Early Last Interglacial environmental changes recorded by speleothems from Katerloch (south-east Austria)

CHARLOTTE HONIAT,1,*, DANIELA FESTI,2 PAUL S. WILCOX,1 R. LAWRENCE EDWARDS,3 HAI CHENG4 and CHRISTOPH SPÖTL1

1Institute of Geology, University of Innsbruck, Innsbruck, Austria
2Institute for Interdisciplinary Mountain Research, Austrian Academy of Sciences, Innsbruck, Austria
3Department of Earth Sciences, University of Minnesota, Minneapolis, MN, USA
4Institute of Global Environmental Change, Xi’An Jiaotong University, Xi’an, China

Received 23 July 2021; Revised 4 November 2021; Accepted 10 November 2021

ABSTRACT: In the European Alps, the Last Interglacial (LIG, ~129–116 ka) has been primarily studied using pollen preserved in mires and lake sediments. These records document the vegetation succession across the LIG, but are poorly constrained chronologically. Here, we present a precisely dated stable isotope record for the early LIG (129.6 ± 0.4 to 125.0 ± 0.8 ka) based on two stalagmites from Katerloch, a cave located on the south-eastern side of the Alps. The onset of the interglacial is marked by a sharp rise in the oxygen isotope values at 129.4 ± 0.4 ka, consistent within dating uncertainty with the timing of Termination II as recorded by other Alpine speleothems. Carbon isotope values show an equally prominent drop at Termination II and the establishment of a forest ecosystem. Although concentrations are low, pollen from these stalagmites provide insights into how the local vegetation changed across the first five millennia of the LIG. The spectra indicate a vegetation optimum recorded by the occurrence of warm-demanding taxa typical of the Eemian mesocratic phase. By combining stable isotopes and pollen data, we propose an absolutely dated chronological framework for peri-Alpine pollen successions from lacustrine sediments covering the first half of the LIG. © 2021 The Authors. Journal of Quaternary Science Published by John Wiley & Sons Ltd.

KEYWORDS: European Alps; Last Interglacial; pollen; speleothems

INTRODUCTION

The Last Interglacial (LIG) was the time period about ~129–116 thousand years (ka) before present when global temperatures were as high as or even higher than in the current Interglacial (Kukla et al., 2002; Otto-Bliensnerr et al., 2013, 2021), greenhouse gas concentrations were higher than during pre-industrial times (e.g. CO₂ up to 285 p.p.m.; Landais et al., 2013), sea level was higher (~about 6–9 m above present sea level) and high-latitude ice sheets were smaller (Dutton et al., 2015; Rovere et al., 2016). Today, the climate is being overprinted by Anthropocene warming, and the modern global temperature is now approaching the warmth of the LIG (Bova et al., 2021). Although the LIG is not a perfect model for the Holocene, mainly due to a different orbital configuration (Yin and Berger, 2015), there is a growing interest in the paleoclimate community to study and document this most recent interglacial before the Holocene as a ‘test bed’ for climate model projections in a purely natural climate forcing scenario (Lunt et al., 2013; Fischer et al., 2018; Otto-Bliensnerr et al., 2021). Mountain regions are ideal sites to investigate the magnitude and impact of climate warming because there are clear indications that the warming rate is amplified with elevation (Pepein et al., 2015). Examples of this include the warming retreat rate of Alpine glaciers and thawing permafrost (e.g. Zekollari et al., 2019; Sommer et al., 2020). In addition, warming of mountain regions has been shown to result in an acceleration of biodiversity change in Alpine ecosystems (Steinbauer et al., 2018).

In the foreland of the European Alps, the LIG has been studied using pollen and plant macro remains preserved in mires and lake sediments (e.g. Woillard, 1979; Drescher-Schneider, 2000; Müller et al., 2005; Pini et al., 2010). These records provide the most detailed and comprehensive record of vegetation changes during the LIG, and include attempts to quantify temperature (Guiot et al., 1989; Kühl and Litt, 2007; Brewer et al., 2008). These studies suggest rather stable temperatures during the LIG with an early optimum followed by a slight cooling. Some of these data were compared to paleoclimate model output (Kaspar, 2005) indicating higher temperatures than today and a W–E gradient in winter temperature with increasing anomalies towards eastern Europe. Although well documented, the timing of these vegetation changes is poorly constrained chronologically (Govin et al., 2015). These chronologies are either unconstrained by radiometric dating (Drescher-Schneider, 2000) or based on correlation [e.g. with orbitally tuned marine records (Müller et al., 2005) or regional speleothem data (Sirocko et al., 2005)]. One of the very few direct age constraints is a 230Th date (128 ± 4 ka) from a peat layer in lacustrine sediments from Füramoos in Bavaria, but no analytical data were reported in this study (Müller et al., 2003). Varved, i.e. annually laminated, sediments spanning the LIG are rare, and only the record from Lago Grande di Monticchio in central Italy (Brauer et al., 2007) seems to cover the full duration of the interglacial. A revised chronology using tephras layers resulted in a mean age uncertainty of 5% (Wulf et al., 2012). Little data are available on non-biological proxies from LIG lake sediments in Europe. Bulk carbonate samples from lake Mondsee in Austria...
record a two-step increase in $\delta^{18}$O at the onset of the LIG followed by rather constant values during the course of the LIG, but the chronology is based on pollen biostratigraphy only (Drescher-Schneider and Papesch, 1998).

Speleothems offer superior age control and can contain sufficient pollen to provide information on the vegetation outside the cave (McGarry and Caseldine, 2004; Dredge et al., 2013; Festi et al., 2016). An increasing number of speleothem records spanning (part of) the LIG have been reported from the Alpine realm (Spötl et al., 2002, 2007; Meyer et al., 2008; Häuselmann et al., 2015; Moseley et al., 2015; Johnston et al., 2021) and their environmental interpretation is largely based on stable isotope proxies. More recent speleothem studies from this mountain range attempted to quantify temperature variations during the LIG (Johnston et al., 2018; Wilcox et al., 2020), while only one study looked into pollen preserved in stalagmites to reconstruct the paleo-vegetation in the Western Alps (Luetscher et al., 2021). In this paper, we present stable isotope data along with a pollen record from two speleothems overlapping in age from a cave from the south-eastern fringe of the Alps. Constrained by $^{230}$Th dates, the isotope record is first compared to Alpine speleothems and then with other European records. Subsequently, both the isotope and pollen record are compared to peri-Alpine lake sediments lacking radiometric age to provide, for the first time, a chronology for their respective pollen zones during the first half of the LIG.

Site description

Katerloch Cave is located at the south-eastern fringe of the Alps, in the Austrian province of Styria (Fig. 1). This region is also known as the ‘Styrian Karst Province’, and the cave host rock is a Devonian limestone (Schöckelkalk). The cave opens at an altitude of 901 m a.s.l. (47.25316°N, 15.55064°E) 20 km north of Graz. The cave developed in a forested ridge dominated by spruce [Picea abies (L.) H. Karst], beech (Fagus sylvatica L.), maple (Acer pseudoplatanus L.), ash (Fraxinus excelsior L.), whitebeam [Sorbus aria (L.) Crantz] and hornbeam (Carpinus betulus L.) (Pratl, 1971). The cave follows the general dip of the host limestone and comprises a series of halls and narrow connections in between. The large entrance hall is followed by a 50-m shaft (Eulenschacht) which connects to the underlying Marteldom. The entrance area is also now connected via a narrow artificial shaft to the speleothem-rich chambers: the Phantasiehalle (where our two stalagmites were retrieved), Zauberreich and the Halle der Einsamkeit. Adjacent to the Zauberreich is the deepest known section of the cave, Seeparadies. The explored maximal vertical distance from the
The cave entrance to the deepest point is 135 m and the total length is slightly over 1 km (Boch et al., 2009).

In terms of climate the cave site receives Atlantic moisture from the west and north-west and is also under the influence of Mediterranean air masses from the south (which are most pronounced during spring and autumn, including local summer thunderstorms). During winter, the North Atlantic Oscillation influences the regional climate (Boch et al., 2009). There is an intermittent snow cover at the site between winter and early spring. The mean annual air temperature measured at the cave entrance is 8°C (2006 to 2008) and ~4°C in Phantasiehalle (Boch et al., 2011), reflecting a cold-trap behavior of the cave which shows a descending geometry lacking a lower entrance.

Katerloch cave is a well-studied and well-monitored cave (Boch, 2008; Boch et al., 2009, 2011). The cave’s micro-meteorology has been modified to some extent because two short tunnels were blasted during show cave development in the 1950s. This probably led to an intensification of the cave ventilation by enhanced winter cooling due to the descending geometry of the cave. A comparison of stable isotope data of modern, late (i.e. pre-show cave) and early Holocene calcite suggests, however, that the effect of the modified cave micrometeorology on the stable isotope composition of calcite is minor. Late Holocene (0.6–2.5 ka) specimens show mean δ18O and δ13C of ~6.1 and ~7.5‰, respectively (Boch, 2008), i.e. the C isotope values of post-1950s calcite is actually lower than that of pre-show cave calcite, arguing against enhanced CO2 degassing and concomitant kinetic isotope fractionation in recent decades. Early Holocene (7–10 ka) speleothems yielded mean δ18O of 6.3 and ~7.9‰ (stalagmite K1) and ~6.3 and ~8.5‰ (stalagmite K3), respectively (Boch et al., 2009), similar to those of the late Holocene samples.

**METHODOLOGY**

**Sampling and petrography**

Stalagmites K2 and K4 were found broken in the same cave room (Phantasiehalle). Their top parts are missing. The stalagmites were cut in half with a diamond blade saw, polished and scanned (Fig. 2). Thin sections were cut along the growth axes of the stalagmites, polished and analyzed using a Nikon Eclipse polarizing microscope.

**230Th dating**

Nine (K4) and eight (K2) samples were hand-drilled along the speleothem growth axis for 230Th dating (Table 1). Between 120 and 180 mg of calcite was used given the low U concentrations (between 80 and 140 p.p.b. for K4 and between 60 and 100 p.p.b. for K2). The samples were prepared following the chemical procedure described by Edwards et al. (1987). The measurements were performed on a Thermo Fisher Neptune Plus MC-ICP-MS at the Xi’an Jiaotong University in China, using the technique described by Cheng et al. (2013).

**Stable isotopes**

Subsamples were microdrilled along the extension axis of both stalagmites at a resolution of 5 mm using a handheld drilling device to obtain ca. 0.3 mg of calcite. Between 250 and 278 stable isotope measurements (SI) were carried out along the growth axis of each stalagmite at a resolution of 5 and 2.5 mm where growth rate slowed down in one section of K2. The isotope analyses were performed using a Delta V Plus isotope ratio mass spectrometer linked to a Gasbench II (both Thermo Fisher, Bremen, Germany; Spötl, 2011) at the University of Innsbruck. Calibration of the instrument was accomplished using international reference materials and the results are reported relative to VPDB. Long-term precision on the 1-sigma level is 0.06 and 0.08‰ for δ18O and δ13C, respectively.

**Pollen analyses**

A total of 14 calcite samples from both stalagmites were processed for pollen, whereby the sample weight ranged from 167 to 460 g per sample for a total of about 4.6 kg of calcite. Pollen and microfossil extraction followed a protocol developed for calcite samples with low pollen content, which allows us to avoid decantation steps preventing the potential loss of microfossils. This was achieved using a combination of filtration and evaporation steps as well as avoiding acetolysis. Pollen extraction included the following steps: (1) weighing, (2) cleaning using HCl (10%; 3–5 s), (3) cleaning with double distilled water, (4) drying at 40°C, (5) weighing, (6) adding HCl (10%) to dissolve carbonates, (7) adding double distilled water (5–10x the amount of HCl), (8) filtering using a 7-μm filter, (9) transferring the content of the filter into a sample tube, (10) adding a few drops of ethanol (96%), (11) adding one drop of glycerol and (12) evaporation at 95°C. To control eventual contamination sources, a blank consisting of double distilled water was added to every batch of samples prepared. Pollen samples were mounted in glycerol, stained with fuchsin and the complete content of microfossils was analyzed. Pollen identification was performed by transmitted-light microscopy at magnifications of 400x and 600x using standard identification keys (Moore et al., 1991; Faegri et al., 1992; Beug, 2004) and a pollen atlas (Reille, 1992). Where the identification of morphological features was not possible, the pollen grains were classified as ‘indeterminata’. Pollen counts were plotted using the C2 software (luggins, 2007)

**RESULTS**

**Petrography**

The fabric of the two stalagmites consists of coarsely crystalline columnar calcite. Macroscopic lamination is noticeable, consistent with white, porous laminae alternating with translu-cent and more compact laminae. The same alternation is also observed microscopically in thin sections. No petrographic evidence of hiatuses was observed.

**230Th dating and age model**

Uranium concentrations of both stalagmites are low, but the detrital 232Th contamination is also low, resulting in relative age uncertainties of 0.37–0.57% (Table 1). OxCal and a Poisson-process deposition model (Ramsey and Lee, 2013) was used to establish depth–age relationships for both stalagmites (Supporting Information Figs. S1 and S2). The average growth rate is 0.45 mm a−1 for K4 and regular along the whole record, while the average growth rate for K2 is 0.42 mm a−1, but with one slower growth section between 127.6 ± 0.5 and 126.2 ± 0.5 ka. The recorded growth intervals of both stalagmites are relatively short: K2 (102 cm) formed from ca. 125.0 ± 0.7 to 128.6 ± 0.5 ka, while K4 (126 cm) covers the period from ca. 126.8 ± 0.5 to 129.6 ± 0.4 ka.
Figure 2. Scan of the longitudinal cross-section of stalagmites K2 and K4 (top right), with the sampling location for stable isotopes, $^{230}$Th dating, and pollen with their sampling distance from top (DFT). Note that the pollen samples were taken on the other half of the stalagmite slabs. [Color figure can be viewed at wileyonlinelibrary.com]
Table 1. $^{230}$Th dating results for stalagmites K2 and K4; ages are given in years BP with 2σ uncertainties. Samples K2-1667-A and B are replicates, where a larger amount of powder was drilled, mixed and divided into two aliquots.

| Sample no. | $^{230}$U (p.p.b.) | $^{232}$Th (p.p.t.) | $^{230}$Th/$^{232}$Th (atomic x10$^{-6}$) | $\delta^{234}$U* (measured) | $^{230}$Th/$^{238}$U (activity) | $^{230}$Th age (yr) (uncorrected) | $^{230}$Th age (yr) (corrected) | $\delta^{234}$U$_{initial}$ (corrected) | $^{230}$Th age (yr BP)$^2$ |
|-----------|-------------------|---------------------|---------------------------------|-------------------------|-------------------------------|-------------------------------|-------------------------------|---------------------------------|---------------------|
| K2-665    | 64.5 ± 0.1        | 596 ± 12            | 1724 ± 35                       | 354.7 ± 1.9             | 0.9671 ± 0.0019               | 125 973 ± 564                | 125 794 ± 577                | 506 ± 3                        | 125 725 ± 577          |
| K2-858    | 75.5 ± 0.1        | 148 ± 3             | 8072 ± 168                      | 345.1 ± 1.9             | 0.9579 ± 0.0020               | 125 609 ± 572                | 125 571 ± 572                | 492 ± 3                        | 125 502 ± 572          |
| K2-1030   | 74.4 ± 0.1        | 135 ± 3             | 8642 ± 180                      | 336.3 ± 1.9             | 0.9501 ± 0.0019               | 125 426 ± 563                | 125 390 ± 563                | 479 ± 3                        | 125 321 ± 563          |
| K2-1187   | 85.3 ± 0.1        | 157 ± 3             | 8364 ± 172                      | 312.1 ± 2.0             | 0.9312 ± 0.0020               | 125 957 ± 599                | 125 919 ± 599                | 445 ± 3                        | 125 850 ± 599          |
| K2-1298   | 78.5 ± 0.1        | 87 ± 2              | 13 854 ± 299                    | 298.3 ± 2.1             | 0.9312 ± 0.0020               | 128 167 ± 648                | 128 144 ± 648                | 428 ± 3                        | 128 073 ± 648          |
| K2-1385   | 87.4 ± 0.1        | 123 ± 3             | 10 912 ± 230                    | 304.0 ± 2.0             | 0.9316 ± 0.0023               | 127 627 ± 690                | 127 596 ± 690                | 436 ± 3                        | 127 529 ± 690          |
| K2-1425   | 98.7 ± 0.1        | 121 ± 3             | 12 532 ± 262                    | 294.3 ± 2.2             | 0.9291 ± 0.0023               | 128 439 ± 727                | 128 414 ± 727                | 423 ± 3                        | 128 344 ± 727          |
| K2-1667-A | 104.8 ± 0.1       | 167 ± 3             | 95 48 ± 198                     | 288.5 ± 1.8             | 0.9248 ± 0.0018               | 128 538 ± 579                | 128 505 ± 579                | 415 ± 3                        | 128 436 ± 579          |
| K2-1667-B | 105.1 ± 0.1       | 159 ± 3             | 10 075 ± 208                    | 286.7 ± 1.6             | 0.9238 ± 0.0017               | 128 663 ± 542                | 128 632 ± 543                | 412 ± 3                        | 128 563 ± 543          |
| K4-10     | 81.2 ± 0.1        | 267 ± 5             | 4 383 ± 89                      | 230.9 ± 2.0             | 0.8738 ± 0.0017               | 127 323 ± 622                | 127 251 ± 624                | 331 ± 3                        | 127 181 ± 624          |
| K4-270    | 83.1 ± 0.1        | 198 ± 4             | 60 38 ± 123                     | 229.3 ± 1.9             | 0.8744 ± 0.0015               | 127 816 ± 576                | 127 763 ± 577                | 329 ± 3                        | 127 693 ± 577          |
| K4-325/315| 85.0 ± 0.1        | 232 ± 5             | 5287 ± 107                      | 235.8 ± 1.7             | 0.8756 ± 0.0017               | 126 768 ± 561                | 126 708 ± 562                | 337 ± 2                        | 126 638 ± 562          |
| K4-490    | 95.1 ± 0.1        | 255 ± 5             | 5313 ± 107                      | 216.8 ± 1.9             | 0.8637 ± 0.0016               | 127 643 ± 585                | 127 583 ± 586                | 313 ± 2                        | 127 513 ± 586          |
| K4-700    | 107.3 ± 0.1       | 170 ± 3             | 8 906 ± 182                     | 206.5 ± 1.4             | 0.8578 ± 0.0013               | 128 277 ± 471                | 128 242 ± 471                | 297 ± 2                        | 128 171 ± 471          |
| K4-820    | 143.7 ± 0.2       | 378 ± 8             | 5 387 ± 109                     | 202.3 ± 1.7             | 0.8587 ± 0.0017               | 129 448 ± 611                | 129 389 ± 612                | 291 ± 2                        | 129 319 ± 612          |
| K4-970    | 123.7 ± 0.1       | 305 ± 6             | 57 26 ± 116                     | 199.7 ± 1.5             | 0.8566 ± 0.0016               | 129 180 ± 548                | 129 124 ± 550                | 286 ± 2                        | 129 054 ± 550          |
| K4-1110   | 127.2 ± 0.2       | 540 ± 11            | 3 196 ± 64                      | 193.2 ± 2.0             | 0.8526 ± 0.0018               | 129 820 ± 671                | 129 720 ± 674                | 279 ± 3                        | 129 650 ± 674          |
| K4-1250   | 126.1 ± 0.1       | 284 ± 6             | 6 251 ± 126                     | 196.6 ± 1.7             | 0.8545 ± 0.0014               | 129 505 ± 539                | 129 458 ± 540                | 284 ± 2                        | 129 398 ± 540          |

U decay constants: $\lambda_{238} = 1.55125 \times 10^{-10}$ (Jaffey et al., 1971) and $\lambda_{234} = 2.82206 \times 10^{-6}$ (Cheng et al., 2013). Th decay constant: $\lambda_{230} = 9.1705 \times 10^{-6}$ (Cheng et al., 2013). Corrected $^{230}$Th ages assume the initial $^{230}$Th/$^{232}$Th atomic ratio of 4.4 ± 2.2 × 10^{-6}. Those are the values for a material at secular equilibrium, with the bulk earth $^{232}$Th/$^{238}$U value of 3.8. The errors are arbitrarily assumed to be 50%.

* $\delta^{234}$U$_{initial}$ was calculated based on $^{230}$Th age (T), i.e. $\delta^{234}$U$_{initial} = \delta^{234}$U$_{measured} \times e^{234xT}$.

*σ stands for 'Before Present' where the 'Present' is defined as the year 1950 AD.
Stable isotopes

Stalagmite K4 started growing 129.6 ± 0.4 ka ago and records the onset of the LIG. The record begins with values of −10‰ for δ18O and −6‰ for δ13C (Fig. 3). Shortly after, there is a rapid rise in δ18O of about 2.5‰ centered at 129.4 ± 0.4 ka and a slightly delayed drop in δ13C of 4‰. A small drop in δ18O (by ~0.5‰) occurs between 128.9 and 128.6 ka, followed by a gradual increase towards a first maximum at 128.4 ka. The remainder of the δ18O record shows an overall slightly increasing trend with superimposed small-scale variations of <~0.5‰ (Fig. 4). The δ13C values depict no long-term trend. The isotope record ends at 126.7 ± 0.5 ka, and the uppermost part of stalagmite K4 is missing.

Pollen analyses

Pollen grains recovered from the Katerloch speleothems are well preserved, and no signs of corrosion or abrasion of the sporopollenin were observed. All speleothem samples contained pollen, with absolute values ranging from four to 339 pollen grains (Fig. 4), leading to a minimum concentration of 0.015 pollen g⁻¹ (K4-90-108; 129.0 ± 0.4 ka), and a maximum of 0.78 pollen g⁻¹ (K2-151-166; 128.4 ± 0.5 ka) (Table 2). Blank samples contained no pollen or spores.

Between 129.6 ± 0.4 and 129.3 ± 0.4 ka (samples K4/119-126 and K4/108-118) the pollen spectra are characterized mainly by the occurrence of Pinus sylvestris/mugo-type (pine), Alnus viridis (green alder), Juniperus (juniper), Salix (willow), and a variety of grasses and fern spores. Between ~129.0 and ~127.8 ka (K4/90-108; K4/74-90; K4/59-74) first thermophilous elements appear, such as Quercus robur-type (common oak), Tilia (lime), Corylus avellana (hazel) and Hedera (ivy), along with pine pollen and the first Picea (spruce) occurrences. While between ~129.6 and ~128.6 ka the pollen concentration remains low, it increases greatly at 128.4 ka reaching its maximum. Sample K2/151-166, dated between 128.6 ± 0.5 ka and 128.2 ± 0.5 ka, yielded the highest pollen and spore concentration (0.78 grains g⁻¹) and pollen counts (339 pollen) and influx (69 grains ka⁻¹ cm⁻²), showing a pollen assemblage rich in warm-demanding trees such as Quercus robur, Ulmus (elm), Tilia and an especially high amount of Hedera, while Pinus values are low. Sample K2/131-150 (between 128.2 ± 0.5 ka and 127.7 ± 0.4 ka) also shows a relatively high concentration and a pollen spectrum similar to the previous sample with the addition of Picea, Carpinus.
During winter, the North Atlantic Oscillation (NAO) controls the temperature and precipitation variability in the southeastern Alpine region (Casty et al., 2005; Efthymiadis et al., 2007). Because of its southerly location, Katerloch also receives moisture from the Western Mediterranean Sea which results in slightly enriched δ18O values of dripwater compared to sites on the northern side of the Alps. The average interglacial δ18O values of the Katerloch speleothems are, however, comparable to those of speleothems in Cesare Battisti cave and Bigonda cave in the Italian Alps (Johnston et al., 2018, 2021) and Baradla cave in north-eastern Hungary (Demeny et al., 2017).

Boch et al. (2011, 2009) performed Hendy tests on calcite from the top of actively growing stalagmites as well as on calcite precipitated on glass plates. They observed a distinct enrichment in 13C with increasing distance from the central axis, suggesting some kinetic fractionation. By contrast, the oxygen isotope values were rather stable and a comparison of the measured isotope values and the expected (equilibrium) values, using the temperature-dependent fractionation factor of Friedman and O’Neill (1977), supports year-round modern calcite precipitation close to O isotopic equilibrium (Boch, 2008). Nevertheless, the main control on large carbon isotopic variation in Katerloch speleothems is soil bioproductivity.

The mean stable isotope values for the LIG (excluding the initial rise) and for the time interval where the two records (K2 and K4) overlap (from 126.8 to 128.6 ka) are the same for stalagmites K2 and K4 (−7.6‰ for δ18O and −9.7‰ for δ13C). Both δ18O and δ13C values of the LIG samples are lower than those of present-day and Holocene samples by about 1.3–1.5 and 0.8–2.2‰, respectively. Speleothems from Cesare Battisti

**DISCUSSION**

**Robustness and significance of the stable isotope record**

The oxygen isotopic composition of drip waters and calcite precipitates in caves is controlled by a combination of several factors. These include the oceanic moisture source (ice-volume effect, sea-surface temperature), the trajectories of the air masses, the altitude of cloud condensation, evapotranspiration in the catchment and the temperature in the cave (Rozanski et al., 1992; McDermott, 2004; Lachniet, 2009). In Katerloch, stalagmite δ18O values (−8.6±0.2‰ VPDD for modern calcite) are closely related to the δ18O values of regional meteoric precipitation (mean δ18O precipitation at the cave site ≈−9.3±0.6‰ VSMOW – Boch, 2008), which principally originates from the Atlantic (relatively low δ18O values) with a Mediterranean imprint (slightly enriched δ18O values) (Sodemann and Zuber, 2010) and also reflect the cave air temperature (Boch et al., 2009). The overall oxygen stable isotope pattern from Katerloch stalagmites (K2 and K4) is therefore similar to that of speleothems from other parts of the Eastern (Moseley et al., 2015), Central (Meyer et al., 2008) and Western Alps (Wilcox et al., 2020; Luetscher et al., 2021), which also receive predominantly Atlantic-derived moisture, and where δ18O primarily reflects atmospheric temperature.

**Table 2.** Pollen samples arranged according to their distance from the top (DFT) of the stalagmites, with their respective top and bottom ages, the duration covered by each sample according to the mean growth rate (with 2σ confidence interval) and the pollen concentration and flux.

| Sample name | Sample size (g) | DFT (mm) | Age (a ± 2σ) | Mean growth rate (mm a⁻¹) | 2σ mean growth rate | Duration (a) | Confidence interval (a) | Sum of pollen and spores (grains g⁻¹) | Concentration (grains ka⁻¹ cm⁻²) | Flux (grains ka⁻¹ cm⁻²) |
|-------------|----------------|----------|--------------|--------------------------|---------------------|-------------|-------------------------|-------------------------------------|----------------------------------|-------------------------------|
| K2/59-85    | 263.4          | 3        | 125 031 ± 779| 0.63                     | ±0.42               | 460         | 276                     | 29                                  | 0.11                             | [4–22]                         |
| K2/85-108   | 288.0          | 29       | 125 520 ± 348| 0.66                     | ±0.34               | 342         | 225                     | 57                                  | 0.20                             | [13–41]                        |
| K2/109-130  | 379.6          | 52.5     | 125 994 ± 433| 0.24                     | ±0.30               | 982         | 436                     | 31                                  | 0.08                             | [1–10]                         |
| K2/131-150  | 460.8          | 76       | 127 694 ± 446| 0.37                     | ±0.13               | 483         | 357                     | 92                                  | 0.20                             | [13–28]                        |
| K2/151-166  | 438.0          | 94       | 128 183 ± 458| 0.41                     | ±0.02               | 394         | 374                     | 343                                 | 0.78                             | [73–82]                        |
| K4/0-12     | 177.4          | 12       | 127 021 ± 418| 0.50                     | ±0.12               | 242         | 216                     | 8                                   | 0.05                             | [5–6]                          |
| K4/12-33    | 443.0          | 12       | 127 023 ± 418| 0.51                     | ±0.09               | 410         | 350                     | 22                                  | 0.05                             | [5–8]                          |
| K4/33-44    | 167.7          | 33       | 127 343 ± 338| 0.44                     | ±0.01               | 247         | 240                     | 8                                   | 0.05                             | [5–6]                          |
| K4/44-59    | 293.6          | 44       | 127 682 ± 333| 0.41                     | ±0.05               | 366         | 323                     | 8                                   | 0.03                             | [3]                            |
| K4/59-74    | 354.8          | 59       | 128 048 ± 321| 0.38                     | ±0.06               | 399         | 343                     | 95                                  | 0.27                             | [24–28]                        |
| K4/74-90    | 344.9          | 74       | 128 448 ± 302| 0.40                     | ±0.14               | 399         | 298                     | 8                                   | 0.02                             | [2–3]                          |
| K4/90-108   | 268.6          | 90       | 128 862 ± 313| 0.46                     | ±0.01               | 390         | 381                     | 4                                   | 0.01                             | [2]                            |
| K4/108-118  | 381.7          | 108      | 129 252 ± 332| 0.49                     | ±0.04               | 205         | 190                     | 40                                  | 0.1                              | [13–14]                        |
| K4/119-126  | 355.1          | 119      | 129 469 ± 368| 0.49                     | ±0.05               | 143         | 130                     | 43                                  | 0.12                             | [15–16]                        |
| K4/126-132  | 126            | 126      | 129 621 ± 410| 0.49                     | ±0.05               | 143         | 130                     | 43                                  | 0.12                             | [15–16]                        |

*Based on minimum growth rate of 0.1 mm a⁻¹.
cave in the Southern Alps of Italy yielded evidence of temperatures during the LIG climax up to 4.5 ± 1.9°C higher than during the present day and show the same pattern of lower δ18O values for LIG speleothems as compared to Holocene ones (Johnston et al., 2018). Although this δ18O difference is smaller (0.5‰) than in Katerloch, these two datasets corroborate the hypothesis of enhanced westerlies during the early LIG. In other words, and supported by speleothem studies in Corchia (Drysdale et al., 2009) and Bigonda cave (Johnston et al., 2021), a northward shift of the Intertropical Convergence Zone (ITCZ) permitted more Atlantic-derived moisture to reach the southern side of the Alps, resulting in low δ18O values in speleothems.

**LIG Alpine speleothem records**

Lower δ18O values in Katerloch south-east of the Alps highlight a different control of the O isotopic composition than for sites north of the Alps (Fig. 5). In the latter caves, LIG values are generally higher than those of the Holocene, reaching highest values during the climate optimum in the first half of the LIG. Apart from the local altitude effect (Sieben Hengste ~1700 m a.s.l.; Melchsee-Frutt ~2000 m a.s.l., Schneckenloch-Hölloch ~1200 m a.s.l.) and the correction for the ice-volume effect (Duplessy et al., 2007) the most likely explanation for the lower δ18O values at Katerloch during intervals warmer than the Holocene is a higher input of Atlantic-derived moisture.

![Figure 5. Comparison of speleothem oxygen (red/orange) and carbon (dark/light blue) isotope records from the Alps. The age uncertainty on Termination II for each dataset is represented by a star and an error bar (mean ± 2σ).](wileyonlinelibrary.com)

Katerloch stalagmite K4 precisely captured Termination II at 129.4 ± 0.4 ka with the climate transition lasting only about ~100 years (according to the age model). The timing of Termination II is in good agreement with other precisely dated Alpine speleothems (Fig. 5). A stalagmite from Melchsee-Frutt in central Switzerland recorded it at 129.6 ± 0.8 ka (Wilcox et al., 2020), and a stalagmite from the nearby Sieben Hengste cave system at 129.7 ± 0.8 ka (Luetscher et al., 2021), consistent within uncertainty with the Katerloch chronology, while stalagmites from Schneckenloch and Hölloch caves in western Austria suggest a slightly older age of 130.9 ± 0.9 and 130.7 ± 0.9 ka, respectively (Moseley et al., 2015). This difference could be partly explained by a larger detrital Th content in both the Schneckenloch and Hölloch speleothems, increasing the dating uncertainty and slightly shifting these ages towards older values. The magnitude of the oxygen isotope rise at Termination II is comparable between the five sites (~2‰). Following the termination there is a small drop in δ18O (~0.5‰) from 128.8 ± 0.4 until 128.4 ± 0.5 ka, which could correspond to a cooling event also identified in the Schneckenloch and Hölloch records between 129.1 ± 0.6 and 128.5 ± 0.5 ka (~0.5‰) and attributed to a cold event because of meltwater input into the North Atlantic (Moseley et al., 2015). In the Melchsee-Frutt record, a later intra-LIG cooling event was identified between 125.8 ± 0.5 and 124.6 ± 1.0 ka based on fluid inclusion and stable isotope data (Wilcox et al., 2020). The Katerloch record lacks evidence of a clear-cut cooling event but, given that the record ends at 125.4 ± 0.4 ka, it might have not been recorded.

With respect to the carbon isotopic composition, the most prominent feature is the massive decrease in δ13C (by 4‰), reflecting a rather rapid (~250 years) recovery of the vegetation and associated soil development after the end of the penultimate glacial period. For the remainder of the LIG the flat δ13C values suggest a stable forest ecosystem at the study site. The Sieben Hengste stalagmite recorded an even more abrupt drop in δ13C lagging Termination II by ~90 years (Luetscher et al., 2021). In contrast to Katerloch, this Western Alpine speleothem never reached negative δ13C values, documenting a strong rock-buffering of the C isotope signal or less soil/vegetation activity due to the high elevation. This is also the case for the stalagmites from the nearby Melchsee-Frutt cave system, which even lack a clear expression of early LIG vegetation signal and show a gradual δ13C decrease from 132 ka across the entire LIG (Wilcox et al., 2020). A stalagmite from Schneckenloch does record a marked drop in δ13C, but the age model suggests an earlier timing (~132 ka; Moseley et al., 2015). No distinct signal is recorded by the coeval stalagmite from the nearby Hölloch cave, underscoring the strong site-specific variability of the stable C isotope signal even across major climate shifts.

Lower δ13C values of Katerloch speleothems during the LIG are attributed to milder (and/or shorter) winters and/or a denser vegetation and/or a higher soil bioproductivity, consistent with the general climate interpretation of the LIG in the greater Alpine realm.

**Katerloch and other European records**

The major temperature rise associated with Termination II in our record is synchronous with the sea-surface temperature increase on the Iberian Margin (Martrat et al., 2007; Tzedakis et al., 2018). After the termination, an Atlantic cold event at ~128.5 ka, identified as C28 (Tzedakis et al., 2018), might have been associated with a small negative excursion in δ18O (~0.5‰) recorded in stalagmite K4 (Fig. 6). This cold event is also observed in Melchsee-Frutt (Wilcox et al., 2020) and
Corchia (Tzedakis et al., 2018). While the structure of Termination II in Katerloch is comparable to other Alpine speleothem records, it is different from Corchia cave speleothems (Drysdale et al., 2009; Tzedakis et al., 2018) which show a more gradual transition (Fig. 6) as changes in $^{18}$O from this record primarily reflect variations in rainfall amount. The nearby Tana Che Urla cave reveals a similar structure of Termination II within age error. These two central Italian speleothems have recorded two events of reduced moisture at ca. 129.6 and 126.0 ka, corresponding within error to prior growth of stalagmite K4 for the first one and slower growth rate in K2 for the second. After 128.4 ± 0.5 ka the Katerloch record shows a gradual warming trend until at least 125.4 ± 0.4 ka (when the record ends), consistent with other central European speleothems (e.g. Meyer et al., 2008; Demény et al., 2017; Pawlak et al., 2021) and pollen records (Sirocko et al., 2007; Brewer et al., 2008). Except for the first part of Termination II, the record from Bigonda cave in the Italian Prealps is very similar to Katerloch (Fig. 6), in terms of both structure and mean $^{18}$O isotope values. With comparably low $^{18}$O values during early LIG, both records corroborate the hypothesis of a northward shift in the ITCZ (Johnston et al., 2021) resulting in moisture of lower $^{18}$O values from the Atlantic and a smaller influence of moisture derived from the Mediterranean and the Adriatic Sea.

Reliability of the pollen data
Pollen counts obtained from the Katerloch speleothems are lower than those obtained from sediments (e.g. lakes), but nevertheless yielded pollen spectra typical of the end of the penultimate glaciation and the beginning of the LIG, with a pollen assemblage dominated by Pinus sylvestris/mugo-type, Quercus, Ulmus, Tilia and the peculiar exceptional abundance of Hedera (Fig. 7). The pollen concentration is low in all Katerloch samples compared to the only other currently available Alpine speleothem LIG record from Sieben Hengste Cave (1–20 grains g$^{-1}$; Luetscher et al., 2021), and the Holocene speleothem record from Milchbach cave (4–564 grains g$^{-1}$; Festi et al., 2016), also located in Switzerland. However, the palynomorph flux into the cave is slightly higher in Katerloch than in Sieben Hengste, reaching up to 73–82 pollen grains ka$^{-1}$ cm$^{-2}$. Given that the growth rate of the Katerloch stalagmites is significantly higher than that of the stalagmite from Sieben Hengste cave (~0.49 vs. ~0.007 mm a$^{-1}$) rather large sample sizes could be used to obtain enough pollen grains without compromising the temporal resolution. Despite the large amount of calcite dissolved, some samples yielded pollen sums that are unsuitable for a reliable calculation of percentage values of pollen taxa. To partially overcome this issue we merged samples into macro-samples to obtain, where possible, a pollen sum of about 100 pollen grains. To this end, we merged adjacent samples from the same speleothem and obtained six macro-samples (Fig. 7; Supporting Information Table S1). Three macro-samples are still below the threshold of 100 pollen grains and these percentage values must be interpreted with caution. This applies in particular to macro-sample K4/0-59 which has a pollen sum of only 46. Despite this limitation, the spectra of these six macro-samples provide important and well-dated insights into the vegetation response during the first part of the LIG.

Early LIG vegetation response at the south-eastern fringe of the Alps
Pre-interglacial vegetation (before 129.4 ± 0.4 ka) was characterized by a forest-steppe including P. sylvestris/mugo, P. cembra and Betula as well as shrubs and xerophytic elements such as Artemisia, confirming that the area was not glaciated. The presence of the vegetation in this phase is well reflected by the low carbon isotope values, which are lower compared to pollen counts obtained from the Katerloch speleothems from other caves in the Alps (Fig. 5). These other caves are located at higher altitudes and their catchments were affected by glaciations during the penultimate glacial maximum. This cold climate is also recorded in two pollen records located south of the Alps, Lake Fimon and Azzano Decimo, by their respective pollen zones FPD10 and AZS4 (Table 3). At Fimon, the vegetation in this period was characterized by the dominance of herb pollen, xerophytes and Pinus, while at Azzano Decimo an open pine forest including P. cembra (arolla pine) was present (Pini et al., 2009, 2010). North of the Alps, the pre-interglacial phase correlates with LPAZ MO1 of Lake Mondsee and DA1 of Samerberg and Eurach which are
A possible rise in temperatures starting at 129.4 ± 0.4 ka (Termination II) is indicated by a shift in the stable isotopic composition and in the pollen record by the expansion of pine-dominated forests with the occurrence of warm-demanding elements starting with Corylus and Hedera. The occurrence of ivy suggests its local presence near the cave (and/or at the cave entrance) already in this period, and points to mild winters (mean temperature of the coldest month above −2°C) as indicated by the modern ecological requirements (Iversen, 1944). North of the Alps at Mondsee, this period corresponds to a reforestation phase that started with the spread of Juniperus (juniper) followed by Pinus in LPAZ MO2, whose upper limit saw a steep rise in isotope values of the bulk carbonate (Drescher-Schneider and Papesch, 1998). Also in Samerberg and Eurach this phase corresponds to the reforestation phase with Pinus, Betula and Juniperus (DA2). South of the Alps, in the Lake Fimon record, this phase is represented by the expansion of pine forests (PAZ FPD11a), which was correlated with the first increase in the oxygen isotope values in a stalagmite from Corchia cave at 132.5 ± 2.5 ka (Drysdale et al., 2009).

In both stalagmites K2 and K4, samples with the largest pollen concentration and influx cover the same period between 128.6 and 128.0 ka. This corresponds to the early growth of stalagmite K2 and a slight increase in δ18O values of stalagmite K4. This period is considered as the LIG climax based on data from Sieben Hengste (Luetscher et al., 2021) as well as the highest percentage of temperate (Mediterranean + Eurosiberian) pollen in deep-sea core MD01-2444 from the Iberian Margin (Fig. 6). The Katerloch pollen record suggests a relatively rapid vegetation response to the temperature increase registered by the δ18O signal, reflecting a quick expansion of warm-demanding deciduous trees (Quercus, Ulmus, Tilia) with exceptionally abundant Hedera. In contrast, the palynological succession of the Sieben Hengste stalagmite and its δ18O record reveal an up to 3-ka-long lag between the

© 2021 The Authors. *Journal of Quaternary Science* Published by John Wiley & Sons Ltd. J. Quaternary Sci., Vol. 37(4) 664–676 (2022)
δ¹⁸O thermal optimum at 128.1 ka and vegetation recorded by pollen data. This gap could be explained by the obvious difference in elevation between these two caves (900 m at Katerloch vs. 1700–2000 m a.s.l. for Sieben Hengste) and it is possibly related also to the fact that the Sieben Hengste area was glaciated before the LIG. The vegetation response seems to have been faster at Katerloch than at Mondsee, where there is a distinct phase of Ulmus expansion anticipating the Quercus peak (Drescher-Schneider and Papesch, 1998; Drescher-Schneider, 2000). In general, at Katerloch this phase corresponds to LP4O 3 and 4. However, in pollen diagrams from Gondiswil, Eaurach and Samerberg, the Ulmus and Quercus peaks coincide as in Katerloch (Beug, 1979; Grüger, 1979; Zagwijn, 1996).

In Lake Fimon, south of the Alps, the onset of the LIG coincided with a sharp rise in humid temperate taxa (Quercus and Corylus) at Corchia cave (Pini et al., 2010). At Azzano Decimo the onset of the LIG occurred within PAZ AZ55, but the lower limit of this zone is represented by a hiatus.

Finally, the timing of the highest pollen concentration and flux in the Katerloch samples (128.6–128.0 ka) is synchronous with the highest abundance of temperate tree pollen retrieved from core MD2444 on the Iberian Margin (Tzedakis et al., 2018). The higher pollen flux at Katerloch in this period probably reflects an increase in pollen productivity driven by the warm climate that allowed the development of a dense forest vegetation.

As already mentioned, the abundance of Hedera pollen is one of the distinctive features of the Katerloch record (Fig. 7). This pollen type is never dominant in sedimentary records but it is recognized as a distinctive feature of LIG vegetation spectra. Considering the exceptional abundance of Hedera in both Katerloch and Sieben Hengste speleothem pollen records, this pollen might be a typical feature of pollen records from LIG speleothems in the Alpine region. The first occurrence of ivy in Sieben Hengste cave is recorded around 127 ka, and the highest values around 125 ka (Luetzsch et al., 2021). In Katerloch, the ivy maximum occurred at 128.4 ± 0.5 ka and led the Sieben Hengste record by ~2 ka. This is again probably related to a difference in altitude, and to the fact that Sieben Hengste is located north of the Alps and in an area that was glaciated during the penultimate glacial maximum. Irrespective of the timing, ivy is clearly better represented in speleothems than in lake sediments, suggesting that this taxon was an important part of the LIG vegetation.

CONCLUSIONS

The Katerloch record provides a replicated, precisely dated, high-resolution stable isotope record of the beginning and the warmest phase of the LIG in the Alps.

Termination II recorded by stalagmite K2 from Katerloch produced using OxCal 4.3. The age model was calculated using the P-sequence with a k-value of 0.1 cm⁻¹, an interpolation rate of 1 cm⁻¹, and k varying between 10⁻² and 10⁻².

Figure S1. Time–depth models for stalagmite K2 from Katerloch produced using OxCal 4.3. The age model was calculated using the P-sequence with a k-value of 0.1 cm⁻¹, an interpolation rate of 1 cm⁻¹, and k varying between 10⁻² and 10⁻².

Figure S2. Time–depth models for stalagmite K4 from Katerloch produced using OxCal 4.3. The age model was calculated using the P-sequence with a k-value of 0.1 cm⁻¹, an interpolation rate of 1 cm⁻¹, and k varying between 10⁻² and 10⁻².

Table S1. Merged pollen samples for the percentage pollen diagram, with their respective top and bottom ages, the duration covered by each sample according to the mean growth rate (with 2σ confidence interval) and the pollen concentration and flux. *Based on minimum growth rate of 0.1 mm a⁻¹.

Appendix S1. Stable isotope data for stalagmite K2 and K4, with their respective age model and pollen counts for K2 and K4.

Acknowledgements. This study was funded by the Austrian Science Fund (FWF) grant P300040 to C.S. We thank Fritz Geisler for providing access to his cave and supporting our scientific work, Manuela Wimmer for her assistance in the stable isotopes laboratory, Werner Kofler for preparing the pollen samples, Haiwei Zhang and Jia
Xue for running additional 230Th ages, Tangy Racine for his help during fieldwork, Gabriella Koltaí for her help in the 230Th Laboratory, and Ronny Boch, Ruth Drescher-Schneider, Roberta Pini and Erwan Messager for discussion. Comments by Kafe Sniderman and an anonymous reviewer helped to improve the clarity of the paper.

**Data Availability Statement**

The stable isotope data, the U/Th data and the pollen counts that support the findings of this study are available in the Supporting Information (Appendix S1).

**Conflict of interest**—The authors declare that there are no conflicts of interest.

**Abbreviations.** ITCZ, Intertropical Convergence Zone; LIG, Last Interglacial; NAQ, North Atlantic Oscillation.

**References**

Beug H. 1979. Vegetationsgeschichtlich-pollenanalytische Untersuchungen am Riß/Würm-Interglazial von Eurchach am Starnberger See. Obb. Geologica Bavaria 80: 91–106.

Beug H. 2004. Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. Plei: München.

Boch R. 2008. Stalagmites from Katerloch Cave, Austria: Growth Dynamics and High-Resolution Records of Climate Change. Leopold-Franzens Universität Innsbruck, Austria.

Boch R, Spötl C, Kramers J. 2009. High resolution age models of speleothems from Katerloch Cave, Austria: origin of lamination in stalagmites from Katerloch Cave, Austria: origin of lamination in stalagmites. Sedimentology 58: 508–531. https://doi.org/10.1111/j.1365-3091.2010.0173x

Boch R, Spötl C, Kramers J. 2009. High-resolution isotope records of Early Holocene rapid climate change from two coeval stalagmites of Katerloch Cave, Austria. Quaternary Science Reviews 28: 2527–2538. https://doi.org/10.1016/j.quascirev.2009.05.015

Bova S, Rosenthal Y, Liu Z. 2009. Messager for discussion. Comments by Kale Sniderman and an anonymous reviewer helped to improve the clarity of the paper.

Brewer S, Guiot J, Sánchez‐Bova S, Rosenthal Y, Liu Z. 2009. Evidence for obliquity forcing of glacial Termination II. Science 325: 1527–1531. https://doi.org/10.1126/science.1170371 [PubMed: 19679773]

Duplecy JC, Roche DM, Kageyama M. 2007. The deep ocean during the Last Interglacial period. Science 316: 89–91. https://doi.org/10.1126.science.1138582 [PubMed: 17412954]

Dutton A, Carlson AE, Long AL et al. 2015. Sea-level rise due to polar ice-sheet mass loss during past warm periods. Science 349: aaa4019–aaa4019. https://doi.org/10.1126/science.aaa4019 [PubMed: 26169051]

Edwards RL, Chen JH, Ku TL et al. 1987. Precise timing of the Last Interglacial period from mass spectrometric determination of thorium-230 in corals. Science 236: 1547–1553. https://doi.org/10.1126/science.236.4808.1547 [PubMed: 17835738]

Efthymiadis D, Jones PD, Briffa KR et al. 2011. Influence of large-scale atmospheric circulation on climate variability in the Greater Alpine Region of Europe. Journal of Geophysical Research 116: D12104. https://doi.org/10.1029/2006JD008021

Faegri K, Iversen J, Kaland et al. 1992. Textbook of Pollen Analysis. John Wiley & Sons: Chichester.

 festi D, Hofmann DL, Luetscher M. 2016. Pollen from accurately dated speleothems supports alpine glacier low-stands during the Early Holocene. Quaternary Research 86: 45–53. https://doi.org/10.1016/j.yqres.2016.05.003

Fischer H, Meissner KJ, Mix AC et al. 2018. Palaeoclimate constraints on the impact of 2°C anthropogenic warming and beyond. Nature Geoscience 11: 474–485. https://doi.org/10.1038/s41561-018-0146-0

Friedman, I., & O’Neil, J. R. 1977. Compilation of stable isotope fractionation factors of geochemical interest. US Government Printing Office Vol. 440.

Gavin A, Capron E, Tzedakis PC et al. 2015. Sequence of events from the onset to the demise of the Last Interglacial: evaluating strengths and limitations of chronologies used in climatic archives. Quaternary Science Reviews 129: 1–36. https://doi.org/10.1016/j.quascirev.2015.09.018

Grüger E. 1979. Spätriß, Riß/Würm und Frühwürm am Samerberg in Oberrhein – ein vegetationsgeschichtlicher Beitrag zur Glierung des Jungjüngsteozans. Geologica Bavaria 90: 5–64.

Guiot J, Pons A, de Beaulieu JL et al. 1989. A 140,000-year continental climate reconstruction from two European pollen records. Nature 338: 309–313. https://doi.org/10.1038/338309a0

Häuselmann AD, Fleitmann D, Cheng H et al. 2015. Timing and nature of the penultimate deglaciation in a high alpine stalagmite from Switzerland. Quaternary Science Reviews 126: 264–275. https://doi.org/10.1016/j.quascirev.2015.08.026

Iversen J. 1944. Viscum, Hedera and flex as climate indicators: a contribution to the study of the post-glacial temperature climate. Geologiska Föreningen i Stockholm Förhandlingar 66: 463–483. https://doi.org/10.1080/11305899409445689

Johnston VE, Borsato A, Frissia S et al. 2018. Evidence of thermophilisation and elevation-dependent warming during the Last Interglacial in the Italian Alps. Scientific Reports 8: 2680. https://doi.org/10.1038/s41598-018-21027-3 [PubMed: 29422638]

Johnston VE, Borsato A, Frisa S et al. 2021. Last interglacial hydroclimate in the Italian Prealps reconstructed from speleothem multi-proxy records (Bigonda Cave, NE Italy). Quaternary Science Reviews 272. https://doi.org/10.1016/j.quascirev.2021.107243 [PubMed: 107243]

Juggins S. 2007. C2 Version 1.5 User guide. Software for ecological and palaeoecological data analysis and visualisation. Newcastle University, Newcastle upon Tyne, UK. 73 pp.

Kaspars P. 2005. A model-data comparison of European temperatures in the Eemian interglacial. Geophysical Research Letters 32: L11703. https://doi.org/10.1029/2005GL022456

Kühl N, Litt C. 2007. Quantitative time-series reconstructions of Holsteinian and Eemian temperatures using botanical data. In Developments in Quaternary Sciences. Elsevier: Amsterdam; 239–254. https://doi.org/10.1016/S1571-0866(07)80041-8

Kukla GJ, Bender ML, de Beaulieu J et al. 2002. European warming and beyond. Nature 416: 553. https://doi.org/10.1038/nature00868

Lüttge U, Eamus D, Ruessink BG et al. 2009. Vegetation History and Archaeobotany 7: 203–240. https://doi.org/10.1007/BF01192914

Manning RN, Hellstrom J, Röckle G et al. 2009. Evidence for obliquity forcing of glacial Termination II. Science 325: 1527–1531. https://doi.org/10.1126/science.1170371 [PubMed: 19679773]

Kukla GJ, Bender ML, de Beaulieu J et al. 2002. European warming and beyond. Nature 416: 553. https://doi.org/10.1038/nature00868

Manning RN, Hellstrom J, Röckle G et al. 2009. Evidence for obliquity forcing of glacial Termination II. Science 325: 1527–1531. https://doi.org/10.1126/science.1170371 [PubMed: 19679773]

Manning RN, Hellstrom J, Röckle G et al. 2009. Evidence for obliquity forcing of glacial Termination II. Science 325: 1527–1531. https://doi.org/10.1126/science.1170371 [PubMed: 19679773]

Manning RN, Hellstrom J, Röckle G et al. 2009. Evidence for obliquity forcing of glacial Termination II. Science 325: 1527–1531. https://doi.org/10.1126/science.1170371 [PubMed: 19679773]

Manning RN, Hellstrom J, Röckle G et al. 2009. Evidence for obliquity forcing of glacial Termination II. Science 325: 1527–1531. https://doi.org/10.1126/science.1170371 [PubMed: 19679773]

Manning RN, Hellstrom J, Röckle G et al. 2009. Evidence for obliquity forcing of glacial Termination II. Science 325: 1527–1531. https://doi.org/10.1126/science.1170371 [PubMed: 19679773]
Lachniet MS. 2009. Climatic and environmental controls on speleothem oxygen-isotope values. Quaternary Science Reviews 28: 412–432. https://doi.org/10.1016/j.quascirev.2008.10.023
Landais A, Dreyfus G, Capron E et al. 2013. Two-phase change in \( \text{CO}_2 \), Antarctic temperature and global climate during Termination II. Nature Geoscience 6: 1062–1065. https://doi.org/10.1038/ngeo1985
Luetscher M, Moseley GE, Festi D et al. 2021. A Last Interglacial speleothem record from the Sieben Hengste cave system (Switzerland): implications for alpine paleovegetation. Quaternary Science Reviews 238: 106238. https://doi.org/10.1016/j.quascirev.2021.106974
Lutjé M, Moseley GE, Spötl C, Cheng H et al. 2015. Correlation of Last Interglacial (MIS 5e) relative sea-level indicators: reconstructing sea-level in a warmer world. Earth-Science Reviews 159: 404–427. https://doi.org/10.1016/j.earscirev.2016.06.006
Rozanski K, Araguás-Araguás L, Goniandinti R. 1992. Relation between long-term trends of oxygen-18 isotope composition of precipitation and climate. Science 258: 981–985. https://doi.org/10.1126/science.258.5084.981 [PubMed: 17794595].
Sirocko F, Clausen M, Litt T et al. 2007. Chronology and climate forcing of the last four interglacials. Developments in Quaternary Sciences. Elsevier: Amsterdam; 597–614. https://doi.org/10.1016/S1571-0686(07)00065-0.
Spötl C, Seoslos K, Schaller K et al. 2005. A late Eemian aridity pulse in central Europe during the last glacial inception. Nature 436: 833–836. https://doi.org/10.1038/nature03905 [PubMed: 16994365].
Sommer C, Malz P, Seeaehaus TC et al. 2020. Rapid glacier retreat and downwasting throughout the European Alps in the early 21st century. Nature Communications 11: 3209. https://doi.org/10.1038/s41467-020-16818-0 [PubMed: 32587270].
Spölt C. 2011. Long-term performance of the Gasbench isotope ratio mass spectrometry system for the stable isotope analysis of carbonate microsamples. Rapid Communications in Mass Spectrometry 25: 1683–1685. https://doi.org/10.1002/rcm.5037 [PubMed: 21594944].
Spölt C, Holzkämper S, Mangini A. 2007. The last and the penultimate interglacial as recorded by speleothems from a climatically sensitive high-elevation cave site in the alps, Developments in Quaternary Sciences. Elsevier: Amsterdam; 471–491. https://doi.org/10.1016/S1571-0866(07)00056-X.
Spölt C, Mangini A, Frank N et al. 2002. Start of the last interglacial at 135 ka: evidence from a high Alpine speleothem. Geology 30: 815–818. https://doi.org/10.1130/0191-9617(2002)30<815:SOULIK>2.0.CO;2.
Steinbauer MJ, Grytnes JA, Jurasinski G et al. 2018. Accelerated increase in plant species richness on mountain summits is linked to warming. Nature 556: 231–234. https://doi.org/10.1038/s41586-018-0005-6 [PubMed: 29618821].
Tzedakis PC, Drysdale RN, Margari V et al. 2018. Enhanced climate instability in the North Atlantic and southern Europe during the Last Interglacial. Nature Communications 9: 4235. https://doi.org/10.1038/s41467-018-06683-3 [PubMed: 30315157].
Wilcox PS, Honiat C, Trüssel M et al. 2020. Exceptional warmth and climate instability occurred in the European Alps during the Last Interglacial period. Communications Earth and Environment 1: 57. https://doi.org/10.1038/s43247-020-00063-w.
Woillard G. 1979. The last interglacial-glacial cycle at Grande Pile in Northeastern France. Bulletin de la Société belge de Géologie, 88(1): 31–69.
Wulf S, Keller J, Paterne M et al. 2012. The 100–133 ka record of Italian explosive volcanism and revised tephrchronology of Lago Grande di Monticchio. Quaternary Science Reviews 58: 104–123. https://doi.org/10.1016/j.quascirev.2012.10.020.
Yin Q, Berger A. 2015. Interglacial analogues of the Holocene and its natural near future. Quaternary Science Reviews 120: 28–46. https://doi.org/10.1016/j.quascirev.2015.04.008.
Zagwijn W. 1996. An arid Eemian climate in Western and Central Europe. Quaternary Science Reviews 15: 451–469. https://doi.org/10.1016/S0277-3791(96)00011-X.
Zekollari H, Huss M, Farinotti D. 2019. Modelling the future evolution of glaciers in the European Alps under the EURO-CORDEX RCM ensemble. Cryosphere 13: 1125–1146. https://doi.org/10.5194/tc-13-1125-2019.