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Dates from an important early Late Pleistocene ice advance in the Aare valley, Switzerland

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Key words: Glaciation, geochronology, Late Pleistocene, Switzerland, Alps

ABSTRACT

Luminescence dating and sedimentological observations at the Thalgut site, Aare Valley, Switzerland, imply deposition of glaciofluvial sediments and consequently a glacier advance during the earliest Late Pleistocene, just after the Last Interglacial. This glaciation possibly reached the margin of the Alpine foreland, but was probably of much smaller extent than the Würm glaciation *sensu stricto*. A significant glacier expansion during the initial Würmian has already been deduced from pollen analyses, indicating cool but moist climatic conditions. The age of fluvial sediments from the Mattstetten site supports this interpretation of prevailing climatic conditions. The dated sediment apparently represents reworked weathered molasse in a periglacial, but presumably moist, environment during the earliest Late Pleistocene.

ZUSAMMENFASSUNG

Lumineszenzdatierungen und sedimentologische Beobachtungen in der Kiesgrube Thalgut, Aaretal, deuten auf eine Ablagerung glaziofluviatiler Sedimente während des frühesten Spätpleistozäns hin. Daraus wird ein Eisvorstoss direkt nach dem Ende des letzten Interglazials abgeleitet. Diese Vergletscherung erreichte wohl den Rand des Alpenvorlandes, war aber sicherlich wesentlich kleiner als die Würm-Vereisung *sensu stricto*. Eine bedeutende Eisausdehnung während der einsetzenden Würmeiszeit wurde bereits aus den Ergebnissen von pollenanalytischen Untersuchungen abgeleitet, die kühle aber feuchte Klimabedingungen anzeigen. Durch die Datierung von fluviatilen Sedimenten aus der Grube Mattstetten wird diese Interpretation der klimatischen Bedingungen unterstützt. Die datierten Sedimente werden als das Ergebnis von Umlagerungsprozessen unter feuchten periglazialen Umweltbedingungen während des frühesten Oberpleistozäns interpretiert.

Introduction

The complexity of climatic patterns during the Late Pleistocene is known from high-resolution archives such as Greenland ice-cores (e.g. Johnsen et al. 1992; Dansgaard et al. 1993), deep-sea sediments (e.g. Bond et al. 1993), and long pollen records (e.g. Allen et al. 1999). However, detailed knowledge of the response of the geosphere to changing climate is rather limited. What particular impact on fluvial systems and glaciers had changes in environmental conditions as reconstructed from climatic archives? Although, there are long established theoretical considerations on how different climates will affect different sedimentary systems, there are only a few studies that combine sedimentology and geochronology to confirm such models (e.g. Törnqvist et al. 2000, 2003). This is mainly due to the lack of suitable dating methods, making reliable correlations of sedimentary events with climatic developments almost impossible.

During recent years, luminescence methods have provided direct age constraint on sediment deposition ages (Aitken 1998). The availability of direct age control for the formation of sediments makes it feasible to establish time frames for depositional events during the course of Quaternary climate change. Presented here are two case studies of dating Late Pleistocene sites situated in the Aare Valley, Switzerland. The Thalgut site is probably one of the most complex archives of Pleistocene glaciations of the Swiss Alpine Foreland (Schlüchter 1989a, b). However, reconstruction of the Pleistocene climate history at this important site has not yet been confirmed by direct dating evidence. The Mattstetten site shows a complex pattern of changing sedimentary dynamics. Most interesting is a unit of sandy sediments, which is rather untypical for the region that is usually dominated by coarse glacial outwash deposits. The results of sedimentological observations and luminescence dating are discussed in terms of the background of the Pleistocene climatic succession in the Swiss Alpine Foreland.

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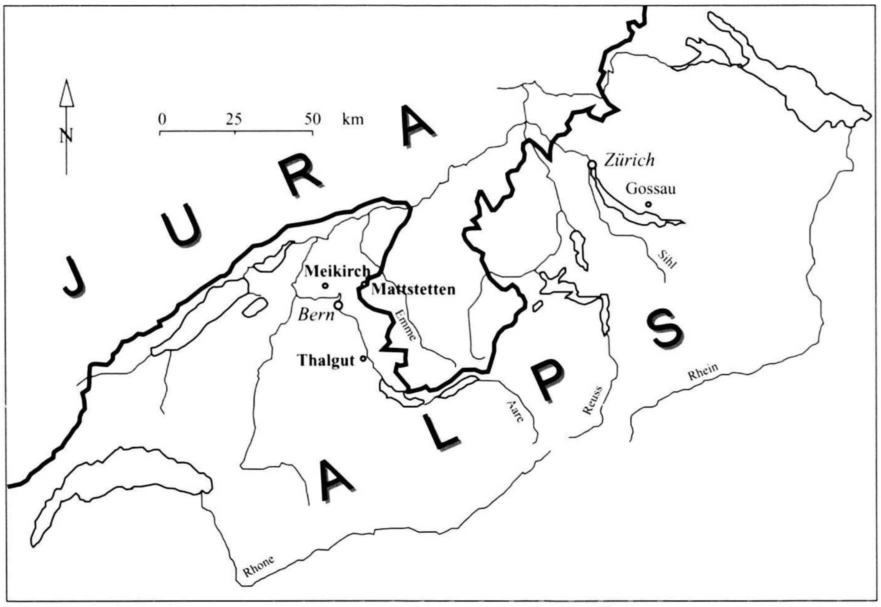

Fig. 1. Map showing the location of relevant sites mentioned in the text.

Geological setting

The Aare Valley is one of the key areas for the reconstruction of the Pleistocene glaciations of the Swiss Alps (Fig. 1). The last maximum extent of Alpine glaciers (Last Glacial Maximum – LGM) is documented at Wangen an der Aare. Erratic boulders resting on terminal push moraines of the Aare/Rhone glacier are dated by surface exposure dating to 20,000 ± 1800 yr using cosmogenic isotopes ^{10}Be, ^{26}Al, and ^{36}Cl (Ivy-Ochs 1996). The correlation of the LGM in the northern foreland of the Alps with marine isotope stage (MIS) 2 (24 to 11 ka, Bassinot et al. 1994) is further confirmed by radiocarbon dating of peat below or above, and wood or bone fragments found within glaciofluvial outwash sediments at various sites (Geyh & Schreiner 1984; Schlüchter et al. 1987; Schlüchter & Röthlisberger 1995; Schoeneich 1998).

The Meikirch drilling site near Bern provides one of the most challenging palaeoclimatic records of the Alpine region (Fig. 2). The lower part of the sequences consists of lacustrine sediments with a total thickness of more than 70 m. Pollen analyses of these sediments show evidence for three interglacial periods, the youngest of which is correlated with the Eemian Interglacial of NW central Europe (Welten 1982, 1988). Welten (1982) named the two older interglacial periods "Holsteinian 1" and "Holsteinian 2" but correlation of these interglacials with the Holstein *sensu stricto* in northern Germany is controversial (Schlüchter 1989a). It appears thus more appropriate to re-name these two interglacials into Meikirch (Holsteinian) 1 and Meikirch (Holsteinian) 2, as long as no reliable correlation is possible. The upper 40 m of the Meikirch drill core is attributed to the last glaciation of the Swiss Alpine Foreland, the Würm glaciation *sensu* Penck & Brückner (1901–09). The sediments consist of glaciofluvial deposits and an up to 10 m of till on top of the sequence. Welten (1982) recognised loamy layers in the lower part of the gravel unit and attributed these, according to pollen analysis (*Pinus/Picea* and some pollen of thermophile trees), to the first early Late Pleistocene Interstadial (Brørup of NW central Europe). If this correlation is correct, the lower part of the gravel must correlate with the earliest Late Pleistocene.

From this evidence, confirmed by findings from several other Swiss pollen sites, Welten (1981) concluded that the cool but wet climate during the first Würmian stadial must have caused an important advance of Alpine glaciers. This supposed glacial advance apparently led to the deposition of gravel in the lower part of the Würmian succession in the Meikirch cores. Likewise, Guiot et al. (1989) and Wegmüller (1992) concluded from pollen assemblages at La Grande Pile, Vosges, and Gondiswil, Swiss Plateau, respectively, that the climatic conditions during the on-set of the Würmian were cool but relatively moist. Such climatic conditions must have caused significant glacial advances within the Alps. Schlüchter (1991) and Keller & Krayss (1998) discussed sedimentary evidence for such a glaciation from several sites along the northern foreland of the Swiss Alps but confirmatory evidence was limited due to a lack of direct age control. Tentatively, Schlüchter (1991) and Keller & Krayss (1998) assumed that a possible early Late Pleistocene glaciation of the Swiss Alps correlates with MIS 4 (71–57 ka). On the other hand, there is strong evidence that the Swiss lowlands were not glaciated during the Middle Würmian (ca. 57–30 ka) (Schlüchter 1991). This indicates that glaciers retreated significantly after a possible first glacial advance.

First direct dating evidence for a glaciation of the foreland subsequent to the Last Interglacial but prior to the LGM is

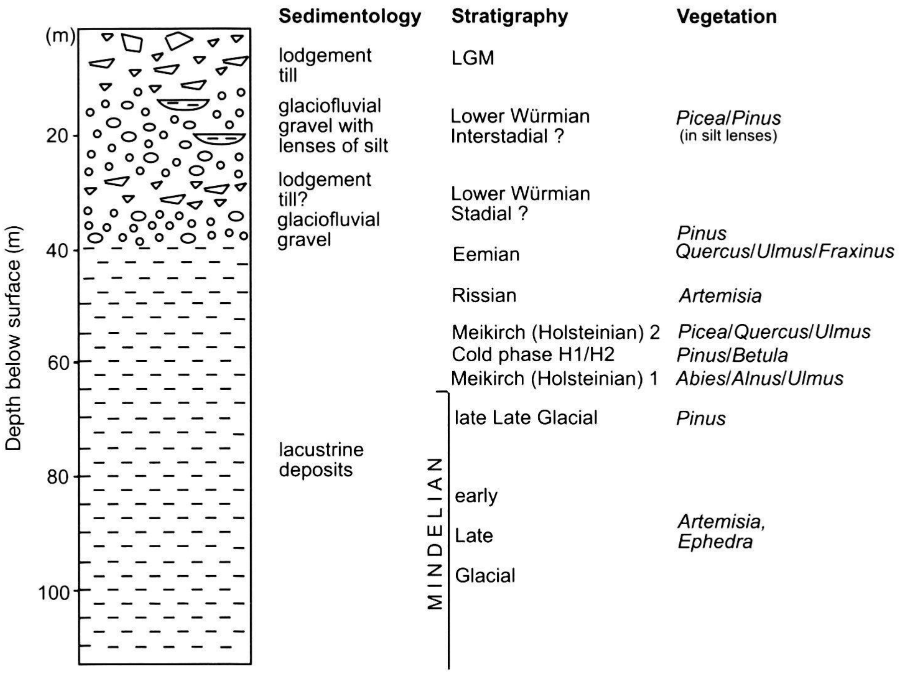

Fig. 2. Schematic sketch of the Meikirch site with vegetation and proposed correlation according to Welten (1982, 1988).

provided from the Gossau site, Lake Zürich area (Preusser et al. 2003). At Gossau, sandy layers within delta deposits that are interpreted to result from an advance of the Linth/Rhein glacier across the Hombrechtikon High into the Lake Zürich area are dated. The delta deposits are attributed to glacial conditions due to the high amount of non-weathered carbonate gravel within the sediment and due to the sedimentological setting (Schlüchter et al. 1987). Forty-two luminescence dates give a mean age of 103,000 ± 18,000 yr (Preusser et al. 2003). This date and pollen assemblages from silty-sand layers within the delta deposits that reflect cold climatic conditions imply a correlation with the first Würmian stadial. Nevertheless, questions about the glacigenic nature of the delta may arise since no till layer is present below or on top of the delta sediments. However, it is possible that the Gossau site was already beyond the limits of the supposed early glaciation.

Investigated sites

Thalgut

The Thalgut quarry is situated in the Aare Valley south of Bern, on the border of the Alps. This area was covered by the Aare glacier during the LGM. A complete description of the site is provided by Schlüchter (1989a, b). A summary is given here of the geology of the upper part of the sequence relevant to the present investigation (Fig. 3).

The lowest unit is the "Kirchberg-Deltaschotter", a sequence of delta fore-sets deposited in a local basin. The petrography of the gravel indicates a local origin from reworked molasse sediment (Schlüchter 1989b). It is thought that the "Kirchberg-Deltaschotter" unit is non-glacigenic, as there is no sign of any input of rocks from the central Alps. A significant input of alpine material, however, would have to be expected in case of a proximal presence of the Aare glacier during delta formation. Above the delta foresets are silty sands followed by lacustrine silts. The lacustrine sediment is correlated with the Last Interglacial (Eemian) according to pollen evidence (Welten 1982). Above the lacustrine series rests a coarsening upward sequence from silty sand to unsorted sand, accompanied by some silty beds that are interpreted to represent filling of small ponds on a sandy river plain. The coarsening upward sequence culminates in glaciofluvial deposits, "Obere Münsingen Schotter". This gravel unit contains a horizon representing intense weathering, reflecting interstadial conditions. This discontinuity is of major importance as it corresponds to an important hiatus in sedimentation. Therefore, the "Obere Münsingen Schotter" unit actually represents two different depositional events, separated by a period of non-sedimentation and weathering. Thus, the coarse accumulation is subdivided into an upper and a lower sub-unit. Both sub-units show a typically alpine spectrum of clast lithics and are presumably of glaciofluvial origin. The top of the Thalgut sequence consists of a basal lodgement till that is assigned to the last glaciation of the Alps.

The geological situation in the Thalgut pit suggests evidence for a glaciation between the Last Interglacial and the LGM that reached the margin of the Alps. This glaciation is represented by the coarsening upward sequence on top of the Last Interglacial lacustrine deposits. There is no indication of

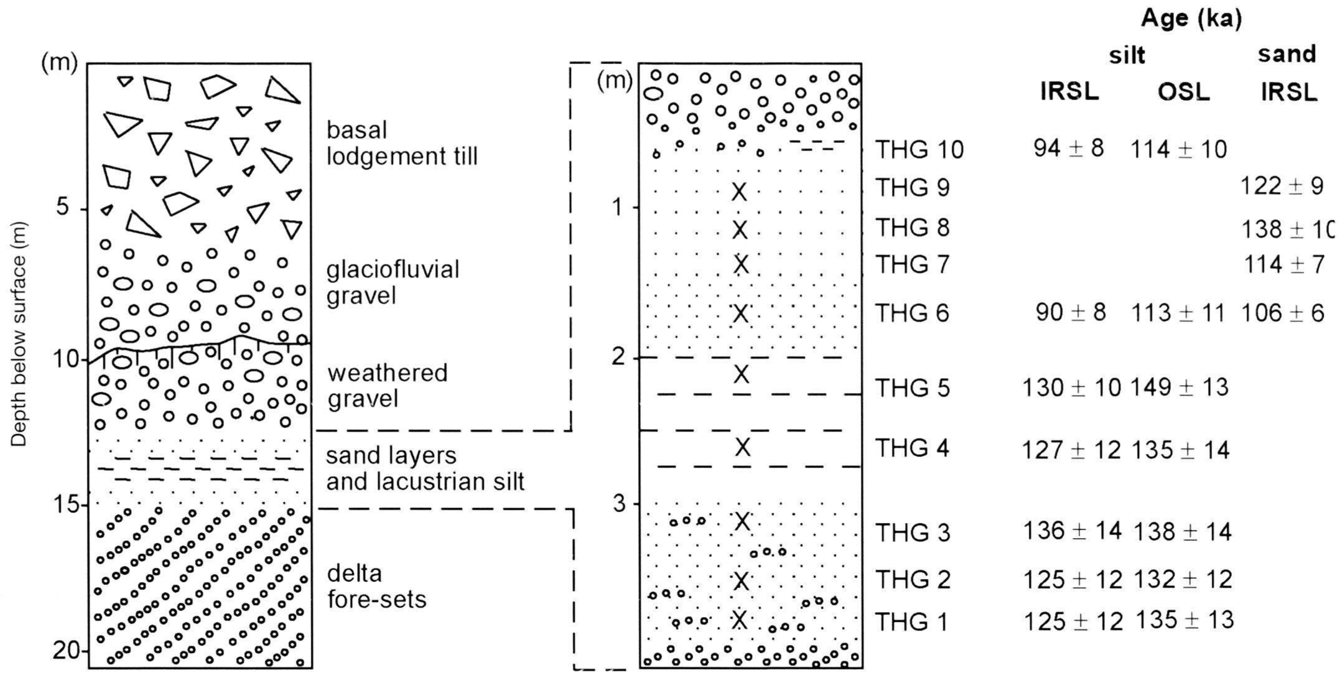

Fig. 3. Schematic sketch of the Thalgut site according to Schlüchter (1989a, b) with luminescence ages. The right column shows the sampled part of the section at an enlarged scale.

any significant break in sedimentation between the limnic deposits and the gravel. Altogether, 10 samples were collected for luminescence dating from the fine-grained part of the sequence (Fig. 3). Samples THG 1–3 are from the sandy to silty transitional layer found between the "Kirchberg-Deltaschotter" and the Last Interglacial limnic deposits. Two samples (THG 4–5) are from the lacustrine sediment and 5 samples (THG 6–10) are from silty to sandy material at the top of the limnic deposit.

Mattstetten

The quarry at Mattstetten is situated to the east of the Aare Valley, about 20 km NE of Bern. The pit is located close to the contact between Quaternary deposits and Tertiary molasse sediments of the Swiss Plateau. A detailed description of the site was carried out by Lauber (2003).

The lower part of the sequence consists of homogenous gravel with sandy channel fills (Fig. 4). This unit is followed by four fining-upward cycles from coarse to sandy gravel showing imbrication of clasts, indicating sediment deposition into a NE direction. A unit of cross-bedded medium-sized gravel that may represent delta foresets deposited into a local basin overlies the fining-up cycles. The cross-bedded unit is followed by gravel that is cut by an erosional surface. On top of this discontinuity rests an up to 4 m thick diamictic material. The petrography of clasts within the till, mainly metamorphic rocks and silicified limestones, indicates an origin of the sediment from the catchment of the Aare glacier. The till is covered by sandy gravel of presumably glacial origin. A residual layer of coarse gravel and boulders marks the top of this unit. The horizon on top of this layer indicates intense weathering and marks another discontinuity. Above the weathered horizon follows an up to 3 m thick unit of fine to medium-grained sand, showing occasional layers of silt and clay, and thin beds of fine to medium-sized gravel. The upper part of the sand exhibits intense weathering and the whole sand unit is disturbed by deformation of presumably glacial origin. In the northern part of the quarry the sand unit is covered by diamictic material of assumed LGM age.

The lower part of the sequence is interpreted to represent outwash sediments and glacigenic deposits. The sandy unit below the LGM lodgement till, however, significantly differs from the rest of the exposed sediments by its textural composition. A primary glacial origin of the sand appears unlikely since similar deposits in the foreland of the Alps are usually much coarser, like the lower part of the sequence. High amounts of sand would be available from nearby molasse sediments, which are usually only weakly to moderately cemented. A period of intense weathering would probably produce enough sand-size debris that will be available for erosion and transportation during phases of reduced vegetation cover. The layers of gravel within the sand, however, show an alpine spectrum in petrography but it is assumed that the gravel represents re-working of older glacial material. Three samples were collected from the sandy unit for luminescence dating (samples MTS 1–3).

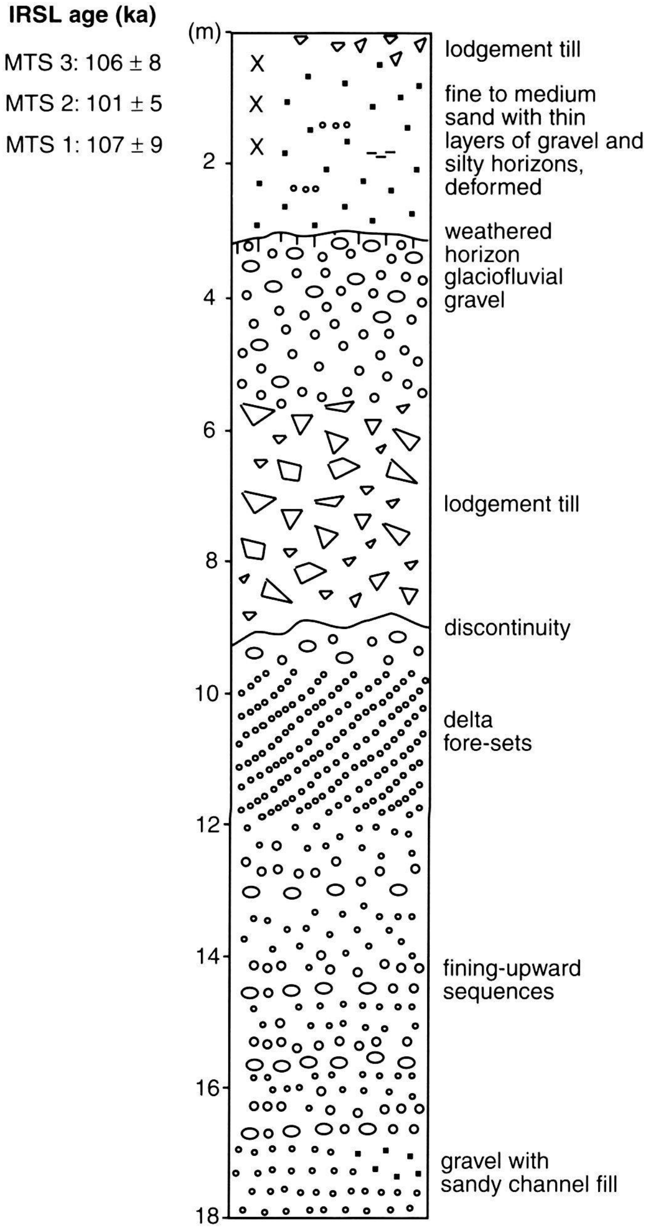

Fig. 4. Schematic sketch of the Mattstetten site, modified after Lauber (2003) and according to own observations with luminescence ages.

Luminescence dating

The following gives a brief overview on the methodological background and potential problems involved with the dating of sediments by luminescence methods. More detailed overviews on methodological aspects have been provided by Aitken (1998), Krbetschek et al. (1997), Wintle (1997), and Wallinga (2002).

Methodological background and potential problems

Luminescence allows the dating of sediment deposition ages. The method uses a light-sensitive signal within quartz and feldspar grains that is zeroed during sediment transport and rises during burial, when the minerals are sealed from sunlight (Aitken 1998). The luminescence signal in minerals results from the absorption of radioactive energy within the crystal lattice. As long as the mineral is not exposed to daylight the latent luminescence signal rises proportionally with time. During exposure to daylight, the mineral emits the absorbed radioactive energy as light. This emitted light is called luminescence.

The intensity of the luminescence signal is a measure of how long the mineral was sealed from sunlight. The amount of absorbed energy is called palaeodose (given in Gray (Gy); 1 Gy = 1 J kg^{-1}) and results from the time since the mineral was last exposed to daylight and from the amount of radioactive radiation within the sediment (dose rate = Gy a^{-1}). Sediment deposition ages are calculated by:

$$\text{Age (a)} = \frac{\text{Palaeodose (Gy)}}{\text{Dose rate (Gy } a^{-1})}$$

Zeroing of the luminescence signal is a prerequisite for dating sediment deposition ages. Incompletely bleached sediments will result in apparently higher age estimates. Different methods to investigate if the sediment grains were completely bleached prior to deposition are discussed by Preusser et al. (2001) and Wallinga (2002).

The upper limit of luminescence dating is reached when a mineral cannot accumulate more absorbed radioactivity. This is highly dependent on the minerals luminescence properties and differs significantly for samples from different regions. Furthermore, sediments having low contents of radioactive elements and thus a low dose rate can be dated further back than sediments having a high dose rate. Usually, samples can be dated at least to the Last Interglacial (*c.* 130,000 yr).

Luminescence methods can be distinguished by how the latent luminescence is activated during laboratory measurements. Thermoluminescence (TL) is recorded while a sample is heated up to 500° C. TL has the disadvantage that non-light sensitive components within the luminescence signal are released from the minerals as well. For dating sediments this problem is avoided by using optical stimulation by either visible (Optically Stimulated Luminescence – OSL) or infrared light (Infrared Stimulated Luminescence – IRSL).

Laboratory procedures

The amount of radioactive elements (K, Th, U) was determined by high-resolution gamma spectrometry as described by Preusser & Kasper (2001). An average internal potassium-content of the feldspars of 12.5 ± 0.5 % has been used following Huntley & Baril (1997) and Clarke & Rendell (2003). Moisture was assumed on basis of sediment composition and the

Tab. 1. Summary information for luminescence dating. Given is the samples grain-size used for dating; the number of aliquots measured and passed through the criteria of the SAR protocol; concentrations of radioactive elements determined by high-resolution gamma spectrometry; assumed sediment moisture and sample depth below present surface as used for determination of the contribution of cosmic radiation; resultant dose rate; palaeodose (ED) for IRSL and OSL measurements and resulting IRSL and OSL ages.

Sample	Grain size (µm)	n	K (%)	Th (ppm)	U (ppm)	Moist. (%)	Depth (m)	D (Gy ka^{-1})	ED_{IRSL} (Gy)	ED_{OSL} (Gy)	Age_{IRSL} (ka)	Age_{OSL} (ka
MTS1	200–250	9/9	1.97 ± 0.04	4.14 ± 0.19	1.10 ± 0.04	15 ± 5	5 ± 2	2.97 ± 0.14	318.7 ± 24.0	–	107 ± 9	–
MTS2	150–200	8/8	1.91 ± 0.04	4.00 ± 0.18	1.10 ± 0.04	15 ± 5	5 ± 2	2.78 ± 0.13	281.5 ± 7.8	–	101 ± 5	–
MTS3	150–200	8/8	1.96 ± 0.04	3.40 ± 0.16	1.01 ± 0.03	15 ± 5	5 ± 2	2.76 ± 0.13	292.6 ± 16.4	–	106 ± 8	–
THG10	4–11	8/8	1.94 ± 0.04	13.02 ± 0.60	4.39 ± 0.15	30 ± 5	11 ± 4	4.16 ± 0.37	391.2 ± 7.1	476.2 ± 8.2	94 ± 8	114 ± 10
THG9	100–200	9/8	2.07 ± 0.04	6.99 ± 0.32	1.74 ± 0.06	10 ± 5	11 ± 4	3.29 ± 0.19	403.2 ± 17.3	–	122 ± 9	–
THG8	100–200	11/8	2.17 ± 0.05	7.73 ± 0.36	1.77 ± 0.06	10 ± 5	11 ± 4	3.44 ± 0.19	472.6 ± 24.1	–	138 ± 10	–
THG7	100–200	12/8	2.24 ± 0.05	10.10 ± 0.46	1.82 ± 0.06	10 ± 5	11 ± 4	3.68 ± 0.20	419.4 ± 14.6	–	114 ± 7	–
THG6	100–200	8/8	1.83 ± 0.04	13.10 ± 0.60	3.79 ± 0.13	20 ± 5	11 ± 4	3.67 ± 0.19	390.0 ± 12.8	–	106 ± 6	–
THG6	4–11	8/8	1.83 ± 0.04	13.10 ± 0.60	3.79 ± 0.13	20 ± 5	11 ± 4	4.26 ± 0.38	381.4 ± 7.4	480.6 ± 10.4	90 ± 8	113 ± 11
THG5	4–11	8/8	1.55 ± 0.03	8.57 ± 0.39	2.19 ± 0.07	30 ± 5	11 ± 4	2.73 ± 0.22	355.0 ± 5.1	408.3 ± 13.9	130 ± 10	149 ± 13
THG4	4–11	10/8	1.70 ± 0.04	8.93 ± 0.41	2.35 ± 0.08	30 ± 5	11 ± 4	2.93 ± 0.23	371.8 ± 19.7	395.2 ± 25.0	127 ± 12	135 ± 14
THG3	4–11	10/7	1.05 ± 0.02	5.37 ± 0.25	2.22 ± 0.08	20 ± 5	12 ± 4	2.27 ± 0.20	307.6 ± 15.0	313.3 ± 16.4	136 ± 14	138 ± 14
THG2	4–11	8/8	1.04 ± 0.02	6.51 ± 0.30	2.32 ± 0.08	20 ± 5	12 ± 4	2.41 ± 0.22	311.2 ± 7.2	325.4 ± 12.5	125 ± 12	132 ± 12
THG1	4–11	8/8	1.03 ± 0.02	5.73 ± 0.26	1.91 ± 0.06	20 ± 5	12 ± 4	2.17 ± 0.19	272.6 ± 7.8	287.1 ± 3.4	125 ± 12	135 ± 13

contribution of cosmic radiation to the dose rate was calculated using present day depth. An a-value of 0.07 ± 0.02 was used.

Sand-sized samples used for luminescence measurements were first sieved and subsequently pre-treated by 10 % HCL and 30 % H_2O_2 to remove carbonates and organic matter. K-rich feldspars were separated using heavy liquid and fixed on stainless steel discs for measurements. The modified single-aliquot regenerative-dose (SAR) protocol as described by Preusser (2003) was applied for the determination of the palaeodose of K-rich feldspars using IRSL. Silt-sized samples were prepared following Frechen et al. (1996). Measurement of the palaeodose was carried out using the SAR protocol of Banerjee et al. (2001). A pre-heat of 270° C for 10 s was applied and IRSL and OSL were subsequently recorded during a 100 s shine-down of IR and blue emitting LEDs, respectively. The first 20 s of the signal were integrated for the reconstruction of dose response curves.

Results

The results of dose rate and palaeodose measurements are summarised in Table 1. The consistency of ages determined at each site indicates that incomplete bleaching of the luminescence signal prior to deposition does not apparently affect these samples. Similar experiences were found with distal glaciofluvial sediments from Bavaria and other parts of Switzerland (Preusser & Graf 2002; Fiebig & Preusser 2001, 2003; Preusser et al. 2003). Furthermore, the scatter of different small aliquots measured from the same sample is rather small. It is concluded that the IRSL and OSL ages are not overestimated due to incomplete bleaching of the luminescence signal prior to deposition.

For the Thalgut site (Fig. 3), three important findings have to be considered. First, IRSL and OSL ages of 127 ± 12 ka, 135 ± 14 ka, 130 ± 10 ka, and 149 ± 13 ka determined for the lacustrine sediment (THG 5–6) agree very well with the expected Last Interglacial age of the horizon as deduced from pollen assemblages (Welten 1982). This indicates that the dating approach being used operates accurately and that the luminescence results have to be considered as reliable. Secondly, luminescence ages obtained on the sand layer below the lacustrine deposits (THG 1–3) that scatter between 125 ± 12 ka and 138 ± 14 ka are indicating a Last Interglacial to latest Penultimate Glacial-age for this horizon. Since the sandy horizon apparently represents a continuous transition from the deposition of the delta sediments to the lacustrine deposits, it is deduced that the "Kirchberg-Deltaschotter" correlates with late MIS 6 (186 – 127 ka). Thirdly, luminescence ages from the sandy horizon on top of the Last Interglacial deposits (THG 6–10) range between 90 ± 8 ka and 138 ± 10 ka and demonstrate that no significant break in sedimentation is recorded in this sequence since the dates are interpreted to represent a late Last Interglacial to early Last Glacial age of the sediment.

The three samples dated at Mattstetten gave IRSL ages of 107 ± 9 ka (MTS 1), 101 ± 5 ka (MTS 2), and 106 ± 8 ka (MTS 3). These dates agree within their standard deviation and indicate an early Last Glacial age of the sandy horizon.

Discussion

The sand beds below and above the Last Interglacial limnic deposits at Thalgut are interpreted to represent an apparently continuous transition from high to low-energy sedimentary conditions and *vice versa*. It is assumed that due to high sedimentation rates these horizons represent deposition over a short time period. The luminescence ages determined for the two horizons are interpreted to reflect more-or-less the age of the gravel units. According to the dating results, it appears that

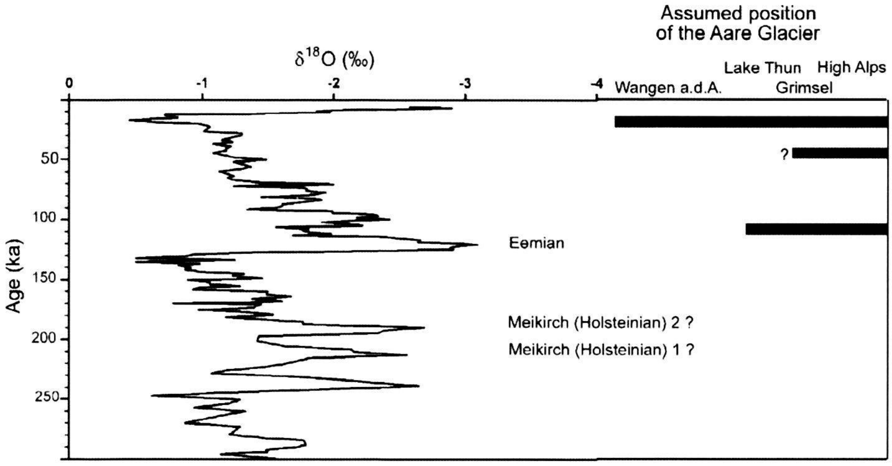

Fig. 5. SPECMAP stag of site Md900963 from the Maldives area as an archive of climate variability and global ice volume (Bassinot et al. 1994). Also indicated is the expected relative position of the Aare glacier during different times of the Würmian glaciation.

the "Kirchberg-Deltaschotter" correlates with late MIS 6 and the lower unit of the "Obere Münsingen Schotter" with MIS 5d (122 – 106 ka). Deposition of the lower unit of the "Obere Münsingen Schotter" took place presumably in the proximity of the Aare glacier. IRSL ages determined for the sand unit at Mattstetten also indicate a MIS 5d age but reflect reworking of sediment under presumably periglacial environmental conditions. Similar sandy deposits are frequently recorded in the region around Mattstetten and thus apparently represent an important depositional event in that area. It is reasonable to assume a considerable availability of water as a prerequisite for such a substantial fluvial activity. Consequently, it is assumed that deposition took place during a period of reduced vegetation cover, probably due to low (summer) temperatures, but with at least seasonally humid conditions.

Sedimentary evidence for a significant glaciation reaching into the Lake Zürich basin during the earliest Late Pleistocene has already been discussed by Preusser et al. (2003). At Meikirch, Welten (1988: 11) reported the presence of a second lodgement till in the lower part of the gravel unit below the overbank deposits he attributed to the first Würmian Interstadial. This led us to re-examine the remaining sediment cores of the Meikirch 1981 drilling. The presence of diamictic material just above the lacustrine sediments could be confirmed, though, it was not possible to prove its glacial origin. Another potential problem is that the pollen of *Picea* and *Pinus* found in the overbank deposits above this potential lower till maybe re-worked.

If the diamict is of glacial origin and if the pollen within the overbank are *in situ*, this would prove the presence of a glacier in the Meikirch area during the early Late Pleistocene. However, why has so little evidence been found of such an important glaciation of the Alps at other sites? One aspect certainly is that this glaciation was of smaller extent than the Würmian maximum during MIS 2. Hence, most morphological features and sediments of this earlier glaciation were removed by subsequent glacial erosion or were deeply buried by LGM glacial deposits. Conservation and accessibility to sediments of glaciations smaller than LGM will thus be only possible at exceptional sites like e.g. Thalgut, Meikirch, and Gossau. Furthermore, in many sequences clear discontinuities such as the weathered horizon at Thalgut might have been eroded, making recognition of important breaks in sedimentation almost impossible. It is difficult to judge if a discontinuity, like the lower one observed at the Mattstetten site, represents a longer time period or is just due to changing aggradational dynamics. From the palaeoclimatological point of view, it is noted that cool and wet conditions during the earliest Würmian as reconstructed from pollen assemblages (Welten 1981, 1982; Guiot et al. 1989; Wegmüller 1992) must have triggered important glacial advances. A glaciation of the Alps during MIS 5d would thus well fit into the reconstructed palaeoclimate evolution.

Mangerud (1991) postulated that the growth of the Last Glacial Scandinavian ice sheet already started about 110 ka ago, during MIS 5d. It is assumed that this ice melted down during MIS 5c (106–97 ka) but another ice sheet developed during MIS 5b (97–86 ka). Both early Last Glacial ice sheets did reach the coastal area but were significantly smaller than the glaciation during MIS 2. A glaciation during the early Würmian was later confirmed by evidence from the Scandinavian Sea (Baumann et al. 1995), Svalbard (Mangerud et al. 1998), and northern Eurasia (Henriksen et al. 2001; Houmark-Nielsen et al. 2001, Mangerud et al. 1999, 2001; Svendsen et al. 1999). It appears that early Last Glacial expansion of glaciers occurred not only in the Swiss Alps, but in more northerly regions as well. A significant increase of global ice volume is also reflected in the low-latitude $\delta^{18}O$ records (Fig. 5).

Conclusions

Luminescence dating of the Thalgut site demonstrates that reliable dating of such sediments is possible using the SAR feldspar technique. This is contrary to earlier work which concluded that luminescence dating of feldspars using the SAR approach is of limited use due to a significant and systematic age underestimation (Wallinga et al. 2000, 2001). However, it has to be considered that these conclusions were exclusively drawn from sediments of the Rhine-Meuse system. Recent evidence from the Alpine Foreland demonstrates that feldspars from this region have different luminescence properties and give reliable dating results of up to at least 130,000 yr (Erfurt et al. 2003; Preusser 2003).

The Thalgut site gives further evidence for a considerable glaciation of the Swiss Alps during the early Würmian (MIS 5d). It is assumed that this glaciation was of smaller extent than the ice advance during MIS 2. Important sediment accumulation under periglacial conditions is recorded in the Mattstetten quarry. Deposition of the sandy sediment was probably initiated by weathering of molasse bedrock in the western part of the Swiss Plateau during the Last Interglacial. With the decline of forest vegetation during the on-set of the Würmian, the sandy material was easily eroded, most likely transported by local streams and deposited at the eastern margin of the Aare Valley.

Our results demonstrate that sedimentary dynamics during the Late Pleistocene were much more complex than previously assumed. It is concluded that there were probably more substantial Pleistocene glaciations of the Alps than indicated in the long established concept based on Penck & Brückner (1901–09), with only four "maximum glaciations". However, phases of smaller than LGM glacier extent are poorly preserved as these were eroded or deeply buried during the Würm glaciation *sensu stricto*. The complexity of Pleistocene sedimentary dynamics agrees with the reconstructions of the vegetation history that reveals phases of climatic deterioration during the early Late Pleistocene that must have triggered glacial advances within the Alps.

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