Quaternary Science Reviews 106 (2014) 186–205

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Palaeoclimate records 60–8 ka in the Austrian and Swiss Alps and their forelands

Oliver Heiri [a, *], Karin A. Koinig [b], Christoph Spötl [c], Sam Barrett [c], Achim Brauer [d], Ruth Drescher-Schneider [e], Dorian Gaar [f], Susan Ivy-Ochs [g], Hanns Kerschner [h], Marc Luetscher [c], Andrew Moran [h], Kurt Nicolussi [h], Frank Preusser [i], Roland Schmidt [j], Philippe Schoeneich [k], Christoph Schwörer [a], Tobias Sprafke [l], Birgit Terhorst [l], Willy Tinner [a]

[a] *Institute of Plant Sciences and Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland*
[b] *Institute of Ecology, University of Innsbruck, Austria*
[c] *Institute of Geology, University of Innsbruck, Austria*
[d] *GFZ German Research Centre for Geosciences, Section 5.2 Climate Dynamics and Landscape Evolution, Germany*
[e] *Graz, Austria*
[f] *Institute of Geological Sciences and Oeschger Centre for Climate Change Research, University of Bern, Switzerland*
[g] *Labor für Ionenstrahlphysik (LIP), ETH Zurich, Switzerland*
[h] *Institut für Geographie, University of Innsbruck, Austria*
[i] *Department of Physical Geography and Quaternary Geology, Stockholm University, Sweden*
[j] *Institute for Limnology, University Innsbruck, Mondsee, Austria*
[k] *Institut de Géographie Alpine, Université Joseph Fourier, Grenoble, France*
[l] *Institute of Geography and Geology, University of Würzburg, Germany*

A R T I C L E I N F O

Article history:
Received 22 November 2013
Received in revised form
3 May 2014
Accepted 21 May 2014
Available online 8 July 2014

Keywords:
Palaeoclimate
Quaternary climate change
Climate reconstruction
Switzerland
Austria
Alps

A B S T R A C T

The European Alps and their forelands provide a range of different archives and climate proxies for developing climate records in the time interval 60–8 thousand years (ka) ago. We review quantitative and semi-quantitative approaches for reconstructing climatic variables in the Austrian and Swiss sector of the Alpine region within this time interval. Available quantitative to semi-quantitative climate records in this region are mainly based on fossil assemblages of biota such as chironomids, cladocerans, coleopterans, diatoms and pollen preserved in lake sediments and peat, the analysis of oxygen isotopes in speleothems and lake sediment records, the reconstruction of past variations in treeline altitude, the reconstruction of past equilibrium line altitude and extent of glaciers based on geomorphological evidence, and the interpretation of past soil formation processes, dust deposition and permafrost as apparent in loess-palaeosol sequences. Palaeoclimate reconstructions in the Alpine region are affected by dating uncertainties increasing with age, the fragmentary nature of most of the available records, which typically only incorporate a fraction of the time interval of interest, and the limited replication of records within and between regions. Furthermore, there have been few attempts to cross-validate different approaches across this time interval to confirm reconstructed patterns of climatic change by several independent lines of evidence. Based on our review we identify a number of developments that would provide major advances for palaeoclimate reconstruction for the period 60–8 ka in the Alps and their forelands. These include (1) the compilation of individual, fragmentary records to longer and continuous reconstructions, (2) replication of climate records and the development of regional reconstructions for different parts of the Alps, (3) the cross-validation of different proxy-types and approaches, and (4) the reconstruction of past variations in climate gradients across the Alps and their forelands. Furthermore,

Abbreviations: AAR, Accumulation area ratio; AMS, Accelerator Mass Spectrometry; ELA, Equilibrium Line Altitude; GIS, Greenland Isotope Stage; GRIP, Greenland ice core project; IRSL, Infrared-stimulated Luminescence; LGM, Last Glacial Maximum; LIA, Little Ice Age; LPS, Loess-palaeosol sequence; MIS, Marine Isotope Stage; NGRIP, North Greenland Ice Core Project; OSL, Optically Stimulated Luminescence; UV, Ultraviolet.

* Corresponding author.
E-mail address: oliver.heiri@ips.unibe.ch (O. Heiri).

http://dx.doi.org/10.1016/j.quascirev.2014.05.021

the development of downscaled climate model runs for the Alpine region 60–8 ka, and of forward modelling approaches for climate proxies would expand the opportunities for quantitative assessments of climatic conditions in Europe within this time-interval.

1. Introduction

Mountain regions provide excellent opportunities for developing palaeoclimatological records and approaches. The pronounced altitudinal and often also spatial climatic gradients allow the development and rigorous calibration of palaeotemperature proxy-indicators in archives as different as lake sediments and peat, speleothems, or tree-ring sequences (e.g. Lotter et al., 1997; Mangini et al., 2005). The landscapes in mountain regions are often strongly influenced by the steep climatic gradients and by past variations in climatic conditions. Therefore, the study of geological landscape features such as moraines, landslides and rock glaciers with appropriate geochronological approaches allows insights into past variations in climate (e.g. Ivy-Ochs et al., 2006; Kerschner and Ivy-Ochs, 2007). Other landscape features, such as the position of the Alpine treeline, are also strongly influenced by climate. Reconstructions of the past altitudinal limits of vegetation zones can, therefore, provide a further approach for constraining past variations in temperature (e.g. Tinner et al., 1996; Nicolussi et al., 2005).

In the European Alps and their forelands the earliest attempts to reconstruct past climate variations include interpretations of glacial landforms such as moraine ridges and erratic boulders as evidence of past glaciations (e.g. Venetz, 1833; Penck and Brückner, 1901/1909). Palynological (pollen-based) records and, more recently, macroscopic plant fossils preserved in lake sediment and peat have been used to make inferences about past vegetation and, indirectly, climatic change (e.g. Tinner et al., 1996; Lotter et al., 2000). In recent decades, stable isotope analyses and radiometric dating methods have broadened the range of archives that can be exploited for developing climate proxy records. Widely-used approaches in the European Alps and their forelands now include stable isotopic analyses in speleothems (e.g. Spötl et al., 2006; Boch et al., 2011) and lake sediment records (e.g. von Grafenstein et al., 1999; Lauterbach et al., 2011), dating of landforms such as terminal and lateral moraines as well as high-precision dating of organic matter deposited in glacier forefields (e.g. Joerin et al., 2006), analysis of fossil assemblages in lake sediment and peat to reconstruct past variations in biota and, indirectly, temperature (e.g. Heiri et al., 2004; Jost-Stauffer et al., 2005; Ilyashuk et al., 2011), and the study of past soil development to reconstruct phases of soil formation, aeolian sediment transport and permafrost (e.g. Terhorst et al., 2013).

Although palaeoclimate records from the Alpine region have a long tradition, are often based on rigorous calibration studies, and have in many cases the potential for providing quantitative estimates of past climatic changes, they are presently underused in studies that examine climatic variations during the Last Glacial-to-interglacial cycle. A number of reasons may be responsible for this discrepancy. Many climate archives in the Alpine region are discontinuous over longer time intervals, since conditions ideal for accumulation of archives and suitable for recording climatic variations change both spatially and altitudinally during the examined time interval. Furthermore, dating accuracy and reliability varies dramatically in most archive types across the glacial–interglacial transition. As a consequence, many Late Pleistocene palaeoclimate records from the Alpine region do not have the resolution necessary for resolving leads or lags with other components of the climate systems, or with potential climate forcing factors. However, palaeotemperature or palaeoprecipitation signals may actually be recorded more reliably than in many other archives in adjacent lowland regions. In contrast to records produced in large, multinational projects, most palaeoclimatic reconstructions from the Alpine region are the products of collaborations between a small number of investigators or even single-author datasets. Although reconstructions are usually available and provided to interested colleagues upon request, many of the climate records from the Alps cannot be found in online climate data repositories. This is another reason why palaeoclimate records from the Alpine region may have been overlooked in synoptic studies of past climatic change.

The INTIMATE project aims at compiling proxy-based palaeoclimate records from Europe for the period 60–8 ka and facilitating the use of these data by the user community. This community includes climate modellers, who depend on independent climate records for evaluating model simulations, palaeoclimatologists developing and interpreting climate proxy records across Europe, and researchers studying the effects of past climatic changes on ecosystems and landscapes. Here we report the results of a workshop supported by INTIMATE which aimed at compiling and reviewing available palaeoclimate records from the Austrian and Swiss sectors of the Alpine region. The workshop, and therefore also the scope of this review, was intentionally restricted to Austria and Switzerland to reduce the complexity of the task and the number of records to be examined (Fig. 1). However, we also discuss a few selected records from eastern France and southernmost Germany since they help to constrain the past climate development in the northern Alpine forelands. Furthermore, it was decided to mainly focus on established proxies which allow quantitative, or at least semi-quantitative estimates of past variations in climate variables, since these reconstructions are directly comparable with other quantitative records of past climate change, climate model output data, and can be used as input variables to derive model based assessments of past ecosystem change (e.g. Heiri et al., 2006; Henne et al., 2011). However, an effort was made to cover a wide range of archives and palaeoclimatological methods, including palaeoecological, geochemical and geomorphological approaches. We first provide an overview of the examined archives and proxy types (Section 2) and the available palaeoclimatic records published for the study region within the time window 60–8 ka (Section 3). In a second step we discuss the spatial and temporal coverage of the presently available records and challenges faced by the community of researchers working with them. Finally, we list future steps necessary to increase the quality, accessibility and usefulness of palaeoclimatic records from the Alpine region in general, using the situation in Austria and Switzerland as an example. This review is complemented by parallel efforts by members of the INTIMATE group focusing on palaeoclimate data 60–8 ka available for Western Europe (Moreno et al., 2014), and Eastern Europe (Feurdean et al., 2014).

As in all other attempts of inter-comparing independently dated late Quaternary records, chronological issues play an important role when compiling climate reconstructions in the Alpine region (Brauer et al., 2014). This is especially true if attempts are made to compare records from different archives, which are dated by different direct dating methods (e.g. radiocarbon, U/Th, annual

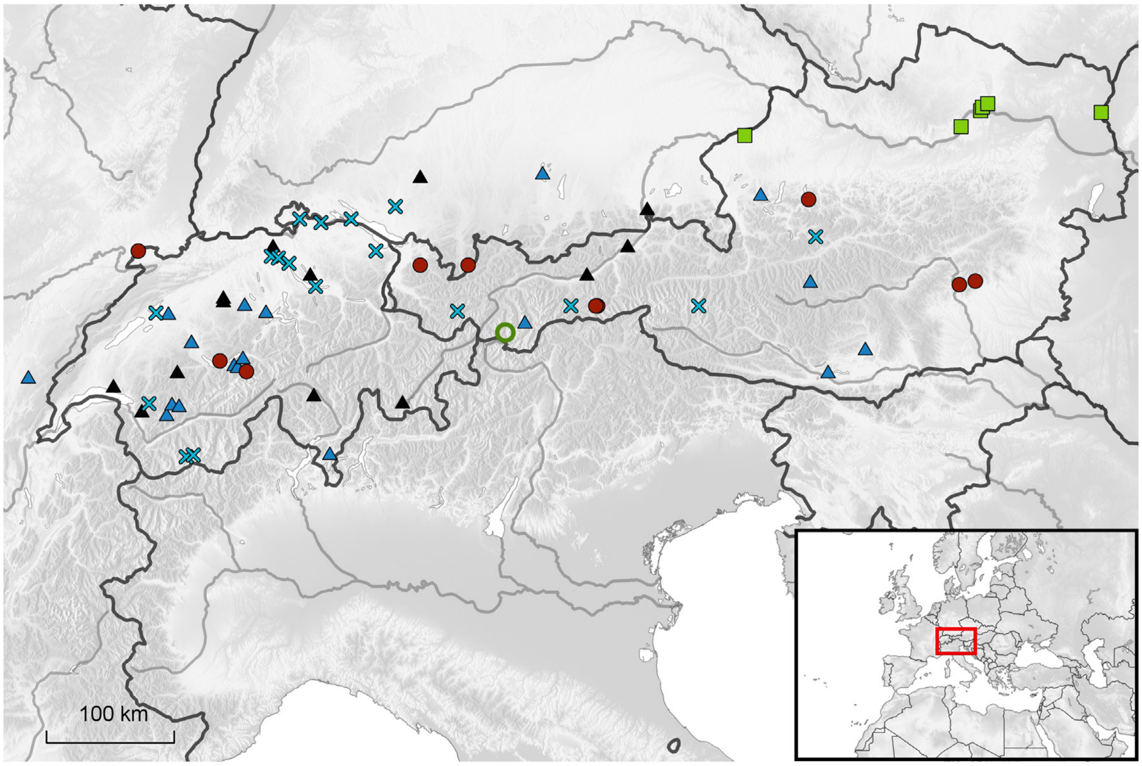

Fig. 1. Location of records discussed in this article within the Alpine region. The symbols indicate different archive types, including lakes (blue triangles), palaeolakes and peat (black triangles), tree megafossils dated by dendrochronology (green circles), speleothems (red circles), moraines and glaciers (blue X symbols), and loess (green squares). A full list of localities is provided in the Supplementary data. The map was produced using stepmap (www.stepmap.de).

layer counting) or by indirect chrono-stratigraphical approaches. Age scales and reference ages which are presently used for late Quaternary records include the calibrated and uncalibrated radiocarbon age scale (0 = 1950 AD), the NGRIP Greenland ice core chronology ("B2k"; 0 = 2000 AD), the BC/AD age scale, and different chronological techniques which consider the time of age determination or field sampling as a reference point. Here we refer to age estimates in thousands of years (ka) before 1950 AD, the zero point for the radiocarbon age scale. In addition, figures include the accepted time-scale for the presented records wherever this is practicable. Calibrated radiocarbon ages presented in the main manuscript text were calibrated using the IntCal13 calibration curve and CALIB 7.0.0 (Reimer et al., 2013) unless indicated otherwise. References to individual calibrated ages are reported as thousands of calibrated radiocarbon years BP (ka cal. BP), whereas ka is used for general age estimates which may be based on radiocarbon or other dating methods, or on a combination of approaches. To refer to climatic events in the Alpine region we use the regionally defined and accepted terms, which differ to some extent between archives (e.g. Table 1). The term "Lateglacial" refers to the common use in the Alpine realm. As used here it includes the Oldest Dryas Stadial (ending ~14.6 ka) and local glacier readvances, in contrast to the Pleniglacial, which refers to the period with extension of piedmont lobes of glaciers into the Alpine foreland

Table 1
INTIMATE Greenland event stratigraphy (Blockley et al., 2012) and age of isotope events in the NGRIP ice core record (provided both as b2k and ka) compared with the established terminology for biozones, climate events, and glacial stages in the northern forelands of the Alps. Zones and events older than the Pleniglacial are not included (see Preusser, 2004 for a detailed compilation of older events and chronozones). Correlation of the Greenland event stratigraphy with biozones follows van Raden et al. (2013) and the correlation between biozones and glacial stages Preusser (2004). The correlation between isotope events in Greenland and biozones in the Alpine region is generally well established for the period <14.6 ka (e.g. van Raden et al., 2013), although there may be minor offsets in the timing and duration of biozones and climate events in Europe relative the Greenland isotope events they are correlated with (e.g. Rach et al., 2014). The correlation of Aegelsee Oscillation with the Older Dryas stadial follows Lotter et al. (1992).

Greenland event stratigraphy	Age in NGRIP ice core (b2k)	Age (ka)	Biozones/climate events		Glacial stage
Holocene	11,703–present	11.7–present	Holocene		
GS-1	12,896–11,703	12.8–11.7	Younger Dryas stadial	Alpine Lateglacial	Egesen
GI-1a, GI-1b, GI-1c	13,954–12,896	13.9–12.8	Allerød Interstadial (incl. Gerzensee Oscillation)		(glaciers shorter than Egesen)
GI-1d	14,075–13,954	14.0–13.9	Older Dryas stadial/Aegelsee Oscillation		
GI-1e	14,692–14,075	14.6–14.0	Bølling Interstadial		
GS-2 and older	>14,692	>14.6	Oldest Dryas Stadial		Daun Clavadel/Senders Gschnitz Steinach Bühl ?
			Pleniglacial		

(the "Alpine LGM"). The relationship of these terms and local Alpine events with events of the INTIMATE event stratigraphy (Blockley et al., 2012), as far as this relationship is established, is provided in Table 1. Use of the chronozones Early Würmian, Middle Würmian and Late Würmian follows Preusser (2004).

2. Examined archives and proxies

2.1. Lake and peat records

Lake sediments and peat deposits are common in the Alpine area, and can be analysed for geochemical and palaeoecological climate proxies. For the period 50–0 ka, these deposits can be reliably dated by radiocarbon dating of terrestrial plant remains. The age of older sediments has to be determined by, e.g., luminescence dating. In varved lake sediments, age estimates can be further constrained by annual layer counting (e.g. Brauer et al., 1999). Depending on the time interval and archive examined, estimated dating uncertainties can range from several years (some varved sequences in the Holocene) to a few centuries or even millennia (e.g. for some sequences older than 15 ka).

A wide range of palaeoecological, sedimentological and geochemical methods has been applied to lake and peat deposits to reconstruct past climatic change. Approaches that have hitherto been most successful in producing quantitative or semi-quantitative estimates of climatic changes 18–8 ka, and which therefore are reviewed here, include the analysis of the oxygen isotopic composition ($\delta^{18}O$) of lake sediment components (e.g. von Grafenstein et al., 1999; Lauterbach et al., 2011), the analysis of plant remains to reconstruct past altitudinal variations in the Alpine tree-line, providing evidence for variations in summer temperature (e.g. Tinner et al., 1996), and the analysis of fossil assemblages of pollen, or aquatic organisms such as chironomids, cladocerans, and diatoms (e.g. Lotter et al., 2000; Ilyashuk et al., 2011; Schmidt et al., 2012).

In central Europe, $\delta^{18}O$ of precipitation, and therefore also of lakewater, is strongly related to ambient air temperature (Rozanski et al., 1992; von Grafenstein et al., 1996). Since lakewater $\delta^{18}O$ determines $\delta^{18}O$ of sediment components produced within lakes, $\delta^{18}O$ records, e.g. from lacustrine carbonate, can be used to provide information about past temperature changes. However, water temperature directly affects and modifies the $\delta^{18}O$ signal recorded by carbonates produced in lakes, and this complicates the interpretation of carbonate $\delta^{18}O$ records (Von Grafenstein et al., 2000, 2013). Analyzing $\delta^{18}O$ of carbonate remains originating from the deep-water fauna of stratified lakes (e.g. ostracods), which remains unaffected by seasonal temperature changes, provides an avenue for alleviating this problem (e.g. von Grafenstein et al., 1999).

In the Alpine region, transfer functions have been widely used to develop palaeoclimate reconstructions from fossil pollen assemblages (e.g. Lotter et al., 2000), or fossil assemblages of aquatic biota such as chironomids, cladocerans, chrysophytes and diatoms (e.g. Schmidt et al., 2004, 2012; Ilyashuk et al., 2011). In Austria and Switzerland these inference models are typically calibrated based on the present-day relationship between these indicators and water temperature (e.g. Schmidt et al., 2012), air temperature (e.g. Lotter et al., 1997), or other seasonal aspects of the temperature regime (e.g. the date of autumn mixing; e.g. Schmidt et al., 2006).

The presence of forests in the northern Alpine forelands and the altitudinal position of the Alpine treeline provide important constraints for past summer temperature, since treeline elevation in the Alps is mainly controlled by temperature during the summer months. The interpretation of palaeobotanical records from many sites within a restricted geographical region allows the reconstruction of past treeline elevations (e.g. Nicolussi et al., 2005), the identification of short-term variations in treeline altitude (e.g. Lang, 1994; Tinner and Theurillat, 2003), and their interpretation as evidence for regional climatic oscillations (e.g. Haas et al., 1998). Reconstruction of past treeline altitude relies to a large extent on the identification, dating and analysis of tree remains in lake sediments and peat deposits, but also on fossil wood deposited in other environments (e.g. glacier forefields, e.g. Nicolussi et al., 2005). At present, the minimum mean July air temperature for the growth of tree species in the Alps is ~7.5–9.5 °C (Landolt, 1992), and this threshold can be used to constrain past summer temperature based on variations in treeline altitude.

For the time interval 60–18 ka few quantitative estimates of past temperature based on lake and peat records are available. However, the presence of lakes during the last glaciation in itself provides valuable palaeoclimatological information, since lacustrine sedimentation requires ice-free conditions. Furthermore, the type and origin of lacustrine deposits (glaciolacustrine, organic lacustrine, peat), as well as plant remains such as pollen and plant macrofossils can provide additional information on the prevailing climate. For this interval we therefore also provide an overview and compilation of dated lake and peat deposits reported from Austria and Switzerland.

2.2. Speleothems

Cave carbonates are among the latest additions to the list of archives utilized to study palaeoclimate in the Austrian and Swiss Alps. First attempts to date Alpine speleothems occured half a century ago (e.g. Franke, 1966), but modern palaeoclimate research started only at the very end of the 20th century. A small number of data sets are currently available for the time interval of interest. These studies used stalagmites and flowstones from caves in Austria and southernmost Germany, and, more recently also from Switzerland. The chronology is exclusively based on the U–Th disequilibrium technique, which allows dating with an accuracy of typically a few hundred years for MIS 3 and better than a few decades for most of the Holocene (Brauer et al., 2014). This is of particular importance for the older part of the INTIMATE time interval where radiocarbon reaches its limit.

The main climate proxy used in speleothem studies is $\delta^{18}O$ of calcite, which reflects $\delta^{18}O$ of precipitation and, in the Alps, is positively correlated with mean annual air temperature (e.g., Darling, 2004). This allows the correlation of speleothem records to e.g. isotope records obtained from regional lake sediments and even to the ice cores from Greenland. Since $\delta^{18}O$ of water feeding speleothems is not only influenced by air temperature but also by changes in moisture sources, seasonality of precipitation, and locally important in-cave processes, translating speleothem $\delta^{18}O$ variations into quantitative estimates of past temperature change is challenging. Mangini et al. (2005) developed a quantitative reconstruction by calibrating $\delta^{18}O$ of a stalagmite from Spannagel Cave, Austria, against empirical constraints and estimates of past temperature for the calibration period 1688–1950 AD. This is currently the only speleothem record from the Alps (and for most of Central Europe) with a robust transfer function.

2.3. Glacier records

Glacier fluctuations are among the best-known and visible effects of climate variations. They represent an integrated signal of changes in accumulation and ablation, which can be parameterized as changes in summer temperature and precipitation. Due to the reaction time of glaciers, they tend to smooth out short-term variations and respond to climatic change with decadal to centennial sensitivity depending on their size and topographic setting. Their use for continuous climate reconstructions is limited due to a number of reasons: First, moraines record only maximal extensions (usually cold phases), while remnants of short extensions overridden during subsequent readvances are destroyed and thus not preserved. Hence, the amplitude of glacier recession during warm phases can usually not be reconstructed. Earlier phases of glacial advances can be recorded by sediments, but the glacial record is almost always discontinuous, with gaps of unknown duration. Second, due to the paucity of organic material for radiocarbon dating in moraines or related sediments, glacial features could until recently almost only be dated indirectly by organic materials found in under- and/or overlying sediments and in some cases by radiocarbon ages from bones found in proglacial deposits. Cosmogenic Nuclides (e.g. ^{10}Be) as well as Optically Stimulated Luminescence (OSL) and Infrared-stimulated Luminescence (IRSL) methods now allow the direct dating of some features, for example erratic boulders and glaciofluvial sediments, respectively. Thus, it has been possible to establish a framework of well-dated critical time points, but chronologies remain poorly constrained. Third, in most cases it is impossible to separate temperature and precipitation signals from the glacier record alone, and an independent proxy for at least one of the two variables is necessary. It is generally assumed that major glacier fluctuations in the Alps were mainly driven by variations in summer temperature, a parameter determining the energy fluxes towards the glacier surface, while regional amplitude differences are best explained by precipitation gradients (e.g. Penck and Brückner, 1901/09; Kerschner and Ivy-Ochs, 2007).

2.4. Loess-palaeosol sequences

Although largely absent within the Alps, loess-palaesol sequences (LPS) in the Alpine forelands record variations in the broader region's palaeoclimate, especially phases of pedogenesis, permafrost and increased dust dynamics. Well-studied, high-resolution LPS are described from Austria (e.g. Haesaerts et al., 1996; Terhorst et al., 2013). No comparable records have been reported from Switzerland yet.

LPS are complex palaeoenvironmental archives that form under variable climatic conditions by dust sedimentation in a dry tundra or (cold-)steppe environment (sedimentary aspect) and syn- to postsedimentary alteration from the surface of the deposits during moister and/or milder conditions and absence of significant dust input (pedogenic aspect). The degree of alteration in comparable parent material (loess) and relief position is a function of time and environmental conditions. Bleached horizons with redoximorphic features (tundra gley soils) indicate permanent water saturation in the active layer above the permafrost table (Antoine et al., 2009), whereas under milder climate (in drainable loess) processes such as humification, bioturbation, decalcification and oxidation lead to the development of humic or cambic horizons. For the interpretation of LPS, variable sedimentation rates, polyphase pedogenesis, redeposition, and erosion have to be considered. The latter two processes may indicate a destabilised geoecosystem associated with rapid climate change. Next to detailed genetic reconstructions, reliable datings are important for correlation, but also to evaluate the degree of pedogenesis. Luminescence dating allows for high resolution dating of eolian sediments, but with relatively large errors (Lomax et al., 2012), whereas the usually more precise radiocarbon ages of LPS in Austria are mainly restricted by the availability of datable material (mostly charcoal from archaeological layers; Haesaerts et al., 1996).

3. Overview of records

3.1. Lake sediments and peat

3.1.1. Lake and peat records 60–18 ka

There are a number of lacustrine and peat archives in the northern Alpine Foreland covering the early part of the Last Glacial cycle (Early Würmian, 115–74 ka; Preusser, 2004), such as Gondiswil, Füramoos, Samerberg, and Mondsee. Deposition of most of these sequences ended in the early Middle Würmian and limited information is available about environmental conditions during the Middle Würmian (74–30 ka) and the time when glaciers were present in the Alpine foreland (30–18 ka; Preusser, 2004). This lack of records can be explained by the filling of basins formed during the Rissian Glaciation, as well as by erosional processes during the Last Glaciation.

Key records, for which the age is constrained by geochronological data, originate from Niederweningen, Gossau and Huttwil-Galgenmoos (all northern Switzerland), and Unterangerberg and Baumkirchen (both western Austria) (Fig. 2). All of these records are floating, lacking continuous deposition until present. The deposits from Niederweningen (northern Switzerland) are known for their vertebrate remains, in particular of mammoth. The sedimentology is characterised by repeated changes of silty pond sediments and peat layers. Radiocarbon and luminescence dating indicate deposition of the peat around 45 ka (Hajdas et al., 2007; Preusser and Degering, 2007). Pollen, plant macrofossils, and beetle remains reflect environmental conditions dominated by open spruce–pine forest with larch and Swiss stone pine, mean summer temperatures between 8 and 13 °C, and mean winter temperatures between −20 and −5 °C (Coope, 2007; Drescher-Schneider et al., 2007).

Sediments exposed in the gravel pit of Gossau show several alternating layers of sandy-silty gravel, silt and peat. Radiocarbon, U series and luminescence dating constrain the sediment age to ~60–30 ka (Preusser et al., 2003). The pollen record reflects open pine–spruce forest with Swiss stone pine during the older peat layer, and open pine forest during the younger peat. The beetle fauna in the younger layer indicates mean summer temperatures between 8 and 12 °C and mean winter temperatures between −21 and −14 °C (Jost-Stauffer et al., 2001). For the lower peat, a mean summer temperature of 12–13 °C, and a mean winter temperature between −15 °C and −7 °C have been reconstructed (Jost-Stauffer et al., 2005).

Sediments from a palaeolake in Unterangerberg revealed a complex lithology comprising diamict, gravel, sand, lignite and thick intervals of fine-grained sediments. Beside sediments older than ~100 ka, the sequence recorded the basin development from the end of the Early Würmian (MIS 5a) up to ~40 ka. Pollen assemblages indicate grassland vegetation with scattered stands of pine during MIS 4 and parts of MIS 3. An interstadial dominated by birch is dated to ~50 ka, a second one with open pine–spruce forest to ~45 ka (Starnberger et al., 2013).

The record from Baumkirchen comprises a >200 m sequence of laminated lake sediments. Uncalibrated radiocarbon ages from 25.5 to 32.4 ka (e.g. Fliri et al., 1971, 1972) originally suggested a sedimentation age for a 26 m-thick section between ~29 and 36 ka. Re-dating of several samples using AMS resulted in a revised age of ~35–36 ka cal. BP (Spötl et al., 2013). Luminescence dating yielded mean ages of 37.3 ± 3.5 ka (IRSL UV emissions) and 37.8 ± 3.6 ka (post-IR OSL UV emissions), whereas IRSL (blue emissions) gave a higher mean age of 45.0 ± 4.3 ka (Klasen et al., 2007). A palynological study of an 86 cm section revealed 17 vegetation periods representing grassland tundra with few birch and pine trees (Bortenschlager and Bortenschlager, 1978).

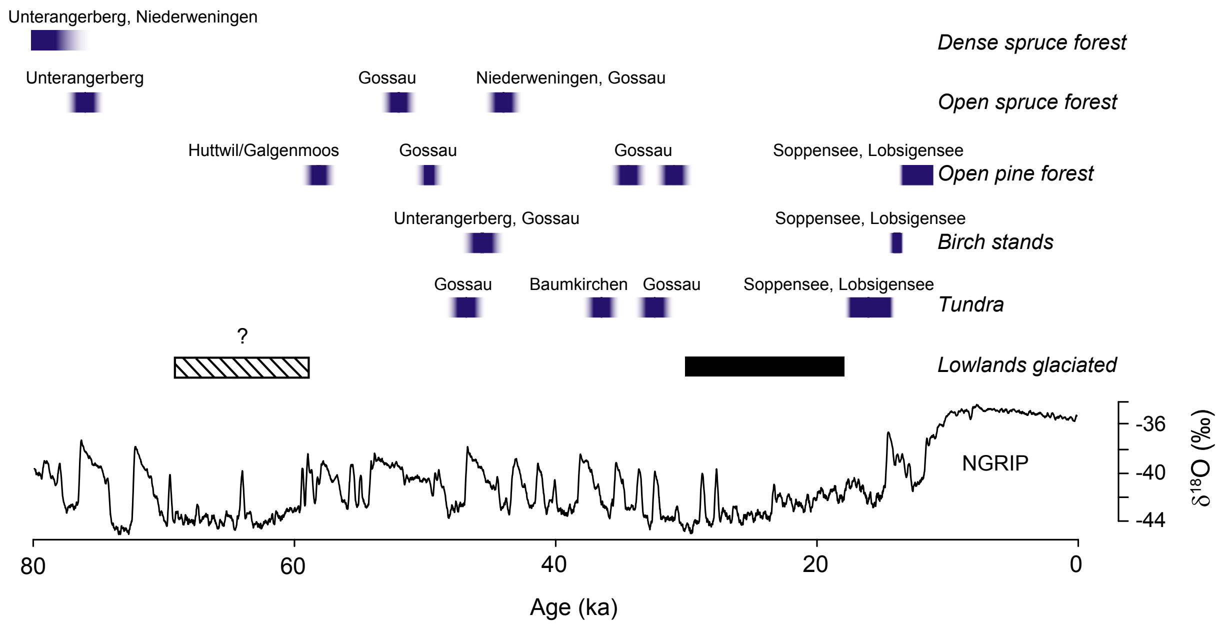

Fig. 2. Summary of palaeovegetation data from key sites in the northern foreland of the Austrian and Swiss Alps (Bortenschlager and Bortenschlager, 1978; Wegmüller et al., 2002; Preusser et al., 2003; Drescher-Schneider et al., 2007; Hajdas et al., 2007; Preusser and Degering, 2007; Spötl et al., 2013; Starnberger et al., 2013). The diagram starts at 80 ka to also include the last forest phase during MIS 5a for comparison. For the time interval prior to the LGM the environmental information is split into five categories and presented only for sites with independent chronological data. After the LGM an increasing number of palaeobotanical records become available for Austria and Switzerland. We schematically present the results from Soppensee and Lobsigensee on the Swiss Plateau (Ammann and Tobolski, 1985; Lotter, 1999). Note that forest succession and dominating tree species during this interval differed considerably in the Austrian lowlands (e.g. Huber et al., 2010). Dating uncertainties for most sites are substantial for the period preceding the LGM and are schematically indicated by the fading of the bars. Intervals when the forelands of the Alps were glaciated are also indicated, with the glaciation during MIS 4 being poorly constrained and under debate. The Greenland oxygen isotope record is shown as a standard Northern Hemisphere reference curve (Svensson et al., 2008).

At Huttwil-Galgenmoos, a 5.6 m-long sediment sequence was sampled. While the upper part (0–3.4 m) consists of sandy-silty slope-wash sediments, the lower part is composed of clastic-rich peaty deposits. The pollen record of the lower layer represents two interstadials, correlated to Hutwil III (assumed to represent MIS 5a), and the Dürnten Interstadial, respectively (Wegmüller et al., 2002; chronological position controversial, cf.; Preusser, 2004). IRSL dating indicates deposition of the sandy-silty slope deposits ~50–15 ka, and deposition of the peaty deposits ~60–50 ka. For the lower part, IRSL dating is inconsistent with pollen-derived age estimates.

3.1.2. Lake and peat records 18–8 ka

Lake sediments and peat deposits covering this time window are poorly dated before reforestation of low elevation regions ~14.6 ka, since terrestrial organic matter, suitable for AMS radiocarbon dating, is sparse in lake sediment records. However, some dated records are available, mainly from localities in the southern part of the region, such as Jeserzersee and Längsee (both Carinthia, Austria; Huber et al., 2010; Schmidt et al., 2012) and Lago di Origlio (Ticino, Switzerland; Samartin et al., 2012b). Available records indicate cool summer temperatures well below modern values for the period >15 ka for the entire study region (e.g. Heiri and Millet, 2005; Lotter et al., 2012; Samartin et al., 2012a) (Fig. 3). For the period ~15–11 ka several temperature reconstructions based on transfer functions are available from the Swiss Alps (e.g. Foppe: Samartin et al., 2012a; Lago di Origlio: Samartin et al., 2012b; Maloja Riegel: Ilyashuk et al., 2009), the Swiss Plateau (e.g. Gerzensee: Lotter et al., 2000, 2012), the adjacent Jura Mountains (Lac Lautrey, France: Heiri and Millet, 2005), and Carinthia (e.g. Längsee: Huber et al., 2010). In addition, two high-resolution $\delta^{18}O$ records based on ostracods, reflecting variations in past $\delta^{18}O$ of precipitation, are available from southern Germany (Ammersee: von Grafenstein et al., 1999) and Upper Austria (Mondsee: Lauterbach et al., 2011). Further reconstructions of precipitation $\delta^{18}O$ are available from Gerzensee on the Swiss Plateau, based on $\delta^{18}O$ of ostracods, molluscs, and charophyte remains (Von Grafenstein et al., 2000, 2013).

At ~14.6 ka, reconstructions uniformly record a rapid warming in summer temperature by about 2–3 °C (e.g. Heiri and Millet, 2005; Lotter et al., 2012; Samartin et al., 2012a, b) (Fig. 3). For the same transition, an increase in $\delta^{18}O$ of precipitation by about 3‰ is inferred (von Grafenstein et al., 1999, 2013). Diverging centennial- to millennial-scale temperature trends are reconstructed during the Bølling/Allerød period (~14.6–12.8 ka) by different proxy types. Chironomid-based reconstructions tend to infer no trend or a gradual warming (e.g. Heiri and Millet, 2005; Lotter et al., 2012; Samartin et al., 2012a). A pollen-based reconstruction from Gerzensee indicates decreasing summer temperatures (Lotter et al., 2012). Reconstructions of $\delta^{18}O$ of precipitation, finally, indicate no distinct centennial- to millennial-scale trend in mean annual temperature (von Grafenstein et al., 1999, 2013; Lauterbach et al., 2011). Lotter et al. (2012) discuss possible reasons for the discrepancy in temperature trends reconstructed by pollen and chironomids at Gerzensee and suggest that it may be explained by the influence of winter temperatures or precipitation on vegetation on the Swiss Plateau. Tree macrofossil and stomata data from the Bernese Alps and their foreland (Fig. 4) suggest that treeline elevation in the northern Alps may have reached 700–1300 m asl. during the Bølling-Allerød period. Paleobotanical records from the Swiss Central Alps and the southern Alps document that treeline during the Bølling-Allerød period had probably already reached elevations around 1600–2000 m a.s.l. (Welten, 1982; Lang and Tobolski, 1985; Tinner and Vescovi, 2007).

$\delta^{18}O$ records provide evidence for decadal to centennial-scale cooling episodes at ~14, ~13.5 and ~12.9 ka (Lotter et al., 1992; von Grafenstein et al., 1999, 2013; Lauterbach et al., 2011). In the Alpine region, these short-term oscillations are not consistently apparent in summer temperature reconstructions based on biotic

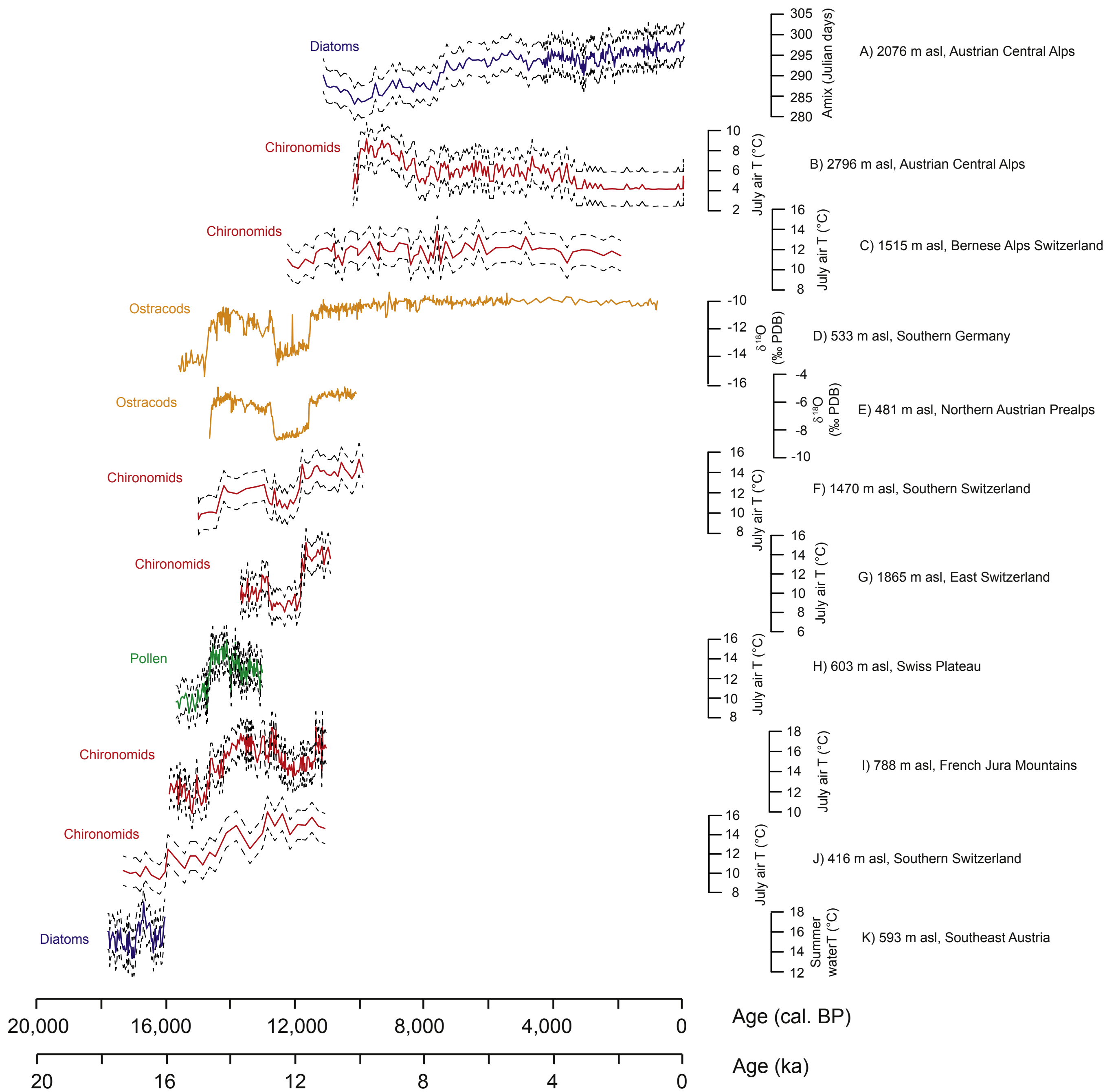

Fig. 3. Examples of temperature reconstructions covering the time window 18–8 ka from lake sediment records in the Austrian and Swiss Alps and their forelands. A) Diatom-inferred date of autumn mixing (Amix), Oberer Landschitzsee, Austria (Schmidt et al., 2006). B) Chironomid-inferred July air temperature, Schwarzsee ob Sölden, Austria (Ilyashuk et al., 2011). C) Chironomid-inferred July air temperature, Hinterburgsee, Switzerland (Heiri et al., 2004). D) Reconstructed $\delta^{18}O$ of precipitation, Ammersee, Germany (von Grafenstein et al., 1999). E) $\delta^{18}O$ of ostracods, Mondsee, Austria (Lauterbach et al., 2011). F) Chironomid-inferred July air temperature, Foppe, Switzerland (Samartin et al., 2012a). G) Chironomid-inferred July air temperature, Maloja Riegel, Switzerland (Ilyashuk et al., 2009). H) Pollen-inferred July air temperature, Gerzensee, Switzerland (Lotter et al., 2012). I) Chironomid-inferred July air temperature, Lac Lautrey, France (Heiri and Millet, 2005). J) Chironomid-inferred July air temperature, Lago di Origlio, Switzerland (Samartin et al., 2012b). K) Diatom-inferred epilimnetic summer water temperature, Jeserzersee, Austria (Schmidt et al., 2012).

remains, perhaps due to their relatively small amplitude, the discontinuous sampling in many records, and the lag which may be expected before biological indicators respond to climatic change. Alternatively, the temperature decrease during these events may have been less prominent during summer than during the rest of the year. In records where they are apparent, the summer temperature decrease during these events has been estimated to ~0.5–1.5 °C (e.g. Lotter et al., 2000; Ilyashuk et al., 2009; Lotter et al., 2012).

A distinct and rapid cooling in summer temperature of ~1.5–3 °C is reconstructed based on pollen, chironomid, and cladoceran records at the beginning of the Younger Dryas cold episode ~12.7 ka, followed by a phase of rapid warming by ~1.5–4 °C at the beginning of the Holocene at ~11.7 ka. These two temperature transitions were accompanied by rapid shifts in $\delta^{18}O$ of precipitation of ~2–2.5‰ in the northern forelands of the Alps (von Grafenstein et al., 1999, 2000; Lauterbach et al., 2011). Treeline declined during the Younger Dryas (Tobolski and Ammann, 2000;

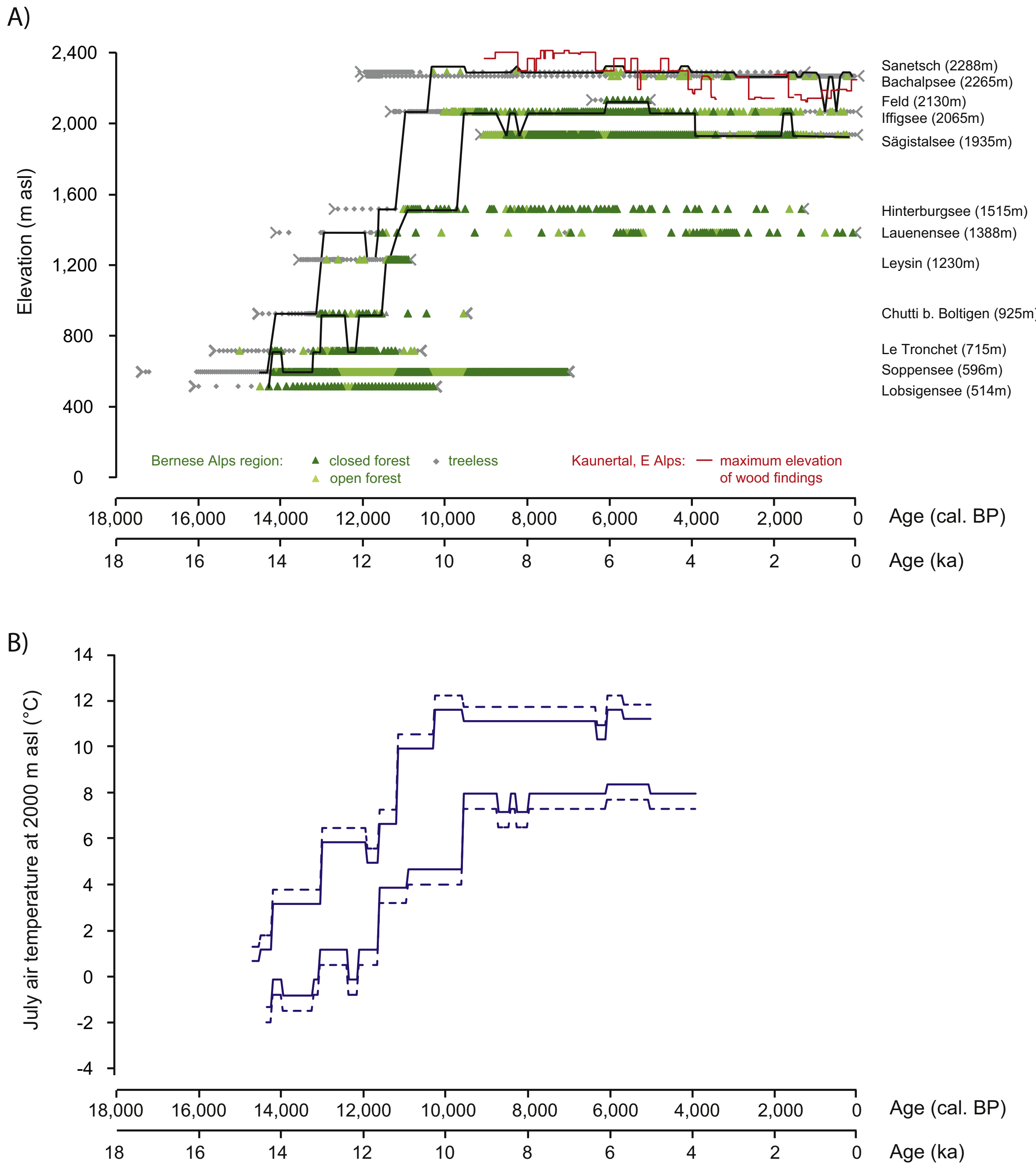

Fig. 4. A) Treeline development in the Bernese Region (central and west Switzerland) based on available plant macrofossil records. Brackets indicate the length of the records, grey diamonds samples without evidence for local tree presence, light green triangles samples with evidence for local presence of treeline vegetation, and dark green triangles samples with evidence for local presence of forest (data from Welten, 1982; Ammann and Tobolski, 1985; Gaillard, 1985; Lotter, 1999; Tobolski and Ammann, 2000; Wick, 2000; Heiri et al., 2003b; Wick et al., 2003; Lotter et al., 2006; Berthel et al., 2012; Rey et al., 2013; Schwörer et al., 2013a). The black lines provide an interpretation of the minimum and maximum altitude of the Alpine treeline based on the presented plant macrofossil records. The red line indicates a reconstruction of treeline elevation in the Kaunertal region, Austria, based on the highest elevation of dendrochronologically dated tree remains (Nicolussi et al., 2005; Nicolussi, 2009). B) Estimated changes in mean July air temperature at 2000 m asl inferred from past maximum and minimum elevations of treeline in the Bernese region as documented in A, assuming minimum July air temperature for tree growth of 7.5–9.5 °C (Landolt, 1992). Dashed lines indicate estimates if an additional uncertainty of 100 m is assumed for determining treeline elevation based on plant macrofossil records. Temperatures are corrected to 2000 m asl using modern lapse rates of 6 °C km^{-1}. Late Holocene treeline (i.e from ~5 to 4 ka onwards) is strongly influenced by human activity and treeline variations for this interval are therefore not translated to July air temperature estimates (see online supplementary data for additional details).

Wick, 2000), however the altitudinal extent of this decline is not clear. Decreases in treeline elevations were apparently relatively minor in the northern Alps (e.g. Fig. 4A) but may have reached 300–400 m altitude in the southern part of the Swiss Alps (Tinner and Vescovi, 2007).

Temperature reconstructions based on lake sediments covering large intervals of the Holocene include the Ammersee $\delta^{18}O$ record, and several transfer function-based reconstructions from fossil assemblage data (e.g. Egelsee: Larocque-Tobler et al., 2009; Hinterburgsee: Heiri et al., 2003a, 2004; Schwarzsee ob Sölden:

Ilyashuk et al., 2011). Furthermore, a number of plant macro- and megafossil records provide constraints for the maximum altitude of past treeline elevations in the Swiss and Austrian Alps (e.g. Tinner and Theurillat, 2003; Nicolussi et al., 2005). Temperature variations of the Holocene are considerably more difficult to track based on lake sediment records than the higher-amplitude variations of the Lateglacial period. Reconstructions of $\delta^{18}O$ of precipitation suggest a number of centennial-scale oscillations (e.g. the Preboreal Oscillation 11.3–11.4 ka; von Grafenstein et al., 1999; Lauterbach et al., 2011), although with the exception of the cooling at 8.2 ka, their amplitude is lower than even minor oscillations recorded during the Lateglacial. Palaeobotanical records from sites near the Alpine treeline similarly provide evidence for centennial-scale temperature decreases (e.g. Haas et al., 1998; Tinner and Theurillat, 2003). Reconstructions from Austria and Switzerland based on fossil assemblages of aquatic biota also document centennial-scale cooling episodes during the Holocene (e.g. Heiri et al., 2003a, 2004; Larocque-Tobler et al., 2009; Ilyashuk et al., 2011). However, not all the oscillations which apparently took place are visible in each of the available records, which may be related to their small amplitude relative to the errors of the applied transfer functions (typically 1–1.5 °C; e.g. Lotter et al., 1997; Heiri et al., 2011), but also to discontinuous sampling, or regional differences in the amplitude of these events across the region. Furthermore temperature variations may have been less extreme in summer than during other seasons. Centennial-scale temperature changes recorded during the recent past in Switzerland (i.e. the temperature rise during the 19th–20th century) were less pronounced during the summer months than during winter and autumn (Begert et al., 2005; Rebetez, Reinhard, 2008).

After the Younger Dryas–Holocene transition, treeline altitude increased and reached maximum elevations in the Austrian and Swiss Alps within the period ~10–5 ka (e.g. Lang, 1994; Tinner and Theurillat, 2003; Nicolussi et al., 2005; Lotter et al., 2006, Fig. 3). The treeline rise in the Bernese Alps was at least 700 m between the Younger Dryas and Holocene optimum, from below 1400 m to over 2100 m asl (Fig. 4A). Similar estimates of treeline rise by about 700–800 m at the onset of the Holocene are available from the Central Swiss and Southern Alps (Tinner and Kaltenrieder, 2005; Tinner and Vescovi, 2007). Transfer function-based reconstructions from fossil assemblage data also indicate a relatively warm early and mid-Holocene in Switzerland, with highest mean July air temperatures inferred within the period ~10–6 ka (e.g. Heiri et al., 2003a, 2004; Larocque-Tobler et al., 2009), although the exact timing of the warmest phase of the Holocene differs between records. The only available transfer function-based July air temperature record from the Austrian Alps indicates highest values in the early Holocene ~10–8.6 ka, followed by cooler temperatures in the mid-Holocene (Ilyashuk et al., 2011).

In comparison to the relatively large number of available palaeotemperature records, few quantitative constraints of past precipitation or moisture changes based on lake sediment records are available for the period 18–8 ka. Examples include lake-level reconstructions based on lithological changes from Western Switzerland and the Swiss Plateau for the Lateglacial and early Holocene (e.g. Magny et al., 2003, 2006) and a pollen-based reconstruction of past precipitation and effective moisture from Le Locle, Swiss Jura (Magny et al., 2003).

3.2. *Speleothems*

3.2.1. *Speleothem records 60–18 ka*

Kleegruben Cave (Austria), a site located at 2165 m asl on the Main Divide of the Eastern Alps, yielded a record spanning ~10 ka of continuous calcite deposition during MIS 3 (Spötl and Mangini, 2002), which was subsequently updated and combined with a second stalagmite from the same site (Spötl et al., 2006). Growth started 58 ka and stopped ~48 ka recording Dansgaard-Oeschger interstadials and stadials at unprecedented resolution (~5a for most of the two records). The high accuracy and precision of the U–Th datings (uncertainties 0.1–0.3 ka, 2 sigma) allow to pinpoint the timing of rapid climate change during MIS 3 (Fig. 5): Greenland Interstadial (GIS) 15b started at 55.7 ka, GIS 15a started at 55.3 ka and the prominent GIS 14 commenced at 54.5 ka (Spötl et al., 2006).

Dansgaard-Oeschger cyclicity was also recorded in a flowstone from nearby Spannagel Cave (~2500 m a.s.l.) whose top part grew between 60 and 53 ka. However, the very slow growth rate (~6 mm/ka) and the possible presence of hiatuses render a detailed correlation with the Kleegruben Cave record difficult (Holzkämper et al., 2005). The magnitude of the isotopic stadial-interstadial changes, however, is comparable to the Kleegruben stalagmites (~2‰).

New records will soon become available from Hölloch (Allgäu Mountains), Germany's currently second largest cave straddling the border to Austria. Preliminary data from one stalagmite show $\delta^{18}O$ jumps of 3‰ at the onset of interstadials between GIS 17 and 11 (Spötl et al., 2011).

Speleothem growth during glacial maxima is unlikely given the lack of soil and vegetation in the catchment of the cave's drip waters. Studies in Spannagel Cave demonstrated, however, that calcite deposition is locally possible when the cave is overlain by ice (Spötl and Mangini, 2007). Three conditions have to be met to allow this rare mode of speleothem formation: first, the presence of sulphide minerals in the aquifer giving rise to corrosive waters upon weathering (driving karst dissolution in the absence of carbon dioxide-enriched waters from soils); second, the presence of a temperate glacier above the cave preventing the karst aquifer from freezing; and, third, galleries that are not flooded by glacier melt waters.

3.2.2. *Speleothem records 18–8 ka*

A stalagmite was retrieved from Hölloch (Allgäu Mountains), which started growing in the Allerød and includes the Holocene, probably compromised by short hiatuses (Wurth et al., 2004). The most prominent isotope excursion is the 2‰ drop in $\delta^{18}O$ coincident with the Younger Dryas (Fig. 5), similar in amplitude as in ostracod $\delta^{18}O$ records from Ammersee (von Grafenstein et al., 1999) and Mondsee (Lauterbach et al., 2011). The published chronology of the Hölloch stalagmite is based on eight U–Th dates and was later adjusted due to a spike correction (Niggemann, 2006).

A few other stalagmites from the Eastern Alps recorded the Allerød–Younger Dryas–Holocene transitions by $\delta^{18}O$ drops consistent with the Hölloch stalagmite. These include, e.g., a stalagmite from Blasloch, Styria (Spötl et al., 2007).

Two sites have been studied for early Holocene speleothem growth in the Eastern Alps, Spannagel Cave and Katerloch (20 km NE of Graz, Austria), and one site in the Western Alps (Milchbach Cave, a site next to the retreating Upper Grindelwald Glacier, Switzerland). Three stalagmites from Spannagel Cave were combined to a stack that comprises the last 9 ka of the Holocene (Vollweiler et al., 2006), recently extended to 11 ka using a total of five stalagmites (Fohlmeister et al., 2013). The most recent part of this record (the last 2 ka) was calibrated as a temperature record using empirical constraints (Mangini et al., 2005).

Katerloch stalagmites yielded the first highly resolved (average 1.5–4.6 a) and well-dated proxy record of the 10.0, 9.1 and 8.2 ka events in the Alps (Boch et al., 2009). These cold spells are expressed by negative $\delta^{18}O$ anomalies of up to 1.1‰, similar in magnitude to the excursions recorded in the $\delta^{18}O$ record from Ammersee (von Grafenstein et al., 1999).

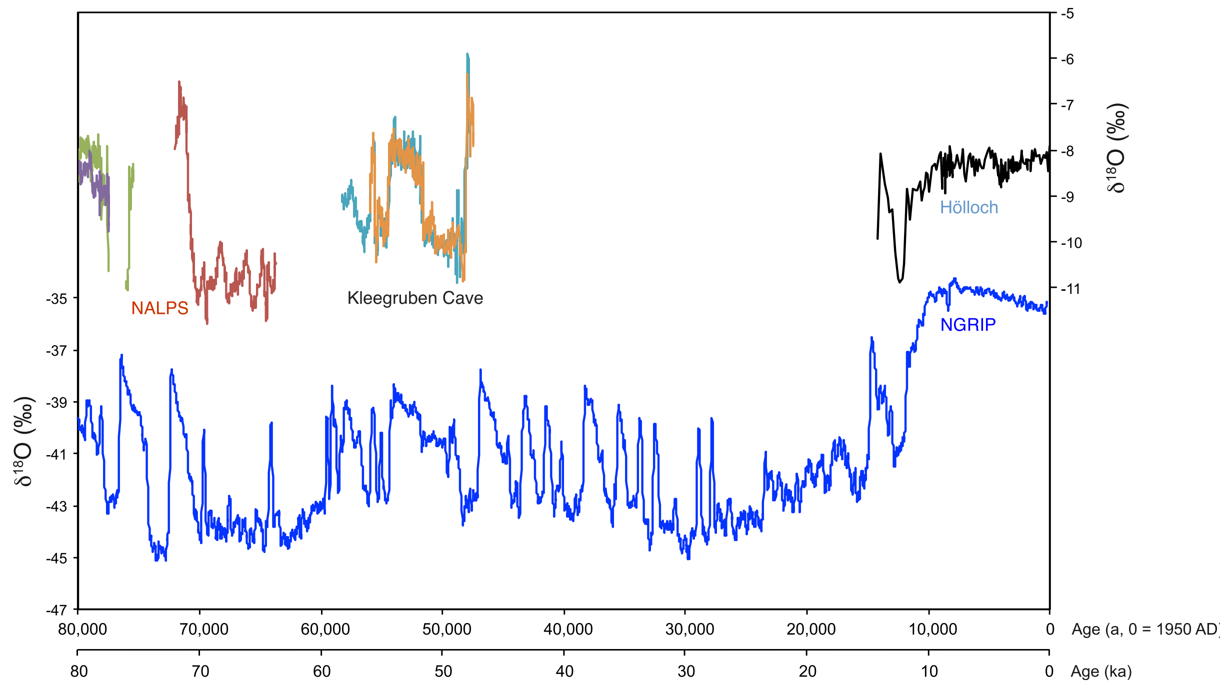

Fig. 5. Speleothem records spanning 80–8 ka in comparison with the Greenland NGRIP $\delta^{18}O$ record (Rasmussen et al. 2006; Svensson et al., 2008). All records including NGRIP are plotted relative to 1950 AD. Three stalagmites of the NALPS record (Boch et al., 2011) fall within the time window of the last 80 ka, as well as two overlapping stalagmites from Kleegruben Cave (plotted with an offset of +4‰ to account for the higher elevation of this site) and one stalagmite from Hölloch Cave. The latter data (Wurth et al., 2004) were plotted using a slightly updated chronology (Niggemann, 2006).

A series of stalagmites from Milchbach Cave (Luetscher et al., 2011) document continuous calcite growth since 9.3 ka. Changes in the calcite fabric as well as in the stable isotopes reflect the waxing and waning of the nearby glacier, which affected soil development, erosion, and cave ventilation regime. Although detailed stable isotope profiles still await publication the data document an extended period of glacier retreat between ~9.3 and 6.8 ka, interrupted only by short advances, the most significant of which occurred at 8.2 ka (Luetscher et al., 2011).

3.3. Glacier records

3.3.1. Glacier records 60–18 ka

The gravel and peat section of Gossau, Switzerland (Preusser et al., 2003; see Section 3.1.1), indicates that the Linth glacier did not reach the foreland of the Alps between ~60 and 30 ka. Similar evidence exists for the Inn valley at Unterangerberg, Austria (Starnberger et al., 2013), and the site of Baumkirchen indicates that the advance of ice into the lower Inn valley occurred subsequent to 32–33 ka (Spötl et al., 2013).

For the last glaciation of the foreland (the "Alpine LGM"), the best constrained data set is available for the Rhine-Linth glacier system, which formed two coalescent piedmont lobes over northern Switzerland and southernmost Germany (data compiled by Keller and Krayss, 2005a, b; re-assessed and calibrated by Schoeneich, 2011). The available data document the progression of the piedmont lobes after ice-free conditions, some oscillations during the phase of maximal extent, and minor readvances during the early recessional phase. Detailed mapping of moraines and melt-water channels allowed the reconstruction of four main stages of the piedmont lobes, known as the Schaffhausen/Kill-wangen, Feuerthalen/Schlieren, Stein am Rhein/Zurich and Konstanz/Hurden stadials (e.g. Keller and Krayss, 2005a) (Fig. 6). The first three stages were formed by glacier advances, followed by several recessional moraines, whereas the last stage represents a phase of ice stagnation.

Eight radiocarbon dates on peat layers covered by till from sites situated between the Alpine front and Lake Constance show that the progradation of the glacier lobes over the foreland started not earlier than 32 ka. The maximal extent at Schaffhausen was reached after 30 ka (Frank and Rey, 1996). At Knollengraben, between the positions of the Stein am Rhein and Konstanz stadials, a peat layer between two tills records an oscillation dated to 26.0–27.5 ka. It might represent a retreat preceding the Stein am Rhein readvance (Weinhold, 1973), but was later reinterpreted as an oscillation during a glacier advance before the maximum (Keller and Krayss, 2005b). OSL dating of melt-water sediments (Preusser et al., 2007) and a comparison with dates from the Linth lobe (Schlüchter and Röthlisberger, 1995) favour the first hypothesis, suggesting a maximal advance between 30 and 27 ka. The presence of glaciers in the foreland is also documented for the northern lobe of the Valais glacier by OSL and radiocarbon dating of the Finsterhennen site (Preusser et al., 2007). Here, the maximum extent is dated by ^{10}Be to ~24 ka (Ivy-Ochs et al., 2008; recalculated after; Balco et al., 2009). Thus, the advance of the northern Alpine piedmont lobes to the furthest extent may have occurred already during GS-5 and/or GS-4, with a second advance when the glaciers were quasi-stationary for a longer period of time during GS-3. Minimum ages for glacier retreat are given by some organic layers overlying till and by palaeomagnetic secular variations in both basins of Lake Constance and in Lake Zurich (Niessen et al., 1992; Wessels, 1996). Measurable secular variations can only be recorded in very fine and calm sedimentation conditions, excluding turbidites, dropstones and any kind of high energy sediments, thus indicating totally glacier free lakes. Accordingly, Lake Constance and Lake Zurich were ice-free no later than ~17–18 ka, but possibly before 20 ka. This result is consistent with the deepest radiocarbon date from the Lake Zurich cores, which yielded an age of 14600 ± 250 ^{14}C yr

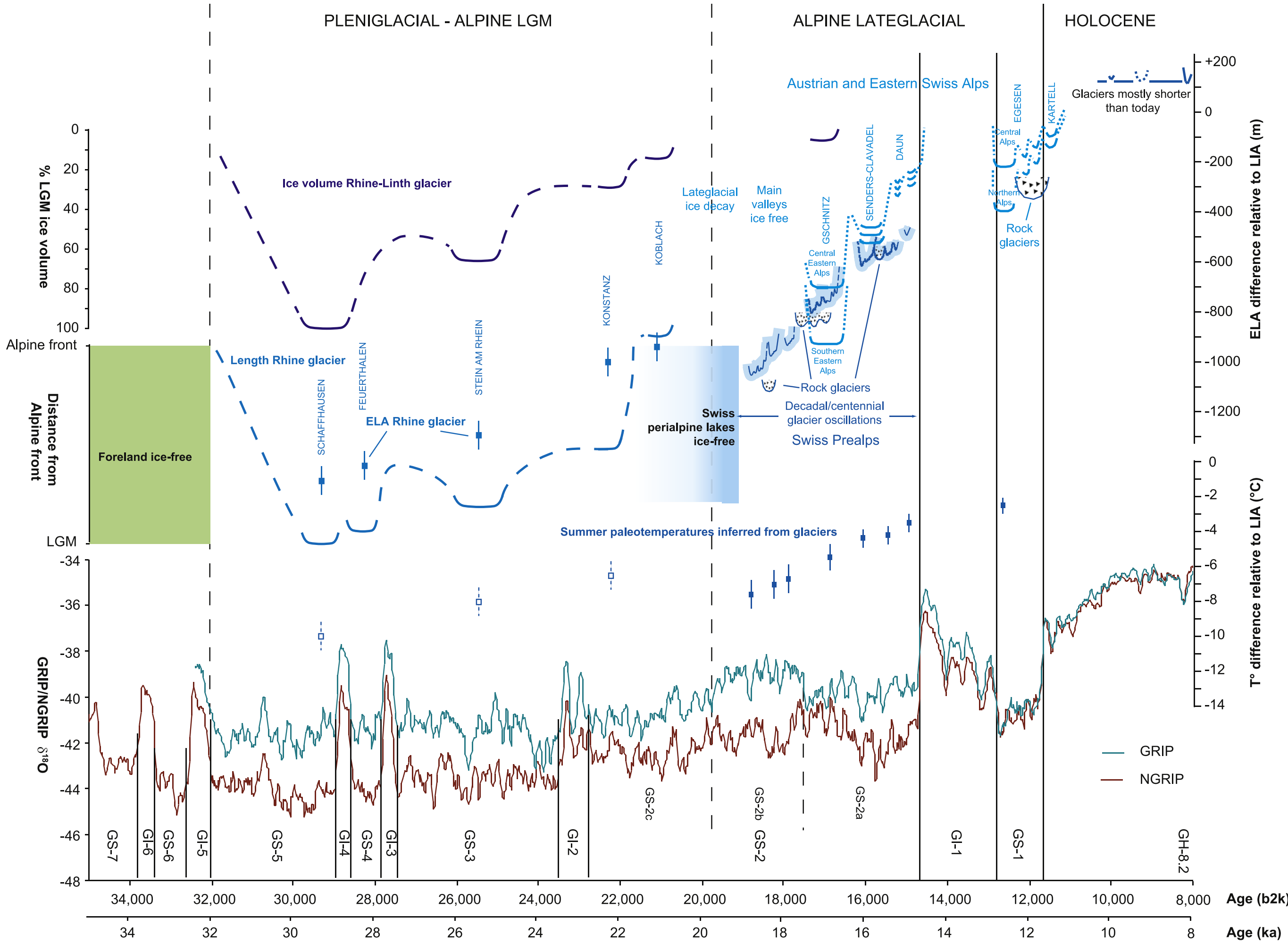

Fig. 6. Examples of glacial geomorphological evidence 35–8 ka, together with palaeotemperature estimates calculated from these data, plotted against the Greenland GRIP and NGRIP δ^{18}O records (GICC05 time scale, Andersen et al., 2006; Rasmussen et al., 2006). Pleniglacial data refer to the Rhine-Linth glacier complex, with glacier length fluctuations and ice volumes interpreted from Benz-Meier (2003), Keller and Krayss (2005b), and Schoeneich (2011). For the Lateglacial and the Holocene, and for selected intervals of the LGM, glacier fluctuations are expressed as ELA (equilibrium line altitude) difference relative to the Little Ice Age (LIA) reference level. Present-day ELA is estimated to be ~120 m above the altitude of the LIA extent. For the early Holocene, evidence about the extent and advances of larger Alpine glaciers indicates that ELA generally varied between ~100 and >200 m above the LIA maximum, and ELA has been drawn accordingly. Data for the Lateglacial of the Austrian and Eastern Swiss Alps are from Ivy-Ochs et al. (2006, 2009). The sequence of the Swiss Prealps is chronologically poorly constrained but clearly represents the interval ~19 to 15 ka, here plotted after Schoeneich (1998a, b). Estimates of past summer temperatures are calculated from the ELA differences, using the glaciological formula of Kuhn (1980) for the Lateglacial (solid symbols) (Schoeneich 1998a, b), and with a gradient approach for the Pleniglacial (open symbols) (Keller and Krayss, 2005b). This approach does not take into account changes in precipitation which may have affected palaeotemperature estimates, especially in the early Lateglacial and Pleniglacial. The dashed vertical lines represent the uncertain dating of the Alpine variations in glacier extent >14.6 ka.

(Lister, 1988) equivalent to ~18.4–17.1 ka cal. BP. AMS radiocarbon dates on terrestrial plant macrofossils (Ericaceae and *Juniperus* wood) show that smaller lakes in the piedmonts of the northern Swiss Alps (e.g. Wauwilermoos) became ice-free before 17.7–18.6 ka cal. BP, when several meters of fine-graded lacustrine sediments had already accumulated on the top of the LGM moraine material (Beckmann, 2004).

The successive piedmont stages of the Rhine-Linth glacier were reconstructed cartographically (Keller and Krayss, 1994, 2005a). Volume calculations based on these maps (Benz-Meier, 2003; Keller and Krayss, 2005b) show that 70% of the ice volume had melted before 20–22 ka, and 95% of the volume was gone before the Gschnitz stadial (Fig. 6).

3.3.2. Glacier records 18–8 ka

The Lateglacial in the Eastern Alpine valleys starts with a poorly constrained period during which the main glaciers in the large longitudinal valleys experienced downwasting and stagnation (Reitner, 2007), whereas smaller, already disconnected glaciers may have experienced a few phases of glacier growth (van Husen, 1997). In the main valleys of the Eastern Alps large systems of ice marginal terraces document the downwasting of the dendritic glacier systems. This phase of the early Lateglacial ice decay is centred on ~19 ka (Klasen et al., 2007), the end is marked by the radiocarbon date of Rödschitz, Austria (18.0–19.1 ka cal. BP, van Husen, 1997).

The first well-defined re-advance is known as the Gschnitz stadial (Penck and Brückner, 1901/09). At the type locality south of Innsbruck (Tyrol, Austria), stabilization of the moraines of a local glacier is dated to 16–17 ka (^{10}Be dates, Ivy-Ochs et al., 2006, recalculated after Balco et al., 2009). Moraines attributed to the Gschnitz stadial are present in other valleys as well. The glacier advance is interpreted as a reaction to the Heinrich 1 ice-rafting event in the North Atlantic. The Gschnitz stadial was followed by a series of glacier oscillations until the onset of the Bølling-Allerød Interstadial. In the Eastern Alps they are known as the Clavadel/Senders and Daun stadials (Maisch, 1981).

In the Swiss Prealps, an exceptionally well-preserved moraine sequence records high-frequency oscillations of small glaciers (0.5–4 km length) (Schoeneich, 1998a, b). The sequence contains up to 6 "stadials", each containing 3 to 5 minor oscillations, with a total of over 30 oscillations bracketed between ~19 and 15 ka. Three generations of rock glaciers are found between stadials. A comparison with historical fluctuations of glaciers of similar size shows that the main advances were of similar amplitude as the main LIA oscillations, and that minor oscillations were in the range of recent decadal oscillations (1890, 1920, 1970's). This suggests that a centennial to decadal variability of similar amplitude as historical variations existed throughout the early Lateglacial.

During the Younger Dryas event, a multi-phase readvance, the so-called Egesen stadial, is well-documented in numerous valleys, and dated at several places in the Alps (Ivy-Ochs et al., 2009; Schindelwig et al., 2011). Field evidence and datings point to at least two separated advance phases with minor oscillations in between. Available dates (recalculated after Balco et al., 2009) suggest that the first and main advance coincides with the first few centuries of the cold event, and the second peak to the second half of the Younger Dryas. Rock-glacier activity at lower altitudes within the glacier-covered areas of the Egesen maximum advance ended at the beginning of the Holocene (Ivy-Ochs et al., 2009).

For the palaeoclimatic interpretation of glacier records 18–8 ka, the equilibrium line altitude (ELA) is the most useful starting point. There, accumulation equals ablation, which can be parameterized by precipitation and summer temperature (Ohmura et al., 1992). For studies in the European Alps, the ELA is usually calculated from a map of the glacier surface using an accumulation area ratio (AAR) of 0.67. ELA fluctuations are reported as differences to the Little Ice Age reference level (ELA depressions) (Gross et al., 1977). For climatic inferences, they must be adjusted to a well-defined standard climate period, such as 1961–90 (Kerschner and Ivy-Ochs, 2007). ELA depressions for the Gschnitz stadial in the central Alps are in the order of 600–700 m. In the Northern Alps, scarce data point to values in the order of 800 m, while in the southern Eastern Alps they range around 900–1000 m. For the Clavadel/Senders stadial, values around 400–500 m are commonly observed in the central Alps. For the Egesen maximum (early Younger Dryas), ELA depressions in the range of 200–250 m are typical in the central Alps. Along the Northern slope of the Alps, ELA depressions may reach 350–>400 m, while in the south, 300–350 m are characteristic (Fig. 6).

Tentative glaciological modelling of the glacier at the Gschnitz type locality indicates a summer temperature lowering in the order of 10 °C relative to mean 20th century values. Precipitation was probably lowered to approximately 30% of present-day amounts (Kerschner and Ivy-Ochs, 2007; Kerschner, 2009).

Younger Dryas summer temperature depressions can be inferred from timberline fluctuations. They should have been in the order of 3.5 °C and certainly not more than 5 °C (cf. Kerschner and Ivy-Ochs, 2007). The large number of available ELAs for the Egesen maximum advance allows a tentative reconstruction of early Younger Dryas precipitation pattern. In a rather dry inner zone of the Alps, precipitation was reduced by 20% or more, while modern values can be expected along the humid outer fringe in the North and probably also in the South close to the Mediterranean Sea (Kerschner and Ivy-Ochs, 2007; Kerschner, 2009).

Tentative summer temperature estimates were made based on the Prealpine Lateglacial sequence using the glaciological formula of Kuhn (1980), assuming constant precipitation (Schoeneich, 1998a). Results range from −8 to −3 °C relative to LIA values (Fig. 6).

Some uncertainties remain concerning the rate and extent of glacier retreat during the rapid warming at the transition of the Younger Dryas to the Holocene. Between the Egesen stadial and 10.5 ka, several oscillations are documented with extents larger than the LIA extent (Ivy-Ochs et al., 2009; Schimmelpfennig et al., 2012).

At the latest after 10.3 ka glaciers were usually as short as or shorter than today (~1990/2010 AD). This is documented by tree remains at the glacier Pasterze (Austrian Alps) for the period 10.2 to 8.9 ka (Nicolussi and Patzelt, 2000) and at the Mont Miné glacier (Swiss Alps) for 9.1–8.2 ka (Hormes et al., 1998; Nicolussi and Schlüchter, 2012). For the latter glacier overridden, dendrochronologically-dated trees document an advance related to the 8.2 ka event, but the glacier extension was less than during the LIA (Nicolussi and Schlüchter, 2012). Brief advances were indirectly documented by speleothems in Milchbach Cave adjacent to the Upper Grindelwald glacier, centering on 9.2 and 8.2 ka (Luetscher et al., 2011). An advance 200 m beyond the LIA maximum of the Tsidjiore Nouve glacier (Swiss Alps) was suggested by Schneebeli and Roethlisberger (1976) and dated to 10.1–8.8 ka.

3.4. Loess-palaeosol sequences

Loess research has a long tradition in Quaternary stratigraphy, but only recent advances in geochronology and the development of high-resolution datasets (e.g. based on magnetic susceptibility, granulometry, geochemistry) have allowed the reconstruction of palaeoclimatic records for different loess regions. As a consequence, first attempts are now made to correlate Late Pleistocene LPS with e.g. ice core records (e.g. Antoine et al., 2009; Haesaerts et al., 2010; Terhorst et al., 2013). Due to high sedimentation rates, the LPS Nussloch near Heidelberg, Germany, is regarded as Central European reference sequence. Based on grain size variations, a correlation with the GRIP dust record has been proposed (Antoine et al., 2009). Here we discuss two well-resolved LPS in eastern Austria (Wachtberg, Willendorf) as examples to demonstrate the type of information about past climatic change that may be developed from loess deposits in the northern Alpine forelands.

The age of the LPS of Willendorf (Fig. 7A) with numerous Upper Palaeolithic cultural layers is relatively well constrained by radiocarbon dating (Haesaerts et al., 1996, 2013; Nigst et al., 2008), thus enabling the compilation of a preliminary age model. Unit E (loess) and units below are not dated yet. Unit D consists mainly of cambic horizons that formed most likely during early to middle MIS 3 (Haesaerts et al., 1996). Mollusc assemblages of mixed forest ecosystems in unit D confirm a climate mild and moist enough for forest development, reflecting the Willendorf interstadial (Haesaerts et al., 1996). An intercalated loess unit (D3; Nigst et al., 2008) represents a cold-dry phase, possibly correlating to Heinrich Event 5. Unit C is a complex sequence of loess and soil horizons, representing on average cooler climate with significant oscillations, including phases of permafrost. Three humic palaeosol horizons are attributed to the Schwallenbach interstadials I to III. This period ended at 31.4–34.7 ka cal. BP (Haesaerts et al., 1996). With the exception of a basal bleached (B4) and one weak humic horizon (B2), Unit B consists of loess, which developed during cold-dry periglacial conditions (27.2–27.7 ka cal. BP; Haesaerts et al., 1996).

At Krems-Wachtberg (Fig. 7C), 24 km downstream of the Danube, an 8 m thick LPS formed between ~40 and 22 ka. Redeposition and erosion was weak at this locality, as indicated by largely continuous luminescence datings (Lomax et al., 2012; Händel et al., 2013). Radiocarbon dates are only available from the archaeological horizons (AH) (full list of calibrated ages provided in the supplementary information). The main AH 4.4 dates to ~31–33 ka cal. BP (Simon et al., 2013). The lower part of the sequence (GH 37-23) with AH 4 in its upper part formed before 30 ka and is characterised by bleached and incipient soil horizons. The absence of well-developed cambic horizons in the upper part of the LPS

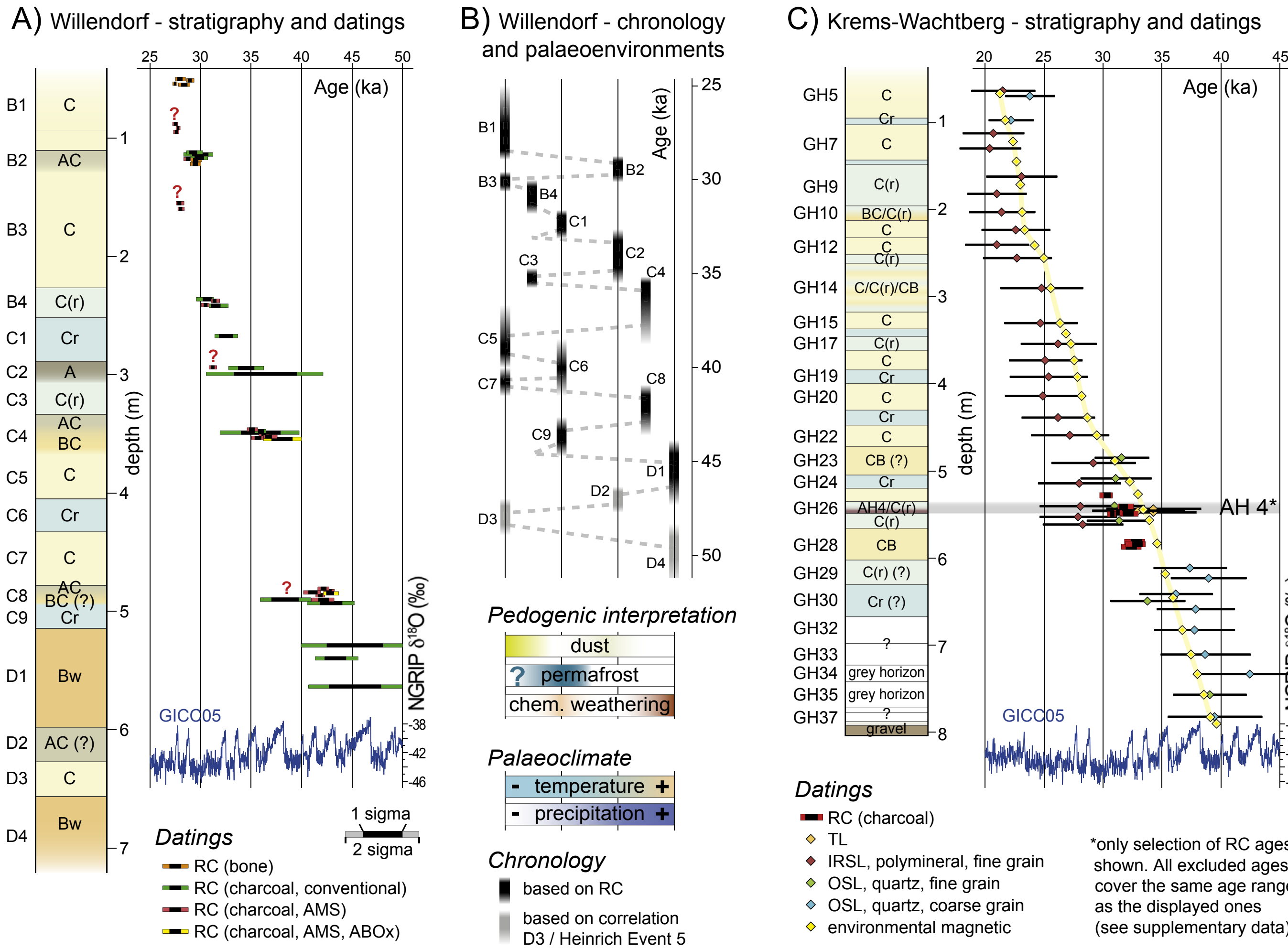

Fig. 7. Examples of two high-resolution loess-palaeosol sequences from Lower Austria (detailed information on data compilation provided in the online Supplementary information). A) Willendorf stratigraphy, lithological descriptions and dating information (Haesaerts et al., 1996, 2013; Nigst et al., 2008). B) Semi-quantitative palaeoenvironmental interpretation from the Willendorf sequence (cf. Haesaerts et al., 1996; Nigst et al., 2008). The relative scale integrates pedogenic information as indicated by the coloured bars below the graph, which in turn can be interpreted as indicating relative variations in temperature and precipitation. For example, C1 is a tundra gley soil (Cr) that formed in loess due to permafrost (blue in the permafrost scale bar), whereas dust accumulation is not significant and chemical weathering is weak. The data thus indicate cold temperatures and low precipitation when C1 was formed. C) Krems-Wachtberg stratigraphy after Händel et al. (2013) and Terhorst et al. (2013) (dating information from Lomax et al., 2012; Simon et al., 2013; Zöller et al., 2013). The environmental magnetic chronology as described by Hambach et al. (2008) is based on the correlation of magnetic susceptibility variations with the Greenland isotope records. It is here adapted to the GICC05 timescale. The Greenland NGRIP $\delta^{18}O$ record is shown for comparison in A) and C) (Svensson et al., 2008). Ah: humic surface horizon, B: subsurface horizon, w: brownish soil structure, C: parent material (loess), r: strong Fe-reduction (tundra gley soil), AH: archaeological horizons; TL: thermoluminescence; IRSL: infra red stimulated luminescence, OSL: optically stimulated luminescence, RC: radiocarbon dating.

indicates increasing sedimentation rates and overall colder climate. A chronological framework for the whole sequence, based on palaeopedological, magnetic, and chemical analyses is suggested by Hambach et al. (2008, Fig. 7C) and further developed by Terhorst et al. (2013).

Palaeoclimatic indications and trends derived from these high-resolution records are supported by data derived from studies on less resolved LPS in the Austrian loess belt. LPS from Stratzing and Langenlois, some km NE to Krems-Wachtberg, contain tundra gley soils that developed during MIS 3 (Thiel et al., 2011), but lack a detailed chronology. Stillfried B in East Austria is a former type section for the Middle- to Late Würmian transition, but this sequence is not consistently dated yet (Terhorst et al., 2011). Poly-pedogenesis and redeposition hamper unambiguous correlations to other records. In the northwest Austrian Alpine forelands, closer to the Alpine margin, LPS are characterized by well-developed pedocomplexes from the MIS 3, most likely due to higher average precipitation compared to the sites further east (Terhorst et al., 2002). First OSL datings indicate phases of advanced weathering, interrupted by permafrost during MIS 3, whereas MIS 2 is represented by a series of loess and tundra gleys (Terhorst et al., 2002).

4. Discussion

The archives and proxy types reviewed in Section 3 document the wide range of approaches used in the Alpine region to quantify past climatic variations 60–8 ka. We restricted this review both geographically (Switzerland, Austria, and some adjacent regions) and in respect to the examined proxies. The main focus was on established approaches providing quantitative palaeoclimate estimates, although, due to the scarcity of records, a number of non-quantitative approaches were discussed for the time window 60–18 ka as well (e.g. Sections 3.1.1, 3.4). Without these constraints the list of available approaches could have been extended considerably. Furthermore, for several proxy types we present case studies and examples suitable for demonstrating the potential of a given proxy (e.g. in respect to treeline changes, glacier fluctuations, or LPS; Sections 3.1, 3.3–3.4), rather than a full overview of all available records. Nevertheless, the discussed examples provide an overview of the state of the art of quantitative palaeoclimate reconstruction 60–8 ka in the Austrian and Swiss Alps and of the steps necessary for further advancements in the field.

4.1. Present situation and issues in respect to existing records

4.1.1. Dating and hiatuses

Even a coarse examination of the different records and archives presented here illustrates the large variation in dating accuracy and resolution between archives. For example, lake sediment records from the Alpine region, even non-varved sequences, can usually be dated with a relatively high accuracy for the early and mid Holocene (e.g. Ilyashuk et al., 2009, Larocque-Tobler et al., 2009, Lauterbach et al., 2011). Dating of sediments deposited 14–11 ka is more problematic, whereas beyond ~14.6 ka dating uncertainties typically increase dramatically (e.g. Huber et al., 2010; Schmidt et al., 2012). The situation is similar for records of past glacier extent. During the Holocene, glaciers expanded several times to altitudes below treeline. Plant macrofossils for radiocarbon dating, that can be used to support and cross-validate other applicable dating methods, are therefore relatively common in glacial deposits and glacier forefields (e.g. Joerin et al., 2006; Nicolussi and Schlüchter, 2012). In older deposits terrestrial plant material tends to be sparse, and dating typically relies on luminescence or on combined approaches, a similar situation as encountered when dating Late Pleistocene loess sequences. Errors associated with all of these approaches inevitably increase in older deposits. Several records are described for which different dating approaches converge, leading to robust and independently validated age estimates even for relatively old deposits (e.g. Starnberger et al., 2013, Fig. 7C). Older records within the time window 60–8 ka are more often affected by hiatuses, either because of discontinuous accumulation (e.g. lakes, speleothems, loess) or because erosive processes triggered by climate change destroyed previously deposited evidence (e.g. glacier advances).

The problems outlined above are to a large extent inherent to late Quaternary deposits, and not restricted to the Alpine region. Since landscapes and deposition processes change with changing climates, the availability of records and the suitability of deposits for different dating approaches change as well. However, several of the problems can be addressed or alleviated to some extent if research projects are designed accordingly. For example, lake sediment studies aiming to obtain larger amounts of sediment (e.g. using larger-diameter corers or replicate coring) will have a higher chance of isolating terrestrial plant remains suitable for radiocarbon dating. Alternatively, newly developed approaches for dating late Quaternary sequences, e.g. compound or fossil-specific radiocarbon dating (e.g. Tennant et al., 2013) or microtephra analyses (e.g. Pollard et al., 2006; Huber et al., 2010), may significantly reduce dating uncertainties for the time interval 50–15 ka. For glacier studies extensive and structured searches for radiocarbon-datable material in glacial deposits or glacier forefields may yield additional age constraints. Further efforts to establish independently cross-validated chronologies based on several independent dating methods are needed to better constrain palaeoclimate records >15 ka. This may allow the development of new proxy data even for time intervals presently without or with very few proxy-based constraints on palaeoclimatic conditions. Recent developments in speleothem research are promising in this respect. New records are now emerging that cover the Alpine LGM (Luetscher and Spötl, unpublished) even though this period has previously been considered to be poorly suited for speleothem growth.

4.1.2. Fragmentary records and replication (temporal coverage)

Proxy records in the Alpine region 60–8 ka are not only affected by hiatuses for some intervals, but also by a relatively short record length and a low degree of replication. For example, several chironomid-based temperature reconstructions are available for Switzerland, making this one of the most replicated approaches for quantitative climate reconstruction based on lake sediments in this region (see Section 3.1.2 and Fig. 3). A number of records are available that cover the transition from the earliest Lateglacial to the early Holocene (~15–11 ka), several that extend from the Younger Dryas to the mid Holocene (~12–8 ka), and a few which extend back to the earliest Lateglacial (>17 ka). However, no record is presently available which encompasses the entire time window 17–8 ka. Temperatures in some sections of this interval (e.g. 15–17 ka) are only constrained by a single dated chironomid record. For other quantitative temperature proxies from lake sediment records, temporal coverage and replication are even sparser than for chironomids. A similar situation is apparent for speleothem records: Variations in $\delta^{18}O$ have only been replicated for a few time intervals and regions (e.g. Spötl et al., 2006; Vollweiler et al., 2006). Large parts of the time period 60–8 ka are, however, represented by only a single speleothem record in the Swiss and Austrian Alps. A better replication of such records within specific sectors of the Alps would allow a more rigorous evaluation of the reliability and regional relevance of individual records (Lotter et al., 1992). For example, a recent record of $\delta^{18}O$ of ostracod valves from Mondsee, Austria (Lauterbach et al., 2011), shows an excellent agreement with an earlier record from Ammersee in the Alpine foreland of southern Germany (von Grafenstein et al., 1999), as well as with a stalagmite from Hölloch Cave (Wurth et al., 2004), supporting the reliability of decadal- to millennial-scale variations recorded in these records. However, this comparison also reveals that a prominent excursion recorded in the Ammersee record within the Younger Dryas cold phase ~12 ka is not represented in the other records, and this event is clearly not representative for the regional climate development.

Some disciplines, such as glaciology and palaeobotany, have a longer tradition in the Alpine region than studies of aquatic proxies in lake sediments or speleothems, and a comparably high number of data and studied sites is available for inferring past glacier variability and vegetation change. However, to develop records representing long-term variations in climatic variables, glaciological and palaeobotanical datasets have to be compiled to regional reconstructions. Here, similar difficulties are apparent as with lake sediments and speleothem records. Few regional reconstructions are available that cover large sections of the interval 60–8 ka. For example, in the Bernese Alps and their foreland a considerable number of plant macrofossil records is now available, each providing information on the presence or absence of tree vegetation at a certain altitude during sections of the Lateglacial period or the Holocene (see Fig. 4A). To produce a continuous reconstruction of past variations in treeline these records have to be assembled and compared, allowing inferences to be made about the altitudinal limits of past tree growth. This information can, in turn, be used to produce estimates of past summer temperature change in the Alps (see, e.g. Fig 4B). Both the overall altitudinal development of treeline within the region and the gaps in the records are not apparent to non-specialists if the data are not compiled into overview diagrams and simplified datasets. A similar situation is apparent regarding loess records and reconstructions of past glacier extent. Without visualising and summarizing the complex stratigraphical and chronological data, often from different study sites (e.g. as done in Figs. 6–7), the records are difficult to interpret for researchers unfamiliar with these approaches.

4.1.3. Regional and local effects (spatial coverage)

Regional differences in the efforts invested into developing and replicating proxy records also make it difficult to identify large-scale patterns in climate development across the Alpine region and separate them from local artefacts. As an example, a recently published chironomid record from Schwarzsee ob Sölden in the Eastern Alps (Ilyashuk et al., 2011) indicates relatively high early Holocene temperatures at the study site compared to chironomid-based reconstructions and treeline records from the northern Swiss Alps (e.g. Heiri et al., 2004 and Fig. 4B). Confirmation of this difference by additional chironomid records is still lacking, and therefore it is unclear whether this finding reflects a true difference in regional temperature development, whether it reflects exceptional early Holocene temperatures at a particular site, or whether the biotic response to climate was amplified due to site-specific conditions. As discussed in Section 3.3.2, regional studies of ELA provide indications for changing precipitation gradients within the Alps during the Younger Dryas. More systematic replication and spatial coverage of proxy records across the Alps would allow similar comparisons to be made for other proxies to detect regional differences in proxy response, and reconstructed temperature development. For example, some of the available palaeobotanical records from around treeline elevation suggest that the Alpine treeline reached maximum elevations earlier in the Central Alpine region (10–5 ka; Tinner et al., 1996) and the Eastern Alps (>6.5 ka; Nicolussi et al., 2005) than in the northern Alpine region (~6–4 ka; Lotter et al., 2006), suggesting regional differences in the timing of the Holocene maximum in summer temperature across the Alps.

4.1.4. Quantification and validation of proxies

For some proxy types, major progress has been made in recent years in quantifying the relationship between proxy indicators and the environmental variable(s) they represent. These advancements typically involve the development of empirical or mechanistic numerical models that allow quantitative inferences about past climatic conditions based on proxy data. An example of this approach is the development of transfer functions based on fossil assemblages from lakes covering a wide range of environmental conditions (calibration in space; e.g. Lotter et al., 1997; Heiri et al., 2011). Alternatively, well-dated proxy sequences can be related to instrumental or observational time series (calibration in time; e.g. Mangini et al., 2005). An example of mechanistic models applied for reconstructing past climatic changes in the Alpine region is provided by reconstructions based on ELA changes. If assumptions are made regarding the remaining variables influencing glacier mass balance, ELA variations can be used to infer past variations of summer temperature or precipitation (e.g. Ivy-Ochs et al., 2006 and Section 3.3.2). Most of these approaches have in common that they have been developed and calibrated based on present-day relationships, or relationships covering the very recent past (i.e. the past ~100–200 a). Furthermore, many of the approaches have been initially developed for reconstructing climatic changes during the Holocene.

Proxy-based approaches to climatic reconstruction rely on indirect, and in many cases empirical relationships between the proxy indicator and climatic variable of interest. It is therefore clear that they can fail when applied to periods and regions in which climatic conditions differed from climatic states represented in calibration data, or if different combinations of proxy state and climatic conditions occurred in the past than are represented in the modern environment. Centennial- to millennial-scale climatic changes during the last glaciation clearly exceeded the range of climates experienced and recorded in the Alpine region during the past two centuries. As a consequence, transfer functions calibrated in time often have limited use for inferring climatic change >11 ka. Even models which have been calibrated based on a range of varying environmental conditions within the Alpine region using the calibration-in-space approach have to be extended and modified to be applied to records covering the Lateglacial, e.g. by extending calibration datasets to encompass boreal and arctic environments (e.g. Heiri et al., 2011). Uncertainties associated with reconstructions of Glacial and Lateglacial climate based on modern calibration data can be reduced by cross validating reconstructions (e.g. Bradley, 1999). Climatic variations and spatial patterns in climate change that are confirmed by several independent lines of evidence can be interpreted with high confidence. This is in contrast to features that are either documented by single approaches only, or by variations that are not consistently recorded by different proxies. Cross validation is ideally based on several quantitative records, such as the reconstructions of July air temperature inferred from chironomid and pollen assemblages in the same Lateglacial record from Gerzensee, Switzerland (Lotter et al., 2012). Within the prediction errors the two reconstructions agree well in the time window ~15.3–13.8 ka, and absolute estimates of past July air temperature in this interval can therefore be interpreted with some confidence. However, reconstructed values deviate in the interval ~13.8–13.0 ka, the chironomids suggesting warmer temperatures than inferred by pollen, pointing towards a potential bias in one or both of these records in this time window. Cross-validation with semi-quantitative or qualitative climate records can also provide independent support for the reliability of climate reconstructions, although the result of this exercise will be less rigorous than an inter-comparison of fully quantitative data (e.g. Heiri et al., 2004).

At present very few systematic cross validation exercises between independent, quantitative approaches are available for the Alpine region for the time window 60–8 ka. The need for inter-calibration and validation also highlights that additional, independent approaches for reconstructing temperature variations 60–8 ka are necessary in order to expand the range of methods available for multi-proxy comparisons. For example, a recently published quantitative temperature reconstruction based on archaeal membrane lipids (TEX86) from Lake Lucerne now provides an additional record for assessing the amplitude of Lateglacial temperature changes in Central Europe (Blaga et al., 2012) that can help to resolve the observed discrepancies between records based on more established approaches.

4.1.5. Records representing variables other than temperature

Our review demonstrates that the vast majority of studies providing quantitative estimates of past climatic change in the study region within the interval 60–8 ka focus on summer temperature (e.g. most biotic proxies, glacier records), or variables believed to mainly reflect past variations in mean annual temperature (e.g. $\delta^{18}O$ of precipitation). Very few records are available that are based on established, quantitative approaches and reconstruct other thermal variables (e.g. reflecting autumn temperature: Schmidt et al., 2006) or changes in precipitation and evaporation (e.g. lake level changes: Magny et al., 2003). Again, this problem is not restricted to the Alpine region. However, the Alps and their forelands, with the large number of proxy types recording past temperature change, would be well suited for developing approaches that take advantage of processes influenced by temperature as well as by precipitation and evaporation (e.g. variations in glacier length and volume, pedogenesis, vegetation composition, lake water $\delta^{18}O$) for developing new records of past changes in effective moisture. Again, replicated and cross-validated temperature reconstructions for different regions of the Alps would be necessary to further develop these approaches. Several recently published records of late and mid Holocene climatic change in the Alpine region (e.g. Kamenik and Schmidt, 2005; Schmidt et al., 2006, 2008) and Late Pleistocene climatic variations in adjacent regions (e.g. Wagner-Cremer and Lotter, 2011) indicate that new approaches to calibrating and interpreting established palaeoenvironmental indicators may also be suited for providing seasonal temperature records from Alpine proxy records for the time window 60–8 ka (e.g. spring temperatures).

4.2. Strategies for the future

Based on the analysis of the present situation, we identify a number of developments that would provide major advancements for quantitative climate reconstruction in the Austrian and Swiss sectors of the Alpine region in the interval 60–8 ka.

(1) Compilations of individual records to continuous reconstructions: Summary datasets describing changes in climatic variables or processes influenced by climate over large sections of the time window 60–8 ka are needed to make the available, fragmentary datasets accessible to the wider user community. Such compilations would not only facilitate the use of Alpine proxy data by palaeoclimatologists interested in climatic change at a European to global scale; they would also highlight where additional records and efforts are necessary to fill gaps in the presently available data. Furthermore, such data compilations would be directly comparable with more continuous Late Quaternary proxy-records developed in regions beyond the maximum ice extent of the last glaciation.

(2) Replication and regional reconstructions of past climatic change: Very few late Quaternary climate reconstructions in the Alpine region are based on several, replicated records from the same region (see discussion above). Such records would allow the detection of local artefacts in individual records. Furthermore, replicated records would allow an assessment of the reliability and reproducibility of individual approaches when applied to multiple sites, and the development of new and more robust numerical approaches to develop regional reconstructions (e.g. consensus reconstructions, stacking of records).

(3) Cross-validation of different proxy types and approaches: As outlined above, cross-validation of different approaches provides a rigorous assessment of which aspects of past climate change (e.g., rates of change, amplitudes of change, maximum or minimum values, or direction of change) are supported by different, independent lines of evidence, and which aspects are presently not robustly constrained by multiple approaches. Since all quantitative approaches to reconstruct climatic change may fail if applied to environmental conditions different than those for which an approach has been developed, or if major assumptions behind the approach are violated, such cross-validation exercises are urgently needed. Furthermore, cross-validations may also highlight periods in the past for which different approaches provide diverging results and which may have been characterised by climates different than today. Whether opportunities for cross-validation develop in the near future is obviously related to the quality and reliability of emerging proxy records. Replication and compilation of available records, identified as major aims above, would therefore also greatly facilitate such intercomparisons. Furthermore, it is clear that additional, newly developed proxy indicators and approaches to reconstruction would expand the options for cross-validation. The development of such new approaches should therefore be pursued in the Alpine region.

(4) Reconstruction of past climatic gradients across the Alps: Replicated regional reconstructions of climatic change from several regions would allow an assessment of variations in climatic gradients across the Alpine region. The Alps are an exceptionally interesting area in this context since regional diverging trends of, e.g., temperature or precipitation would allow insights into past circulation patterns and adiabatic effects within the Alpine arch (e.g. Florineth and Schlüchter, 2000). Presently available records are too sparse for most regions, or poorly accessible, complicating such an approach. However, regional differences apparent in some proxy types, e.g. in Younger Dryas ELA between central and outer sectors of the Alps, clearly highlight the potential of such regional, time-transgressive comparisons.

(5) Downscaling of model results to Alpine topography. Climate proxy records play an important role for establishing long-term climate trends and climate linkages, and for understanding leads and lags between climate forcing factors and climatic change. Climate proxy records are also increasingly used for evaluating climate model runs under boundary conditions of the Late Pleistocene or the Holocene (e.g. Renssen et al., 2009). Such comparisons allow an assessment of whether climate models can adequately infer climatic conditions for time periods when climate and climate forcing conditions differed significantly from the modern state. The spatial resolution of most available climate models used to hindcast climate change during the late Quaternary is too coarse for the complex Alpine orography to be adequately represented. Therefore, it is presently difficult to assess whether differences between proxy records from the Alps, influenced by local effects, and climate model hindcasts, typically representing large-scale circulation patterns, are significant. Downscaling of climate model runs 60–8 ka to take into account the Alpine orography would allow a more refined comparison of climate proxy data and model runs. Such runs would highlight under which conditions diverging climatic trends are expected for different sectors of the Alps. Furthermore, they would provide information regarding the climatic sensitivity of different regions and altitudinal belts within the Alps to past and future changes in atmospheric circulation.

(6) Forward modelling of proxies. The majority of approaches to climate reconstruction 60–8 ka rely on empirical relationships between proxy indicators and climatic variables to reconstruct past climatic change. In a second step, climate reconstructions are then compared amongst themselves, with climate model data, or with climate forcing records. An alternative to assess whether a climate scenario is compatible with proxy records is to model the proxy state (e.g. treeline altitude, ELA, permafrost distribution) based on available palaeoclimate data and to compare the result with independent proxy data (e.g. plant macrofossil records obtained from sensitive altitudes, changes in glacier mass or size, evidence for permafrost in LPS). Heiri et al. (2006), Henne et al. (2011) and Schwörer et al. (2013b) used this approach to model expected variations in treeline vegetation in the early and mid Holocene from chironomid-based temperature variations using dynamic vegetation models. The model results were then compared with palaeobotanical proxy data. This forward modelling approach also opens new avenues for assessing whether climate model runs are compatible with proxy records by integrating forward

models with climate modelling (e.g. Schmidt, 2010; Sturm et al., 2010). Furthermore, the approach has the advantage that it can provide insights into past climatic change based on proxy types that are strongly influenced by several climatic variables, as long as independent estimates for the variables other than the one to be reconstructed are available. Replicated proxy compilations for different regions of the Alps, ideally based on multiple, independent approaches, would provide further opportunities to develop forward modelling as a palaeoclimatic tool in the Alpine region. Similarly, downscaled climate model results would provide the opportunity of modelling proxy response and comparing the outcome with observational data. The development of refined modelling techniques for forward modelling landscape processes and ecosystem development would therefore be an important contribution to palaeoenvironmental reconstruction in the Alpine region.

Datasets presented in Figs. 3–5 and 7 (or links to repositories archiving these datasets), together with the pleniglacial dataset shown in Fig. 6 are provided in the Online Supplementary Data.

Acknowledgments

We thank Colin Murray–Wallace, Cesare Ravazzi, and an anonymous reviewer for their comments on an earlier version of this manuscript. This work and the workshop leading to this publication have been supported by the Cost Action ES0907 "Integrating ice core, marine and terrestrial records – 60,000–8000 years ago (INTIMATE)". OH acknowledges support from the European Research Council) (Starting Grant Project RECONMET under the European Union's Seventh Framework Programme (FP/2007-2013) (ERC Grant Agreement n. 239858) and KK by the Autonomous Province Bozen (Grant for Research and Innovation, project "Nickel Control", no. 32.06-671599), and CS and WT by the Dr. Alfred Bretscher Foundation.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2014.05.021.

References

Ammann, B., Tobolski, K., 1985. Lobsigensee – Late-glacial and Holocene environments of a Lake on the Central swiss plateau. In: Lang, G. (Ed.), Swiss Lake and Mire Environments during the Last 15000 Years, Dissertationes Botanicae, vol. 87, pp. 127–170.

Andersen, K., Svensson, A., Johnsen, S., Rasmussen, S., Bigler, M., Rothlisberger, R., Ruth, U., Siggaard-Andersen, M., Steffensen, J., Dahl-Jensen, D., Vinther, B., Clausen, H., 2006. The Greenland ice core chronology 2005, 15–42 ka. Part 1: constructing the time scale. Quat. Sci. Rev. 25, 3246–3257.

Antoine, P., Rousseau, D.-D., Moine, O., Kunesch, S., Hatté, C., Lang, A., Tissoux, H., Zöller, L., 2009. Rapid and cyclic aeolian deposition during the Last Glacial in European loess: a high-resolution record from Nussloch, Germany. Quat. Sci. Rev. 28, 2955–2973.

Balco, G., Briner, J., Finkel, R.C., Rayburn, J.A., Ridge, J.C., Schaefer, J.M., 2009. Regional beryllium-10 production rate calibration for late-glacial northeastern North America. Quat. Geochronol. 4, 93–107.

Beckmann, M., 2004. Pollenanalytische Untersuchungen der Zeit der Jäger und Sammler und der ersten Bauern an zwei Lokalitäten des Zentralen Schweizer Mittellandes. Diss. Bot. 390, 1–223.

Begert, M., Schlegel, T., Kirchhofer, W., 2005. Homogeneous temperature and precipitation series of Switzerland from 1864 to 2000. Int. J. Climatol. 25, 65–80.

Benz-Meier, C., 2003. Der würmeiszeitliche Rheingletscher-Maximalstand: digitale Rekonstruktion, Modellierung und Analyse mit einem geographischen Informationssystem. PhD thesis. Geographisches Institut Universität Zürich, Zürich.

Berthel, N., Schwörer, C., Tinner, W., 2012. Impact of Holocene climate changes on alpine and treeline vegetation at Sanetsch Pass, Bernese Alps, Switzerland. Rev. Palaeobot. Palynol. 174, 91–100.

Blaga, C.I., Reichart, G.-J., Lotter, A.F., Anselmetti, F.S., Damsté, J.S.S., 2012. A TEX86 lake record suggests simultaneous shifts in temperature in Central Europe and Greenland during the last deglaciation. Geophys. Res. Lett. 40, 948–953.

Blockley, S.P.E., Lane, C.S., Hardiman, M., Rasmussen, S.O., Seierstad, I.K., Steffensen, J.P., Svensson, A., Lotter, A.F., Turney, C.S.M., Ramsey, C.B., INTIMATE members, 2012. Synchronisation of palaeoenvironmental records over the last 60,000 years, and an extended INTIMATE event stratigraphy to 48,000 b2k. Quat. Sci. Rev. 36, 2–10.

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. Quat. Sci. Rev. 28, 2527–2538.

Boch, R., Cheng, H., Spötl, C., Edwards, R.L., Wang, X., Häuselmann, P., 2011. NALPS: a precisely dated European climate record 120–60 ka. Clim. Past 7, 1247–1259.

Bortenschlager, I., Bortenschlager, S., 1978. Pollenanalytische Untersuchung am Bänderton von Baumkirchen (Inntal, Tirol). Z. für Gletscherkd. Glazialgeol. 14, 95–103.

Bradley, R.S., 1999. Paleoclimatology. Reconstructing Climates of the Quaternary. Academic Press, San Diego, 610 pp.

Brauer, A., Endres, C., Günter, C., Litt, T., Stebich, M., Negendank, J.F.W., 1999. High resolution sediment and vegetation responses to Younger Dryas climate change in varved lake sediments from Meerfelder Maar, Germany. Quat. Sci. Rev. 18, 321–329.

Brauer, A., Hajdas, I., Blockley, S.P.E., Bronk Ramsey, C., Christl, M., Ivy-Ochs, S., Moseley, G.E., Nowaczyk, N.N., Rasmussen, S.O., Roberts, H.M., Spötl, C., Staff, R.A., Svensson, A., 2014. The importance of independent chronology in integrating records of past climate change for the 60–8 ka INTIMATE time interval. Quat. Sci. Rev. 106, 47–66.

Coope, G.R., 2007. Coleoptera from the 2003 excavations of the mammoth skeleton at Niederweningen, Switzerland. Quat. Int. 164/165, 130–138.

Darling, W.G., 2004. Hydrological factors in the interpretation of stable isotopic proxy data present and past: a European perspective. Quat. Sci. Rev. 23, 743–770.

Drescher-Schneider, R., Jacquat, C., Schoch, W., 2007. Palaeobotanical investigations at the mammoth site of Niederweningen (Kanton Zürich), Switzerland. Quat. Int. 164/165, 113–129.

Feurdean, A., Perşoiu, A., Tanţău, I., Stevens, T., Magyari, E.K., Onac, B.P., Marković, S., Andrič, M., Connor, S., Fărcaş, S., Gałka, M., Gaudenyi, T., Hoek, W., Kolaczek, P., Kuneš, P., Lamentowicz, M., Marinova, E., Michczyńska, D.J., Perşoiu, I., Płóciennik, M., Słowiński, Stancikaite, M., Sumegi, P., Svensson, A., Tămaş, T., Timar, A., Tonkov, S., Toth, M., Veski, S., Willis, K.J., Zernitskaya, V., 2014. Climate variability and associated vegetation response throughout Central and Eastern Europe (CEE) between 60 and 8 ka. Quat. Sci. Rev. 106, 206–224.

Fliri, F., Hilscher, H., Markgraf, V., 1971. Weiter Untersuchungen zur Chronologie der alpinen Vereisung (Bänderton von Baumkirchen, Inntal, Nordtirol). Z. für Gletscherkd. Glazialgeol. 7, 5–24.

Fliri, F., Felber, H., Hilscher, H., 1972. Weitere Ergebnisse der Forschung am Bänderton von Baumkirchen. Z. für Gletscherkd. Glazialgeol. 8, 203–2013.

Florineth, D., Schlüchter, C., 2000. Alpine evidence for atmospheric circulation patterns in Europe during the Last Glacial Maximum. Quat. Res. 54, 295–308.

Fohlmeister, J., Vollweiler, N., Spötl, C., Mangini, A., 2013. COMNISPA II: update of a mid-European isotope climate record, 11 ka to present. Holocene 23, 749–754. http://dx.doi.org/10.1177/0959683612465446.

Frank, S., Rey, R., 1996. N4 Flurlingen: durch Tunnelbau beschleunigte Kriechbewegungen und deren Konsequenzen für die Bauausführung. In: Oddson, B. (Ed.), Instabile Hänge und andere risikorelevante natürliche Prozesse. Birkhäuser, Basel, pp. 203–218.

Franke, H.W., 1966. Ein speläochronlogischer Beitrag zur postglazialen Klimageschichte. Eiszeitalt. Ggw. 17, 149–152.

Gaillard, M.J., 1985. Late-glacial and holocene environments of some ancient lakes in the western Swis plateau. In: Lang, G. (Ed.), Swiss Lake and Mire Environments during the Last 15000 Years, Dissertationes Botanicae, vol. 87, pp. 273–336.

Gross, G., Kerschner, H., Patzelt, G., 1977. Methodische Untersuchungen über die Schneegrenze in alpinen Gletschergebieten. Z. für Gletscherkd. Glazialgeol. 7, 223–251.

Haas, J.N., Richoz, I., Tinner, W., Wick, L., 1998. Synchronous Holocene climate oscillations recorded on the Swiss Plateau and at timberline in the Alps. Holocene 8, 301–309.

Haesaerts, P., Damblon, F., Bachner, M., Trnka, G., 1996. Revised stratigraphy and chronology of the Willendorf II sequence, Lower Austria. Archaeol. Austr. 80, 25–42.

Haesaerts, P., Borziac, I., Chekha, V.P., Chirica, V., Drozdov, N.I., Koulakovska, L., Orlova, L.A., van der Plicht, J., Damblon, F., 2010. Charcoal and wood remains for radiocarbon dating Upper Pleistocene loess sequences in Eastern Europe and Central Siberia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 291, 106–127.

Haesaerts, P., Damblon, F., Nigst, P., Hublin, J.J., 2013. ABA and ABOx radiocarbon cross-dating on charcoal from Middle Pleniglacial loess deposits in Austria, Moravia, and Western Ukraine. Radiocarbon 55, 641–647.

Hajdas, I., Bonani, G., Furrer, H., Mäder, A., Schoch, W., 2007. Radiocarbon chronology of the mammoth site at Niederweningen, Switzerland: results from dating bones, teeth, wood, and peat. Quat. Int. 98, 164/165–105.

Hambach, U., Zeeden, C., Hark, M., Zöller, L., 2008. Magnetic dating of an upper palaeolithic cultural layer bearing loess from the Krems-Wachtberg site (Lower Austria). Abh. geol. Bundesanst. 62, 153–157.

Händel, M., Einwögerer, T., Simon, U., Neugebauer-Maresch, C., 2013. Krems-Wachtberg excavations 2005–12: main profiles, sampling, stratigraphy, and site formation. Quat. Int. http://dx.doi.org/10.1016/j.quaint.2013.02.024.

Heiri, O., Millet, L., 2005. Reconstruction of Late Glacial summer temperatures from chironomid assemblages in Lac Lautrey (Jura, France). J. Quat. Sci. 20, 33–44.
Heiri, O., Lotter, A.F., Hausmann, S., Kienast, F., 2003a. A chironomid-based Holocene summer air temperature reconstruction from the Swiss Alps. Holocene 13, 477–484.
Heiri, O., Wick, L., van Leeuwen, J.F.N., van der Knaap, W.O., Lotter, A.F., 2003b. Holocene tree immigration and the chironomid fauna of a small Swiss subalpine lake (Hinterburgsee, 1515 m asl). Palaeogeogr. Palaeoclimatol. Palaeoecol. 189, 35–53.
Heiri, O., Tinner, W., Lotter, A.F., 2004. Evidence for cooler European summers during periods of changing melt-water flux to the North Atlantic. Proc. Natl. Acad. Sci. U. S. A. 101, 15285–15288.
Heiri, C., Bugmann, H., Tinner, W., Heiri, O., Lischke, H., 2006. A model-based reconstruction of Holocene treeline dynamics in the Central Swiss Alps. J. Ecol. 94, 206–216.
Heiri, O., Brooks, S.J., Birks, H.J.B., Lotter, A.F., 2011. A 274-lake calibration data-set and inference model for chironomid-based summer air temperature reconstruction in Europe. Quat. Sci. Rev. 30, 3445–3456.
Henne, P., Elkin, C., Reineking, B., Bugmann, H., Tinner, W., 2011. Did soil development limit spruce (Picea abies) expansion in the Central Alps during the Holocene? Testing a palaeobotanical hypothesis with a dynamic landscape model. J. Biogeogr. 38, 933–949.
Holzkämper, S., Spötl, C., Mangini, A., 2005. High-precision constraints on timing of Alpine warm periods during the middle to late Pleistocene using speleothem growth periods. Earth Planet. Sci. Lett. 236, 751–764.
Hormes, A., Schlüchter, C., Stocker, T.F., 1998. Minimal extension phases of Unteraarglacier (Swiss Alps) during the Holocene based on 14C analysis of wood. Radiocarbon 40, 809–817.
Huber, K., Weckström, K., Drescher-Schneider, R., Knoll, J., Schmidt, J., Schmidt, R., 2010. Climate changes during the last glacial termination inferred from diatom-based temperatures and pollen in a sediment core from Längsee (Austria). J. Paleolimnol. 43, 131–147.
Ilyashuk, B., Gobet, E., Heiri, O., Lotter, A.F., van Leeuwen, J.F.N., van der Knaap, W.O., Ilyashuk, E., Oberli, F., Ammann, B., 2009. Lateglacial environmental and climatic changes at the Maloja Pass, Central Swiss Alps, as recorded by chironomids and pollen. Quat. Sci. Rev. 28, 1340–1353.
Ilyashuk, E.A., Koinig, K.A., Heiri, O., Ilyashuk, B.P., Psenner, R., 2011. Holocene temperature variations at a high-altitude site in the Eastern Alps: a chironomid record from Schwarzsee ob Sölden, Austria. Quat. Sci. Rev. 30, 176–191.
Ivy Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., Kubik, P., Schlüchter, C., 2008. Chronology of the last glacial cycle in the European Alps. J. Quat. Sci. 23, 559–573.
Ivy-Ochs, S., Kerschner, H., Kubik, P.W., Schlüchter, C., 2006. Glacier response in the European Alps to Heinrich event 1 cooling: the Gschnitz stadial. J. Quat. Sci. 21, 115–130.
Ivy-Ochs, S., Kerschner, H., Maisch, M., Christl, M., Kubik, P.W., Schlüchter, C., 2009. Latest Pleistocene and Holocene glacier variations in the European Alps. Quat. Sci. Rev. 28, 2137–2149.
Joerin, U.E., Stocker, T.F., Schlüchter, C., 2006. Multicentury glacier fluctuations in the Swiss Alps during the Holocene. Holocene 16, 697–704.
Jost-Stauffer, M., Coope, G.R., Schlüchter, C., 2001. A coleopteran fauna from the middle Würm (Weichselian) of Switzerland and its bearing on palaeobiogeography, palaeoeclimate and palaeoecology. J. Quat. Sci. 16, 257–268.
Jost-Stauffer, M., Coope, G.R., Schlüchter, C., 2005. Environmental and climatic reconstructions during Marine Oxygene Isotope Stage 3 from Gossau, Swiss Midlands, based on coleoteran assemblages. Boreas 34, 53–60.
Kamenik, C., Schmidt, R., 2005. Chrysophyte resting stages: a tool for reconstructing winter/spring climate from Alpine lake sediments. Boreas 34, 477–489.
Keller, O., Krayss, E., 1994. Die Bodensee-Vorlandvereisung des Rheingletschers im Konstanz-Stadium der letzten Eiszeit. Berichte St-Gallischen naturwissenschaftlichen Ges. 87, 31–40.
Keller, O., Krayss, E., 2005a. Der Rhein-Linth-Gletscher im letzten Hochglazial. 1. Teil: Aufbau und Abschmelzen des Rhein-Linth-Gletschers im Oberen Würm. Vierteljahrsschrift der Naturforschenden Gesellschaft Zürich 150, 19–32.
Keller, O., Krayss, E., 2005b. Der Rhein-Linth-Gletscher im letzten Hochglazial. 2. Teil: Datierung und Modelle der Rhein-Linth Vergletscherung. Klima-Rekonstruktionen. Vierteljahrsschrift der Naturforschenden Gesellschaft Zürich 150, 69–85.
Kerschner, H., 2009. Gletscher und Klima im Alpinen Spätglazial und frühen Holozän. In: Schmidt, R., Matulla, C., Psenner, R. (Eds.), Klimawandel in Österreich. Die letzten 20.000 Jahre und ein Blick voraus. Innsbruck University Press, Innsbruck, pp. 5–26.
Kerschner, H., Ivy-Ochs, S., 2007. Palaeoclimate from glaciers: examples from the Eastern Alps during the Alpine Lateglacial and early Holocene. Global Planet. Change 60, 58–71.
Klasen, N., Fiebig, M., Preusser, F., Reitner, J.M., Radtke, U., 2007. Luminescence dating of proglacial sediments from the Eastern Alps. Quat. Int. 164–165, 21–32.
Kuhn, M., 1980. Die Reaktion der Schneegrenze auf Klimaschwankungen. Zeitschrift für Gletscherkunde und Glazialgeologie 16, 241–254.
Landolt, E., 1992. Unsere Alpenflora. Brugg. Verl. Schweiz. Alpen-Club, 318.
Lang, G., 1994. Quartäre Vegetationsgeschichte Europas. Methoden und Ergebnisse. G. Fischer, Jena.
Lang, G., Tobolski, K., 1985. Hobschensee: late-Glacial and Holocene environment of a lake near the timberline. Diss. Bot. 87, 209–228.
Larocque-Tobler, I., Heiri, O., Wehrli, M., 2009. Late Glacial and Holocene temperature changes at Egelsee, Switzerland, reconstructed using subfossil chironomids. J. Paleolimnol. 43, 649–666.
Lauterbach, S., Brauer, A., Andersen, N., Danielopol, D.L., Dulski, P., Hüls, M., Milecka, K., Namiotko, T., Obremska, M., von Grafenstein, U., Declakes participants, 2011. Environmental responses to Lateglacial climatic fluctuations recorded in the sediments of pre-Alpine Lake Mondsee (northeastern Alps). J. Quat. Sci. 26, 253–267.
Lister, G.S., 1988. A 15,000-year isotopic record from Lake Zürich of deglaciation and climatic change in Switzerland. Quat. Res. 29, 129–141.
Lomax, J., Fuchs, M., Preusser, F., Fiebig, M., 2012. Luminescence based loess chronostratigraphy of the Upper Palaeolithic site Krems-Wachtberg, Austria. Quat. Int. http://dx.doi.org/10.1016/j.quaint.2012.10.037.
Lotter, A.F., 1999. Late-glacial and Holocene vegetation history and dynamics as shown by pollen and plant macrofossil analyses in annually laminated sediments from Soppensee, central Switzerland. Veg. Hist. Archaeobot. 8, 165–184.
Lotter, A.F., Eicher, U., Siegenthaler, U., Birks, H.J.B., 1992. Late-glacial climatoc oscillations as recorded in Swiss lake sediments. J. Quat. Sci. 7, 187–204.
Lotter, A.F., Birks, H.J.B., Hofmann, W., Marchetto, A., 1997. Modern diatom, cladocera, chironomid, and chrysophyte cyst assemblages as quantitative indicators for the reconstruction of past environmental conditions in the Alps. I. Climate. J. Paleolimnol. 18, 395–420.
Lotter, A.F., Birks, H.J.B., Eicher, U., Hofmann, W., Schwander, J., Wick, L., 2000. Younger Dryas and Allerød summer temperatures at Gerzensee (Switzerland) inferred from fossil pollen and cladoceran assemblages. Palaeogeogr. Palaeoclimatol. Palaeoecol. 159, 349–361.
Lotter, A.F., Heiri, O., Hofmann, W., van der Knaap, W.O., van Leeuwen, J.N.F., Walker, I., Wick, L., 2006. Holocene timber-line dynamics at Bachalpsee, a lake at 2265 m a.s.l. in the northern Swiss Alps. Veg. Hist. Archaeobot. 15, 295–307.
Lotter, A.F., Heiri, O., Brooks, S., van Leeuwen, J.F.N., Eicher, U., Ammann, B., 2012. Rapid summer temperature changes during Termination 1a: high-resolution multi-proxy climate reconstructions from Gerzensee (Switzerland). Quat. Sci. Rev. 36, 103–113.
Luetscher, M., Hoffmann, D., Frisia, S., Spötl, C., 2011. Holocene glacier history from alpine speleothems, Milchbach cave, Switzerland. Earth Planet. Sci. Lett. 302, 95–106.
Magny, M., Thew, N., Hadorn, P., 2003. Late-glacial and early Holocene changes in vegetation and lake-level at Hauterive/Rouges-Terres, Lake Neuchâtel (Switzerland). J. Quat. Sci. 18, 31–40.
Magny, M., Aalbersberg, G., Bégeot, C., Benoit-Ruffaldi, P., Bossuet, G., Disnar, J.-R., Heiri, O., Laggoun-Defarge, F., Mazier, F., Millet, L., Peyron, O., Vannière, B., Walter-Simonnet, A.-V., 2006. Environmental and climatic changes in the Jura mountains (eastern France) during the Lateglacial–Holocene transition: a multi-proxy record from Lake Lautrey. Quat. Sci. Rev. 25, 414–445.
Maisch, M., 1981. Glazialmorphologische und gletschergeschichtliche Untersuchungen im Gebiet zwischen Landwasser-und Albulatal. (Kt. Graubünden, Schweiz.) Phys. Geogr. 3, 1–216.
Mangini, A., Spötl, C., Verdes, P., 2005. Reconstruction of temperature in the Central Alps during the past 2000 years from a ^{18}O stalagmite record. Earth Planet. Sci. Lett. 235, 741–751.
Moreno, A., Svensson, A., Brooks, S.J., Connor, S., Engels, S., Fletcher, W., Genty, D., Heiri, O., Labuhn, I., Persiou, A., Peyron, O., Sadori, L., Valero-Garcés, B., Wulf, S., Zanchetta, G., 2014. A compilation of Western European terrestrial records 60-8 ka BP: towards an understanding of latitudinal climatic gradients. Quaternary Science Reviews this issue.
Nicolussi, K., 2009. Alpine Dendrochronologie – Untersuchungen zur Kenntnis der holozänen Umwelt- und Klimaentwicklung. In: Schmidt, R., Matulla, C., Psenner, R. (Eds.), Klimawandel in Österreich, Alpine Space – Man and Environment, vol. 6. Innsbruck University Press, pp. 41–54.
Nicolussi, K., Patzelt, G., 2000. Discovery of early-Holocene wood and peat on the forefield of the Pasterze Glacier, Eastern Alps, Austria. Holocene 10, 191–199.
Nicolussi, K., Schlüchter, C., 2012. Calendar-dated glacier response in the Alps – the 8.2 ka event. Geology 40, 819–822.
Nicolussi, K., Kaufmann, M., Patzelt, G., van der Plicht, J., Thurner, A., 2005. Holocene tree-line variability in the Kauner Valley, Central Eastern Alps, indicated by dendrochronological analysis of living trees and subfossil logs. Veg. Hist. Archaeobot. 14, 221–234.
Niessen, F., Lister, G., Giovanoli, F., 1992. Dust transport and palaeoclimate during the Oldest Dryas in Central Europe – implications from varves (Lake Constance). Clim. Dyn. 8, 71–81.
Niggemann, S., 2006. Das Hölloch als Archiv des Paläoklimas. In: Stautz, G., Wolf, A. (Eds.), Das Hölloch im Mahdtal, Höhlenverein Sonthofen, Sonthofen, pp. 254–257.
Nigst, P.R., Viola, T.B., Haesaerts, P., Trnka, G., 2008. Willendorf II. Wissenschaftliche Mitteilungen aus dem Niederösterreichischen. Landesmuseum 19, 31–58.
Ohmura, A., Kasser, P., Funk, M., 1992. Climate at the equilibrium line of glaciers. J. Glaciol. 38, 397–411.
Penck, A., Brückner, E., 1901/1909. Die Alpen im Eiszeitalter. Tauchnitz, Leipzig.
Pollard, A.M., Blockely, S.P.E., Lane, C.S., 2006. Some numerical considerations in the geochemical analysis of distal microtephra. Appl. Geochem. 21, 1692–1714.
Preusser, F., 2004. Towards a chronology of the Late Pleistocene in the northern Alpine Foreland. Boreas 33, 195–210.

Preusser, F., Degering, D., 2007. Luminescence dating of the Niederweningen mammoth site, Switzerland. Quat. Int. 164/165, 106–112.
Preusser, F., Geyh, M.A., Schlüchter, C., 2003. Timing of Late Pleistocene climate change in lowland Switzerland. Quat. Sci. Rev. 22, 1435–1445.
Preusser, F., Blei, A., Graf, H.R., Schlüchter, C., 2007. Luminescence dating of Würmian (Weichselian) proglacial sediments from Switzerland: methodological aspects and stratigraphical conclusions. Boreas 36, 130–142.
Rach, O., Brauer, A., Wilkes, H., Sachse, D., 2014. Delayed hydrological response to Greenland cooling at the onset of the Younger Dryas. Nat. Geosci. 7, 109–112.
Rasmussen, S.O., Andersen, K.K., Svensson, A.M., Steffensen, J.P., Vinther, B.M., Clausen, H.B., Siggaard-Andersen, M.L., Johnsen, S.J., Larsen, L.B., Dahl-Jensen, D., Bigler, M., Rothlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M.E., Ruth, U., 2006. A new Greenland ice core chronology for the last glacial termination. J. Geophys. Res.-Atmos. 111, D06102.
Rebetez, M., Reinhard, M., 2008. Monthly air temperature trends in Switzerland 1901-2000 and 1975–2004. Theor. Appl. Climatol. 91, 27–34.
Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., van der Plicht, J., 2013. IntCal13 and MARINE13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55, 1869–1887.
Reitner, J.M., 2007. Glacial dynamics at the beginning of Termination I in the Eastern Alps and their stratigraphic implications. Quat. Int. 164/165, 64–84.
Renssen, H., Seppä, H., Heiri, O., Roche, D.M., Goosse, H., Fichefet, T., 2009. The spatial and temporal complexity of the Holocene thermal maximum. Nat. Geosci. 2, 411–414.
Rey, F., Schwörer, C., Gobet, E., Colombaroli, D., van Leeuwen, J.F.N., Tinner, W., 2013. Climatic and human impacts on mountain vegetation at Lauenensee (Bernese Alps, Switzerland) during the last 14000 years. Holocene 23, 1415–1427.
Rozanski, K., Araguàs-Araguàs, L., Gonfiantini, R., 1992. Relation between long-term trends in oxygen-18 isotope composition of precipitation and climate. Science 258, 981–985.
Samartin, S., Heiri, O., Vescovi, E., Brooks, S.J., Tinner, W., 2012a. Lateglacial and early Holocene summer temperatures in the southern Swiss Alps reconstructed using fossil chironomids. J. Quat. Sci. 27, 279–289.
Samartin, S., Heiri, O., Lotter, A.F., Tinner, W., 2012b. Climate warming and vegetation response after Heinrich event 1 (16 700–16 000 cal yr BP) in Europe south of the Alps. Clim. Past 8, 1913–1927.
Schimmelpfennig, I., Schaefer, J.M., Akçar, N., Ivy-Ochs, S., Finkel, R.C., Schlüchter, C., 2012. Holocene glacier culminations in the Western Alps and their hemispheric relevance. Geology 40, 891–894.
Schindelwig, I., Akçar, N., Kubik, P.W., Schlüchter, C., 2011. Lateglacial and early Holocene dynamics of adjacent valley glaciers in the Western Swiss Alps. J. Quat. Sci. 27, 114–124.
Schlüchter, C., Röthlisberger, C., 1995. 100'000 Jahre Gletschergeschichte. In: Gletscher im ständigen Wandel. Zürich, Vdf, pp. 47–63.
Schmidt, G.A., 2010. Enhancing the relevance of palaeoclimate model/data comparisons for assessments of future climate change. J. Quat. Sci. 25, 79–87.
Schmidt, R., Kamenik, C., Kaiblinger, C., Hetzel, M., 2004. Tracking Holocene environmental changes in an alpine lake sediment core: application of regional diatom calibration, geochemistry, and pollen. J. Paleolimnol. 32, 177–196.
Schmidt, R., Kamenik, C., Tessadri, R., Koinig, K.A., 2006. Climatic changes from 12,000 to 4,000 years ago in the Austrian Central Alps tracked by sedimentological and biological proxies of a lake sediment core. J. Paleolimnol. 35, 491–505.
Schmidt, R., Roth, M., Tessadri, R., Weckström, K., 2008. Disentangling late-Holocene climate and land use impacts on an Austrian alpine lake using seasonal temperature anomalies, ice-cover, sedimentology, and pollen tracers. J. Paleolimnol. 40, 454–469.
Schmidt, R., Weckstrom, K., Lauterbach, S., Tessadri, R., Huber, K., 2012. North Atlantic climate impact on early late-glacial climate oscillations in the south-eastern Alps inferred from a multi-proxy lake sediment record. J. Quat. Sci. 27, 40–50.
Schneebeli, W., Roethlisberger, F., 1976. 8000 Jahre Walliser Gletschergeschichte : ein Beitrag zur Erforschung des Klimaverlaufs in der Nacheiszeit. Schweizer Alpen-Club, Bern, 152 pp.
Schoeneich, P., 1998a. Le retrait glaciaire dans les vallées des Ormonts, de l'Hongrin et de l'Etivaz (Préalpes vaudoises). Institut de Géographie, Université de Lausanne. Trav. rech. 14, 1–483.
Schoeneich, P., 1998b. Les stades tardiglaciaires des Préalpes vaudoises et leur corrélation avec le modèle des Alpes orientales. ETHZ, VAW-Mitteilungen 158, 192–206.
Schoeneich, P., 2011. The age of the LGM in the Western and Northwestern Alps (Switzerland and France). Quat. Int. 279–280, 437.
Schwörer, C., Kaltenrieder, P., Glur, L., Grosjean, M., Hafner, A., Tinner, W., 2013a. Holocene climate, fire and vegetation dynamics at the treeline in the North-western Swiss Alps. Veg. Hist. Archaeobot. http://dx.doi.org/10.1007/s00334-013-0411-5.
Schwörer, C., Henne, P., Tinner, W., 2013b. A model-data comparison of Holocene timberline changes in the Swiss Alps reveals past and future drivers of mountain forest dynamics. Glob. Change Biol. http://dx.doi.org/10.1111/gcb.12456.
Simon, U., Händel, M., Einwögerer, T., Neugebauer-Maresch, C., 2013. The archaeological record of the Gravettian open air site Krems-Wachtberg. Quat. Int. http://dx.doi.org/10.1016/j.quaint.2013.08.009.
Spötl, C., Mangini, A., 2002. Stalagmite from the Austrian Alps reveals Dansgaard-Oeschger events during isotope stage 3: implications for the absolute chronology of Greenland ice cores. Earth Planet. Sci. Lett. 203, 507–518.
Spötl, C., Mangini, A., 2007. Speleothems and paleoglaciers. Earth Planet. Sci. Lett. 254, 323–331.
Spötl, C., Mangini, A., Richards, D.A., 2006. Chronology and paleoenvironment of Marine Isotope Stage 3 from two high-elevation speleothems, Austrian Alps. Quat. Sci. Rev. 25, 1127–1136.
Spötl, C., Offenbecher, K.-H., Boch, R., Meyer, M., Mangini, A., Kramers, J., Pavuza, R., 2007. Tropfstein-Forschung in österreichischen Höhlen – ein Überblick. Jahrb. Geol. Bundesanst. 147, 117–167.
Spötl, C., Boch, R., Wolf, A., 2011. Eiszeitliche Klimadynamik im Spiegel eines Stalagmiten aus dem Hölloch (Bayern/Vorarlberg). Die Höhle 62, 46–53.
Spötl, C., Reimer, P.J., Starnberger, R., Reimer, R., 2013. A new radiocarbon chronology of Baumkirchen, stratotype for the onset of the Upper Würmian in the Alps. J. Quat. Sci. 28, 552–558 http://dx.doi.org/10.1002/jqs.2645.
Starnberger, R., Drescher-Schneider, R., Reitner, J.M., Rodnight, H., Reimer, P.J., Spötl, C., 2013. Late Pleistocene climate change and landscape dynamics in the Eastern Alps: the inner-alpine Unterangerberg record (Austria). Quat. Sci. Rev. 68, 17–42.
Sturm, C., Zhang, Q., Noone, S., 2010. An introduction to stable water isotopes in climate models: benefits of forward proxy modelling for paleoclimatology. Clim. Past 6, 115–129.
Svensson, A., Andersen, K.K., Bigler, M., Clausen, H.B., Dahl-Jensen, D., Davies, S.M., Johnsen, S.J., Muscheler, R., Parrenin, F., Rasmussen, S.O., Röthlisberger, R., Seierstad, I., Steffensen, J.P., Vinther, B.M., 2008. A 60 000 year Greenland stratigraphic ice core chronology. Clim. Past 4, 47–57.
Tennant, R.K., Jones, R.T., Brock, F., Cook, C., Turney, C.S., Love, J., Lee, R., 2013. A new flow cytometry method enabling rapid purification of fossil pollen from terrestrial sediments for AMS radiocarbon dating. J. Quat. Sci. 28, 229–236.
Terhorst, B., Frechen, M., Reitner, J., 2002. Chronostratigraphische Ergebnisse aus Lößprofilen der Inn- und Traun-Hochterrassen in Oberösterreich. – Zeitschrift für Geomorphologie N.F. Suppl. Band. 127, 213–232.
Terhorst, B., Thiel, C., Peticzka, R., Sprafke, T., Frechen, M., Roetzel, R., Neugebauer-Maresch, C., Fladerer, F.A., 2011. Casting new light on the chronology of the loess/paleosol sequences in Lower Austria. G. Quat. Sci. J. 60/2–3, 270–277.
Terhorst, B., Kühn, P., Damm, B., Hambach, U., Meyer-Heintze, S., Sedov, S., 2013. Paleoenvironmental fluctuations as recorded in the loess-paleosol sequence of the Upper Paleolithic site Krems-Wachtberg. Quat. Int. http://dx.doi.org/10.1016/j.quaint.2013.03.045.
Thiel, C., Buylaert, J.-P., Murray, A.S., Terhorst, B., Hofer, I., Tsukamoto, S., Frechen, M., 2011. Luminescence dating of the Stratzing loess profile (Austria) – testing the potential of an elevated temperature post-IR IRSL protocol. Quat. Int. 234, 23–31.
Tinner, W., Kaltenrieder, P., 2005. Rapid responses of high-mountain vegetation to early Holocene environmental changes in the Swiss Alps. J. Ecol. 93, 936–947.
Tinner, W., Theurillat, J.P., 2003. Uppermost limit, extent, and fluctuations of the timberline and treeline ecocline in the Swiss Central Alps during the past 11,500 years. Arct. Antarct. Alp. Res. 35, 158–169.
Tinner, W., Vescovi, E., 2007. Ecologia e oscillazioni del limite degli alberi nelle Alpi dal Pleniglaciale al presente. Studi Trentini Sci. Nat. Acta Geol. 82 (2005), 7–15.
Tinner, W., Ammann, B., Germann, P., 1996. Treeline fluctuations recorded for 12,500 years by soil profiles, pollen, and plant macrofossils in the Central Swiss Alps. Arct. Alp. Res. 28, 131–147.
Tobolski, K., Ammann, B., 2000. Macrofossils as records of plant responses to rapid Late Glacial climatic changes at three sites in the Swiss Alps. Palaeogeogr. Palaeoclimatol. Palaeoecol. 159, 251–259.
van Husen, D., 1997. LGM and Late-Glacial fluctuations in the Eastern Alps. Quat. Int. 38/39, 109–118.
van Raden, U., Colombaroli, D., Gilli, A., Schwander, J., Bernasconi, S., van Leeuwen, J., Leuenberger, M., Eicher, U., 2013. High-resolution late-glacial chronology for the Gerzensee lake record (Switzerland): $\delta^{18}O$ correlation between a Gerzensee-stack and NGRIP. Palaeogeogr. Palaeoclimatol. Palaeoecol. 391, 13–24.
Venetz, M., 1833. Mémoire sur les variations de la température dans les Alpes de la Suisse. Denkschr. Allg. Schweiz. Ges. für Gesamte Nat. 1, 1–38.
Vollweiler, N., Scholz, D., Mühlinghaus, C., Mangini, A., Spötl, C., 2006. A precisely dated climate record for the last 9 kyr from high alpine stalagmites. Geophys. Res. Lett. 33, L20703, http://dx.doi.org/10.1029/2006GL027662.
von Grafenstein, U., Erlenkeuser, H., Moller, J., Trimborn, P., Alefs, J., 1996. A 200 year mid-European air temperature record preserved in lake sediments: an extension of the $^{18}O_p$-air temperature relation into the past. Geochim. Cosmochim. Acta 60, 4025–4036.
von Grafenstein, U., Erlenheuser, H., Brauer, A., Jouzel, J., Johnsen, S., 1999. A mid-European decadal isotope climate record from 15,500 to 5000 years BP. Science 284, 1654–1657.
Von Grafenstein, U., Eicher, U., Erlenkeuser, H., Ruch, P., Schwander, J., Ammann, B., 2000. Isotope signature of the Younger Dryas and two minor oscillations at Gerzensee (Switzerland): palaeoclimatic and palaeolimnologic interpretation

based on bulk and biogenic carbonates. Palaeogeogr. Palaeoclimatol. Palaeoecol. 159, 215–229.

von Grafenstein, U., Belmecheri, S., Eicher, U., van Raden, U.J., Erlenkeuser, H., Andersen, N., Ammann, B., 2013. The oxygen and carbon isotopic signatures of biogenic carbonates in Gerzensee, Switzerland, during the rapid warming around 14,685 years BP and the following interstadial. Palaeogeogr. Palaeoclimatol. Palaeoecol. 391, 25–32. http://dx.doi.org/10.1016/j.palaeo.2013.08.018.

Wagner-Cremer, F., Lotter, A.F., 2011. Spring-season changes during the Late Pleniglacial and Bølling/Allerød interstadial. Quat. Sci. Rev. 30, 1825–1828.

Wegmüller, S., Preusser, F., Müller, B.U., 2002. Palynostratigraphische Untersuchung und Lumineszenzdatierung des Profils Galgenmoos und Implikationen für die Chronologie des letzten Glazialzyklus im nördlichen Alpenvorland der Schweiz. Eclogae Geol. Helvet. 95, 115–226.

Weinhold, H., 1973. Beiträge zur Kenntnis des Quartärs im württembergischen Allgäu zwischen östlichem Bodensee und Altdorfer Wald. Diss. Univ. Tübingen.

Welten, M., 1982. Vegetationsgeschichtliche Untersuchungen in den westlichen Schweizer Alpen: Bern-Wallis. Birkhäuser, Basel.

Wessels, M., 1996. Bodensee-Sedimente als Abbild von Umweltänderungen im Spät- und Postglazial. Göttinger Arb. zur Geol. Paläontol. 66, 1–105.

Wick, L., 2000. Vegetational responses to climatic changes recorded in Swiss Late Glacial lake sediments. Palaeogeogr. Palaeoclimatol. Palaeoecol. 159, 231–250.

Wick, L., van Leeuwen, J.F.N., van der Knaap, W.O., Lotter, A.F., 2003. Holocene vegetation development in the catchment of Sägistalsee (1935 m asl), a small lake in the Swiss Alps. J. Paleolimnol. 30, 261–272.

Wurth, G., Niggemann, S., Richter, D.K., Mangini, A., 2004. The Younger Dryas and Holocene climate record of a stalagmite from Hölloch Cave (Bavarian Alps, Germany). J. Quat. Sci. 19, 291–298.

Zöller, L., Richter, D., Blanchard, H., Einwöger, T., Händel, M., Neugebauer-Maresch, C., 2013. Our oldest children: age constraints for the Krems-Wachtberg site obtained from various thermoluminescence dating approaches. Quat. Int. http://dx.doi.org/10.1016/j.quaint.2013.05.003.