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Towards an understanding of the relationships between environmental changes and human societies: analytical techniques, and examples from the Alps.

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ABSTRACT - Paleo-records show that climate and environmental changes had profound effects on human societies. In the Alps, only hypogean carbonate deposits allow to reconstruct climate and environmental changes at annual to decadal and centennial scale for periods such as the Mesolithic and the Paleolithic. From a stalagmite record we infer that, in the Trento Province area, the decline of hunter-gatherers societal structure may be related to the Early Holocene transition from dry and cool to warm and humid conditions, and that the relatively dry conditions of the Mid-Holocene may have favoured passage across the high Alpine passes. The physico-chemical characteristics on hypogean carbonates provide valuable information not only on climate evolution, but also on land- and water resource use. The textural and chemical characteristics of a Roman aqueduct sinter, for example, indicate that by Roman times deforestation had already degraded the soil of high alpine regions. Direct correlation between climate events and the evolution of alpine society is, however, has been difficult because of the different resolution of the chronological control, and the qualitative nature of archaeological data. The recent use of archaeometry techniques, and the better chronological constraints are bridging the gap between paleoclimatology and archaeology. In this perspective, the present article discusses some archaeometry and paleoclimate techniques and provides two examples of their application.

Parole chiave: stalagmiti, clima, ambiente, società.
Key words: speleothems, climate, environment, society.

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1. INTRODUCTION

Paleo-records show that climate variability is a natural part of the Earth System, and that sudden and persistent environmental changes affected human societies. Societies have repeatedly demonstrated the ability to develop technologies that help adapt to external changes. In some cases, however, human societies have collapsed due to climate variations in the past. For example, images of giraffes, elephants, and antelopes on rock outcrops in the Sahara reveal that a dramatic shift in climate parameters, such as mean annual rainfall amount, must have occurred in that region during the Late Pleistocene and Holocene. From lake-core records we know that between 15,500 and 5,500 years ago it was considerably wetter, enabling a savannah ecosystem to exist. Agricultural activities, rising of domestic cattle, and fishing activities in lakes and rivers were, therefore, possible. A rapid decline in rainfall amount, and subsequent profound, persistent droughts, were one of the most devastating hazards faced by North African human societies after 5500 years BP (2500 AC). Such long, dry periods were linked to global scale climate variations (Markgraf, 2001).

The transition from humid to more arid climate mode in the Sahara and the Mediterranean region about 5500 years ago correlates with an overall temperature decline, and both phenomena were apparently a response to orbital-related, declining summer insolation (Bradley, 2000; Beer *et al.*, 2000; Fig. 1). Superimposed on the millennial scale cooling trend were century to decadal scale climate changes, which may have been influenced by variations in solar output through the entire Holocene (Bond *et al.*, 2001).

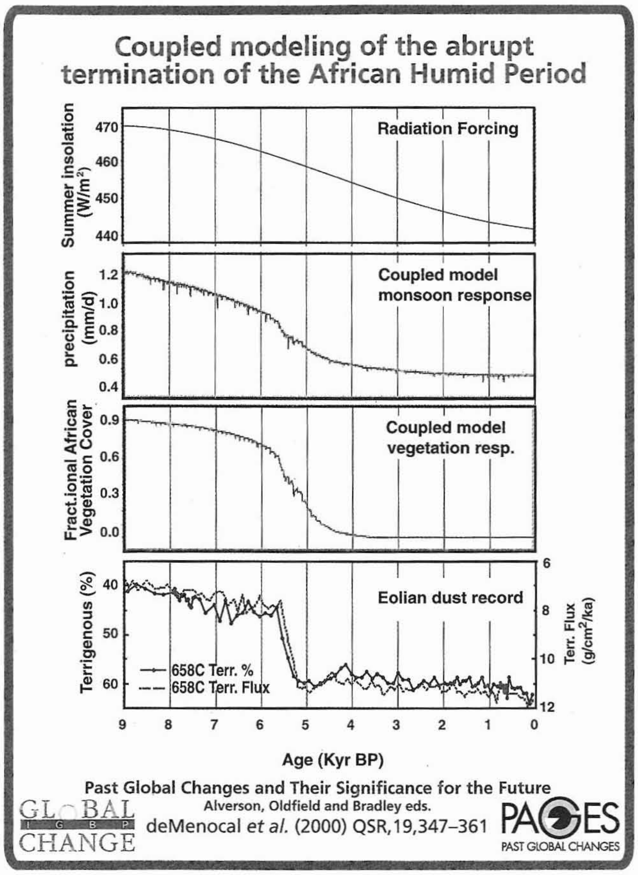

Fig. 1 - The termination of wet climate conditions in Africa is related to decrease in summer insolation. The abrupt transition from humid to dry climate, however, is better explained when the vegetation contribution is accounted for in the model. The eolian dust record supports the coupled model with vegetation response: at about 5,000 years ago a rapid climate change occurred. This change influenced also the Mediterranean area and the Alps (courtesy of PAGES).

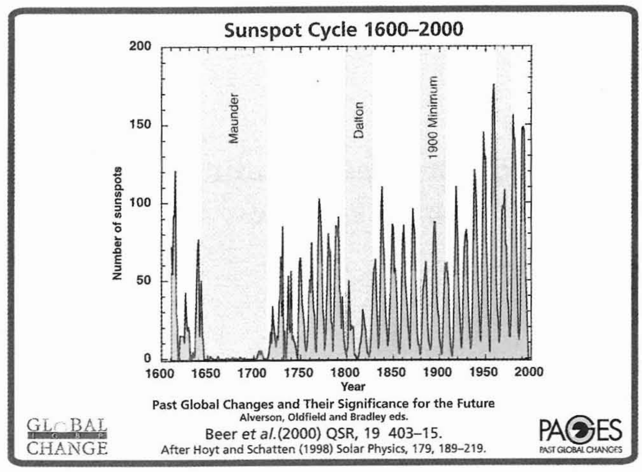

Fig. 2 - Solar influence on the climate of the past 400 years. Note that the Little Ice Age corresponds with a reduced number of sunspots (courtesy of PAGES).

Data support the suggestion that the Little Ice Age and the Medieval Warm Periods may have been entirely linked to changes in solar irradiance (Bond *et al.*, 2001, Fig. 2). Both periods had a tremendous impact on the economy, health and life-style of societies in the Alps. During the Little Ice Age, for example, the greatest glacier advance of the whole Holocene occurred (Hormes *et al.*, 2001). Former passageways across the Alps were probably blocked by the ice, deforestation was intense to supply wood and charcoal, warmer climate species disappeared, but water resources were considerably greater than today. Solar variability, therefore, appear to have influenced alpine climate changes during the Holocene, and will probably continue to influence climate in the Alps.

Millennial to decadal scale climate anomalies that may have influenced alpine societies must be deciphered from proxies recorded in long archives that possess the attributes of a firm dating control and highly resolved climate response. Tree-ring data provide such precise dating and highly resolved climate responses for yearly to centennial time-scales. In the high Alpine region, however, it is difficult to obtain continuous, long series with extensive area coverage, as required by the meticulous process of cross-comparison of multiple annual-growth series and statistical approaches (Briffa *et al.* 1996). Hypogean carbonate deposits, such as cave and rock shelter speleothems, provide good, high-resolution proxies of climate variability within a rigid dating framework, and long time coverage (McDermott *et al.*, 1999). Aqueduct sinters can also be used to extract climate proxies for historical times (Guendon & Vaudour, 1986).

The precise dating and highly resolved climate responsiveness of many, layered hypogean carbonate deposits provide a source of recoverable information about primary (mean annual temperature, air mass trajectories, mean annual precipitation) and derived (timberline elevation, soil activity, duration of snow cover or permafrost), climate variables. They can also provide the means of reconstructing timing of major earthquakes, nature of exploitation of water resources. There is, therefore, the potential of useful exploitation of paleodata obtained from hypogean carbonate archives by human paleontologists and archaeologists, who attempt at relating societal and environmental in the Alps. The nature of the alpine prehistoric record, however, is such that a coherent picture of true temporal and spatial evolution of events is still in the process of being achieved. Part of the problem is identified by the different quality of dating. When possible, archaeological events can be dated precisely through radiometric techniques. Radiocarbon ages, however, are commonly obtained from wood (and charcoal), of which the age prior to its use is unknown. Flints and metals cannot be dated, and techniques such as thermoluminescence on pottery fragments yield ages that can have an error bar of up to 50%. The most precise age constraints can be possibly obtained for artifacts included in burials, where bone collagen can be precisely dated. Radiocarbon age uncertainties of ± 200 years, however, are still common even for biologic relics younger than 6,000 years (PRINOTH-FORNWAGNER & NIKLAUS, 1994). Age resolution of prehistoric societal events at yearly, or even decadal, timescales is, consequently, still unavailable.

The correlation of environmental and cultural history for pre historic times would seem to be fraught by technological problems. Progress in methodology, theory and application of the wide field of archaeometry has been, however, rapid in recent decades, and is rapidly ameliorating the quality of archeological data. In this perspective, the present article aims at providing an overview of methods that can help us to bridge bridging the gap between the quality of archeological data and that of paleoenvironmental data recovered from the physico-chemical properties of natural archives. Examples from our research in the Alps are also presented.

2. ANALYTICAL TECHNIQUES

2.1. *Dating*

Precise dating of hypogean, inorganic carbonates is commonly obtained through the uranium series method. Very small quantities of natural uranium enter the lattice of calcite and aragonite (REEDER *et al.*, 2001), which precipitate in caves or aqueducts. Uranium is inherited from the parent water, which contain the isotopes ^{238}U and its first decay daughter ^{234}U that are readily weathered forming uranyl species in solution. As soon as ^{234}U is trapped in the lattice of hypogean carbonates, it decays to ^{230}Th, which is unsoluble, and thus will not be precipitated in a speleothem (FORD, 1997). The dating method measures the increase in concentration of the radionuclide ^{230}Th from the ^{234}U, which is a function of time, until the rate of decay of ^{230}Th comes into equilibrium with its production from ^{234}U (Fig. 1). This is the theoretical limit of the method. In practice, the limit of the method depends on the technique used to detect ^{234}U and ^{230}Th isotopes. Alpha spectrometry has a limit of 400 ka BP, and high error bar. This technique is, therefore, becoming obsolete. At present, dating is performed by measuring the $^{230}Th/^{234}U$ isotope ratio in carbonates by using thermal ionization mass spectrometry (TIMS) on small samples (weight ranges from 0.1 to 2.0 g). Age uncertainties are commonly ± 0.5 to 1% of the calculated age at the 1s level, and TIMS allows good definition of the age of a sample as far back as 600 ka BP. Recent developments in uranium-series dating techniques propose the use of ICP-MS (Ion Coupled Plasma Mass Spectrometry) to detect the concentration of ^{230}Th and ^{234}U (Fig. 3).

The uranium series method is an invaluable technique for dating archaeological sites beyond the range of radiocarbon dating. A good example is provided by the significant contribution of TIMS $^{230}Th/^{234}U$ dates to the understanding of the relationships between Neanderthals and early Homo sapiens in Israel. Layers containing Neanderthal skeletons from Tabun were dated at circa 110 ± 30 ka by electronic spin resonance (ESR). Thermoluminescence dating of Qafzeh early modern Homo sapiens flints yielded ages of 92 ± 5 ka BP and ESR dates were in the 80-120 ka range. These thermoluminescence and ESR dates were viewed with skepticism by many paleoanthropologists, because (even by taking into account that the error bar range can be more than 20%), ESR dates indicated that early modern Homo sapiens were coeval with Nenderthals. High-precision (± 1-2%), TIMS $^{230}Th/^{234}U$ dates obtained on small aliquots of dentine and enamel from different archaeological layers associated with Neanderthals yielded U-series ages from 97.8 ± 0.4 ka to 168.1 ± 2.6 ka (MCDERMOTT *et al.*, 1993). Dating of dentine and enamel of teeth associated with Homo sapiens-bearing layers at Quafzeh yielded ages in the range 88.6 ± 3.2 ka to 106.4 ± 2.4 ka (MCDERMOTT *et al.*, 1993). The hypothesis that early modern Homo sapiens were coeval with Neanderthals in the Levant was, therefore, confirmed by the precise and unequivocal TIMS U-series ages.

Application of the uranium-series technique to calcrete (calcium carbonate soils) matrix found adhering to the exterior of a Singa (Sudan) hominid skull and to the teeth of associated animals indicate that the hominid

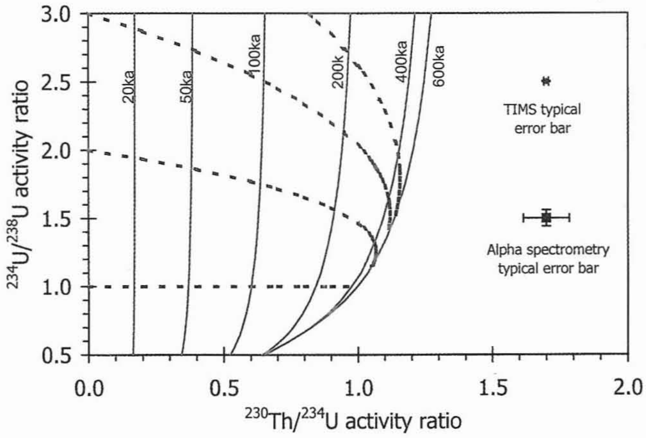

Fig. 3 – Diagram illustrating the fundamentals of the U/Th dating method. The diagram is used to calculate ages from the $^{230}Th/^{234}U$ and $^{234}U/^{238}U$ ratios, which are analysed by mass spectrometry. The error bar for the TIMS technique is very small compared to that of alpha spectrometry. The diagram shows that the dating limit of the technique is about 600,000 years BP.

is at least 133 ± 2 ka old. U-series ages and skull morphology observations allowed the identification of the Singa specimen as one of the earliest and most primitive members of the Homo sapiens clade (McDermott *et al.*, 1996). The potential of the application of the uranium series method in archaeology is, therefore, high. U-series dating does not require calibration, because it is independent from radionuclide production in the atmosphere, and the ages obtained through this method are calendar ages before the time of removal of the sample.

In the Trento Province, the U-series technique has yet to be applied to determine the age of archaeological specimens. It has been to date stalagmites from the archaeological site of Grotta di Ernesto (McDermott *et al.*, 1999) for palaeoclimate studies, although the cave carbonate specimens were not directly associated with the Mesolithic layers containing charcoals and bones. Dating of speleothems from caves in Trentino couples the counting of stalagmite and stalactite annual growth laminae, and $^{230}Th/^{234}U$ ages, which allow the recognition of possible growth hiatus. A yearly time-scale is obtained, which provides a realistic duration for climate anomalies.

Radiocarbon dating is still the most common technique in used to obtain absolute ages for organic specimens of archaeological interest. Radiocarbon dating is based on the uptake of $^{14}CO_2$ by organisms during their lifetime. When the organism dies, ^{14}C decays into ^{14}N. The measure of the residual ^{14}C in a dead organism yields its age. Carbon-14 is created by cosmic radiation in the Earth's upper atmosphere, and its production, therefore, depends on solar activity (Stuiver & Braziunas, 1993). The precision of ^{14}C ages depends on the calibration curves, and, sometimes, we obtain two or three age intervals, which indicate decreasing probability that the real age of the sample falls in the first or the third time interval. In addition, radiocarbon ages are referred to a conventional "present" that is already 50 years old. Care should, therefore, be taken when correlating samples dated through the radiocarbon method and those dated with the uranium series method. Radiocarbon dating can also be applied on the organic fraction of carbonate deposits, such as tufa (travertine), cave moonmilk (Borsato *et al.*, 2000) and aqueduct sinters. The major problem in the accuracy of the dates of the biogenic fraction in carbonates is represented by the possible contribution of old radiocarbon from soil organic matter.

2.2. *Chemical and Physical properties of materials*

2.2.1. *Major and trace element analysis*

Cation and anion analyses of materials are commonly carried out by ion coupled plasma atomic emission spectrometry (ICP-AES), and ion chromatography, respectively. The two techniques, however, are destructive, because they require dissolution of the samples. Despite the high precision, and high detection limit (ppm), therefore, ICP-AES and ion chromatography are not suitable analytical techniques if the samples must be preserved, and if we need to record the textural characteristics of the area under analysis. For this reason, energy dispersive spectrometers are suitable micro-analytical tools, because they are combined with scanning and transmission electron microscopes. The observation of scanned, or transmitted, images of the samples can thus be coupled with the detection of the chemical composition of the spot under analysis. Inelastic scattering of the electron beam gives rise to the emission of x-rays whose energies are characteristic of the elements in the specimen. Modern systems are computer controlled with software that permits on-line identification of elements and their approximate proportions. Alternatively, the acquired spectra can be stored, retrieved at a later time, and analyzed with software that determines peak intensities (areas), makes appropriate corrections and calculates compositions.

Relatively complete chemical analytical data can be obtained through the EDS technique, which we used, for example, to obtain the chemical composition of a roman aqueduct sinter. Thin sections of the sinter were polished and carbon coated. The thin sections were then analysed by an OXFORD MICROPROBE, equipped with Link Pentafet detector, which has a resolution of 138 eV, acceleration voltage of 20 kV, working distance 25 mm, and beam current 170 pA coupled with a CAMBRIDGE stereoscan 360 scanning electron microscope. The detection limit of EDS, however, is about 0.1 %. The EDS technique, therefore, is not applicable when the elements to be detected are present at ppm to ppb concentration, which is the case for important elements in paleoenvironment and archeometallurgy studies. The EDS is a convenient method, because of the easy transfer from easily interpreted images and chemical analyses, with resolutions approaching 20 nm. However, EDS analyses are of lower precision and sensitivity with respect to electron microprobe or ICP-AES analyses. The principal drawback of the EDS method is that absolute concentrations cannot be obtained; rather, only ratios of concentrations can be measured (Peacor, 1993). For example, in the EDS analyses of aqueduct sinter the concentration of oxygen is qualitative. Furthermore, light elements such as H cannot be detected. The ion probe (SIMS) allows for a much accurate quantitative analysis, and for the detection of light elements such as H. SIMS allows for direct spatial observations, and has a high resolution (spot-size about 10 mm). Trace element analyses are carried out on polished mounts by secondary ion mass spectrometry (SIMS), in order to obtain high spatial resolution, high precision and low detection limits. SIMS has been recently used to recognize high frequency oscillations of Mg/Ca, Sr/Ca, and Ba/Ca ratios in stalagmites and stalactites from the archeological site of Grotta di Ernesto (HUANG *et al.*, 2001). Analyses of carbonates are commonly carried out using the isotope mode, and measuring conditions are 20nA primary beam with diameter of ~ 30mm, 25mm image field aperture. Secondary ions with high energy (75±20eV offset) are measured to minimize interference. Twenty to forty cycles of data for each measurement are normally collected during which time the beam penetrates up to 5 mm into the crystal. Relative precision of the trace element measurements is associated with the beam intensities for each element. Typical measurement precisions are 0.5% to 3%.

Drawback of the SIMS technique is its detection limit, which is not sufficient to detect elements at ppb concentration (such as Pb, U, Th or trace metals). A much powerful technique that allows to detect trace elements variations at micrometer scale along the direction of speleothem growth, or along traverses in objects of archeological interest is the non-destructive, high energy source known as synchrotron. The synchrotron beamlines appear suitable to characterize element distribution, subtle textural and mineralogy changes at very high spatial resolution and with the ppb detection limit. The synchrotron is non-destructive, and is, therefore, highly recommended to perform chemical and mineralogical analyses of precious archeological specimens.

2.2.2. *Stable isotope analysis*

The $^{18}O/^{16}O$ fractionation is the most significant isotope partitioning for paleoclimate reconstructions from biogenic and inorganic carbonates, biogenic silica tests (diatoms) and phosphates (bones). The significance of $^{18}O/^{16}O$ fractionation in carbonates and phosphates, which is expressed by convention by a δ‰ notation has been extensively discussed in many research articles and books (BAR-MATTHEWS *et al.*, 1997; DORALE *et al.*, 1998; MCDERMOTT *et al.*, 1999; LONGINELLI & DEGANELLO, 1999; WILLIAMS *et al.*, 1999; ANDREWS *et al.*, 2000). Calcite $^{13}C/^{12}C$ ratio ($\delta^{13}C_c$) is related to the $\delta^{13}C_w$ value of seepage waters, which, in turn, depends on the rate of organic matter degradation and on atmospheric $\delta^{13}C$ variability.

Stable isotope analyses have been commonly carried out by mass spectrometry on powdered samples. The resolution of the method depends on the technique used to extract the powders. The most common technique is to drill small furrows along a single growth lamina (of stalagmites, sinters, tufa, corals, shells etc.), through a small diamond drills, with a diameter of 0.5 mm. The newest mechanical methodology is computer-controlled and very sophisticated. A very fine diamond drill is moved along the axis of a polished sample, which is constantly monitored through a microscope connected with a screen.. The computer controls depth and length of the furrows, and the distance between furrows (down to 0.1 mm). According to growth rate of the specimen, each stable isotope sample represents from a year to 10 years, and is, therefore, very high. The only problem is the collection of that powder from a furrow may eventually pollute the powder from the next furrow. Laser ablation is an alternative, "clean" method, which allows decadal to centennial sampling resolution.

Carbonate $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios were commonly determined by mass spectrometry on CO_2 produced from calcite reacted with 100% phosphoric acid at 90°C (analytical precision < 0.1%, 1s). The new mass spectrometers are equipped with automatic insertion of the reactants in airtight vials containing the samples, through needles that cross their rubber top.

2.2.3. *Textural analysis*

Textural analysis is fundamental to check the validity of chemical analyses and radiometric dating. Textural analyses determine whether or not a sample has been affected by exchange with fluids that altered its original characteristics. Textural analysis is carried out by means of conventional optical transmitted light microscopy on thin sections, optical reflected light microscopy on whole objects or fragments, and scanning electron microscopy (SEM). Transmission electron microscopy (TEM) can be also used if information on the microstructural characteristics of material at sub-micrometer-scale is needed. The TEM technique allows the immediate identification of minerals by combining the image and the electron diffraction modes on selected areas (selected area diffraction patterns. TEM observation and analyses are carried out on electron transparent samples obtained through ion milling.

3. EXAMPLES

3.1. *Early and Mid-Holocene climate events from speleothems*

Hypogean calcite deposits (stalagmites) from Grotta di Ernesto (Fig. 3) preserve paleo-data series, which encompass the Holocene (McDermott et al., 1999; Frisia et al., 2002). The series indicate that climate anomalies recurred at ca. 1 cycle per 1.0 ka for

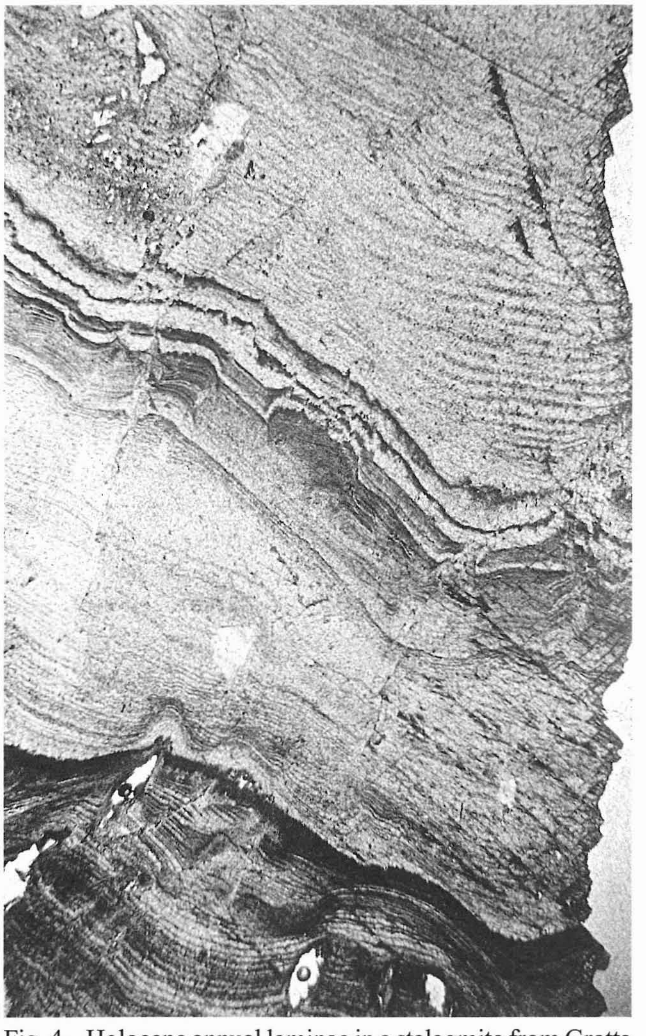

Fig. 4 – Holocene annual laminae in a stalagmite from Grotta di Ernesto. The white part is pure calcite, which, at present-day conditions develop from winter to summer. The dark part is organic-rich, and commonly forms in autumn. Base of the photograph 6.5 mm.

the past 3.5 to 8.5 ka, which may be related to astronomical forcing (e.g. long term sunspot cycles) (FRISIA *et al.*, 2001). These recurrent anomalies, however, are not the most extreme events, those that might have had an impact on society. On the contrary, the stalagmite stable isotope records indicate dry conditions affecting the areas where hunter-gatherers shelters and temporary high mountain dwellings were located (Marcesina Plateau) for the Early Holocene. U-series dating and lamina counting (Fig. 4) allow precise dating of the proxy-series shifts starting at 8.25 ka BP and culminating with an aridity peak at 8.0 ka BP.

Cooling events dated between 8.4 and 8.0 ka BP have been documented in Europe, North America, Canada, and in the Asian and North Africa monsoon regions. In particular, MCDERMOTT *et al.*, (2001) detected an exceptional shift to low $\delta^{18}O_c$ of – 8‰ at 8.32 ka BP in a stalagmite from Ireland, which is coherent with the "8.2" ka event recorded by the Greenland ice cores. The Greenland "8.2" ka event has been interpreted as reflecting a cooling of 7° ± 3°C. The effects of this cooling on the Alpine climates appear to be a dramatic reduction of mean annual rainfall rate. This inference is supported by evidence from glacier retreats in the Central Swiss Alps (HORMES *et al.*, 2001).

The possible impact of the "8.2" event on hunter-gatherers societies in the Alps is difficult to assess. The lack of precise chronological constraints for the timing of abandonment of high-mountain sites by Mesolithic hunter-gatherers makes a correlation between the climate and the societal events highly speculative. The onset of milder and wet conditions after the 8.0 event might, as well, have been a critical period for the hunter-gatherer economy, which was adapted to the relati-

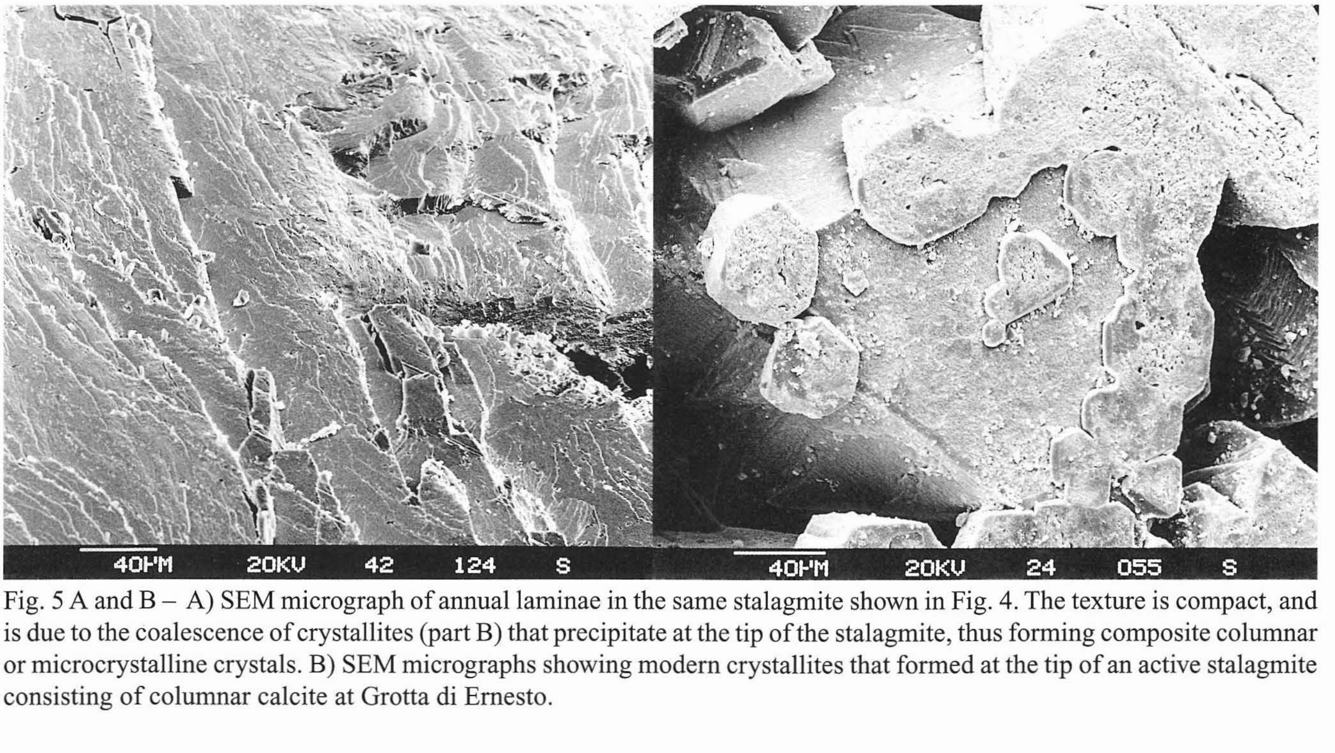

Fig. 5 A and B – A) SEM micrograph of annual laminae in the same stalagmite shown in Fig. 4. The texture is compact, and is due to the coalescence of crystallites (part B) that precipitate at the tip of the stalagmite, thus forming composite columnar or microcrystalline crystals. B) SEM micrographs showing modern crystallites that formed at the tip of an active stalagmite consisting of columnar calcite at Grotta di Ernesto.

vely barren, high altitude landscape. During the Allerød and Bölling the vegetation did not reach the elevation of the Marcesina Plateau shelters (about 1200 m), as documented by the lack of stalagmite formation in caves. The $\delta^{13}C$ record from speleothems in Trentino indicate a rapid increase in soil thickness (and soil activity) starting 7.8 ka B.P., and coeval with a shift to wetter conditions encoded in the parallel $\delta^{18}O$ profile (see FRISIA *et al.*, 2002). These wet conditions lasted until 5.3 ka B.P., when a major circulation change occurred.

Most paleo proxy data series indicate a change from more negative to more positive trends between 6000 and 4000 years BP, which have been interpreted as climate response to insolation forcing (DEMENOCAL *et al.*, 2000 – see Fig. 1; NEFF *et al.*, 2001). The long-term trends of ^{18}O and trace element ratios in speleothems from the Alps indicate that alpine climate were also sensitive to insolation forcing. The local climate response was almost as abrupt as that recorded in proxies from subtropical North Africa (deMenocal et al., 2000), and the effect was the onset of the current trend towards a decrease in precipitation rate.

The alpine speleothem climate proxy record ($\delta^{18}O$, $\delta^{13}C$ and trace elements) indicate that climate has been relatively dry in the past 5300 years (FRISIA *et al.*, 2002), with the onset of similar to present-day conditions. Seasonal contrast, with development of marked laminae(Fig. 4, 5), and relatively dry-than-today conditions in the dry season influenced calcite chemistry and textures between 5.3 to 4.4 ka B.P (FRISIA *et al.*, 2002). The climate scenario inferred from the stalagmite correlates rather well with a long, glacier minimal extension period (HORMES *et al.*). The question of how the Iceman than became buried in the glacier is, therefore, still open, because there is no evidence of glacier advance starting at c. 5200 cal yr BP (his radiocarbon age), for a least a thousand years. On the contrary, the Alpine speleothem record supports inference that transhumance between alpine valleys and across high passes was indeed feasible until the Little Ice Age, because glaciers were almost the same as (or smaller than) today. The Little Ice Age is recorded in the speleothem by an abrupt decrease in growth rate, that resulted in the predominance of the dark, organic-rich, part of the laminae over the white, pure calcite part of the laminae (Fig. 6).

Fig. 6 – The Little Ice Age in the stalagmite from Grotta di Ernesto is marked by a dark layer, which consists of predominant, soil-derived, organic-rich laminae. Base of the picture: 2 mm.

mm from the base	$\delta^{13}C$ ‰ (vs. PDB)	$\delta^{18}O$ ‰ (vs. PDB)
9-11	-11.33	-8.91
22-24	-10.80	-8.64
46-48	-10.81	-8.63
52-54	-10.93	-8.80
68-70	-10.78	-8.51
76-78	-10.86	-8.51

Table 1. Stable isotope trends from bottom to the top of the Trento Roman aqueduct sinter.

3.2. *Climate in Roman times from aqueduct sinters*

Oxygen isotope values for the Trento Roman Aqueduct (Table 1) reflect the signal of the meteoric precipitation in the catchment basin 2000 years ago. The catchment area, which was unknown, has been reconstructed from trace element analyses of the sinter. The EDS analysis detected the presence of Fe, Zn, Zr, Co, and As. Textural analyses indicate that iron-rich waters were flowing in the aqueduct. In fact, thin sections show iron peloids (Fig. 3). Iron-rich waters with traces of Zn, Zr, Co, and As could have been captured from the Fersina stream, the catchment of which is in igneous rocks, in an area that reaches the elevation of 2390 m a.s.l. By assuming that the local, meteoric precipitation $\delta^{18}O$ signal (about -9 ‰) has not changed since Roman times (cf. MCDERMOTT *et al.*, 1999; FRISIA *et al.*, 2001), and considering that the calcite-water fractionation is – 0.24 ‰ °C^{-1}, temperature in the catchment was slightly cooler than at present-day.

The ^{13}C values of the aqueduct (Table 1) reflect the influence of rapid degradation of organic matter in soil that supported pure C3 vegetation in the catchment. Similar negative values were recorded in the same time-span by the Grotta di Ernesto stalagmites (FRISIA *et al.*, 2002). At present-day conditions, the highest soil activity at the high elevation reached by the Fersina stream catchment are recorded by soil that supports only grass, whereby no trees shade the direct sunlight (BORSATO *et al.*, 2000). Two hypotheses are, therefore, possible to explain the low ^{13}C values: 1) deforestation; 2) favorable warm and wet climate conditions. The second hypothesis is to be discarded on the basis of $\delta^{18}O$ data. Consequently, the low $\delta^{13}C$ values may be related to deforestation. Discharge fluctuations are recorded by textural variability, which shows irregular alternation of dirty calcite with detrital contamination, and clear calcite (Fig. 7). Such fluctuations may have been another evidence of deforestation, which was accompanied by soil erosion (and, therefore, soil particles were periodically transported into the aqueduct).

Fig. 7 – Photograph of the typical textures of the Trento Roman aqueduct sinter, which shows layering, and the presence of particles such as iron oxides, mica, and even small bivalve shells. Base of the photograph: 3 mm.

4. CONCLUSIONS

The physico-chemical characteristics on hypogean carbonates have the potential to provide valuable information on paleoclimate evolution and land-use. Direct correlation with the evolution of alpine society is, however, difficult because of the different quality of the chronological control.

Textural and chemical analyses of alpine hypogean carbonates allowed the following inferences:

1) the decline of hunter-gatherers societal structure may be related to the Early Holocene transition from dry and cool to warm and humid conditions. More archaeological data, with tight chronological control, however, have to be collected before such hypothesis can be confirmed or discarded;
2) relatively dry conditions in the Mid-Holocene that lasted until the Little Ice Age allowed transhumance across the high Alpine passes;
3) geochemical analyses of the roman aqueduct sinter indicate that by Roman times deforestation had already degraded the soil of high alpine regions. It is possible that deforestation started well before 2000 years ago, but the sinter provides unequivocal evidence of the its impact on the environment;
4) only the combination of environmental and climate records, cultural history, and archaeometry techniques coupled with tight chronological constraints will allow to understand if alpine society was vulnerable to climate variability and how it adapted to environmental changes.

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