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Chronology of the last glacial cycle in the European Alps

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ABSTRACT: Chronological data for glacier advances in the European Alps between the Last Interglacial (Eemian) and the Holocene are summarised (115 to 11 ka). During this time glaciers were most extensive, extending tens of kilometres out onto the forelands, between 30 and 18 ka, that is, synchronous with the global ice volume maximum of Marine Isotope Stage (MIS) 2. Evidence for ice expanding to just past the mountain front for an earlier major glacier advance comes from Swiss sites, where advances have been luminescence dated to MIS 5d (100 ka) and MIS 4 (70 ka). Up to now no such evidence has been found in the Eastern Alps. By 18 ka, more than 80% of the Late Würmian ice volume had gone. Subsequently glaciers readvanced, reaching into the upper reaches of the main valleys during the Lateglacial Gschnitz stadial, which likely occurred around 17 ka, with final moraine stabilisation no later than 15.4 ka. The link of the Egesen stadial with the Younger Dryas climate deterioration is supported by exposure ages from four sites as well as minimum-limiting radiocarbon dates from bogs within former glacier tongue areas. Key questions on the spatial and temporal variability of ice extents throughout the last glacial cycle have yet to be answered. Copyright © 2008 John Wiley & Sons, Ltd.

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KEYWORDS: cosmogenic ^{10}Be; luminescence; Last Glacial Maximum; Würmian; Lateglacial.

Introduction

The landscape of the Alps bears witness to repeated glacial sculpting on a massive scale. Sediment was carved out of the mountains, carried downvalley by the glaciers and deposited far out onto the Alpine forelands (Fig. 1). Centuries before Agassiz published his '*Études sur les Glaciers*' (Agassiz, 1840) the local people were familiar not only with advancing glaciers but with the notion that glaciers had been vastly larger in the past. Beginning already in the early 1800s, glaciers, moraines and outwash as well as glacially scoured bedrock features were studied and mapped in detail (Venetz, 1833; Agassiz, 1840; de Charpentier, 1841). Penck and Brückner (1901/09) developed the well-known fourfold Alpine glacial chronology (from oldest to youngest): Günz, Mindel, Riss and Würm, based on their mapping results both on the forelands and in the Alps. Since that time detailed studies on the terrestrial record of Quaternary glaciations have led to the conclusion that there have been many more than four glaciations during which the glaciers extended out of the Alps and onto the forelands (summaries in Fiebig *et al.*, 2004; Preusser, 2004; Schlüchter, 2004; van Husen, 2004). The record for the Swiss Alps indicates at least 15 independent glaciations (Schlüchter, 2004).

In this paper we provide a brief overview of the existing chronological data, especially cosmogenic nuclide surface exposure, luminescence and radiocarbon ages, for glaciations of the Alps during the last glacial cycle. The basis of the chronological data is more than a hundred years of detailed field research. In the Alps, the last glacial cycle (Würmian) covers the time from the end of the Last Interglacial (Eemian = Marine Isotope Stage (MIS) 5e) to the beginning of the Holocene. The Würmian glaciation has been subdivided into Early, Middle and Late Würmian (Chaline and Jerz, 1984). Reflecting the regional distribution of the available chronological data we focus on the northern regions of the Alps and their forelands (Austria, Germany and especially Switzerland).

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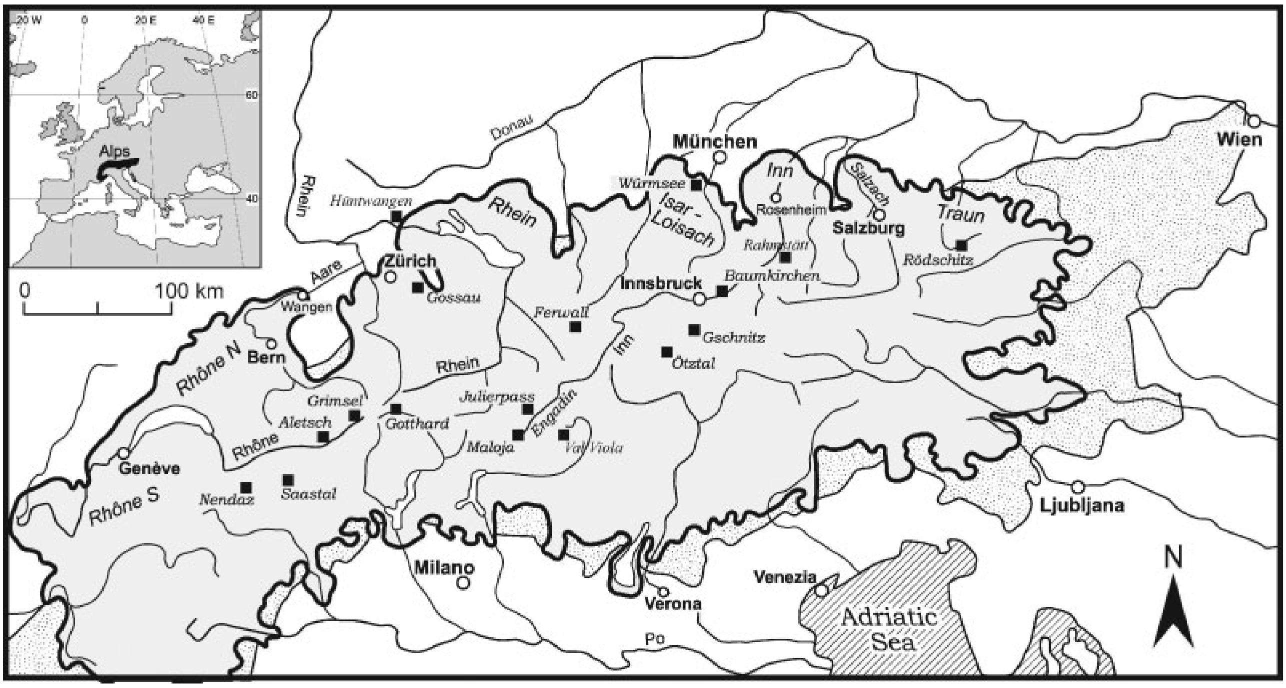

Figure 1 Reference map for site locations discussed in the text. The Alps are shown as a stippled pattern. The extent of ice during the Last Glacial Maximum (based on Ehlers and Gibbard, 2004) is indicated by the shaded area inside the bold line

Geographic setting

The European Alps are situated close to the southern fringe of the European mainland. From the Mediterranean coast between the Rhône delta in France and Genoa in Italy, they trend northwards towards the Mont Blanc massif. There, they bend in an easterly direction. The main body of the Alps between Valence (France) and Vienna (Austria) is about 950 km long. Between 10° and 12° E latitude in the Tyrol region (Austria and Italy), the Alps reach their largest N–S extent of roughly 300 km. Wide structurally controlled longitudinal valleys (Rhône, Rhein, Inn) and intramontane basins are frequent. The highest peaks, well above 4000 m above sea level (a.s.l.), are situated in western Switzerland and neighbouring southeastern France (highest peak of the Alps: Mt Blanc, 4809 m a.s.l.). There, mountain passes are generally above 2000 m a.s.l. Further east, the characteristic altitude remains generally below 2000 m a.s.l., with the highest peaks reaching around 3000 m a.s.l.

Presently, the Alps are exposed to the westerlies, which are an important source of moisture coming in from the North Atlantic Ocean. They cause high precipitation sums along the northern and western fringe of the Alps. Lee cyclogenesis in the Gulf of Genoa plays an important role for precipitation extremes in the Southern and Eastern Alps. Winter precipitation shows a clear dependency on the orography with well-developed stau and lee situations relative to the dominant airflow. In summer very low pressure gradients over continental Europe are frequent and orographically induced convective precipitation plays an important role. Annual precipitation sums along the northern and southern fringe are rather similar, but due to the topographic barriers in the north and south the inner Alpine valleys are usually rather dry (Fliri, 1974; Frei and Schär, 1998). As the Alps are a mid-latitude mountain chain, air temperatures are presently rather mild and usually similar to those from sites outside the Alps at similar altitudes. Summer temperatures at the equilibrium line altitude (ELA) of the Alpine glaciers are usually positive, and hence most of the Alpine glaciers are temperate glaciers. Winter temperatures generally decrease eastwards, as cold air spells from eastern Europe (related to the strength of the Siberian High) are more frequent in eastern Austria.

Methods

Fundamental understanding of the glaciations of the Alps is based on detailed mapping and therefore interpretation of morpho- and lithostratigraphic field relationships. This allowed construction of a relative temporal framework. Since their development, radiocarbon, surface exposure, U/Th dating and luminescence methods have been used to provide chronological constraints. Each method has its important niche based on material that can be dated and on applicable time ranges (cf. Preusser, 2004; Ivy-Ochs *et al.*, 2006b).

Since 1991, numerous bedrock and boulder surfaces in the Alps have been dated with surface exposure dating with cosmogenic ^{10}Be, ^{21}Ne, ^{26}Al and ^{36}Cl (Ivy-Ochs, 1996; Ivy-Ochs *et al.*, 1996, 2004, 2006a,b; Kelly *et al.*, 2004b, 2006). Here, we focus on ^{10}Be data (half-life used 1510 ka). To calculate exposure ages we have used a ^{10}Be production rate of 5.1 ± 0.3 atoms $^{10}Be\ g^{-1}\ SiO_2\ a^{-1}$ (with 2.2% production due to muons), and scaling to the site location based on Stone (2000). Ages have been corrected for erosion, snow and/or vegetation cover on a site-by-site basis as discussed in Ivy-Ochs *et al.* (2006b), Kelly *et al.* (2006) and Reuther (2007). We have used an exponential model depth profile and an attenuation length of $157\ g\ cm^{-2}$. No correction has been made for changes in magnetic field intensity over the exposure period (Masarik *et al.*, 2001). The errors given for individual boulder ages reflect analytical uncertainties (dominated by accelerator mass spectrometry measurement parameters). Average landform ages include uncertainties in the ^{10}Be production rate, but do not include uncertainties in the scaling to the site (cf. Gosse and Phillips, 2001). We include the recent data from the Isar–Loisach

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Glacier Late Würmian site (Reuther, 2007). In addition, the data of Kelly *et al.* (2004b) for the Great Aletsch Glacier site have been recalculated using the production rate and scaling of Stone (2000).

The application of luminescence methods for dating deposits directly related to Alpine glaciations is limited to not much more than about a dozen sites. Owing to the limited suitability of most quartz in the area (Preusser, 1999a) most of these studies have used K-feldspar as natural dosimeter. While the first studies were carried out using the multiple-aliquot additive dose (MAA) procedure, more recently the single-aliquot regenerative dose (SAR) protocol has been applied, both using infrared stimulated luminescence (IRSL). In contrast to some other areas, K-feldspars from the Alps are apparently not affected by anomalous fading of the IRSL signal. This has been proven by both experimental evidence (Preusser, 1999a; Visocekas and Guérin, 2006) as well as by comparison of IRSL ages with independent age control (Preusser, 1999b, 2003; Preusser *et al.*, 2003). A more recent study has demonstrated the suitability of SAR quartz methodology in sediments on the foreland of the Swiss Alps (Preusser *et al.*, 2007) but this mineral is apparently affected by important methodological problems in the Bavarian Alpine foreland, making it virtually unsuitable for luminescence dating (Klasen, 2007).

For brevity in this paper we only discuss radiocarbon dates that we consider are key with respect to interpretations of glacier variations and have unambiguous stratigraphic relationships. Uncalibrated radiocarbon dates are indicated by ^{14}C a BP and calibrated dates by cal. a BP. Radiocarbon dates which correspond to 26 cal. ka BP or less have been calibrated using OxCal 4.0 (Bronk Ramsey, 2001) with the IntCal04 data set (Reimer *et al.*, 2004). For older dates we have used the dataset of Hughen *et al.* (2006) to obtain an estimate of calendar dates; the term 'cal.' is not used. Use of other datasets will result in somewhat different calibrated ages. Specific site locations for the radiocarbon dates as well as laboratory numbers are found in the original references.

As a standard in the Alps, equilibrium line altitudes are calculated with an accumulation area ratio (AAR) of 0.67 from contour line maps of the reconstructed Lateglacial palaeoglaciers. This works well under most Alpine conditions, because the method was originally calibrated with a large sample of glaciers from the European Alps (Gross *et al.*, 1977; Maisch, 1992). However, under colder and drier conditions, slightly larger AARs (0.70–0.75, e.g. White Glacier on Axel Heiberg Island, Canada; Cogley *et al.*, 1996) could be more appropriate, because in such cases mass balance gradients are smaller and mass turnover is reduced. ELA depressions are given relative to the average Little Ice Age (LIA) ELA of the individual glacier's catchment, which can be determined more reliably than a 'present-day' ELA (Gross *et al.*, 1977). Palaeoglaciological (Maisch and Haeberli, 1982) and palaeoclimatic (Kerschner and Ivy-Ochs, 2008) interpretation of the former glacier topographies provides some insight into the climatic conditions during the Lateglacial stadials.

The last glacial cycle in the Alps

Early and Middle Würmian

During the glaciation ('Rissian' in classical terms) which preceded the Last Interglacial (Eemian), the pre-existing, partially filled Alpine foreland basins were excavated and deepened. They were subsequently filled with sediment where environmental conditions during the Würmian are recorded, especially vegetation dynamics in the surroundings of the lakes by means of fossil pollen. While most of these foreland basin archives such as Dürnten (Welten, 1982), Füramoos (Müller *et al.*, 2003), Gondiswil (Wegmüller, 1992), Les Echetes (de Beaulieu and Reille, 1994), Mondsee (Drescher-Schneider, 2000), Samerberg (Grüger, 1979) and Wurzach (Grüger and Schreiner, 1993) show a well-developed Early Würmian record (equivalent to MIS 5), the Middle Würmian is usually poorly preserved and information is restricted to a few sites. Although direct dating evidence is limited to a few U/Th datings of peat and some luminescence ages, the correlations indicated below are mainly accepted (Fig. 2) (cf. Preusser, 2004).

The equivalent of MIS 5e (Eemian) around the Alps is reflected by interglacial conditions with broadleaf deciduous forests followed by a harsh climatic deterioration during MIS 5d (1. Stadial). This led, at least in the northern Alps, to a complete collapse of vegetation, leaving only steppe to tundra-like environments (Welten, 1981). This first cold period was followed by a temperate phase with boreal forest (*Picea*, *Pinus* and some deciduous trees: 1. Interstadial), a second but less pronounced cold phase (2. Stadial) and a second temperate phase (2. Interstadial), which represents environmental conditions similar to those of the 1. Interstadial. Glacier extension during the Early Würmian is poorly constrained and remains controversial. In the Eastern Alps, evidence from the area around Hopfgarten implies that glaciers most likely did not reach into the main Alpine valleys during the two cold stages of the Early Würmian (Reitner, 2005, 2007). This is supported by U-series dates on calcite flowstones implying that the Inn Valley was ice-free between 102 and 70 ka (MIS 5c to 5a) (Spötl and Mangini, 2006). In contrast, dating evidence from two sites close to the margin of the Swiss Alps (Gossau: Preusser *et al.*, 2003; Thalgut: Preusser and Schlüchter, 2004) indicates that glaciers probably extended onto the foreland during MIS 5d. At Gossau, a suite of 42 luminescence ages (MAA K-feldspar, polymineral fine grains, quartz) yields a mean age of 103 ± 13 ka for this advance (Preusser *et al.*, 2003).

By the definition of the Subcommission on European Quaternary Stratigraphy (SEQS) the end of the 2. Würmian Interstadial at the Samerberg site marks the transition from the Early to the Middle Würmian (Chaline and Jerz, 1984). This

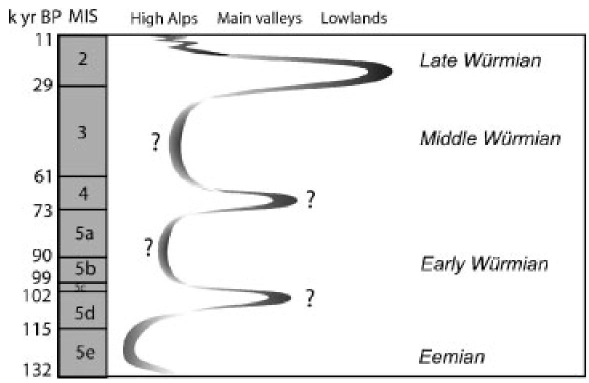

Figure 2 Time–distance diagram for the last glacial cycle in the Swiss Alps and foreland (modified from Preusser and Schlüchter, 2004). Position and timing of the Late Würmian maximum are well known, while possible earlier glacier advances are at present poorly constrained, as indicated by the question marks (cf. Preusser, 2004). In the Austrian sector no clear-cut evidence has been found for advances reaching the main valleys between the Eemian Interglacial and the Late Würmian (van Husen, 2000, 2004; Reitner, 2005). Marine Isotope Stage boundaries from Martinson *et al.* (1987) and Shackleton *et al.* (2002). For a detailed view of the Lateglacial stadials see Fig. 5

transition is usually set to the boundary MIS 5/4 (see Preusser, 2004, for discussion). Tundra-like environments after the 2. Interstadial are accordingly interpreted to reflect cold conditions during MIS 4. The following Interstadial (3. Interstadial termed Dürnten), which is less temperate than its predecessors, most likely reflects earliest MIS 3 (Welten, 1981; Chaline and Jerz, 1984; Wegmüller *et al.*, 2002; Preusser, 2004). This period is characterised by open boreal forests and relatively temperate conditions (Welten, 1982). Relatively warm climatic conditions during early MIS 3 have also been identified in speleothem records from the Inn Valley area (Spötl and Mangini, 2002).

Similar to the Early Würmian cold phases, in particular MIS 5d, there is controversial discussion about glacier extents during MIS 4. While in the Eastern Alps no evidence for the presence of glaciers in the main Alpine valleys has been found (van Husen, 2000; Reitner, 2005), an important glaciation reaching the lowlands of the Western Alps during MIS 4 has been largely accepted (Welten, 1982; Frenzel, 1991; Schlüchter, 1991; Keller and Krayss, 1998). Direct dating of associated deposits is limited to two key studies. In western Switzerland (Finsterhennen), proglacial outwash underlying a residual (weathered) till has been dated by SAR–optically stimulated luminescence (OSL) (quartz) to ca. 70 ka (Preusser *et al.*, 2007). The glaciofluvial sediments on top of the till are dated to between 30 and 25 ka and hence represent the last glaciation (Late Würm) of the Alps (see below). In the Kempten Basin (SW Bavaria), three phases of lake formation have been identified, which are interpreted to reflect glacial advances into the area (Link and Preusser, 2006). While the youngest of these phases is dated to MIS 2 and the oldest is of pre-Würmian age, the middle phase has been dated by luminescence to MIS 3/4. Further dating evidence supporting early to middle Late Pleistocene glacial advances is to some extent given by luminescence dating of braided-river terrace deposits from several sites in both northern Switzerland (Preusser and Graf, 2002) and Bavaria (Ingolstadt; Fiebig and Preusser, 2003) (see also Preusser, 2004). However, the presence of braided rivers in the Alpine foreland for a given time does not directly allow any conclusion about the presence of glaciers in the catchment of these rivers, as the response of rivers to environmental condition is rather complex. Braided river systems may well become established without any direct glacial influence.

Multi-dating (radiocarbon, U/Th, luminescence) evidence from the Gossau site (Fig. 1) clearly illustrates that the lowlands of Switzerland were ice-free during all of MIS 3 (Schlüchter *et al.*, 1987; Preusser *et al.*, 2003). Apparently environmental conditions were unstable but remained mainly cool to weakly temperate. Maximum summer temperatures of up to $\sim 13^{\circ}C$ have been estimated based on fossil beetle assemblages (Jost-Stauffer *et al.*, 2001, 2005; Coope, 2007). A weakly developed interstadial during mid MIS 3 has been dated to ca. 45 ka at both Gossau as well as Niederweningen and this period is characterised by the expansion of open *Picea* forest (Drescher-Schneider *et al.*, 2007; Hajdas *et al.*, 2007; Preusser and Degering, 2007). The end of MIS 3 (= Middle Würmian) has been defined by SEQS at Baumkirchen (Fig. 1) (Chaline and Jerz, 1984). At this site, laminated silty lake deposits are overlain by till attributed to the last glaciation. Wood fragments gathered from the silty lake deposits have been dated to between 26 and 31 ^{14}C ka BP (Fliri *et al.*, 1970; Fliri, 1973). Recently obtained luminescence ages, ca. 35 and 45 ka, are slightly higher, even in light of the fact that the radiocarbon ages are uncalibrated (Klasen *et al.*, 2007). If the luminescence ages are correct, the site would actually not represent the latest part of MIS 3. In any case, it is clear that glaciers were absent in the Inn Valley during (at least most of) MIS 3.

Late Würmian

Data from several sites show that Alpine glaciers had nearly reached the mountain front by 30 ka. This is impressively demonstrated at several sites where outwash deposits overlie peat, dated to about 30 ka (cf. Schlüchter *et al.*, 1987; Schoeneich, 1998; Preusser, 2004). During the Late Würmian, large valley glaciers formed as glaciers flowed out of the main accumulation areas and ice domes in the high Alps (Florineth, 1998; Florineth and Schlüchter, 1998; Kelly *et al.*, 2004a). Upon reaching the lowlands, the glaciers spread out into broad, often coalescing, piedmont lobes (Penck and Brückner, 1901/1909). Steep-walled moraines, broad ridges, as well as hummocky ground found over several to in some cases tens of kilometres, comprise the terminal landforms of the piedmont glaciers. The ELA depression associated with the Late Würmian glaciers with respect to the LIA ELA was around 1200–1500 m (Haeberli, 1991; van Husen, 1977, 1997; Keller and Krayss, 2005a) (Table 1). Here we summarise (from west to east) key chronological data for the most important piedmont lobes (Fig. 1), which are generally representative for the northern forelands.

Rhône Glacier

As the Late Würmian Rhône Glacier extended onto the foreland it split into a southern (Geneva) and northern (Solothurn) lobe. A mammoth tusk recovered from fluvioglacial gravel deposited in front of the advancing Rhône glacier yielded an age of 25 370 ± 190 ^{14}C a BP (Finsterhennen; Schlüchter, 2004) (30.2–28.5 ka). Recent luminescence dating of sediment from the Finsterhennen site provides a similar age (Preusser *et al.*, 2007). The Rhône Glacier reached its maximum position in the region of Wangen an der Aare, where broad, indistinct moraines mark the former ice margin. The ^{10}Be ages from four boulders located on a broad ridge of the outermost right lateral moraine just inside a major meltwater drainage system (Fig. 3) range from 17.1 to 20.9 ka (Ivy-Ochs *et al.*, 2004, 2006b). The ages of 20.8 ± 1.3 and 20.9 ± 0.9 ka mark the beginning of moraine stabilisation. By 19.6 ± 1.3 ka the terminal moraines had been completely abandoned by the Rhône glacier. The youngest age (17.1 ± 1.2 ka) reflects post-depositional processes such as spalling or toppling of the boulder associated with prolonged moraine instability (see also below). Upstream of the Wangen site, on the northern end of Lac de Neuchâtel, pollen and macrofossil data indicate that the lake basin became free of ice during the earliest phase of the Oldest Dryas (Hadorn *et al.*, 2002; Magny *et al.*, 2003). There, the oldest radiocarbon date is 14 250 ± 95 ^{14}C a BP (16 800–17 400 cal. a) (Hauterive/Rouges-Terres; Hadorn *et al.*, 2002).

Rhein Glacier

The foreland piedmont Rhein Glacier was comprised of the Linth/Rhein lobe in the west and the Rhein Glacier in the Bodensee region. The Linth/Rhein piedmont lobe was fed by both the Linth Glacier originating in the Glärnisch region and the Walensee arm of the Rhein Glacier (Penck and Brückner, 1901/1909). Data from the Gossau site (Fig. 1), where radiocarbon ages (Schlüchter *et al.*, 1987) are verified by both U/Th (Geyh *et al.*, 1997) as well as several luminescence ages (Preusser *et al.*, 2003), indicate that the Linth/Rhein Glacier reached this site, which is some 30 km from the margin of the

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Table 1 Summary of Last Glacial Maximum to Lateglacial glacier variations in the northern European Alps (modified from Ivy-Ochs *et al.*, 2006b)

Stadial	Moraine and glacier characteristics	Regional situation	ELA depression *versus* LIA ELA	Time-stratigraphic position ^{10}Be ages (ka): site
Kartell	Well-defined, blocky, multiple moraine ridges, small rock glaciers	Cirque and valley glaciers, clearly larger than LIA, but smaller than innermost Egesen phase	−120 m at type locality	Preboreal oscillation? 10.8 ± 1.0: Kartell cirque
Egesen	Sharp-crested, often block-rich, multiple moraine ridges well documented in wide areas of the Alps. Three-phased readvance of valley glaciers and cirque glaciers Development of extensive rock glacier systems during later parts of the stadial	Cirque and valley glaciers, very few dendritic glaciers	−450 to −180 m for the maximum advance, depending on location	Younger Dryas 12.3 ± 1.5: Julier Pass, outer 11.3 ± 0.9: Julier Pass, inner 12.2 ± 1.0: Schönferwall 11.2 ± 1.1: Aletsch[a] 11.2 ± 0.9: Val Viola[b]
Daun	Well-defined but smoothed moraines, relatively few boulders, solifluction overprint during YD (Egesen); moraines usually missing in more oceanic areas of the Alps (overrun by Egesen?). Smaller than Clavadel/Senders	Glaciers slightly larger than local Egesen glaciers	∼−400 to −250 m depending on location	Before Bølling
Clavadel/ Senders	Well defined, often sediment-rich moraines Clearly smaller than 'Gschnitz'	Cirque and valley glaciers, some dendritic glaciers still intact	∼−400 to −500 m depending on location	Before Bølling
Gschnitz	Steep-walled, somewhat blocky, large single moraines, no solifluction overprint below 1400 m Widespread readvance of large valley glaciers on a timescale of several centuries	Many valley glaciers, some large dendritic glaciers still intact	∼−650 to −700 m	Before Bølling >15.4 ± 1.4: Gschnitz valley
Phase of early Lateglacial ice decay	General downwasting and recession of piedmont glaciers in the foreland with some oscillations of the glacier margins.[c,d,e] Mainly ice marginal deposits; moraines indicating glacier advance in smaller catchments.[c] Glacial advances also due to ice-mechanical causes.[b] Comprises the classical 'Bühl' and 'Steinach' stadials	Downwasting dendritic glaciers, increasing number of local glaciers	Largely undefined, between ± LGM and −800 m	Before Bølling, older than 15 400 ± 470 ^{14}C a BP (18 020–19 010 cal. a BP)
LGM	Chains of terminal moraines from the often coalescing piedmont lobes; often possible to subdivide into three phases[d,e]	Ice domes in the high Alps, outlet glaciers, piedmont glaciers on the forelands	−1200 to −1500 m	Final deglaciation 20.9 ± 1.5: Wangen

For complete references see Ivy-Ochs *et al.* (2006b). Additional references:
[a] Kelly *et al.* (2004b).
[b] Hormes *et al.* (2008).
[c] Reitner (2005, 2007).
[d] Keller and Krayss (2005a,b).
[e] van Husen (1977, 1997, 2000). Site locations shown in Fig. 1.

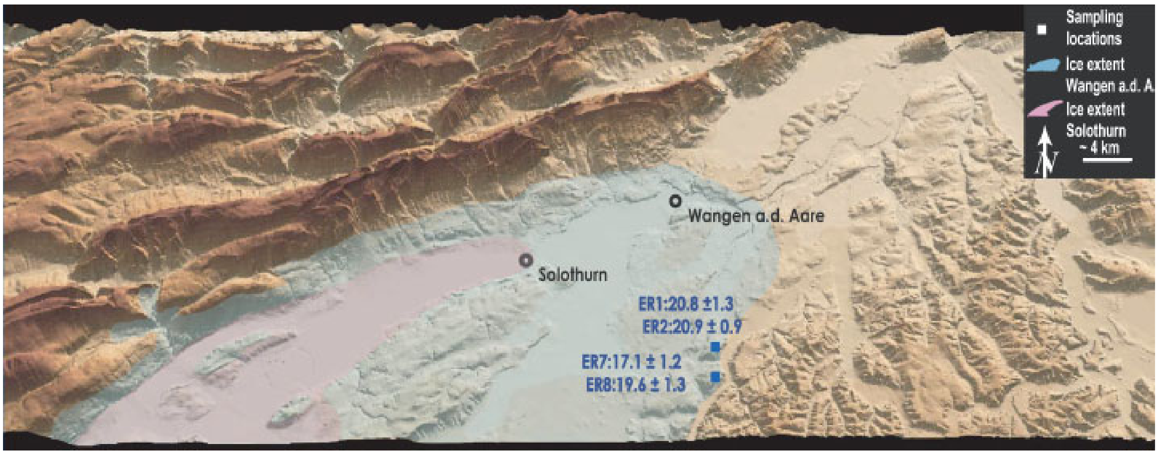

Figure 3 Digital elevation model based on DHM25 dataset (reproduced by permission of swisstopo© (JA082267)) for the region of the terminal moraines of the northern lobe of the Rhône Glacier (figure modified from Ivy-Ochs *et al.*, 2006b). Locations and ^{10}Be ages of sampled boulders are shown. Vertical exaggeration is three times. Darker shading shows higher elevations. Scale varies with perspective

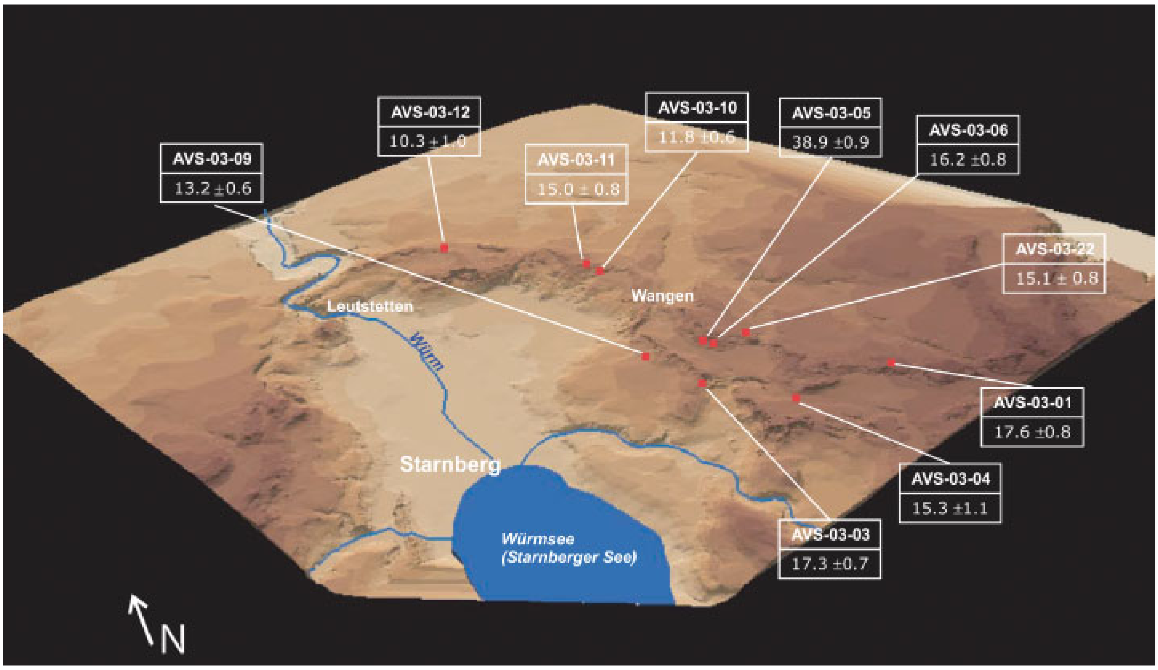

Figure 4 Relief of the moraine complex surrounding the Würmsee (Isar-Loisach Glacier) with boulder locations and ^{10}Be exposure ages. Darker shading shows higher elevations. The moraines are represented by the darker shaded ridges. The digital elevation model is interpolated from the 1:5000 topographic map (five times exaggerated). Scale varies with perspective. For reference, the distance between Leutstetten and the lakeshore is approximately 4 km

Table 2 Cosmogenic nuclide concentrations and calculated exposure ages for the Isar–Loisach and Inn piedmont glaciers

Boulder no.	Glacier	Latitude	Longitude	Alt. (m a.s.l.)	Thick. (cm)	Shield. corr.	10^4 atoms g^{-1}	Exposure age (a)	Corrected exposure age[a] (a)
AVS-03-01	Isar–Loisach	47.975	11.421	670	5.6	0.997	14.99 ± 0.78	16 890 ± 790	17 590 ± 830
AVS-03-03	Isar–Loisach	47.995	11.390	656	5.5	0.997	14.74 ± 0.66	16 660 ± 680	17 340 ± 710
AVS-03-04	Isar–Loisach	47.950	11.392	659	4.5	0.996	12.95 ± 1.02	14 640 ± 1060	15 250 ± 1100
AVS-03-05	Isar–Loisach	47.987	11.400	645	4.5	1.000	32.43 ± 0.97	37 040 ± 880	38 920 ± 920
AVS-03-06	Isar–Loisach	47.986	11.401	650	5.0	1.000	13.71 ± 0.77	15 580 ± 790	16 220 ± 830
AVS-03-09	Isar–Loisach	48.000	11.375	625	5.5	1.000	11.04 ± 0.51	12 640 ± 540	13 170 ± 560
AVS-03-10	Isar–Loisach	48.018	11.400	650	4.5	0.999	10.03 ± 0.50	11 350 ± 530	11 840 ± 550
AVS-03-11	Isar–Loisach	48.021	11.399	655	5.0	0.987	12.52 ± 0.70	14 350 ± 740	14 950 ± 770
AVS-03-12	Isar–Loisach	48.034	11.387	645	4.0	0.926	8.04 ± 0.80	9800 ± 910	10 250 ± 960
AVS-03-22	Isar–Loisach	47.986	11.403	685	5.5	0.994	13.02 ± 0.74	14 510 ± 760	15 110 ± 790
AVC-04-01	Inn	47.810	11.934	495	4.5	1.000	11.87 ± 0.72	15 370 ± 850	16 010 ± 890

[a] Erosion-, snow- and vegetation-corrected exposure ages (for details see Reuther, 2007). Boulder locations shown in Fig. 4.

Alps, after 32 ka ago. Further out on the foreland, based on radiocarbon ages from the Zürichberg site the Linth/Rhein Glacier reached its maximum extent near the village of Killwangen (10 km north-west of Zürich) and receded to the Schlieren stadial position between 28 060 ± 340 ^{14}C a BP (32.1–32.9 ka) and 19 820 ± 190 ^{14}C a BP (23 450–24 010 cal. a BP) (Schlüchter and Röthlisberger, 1995), after which it downwasted with a marked stillstand at the Zürich stadial position (Schindler, 2004; Keller and Krayss, 2005a). Although much of the terminal landforms have been removed by the Limmat River, spectacular lateral moraines, several tens of metres high, of the Zürich stadial line the shores of Lake Zürich. Complete deglaciation is marked by the end of meltwater influence on δ^{18}O as determined from Lake Zürich sediment which occurred before 14 600 ± 250 ^{14}C a BP (Lister, 1988) (17 130–18 030 cal. a BP).

In the region of Bodensee, the Rhein Glacier spread out into a broad piedmont lobe extending to just past the Schaffhausen region at its maximum extent. The pattern of sub-parallel sets of terminal moraines connected to extensive outwash plains and an intricate network of meltwater channels allowed subdivision into three main stadials (Schaffhausen, Stein am Rhein, Konstanz) (Keller and Krayss, 2005b). A date of 24 910 ± 215 ^{14}C a BP (Ingoldingen; Schreiner, 1992) (29.6–30.2 ka) was obtained from a mammoth tusk found underlying the lower-most till of the Late Würmian advance. Radiocarbon dates obtained on mammoth bone fragments in proximal outwash at Hüntwangen (Fig. 1) are 18 240 ± 130 ^{14}C a BP (21 180–22 130 cal. a BP), 21 510 ± 160 ^{14}C a BP (25.2–26.1 ka) and 22 190 ± 170 ^{14}C a BP (26.2–27.4 ka). Recent OSL dates from that site are in accordance with these ages (Preusser *et al.*, 2007). Based on lithostratigraphy and correlation with the Lake Zürich cores, Wessels (1998) concluded that Bodensee was completely free of ice by 17.5 to 18 ka.

Isar–Loisach Glacier

The Isar–Loisach Glacier originated from local glaciers in the Northern Calcareous Alps but was supplemented substantially by ice transfluence from the Inn Valley (shown also by the prevalence of central Alpine clasts in the deposits) (Reuther, 2007, and references therein). Thick outwash gravel deposits from the Isar–Loisach as well as from the Inn Glacier form the Munich gravel plain (Jerz, 1993), which is the type area for the Würmian glaciation of the Alps (Penck and Brückner, 1901/1909). Sets of arcuate terminal moraine ridges are found along the margins of the lake basins of Würmsee and Ammersee (Feldmann, 1992; Jerz, 1993). The ridges are in parts well preserved but disrupted by numerous kettle holes, which today are filled with fens or seasonal kettle ponds (Jerz, 1987a,b). The moraines are steep-walled, up to 40 m high and several hundred metres wide. The ten most suitable erratic boulders from the terminal moraine complex were sampled (for detailed discussion see Reuther, 2007). The ^{10}Be exposure ages of the boulders range from 10.3 to 38.9 ka (Table 2). Boulders AVS-03-05 and AVS-03-06 are located within only 20 m on the same moraine ridge (Fig. 4). Nevertheless, boulder AVS-03-05 yields an age (38.9 ± 0.9 ka) which is more than double the age of the boulder AVS-03-06 (16.2 ± 0.8 ka). This anomalously old exposure age likely reflects pre-exposure. The boulder may possibly have been reworked from deposits of an older advance (Reuther, 2007). The exposure age of the boulder (AVS-03-12) (10.3 ± 1.0 ka) located in a meltwater channel just distal to the Late Würmian moraines is significantly younger than the other boulders. The boulder likely fell into the channel after moraine stabilisation. Two boulders (AVS-03-09, AVS-03-10) showed obvious chip marks at the sides but not on the top where they were sampled. The notably younger exposure ages (13.2 ± 0.6 ka, 11.8 ± 0.6 ka, respectively) of these two boulders likely reflect human impact. Overall the distribution of boulder ages does not show any clear relationship with respect to location on the moraines in light of the former ice margin. Disregarding the age of AVS-03-05 (due to pre-exposure), the oldest ages were obtained on boulder AVS-03-01 (17.6 ± 0.8 ka) on the crest of the outer moraine ridge and on boulder AVS-03-03 (17.3 ± 0.7 ka) on the crest of the inner moraine ridge (Fig. 4). These boulders (AVS-03-01, AVS-03-03) are located right on top of well-preserved ridges which likely were some of the first to stabilise. The fact that these ridges have maintained their shape suggests that they have remained stable. The younger boulders are located on crests but in regions of hummocky relief. This evidence suggests prolonged instability of the landforms perhaps due to dead ice cores or subsequent periglacial activity (Reuther, 2007). Under periglacial conditions severe frost weathering enhances the rate of shattering, crumbling and toppling of boulders (Reuther *et al.*, 2006).

Inn Glacier

The Inn Glacier spread out onto the foreland as a large piedmont lobe east of the Isar–Loisach Glacier and excavated the Rosenheimer Becken (basin), which is rimmed by prominent moraine ridges up to 50 m high. To the east, the ice masses from the Tiroler Ache valley spread out onto the forelands and excavated the Chiemsee basin. The two lobes joined to form the large Inn–Chiemsee Glacier. An outer maximum advance as well as a maximum and two recessional moraines have been recognised (Troll, 1924). A branch found in a sand layer in fluvioglacial deposits underlying the Würmian till on the Alpine foreland near Wasserburg am Inn gave an age of 21 990 +1230/−1070 ^{14}C a BP (25.7–31.2 ka) (Habbe *et al.*, 1996). This provides a maximum age for the glacier reaching that location. A single boulder, AVC-04-01, the largest found in the glacial deposits of the Late Würmian Inn Glacier, was exposure dated with ^{10}Be. This boulder is 2.5–3 m high with a 10–6 m wide base and located on a wide, morphologically indistinct rampart above Rosenheimer Becken. The boulder shows chip marks on the sides and a small chapel is built into the side of it. In this light, we consider the age of AVC-04-01 (16.0 ± 0.9 ka) as a minimum age due to human destruction of the boulder surfaces.

The Alpine Lateglacial

The final withdrawal of the glaciers from the innermost Würmian moraines marks the beginning of the Alpine Lateglacial period (Alpines Spätglazial). It lasted until glaciers finally reached the dimensions of the Holocene maximum extent. The LIA maximum, which was in most places attained around the middle of the 19th century, is a good measure for the Holocene maximum in most catchments of the Alps. During the Lateglacial, a period of just less than 10 ka, glaciers readvanced several times to successively smaller positions (stadials), thereby leaving prominent moraines in the valleys and cirques (Table 1, Fig. 5). Traditionally these stadials are thought to represent glacier tongues in equilibrium with the climatic environment after an advance over ice-free terrain. Already a century ago, these moraines were used by Penck and Brückner (1901/1909) to build a simple threefold glacial event

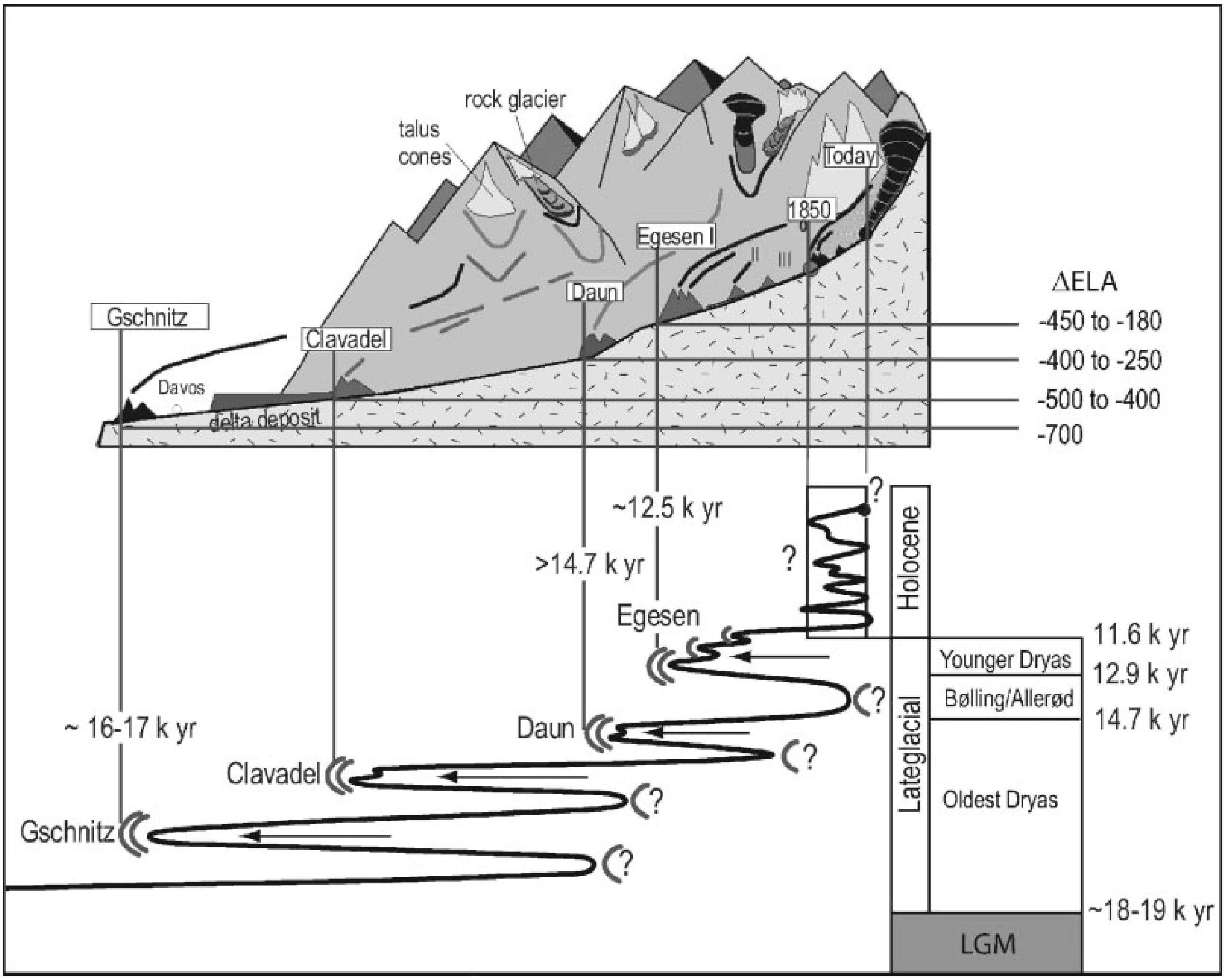

Figure 5 Schematic summary of Lateglacial stadials in the Bündner Alpen (Davos region) (modified from Maisch, 1992; Maisch *et al.*, 1999). Equilibrium line altitude (ELA) depressions with respect to the Little Ice Age reference ELA as summarised in Table 1. Approximate horizontal scale is 15–20 km

stratigraphy (from older to younger: Bühl–Gschnitz–Daun). This chronology has been refined and revised by numerous authors since then, which inevitably led to some terminological confusion due to unintentionally ambiguous definitions and methodological shortcomings in the older literature (Kerschner, 1986). As shown in Fig. 5 and Table 1, the Lateglacial stadials from oldest to youngest are Gschnitz, Clavadel/Senders, Daun and Egesen.

Methodologically, assignment of a moraine to a stadial is based on a catalogue of criteria, which are based on the results of decades of field mapping and the definition of type localities (Penck and Brückner, 1901/1909; Mayr and Heuberger, 1968; Maisch, 1981). Among these criteria are the position of the moraines within the valley and relative to other moraines in the surrounding valleys, a comparison with the type localities, the morphology of the moraines (overall shape and freshness of the landform as well as boulder content) and their stratigraphic positions to related deposits like rock glaciers, the ELA depression and the absolute altitude of the EL relative to the ELA of glaciers in the vicinity with similar characteristics (i.e. size, aspect). The absolute age of the stadials was unknown for most of the time, although minimum-limiting radiocarbon ages indicated that most of them occurred before the onset of the Bølling interstadial at 14.7 ka (Patzelt, 1972; Maisch, 1981, 1982; Furrer *et al.*, 1987). More recently, surface exposure dating has provided a timeframe which has essentially confirmed and refined the earlier ideas on the age of these distinct glacier advance periods (Ivy-Ochs *et al.*, 2006b).

Early Lateglacial ice decay

The initial downwasting of the Late Würmian glaciers may have taken no more than a few centuries with calving into lakes as an important mechanism for enhanced ablation (van Husen, 2000). During this period of early Lateglacial ice decay (Reitner, 2005, 2007), which marks the beginning of Termination 1 in the Alps, glaciers readvanced locally several times. This was partly due to ice-mechanical causes, but in some instances may have also been climatically controlled (Reitner, 2007). It seems that only small local glaciers were active in the Eastern Alps at this time, while the larger dendritic glaciers in the main longitudinal valleys were essentially stagnant and downwasting ice bodies and not responding to climatic fluctuations. This period is roughly centred around 19 ka, which has been confirmed by OSL dating (Klasen *et al.*, 2007) from proglacial sediments in the lower Inn Valley region (Rahmstätt, Fig. 1). The deglaciation of the inner Alpine valleys must have been complete by around 18 ka, which is supported by a number of radiocarbon dates for the start of early colonisation by vegetation in an ice-free environment (Reitner, 2007). This phase of the early Lateglacial comprises the stadials of Bühl and Steinach of the traditional morphostratigraphy (Penck and Brückner, 1901/1909; Senarclens-Grancy, 1958). The concept of stadials does not hold for these advances, as the active parts of the glaciers were still in contact with stagnant ice masses farther downvalley.

Gschnitz stadial

The first clear post-Late Würmian readvance of mountain glaciers, when glacier termini were already situated well inside the mountains, is recorded by the Gschnitz stadial moraines. Morphological evidence shows that glaciers advanced over ice-free terrain for considerable distances (Kerschner and Berktold, 1982; Kerschner *et al.*, 2002), indicating a true readvance and not a stillstand during ice recession. A rough estimate is that about 80–90% of the Late Würmian ice volume was already gone. Gschnitz stadial moraines are tens of metres high and morphologically prominent, incorporating large amounts of sediment. The ELA lowering at the type locality (Trins), which is located in the central Alps of Tyrol, was 700 m. In regions closer to the northern fringe of the Alps, it was slightly higher, of the order of 800 m, but in the southern chains closer to the Adriatic Sea it was around 1000 m (Kerschner *et al.*, 1999; Kerschner and Ivy-Ochs, 2008).

The basal age of the Rödschitz peat bog (Traun Valley, Austria; van Husen, 2004) of 15 400 $\pm$ 470 ^{14}C a BP (Draxler, 1977, 1987) (18 020–19 100 cal. a BP) can be seen as a maximum age for Gschnitz advances, while ^{10}Be surface exposure ages from several boulders on the Gschnitz type locality moraine at Trins provide a minimum age for moraine stabilisation there. The mean ^{10}Be age is 15.4 $\pm$ 1.4 ka; the oldest age is 16.1 $\pm$ 1.0 ka (Ivy-Ochs *et al.*, 2006a). The situation of the individual boulders shows that post-depositional exhumation, overturning of blocks and rock surface spalling enhanced by tree roots cannot be excluded (Ivy-Ochs *et al.*, 2006a,b, 2007). Dead ice hollows in the left-hand part of the moraine show that wide areas of the moraine consisted of ice-cored rockslide debris. Therefore, it is rather safe to conclude that the moraine was deposited some hitherto unknown time (maybe a few centuries) before its final stabilisation. This estimate is supported by a number of radiocarbon dates from peat bogs inside areas that were formerly covered by Gschnitz stadial glaciers (summarised in Ivy-Ochs *et al.*, 2006a). Similarly, pollen data point to ice-free conditions even in the higher valleys during the Oldest Dryas (Furrer, 1991; Ammann *et al.*, 1994; Wohlfarth *et al.*, 1994; Burga and Perret, 1998). A comparison with the development of vegetation in the Alps (e.g. compilation by Vescovi *et al.*, 2007) suggests that the Gschnitz stadial occurred around 17–17.5 ka after a distinct warming phase.

Clavadel/Senders stadial and Daun stadial

After the Gschnitz stadial, glaciers readvanced again with glacier tongues at higher altitudes, leaving prominent moraines. After a type locality near Davos (Maisch, 1981, 1987) and another near Innsbruck (Kerschner and Berktold, 1982), this advance is called the Clavadel stadial or Senders stadial, which are probably equivalent. The available ELA depressions are of the order of 400–500 m, with lower values in the more sheltered positions. There are no ^{10}Be ages available yet, but minimum radiocarbon ages show that the stadial clearly occurred before the onset of the Bølling warm phase at 14.7 ka (Ivy-Ochs *et al.*, 2006a). The basal age of a peat bog at Maloja Pass (13 515 $\pm$ 95 ^{14}C a BP; Studer, 2005) gives a minimum age of about 16 ka (15 650–16 530 cal. a BP) for ice recession after the Clavadel stadial (Upper Engadine: Cinuos-chel stadial) and, as a consequence, also for the preceding Gschnitz stadial.

Upvalley from the Clavadel/Senders moraines, a series of moraines can be observed. They are usually of a rather subdued morphology with clear solifluction overprint. Such moraines are classified as Daun stadial in the sense of Heuberger (1966). Field relationships suggest that at some localities the moraines were deposited in close connection with the Clavadel/Senders stadial. In fact, the Daun stadial may be not much more than the 'appendix' of the preceding Clavadel/Senders stadial. Pollen analysis of sediment from the Crap Alv peat bog suggests a pre-Bølling age for the Daun stadial (Burga in Maisch, 1981). A single ^{10}Be exposure date from an eroded Daun moraine (Il Dschember site) east of Julier Pass yielded a pre-Egesen minimum age (Ivy-Ochs *et al.*, 2006b). A preliminary ^{10}Be date from a bedrock wall just outside the prominent Egesen moraine complex of Morteratsch Glacier at Pontresina (Upper Engadin, eastern Swiss Alps) yielded an age in the region of 15.5 ka. This date supports the assumed pre-Bølling age of the glacial landscape right outside the ice margins of Younger Dryas moraines (Maisch, unpublished data).

The rapid warming at the onset of the Bølling interstadial at 14.7 ka put an end to the series of glacier advances. During the Lateglacial interstadial (Bølling/Allerød), a number of climatic oscillations occurred, which likely led to glacier advances beyond the LIA extent, as can be inferred from sedimentological analysis of the Upper Engadine Lakes (Switzerland; Ohlendorf, 1998), but the moraines were overrun and wiped out during the successive period of glacier advances of the Younger Dryas.

Egesen stadial

The Younger Dryas cold phase is represented by the moraines of the Egesen stadial in the sense of Heuberger (1966). Outside of the LIA moraines, the moraines that were constructed during the Egesen stadial are by far the most spectacular and are found in numerous valleys throughout both the Eastern and Western Alps (Kerschner *et al.*, 2000, and references therein). During the past few decades, Egesen moraines were mapped by a number of authors (see bibliographies in Furrer *et al.*, 1987, and Kerschner *et al.*, 2000). For field mapping, Egesen is defined as a series of morphologically fresh, steep-walled and often well-preserved moraines downvalley from the LIA moraines. The maximum Egesen advance is characterised by a clear morphological boundary; older moraines farther downvalley show much more subdued forms and clear signs of post-depositional solifluction overprint (Daun stadial). Egesen moraines are sometimes prominent landmarks with local names like the 'Grand Toît' ('Big Roof') moraine in the Val de Nendaz in south-west Switzerland (Müller *et al.*, 1981). Two and sometimes three distinct groups of moraines can be distinguished. In many places, Egesen moraines are typically rich in large blocks and boulders, in particular those of the second phase (Bocktentälli phase). Along the central E–W axis of the Alps, ELA depressions associated with the Egesen maximum moraines are of the order of 200 m, but closer to the northern and western fringe they are clearly larger, with local extremes of up to 400 m (Kerschner, 1978b; Maisch, 1981, 1987). South of the Alpine main divide, ELA depressions are of the order of 200 m (Kerschner *et al.*, 2000).

Surface exposure dating of moraines of the Egesen maximum at Julier Pass (Fig. 1) and Schönferwall (Ferwall in Fig. 1) gives average moraine stabilisation ages of 12.3 ± 1.5 ka (three boulders) and 12.2 ± 1.0 ka (four boulders), respectively (Ivy-Ochs *et al.*, 1996, 1999, 2006b). Slightly younger ^{10}Be ages from four boulders (10.6 to 11.9 ka; recalculated from data in Kelly *et al.*, 2004b), with a mean age of 11.2 ± 1.1 ka, were obtained for the Egesen maximum left lateral moraine of the Great Aletsch Glacier (Fig. 1). At Julier Pass, exposure dates from the hummocky inner moraine (likely Bocktentälli Egesen II phase) indicate final stabilisation around 11.3 ± 0.9 ka (three boulders) (Ivy-Ochs *et al.*, 1996, 1999, 2006b). Similarly, at Val Viola (Fig. 1) the average of two ^{10}Be boulder ages, 11.2 ± 0.9 ka, provides a stabilisation age for the first inner moraine of the Alp Dosdé Egesen moraine complex (Hormes *et al.*, 2008).

Rock glaciers developed in many places during the Egesen stadial, sometimes advancing into areas which became ice free right after the Egesen maximum advance. They indicate the presence of permafrost at that time down to 2000–1900 m a.s.l. (Kerschner, 1978a; Sailer and Kerschner, 1999; Frauenfelder *et al.*, 2001). At Julier Pass, a rock glacier developed from melt-out till and slope debris in the region just inside the right lateral moraine (Frauenfelder *et al.*, 2001). The data show that rock glacier activity continued throughout the later part of the Younger Dryas and finally ended after the Preboreal oscillation (see also below). Glaciers in the Grimsel Pass region (Switzerland) receded from their Younger Dryas extent between 11.7 and 10.8 ka (Kelly *et al.*, 2006; Ivy-Ochs *et al.*, 2006b, 2007).

Radiocarbon dates for the abandoned former glacier tongue regions provide minimum-limiting dates for final decay of Egesen glaciers (sites shown in Fig. 1). Minimum radiocarbon ages for the Egesen maximum of the Ötztal Glacier are $10\,235 \pm 80$ ^{14}C a BP (12110–11760 cal. a BP) and $10\,100 \pm 115$ ^{14}C a BP (12 100–11 400 cal. a BP). In both cases it can be shown that trees already existed at an altitude of 1800 m a.s.l., which survived the Younger Dryas cold phase above the lateral moraine of the Egesen glacier (Bortenschlager, 1984). An age of 9950 ± 290 ^{14}C a BP (12 150–11 050 cal. a BP) was obtained for a site 15 km upvalley from the end moraines of the Egesen maximum in Ötztal. An age of 9630 ± 95 ^{14}C a BP (11 250–10 790 cal. a BP) at an altitude of 2155 m a.s.l. is a minimum age for the innermost moraine system (Kerschner, 1978b; Weirich and Bortenschlager, 1980) of a local glacier in the Stubai Mountains near Innsbruck. Radiocarbon dates from sites further to the west give similar minimum ages for downwasting of Egesen glaciers. A minimum age of 9635 ± 160 ^{14}C a BP (11 190–10 770 cal. a BP) was obtained by Beeler (1977) for inside the Egesen moraines of the Palü Glacier. Renner (1982) reports a minimum age of 9730 ± 120 ^{14}C a BP (11 250–10 800 cal. a BP) from the Gotthard region. Further to the west, in Saastal, Bircher (1982) obtained a minimum age of 9760 ± 175 ^{14}C a BP (11 390–10 780 cal. a BP) for the end of the Egesen stadial.

Kartell Stadial

In many valleys, in a variable but clear horizontal distance outside the LIA moraines (generally <1 km), prominent moraines can be distinguished. In the Ferwall group (Fig. 1) they were named 'Kartell Stadial' (Fraedrich, 1979). The ELA depression is 120 m. At the Kartell site, three boulders gave ^{10}Be ages ranging between 10.4 and 11.2 ka with a mean of 10.8 ± 1.0 ka (Ivy-Ochs *et al.*, 2006b). Taken as minimum ages being close to the time of deposition the Kartell moraines were probably deposited during the Preboreal oscillation. Similarly, small rock glaciers that had developed in the sediment-rich newly ice-free forefields of Egesen glaciers remained active well into the Preboreal. This was determined at Julier Pass, for example, where rock glacier activity in the Egesen complex deposits persisted until 10.4 ± 0.4 ka (Ivy-Ochs *et al.*, 2006b).

Discussion

One of the most important open questions with regard to the environmental history of the Alps is whether or not post-Eemian glaciers reached the lowlands prior to the well-documented last glaciation (Late Würmian), which occurred between about 30 and 18 ka ago. In particular, important glaciations during MIS 4 and, to some extent, during MIS 5d have been discussed. As discussed above, the evidence for the presence and the extent of such glaciers decreases from the Western to Eastern Alps. While evidence for the existence of major glaciations in the Western Alps during MIS 4 is convincing, no such evidence has been found in the Eastern Alps. Indeed, in the French Alps it is even considered that the last maximum extent of glaciers occurred during MIS 4 rather than MIS 2 (Guiter *et al.*, 2005), but the dating evidence is equivocal (Preusser *et al.*, 2006). Originally, the idea of Early Würmian glaciations was raised from the fact that three insolation minima occurred during the last 100 ka (Köppen and Wegener, 1924). The theory of Early Würmian glaciations was later supported by palynological evidence. Welten (1981, 1982) pointed out that the environmental conditions during MIS 5d and MIS 4 were cool to cold but temporarily also rather humid. Such conditions likely caused glacial advances. The fact that more pronounced advances have been identified in the west may be explained by three different scenarios (or a combination of all three). Firstly, it may be possible that the geological evidence is either not recorded, it has since been eroded or that it has not yet been identified in the Eastern Alps. Secondly, it has to be kept in mind that the Western Alps are on average about 1000 m higher than the Eastern Alps and, accordingly, potential ice accumulation areas are larger. Additionally, in many cases the distance from the highest peaks to the foreland is shorter than farther to the east. Thirdly, atmospheric circulation and hence sources of moisture were most likely different in the past from today. For the Late Würmian this has been elucidated by Florineth and Schlüchter (2000) (see below) but little is actually known about weather patterns prior to the Late Würmian. A possible scenario would be that storm tracks had a more westerly direction than today and moisture was, as a consequence, mainly supplied towards the western part of the Alps (mainly French Alps) during the Early Würmian. This, in combination with the higher elevation of the Western Alps, may explain the apparent discrepancy in the geological record but needs to be confirmed by fieldwork and dating.

The last glaciation (Late Würmian) of the lowlands occurred sometime after 30 ka ago. ^{10}Be exposure ages from the Rhône Glacier Wangen site show that terminal moraines had already begun to stabilise by 21.0 ka (Ivy-Ochs *et al.*, 2004, 2006b). The two oldest ^{10}Be ages from the Isar–Loisach Late Würmian end moraines agree within the stated errors with the younger boulder age from the Wangen site. In the latter case prolonged moraine instability perhaps related to periglacial activity may have led to 'too young' exposure ages (Reuther *et al.*, 2006; Reuther, 2007). Both datasets, in concert with OSL and radiocarbon data, support the hypothesis that Alpine piedmont glaciers reached their maximum extents during the Last Glacial Maximum (MIS 2) (cf. Schaefer *et al.*, 2006). Based on the configuration of ice domes and main ice accumulation areas in the Alps, notably the evidence of northward ice transfluences over numerous passes (for example at Grimsel Pass; Florineth and Schlüchter, 1998), Florineth and Schlüchter (2000) proposed that during the Late Würmian weather patterns were dominated by southerly airflow. The oceanic polar front, with associated storm tracks, was displaced southwards to the latitude of Spain and Italy. Consequently, the Mediterranean Sea was the most important source of moisture for glaciers in the Alps during the Late Würmian, whereas the partly frozen North Atlantic Ocean played only a minor role. An important question therefore is the synchrony of deglaciation in both space and time across the Alps, not only with respect to west to east but also north to south. Recently reported radiocarbon dates from the Tagliamento morainic amphitheatre in NE Italy show that glacier advances were synchronous with those on the northern forelands (Monegato *et al.*, 2007). In the Tagliamento morainic amphitheatre a two-phased glacial maximum is present. The older more extensive advance was between 26.5 and 23 cal. ka, while the younger advance between 24 and 21 cal. ka is contemporaneous with the maximum extent in the northern forelands. This agrees well with van Husen's (2004) description of an early Maximalstand and subsequent Hochstand for the two main advances of the Late Würmian Traun Glacier (Fig. 1) (cf. Monegato *et al.*, 2007). ^{10}Be data from boulders on moraines in the Ivrea morainic amphitheatre in NW Italy (Gianotti *et al.*, 2008) support the hypothesis that the onset of ice decay at 20.8 ± 1.5 ka in the southern ranges occurred simultaneously with the northern regions.

In the Eastern Alps, both radiocarbon and OSL data point to ice-free longitudinal valleys already by 18–19 ka (van Husen, 2000; Klasen *et al.*, 2007). The oldest date yet obtained for an ice-free Swiss foreland is 17–18 ka, but it is a minimum age. Pinning down the timing during this period remains difficult. Organic material for radiocarbon dating is rare and is often reworked. Exposure dating of early Lateglacial deposits is problematic as this period is largely defined by ice-marginal landforms such as kame terraces (Reitner, 2005, 2007); large boulders suitable for exposure dating are rare.

Around 17 ka, after more than 80% of the Late Würmian ice volume had been lost, glaciers readvanced markedly during the Gschnitz stadial. From a glacier flow model it can be inferred that the glacier at the Gschnitz type locality was still of the subarctic type with low basal shear stresses, low flow velocities and correspondingly flat ablation gradients (Kerschner *et al.*, 1999; Ivy-Ochs *et al.*, 2006a). Accumulation must have been very low, and summer temperatures must have been low as well. According to the model, precipitation in the central Alps of Tyrol reached only about 30% of its present-day values. Summer temperatures were about 9–11°C lower than today (Kerschner *et al.*, 1999; Ivy-Ochs *et al.*, 2006a). Comparatively high ELA depressions in the Southern Alps indicate that precipitation was less reduced there, whereas in the northern chains the situation resembled that in the well-shielded central valleys (Kerschner and Ivy-Ochs, 2008). This implies that a Late Würmian-type circulation pattern with moisture advection dominantly from the south (Florineth and Schlüchter, 2000) persisted well into the Gschnitz stadial.

Moraines that likely formed during the Gschnitz stadial can be found in many tributary valleys but appear to be missing in most of the main valleys, where glaciers at that time were still large (Ivy-Ochs *et al.*, 2006a). For example, in the Rhône Valley, the upper Aare Valley and its tributaries, or the Swiss/Tyrolean Inn Valley, Gschnitz moraines have not been found despite almost a century of mapping. An important open question is whether such moraines were not formed (many glaciers were probably calving into lakes), whether they were not preserved or whether they are simply buried. Because of the likely association of Gschnitz advances with changes in North Atlantic Ocean circulation (Heinrich event 1), clear identification of glacier extents during this time period is crucial. Further identification of datable Gschnitz stadial moraines is needed to map out patterns in space and time across the Alps during the early Lateglacial.

Although based on the available evidence it is likely that the Daun and Clavadel/Senders stadials took place before the onset of the Bølling interstadial, direct dating of these moraines is still lacking.

The Younger Dryas was a relatively long (ca. 1300 a) and climatically unstable period (Kerschner *et al.*, 2000). Moraines deposited during the Egesen stadial show marked regional variations. In some valleys several Egesen moraines are found spread out over a few kilometres. In other cases moraines are closely nested or even cross-cutting (Maisch, 1981). On the basis of the ELA depressions of the Egesen maximum advance, early Younger Dryas precipitation patterns can be inferred with simple glacier–climate models (Kerschner *et al.*, 2000; Kerschner and Ivy-Ochs, 2008). In general, under the assumption of a summer temperature lowering of 3.5°C rather humid conditions prevailed along the western and northern margins of the Alps in western Austria and eastern Switzerland, whereas in the well-shielded valleys of the interior and also along the southern margin climate was clearly drier than today with precipitation reduced by 20–30%. During the second phase of the Younger Dryas, climate was much drier throughout the study area. A reduction of annual precipitation by 50% in the central valleys seems to be realistic. The spatial pattern of precipitation change suggests an atmospheric circulation pattern with predominantly westerly to northwesterly airflow.

The age of the frequently found moraines that lie just beyond the LIA moraines appears to be early Holocene but this is based only on data from the Kartell site (Ivy-Ochs *et al.*, 2006b). This time period roughly corresponds to the 'Palü' cold event that was identified in the Central Alps based on pollen and lithological data in bog sediments (Zoller *et al.*, 1998). Nevertheless, whether all the similar 'intermediate moraines' found between the LIA and Egesen moraines were deposited during the Preboreal oscillation remains an open question. In any case the Kartell moraines show that the transition between Younger Dryas and Holocene climatic conditions was interrupted by marked periods of glacier-friendly climate.

Conclusions

Clarification of the timing for maximum ice extent across the Alps during the last glacial cycle is crucial. For the Swiss Alps, major glaciations during MIS 5d and 4 have been inferred based on interpretation of lithostratigraphy and luminescence dating, but no terminal landforms are preserved. They were obliterated during the subsequent more extensive Late Würmian (MIS 2) advances. In stark contrast, no such evidence for significant Early or Middle Würmian glaciations has yet been found in the Eastern Alps. Similarly, few good tie points are available for the Lateglacial glacier readvances apart from the definitive linking of the Egesen with the Younger Dryas. Indeed, there are still a considerable number of open questions regarding the correlation between the Lateglacial moraine sequences of the

Eastern and Western Alps. Additional detailed field investigations and dating are required to resolve some of these differences and clarify regional variations.

The location of the Alps downwind from the North Atlantic Ocean and its radically changing circulation patterns (shifts of the oceanic polar front; changes in deep water formation) leads to significant variations in moisture delivery through time. This fact is amplified by the sweeping length of the Alps and their arching shape, which results in different weather patterns dominating across their length and width during given time intervals. Key information about past changes can be elucidated through the study of the glacial record. Detailed litho- and morphostratigraphic mapping provides relative ice-marginal positions in an age sequence but direct dating is crucial. Looking at it from the other side, the detailed mapping over vast regions of the Alps affords a strong foundation against which the results of the various dating methods can be compared and evaluated.

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