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Multicentury glacier fluctuations in the Swiss Alps during the Holocene

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Abstract: Subfossil remains of wood and peat from six Swiss glaciers found in proglacial fluvial sediments indicate that glaciers were smaller than the 1985 reference level and climatic conditions allowed vegetation growth in now glaciated basins. An extended data set of Swiss glacier recessions consisting of 143 radiocarbon dates is presented to improve the chronology of glacier fluctuations. A comparison with other archives and dated glacier advances suggests 12 major recession periods occurring at 9850–9600, 9300–8650, 8550–8050, 7700–7550, 7450–6550, 6150–5950, 5700–5500, 5200–4400, 4300–3400, 2800–2700, 2150–1850, 1400–1200 cal. yr BP. It is proposed that major glacier fluctuations occurred on a multicentennial scale with a changing pattern during the course of the Holocene. After the Younger Dryas, glaciers receded to a smaller extent and prolonged recessions occurred repeatedly, culminating around 7 cal. kyr BP. After a transition around 6 cal. kyr BP weak fluctuations around the present level dominated. After 3.6 cal. kyr BP less frequent recessions interrupted the trend to advanced glaciers peaking with the prominent 'Little Ice Age'. This trend is in line with a continuous decrease of summer insolation during the Holocene.

Key words: Multicentury, glacier recession, glacier fluctuations, climate records, climate variability, Alps, Switzerland, Holocene.

Introduction

A stable level of Holocene climate is revealed by oxygen isotopes as a proxy of annual temperature in greenland ice cores (Johnsen *et al*., 1997) and northern Alpine lake sediments (von Grafenstein *et al*., 1999). This is surprising given the decreasing summer insolation reduction at 65°N totalling about 50 W/m^2 since 10 kyr BP (Berger, 1978). However, a growing number of studies (Mayewski *et al*., 2004 and references therein) have demonstrated that distinct periods of climate change occurred repeatedly throughout the Holocene. Considering the Alps, the analysis of lake sediments provided broad insights into the characteristics of Holocene environmental conditions. Several periods with pronounced warming were identified during the Holocene by studies based on pollen (Haas *et al*., 1998), tree line positions (Tinner and Theurillat, 2003) or chironomid assemblages (Heiri *et al*., 2003). The impact of cooler conditions, including the well known 8.2 ka event (Alley *et al*., 1997), was reported by studies on biotic proxies (von Grafenstein *et al*., 1999; Tinner and Lotter, 2001) and by model simulations (Renssen *et al*., 2001). These cold events have been related to known periods of glacier advances (Denton and Karlén, 1973), but information on retreated glaciers during warmer periods remained sparse (Röthlisberger, 1986). In fact, the exceptional trend of warming during the twentieth century in relation to the last 1000 years (Intergovernmental Panel on Climate Change (IPCC), 2001) highlights the importance of assessing natural variability of climate change including periods of both, cooling and warming.

After the 'Little Ice Age' (AD 1850) alpine glaciers have retreated substantially, exposing high walls of lateral moraines. In some places, these moraines consist of a stack of different till units indicating several Holocene glacial advances. Previous work focused on mapping and dating of organic soils in moraine sequences, interpreting radiocarbon ages as the date of embedding related to glacier advances (Röthlisberger, 1986). However, reconstructions based only on moraines are incomplete because of discontinuous deposition and are subject to problems concerning the dating of palaeosoils (Matthews, 1997; Hormes *et al*., 2004) and their stratigraphic interpretation (Matthews, 1997). Information is generally sparse on periods of retreated glaciers because subsequent glacier advances destroyed smaller moraines. Some studies indicated

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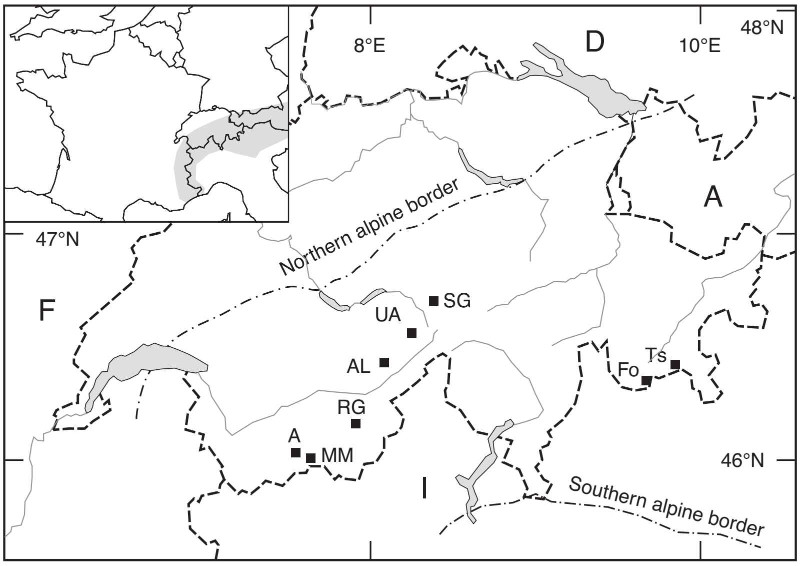

Figure 1 Sketch map of the Swiss Alps showing the locations of the investigated glaciers. Fo, Forno Glacier and Ts, Tschierva Glacier belong to the Bernina Massif; SG, Steinlimi Glacier; UA, Unteraar Glacier (Grimsel); MM, Mont Miné Glacier; and RG, Ried Glacier (Valais). Further locations A, Arolla; AL, Aletsch Glacier

that glaciers were once smaller (Porter and Orombelli, 1985; Slupetzky, 1993), but the temporal and spatial singularity of data precluded an accurate control on the timing and extent of retreated glaciers. Recent findings of wood and peat fragments associated with meltwater outburst events have directed attention to the palaeoclimatic significance of subglacial sedimentary basins (Nicolussi and Patzelt, 2000a; Hormes *et al.*, 2001).

This study examines Holocene glacier recessions in the Swiss Alps based on radiocarbon-dated material found in proglacial fluvial sediments of subglacial origin. New data, mainly from the Bernina Massif, are combined with earlier data resulting in a chronology of Swiss glacier fluctuations.

Characterization of glaciers and subfossil wood and peat

Location and characteristics of the investigated glaciers are presented in Figure 1 and Table 1. Tschierva and Forno Glaciers belong to the Bernina Massif of the Eastern Swiss Alps with precipitation originating mainly from the south. The Unteraar and Steinlimi Glaciers are located in the Central Swiss Alps (Grimsel) dominated by North-Atlantic weather. Ried and Mont Miné Glaciers experience the inner alpine, relatively dry climate of the Valais surrounded by high mountains (Figure 1).

The following criteria for the selection of suitable glaciers were used in order to obtain a consistent data set: (1) no modern sources of wood growth on unglaciated slopes in the catchment, (2) no possible input of wood fragments from avalanches, (3) no short or steep glaciers, because of their short response times to climatic fluctuations and other limitations such as topography or special local wind conditions. All glaciers of this study satisfy these criteria by being long and flat with low bed roughness. All glaciers terminate at an altitude of 1950 to 2300 m a.s.l., which is close to the local tree line. The volume response time was estimated as the ratio of maximum ice thickness to ablation at the terminus (Johannesson *et al.*, 1989). Response times of 21 to 67 years resulting from the estimates given in Table 1 indicate that the investigated glaciers reflect significant periods of climatic change with durations exceeding 50 years. Therefore, we assume that our samples are evidence of vegetation growth in basins that are unvegetated at present. Because of rapid downwasting of glacier tongues for the last 15 years glaciers are far out of equilibrium. This does not allow a reasonable relation of terminus position to climatic conditions. Since glaciers readvanced after 1965, approaching a near equilibrium state around the early 1980s, the glacier length in 1985 was chosen as a reference level (approximating present conditions). Therefore, the usage of the term 'recession' refers to the fact that glacier length was shorter than the 1985 reference level and the corresponding climatic conditions (Table 1).

Table 1 Properties of investigated glaciers in the Swiss Alps on the 1985 reference date and according to the Swiss Glacier observation network data base

	Unit	Tschierva	Forno	Ried	Mont Miné	Unteraar	Steinlimi
Terminus altitude	m a.s.l.	2280	2210	2000	2000	1950	2140
Glacier area[a]	km^2	6.2	8.72	8.22	10.97	29.48	2.3
Length of flowline[a]	km	4.75	6.15	6.35	8.35	12.95	2.8
$H_{\max}$ (estimated)[b]	m	200	300	250	250	400	150
Ablation at terminus[a]	m/yr	8	7	6.5	6	6	7
Response time	yr	25	43	38	42	67	21

[a] Data from http://glaciology.ethz.ch/swiss-glaciers/ (last accessed 27 April 2006).

[b] The maximum ice thickness ($H_{\max}$) is estimated based on reconstructions of glaciers and topography after Maisch *et al.* (1999).

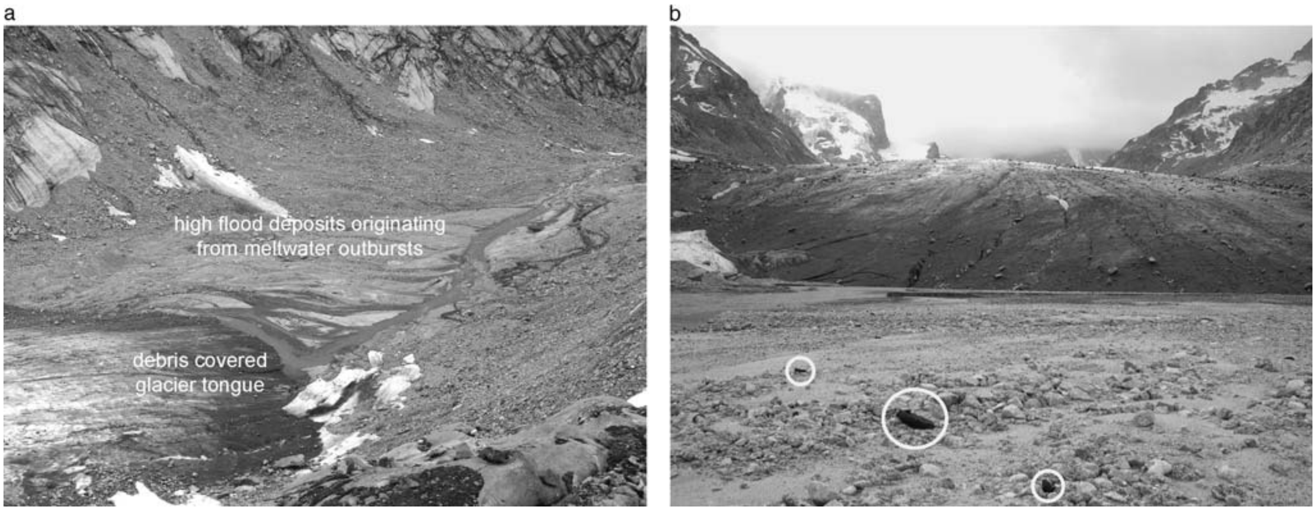

Figure 2 (a) The geological setting at the Forno Glacier forefield (oblique view, 17 July 2004). The glacier descends from left to right with a debris-covered tongue from which meltwaters emerge and subsequently flood the outwash plain. Large areas beside the main channel (shown at medium water level) are composed of high flood sediments originating from outburst events. (b) A closer view towards the Forno Glacier tongue with peat samples marked (white circles) imbricated in higher elevated flood deposits (photo by S. Strasky, 18 July 2004)

The post 'Little Ice Age' retreat of glaciers has led to extended forefields where unconsolidated glacial and fluvioglacial sediments are exposed to fluvial processes of meltwater rivers. Occasional meltwater outbursts from the glacier terminus remobilize large amounts of sediment, which produce aggradations. Figure 2a illustrates the geological setting at the Forno Glacier forefield as an example. Pieces of subfossil wood and peat were found on aggradations in front of the glacier tongue, as shown in Figure 2b. The wood samples, usually fragments of a log, show abrasion and polished surfaces, are often heavily deformed because of subglacial transport and are imbricated in the coarse meltwater deposits. Peat samples are flat discs of parallel layers of sand and organic material. The peat is heavily compressed, indicating burial beneath glacial overburden, and their rounded shape is due to abrasion during meltwater transport (Figure 2).

Original information about the samples was reported by Hormes *et al.* (2001). Since then, additional samples were collected at Unteraar and Steinlimi Glaciers and the investigation was extended to Forno and Tschierva Glaciers. Because of different glaciological factors that influence the frequency of meltwater outbursts, the number of recovered samples varies between 5 at Ried Glacier and > 100 at Tschierva Glacier and at Unteraar Glacier.

Conventional radiocarbon dating on the outermost 10 to 20 rings of a log fragment was used for age determinations. In case of observed bark or a terminal ring, such ages are interpreted as the date of death of a given tree. However, most ages is this study represent dates older than the tree death, because some outer rings were eroded during subglacial transport. The duration of tree growth is given by the number of rings, but our lifespan estimations are based on counted rings only and an estimation of the missing part due to abrasion. The estimated lifespans are rounded to the nearest 50 years. Fragments of roots are classified as samples with an estimated 50 year lifespan. The dated material of peat samples was taken from the top layer of bulk sediment. The measured conventional radiocarbon ages were calibrated by applying the CALIB Rev 5.0 program (Stuiver and Reimer, 1993) in combination with the IntCal04 calibration data set (Reimer *et al.*, 2004). The corresponding lowest and highest limits of the 2-sigma standard deviation and the median of the calibrated ages are reported here.

Results and discussion

Periods of small ice extent

Alpine glacier recessions occurred at least 12 times during the Holocene (Table 2). This result is based on 143 radiocarbon ages (Table 3) of which 70 ages were reported previously by Hormes (2001). Figure 3a shows a histogram counting the number of samples per century using the median calibrated age. The bin size is 100 years and centred around multiples of 100 cal. yr (eg, a bin starts at $x+51$ and ends at $x+150$ cal. yr BP). The dates are clustered into distinct periods, which we call major glacier recessions, because all ($n=143$) dates indicate a smaller glacier extent than the 1985 reference level. In principle, each sample represents a receded glacier position for a certain period defined by the lifetime of the plant before its death. Adding the estimated lifespans to the calibrated radiocarbon ages links various dated samples to one recessional phase because of overlapping tree growth (Figure 3b).

Figure 3b displays the backward overlaps resulting from the lifespan estimations. The combination of Figure 3a and 3b defines the periods of glacier recessions, shown as shaded bars in Figure 3. An overview of the durations of the periods is listed in Table 2, where all numbers are rounded to the next

Table 2 Major periods of glacier recessions in the Swiss Alps based on 143 dated wood and peat fragments. Dates are given in calibrated years before present (AD 1950) and rounded to the next 50 years

Period	Begin	End	Duration	No. of samples
1	1400	1200	200	3
2	2150	1850	300	4
3	2800	2700	100	1
4	4300	3400	900	23
5	5200	4400	800	14
6	5700	5500	200	9
7	6150	5950	200	3
8	7450	6550	900	55
9	7700	7550	150	3
10	8550	8050	500	11
11	9300	8650	650	14
12	9850	9600	250	3
Total			5150	143

Table 3 New radiocarbon dates and calibration results of this study, which are used together with earlier results (Hormes *et al*., 2001, not included in this table) to define the glacier recessions in the Swiss Alps

Sample[a]	Labcode[b]	^{14}C age[c]	1 std[d]	δ^{13}C	2-std, cal. yr BP	Median	Material	Lifespan[e]
Fo-101	B-8518	8252	31	– 24.3	9120–9400	9230	wood	no
Fo-102	B-8519	8016	31	– 24.0	8770–9010	8890	wood	no
Fo-03	B-7785	6836	51	– 25.9	7590–7790	7670	wood	no
Fo-10	B-7766	6807	49	– 26.0	7570–7730	7640	wood	no
Fo-16	B-7611	6652	40	– 25.4	7440–7590	7530	wood	no
Fo-11A	B-7786	6150	38	– 26.3	6950–7160	7060	peat	no
Fo-09A	B-7613	6137	39	– 29.4	6910–7160	7040	peat	no
Fo-04	B-7612	6032	39	– 28.7	6760–6980	6880	wood	no
Fo-12-1	B-76161	5826	39	– 21.9	6500–6740	6640	peat	no
Fo-12	B-7616	5774	37	– 22.4	6490–6670	6580	peat	no
Fo-105	B-8521	5184	26	– 26.2	5910–5990	5940	peat	no
Fo-17	B-7615	4809	36	– 28.6	5470–5610	5520	peat	no
Fo-14	B-7614	4785	35	– 27.1	5330–5600	5520	peat	no
Fo-15	B-7767	4785	76	– 26.8	5320–5650	5510	wood	no
Fo-19	B-7765	4783	28	– 23.1	5470–5590	5520	wood	no
Fo-21	B-7787	4759	37	– 26.2	5330–5590	5520	peat	no
Fo-106	B-8522	3835	24	– 26.3	4150–4410	4230	wood	no
Fo-104	B-8520	3398	23	– 25.6	3580–3700	3650	wood	no
Ts-25	B-7627	8221	34	– 24.0	9030–9300	9190	wood	34
Ts-54	B-7783	6471	30	– 24.4	7320–7430	7380	wood	no
Ts-57	B-7762	6302	30	– 24.0	7170–7290	7220	wood	no
Ts-08	B-7758	6253	29	– 23.2	7030–7260	7210	wood	no
Ts-10a	B-7623	6237	29	– 25.7	7020–7250	7180	wood	no
Ts-13a	B-7773	6233	28	– 24.0	7020–7250	7170	wood	no
Ts-47	B-7761	6205	29	– 24.3	7000–7240	7090	wood	no
Ts-39a	B-7764	6182	39	– 22.8	6950–7230	7080	wood	no
Ts-16	B-7618	6098	29	– 25.4	6880–7160	6970	wood	no
Ts-40	B-7780	6085	28	– 25.0	6810–7150	6950	wood	no
Ts-143	B-8554	6052	37	– 23.4	6790–7000	6910	wood	177
Ts-26	B-7775	6047	30	– 24.4	6800–6970	6900	wood	no
Ts-04	B-7757	6044	30	– 25.6	6800–6970	6900	wood	no
Ts-05	B-7622	6015	29	– 24.4	6760–6940	6860	wood	no
Ts-41	B-7760	6010	28	– 23.4	6760–6940	6850	wood	no
Ts-53	B-7782	6004	30	– 23.0	6750–6940	6840	wood	no
Ts-39b	B-7779	5998	30	– 23.6	6750–6930	6840	wood	no
Ts-29	B-7628	5990	30	– 25.1	6740–6910	6830	wood	109
Ts-06	B-7624	5975	40	– 26.4	6680–6930	6810	wood	no
Ts-15-1	B-76171	5972	39	– 23.9	6680–6910	6810	wood	no
Ts-32	B-7777	5968	28	– 25.0	6730–6890	6800	wood	no
Ts-12	B-7621	5964	28	– 24.5	6730–6890	6790	wood	no
Ts-06	B-7619	5962	28	– 25.4	6720–6890	6790	wood	no
Ts-09	B-7620	5959	28	– 26.2	6700–6880	6790	wood	no
Ts-37	B-7778	5947	30	– 24.1	6680–6880	6770	wood	no
Ts-55	B-7784	5946	29	– 23.1	6680–6860	6770	wood	no
Ts-13b	B-7625	5936	30	– 25.8	6670–6850	6760	wood	no
Ts-28	B-7776	5914	28	– 24.4	6670–6790	6730	wood	no
Ts-15	B-7617	5909	28	– 26.2	6670–6790	6730	wood	no
Ts-24	B-7774	5899	30	– 24.0	6660–6790	6720	wood	no
Ts-112	B-8302	5896	28	– 22.1	6660–6780	6710	wood	no
Ts-63	B-7630	5890	38	– 26.8	6640–6800	6710	wood	no
Ts-10b	B-7759	5873	38	– 24.3	6570–6790	6700	wood	no
Ts-22	B-7626	5869	28	– 25.2	6640–6770	6690	wood	no
Ts-42	B-7781	5822	30	– 24.3	6540–6730	6640	wood	no
Ts-36	B-7629	5756	28	– 26.5	6480–6640	6560	wood	no
Ts-58	B-7763	5261	27	– 24.9	5930–6180	6020	wood	no
Ts-111	B-8301	4912	26	– 22.2	5590–5710	5630	wood	no
UA-2001A	B-8001	8712	34	– 25.0	9550–9880	9650	wood	no
UA-160	B-8132	6418	30	– 24.3	7280–7420	7360	wood	no
UA-233	B-8133	6246	31	– 25.7	7030–7260	7200	wood	174
UA-201	B-8135	6015	28	– 25.8	6760–6940	6860	wood	147
UA-2001B	UZ-1899	5880	75	– 25.6	6500–6880	6700	wood	no
UA-126	B-8130	4938	26	– 24.5	5600–5720	5660	wood	no
UA-226	B-8131	4910	26	– 25.3	5590–5710	5630	wood	no
UA-209	B-8134	4089	25	– 24.0	4450–4810	4590	wood	114
UA-252b	B-8180	3741	33	– 25.0	3980–4230	4100	wood	no
UA-252a	B-8179	3694	33	– 26.1	3930–4150	4040	peat	no
UA-254	B-8141	3672	25	– 24.7	3910–4090	4010	peat	no
UA-2000A	UZ-1897	3655	65	– 27.6	3780–4220	3980	peat	no

Table 3 (*continued*)

Sample[a]	Labcode[b]	^{14}C age[c]	1 std[d]	δ^{13}C	2-std, cal. yr BP	Median	Material	Lifespan[e]
UA-2000B	UZ-1898	3500	60	− 25.2	3630–3960	3770	peat	no
UA-255	B-8140	3406	25	− 25.1	3580–3720	3660	peat	no
SG-Rb14a	B-8136	2103	30	− 22.8	2000–2150	2080	peat	no
SG-Rb14b	B-8137	1968	30	− 23.8	1840–1990	1920	peat	no
SG-01	B-8006	4108	25	− 26.0	4530–4810	4620	peat	no

[a] Abbreviations for the glaciers are as given Figure 1.
[b] Labcode: radiocarbon measurements by Physics Institute, University of Bern (B) and by University of Zürich/ETHZ (UZ).
[c] ^{14}C age is conventional radiocarbon age.
[d] 1 std is 1-σ standard deviation; calibrated ages are given at the 2-σ level applying the Intcal04 calibration data set (Reimer *et al.*, 2004).
[e] Lifespan denotes the values rounded to the nearest 50 yr used for Figure 3b.

50 years accounting for uncertainties of the dating and calibration procedure as well as the lifespan estimates. The total duration of dated recessions counts more than 51 centuries, amounting to about half of the Holocene epoch, which is approximately double previous estimates (Röthlisberger, 1986).

The decreasing number of samples that are found since about 7 cal. kyr BP (Figure 3a) suggests that glacier recessions have decreased in frequency since then, culminating in the maximum glacier extent of the ‘Little Ice Age’. It appears that the record shows both the fluctuations of glacier extent

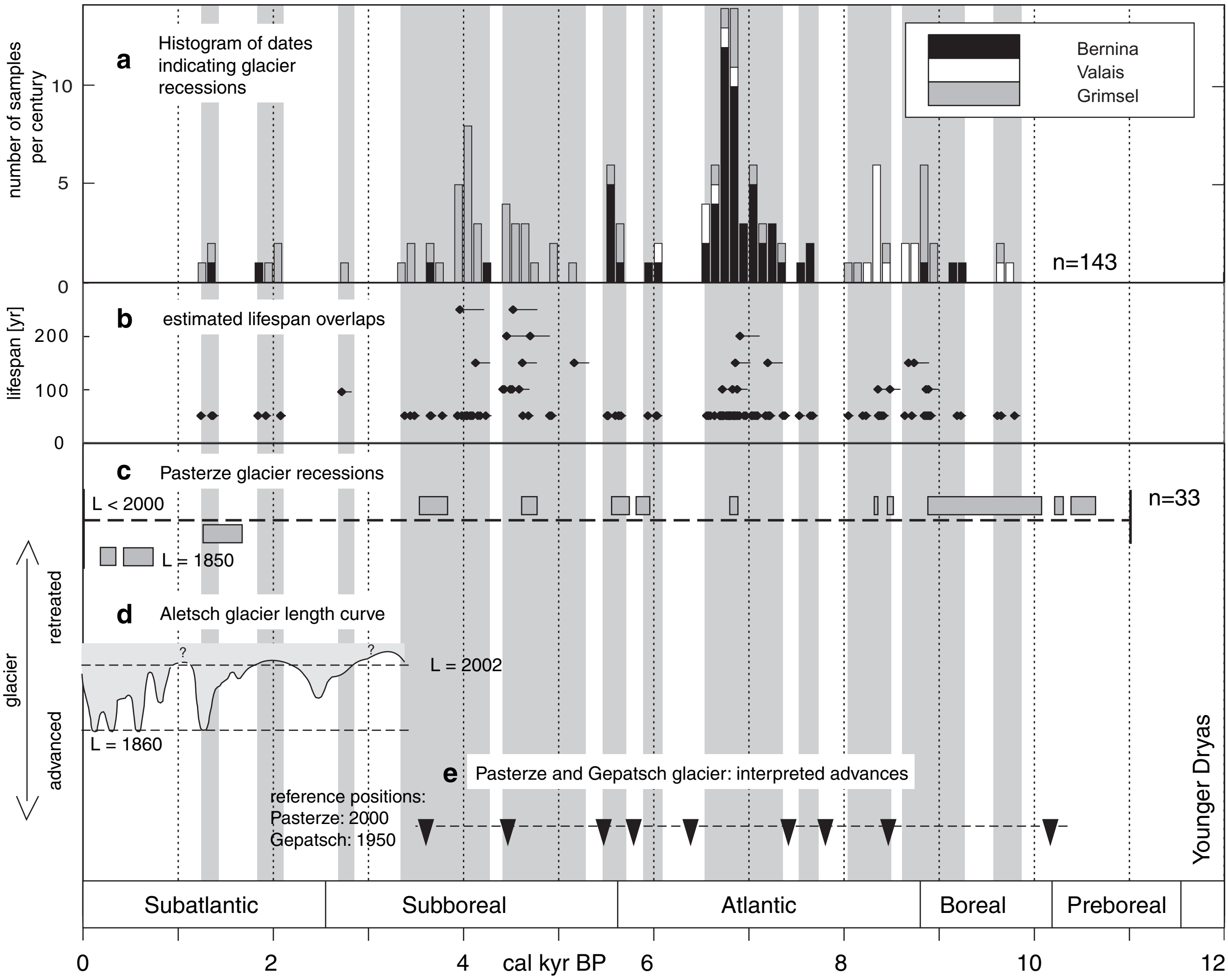

Figure 3 Overview of dated glacier recessions compared with glacier advances in the European Alps. (a) Histogram of dated glacier recessions from the Swiss Alps (this study). (b) Estimated lifespans of the dated samples illustrating the overlaps of individual tree growth. The combination of (a) and (b) determines the 12 periods of recessions (grey shaded). (c) Schematic plot of recession periods of Pasterze Glacier, Austria (Nicolussi and Patzelt, 2000b). Boxes above the dashed line represent evidence for smaller glacier length ($L < 2000$) and boxes in the lower part indicate advanced positions with the maximum during the ‘Little Ice Age’ ($L = 1850$). (d) Aletsch Glacier length curve after Holzhauser *et al.* (2005) indicating a small glacier length above the upper line (comparable with AD 2002) and a position comparable with the ‘Little Ice Age’ extent (lower line, $L = 1860$). (e) Arrows represent interpreted advances when Pasterze Glacier or Gepatsch Glacier advanced from a smaller extent over the reference position, which is the glacier terminus position at Pasterze Glacier in AD 2000 and at Gepatsch Glacier in AD 1950, respectively (Nicolussi and Patzelt, 2000b)

associated with natural climate variability on a multicentury timescale and a superimposed long-term, multimillennial trend of increasing Alpine glaciation during the Holocene. Such a trend is in line with the precessional signal found in summer insolation at 65°N (Berger, 1978), which has been decreasing since about 10 kyr BP. The associated cumulative change of summer insolation amounts to approximately 50 W/m^2. A synthesis of reconstructions of sea surface temperatures from marine sediments cores from the North Atlantic revealed a consistent large-scale pattern of decreasing temperatures during the Holocene (Marchal *et al*., 2002). The multimillennial decrease of recession frequency could thus be due to a continuous decrease in summer insolation in the Northern Hemisphere and the associated reduction in summer melting.

Glaciological interpretation of dated samples

The resolution of the histogram is limited to a class width of 100 years because of uncertainties of dating and calibration and in order to retain a sizeable sample number per bin. The investigated glaciers reflect changes in climate on a scale longer than their response time (Table 1). Each sample indicates a minimum of 50 years of ice-free conditions based on the estimated lifespan (> 30 yr) and the recolonization time defined as the delay until the first trees start to grow on a newly exposed (ice-free) forefield. Although the recolonization strongly depends on local conditions, a period of 20 yr as a first order approximation agrees with reconstructions (Luckman, 1993) and observations (Nicolussi *et al*., 2005). Trees start to grow within the extent of the 1985 position (Swiss glacier length observation network). These considerations suggest that our indicator is suitable to reconstruct centennial-scale but not decadal-scale fluctuations of glacier extent.

The period from 7450 to 6550 cal. yr BP stands out because of the large number of recovered wood samples and its long duration. Its abrupt end is best documented at the Tschierva Glacier with a series of well-preserved pieces of logs suggesting that trees were overridden by an advancing glacier and rapidly embedded into till. This process of rapid embedding was verified by dendrochronological studies (Ryder and Thomson, 1986). Dating of inner parts of long-lived trees or different peat layers could lead to a dating spread of no more than 300 years for a recession period. However, the embedding of wood fragments for periods longer than 500 yr documented in the recessions from 7450 to 6550 and 5200 to 4400 cal. yr BP suggests an additional mechanism. We interpret the morphology of the tree fragments as indicating that roots or trunks were embedded on an outwash plain during events of rapid sediment aggradation. Subsequently, preservation of organic remains prevailed in small-scale basins with a high groundwater table. Finally, the emergence of a subfossil sample in the glacier forefield depends on the varying conditions of subglacial erosion. The gaps between the clusters of dates (Figure 3a) are interpreted as periods with possible glacier advances. An alternative interpretation attributes the gaps to a reduced remobilization of buried fragments.

Chronology of glacier fluctuations within the Alps

The results from studies by Nicolussi and Patzelt (2000a,b) at Pasterze Glacier (Austrian Alps) using a similar approach are displayed in Figure 3c. The boxes above the reference line represent evidence for smaller glaciers. Most periods coincide with our recessions except for the Preboreal (*c*. 11 600–10 200 cal. yr BP), for which no dated material has yet been discovered in the Swiss Alps. Conversely, a few dates for the Pasterze Glacier fall into the extended recession from 7450 to 6550 cal. yr BP. Both discrepancies are interpreted to depend on different preservation and subglacial erosion, or on the different number and selection criteria of dated samples. Nevertheless, the data suggest a general agreement between the Austrian and the Swiss Alps.

The only known Holocene moraines situated below the LIA reference level (Patzelt and Bortenschlager, 1973) belong to smaller glaciers with faster adjustment to climatic deteriorations compared with the glaciers of this study. Three periods of early Holocene moraine deposition were determined by stratigraphic correlations to peat bogs using minimum and maximum ages as limits but no direct dating of till units. The oldest advance occurred before 10.2 cal. kyr BP, predating our record of recessions. A younger cold phase was confined to Boreal age coinciding with a moraine at Arolla (age after Röthlisberger (1986) recalibrated to 9500 ± 200 cal. yr BP). With regard to our results it is suggested that glacier advance(s) were limited to the period from 9.6 to 9.3 cal. kyr BP. The subsequent period from 8.8 to 5.8 cal. kyr BP indicates several deteriorations based on pollen profiles (Patzelt and Bortenschlager, 1973) and results at Pasterze and Gepatsch Glaciers (Nicolussi and Patzelt, 2000b). Such a deterioration is consistent with cooling sea surface temperatures found in the North Atlantic during this period (Marchal *et al*., 2002). In general, our data show that conditions for prolonged recessions prevailed. Short gaps around 8500, 8000–7800, 7500 and 6500–6200 indicate possible periods of glacier advances, which are in agreement with the interpreted advances in the Austrian Alps (Nicolussi and Patzelt, 2000b). The arrows in Figure 3e indicate that glaciers were smaller than the reference position at the beginning, but advanced over the reference position for the dated periods. The reference position is defined as the glacier extent at Pasterze Glacier in AD 2000 and at Gepatsch Glacier in AD 1950, respectively. With regard to the different response times of the glaciers it is proposed that the dated advances occurred as short pulses interrupting long (= several centuries) recessions during the first part of the Holocene.

One prominent event with reduced δ^{18}O in the Greenland ice cores is centered around 8.2 kyr BP lasting for about 300 years (Alley *et al*., 1997). Two of our samples fall into this period: UA-129 (8050–8320 cal. yr BP) and UA-182 (7970–8160 cal. yr BP). One possible explanation is that both trees were overridden by an advancing glacier, assuming a time lag of a few decades. This would be the first, albeit circumstantial, indication that the Alpine glaciers responded to the 8.2 ka cold event. An alternative interpretation assumes that glaciers were very small before the 8.2 ka event, and a minor advance did not exceed the present level.

Subsequent to advances around 5800 and 5400 cal. yr BP, our data suggest persistent recessions until 3300 cal. yr BP with the exception of minor fluctuations possibly at 4300 or 3600 cal. yr BP. It is interpreted that glaciers fluctuated around a level comparable with the 1985 reference position. After 3300 cal. yr BP, the Great Aletsch Glacier record indicates advances (Figure 3d) peaking around 90, 290, 580, 800, 1250, 2500 cal. yr BP (Holzhauser *et al*., 2005). Two additional advances (marked by '?' in Figure 3d) possibly occurred around 1050 cal. yr BP and 3200 cal. yr BP following earlier interpretations of dated sections at Aletsch Glacier (Wanner *et al*., 2000; Holzhauser, 1997). Several studies documented conditions favouring glacier advances around 3.2 kyr BP (Denton and Karlén, 1973; Schneebeli and Röthlisberger, 1976; Nicolussi and Patzelt, 2000b). No evidence of advances was found at Great Aletsch Glacier prior to 3.3 cal. kyr BP. These results are in agreement with our data indicating recessions around 2750, 2150–1850 and 1400–1200 cal. yr BP, which are relatively short in comparison with the recessions before 3.2 cal. kyr BP. Constraints on the successions of glacier fluctuations come from a partial overlap of the Aletsch Glacier advance around 1250 cal. yr BP and the dated recession from 1400 to 1200 cal. yr BP. Given the uncertainty of the radiocarbon dates, the two records could be interpreted consistently as an indication of rapid climate change around 1250 cal. yr BP supporting the conclusions of Mayewski *et al.* (2004). The combination of these records, and the coincidence with the evidence of advancing glaciers and moraine formations from the Valais (Schneebeli and Röthlisberger, 1976), is interpreted as a trend to more frequent and longer lasting advances disrupted by reduced recessions.

Conclusions

The radiocarbon ages of tree fragments and peat discs found on proglacial forefields indicate 12 phases of glacier recessions during the Holocene. Locations and type of occurrence of the dated samples show that trees and mires grew where glaciers exist at present and, therefore, glaciers were smaller at that time. The extended data set of recessions limits periods of glacier advances in a complementary way and improves on the chronology of natural climate fluctuations in the Alpine region. As a result, it is suggested that major glacier fluctuations occurred on a multicentennial scale and that their pattern changed from long recessions (> 500 yr) interrupted by short advances (< 200 yr) during the early Holocene to the opposite pattern with relatively short recessions and prolonged advances during the late Holocene (after 3.3 cal. kyr BP). It is important to recognize that this natural variability of glacier extent, which occurs on a centennial timescale, is superimposed on a much longer term, multimillennial-scale trend towards increased glacier extent culminating in the ‘Little Ice Age’. This is indicated in our data as a progressively reduced occurrence of wood and peat remnants through the course of the Holocene, which is consistent with a long-term reduction of sea surface temperatures in the North Atlantic. The multimillennial trend that is indicated in our data, therefore, is likely forced by changes in summer insolation and hence of astronomical origin. Studies attempting to identify the amplitudes of glacier fluctuations will help to improve the understanding of the pattern and forcings of climate change during the Holocene.

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