Ötzi, the prehistoric Iceman

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Abstract

This paper presents a brief recollection of the discovery of the Iceman "Ötzi", an extraordinary archaeological find which opened up a window to prehstoric life some 5000 years ago. A selected number of investigations is also presented, with particular emphasis on the ^{14}C dating method.

1. Introduction

It is well known that archaeology is concerned with things that happened in the past, and often one is forced to reconstruct the past from meager evidence. Not surprizingly, the further back in time one goes, the less evidence is available on which to base one's imagination. Often one finds nothing else but some broken tools and pots, and if one is lucky also some bones of animals and humans. Most of the knowledge about man of prehistoric times (i.e. before written record appeared some five thousand years ago) comes from studying burial sites. This tells something about how the dead were treated, but little about how people actually lived. In particular, no complete body was ever recovered from the stone age to give us direct evidence of life at that time. The find of the Iceman changed this situation dramatically, since it provided for the first time a window to true life in the latest part of the stone age, the so-called Neolithicum (~7000 - 4000 years ago). Apparently, the Iceman was taken out from full life when he perished high up in the Austrian-Italian Alps some 5200 years ago. By getting naturally mummified and entombed in a shallow glacier, his body was preserved until our time in an unprecedented good condition.

We know pretty well that prehistoric man lived up to about 10,000 years ago mainly as hunter and gatherer. Around that time agriculture evolved, probably first in the Middle East, spreading eventually to other parts of Europe. The last 100,000-year-long cold period of the ice ages ended about 10,000 years ago, giving way to a warmer climate lasting until today. However, 10,000 years ago the European Alps were still covered with huge ice shields built up during the long cold period. As the warm climate persisted, the Alpine ice sheets gradually receeded from the lower parts of the Alps making more land available for vegetation and animal life. Eventually also man moved into the Alpine regions. It is now believed that agriculture started between 6000 to 5000 years ago in the Alps, that is during the latter part of the Neolithicum. At the same time many valleys of the Alps developed good grazing grounds above the timber line (nowadays called "Alms"), where it was relatively easy to feed domesticated animals like goats and sheep during the summer time. In particular, the southern slopes of the Alps were probably a tempting ground for prehistoric man to move up to higher altitudes. Yet, little evidence existed to support such theories. This all changed on a beautiful late-summer day in 1991.

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2. The discovery of the Iceman

There exists a very detailed account [1] of the discovery of the Iceman "Ötzi", as he was quickly nicknamed after the mountain range where he was found. Here we can give only an abbreviated description. On 19 September 1991 two mountain hikers from Nürnberg, Erika and Helmut Simon, had scaled the Finailspitze (3516 m) in the Ötztal Alps and were on their way back to the Similaun Hut (3019 m) located at the lowest part of a mountain ridge connecting the Finailspitze and the Similaun (3607 m). This ridge forms the border between Austria (to the north) and Italy (to the south) and is also the water divide between the water systems of the Danube River in Austria and the Po River in Italy. As the hikers were approaching a point at 3210 m altitude on the rocky ridge (Fig. 1), they saw the upper part of a body sticking out from a shallow, ice-filled depression (Fig. 2). The unusual climatic conditions of 1991 (including dust from the Sahara resulting in enhanced melting of snow) had partly freed this body from its icy resting place, leading to the startling discovery. The find was reported to the warden of the Similaun hut. In the first few days after the discovery, several people visited the finding place, but nobody suspected that the body could be from prehstoric times. Rather one thought that it might be a mountain hiker who perished on the glacier some time ago. Such finds are not entirely unusual. Among the visitors was the world-renowned mountain climber Reinhold Messner (Fig. 3), who made a first guess that the body might be as old as 500 years. Four days after the discovery the body was freed from the ice and brought to the Institut für Gerichtliche Medizin (Forensic Medicine) at the University of Innsbruck. When Konrad Spindler from the Institut für Ur-und Frühgeschichte (Pre- and Protohistory) at the University of Innsbruck saw the unusual pieces of equipment found together with the body, he estimated a very old age (~ 4000 years) of the find. This immediately created great excitement for both scientists and the public, resulting in many "colorful" events in the ensuing weeks.

One of the more serious events was the determination of the exact location of the finding place as it was very close to the Austrian-Italian border. After an official remeasuring of the border line it was established that the Iceman had been found in Italy, 92 m away from the border. According to international regulations, the Iceman therefore belonged to Italy. Nevertheless, it remained more than six years at the University of Innsbruck, from where most of the scientific work was organized. The results of numerous investigations are published in a series of monographs [2-5]. In January 1998 Ötzi was brought to a newly established Archaeological Museum in Bolzano, Italy, where he is on display for the public, safely stored in a glas vitrine with controlled temperature (-6 °C) and humidity (98%) at glacier-like conditions. Some interesting details about Ötzi (in German) can be found in the the "Südtirol Online" web page (http://www.stol.it/tmh/texte/oetzi/oetzi.asp; accessed on 4 December 1999).

3. The ^{14}C (radiocarbon) dating of Ötzi

It was obvious from the onset of this unusual find, that an age determination using the well-established radiocarbon dating method should be performed. However, since this method is on the one hand straightforward, but on the other hand full of non-trivial subtleties, some important details of the method will be given below.

3.1. The formation of ^{14}C

All natural carbon on earth contains two stable isotopes, ^{12}C (98.9%) and ^{13}C (1.1%). Radiocarbon (^{14}C) is a long-lived isotope of carbon, with a half-life of (5730 ± 40) years [6].

It is produced in the upper atmosphere by the capture of slow neutrons on nitrogen nuclei (the atmosphere contains 78% of nitrogen), inducing the nuclear reaction $^{14}N + n \rightarrow {}^{14}C + p$. The neutrons are the product of a preceeding nuclear spallation reaction, which is induced by highly energetic protons (primary cosmic rays) impinging on the outer layers of the earth's atmosphere from space. After a fresh ^{14}C atom is formed, chemical reactions with oxygen (the atmosphere contains 21% of O_2) quickly produce carbon monoxide via the reaction $^{14}C + \frac{1}{2}O_2 \rightarrow {}^{14}CO + O$. The ^{14}CO molecule is further oxidized to carbon dioxide via the reaction $^{14}CO + HO \rightarrow {}^{14}CO_2 + H$ [7]. It is interesting to note that this second oxidation step is induced by the hydroxyl radical, which has a concentration of only 3×10^{-14} in air! Due to its enormously reactive power the OH molecule has been called the "detergent" of the atmosphere, governing the removal of almost all trace gases [8]. After $^{14}CO_2$ has formed, it stays in the atmosphere for an average of 6 to 8 years before it exchanges with the biosphere and the ocean. This long residence time leads to a uniform distribution of ^{14}C in the atmosphere, an important prerequisite for radiocarbon dating. All carbon in exchange with atmospheric CO_2, acquires the same isotopic ratio of $^{14}C/^{12}C \cong 1 \times 10^{-12}$. Due to the long half-life of ^{14}C the decay rate is very small (13.6 decays per minute per gram of carbon), and measuring the presence of ^{14}C through the decay is therefore not a very sensitive method (see Sec. 3.3 below).

3.2. The radiocarbon dating method

In 1960 Willard F. Libby received the Nobel Prize in Chemistry for "his method to use carbon-14 for age determination in archaeology, geology, geophysics, and other branches of science". This rewarded the development [9-11] of an enormously successful method to determine the age of carbon-containing objects within the last 10,000 years, i.e. the most important period for the development of modern civilization. In principle, modern analytical techniques allow one to follow the ^{14}C decay for about ten half-lives (~ 57,000 years), when the original ^{14}C content decayed to $1/(2^{10}) \approx 1/1000$. However, there is a serious complication in radiocarbon dating. The age (t) is determined from the exponential decrease in isotope ratio, $(^{14}C/^{12}C)_t = (^{14}C/^{12}C)_{t=0}\, e^{-\lambda t}$, by measuring the present-day ratio $(^{14}C/^{12}C)_t$. The decay constant is related to the half-life by the relation $\lambda = (\ln 2)/t_{1/2}$. The calculation of the age requires to know the initial ratio $(^{14}C/^{12}C)_{t=0}$. As this ratio was not constant in time (Fig.4), elaborate calibration procedures were implemented. Measuring the ^{14}C content in tree rings of known age obtained from dendrochronological work, one has extended the calibration back to ~12,000 years [12], The calibration curve can be extended further back in time (to ~24,000 years) by measuring ^{14}C in corals and sediments absolutely dated by other means [12]. (If the ratio of $^{14}C/^{14}N^*$ could be measured, where $^{14}N^*$ is the decay product of ^{14}C, there would be no need to know the initial ^{14}C content. However, it seems virtually impossible to detetct the minute amounts of radiogenic $^{14}N^*$ in the presence of omnipresent ^{14}N. Nevertheless, some attempts to try this have been discussed [13]). Typically, from the measured $(^{14}C/^{12}C)_t$ ratio one first calculates an uncalibrated age (the so-called radiocarbon age) using an internationally agreed upon reference value for the $(^{14}C/^{12}C)_{t=0}$ ratio. This radiocarbon age is not to be confused with the true calendar age, which can only be obtained by using the calibration curve. Often both the radiocarbon age and the calendar age are given. The former is a fixed value whereas the latter depends on the status of the calibration curve which is continuously updated [12] and extended towards the radiocarbon dating limit.

3.3 ^{14}C measurement with accelerator mass spectrometry (AMS)

One milligram of contemporary organic carbon contains $N \cong 6\times10^7$ ^{14}C atoms. Although this seems to be a lot of atoms, it follows from the radioactive decay law ($dN/dt = -\lambda N$, with $\lambda = 1.4\times10^{-8}\ h^{-1}$), that only about one decay per hour happens. It was pointed out some time ago that mass spectrometry (MS) should do much better [14]. Even with a moderate detection efficiency one should detect many more ^{14}C atoms, since MS measures ^{14}C directly rather than waiting for the infrequent decay. However, only with the use of an accelerator is it possible to reduce the background to a level where the minute $^{14}C/^{12}C$ ratios in the range of 10^{-12} to 10^{-15} can actually be measured. With AMS one is able to detect about 1% of all the ^{14}C atoms in one hour, increasing the detection sensitivity by almost a factor of a million! Compared to decay counting, one can thus measure 1000 times smaller samples (one milligram instead of several grams) in 100 times less time (one hour instead of several days). This meant a true renaissance of the radiocarbon method, which at the invention of the AMS method in the late seventies [15-17] was already 30 year old and well advanced in its principle methodology by using decay counting only. For extended descriptions of the AMS technique and its applications, we refer the interested reader to review papers [18-22] and a monograph [23], where detailed information can be found. Since Ötzi was a precious archaeological object of which one would like to preserve as much as possible, it was clear that AMS was the method of choice for the ^{14}C age determination.

3.4. The age of the Ötzi find

Radiocarbon measurements of bone and tissue from Ötzi were first performed at the AMS facilities in Zürich [24, 25] and Oxford [24, 26]. Grass found together with Ötzi was also dated at these facilities, and also at the AMS facility of Gif-sur-Yvette and Uppsala. All early ^{14}C datings were summarized at the AMS Conference in Australia [27]. The combined radiocarbon age (uncalibrated) was found to be (4546 ± 17) yr BP (Before Present = 1950). However, Figure 5a shows that the calibration shifts this age by approximately 650 years further back in time, and increases the uncertainty of the age to about 250 years (Fig. 5b). Nevertheless, the calibrated time range is important for archaeologists to narrow down possible cultures north and south of the Alps, where Oetzi may have come from (Fig. 6). After the Vienna Environmental Research Facility (VERA) came into operation in 1996 [28, 29], new AMS measurements on the equipment of Ötzi were performed at this facility and summarized together with similar measurements in Uppsala and Gif-sur-Yvette [30, 31]. Fig. 7 shows a comparison of these dates. As can be clearly seen, essentially all of the equipment and botanical remains found with Ötzi date to the same time range. However, there are two notable exceptions. These samples provide evidence that the site of the Iceman was used as a transition between the southern and the northern slopes of the Alps at substantially earlier and later times. In a collaboration with the Institut für Botanik at the University of Innsbruck, we are currently engaged at VERA in radiocarbon dating of about 50 botanically identified species [32], which have been recovered from sediments of the shallow depression (Fig.1) where Ötzi was found. Since botanists can correlate the occurrence of particular species with particular climatic conditions, it may be possible to find evidence for other warm periods in the past [33].

4. Other investigations of Ötzi

Although the results of radiocarbon dating unambigiously point to a Neolithic origin of Ötzi, the excellent status of preservation of both body and equipment for more than 5000 years, are truly amazing and cannot easily be put into a complete picture [34]. However, accepting that the preservation of a Neolithic body into our time is a very unlikely but real event, we discuss briefly some more of the interesting results from Ötzi.

4.1. The unfinished bow

One of the puzzling facts of the Ötzi find was the unfinished state of some pieces of his equipment. For example, the main body of the bow, neatly carved out of a yew, was finished but there was neither a string attached to it nor were there notches to mount a string. Non-destructive, computer-tomographical X-ray scanning revealed that the bow (3.5 cm diameter) was carved out of a yew with a minimum stem diameter of 9 cm [35]. Yews have very narrow tree rings (<1 mm), which give the wood a sturdy elasticity well suited for bows. This, is, however, just below the image resolution of the X-ray tomography. Assuming that a cross section of the bow would be made available for ^{14}C measurements with AMS, one could determine a sequence of ^{14}C dates with a known distance of years in between them. Such results could then be used to possibly narrow down the time period when Ötzi lived by a process called "wiggle matching" [31].

4.2. The CO_2 concentration in the atmosphere at the time of Ötzi

Plants take up CO_2 from the air through so-called stomata, which are micron-sized openings in their leaves. It has been shown [36], that the stomatal density of *Salix herbacea* (dwarf willow), a plant recovered at the Ötzi finding place, is inversely proportional to the absolute CO_2 concentration in the air (and thus changes with altitude). With the proper calibration of stomatal density from leaves at different altitudes, the CO_2 concentration of the air at Ötzi's time was reconstructed. A relative volume concentration of CO_2 of (319 ± 20) ppmv was derived from these values, which indicates that the CO_2 concentration 5000 years ago was approximately the same as the pre-industrial CO_2 value of 280 ppmv derived from air bubbles trapped in ice cores [37].

4.3. Tracing the water which Ötzi drank

All water we drink contains micron-sized autotrophic organisms called diatoms which have distinct silica structures. An endoscopic sample from the colon of Ötzi was investigated for these species with a scanning electron microscope, and 24 diatom taxa ranging from 10 to 50 μm were identified [38]. Since the turnover time of diatoms in the body is only a few hours and the distribution of diatom taxa in mountain streams changes with altitude, the particular distribution found in the colon of Ötzi indicated that he drank water from different altitudes above and below 1500 m. Whether or not he drank the water directly out of the streams or carried it with him to drink it later, cannot be determined. In any case, it seems likely from this finding that he was walking up from a valley (probably from the south) to high altitude on the last day before he perished.

4.3. Stereolithography of the skull

For anthropologists it is important to be able to study the skeletal features of a body in great detail. Since Ötzi can only be accessed 20 minutes at a time outside his glacier-like state of preservation, a non-distructive, yet truly reproductive model of the skull was a very desireable thing to produce. To this end, stereolithography in combination with computed X-ray tomography (CT) was performed on the skull of Ötzi [39]. A transparent, three-dimensional model of the skull was re-created by intersecting a CT-guided, ultraviolet laser with a liquid polymer, which solidifies at laser impact. This created a point-by-point reconstruction of the

the complete skull, available for detailed anthropological measurements and studies. The transparency of the plastic model makes it particularly useful for those investigations.

5. Conclusions

It is impossible in this brief review to give an adequat description of the large variety of investigations performed on the Iceman and his equipment. For a comprehensive review, the reader is referred to the series of monographs mentioned above [2-5]. One may however conclude from this "random"selection of topics that Ötzi is a unique object, which provides input into many fields of research. Whatever the cause of his miraculous preservation for 5000 years may have been, he is a true gift of nature to those who are interested to find out more about our distant past.

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Figure Captions

Fig. 1 The finding place of Ötzi: A shallow, icefilled depression at 3210 m on a mountain ridge of the Ötztal Alps, forming the border between Austria and Italy.

Fig. 2 First picture of Ötzi on 19 September 1991, as he was accidentally dicovered by Erika and Helmut Simon (Photo by H. Simon). One has estimated that Ötzi may have surfaced from the melting ice only three days prior to the discovery.

Fig. 3 The partly freed Ötzi as watched by Reinhold Messner (right) and Hans Kammerlander on 21 September 1991 (Picture taken by K. Fritz, Photo Paul Hanny). Kammerlander holds part of a wooden structure later identified as a carrying support of Ötzi. In the right upper corner of the picture the bow can be seen, its lower part stuck in the ice and the upper one leaning against the rocks. Just below the tip of the ski pole held by Messner one can see the smashed remains of a container made of bark from a birch-tree, probably used to carry equipment for making fire.

Fig. 4 Deviation of the atmospheric ^{14}C content from the reference value (dashed horizontal line) as established from tree-rings back to 12,000 years, and from corals and sediments beyond that point [12]. The lower abscissa gives calibrated years BP (before present = 1950), whereas the upper abscissa shows the calender age in years BC (Before Christ) and AD (*Anno Domini*). The insert extends the $\Delta^{14}C$ values back to 40,000 years, but is based on only two measurements beyond 24,000 years (double dashed curve). A substantial increase of ^{14}C going back in time is observed.

Fig.5 The calibration of the radiocarbon dates for bone and tissue from Ötzi. The combined radiocarbon age from the AMS measurements at Zürich [25] and Oxford [26] is (4550 ± 19) years BP. a) Calibration curve from 2000 to 4000 BC, The straight line at 45° indicates a 1:1 transformation of the radiocarbon age into an uncalibrated calendar age. The intersection of the radiocarbon age with this line and the tree.ring calibration curve shows a shift of approximately 650 years back to an older age. b) The "wiggly" section of the calibration curve leads to three different solutions for the calendar age spanning 250 years. The calibration has been performed with the program OxCal using the INTTCAL98 calibration curve [12]. The small rectangular brackets beneath the peaks indicate fractions of the 68.2% (1 σ)confidence ranges of 3360BC to 3330BC (0.44), 3210BC to 3190BC (0.29), and 3160BC to 3130BC (0.28). The large brackets indicate the 95.4% (2 σ) confidence fractions of 3370BC to 3320BC (0.36), and 3230BC to 3100BC (0.64).

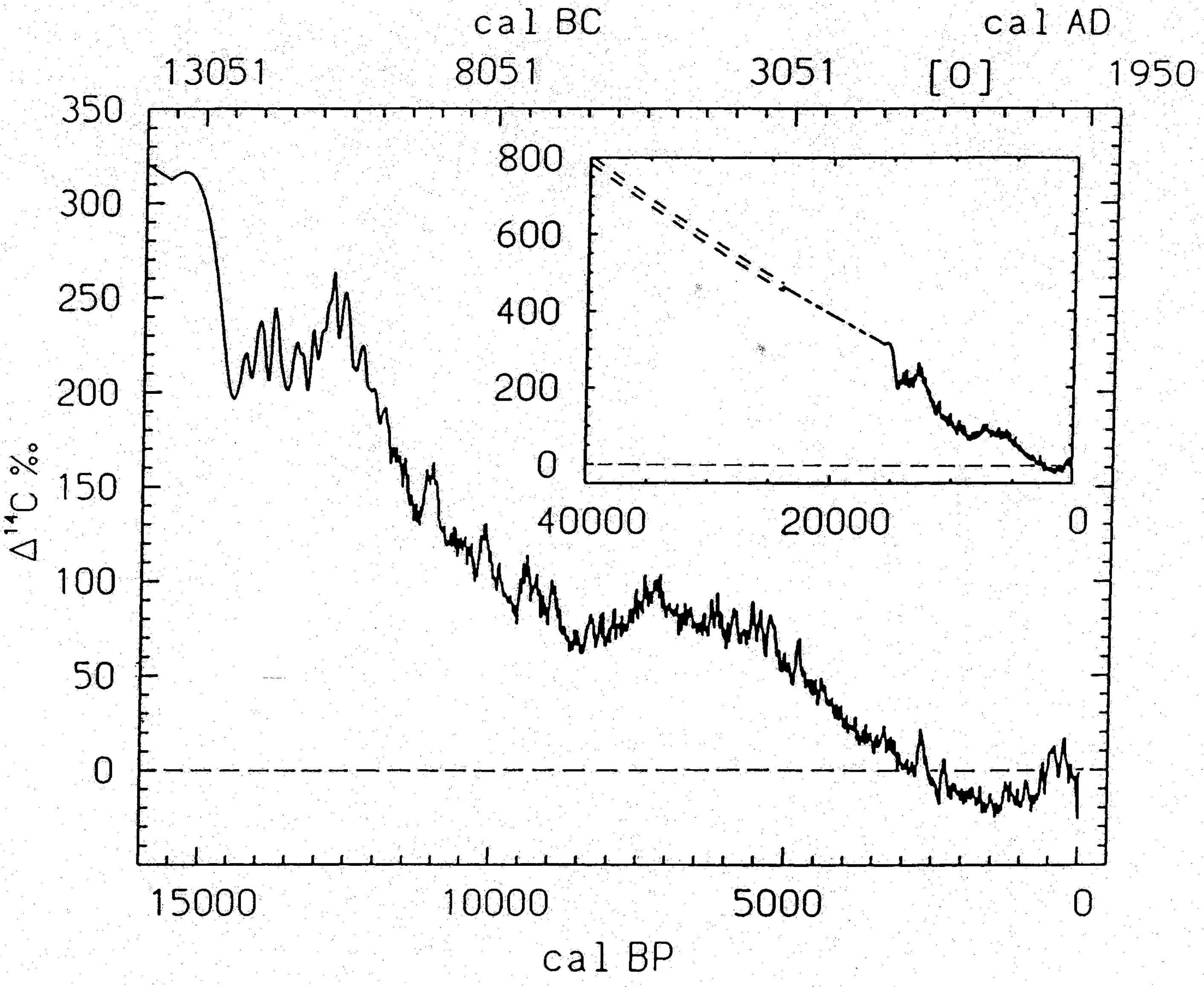
Fig, 6 Comparison of time periods for cultures north and south of the Alps during the latest part of the Neolithicum with the time period of Ötzi [27]. This comparison allows archaeologists to reduce the number of cultures from which Ötzi might have originated.

Fig. 7 Summary of measurements on equipment and other objects found at the Ötzi site.[31]. Horizontal bars indicate 95.4% confidence ranges (2 σ). The dashed vertical lines show the 2-σ range obtained from tissue and from bone samples measured at the AMS laboratories of Zürich [25] and Oxford [26].

Fig. 1

Fig. 2

Fig. 3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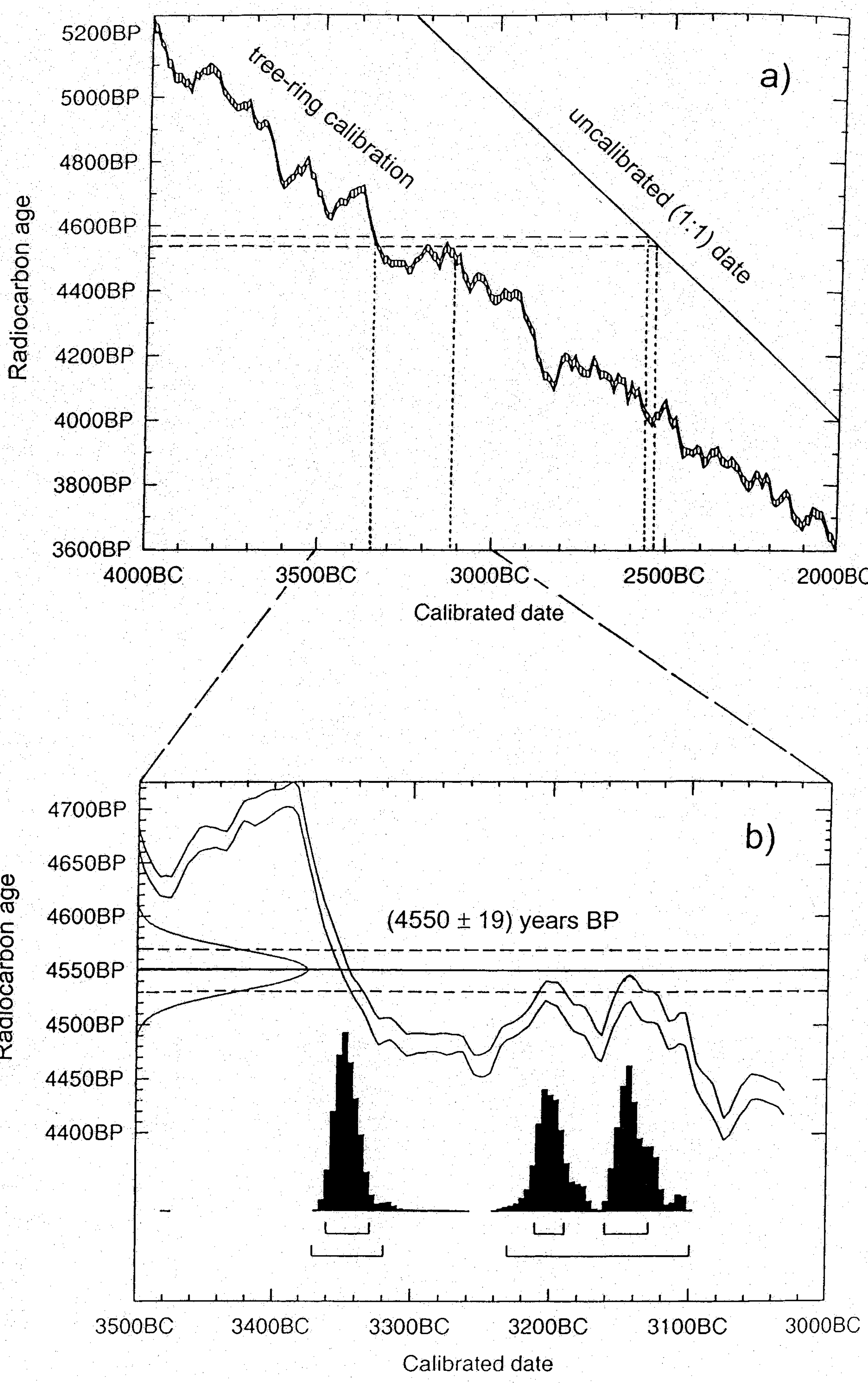
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Fig. 5

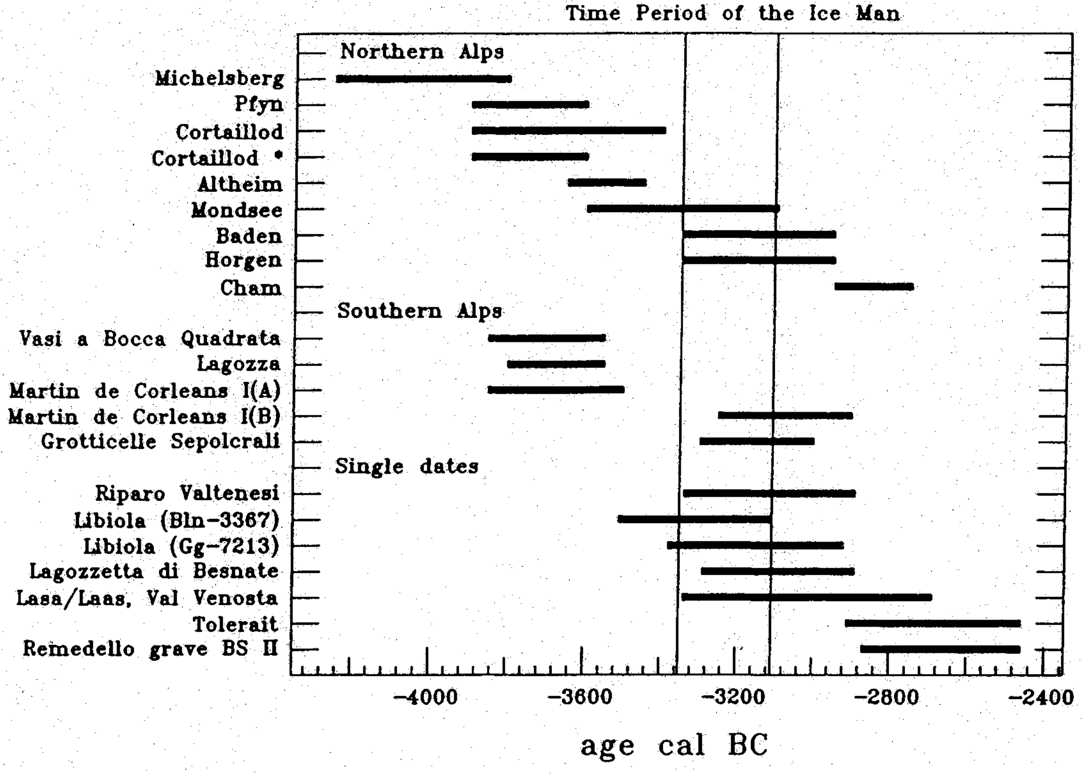
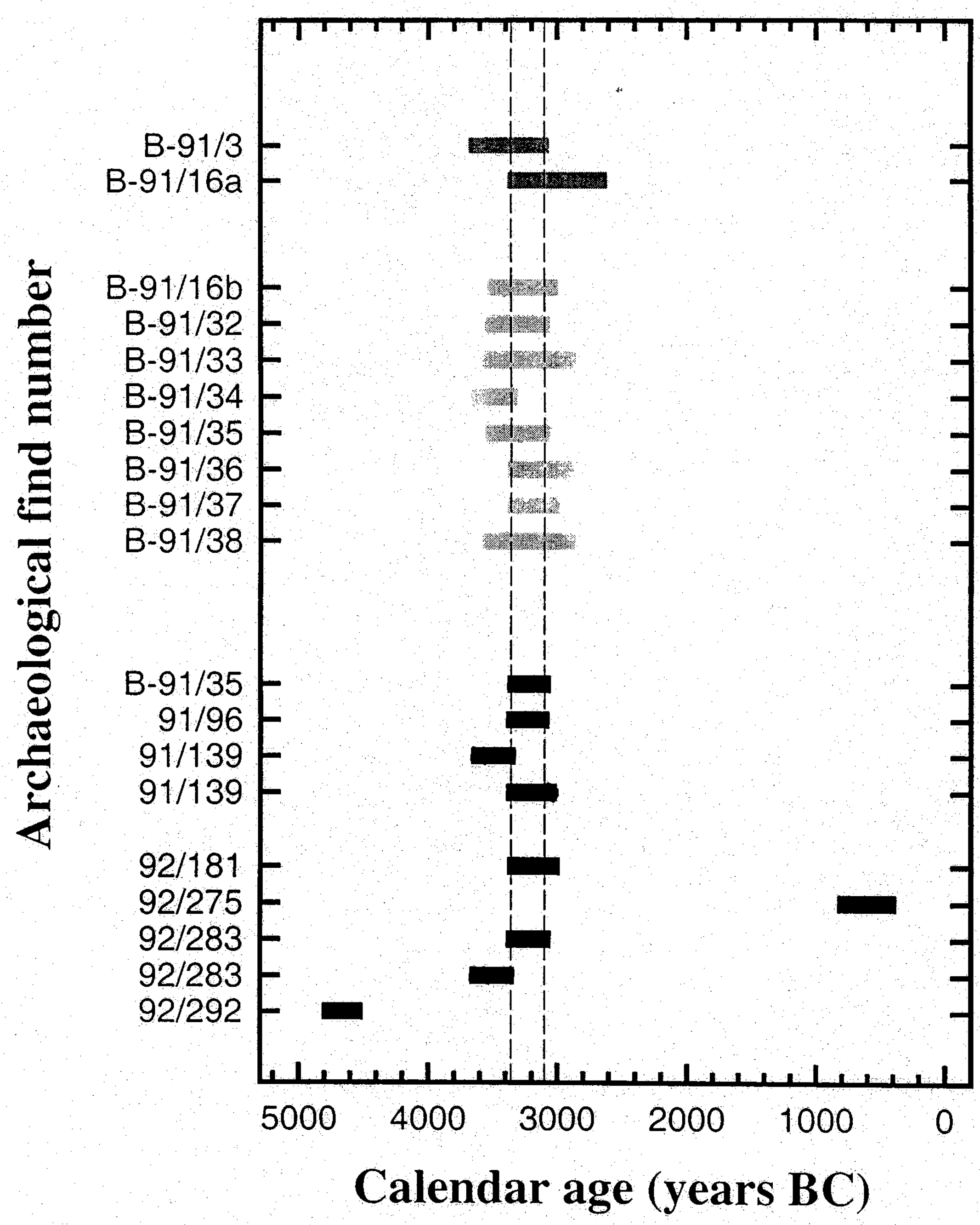

Time Period of the Ice Man
Northern Alps
Michelsberg
Pfyn
Cortaillod
Cortaillod *
Altheim
Mondsee
Baden
Horgen
Cham
Southern Alps
Vasi a Bocca Quadrata
Lagozza
Martin de Corleans I(A)
Martin de Corleans I(B)
Grotticelle Sepolcrali
Single dates
Riparo Valtenesi
Libiola (Bln-3367)
Libiola (Gg-7213)
Lagozzetta di Besnate
Lasa/Laas, Val Venosta
Tolerait
Remedello grave BS II
-4000
-3600
-3200
-2800
-2400
age cal BC

Fig. 6



AMS lab and sample material

Uppsala:
Leaves, Grasses (*Poaceae*)
Leaves, Grasses (*Poaceae*) a)

Gif-sur-Yvette:
Leaves, Grasses (*Poaceae*) a)
Stiffening of the quiver, Hazel (*Corylus avellana*)
Wood from the pannier, Hazel (*Corylus avellana*)
Wood from the pannier, Hazel (*Corylus avellana*)
Wood from the bow, Yew (*Taxus baccata*)
Wood from the axe-shaft, Yew (*Taxus baccata*)
Wood from the pannier, Hazel (*Corylus avellana*)
Leaves from the ember vessel,
Norway Maple Tree (*Acer platanoides*)

Vienna:
Wood from the bow, Yew (*Taxus baccata*)
Wood, Hazel (*Corylus avellana*)
Charcoal from the ember vessel, Conifers
Leaves from the ember vessel,
Norway Maple Tree (*Acer platanoides*)
Leather
Wood, binding material, Green Alder (*Alnus viridis*)
Hairs, Ibes (*Capra ibex*)
Mosses (*Polytrichum sexangulare*)
Wood, Pine (*Pinus* sp.)

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a) parallel samples

Fig. 7