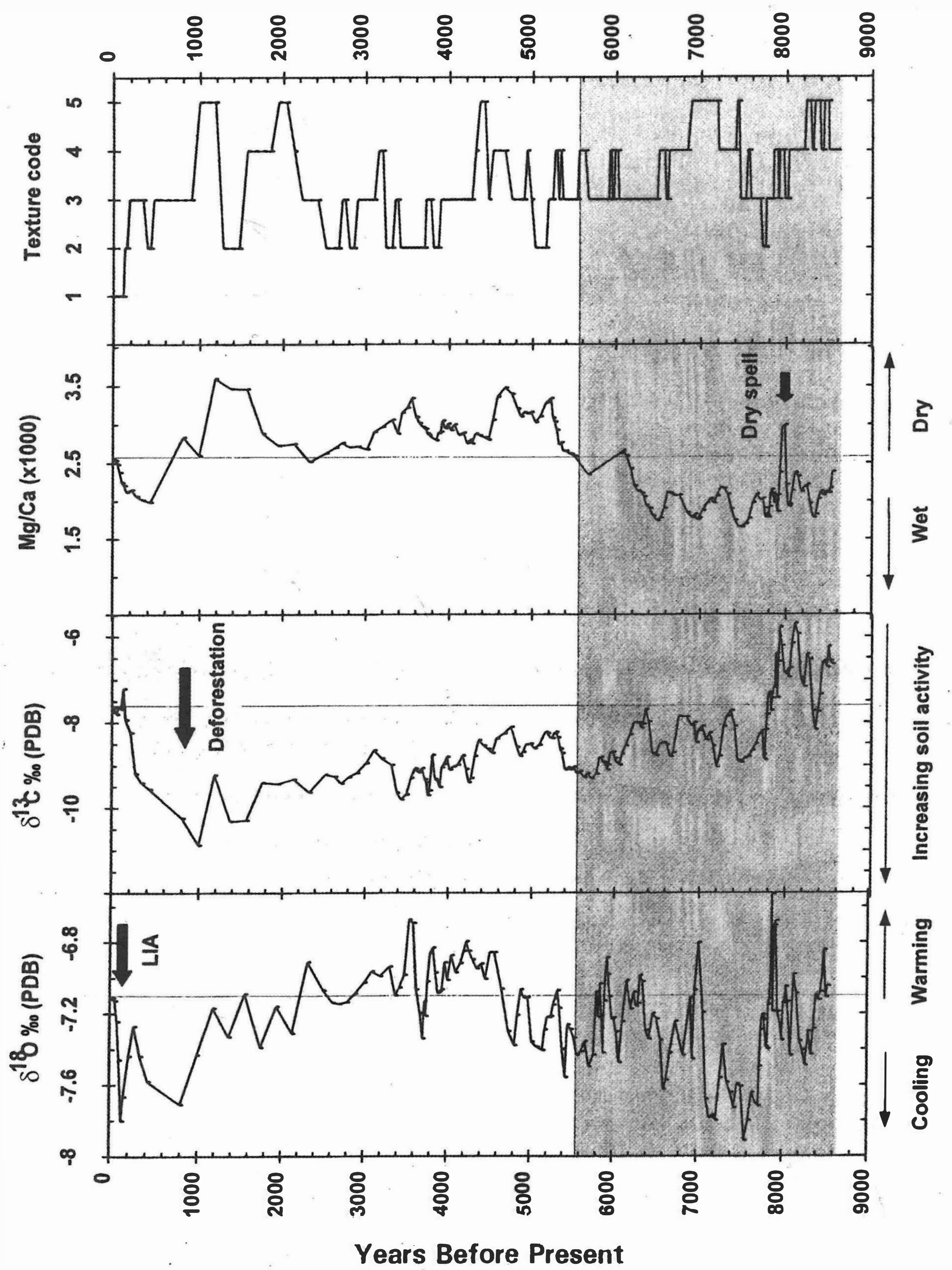


Fig. 1 - Holocene climate-proxy series extracted from ER 76 stalagmite. From left to right: $\delta^{18}O$, $\delta^{13}C$, Mg/Ca ratio and calcite texture (fabrics) fluctuations in the last 8600 years. The age before present is expressed in calendar years, as calculated from U/Th dating and annual lamina counting between radiometric ages. The grey shading highlights the Atlantic chronozone as determined by calibrated radiocarbon ages. Arrows indicate the dry spell at 7900 BP, which is marked by a shift to higher values of the Mg/Ca ratio, the deforestation (negative shift of the $d^{13}C$ curve) and the Little Ice Age temperature drop (negative shift of $d^{18}O$ curve). The full explanation of the paleoclimate proxy trends is given in the text.