Start of the last interglacial period at 135 ka: Evidence from a high Alpine speleothem

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ABSTRACT

A detailed study of growth periods of a flowstone from Spannagel Cave in the Zillertal Alps (Austria) at ~2500 m above sea level, a site highly sensitive to climate changes, offers unprecedented new insights into Pleistocene climate change in Central Europe. Flowstone sample SPA 52 has a high U content (to 116 ppm); analyses of this sample reveal that episodes of calcite deposition started at 204 ± 3 ka, 135 ± 1.2 ka, and 122 ka, suggesting that at these times, the mean air temperature at this high Alpine site was within 1.5 °C of the present-day condition. The beginning of growth at 135 ka corresponds to the ending of the last glaciation and is concordant with a midpoint age for the penultimate deglaciation at 135 ± 2.5 ka, as deduced from the absolutely dated oxygen isotope curve in sediments from the Bahamas, as well as with recent coral evidence from Barbados indicating a high sea level already by 135.8 ± 0.8 ka. This set of data supports evidence against Northern Hemisphere forcing of termination II, because the insolation maximum is at 127 ka.

Keywords: Pleistocene, interglacial, speleothems, uranium-series method, Alps.

INTRODUCTION

Transitions from glacials into interglacials, known as terminations, are key elements of Earth's climate system. Our knowledge of the onset and duration of interglacials prior to the Holocene relies primarily on data from corals, which track the sea level. Most of these data, particularly those of sea-level highstands, are consistent with the Milankovitch orbital-forcing theory (Stirling et al., 2001). However, there is a growing body of evidence suggesting that factors other than changes in the summer insolation at 65°N may have triggered the rapid deglaciations (Winograd et al., 1997; Esat et al., 1999; Henderson and Slowey, 2000; Gallup et al., 2002).

Here we report the first precisely dated climate record of Alpine Europe that extends back beyond the last glacial cycle and provides evidence against Northern Hemisphere climate forcing during termination II.

GEOLOGICAL SETTING

We examined speleothem samples from a newly investigated high-altitude cave site in the Central Alps of Austria, Spannagel Cave (Fig. 1). The cave developed beneath a broad ridge extending from 2531 m, where the main entrance to the cave is located, down toward the north-northwest, and reaching ~2300 m ground elevation above the northernmost cave termination. The cave has a long and probably complex history, as indicated by a series of Th-U and U-Pb dates of speleothems extending from the Holocene to as old as ca. 524 ka (Spötl et al., 2002; Cliff and Spötl, 2001). It developed in Jurassic marbles, which are underlain and overlain by gneiss. Its currently surveyed length is 9.1 km. The area above the cave shows typical Alpine soils with grass vegetation. Modern timberline is at 1900–2000 m altitude. During 7–8 months of the year, the surface above Spannagel Cave is snow covered. The cave is close to the currently retreating Hintertux Glacier. During the Little Ice Age, this and a neighboring glacier advanced on both sides of the ridge, leaving behind sharp-crested marginal-moraine ridges (Fig. 1). During the Last Glacial Maximum, the cave was covered by as much as 150–250 m of ice; the glacier-surface elevation above Spannagel Cave was ~2600–2700 m at that time (van Husen, 1987).

SPELEOTHEMS

Calcitic flowstones from Spannagel Cave are very sensitive archives enabling reconstruction of past warm climatic conditions be-

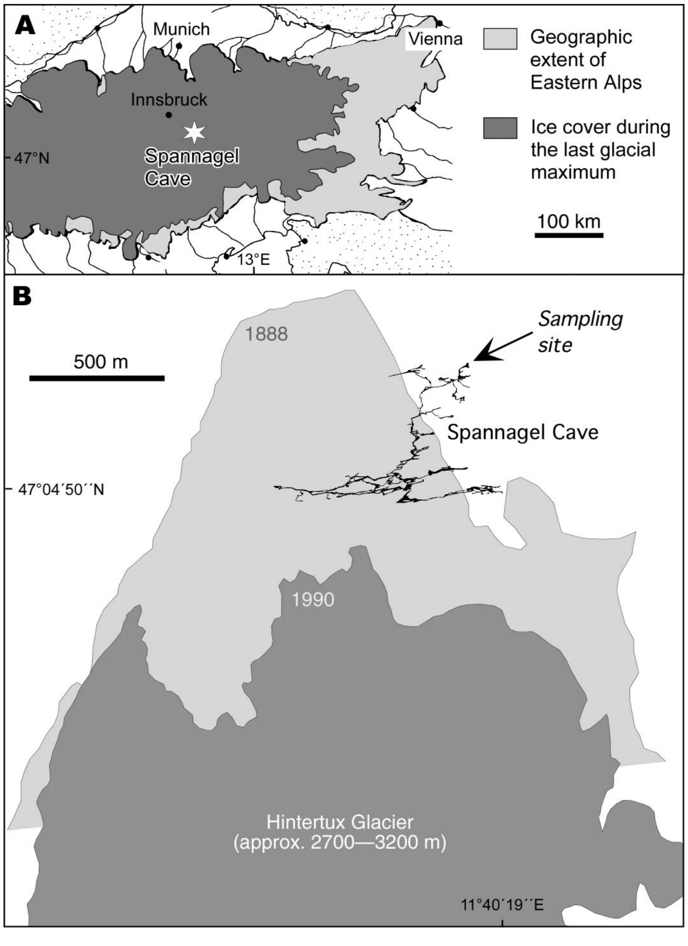

Figure 1. A: Location of Spannagel Cave in western Zillertal Alps, Central Alps of Austria (asterisk). This high Alpine site was well within accumulation area of East Alpine glaciers during Last Glacial Maximum (dark shaded area; nunataks are omitted for simplicity). B: Spannagel Cave adjacent to Hintertux Glacier, which partially covered area above cave during Little Ice Age (glacier extents of 1888 and 1990 shown in light and dark gray shading, respectively). Sample SPA 52 is from flowstone in northern part of cave.

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cause the constant year-round temperature in the interior of this cave is only slightly above freezing (+1.2 to +2.2 °C), which corresponds closely to the mean annual air temperature for this altitude. Although speleothems can rarely form in caves beneath glaciers (Ford et al., 1983; Atkinson, 1983), these are exceptional cases, and it is widely accepted that speleothem deposition, particularly those of laterally extensive flowstone, will completely cease once the surface of the karst is covered by permafrost or ice (Ford and Williams, 1989; Lauritzen, 1993, 1998; Lauriol et al., 1997). We therefore interpret the periods of calcite deposition as evidence of initial warming in the Alps, causing ice-free conditions and the availability of liquid water in the karst-fissure network at 2500 m altitude in the central European Alps.

We sampled a flowstone in the northern part of the cave system, SPA 52 (Fig. 1). The flowstone, having an area of ~4 m^2, is inactive at present, is cut by small erosion gullies, and is partially covered by debris that fell down from the ceiling of the chamber. A second sample, SPA 11, was taken as a control sample from the same flowstone, 40 cm away from SPA 52. Ground elevation above the sampling site is 2345 m, and the cave chamber is ~17 m beneath the surface. Speleothems in this part of the cave are fossil, except for some possibly active stalactites. Other parts of the cave system, however, host speleothems that are clearly active today or have been active throughout the early and middle Holocene, respectively, as shown by Th-U data.

The samples are composed of coarsely crystalline, columnar, detritus-poor, low-Mg calcite. Both samples, SPA 52 and SPA 11, display the same sequence of units, although their thickness is slightly different. The internal stratigraphy is characterized by unconformities (H1 through H3; Fig. 2). These three distinct boundaries separate four consecutive layers of flowstone.

METHODS

Transects across SPA 52 and SPA 11 were microdrilled and analyzed for their oxygen isotope compositions. Samples were analyzed with an on-line, continuous-flow, carbonate preparation system (Gasbench II) linked to a Finnigan Delta plusXL mass spectrometer. Results are reported relative to the Vienna Peedee belemnite (VPDB) standard, and the standard deviations (1σ) of replicate analyses of δ^{18}O are <0.10‰.

Samples for U-series dating were drilled from polished rocks slabs using a 2 mm drill bit. Chemical purification and separation of U and Th followed methods in Frank et al. (2000). Th and U measurements were performed on a Finnigan MAT 262 RPQ with a double-filament technique. Half-lives of ^{234}U and ^{230}Th are based on Cheng et al. (2000). TIMS (thermal ionization mass spectrometry) dates were measured across SPA 52, supplemented by four additional dates from control sample SPA 11. Chemical blanks yielded less than 0.1 ng for both ^{238}U and ^{232}Th. The external reproducibility was determined with concentration measurements of standard solution prepared with NBL 112a (^{238}U = 4.390 ppm) and with an internal standard of ^{230}Th and yields 0.3% and 0.6% (2σ), respectively. Ages were corrected for initial detrital ^{230}Th under the assumption of an activity ratio of ^{230}Th/^{232}Th like that of average crust. The correction is <100 yr, except for one sample (at 13 cm; Data Repository Table DR1[1]) with a value of ~200 yr.

RESULTS

The first episode of calcite growth in flowstone sample SPA 52 is dated between 207 and 180 ka, revealing a warm climatic period in the Alps at the end of marine oxygen isotope stage (MIS) 7. This growth episode is represented by two petrographically distinct units of flowstone (Fig. 2). No calcite is preserved between 180 and 136 ka, which brackets the penultimate glaciation (MIS 6). A second phase of calcite deposition started at 135 ± 1.2 ka (Fig. 2). This calcite is overlain by an unconformity (hiatus H3; Fig. 2), after which bright white calcite formed (122–116 ka). TIMS dates from the second sample (SPA 11) are in agreement with these results (Table 1; see footnote 1).

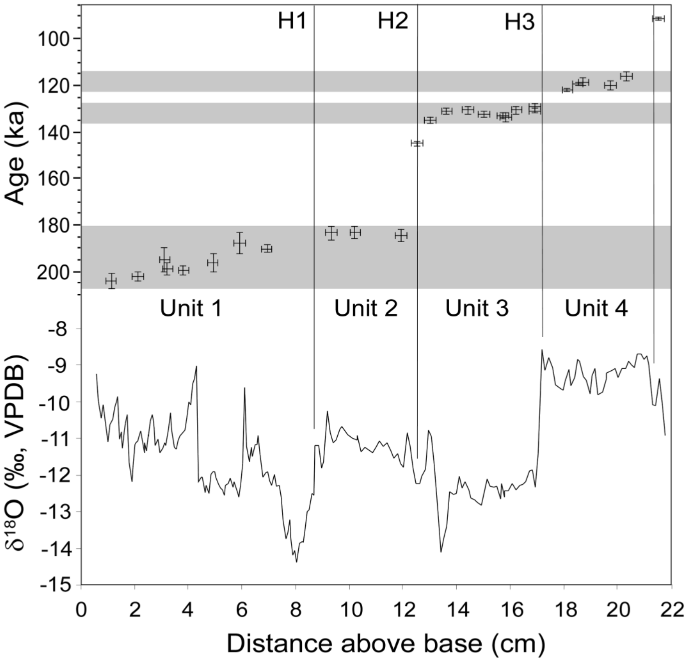

Figure 2. Th-U chronology and oxygen isotope traverse of sample SPA 52 (base of flowstone to left). Sample SPA 52 represents 20 cm of flowstone accretion over gneiss. SPA 11 was used as control run and was sampled at lower resolution than SPA 52 (Table DR1 [see text footnote 1]; results not shown on this graph). Th-U thermal ionization mass spectrometry dates (crosses) are shown with 2σ uncertainties. Note that sample at 145 ka was taken exactly at unconformity between units 2 and 3, and its age probably represents mixture. Topmost layer of unit 4 yielded significantly younger age (91 ka), which suggests minor calcite deposition during late marine oxygen isotope stage 5 (not discussed in this paper). Horizontal shaded bars highlight growth periods. Hiatuses H1–H3 are marked by vertical lines. VPDB—Vienna Peedee belemnite.

The oxygen stable isotopic composition varies substantially, from −14.2‰ to −8.3‰, along the vertical growth direction of the flowstone (Fig. 2). The low-resolution δ^{18}O record in the adjacent speleothem SPA 11 demonstrated the same features as those seen in SPA 52.

DISCUSSION

Th-U dates from Spannagel Cave provide the first precise chronological constraints of climate change in the Alps prior to the Last Glacial Maximum. Given the sensitive high-altitude setting close to the 0 °C isotherm, speleothems for this site are reliable indicators of the presence of ice-free conditions in an area that is adjacent to modern glaciers.

Chronology of Speleothem Deposition

This first growth phase in Spannagel Cave, from 207 to 180 ka, reveals a warm climatic period in the Alps at the end of MIS 7, possibly separated by a period of climate deterioration, as indicated by H1. The duration of H1 was probably short, because the TIMS dates beneath and above the hiatus are within their analytical uncertainties. Because our sampling site is well within the accumulation area of Last Glacial Maximum glaciers (Fig. 1A) and presumably also within that of MIS 6 glaciers, significant buildup of ice cannot have started prior

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[1] GSA Data Repository item 2002095, Table 1, Th-U dates, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

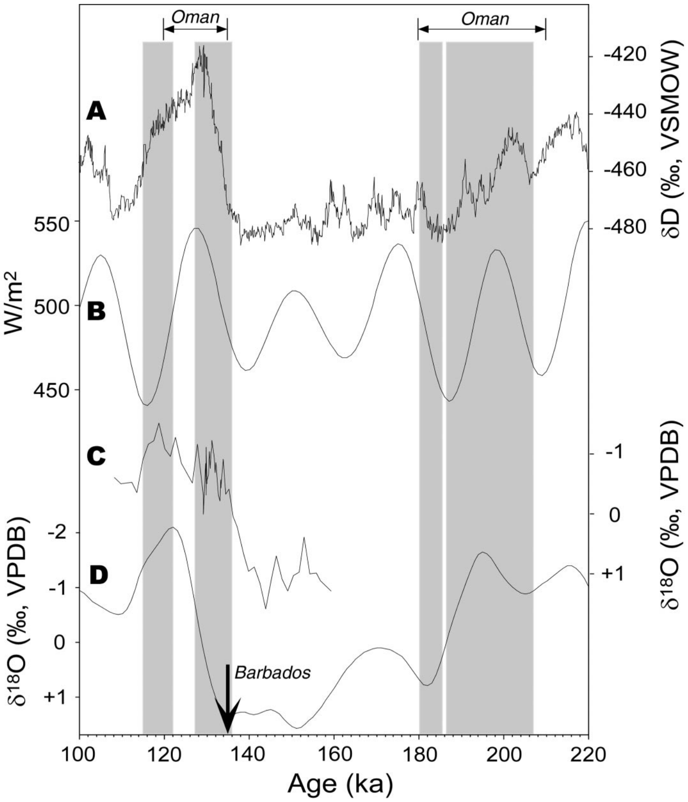

Figure 3. Flowstone accretion (gray bars, as in Fig. 2 except for short hiatus H1 ca. 186 ka, include 2σ analytical errors) in Spannagel Cave during marine oxygen isotope stages 7–5 in comparison to Pleistocene climate records. A: δD of ice at Vostok, proxy of air temperature above Antarctica dated by ice-flow modeling (Petit et al., 1999). B: 65°N summer insolation curve. C: $\delta^{18}O$ of sediments from Bahamas dated by Th-U isochron dates (Henderson and Slowey, 2000). D: Benthic SPECMAP stack (Martinson et al., 1987), proxy for past sea-level change tuned to orbital parameters. Thick vertical arrow indicates high sea level (−18 ± 3 m) at 135 ± 0.8 ka on Barbados, and horizontal arrows indicate ranges of growth periods of speleothems from Oman (Burns et al., 2001). VPDB—Vienna Peedee belemnite; VSMOW—Vienna standard mean ocean water.

to ca. 180 ka. This growth phase in Spannagel Cave coincides with a sea-level highstand from the Mediterranean Coast during MIS 7.3 (190–202 ka; Bard et al., 2002), as well as with a period of growth of stalagmites from Oman (Burns et al., 2001), ascribed to a northern shift of the Intertropical Convergence Zone and enhanced Indian Monsoon (Fig. 3). Because the stalagmite record from Oman shows no further wet phases between MIS 7 and MIS 9, we infer that MIS 7.1 may have been the warmest period in MIS 7. Comparison with the orbitally tuned time scale of the SPECMAP (spectral mapping project) record shows that this growth phase of SPA 52 is difficult to reconcile with the SPECMAP stack, which shows that the MIS 7 to MIS 6 transition had already occurred at 190 ka (Fig. 3).

Although cessation of calcite deposition during MIS 6 is fully conceivable at this high Alpine site, it is interesting to note renewed flowstone deposition at 135 ± 1.2 ka. Because growth can only have started after retreat of the glacier and after air temperatures reached values close to the present-day ones, this age is considered to be a lower limit for the beginning of the warming. Warm temperatures at 135 ± 1.2 ka in the Central Alps support Th-U isochron dates from the Bahamas (Henderson and Slowey, 2000) suggesting a midpoint age for the penultimate deglaciation of 135 ± 2.5 ka, significantly earlier than the timing of termination II of SPECMAP (Fig. 3). Warming in the Central Alps and the Bahamas clearly preceded the 65°N insolation maximum at 127 ka (Fig. 3); this argues against orbital forcing as the trigger for the penultimate deglaciation. Coral data from Huon Peninsula and Western Australia indicate that sea level was already within 14–20 m of the present datum level ca. 135 ka (Esat et al., 1999; Stirling et al., 1998). Gallup et al. (2002) reported combined ^{230}Th and ^{231}Pa dates of corals from the last interglacial terrace on Barbados; these data indicate that sea level was only 18 ± 3 m below the present sea level at 135.8 ± 0.8 ka, demonstrating that most of the termination II sea-level rise occurred before 135 ka.

The episode of growth in SPA 52 at the beginning of MIS 5 is overlain by an unconformity (hiatus H3), after which bright, inclusion-poor calcite typical of interglacial conditions formed (until 116 ka). The unconformity that underlies this calcite layer indicates a cessation of calcite deposition at this site and partial dissolution. The origin of this hiatus remains elusive. Growth cessation could be related to a period of climatic deterioration, which would be in accordance with data from a variety of climate archives elsewhere, suggesting that the initial warming during the penultimate deglaciation was interrupted by a period of colder and drier conditions (Seidenkrantz et al., 1996; Sánchez Goñi et al., 1999). This possible cold event and the following full interglacial also appear synchronously in the $\delta^{18}O$ curve of the MIS 5e section of the Bahamas (Henderson and Slowey, 2000) (Fig. 3). Alternatively, the lack of calcite may be a site-specific phenomenon reflecting switching of seepage water routes across a surface for the flowstone. Ongoing work on additional samples from other cave sections will help to resolve this ambiguity.

The second period of rapid speleothem deposition between 122 and 116 ka indicates fully interglacial conditions at this high Alpine site, consistent with the rise in oxygen isotope values (see next section). The top age of 116 ka is consistent with the end of the last interglacial, as suggested by Shackleton et al. (2002) in their study of marine cores off the coast of Portugal.

Oxygen Isotope Record

The oxygen isotope data permit further constraints on the processes that governed the formation of these high-altitude speleothems. That today's cave's interior temperatures are only slightly above freezing suggests that the oxygen isotope variations recorded in SPA 52 most likely reflect temporal changes in water sources.

Mean annual air temperature is known to correlate with the oxygen isotope composition of mean annual precipitation, the latter being higher during warm years and vice versa (Dansgaard, 1964). The $\delta^{18}O$ values lower by 3‰–5‰ than the values during the 122–116 ka period, however, are difficult to reconcile with the presence of liquid water (and hence nonfreezing conditions) in the cave, considering that the present-day air temperature in the cave interior is only +1.2 to +2.2 °C. Under present climatic conditions, this drop in $\delta^{18}O$ requires a decrease in mean annual air temperature of 5–8 °C, which would most likely cause permafrost development above the cave and cessation of speleothem deposition (the lower limit of modern discontinuous permafrost in the Central Alps is 2500–2600 m, according to Lieb [1998]). A gradient sufficiently high to account for the difference in $\delta^{18}O$ while keeping temperatures above 0 °C, however, appears unrealistic.

The large shifts in $\delta^{18}O$ values therefore imply major changes in the source of the seepage waters. Relatively high $\delta^{18}O$ values (−9‰) of calcite deposited during interglacial times are similar to those measured in Holocene speleothems from this cave (Spötl et al., 2002). Modern seepage waters at Spannagel Cave are directly derived from precipitation (rain and snow) that falls on the barren karst surface or percolates through the soil. Significantly lower isotopic values (−14‰) are recorded in the calcite of the upper part of unit 1 (MIS 7.1) and particularly at the beginning of MIS 5 (Fig. 2). It is conceivable that waters entering the karst system at the transition from cold to warm periods were not directly derived from precipitation, but were meltwaters from glaciers. Melting of winter snow during the warm season will transport water having an ^{18}O-depleted signature into the cave that may have dominated the annual δ^{18}O water signature recorded by calcite precipitation.

In essence, the low δ^{18}O values during termination II are consistent with the model of early ice-free conditions in the Central Alps, when summer meltwaters of decaying glaciers entered the karst environment and soils were not yet developed. By 135 ± 1.2 ka, liquid water was present in the cave and speleothems formed. Warming and decay of ice must have been well under way by then. Although there is uncertainty as to the extent of the MIS 6 piedmont glaciers north of the Alps relative to the size of their better known Last Glacial Maximum counterparts (Schlüchter, 1986; van Husen, 2000), the inner Alpine ice cover was probably similar during both glacial maxima. Ice-free conditions at 135 ka in the former accumulation area therefore suggest that the downwasting of MIS 6 valley glaciers was already near completion by that time.

CONCLUSIONS

The growth history of flowstone SPA 52 represents the first precisely dated paleoclimate archive from the Alps for a time period prior to the last glacial cycle. The peculiar physiographic setting of the cave system close to the present-day 0 °C isotherm and adjacent to modern glaciers renders this site exceptionally sensitive to climate change. Deposition of calcite can thus be regarded as evidence for the presence of liquid water and temperatures above freezing. The flowstone preserves segments of calcite deposition during warm periods at the end of MIS 7 and early during termination II as well as during the late MIS 5e. Calcite deposition at 135 ka provides the first chronologically well defined benchmark for the onset of the last interglacial period from a land-based climate archive. The new data are consistent with U-series data from marine records (Henderson and Slowey, 2000; Gallup et al., 2002) indicating that the rise in Northern Hemisphere summer insolation did not trigger the penultimate deglaciation.

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