The Alps with little ice: evidence for eight Holocene phases of reduced glacier extent in the Central Swiss Alps

Anne Hormes,* Benjamin U. Müller and Christian Schlüchter

(Quartärgeologie, Geologisches Institut, Baltzerstrasse 1, CH-3012, Bern, Switzerland)

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Abstract: Glacially deformed pieces of wood, organic lake sediments and clasts of reworked peat have been collected in front of Alpine glaciers since AD 1990. The palaeoglaciological interpretation of these organic materials is related to earlier phases of glacier recession surpassing that of today's shrunken glaciers and to tree growth and peat accumulation in the valleys now occupied by the glaciers. Glacial transport of the material is indicated by wood anatomy, incorporated silt, sand and gravel particles, missing bark and deformed tree-rings. A total of 65 samples have been radiocarbon dated so far, and clusters of dates provide evidence of eight phases of glacier recession: 9910–9550, 9010–7980, 7250–6500, 6170–5950, 5290–3870, 3640–3360, 2740–2620 and 1530–1170 calibrated years BP. Allowing for the timelag between climatic fluctuations, glacier response and vegetation colonization, these recession phases may lag behind climatic changes by 100–200 years.

Key words: Glacier variations, glacier retreat phases, minimal glacier extension, radiocarbon dating, climatic change, Holocene, Swiss Alps.

Introduction

A key question in palaeoclimatology with regard to a global warming scenario is the amplitude of Holocene natural climate variability. In answering this question, mountain glaciers are a highly sensitive archive because their change in extension can be dated. Existing studies on glacier oscillations have approached the problem of Holocene glacier variability (Denton and Karlén, 1973; Patzelt, 1977; Gamper and Suter, 1982; Röthlisberger *et al*., 1980; Phillips *et al*., 1996; Karlén and Kuylenstierna, 1996). The Younger Dryas and some Holocene advances are well documented geologically. However, to address the full amplitude of changes in glacier ice volume it is necessary to reconstruct glacier recessions in space and time. Data on glacier positions smaller than today are rare. There is some information, for example, from northern Italy (Porter and Orombelli, 1985), Canada (Luckman *et al*., 1993), Scandinavia (Karlén and Kuylenstierna, 1996), the Austrian Alps (Patzelt, 1996; Slupetzky *et al*., 1998; Nicolussi and Patzelt, 2000), Arctic Russia (Lubinski *et al*., 1999) and the Swiss Alps (Röthlisberger *et al*., 1980; Schlüchter, 1994). For the last 3200 radiocarbon, detailed reconstructions have been possible from the Central Alps (Holzhauser, 1997), but still without positioning the minimum extents of glaciers in the valleys. The early and mid-Holocene are much less known, as data sets are rare and not always unequivocally interpreted (Grove, 1997).

We present a radiocarbon data set of wood and peat samples documenting that six glaciers in the Central Alps were smaller in areal extent than today at various time intervals during the Holocene. The radiocarbon dates obtained are not distributed randomly over the time period sampled. They cluster in eight time windows indicating episodes of glacial contraction and climatic amelioration with development of vegetation at higher elevations than at present. The present potential tree-line in the Central Alps is between 2050 and 2250 m (Table 1). Palynological and macrofossil studies indicate a tree-line of about 100–200 m higher than that of the mid-Holocene in the Swiss Alps (Burga, 1988). Palynological studies show that the tree-line has decreased since the mid-Holocene, but it is not clear if this is because of climatic deterioration or because of anthropogenic influence.

Today mean annual temperatures are between 1.5°C and –1.5°C and annual precipitation is between 2000 and 2800 mm at the elevation of the glacier termini (Schweizerische Meteorologische Anstalt, Zürich, 1998). Reconstructions from timber-lines have shown that Holocene mean summer temperatures varied with an amplitude of 0.7–0.9°C above present values in the Central Alps (Haas *et al*., 1998). Little is known about changes in precipitation. Present equilibrium line altitudes of the investigated glaciers are between 2800 and 3290 m (Table 1).

A second issue addressed in this article is whether the accuracy

*Present address: ANPA, Via V. Brancati 48, 00144 Roma, Italy (hormes@anpa.it).

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Table 1 Characteristics of the investigated glaciers. Data are selected from topographic maps, Hoelzle and Haeberli (1999) and for Unteraargletscher partially from Gudmundsson (1994). The reaction time of glaciers on climate change is based on model calculations considering climate and glacier bed geometry (Müller, 1988)

Glacier	Unteraar	Mont Miné	Forno	Ried	Tschierva	Trient
Coordinates	46.57 N 8.2 E	46.01 N 7.55 E	46.3 N 9.7 E	46.14 N 7.85 E	46.4 N 9.88 E	46.01 N 7.03 E
Tree-line	2000–2200 m	~2200 m	2200–2250 m	~2200 m	~2250 m	2240–2260 m
Highest elevation	4078 m	3720 m	3360 m	4280 m	4000 m	3490 m
Proglacial area	1950 m	1980 m	2180 m	2060 m	2180 m	1800 m
Mean equilibrium line altitude	2800 m	3140 m	2830 m	3290 m	3050 m	2800 m
Aspect of tongue	E	NNE	N	NNW	NW	NW
Length of central flow line (km)	11.9	6.6	6.8	5.6	4.5	4.6
Glacier type	valley	ice-field	valley	valley	valley	valley
Total area	28.41 km^2	10.89 km^2	8.74 km^2	8.26 km^2	6.83 km^2	6.58 km^2
Mean elevation accumulation	uncertain	3320 m	3020 m	3540 m	3300 m	uncertain
Mean elevation ablation	uncertain	2960 m	2640 m	3040 m	2800 m	uncertain
Tongue activity 1978–1998	–23.6 m	–9 m	–20 m	–12 m	–6 m	–10 m
Reaction time (yr)	43	17.8	15.2	16.9	14.5	15.1

of radiocarbon dating is adequate to constrain chronologies derived from organic material eroded from the glacier bed. In order to produce such a dense chronology we suggest hypotheses of how the peat and wood developed in areas now occupied by glacier ice and how the material was eroded, transported, stored and melted out.

Subfossil trees and peat referred to episodes of reduced glacier extent

Organic material, including pieces of peat and wood of trees, occurs in basal shear planes of the glacier and in the proglacial outwash of at least six glaciers (Figures 1 and 2). The lowest elevation at which organic clasts were sampled is at 1800 m at Glacier du Trient; the highest sampling site is 2180 m at Vadret da Tschierva and Vadrec del Forno. The most probable *in-situ* location of the trees, which reach an age of up to 170 years, must have been at the margins of basins that are presently occupied by glacier tongues. The organic clasts were either transported to the ice margin by basal shearing (Riedgletscher, Glacier du Mont Miné, Glacier du Trient, Vadret da Tschierva, Vadrec del Forno) or during jökulhlaup-type flooding (Unteraargletscher). Proglacial areas of Vadret da Tschierva and Vadrec del Forno are situated above the potential tree-line. The finds near Riedgletscher, Mont Miné and Trient are not situated above the regional tree-line (Table 1), but above the local tree-line. Local glacier winds are partially responsible for the present lack of tree growth on all investigated outwash plains.

The mean equilibrium-line altitude of the glaciers under study is at 2985 m and the mean snow-line altitude is at 3295 m (Table 1). Since the 19th century, glaciers have retreated with two readvance periods around 1920 and 1980.

In the following account, all sites are described and discussed. Several indications are useful for identifying wood that has undergone glacial transport, including: (1) alteration of wood anatomy with compressed cell walls, in some cases, destroyed or wavelike; (2) gravel particles pressed into the wood clast; (3) missing bark; and (4) deformed tree-rings (Figure 3). We conclude that the clasts of fossil wood are primarily evidence for englacial and subglacial transport and that trees were not transported by avalanches or humans to the places of sampling. At Unteraargletscher only one piece of birch with preserved bark was recovered (B-6706). The clasts of peat are shaped like discs or cakes due to transportation in the high-energy meltwater stream.

Unteraargletscher

The Unteraargletscher is situated in the Central Swiss Alps near Grimselpass (Figure 1). It is formed by the confluence of Lauteraar- and Finsteraargletscher. Between AD 1876 and 1997 the Unteraargletscher retreated 2100 m upvalley at an average of 16.8 m per year; between 1978 and 1998 the rate of retreat increased to 23.6 m per year (Hoelzle and Haeberli, 1999). Today's maximum summer flow velocity of 55 m/a^{-1} and maximum winter velocity of 35 m/a^{-1} (Gudmundsson, 1994) are different compared to the average velocity of 107 m/a^{-1} during the 'Little Ice Age' advance (1827–1839) (Haefeli, 1970). The proglacial area of the Unteraargletscher is divided into three terrace levels: 0.5–1 m (level I), 1–2 m (level II), or >2 m (level III) above the main Aare meltwater stream. The floodplain (level I) is rapidly changing due to the shifting braided river. Level III contains complex moraine and fluvioglacial deposits. Clasts of organic material were flushed out of the glacier by a jökulhlaup-type flood. Subglacial channels and water bodies are subject to constant changes of a continuous and discontinous nature (plastic deformation of the ice and collapse of drainage systems). Due to drainage processes, water passages are created, widened or destroyed because of variations in hydrostatic water pressure (Iken *et al*., 1983). As a consequence of such processes, sudden and rapid draining of water from within a glacier may occur (jökulhlaups or 'glacier burst' floods) (Maizels, 1997; Paterson, 1994). From levels I and II, 112 wood and 166 clasts of peat were sampled in October 1995 and 13 wood samples in September 1996. From these 125 wood samples, which were up to 126 cm long and 30 cm in diameter, 36 pieces were radiocarbon dated. Two peat clasts were radiocarbon dated both as bulk samples and as humic acid extracts (ETH-14920 and B-6619, respectively). Five radiocarbon dates were obtained from terrestrial wood fragments (*Salix* sp.) picked manually from different fen peat clasts (B-6697, B-6696, B-6705, B-6694, B-6695).

Glaciers in the Bernina Massif

In July 1999, 68 fossil tree trunks were sampled on the floodplain level 0.5–1.0 m above the braided meltwater stream from Vadret da Tschierva northwest of Piz Bernina. Two wood samples (up

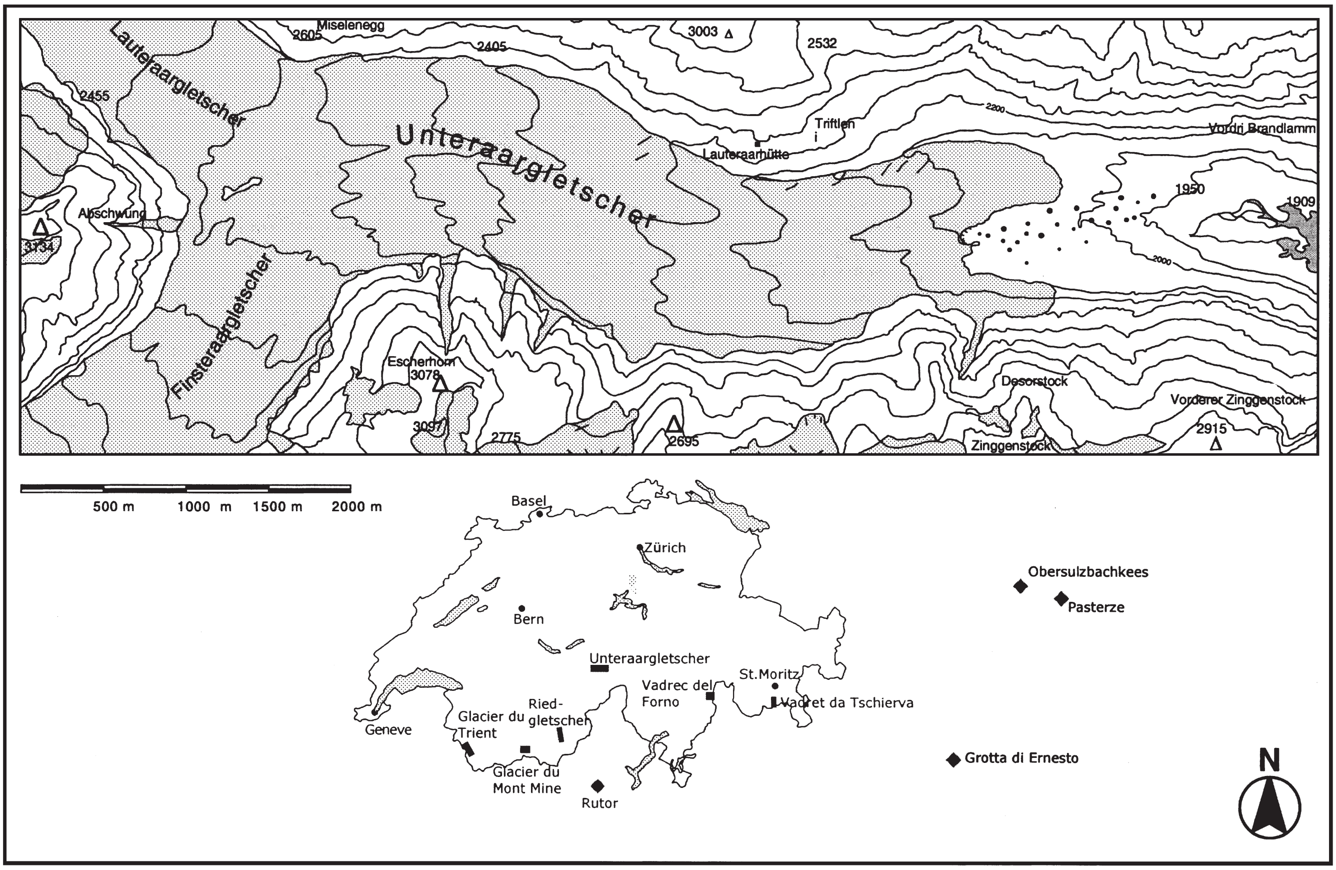

Figure 1 Location map of the investigated glaciers and some key palaeoarchives from literature in the Central Alps, where peat clasts and wood fragments have been recovered in the proglacial area. Not all the samples from Unteraargletscher are represented as dots, because of their abundance.

to 60 cm in length) were sampled directly melting out from the ice at the glacier terminus (B-7316, B-6053). Disc-shaped peat clasts and wood pieces were found in the outwash plain (2180 m) of Vadrec del Forno at Malojapass in the western part of Bernina Massif in July 1999 (Table 1). Samples from Forno and Tschierva collected in 1999 are not dated yet.

Riedgletscher

The Riedgletscher is the northernmost glacier of the Mischabel group (Table 1). Six tree trunks were melting out from the glacier in 1995 and accumulated in the outwash plain (2060 m) (Figure 2). Five of these trunks were radiocarbon dated. In 1998 a stem of *Larix* (Ried-6) of 20 cm in diameter and 1 m length was discovered but is not dated yet.

Glacier du Mont Miné

Glacier du Mont Miné is located in the Alps of Valais (Figure 2, Table 1). The two glaciers Mont Miné and Ferpècle still coalesced in 1964 (Bearth and Lombard, 1964). Subfossil wood samples were collected in front of Mont Miné glacier at 1980 m. Fifteen out of 20 pieces of wood (six collected in the year 1995, two in 1996, eight in 1997 and four in 1998) were radiocarbon dated. The subfossil trees were up to 180 cm long and 20 cm in diameter and were found on the floodplain. The heavily deformed stem Mont Miné-1 (B-6230) was observed shearing out at the glacier terminus.

Glacier du Trient

Glacier du Trient is located at the Swiss-French border within the Mont Blanc Massif (Table 1; Figure 2). The tree stems Trient-4 (B-6227) and Trient-7 (B-6226) were collected on the floodplain at 1800 m.

The geological interpretation

A crucial factor is the original growing location of the subfossil trees and of the peat: did the trees and peat grow where glaciers now fill the basin? This is undoubtedly the case because the reworked peat is glacially compressed and in geological terms we are dealing with a sedimentary basin confined by the Holocene lateral moraine complexes. Peat clasts from Unteraargletscher and Vadrec del Forno point to the existence of *in-situ* organic material in former proglacial areas which are now occupied by the glaciers (Figure 4). In particular, the steep slopes of the environment are far from suitable habitats for substantial peat growth and suggest that the peat grew in the former proglacial area itself and, therefore, cannot have been fallen onto the glaciers. Radiocarbon dates on wood and peat clasts therefore correspond with the time of glacial recessions and tree growth at higher elevations than at present. The reworked and mechanically deformed condition of the wood samples indicate that glacial readvance did actively override trees and peat. This is supported by palaeovegetational evidence that the tree-line was up to 100–200 m higher than present during the Holocene (Burga, 1988; Tinner *et al*., 1996). This higher position of potential lateral tree-fragment input to the glaciers is insufficient to bring the samples to the basal shear zone of the ice. Given the locations of our samples, we are considering organic sedimentation and tree growth in the basins now occupied by the glaciers.

In order to constrain the time of advance, only the outer 5–10 tree-rings without bark were dated. It is possible, however, that the end of tree growth was not caused by the glacier advance itself. The sedimentary infill of these besins, including organic sedimentation prior to the 'Little Ice Age' advance must have been substantial. As the present glaciers can be considered as the

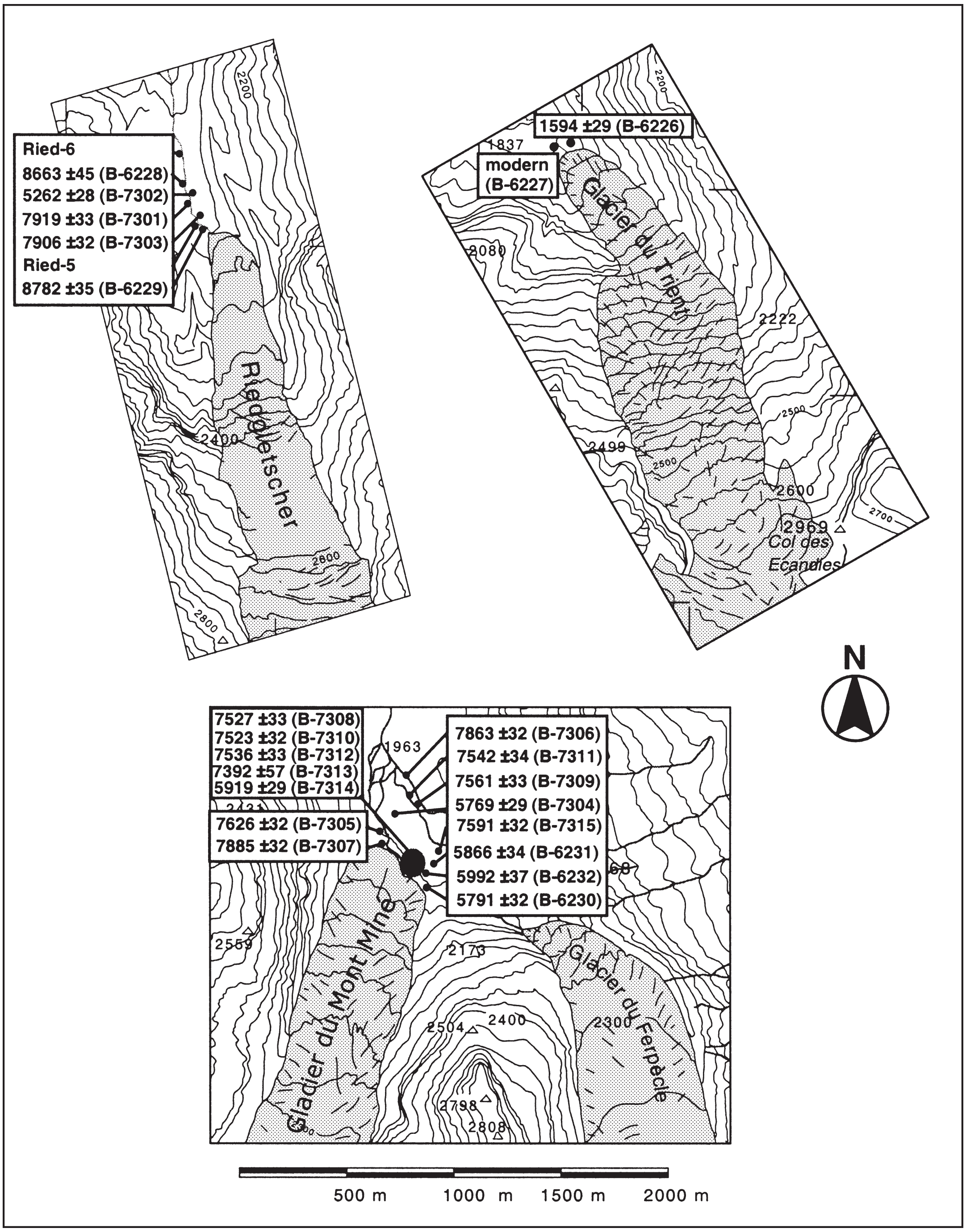

Figure 2 Location of wood, peat and organic material recovery in the proglacial areas of the glaciers in the Valais: Riedgletscher, Glacier du Mont Miné and Glacier du Trient.

decaying remnants of larger 'Little Ice Age' glaciers, at least partial reworking of our samples during that advance is likely. Final delivery of the samples to the glacier forefield, however, occurred only with the 1979–91 readvance and subsequent retreat.

Radiocarbon dating

All conventional radiocarbon measurements reported here were carried out at the University of Bern, Laboratory of Climate and Environmental Physics, using low activity copper proportional counters filled with CH_4 (Fairhall *et al*., 1961). Screening techniques and the method of proportional gas counting are described in previous work (Loosli *et al*., 1980; Geyh and Schleicher, 1990). One sample was measured at the ETH/PSI AMS facility in Zürich.

Identification and preparation of the wood was done following guidelines by Schoch *et al*. (1988) and Schweingruber (1990). Radiocarbon dates are reported in radiocarbon years Before Present (yr BP, where the present is defined as AD 1950). All calibrations of radiocarbon dates (expressed as cal. yr BP) were made using Calib 4.1© by Stuiver and Reimer (1999) based on the calibration data set of Stuiver *et al*. (1998).

Different chemical pretreatment methods have been applied to exclude possible contamination of cell composition during glacial transportation and storage. We compared subsamples treated with standard chemical analysis with extractions of lignin and α-cellu-

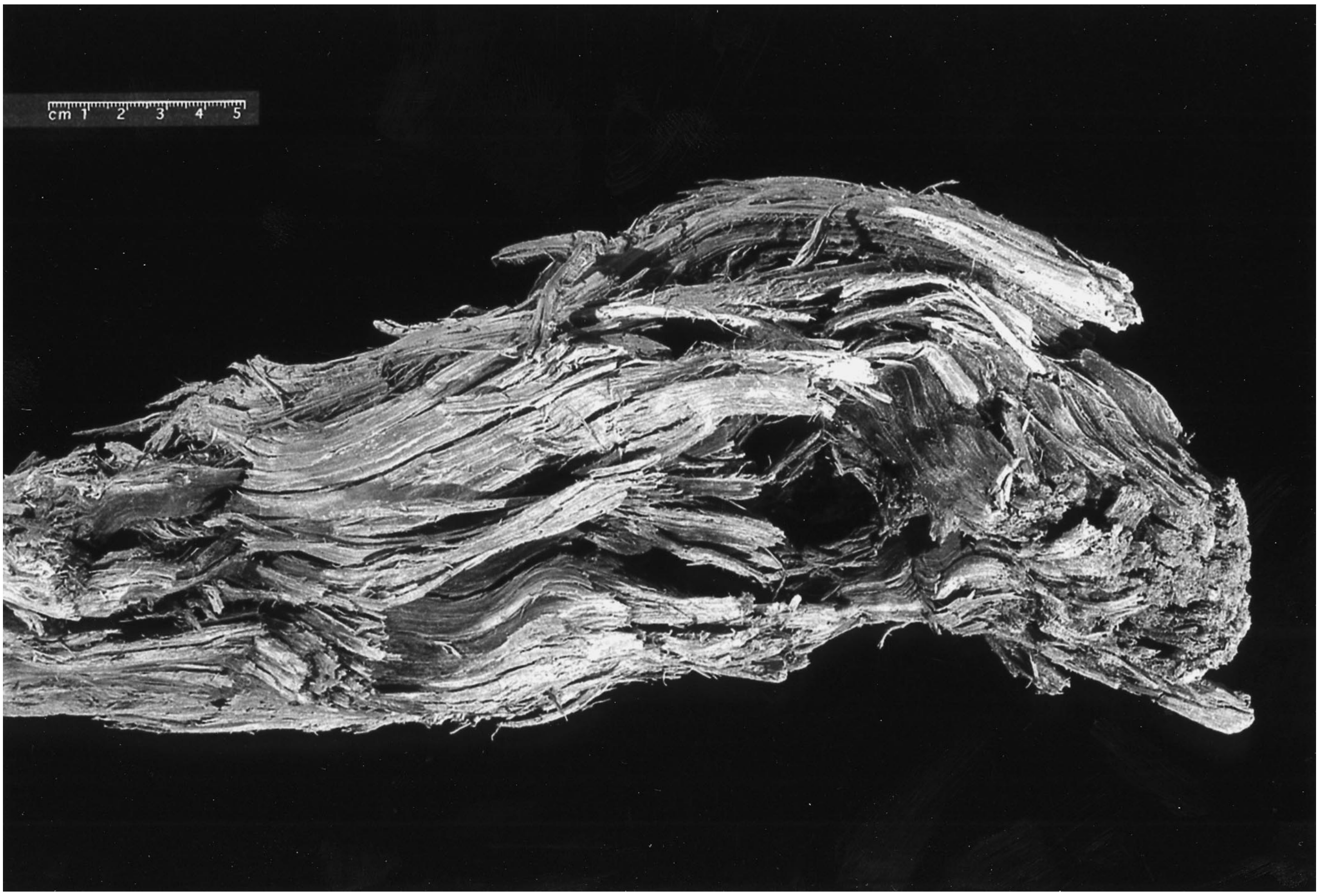

Figure 3 Photograph of deformed wood. The tree samples show mechanical alteration of wood anatomy, deformed tree-rings, and brittle and distorted wood structure. Most of the pieces are flattened and small gravel clasts are pressed into the wood by shearing during basal glacial transport.

lose. From one fen peat sample humic acid and organic residue was dated. Eight out of 10 wood samples from Unteraargletscher show very high statistical consistency between the different chemically treated subsamples (Hormes, 2001). The chemically treated wood extractions contained 32–56% carbon.

Results

Radiocarbon dating results

Our dates (Tables 2 and 3) cluster in eight defined periods: 8820–8620, 8060–7200, 6310–5740, 5290–5230, 4530–3590, 3380–3120, 2580–2530 and 1625–1240 yr BP. These age ranges based on conventional radiocarbon ages are calibrated to 9910–9550, 9010–7980, 7250–6500, 6170–5950, 5290–3870, 3640–3360, 2740–2620 and 1530–1170 cal. yr BP (Figure 5). In the following we use calibrated radiocarbon years only (cal. yr BP).

The two oldest samples (9910–9550 cal. yr BP) were found at Riedgletscher in the Valais. Five clusters are represented in the western Alps (Valais): 9910–9550, 8980–8060, 6870–6500, 6170–5950 and 1530–1420 cal. yr BP (Figure 5). At Unteraargletscher six of the clusters are represented: 9010–7980, 7150–6570, 5290–3870, 3640–3360, 2740–2620, 1260–1170 cal. yr BP. One data cluster is indicated in the Bernina Massif between 7250 and 6950 cal. yr BP. The youngest cluster has been found at two different sites in the Valais and Berner Oberland between 1530 and 1170 cal. yr BP. The cluster between 6170 and 5950 cal. yr BP is only represented at Riedgletscher. One sample has a modern age: a wood sample (B-6227) from Glacier du Trient.

Palaeovegetation

The tree-line in the region of Unteraargletscher is dominated today by *Pinus cembra* (Swiss stone pine) and *Larix decidua* (larch) (Eggenberg, 1994). *Betula* (birch) occurs only on aspects exposed to the sun. Our data show that early-Holocene glacier recession periods with growth of trees in high-altitude areas were dominated by *Picea*. *Larix* grew in the area of Unteraargletscher after approximately 8540 cal. yr BP. *Pinus cembra* started to dominate high-altitude areas after 7250 cal. yr BP only in the Bernina Massif (Tschierva), at least since 6990 cal. yr BP at Unteraargletscher and since 8410 cal. yr BP in the Valais (Mont Miné) (Tables 2 and 3). *Betula* and *Pinus cembra* were abundant at Unteraargletscher between 3460 and 3360 cal. yr BP.

The period between 5290 and 3870 cal. yr BP is marked by *Picea*, *Larix*, *Pinus cembra*, *Betula* and *Salix* sp. In the Unteraar proglacial area peat grew between 4230 and 3870 cal. yr BP (Figure 5). The peat is dark brown, compressed, and consists of a mixture of silt, sand, small stones and wood. Some wood (*Betula* sp., *Alnus* sp., *Salix* sp.) and seeds (*Betula nana*, *Carex restrata*, *C. sempervirens*, *C. sylvatica*, *C. vulpina* agg., *C. ornithopoda*, *C. nigra*, *C. pallescens*, *C. panicea*, *C. paniculata*, *C. pseudocyperus*, *Juniperus communis* ssp. *communis*) were (manually) extracted from the peat samples and identified. The peat can be identified as groundwater-influenced minerotrophic peat which developed in the basin now filled by the glacier. The *Cyperaceen*-fen peat also includes a beetle fauna, which was investigated in detail by Jost-Stauffer (2001). The beetle assemblage indicates a marshy Alpine area with running water, small lakes or ponds and flowering meadows and shrubs (Jost-Stauffer, 2001). Today, shrubs grow on the proglacial level III at a distance of 600–700 m to the east of the

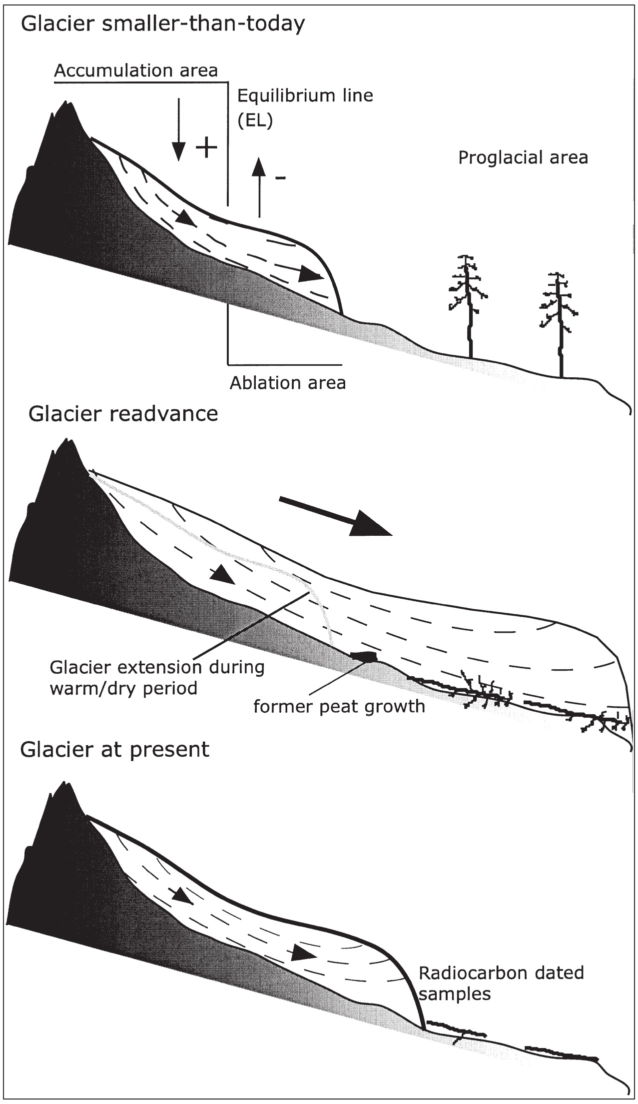

Figure 4 Mechanism of tree growth in proglacial areas during small glacier extensions: the glacier terminus retreated upvalley during tree and fen peat development. This organic matter was eroded by a renewed glacier advance, transported and stored within glacigenic and fluvioglacial sediments and sheared out at the glacier front due to present glacier recession.

glacier front. Seeds of *Juniperus communis* ssp. *communis* (currently restricted to Subalpine regions) extracted from the peat suggest such an environment at least at 1925 m at some time during the Holocene. The interpretation that between 4230 and 3870 cal. yr BP (Table 2) environmental changes took place is underlined by the juniper seeds.

Discussion

Glacier and vegetation response to climatic change

To exclude ^{14}C dating reservoir effects, especially for the groundwater-influenced fen peat accumulation sites at Unteraargletscher and Vadrec del Forno, bedrock geology must be considered. Crystalline bedrock like the Central Aare granite at Unteraargletscher, as well as gneisses at Glacier du Trient, Glacier du Mont Miné and Riedgletscher (Bearth and Lombard, 1964), and the Bergell granitic intrusion at Forno glacier, should have no reservoir influence on radiocarbon ages. The extent of the correspondence between clusters of dates across the region indicates a non-random common cause for time-parallel phases of glacier recession, rather than variations in reservoir effects.

The modern age of sample B-6227 from Glacier du Trient (Figure 5) shows that lateral avalanche input is possible but the distributions of ages and the glacial transport features indicate the Trient-sample as exception.

Glaciers respond sensitively to climate change but direct feedback mechanisms are not fully understood. Glaciers react not only to temperature or accumulation variations but also to glacier bed geometry, glacier size and flow dynamics (Sugden and John, 1976). Nevertheless, changes in the elevation of the ELA reflects changes in the mass balance of a glacier which, in turn controls the position of the glacier terminus (Paterson, 1994; Porter, 1975; Müller, 1988; Bauder, 1996). The equilibrium-line altitude and the mass balance are controlled by winter precipitation and summer temperature (Messerli *et al*., 1978; Müller, 1988; Oerlemans, 1994; Leonard, 1989). The response-time to glacier volume changes (t_{Vol}) can be approximated by:

$$t_{Vol} = \frac{H_{Max}}{-b_t} \tag{1}$$

where H_{Max} is the maximal thickness of the glacier at the ELA and b_t is the ablation at the glacier terminus (Johannesson *et al*., 1989). For our set of glaciers, suitable data are available only for Unteraargletscher (H_{Max} = 300 m; b_t = 6 m/a); the response time (t_{Vol}) being about 43 years (Gudmundsson, 1999, personal communication). This approximation is important as this value is close to the standard deviation of our ^{14}C measurements. The reaction time of glaciers to reach a steady-state with climate parameters have been modelled for Swiss glaciers by Müller (1988) considering glacier bed geometry and mass balance linkages. The investigated Alpine glaciers show a lag to changes of climate parameters between 15 and 17.8 years. Again, this value is within the standard deviation of our radiocarbon ages (Table 2).

In order to interpret our radiocarbon dates we also have to consider the time for the re-establishment of vegetation after glacial recession and the fact that trees were up to 170 years old. On glacier forefields tree growth starts between 40 and 50 years after glacier retreat in Central Alpine high-altitude areas (Holzhauser, 1997). Therefore, a moderate climate is likely to have existed approximately 100–200 years prior to the corresponding radiocarbon data point.

Comparison with other palaeoarchives

Figure 5 gives a summary of all smaller-than-today glacier periods in comparison to cold/wet and warm/dry periods interpreted from other key Alpine palaeoarchives located in Figure 1.

In the eastern Alps minimal extension periods of the Pasterze are given by subfossil wood even older than the Swiss samples between 10 500 and 10 200 cal. yr BP. Several dates on glacier oscillations are consistent with our data set. The recession between 9470 and 8660 cal. yr BP (Slupetzky *et al*., 1998) is consistent with the phase of reduced glacier extent at 9010–7980 cal. yr BP in the Swiss Alps, but appears to have started earlier. Zmutt glacier in the Valais, for example, was smaller than in AD 1973 between 8600 and 8200 cal. yr BP (Röthlisberger and Schneebeli, 1976). Mont Miné was smaller between 6990 and 6730 cal. yr BP (Röthlisberger and Schneebeli, 1976). A brief advance of Glacier du Tour in the western Alps is documented between 7500 and 6900 cal. yr BP (Mayr, 1969). Pollen data suggest 0.25–2°C higher temperatures in the Alps for the contraction phase between 7250 and 6500 cal. yr BP at Tschierva, Unteraar and Mont Miné (Masson *et al*., 1999). Subfossil wood from Tschierva glacier was dated to 5900–5990 cal. yr BP (Röthlisberger and Schneebeli, 1976) and high tree-lines occurred around 6000 cal. yr BP in the Bernina area of eastern Switzerland (Zoller *et al*., 1998). In the Massif des Ecrins (French Alps) the Glacier de Sellettes was smaller between 5920 and 5910 cal. yr BP than in AD 1984 (Couteaux, 1984). For the mid-Holocene recession phase between

Table 2 Radiocarbon dating results from Unteraargletscher (including 1 σ standard deviation). Only the outer 5–10 tree-rings without bark were dated. Thirty single samples from Unteraargletscher were radiocarbon dated with standard pretreatment. Ten wood samples were portioned into subsamples and radiocarbon dated with different chemical pretreatment (lignin, cellulose and standard). One fen peat sample was dated twice (standard and humic acid). Radiocarbon ages with * have been published previously (Hormes *et al*., 1998)

^{14}C years BP	Material	UA code	Lab. code	yr cal. range 1 σ	yr cal. median
8043 ± 44	*Picea* sp. Cellulose	132	B-6686	9010–8810	9004
8029 ± 33*	*Picea*/*Larix*	124	B-6691	9010–8810	9000
8109 ± 34	*Picea*/*Larix*	178	B-7037	9010–8790	8997
7990 ± 33	*Picea* sp.	179	B-7298	9000–8780	8876
7973 ± 31*	*Picea*/*Larix*	140	B-6690	8990–8720	8867
7972 ± 32	*Picea* sp. Standard	132	B-6686	8980–8720	8880
7960 ± 32*	*Picea*/*Larix*	127	B-6692	8980–8660	8917
7953 ± 33	*Picea* sp. Lignin	132	B-6686	8980–8650	8896
7702 ± 31*	*Larix* sp.	163	B-6700	8540–8410	8438
7375 ± 33	*Picea* sp.	129	B-7322	8190–8110	8176
7234 ± 33	*Picea* sp.	182	B-7040	8110–7980	8103
6133 ± 30	*Pinus cembra*	122	B-7317	7150–6950	6999
6083 ± 39	*Pinus cembra* Cellulose	135	B-6704	6990–6810	6922
6032 ± 36	*Pinus cembra* Standard	135	B-6704	6900–6760	6819
6032 ± 28	*Pinus cembra* Standard	162	B-6689	6890–6760	6819
6030 ± 29	*Pinus cembra* Lignin	135	B-6704	6890–6760	6819
6000 ± 60	*Pinus cembra*	162	B-6689	6890–6730	6824
5985 ± 34	*Pinus cembra* Lignin	162	B-6689	6860–6750	6796
5973 ± 32	*Pinus cembra* Cellulose	162	B-6689	6850–6730	6769
5902 ± 31	*Pinus cembra* Standard	176	B-6842	6780–6670	6696
5872 ± 32	*Pinus cembra* Cellulose	176	B-6842	6730–6660	6702
5804 ± 28	*Pinus cembra* Lignin	176	B-6842	6660–6570	6575
4494 ± 26	*Picea* sp. Lignin	1	B-6687	5290–5050	5121
4471 ± 26	*Picea* sp. Cellulose	1	B-6687	5280–5000	5192
4459 ± 26	*Picea* sp. Standard	1	B-6687	5260–4980	5046
4340 ± 25*	*Pinus cembra*	161	B-6707	4870–4860	4866
4155 ± 28	*Picea*/*Larix*	154	B-7318	4820–4590	4699
4136 ± 27	*Salix* sp.	180	B-7038	4810–4550	4764
4103 ± 27	*Picea*/*Larix*	148	B-7320	4790–4530	4602
4049 ± 26	*Picea* sp.	149	B-7319	4570–4450	4458
4045 ± 25*	*Picea* sp.	136	B-6703	4570–4450	4460
4039 ± 25*	*Larix*/*Picea*	166	B-6688	4570–4440	4464
3972 ± 25*	*Picea* sp.	121	B-6702	4500–4410	4419
3956 ± 27	*Pinus cembra*	181	B-7039	4430–4410	4416
3954 ± 26	*Pinus cembra* Cellulose	133	B-6699	4420–4410	4416
3945 ± 26	*Pinus cembra* Standard	133	B-6699	4420–4410	4414
3930 ± 25	*Pinus cembra* Lignin	133	B-6699	4420–4300	4411
3890 ± 32	*Pinus cembra* Cellulose	150	B-6701	4410–4250	4327
3831 ± 25	*Pinus cembra* Lignin	150	B-6701	4250–4150	4195
3798 ± 25	*Picea* sp. Lignin	119	B-6693	4240–4100	4209
3789 ± 25*	*Salix* sp./peat	41	B-6697	4230–4090	4151
3778 ± 25*	*Salix* sp./peat	40	B-6696	4220–4090	4149
3761 ± 25	*Pinus cembra* Standard	150	B-6701	4150–4090	4115
3730 ± 32	peat	192	B-6619	4150–3990	4088
3715 ± 50	peat	Test-1	ETH-14920	4150–3930	4027
3724 ± 26	peat	192	B-6619	4140–3990	4024
3702 ± 38	*Picea* sp. Cellulose	119	B-6693	4090–3930	4031
3694 ± 33*	*Salix* sp./peat	117	B-6705	4090–3930	4042
3686 ± 27*	*Salix* sp. stem	170	B-6618	4090–3930	4048
3683 ± 24*	*Salix* sp./peat	19	B-6694	4080–3930	4049
3656 ± 24*	*Picea*/*Larix*	118	B-6698	4060–3930	3938
3656 ± 33	*Pinus cembra* Cellulose	175	B-6832	4070–3910	3938
3645 ± 27	*Picea* sp. Standard	119	B-6693	3980–3900	3944
3623 ± 27	*Pinus cembra* Standard	175	B-6832	3980–3890	3951
3645 ± 27	*Pinus cembra* Lignin	175	B-6832	4060–3900	3944
3622 ± 32*	*Salix* sp./peat	112	B-6695	3980–3870	3925
3349 ± 33	*Pinus cembra* Cellulose	174	B-6891	3640–3480	3606
3276 ± 24	*Pinus cembra* Lignin	174	B-6891	3550–3470	3472
3262 ± 26	*Pinus cembra* Standard	174	B-6891	3550–3470	3470
3227 ± 25*	*Betula* sp.	172	B-6706	3470–3400	3464
3149 ± 25	*Pinus cembra*	125	B-7321	3380–3360	3370
2555 ± 25	*Pinus cembra*	183	B-7299	2740–2620	2736
1265 ± 23	*Pinus cembra*	190	B-7300	1260–1170	1207

Table 3 Radiocarbon dating results from additional sites: 15 samples from Glacier du Monte Miné, five from Riedgletscher, three from Steinlimigletscher, two from Steingletscher, two from Glacier du Trient and two from Vadret da Tschierva

Field code	^{14}C years BP	Material	Lab. code	yr cal. range 1 σ	yr cal. median
Riedgletscher-4	8782 ± 35	*Picea*	B-6229	9910–9700	9850
Riedgletscher-2	8663 ± 45	*Picea*	B-6228	9680–9550	9592
Riedgletscher-10	7919 ± 33	*Larix*/*Picea*	B-7301	8975–8640	8713
Riedgletscher-3	7906 ± 32	*Larix*/*Picea*	B-7303	8930–8610	8682
Mont Miné-1/97	7885 ± 32	*Larix*/*Picea*	B-7307	8750–8600	8639
Mont Miné-12/98	7863 ± 32	*Larix*/*Picea*	B-7306	8675–8595	8619
Mont Miné-11/98	7626 ± 32	*Pinus cembra*	B-7305	8410–8390	8406
Mont Miné-5/94	7591 ± 32	*Pinus cembra*	B-7315	8410–8370	8388
Mont Miné-4/97	7561 ± 33	*Larix*/*Picea*	B-7309	8390–8350	8375
Mont Miné-6/97	7542 ± 34	*Larix*/*Picea*	B-7311	8390–8340	8367
Mont Miné-7/97	7536 ± 33	*Pinus cembra*	B-7312	8380–8340	8364
Mont Miné-3/97	7527 ± 33	*Pinus cembra*	B-7308	8380–8335	8353
Mont Miné-5/97	7523 ± 32	*Pinus cembra*	B-7310	8370–8220	8352
Mont Miné-2/96	7392 ± 57	*Pinus cembra*	B-7313	8320–8065	8180
Tschierva-2	6276 ± 31	*Pinus cembra*	B-7316	7250–7103	7216
Tschierva-1	6133 ± 30	*Pinus cembra*	B-6053	7150–6950	6999
Mont Miné-6	5992 ± 37	*Pinus cembra*	B-6232	6870–6750	6798
Mont Miné-4/94	5915 ± 29	*Pinus cembra*	B-7314	6780–6670	6729
Mont Miné-3	5866 ± 34	*Pinus cembra*	B-6231	6730–6640	6703
Mont Miné-1	5791 ± 32	*Pinus cembra*	B-6230	6660–6500	6583
Mont Miné-10/98	5769 ± 29	*Pinus cembra*	B-7304	6640–6500	6593
Riedgletscher-1	5262 ± 28	*Pinus cembra*	B-7302	6170–5950	5991
Trient-7	1594 ± 29	wood	B-6226	1530–1420	1518
Trient-4	modern	wood	B-6227		

5290 and 3870 cal. yr BP subfossil wood samples are known from Tschierva (5310–4980 cal. yr BP) and Ferpècle glaciers (4840–4150 cal. yr BP; Röthlisberger and Schneebeli, 1976). In eastern Switzerland buried soils in St Moritz were radiocarbon dated and indicate slope stability phases between 4600 and 3800 cal. yr BP and around 3400 cal. yr BP (Schlüchter, 1988). The samples of Unteraargletscher defining the 2620–2740 cal. yr BP recession phase are consistent with samples from Aletschgletscher between 2500 and 2770 cal. yr BP (Holzhauser, 1997). Two radiocarbon dates of Unteraargletscher and Glacier du Trient suggest that between 1530 and 1170 cal. yr BP glaciers were smaller than at present. Also Riedgletscher was smaller about 1600 cal. yr BP (Holzhauser, 1985) than in the beginning of the 1980s. Such a reduction in the size of glaciers during Roman times is also confirmed by Roman passageways in the Alps which are covered by glaciers at present, e.g., Col d'Hérens (3462 m) (Röthlisberger and Schneebeli, 1976).

Two glacier recession phases in the Central Alps correlate with speleothem growth in Grotta di Ernesto in northwestern Italy at 1165 m altitude. Dry conditions and higher temperature are indicated by high δ^{13}C and δ^{18}O values between 9200 and 7800 cal. yr BP (McDermott *et al*., 1999). During the same time interval the first expansion of *Picea* from the Inn valley to the Valtellina occurred (9000–8200 cal. yr BP; Zoller *et al*., 1998), which is consistent with our result that *Picea*, *Larix* and *Pinus cembra* were abundant also in the Valais and Berner Oberland (Tables 2 and 3).

In Figure 5, data from glacier oscillations known from older studies show some overlap with our smaller-than-today glacier data set. The Misox cold period between 8100 and 7400 cal. yr BP is confirmed (Zoller, 1977) as our data set suggests that no trees grew in proglacial areas between 8000 and 7250 cal. yr BP. Two glacier advances are registered in the Austrian and Swiss Alps (Rotmoos and Piora cold phases I and II) around 6100–5700 and 5500–5000 cal. yr BP (Patzelt and Bortenschlager, 1973; Zoller, 1977), which partially overlap with our dated recession phases (Figure 5). The Löbben cold period with advances of several glaciers in the Austrian and Swiss Alps based on moraine investigations, dendrodensity studies of wood and solifluction of soils occurred between 3450 and 3250 cal. yr BP (Patzelt, 1977; Gamper and Suter, 1982). This period partially overlaps with dates from Unteraargletscher (3640–3360 cal. yr BP). There is indication from Aletschgletscher for a warm period between 3470 and 2900 cal. yr BP (Holzhauser, 1997) which correlates with the data from Unteraargletscher and also with dry conditions shown by dendrite-like texture of speleothems between 3400 and 3200 cal. yr BP (McDermott *et al*., 1999). Our data set covers the early and mid-Holocene very well, whereas for the late Holocene the dendrochronological data from Holzhauser (1997) provides a high-resolution chronology, as well as historical records of glacier oscillations (e.g., Pfister, 1985).

There is also some agreement between our reconstructed phases of glacier recessions and glacier behaviour beyond the Alps. Records of glacier fluctuations from Scandinavia, for example, show glacier recessions in the periods 10 000–8500, 7900–7500, 7200–6500, 6100–5900, 5800–5500, 5200–5050, 4900–4500, 4200–3400, 3200–3050, 2800–2700, 2050–1900, 1600–1200 and 1000–700 cal. yr BP (Karlén and Kuylenstierna, 1996; Boulton *et al*., 1997). These periods of glacial recession coincide almost exactly with the recession phases in Switzerland with the following exceptions: recession at 3640–3360 cal. yr BP is absent so far in the Scandinavian record and the Scandinavian recession periods at 7900–7500, 3200–3050 and 1000–700 cal. yr BP seem to be absent in the Alpine data set. Regional influences of ocean-atmosphere interactions may explain this small degree of asynchronism.

Conclusions

(1) We collected subfossil wood and peat samples from six glacier forelands in the Central Swiss Alps, and 65 samples have been radiocarbon dated (11 samples were multi-dated).

(2) The investigated glaciers were smaller-than-today during the phases which are represented by the radiocarbon dates, the

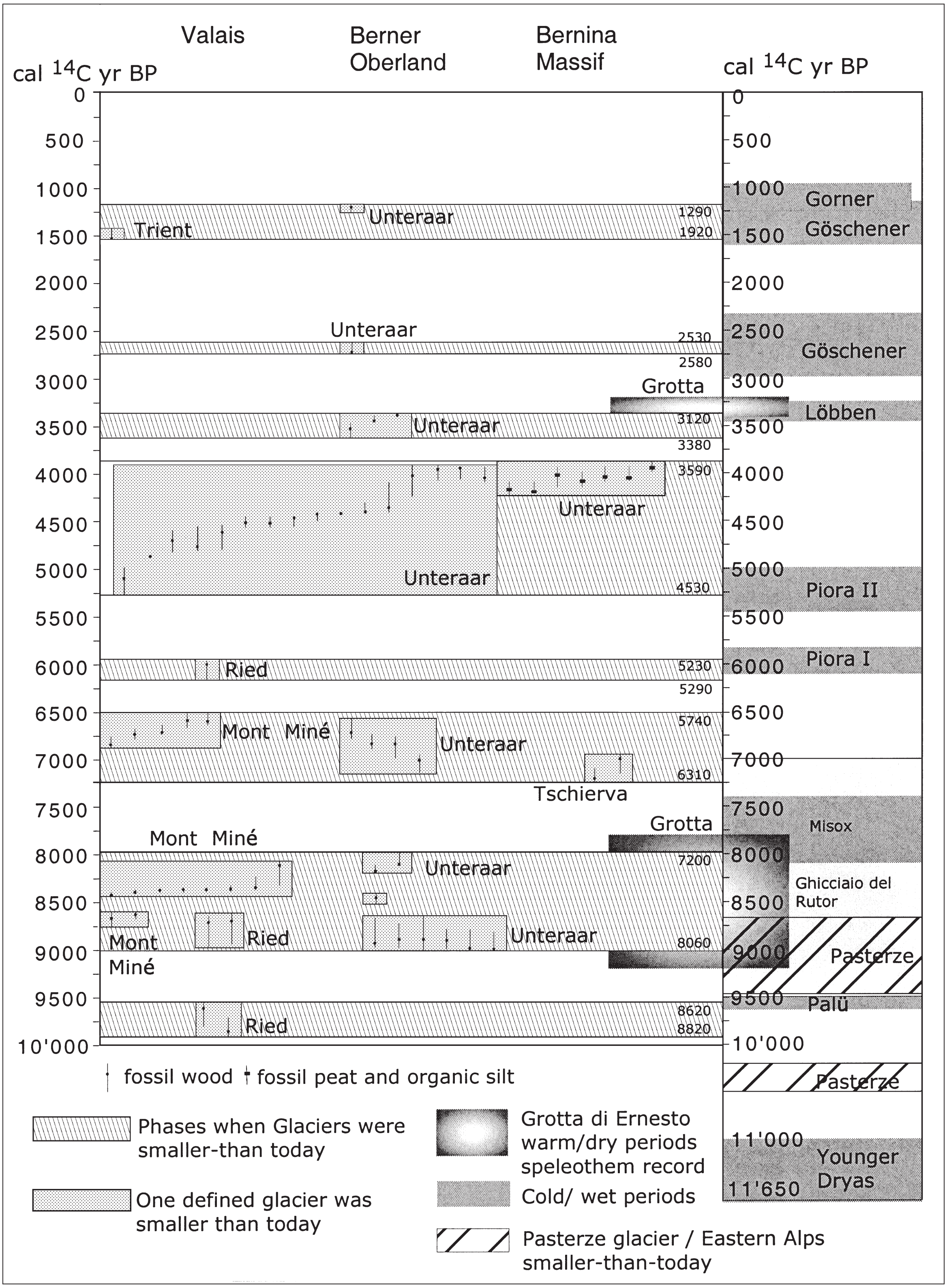

Figure 5 Calibrated radiocarbon ages defining glacier minimal extension periods. The uncalibrated radiocarbon years of the recession periods are given in ciphers inside the column. The vertical extension of the light-grey bars corresponds to the time period (cal. yr BP) of tree or peat growth; horizontal extension corresponds to the number of samples dated within this time period. The darker-grey bars inside the light-grey bars represent the interval of a smaller-than-today extension at one single glacier. The black dots represent the single calibrated radiocarbon age results with 1 σ error bar of wood samples. The black squares represent samples of organic material and peat. On the right-hand side of the figure, important cold and warm events from previously published studies mentioned in the text are listed. The Younger Dryas cold event is based on data from Hajdas (1993).

subfossil samples having been melted out of glaciers following subglacial and englacial transport.

(3) The radiocarbon dates do not indicate a random distribution over the Holocene but form eight clusters indicating phases of glaciers contraction with glaciers smaller than present. These cluster recession phases are: 9910–9550, 9010–7980, 7250–6500, 6170–5950, 5290–3870, 3640–3360, 2740–2620 and 1530–1170 cal. yr BP (Figure 5).

(4) Considering the start of tree growth after glacier recession of approximately 100 years, a moderate climate may have existed

prior to data points and periods of smaller-than-today glaciers should therefore be prolonged by some 100–200 years.

(5) The phases of glacier recession are consistent with other palaeoclimatic data sets. Some previously published data should be reconsidered in the light of the new data set: the Misox cold period between 8100 and 7400 cal. yr BP; the glacier advances Rotmoos and Piora I and II around 6100–5700 and 5500–5000 cal. yr BP; and also the Löbben cold period recorded in the Austrian and Swiss Alps.

(6) The glacial recessions indicate an unstable Holocene climate, the driving mechanisms of which are not understood in detail.

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References

Bauder, A. 1996: Massenbilanzmodellierungen mit photogrammetrischen Messungen und eismechanischen Berchnungen am Beispiel des Unteraargletschers. Diploma thesis, Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich.

Bearth, P. and **Lombard, A.** 1964: Carte géologique générale de la Suisse. Feuille 6, Sion. Bern: Commission Géologique Suisse.

Beniston, M. and **Rebetez, M.** 1996: Regional behaviour of minimum temperatures in Switzerland for the period 1979–1983. *Theoretical Applied Climatology* 53, 231–43.

Boulton, G.S., Mason, P., Ballantyne, C.K., Karlén, W., Matthews, J.A. and **Nesje, A.** 1997: Holocene glacier fluctuations in Scandinavia. In Frenzel, B., Boulton, G.S., Gläser B. and Huckriede, U., editors, *Glacier Fluctuations during the Holocene*, Stuttgart: Gustav Fischer Verlag, 5–23.

Bronk Ramsey, C. 1995: Radiocarbon calibration and analysis of stratigraphy: the OxCal program. Proceedings of the 15th International ^{14}C Conference. *Radiocarbon* 27, 425–30.

Burga, C.A. 1988: Swiss vegetation history during the last 18,000 yr. *New Phytologist* 110, 581–602.

Courty, M.-A. and **Weiss, H.** 1997: The scenario of environmental degradation in the Tell Leilan region, NE Syria, during the late third millennium abrupt climate change. In Dalfes, H.N., Kukla, G. and Weiss, H., editors, *Third millennium BC climate change and Old World collapse*, NATO ASi Series, Berlin: Springer-Verlag, 107–47.

Couteaux, M. 1984: Présence, datages et signification phytosociologique de macro-restes de *Pinus* et de pollens de *Pinus cembra* L. à 2050 m dans le vallon de la Lavey (Massif des Ecrins, Isère, France). Genève: Paléobiologie, 55–62.

Denton, G.H. and **Karlén, W.** 1973: Holocene Climatic variations – their pattern and possible cause. *Quaternary Research* 31, 155–205.

Eggenberg, S. 1994: Dynamik der Vegetation an der Waldgrenze und die Abhängigkeit ihrer Zusammensetzung vom Klima, Bern (Diss. Phil.-naturwiss.).

Fairhall, A.W., Schell, W.R. and **Takashima, Y.** 1961: Apparatus for methane synthesis for radiocarbon dating. *The Review of Scientific Instruments* 32, 323–25.

Gamper, M. and **Suter, J.** 1982: Postglaziale Klimageschichte der Schweizer Alpen. *Geographica Helvetica* 37, 105–14.

Gehy, M.A. 1983: Physikalische und Chemische Datierungsmethoden in der Quartärforschung. Clausthal-Zellerfeld: Ellen Pilger, 163 pp.

Geyh, M.A. and **Schleicher, H.** 1990: *Absolute age determination: physical and chemical dating methods and their application*. Berlin: Springer, 503 pp.

Grove, J.M. 1997: The spatial and temporal variations of glaciers during the Holocene in the Alps, Pyrenees, Tatra and Caucasus. In Frenzel, B., Boulton, G.S., Gläser, B. and Huckriede, U., editors, Glacier fluctuations during the Holocene, Stuttgart: Gustav Fischer Verlag, 95–103.

Gudmundsson, G.H. 1994: Glacier sliding over sinusoidal bed and the characteristics of creeping flow over bedrock undulations. Mitteilungen Versuchsanstalt Wasserbau, Hydrologie und Glaziologie, ETHZ, 102.

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

Haefeli, R. 1970: Changes in the behaviour of the Unteraargletscher in the last 125 years. *Journal of Glaciology* 9, 195–212.

Hajdas, I. 1993: Extension of the radiocarbon calibration curve by AMS dating of laminated sediments of lake Soppensee and lake Holzmaar. Zürich, Diss. ETH Nr. 10157, 147 pp.

Hoelzle, M. and **Haeberli, W.** 1999: World Glacier Monitoring Service. World Glacier Inventory. Digital data available from the National Snow and Ice Data Center, volume 1999, nsidc@kryos.colorado.edu. University of Colorado, Boulder, Colorado.

Holzhauser, H. 1985: Neue Ergebnisse zur Gletscher- und Klimageschichte des Spätmittelalters und der Neuzeit. *Geographica Helvetica* 4, 168–85.

—— 1997: Geltscherschwankungen innerhalb der letzten 3200 Jahre am Beispiel des grossen Aletsch- und des Gornergletschers. Neue Ergebnisse. In Salm, B., editor, Gletscher im ständigen Wandel, Zürich: vdf-Hochschulverlag AG an der ETH, 101–22.

Hormes, A. 2001: The ^{14}C perspective of glacier recessions in the Swiss Alps and New Zealand. Inaugural Dissertation, Universität Bern. Osnabrück: Der Andere Verlag, 176 pp.

Hormes, A., Schlüchter, C. and **Stocker, T.F.** 1998: Minimal extension phases of Unteraarglacier (Swiss Alps) during the Holocene based on ^{14}C analysis of wood. In Mook, W.G. and van der Plicht, J., editors, *Radiocarbon* 40, Proceedings of the 16th International ^{14}C Conference, 809–17.

Iken, A., Röthlisberger, H., Flotron, A. and **Haeberli, W.** 1983: The uplift of the Unteraargletscher at the beginning of the melt season – a consequence of water storage at the bed? *Journal of Glaciology* 29, 28–47.

Johannesson, T., Raymond, C.F. and **Waddington, E.D.** 1989: A simple method for determining the response time of glaciers. In Oerlemans, J., editor, Glacier fluctuations and climate change, Dordrecht: Kluwer, 343–52.

Jost-Stauffer, M. 2001: A Holocene fossil coleopteran (beetle) assemblage from the Central Swiss Alps: climate and ecology. *Eclogae Geologicae Helveticae*, in press.

Karlén, W. and **Kuylenstierna, J.** 1996: On solar forcing of Holocene climate: evidence from Scandinavia. *The Holocene* 6, 359–65.

Leonard, E.M. 1989: Climatic change in the Colorado Rocky Mountains: estimates based on modern climate at the Pleistocene equilibrium lines. *Arctic and Alpine Research* 21, 245–55.

Loosli, H.-H., Heimann, M. and **Oeschger, H.** 1980: Low-level gas proportional counting in an underground laboratory. *Radiocarbon* 22, 461–69.

Lubinski, D.J., Forman, S.L. and **Miller, G.H.** 1999: Holocene glacier and climate fluctuations on Franz Josef Land, Arctic Russia, 80 degrees N. *Quaternary Science Reviews* 18, 85–108.

Luckman, B.H., Holdsworth, G. and **Osborn, G.D.** 1993: Neoglacial glacier fluctuations in the Canadian Rockies. *Quaternary Research* 39, 144–53.

Maisch, M., Wipf, A., Denneler, B., Battaglia, J. and **Benz, C.** 1999: *Die Gletscher der Schweizer Alpen. Gletscherhochstand 1850, Aktuelle Vergletscherung, Gletscherschwund-Szenarien*. Zürich: vdf, 373 pp.

Maizels, J. 1997: Jökulhlaup deposits in proglacial areas. *Quaternary Science Reviews* 16, 793–819.

Masson, V., Cheddadi, R., Braconnot, P., Joussaume, S., Texier, D. and **PMIP participants** 1999: Mid-Holocene climate in Europe: what can we infer from PMIP model-data comparisons? *Climate Dynamics* 15, 163–82.

Mayr, F. 1969: Die Postglazialen Gletscherschwankungen des Mont Blanc-Gebietes. *Zeitschrift für Geomorphologie*, N.F. Suppl. 8, 31–57.

McDermott, F., Frisia, S., Huang, Y., Longinelli, A., Spiro, B., Heaton, T.H.E. Hawkesworth, C.J., Borsato, A., Keppens, E., Fairchild, I.J., van der Borg, K., Verheyden, S. and **Selmo, E.** 1999: Holocene climate variability in Europe: evidence from $\delta^{18}O$, textural and extension-rate variations in three speleothems. *Quaternary Science Reviews* 18, 1021–38.

Messerli, B., Messerli, P., Pfister, C. and **Zumbühl, H.J.** 1978: Fluctuations of climate and glaciers in the Bernese Oberland, Switzerland, and their geoecological significance, 1600 to 1975. *Arctic and Alpine Research* 10, 247–60.

Müller, P. 1988: Parametrisierung der Gletscher-Klima-Beziehung für die Praxis: Grundlagen und Beispiele. *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie* 95, 228.

Nicolussi, K. and **Patzelt, G.** 2000: Discovery of early-Holocene wood and peat on the forefield of the Pasterze Glacier, Eastern Alps, Austria. *The Holocene* 10, 191–99.

Oerlemans, J. 1994: Quantifying global warming from the retreat of glaciers. *Science* 264, 243–32.

Paterson, W.S.B. 1994: *The physics of glaciers*. Oxford: Pergamon, 480 pp.

Patzelt, G. 1977: Der zeitliche Ablauf und das Ausmass postglazialier Klimaschwankungen in den Alpen. In Frenzel, B., editor, *Dendrochronologie und postglaziale Klimaschwankungen in Europa*, volume 13, Wiesbaden: Steiner, 248–59.

—— (with contributions by Bortenschlager, S. and Poscher, G.). 1996: *Tirol: Ötztal-Inntal.-DEUQUA-Exkursion A1*. Institut für Hochgebirgsforschung, Univ. Innsbruck, 23 pp.

Patzelt, G. and **Bortenschlager, S.** 1973: Die postglazialen Gletscher- und Klimaschwankungen in der Venedigergruppe (Hohe Tauern, Ostalpen). *Zeitschrift für Geomorphologie Neue Folge* 16, Supplement, 25–72.

Pfister, C. 1985: Veränderungen der Sommerwitterung im südlichen Mitteleuropa von 1270–1400 als Auftakt zum Gletscherhochstand der Neuzeit. *Geographica Helvetica* 40, 186–95.

Phillips, F.M., Zreda, M.G., Benson, L.V., Plummer, M.A., Elmore, D. and **Sharma, P.** 1996: Chronology for fluctuations in late Pleistocene Sierra Nevada glaciers and lakes. *Science* 274, 749–51.

Porter, S.C. 1975: Equilibrium-line altitudes of late Quaternary glaciers in the Southern Alps, New Zealand. *Quaternary Research* 5, 27–47.

Porter, S.C. and **Orombelli, G.** 1985: Glacier contraction during the middle Holocene in the western Italian Alps: evidence and implications. *Geology* 13, 296–98.

Röthlisberger, F., Haas, P., Holzhauser, H., Keller, W., Bircher, W. and **Renner, F.** 1980: Holocene climatic fluctuations – radiocarbon dating of fossil soils (fAh) and woods from moraines and glaciers in the Alps. *Geographica Helvetia* 35(5), 21–52.

Röthlisberger, F. and **Schneebeli, W.** 1976: Gletscher- und Klimaschwankungen im Raum Zermatt, Ferpècle und Arolla. In Schneebeli, W. and Röthlisberger, F., editor, *8000 Jahre Walliser Gletschergeschichte*, Bern: SAC, 59–150.

Ruch, P., Eicher, U., Stücki, N., Thew, N., Wick, L., Zeh, M. and **Zbären, D.** 1997: Comparaisons des signatures isotopiques, chimiques, minéralogiques et biologiques dans le Gerzensee (BE). Signification des réponses. Corrélation des $\delta^{18}O$ avec les glaces du Groenland pour le Postglaciaire.

Schlüchter, C. 1988: Instabilities in the area of St Moritz, Switzerland – geology, chronology, geotechnology. In Bonnard, C., editor, *Landslides*, Proceedings of the Fifth International Symposium on landslides, 10–15 July, Volume 2, Lausanne, Rotterdam: Balkema, 1375–80.

—— 1995: Die grünen Alpen vor 2000 Jahren. *Cratschla* 60.

Schoch, W.H., Pawlik, B. and **Schweingruber, F.H.** 1988: *Botanische Makroreste*. Bern: Paul Haupt, 227 pp.

Schweingruber, F.E. 1990: *Anatomie europäischer Hölzer: ein Atlas zur Bestimmung europäischer Baum-, Strauch- und Zwergstrauchhölzer*. Bern: Paul Haupt, 800 pp.

Slupetzky, H. and **Krisai, R.** 1991/92: Erfänzende Radiokarbondatierungen aus dem Vorfeld des Obersulzbachkeeses, Venedigergruppe, Hohe Tauern. *Zeitschrift für Gletscherkunde und Glazialgeologie* 27/28, 145–49.

Slupetzky, H., Krisai, R. and **Lieb, G.K.** 1998: Hinweise auf kleinere Gletscherstände der Pasterze (Nationalpark Hohe Tauern, Kärnten) im Postglazial – Ergebnisse von ^{14}C-Datierungen und Pollenanalysen. *Wissenschaftliche Mitteilungen aus dem Nationalpark Hohe Tauern* 4.

Staub, R. 1946: Geologische Karte der Bernina-Gruppe und ihrer Umgebung im Oberengadin, Val Malenco, Puschlav und Livigno.

Stuiver, M. and **Reimer, P.** 1993: Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. In Stuiver, M., Long, A. and Kra, R.S., editors, Calibration 1993, *Radiocarbon* 35, 215–30.

—— 1999: 1999 CALIB (computer program) URL. http://depts.washington.edu/qil/.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., van der Plicht, J. and **Spurk, M.** 1998: INTCAL98 radiocarbon age calibration, 24,000–0 cal. BP. *Radiocarbon* 40, 1041–83.

Sugden, D.E. and **John, B.S.** 1976: *Glaciers and landscape: a geomorphological approach*. London: Arnold.

Tinner, W., Ammann, B. and **Germann, P.** 1996: Treeline fluctuations recorded for 12,500 years by soil profiles, pollen and plant macrofossils in the Central Swiss Alps. *Arctic and Alpine Research* 28(2), 131–47.

Zoller, H. 1977: Alter und Ausmass postglazialer Klimaschwankungen in den Schweizer Alpen. In Frenzel, B., editors, *Dendrochronologie und postglaziale Klimaschwankungen in Europa, Volume Erdwissenschaftliche Forschung* 13, 271–81.

Zoller, H., Athanasiadis, N. and **Heitz-Weniger, A.** 1998: Late-glacial and Holocene vegetation and climate change at the Palü glacier, Bernina Pass, Grisons Canton, Switzerland. *Vegetation History and Archaeobotany* 7, 241–49.